Pacific Minerals in the New Millennium

Science, Exploration, Mining and Community

The Jackson Lum Volume

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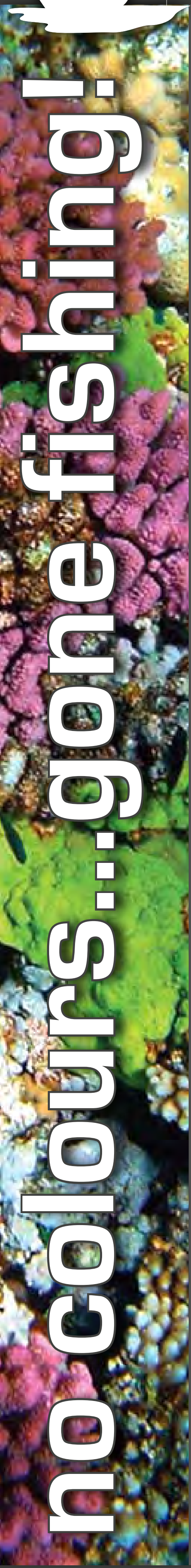

Obituary: Jackson Lum 12th May 1954 to 31st May 2001

JACKSON LUM

Many an exploration geoligist ater a long toil in the sun looking for gold up the creeks on our Pacific islands knows well the meaning of “no colours”. The frustration of finding no sign of a new gold prospect. It might well be softened at the thought of going fishing. Jackson Lum, an exploration geologist by profession, gave up a long toil with cancer when he passed away peacefully at his home in Suva at the young age of 47. Jack has gone fishing.

To many who know him, outside of his private family life, Jack had two passions; one was his work and the second fishing.

His work involved an all too short a career during which he spent over half as a servant of the region. Born in Ba, Fiji, Jack was educated at Xavier College and the University of the South Pacific before joining the Fiji Mineral Resources Department. Subsequently, at the University of Leeds he gained a Masters degree in geochemistry. Following further work back in Fiji, Jack began his regional career first at the East-West Centre at the University of Honolulu and then to the South Pacific Applied Geoscience Commission (SOPAC) where he has been head of the Mineral Resources Unit for the past nearly 9 years.

His career has taken him into the field in many Pacific island countries, notably in Melanesia. During these times in “the bush” Jack honed his knowledge of the region, about its geology and the people. For sure, during bush-life with local field assistants he developed his deep desire to pass on his skills to other nationals from the region. He was a good teacher. His geological knowledge of the region extended from the islands themselves and their contained mineral resources to the deep ocean floor. Whilst at SOPAC he was responsible for the overall coordination of all deep ocean mineral exploration in the region, most notably the multi-million dollar intergovernmental Japan/SOPAC Deepsea Mineral Exploration Programme which is now in its 17th year and has included work in waters of Cook islands, Federated States of Micronesia, Fiji, Kiribati, Marshall Islands, Papua New Guinea, Solomon Islands, Tonga, Tuvalu and Vanuatu. This potential seabed wealth includes the polymetallic manganese nodules, the cobalt-enriched manganese crusts as well as the hydrothemal vent massive sulphide ores with their unique biota.

Only a few years ago, Jack like many others, did not consider that licences to private companies for seabed exploration would be issued before the turn of the century. When Papua New Guinea did so, all were proved wrong, and legislation was left wanting. At the time of his death Jack had been assisting Papua New Guinea and other countries of the region with potential seabed mineral wealth, develop guidelines to assit them with developing their offshore mining potential. The “Madang guidelines.....” produced in 1999 will live as testimony to Jack’s efforts in this regard.

Back “on island” Jack’s regional knowledge of mineral potential was second to none. He provided ongoing advice to Kiribati with work on the phosphate deposit on Banaba as well as the much lesser known gypsum deposit on Malden. But inevitably it was the islands of Melanesia that dominate the “Pacific Ring of Fire” in the south and west Pacific that commanded much of Jack’s time. When Solomon Islands was moving forward to reopen Gold Ridge, Jack was recruited as an adviser to the Government. When Vanuatu wanted an education programme for landowners about mineral exploration they turned to Jack. In Fiji following on from his earlier career days with Mineral Resources, Jack spent his last days in the field loking for gold ‘colours’ in the Nasivi River delta draining across the Tavua Volcano that contains the Vatukoula Gold Mine. These “colours” maybe leading the way to alluvial gold dredging in the furture.

Throughout his working life Jack was fascinated by the potential for alluvial (placer) gold potential around the high islands of Melanesia. In his paper “Placer Gold Potential of Fiji, Solomon Islands and Vanuatu”, published in 1995. Jack’s words express clearly his passionate belief.

“Although most of the South Pacific deposits were discovered by following “colours” in the respective rivers and coastline, there is so far no major discovery of a large economic placer occurence. Why ? Simply there has been little or no exploration ....”.

Jack’s other passion, fishing, brought with it all and more of the usual fishing stories about the one that got away. Whatever the yarn about what happened fishing was never any doubt about Jack’s passion for fishing left in the mind of a person who had the privilege to watch him prepare the sashimi from the unfortunate tuna that didn’t get away.

As the sun sets over Dogowale, the evening shadows are cast on the peace and tranquility of Yarawa Bay and Serua Reef, a favourite fishing area of Jack’s along the southern Viti Levu coast. Jack is now at rest, gone fishing, after an all too short a career looking for “colours”.

Sadly, the region has lost a sincere and faithful servant. To Norah and family members, we extend to you our deepest sympathies.

PACIFIC MINERALS IN THE NEW MILLENNIUM: SCIENCE, EXPLORATION, MINING, AND COMMUNITY

The Jackson Lum Volume

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INTRODUCTION

It gives me great pleasure to introduce this volume which focuses on exploration, scientific, political, economic, cultural, environmental and social issues related to mineral development. It is unusual that such a wide range of issues are addressed in one volume and I am particularly pleased that there are notable first-author contributions from Pacific Island nationals. I am sure that this volume will contribute to mineral development and the various related complex strategic planning issues for many years to come.

The volume began life as a series of oral presentations and abstracts presented at the Tanoa Hotel, Nadi, Fiji, on 23 - 25 September 1998, although several of the papers have been submitted by other interested researchers who could not make the original meeting.

The papers are arranged in thematic order and address key themes such as: political, economic, social and environmental factors which influence mineral development at local, regional and global scales; the vital importance of industrial minerals to the development of Small Island Pacific states; recent interpretations of airborne geophysical surveys flown over Fiji; the implications of geotectonic modelling and exploration methodologies for metallogeny in Solomon Islands and Fiji; the first geological map of the last large Solomon island to be mapped; and an analysis of mineralising hydrothermal systems. This variety of themes is central to the SOPAC mission which aims to deliver high quality and relevant applied geoscience for the benefit of all Pacific people.

Allen Clark introduces the volume with an analysis of regional and worldwide economic, social, environmental and political issues which are impacting on the mining world of today. Dr Clark stresses the importance of mining companies engaging in dialogue with communities at all levels to ensure the success of a mining proposal.

Graeme Hancock reviews the history of mining and mineral exploration in PNG from 1888 to the present day. Dr Hancock's paper underlines the importance of mines such as Misima, Lihir, and Porgera to the economy of PNG and highlights a number of future prospective areas.

George Niumataiwalu presents his thinking on the impact of mining on communities in Fiji. Sustainable development may provide a potential successful framework for diverse stakeholder involvement at all levels in the community and assist key decision makers in developing strategic mineral plans which aim to benefit a wide range of society and minimise environmental impact.

Donn Tolia describes the key elements of the geology of Solomon Islands and its relevance to mineral exploration. Dr Tolia's paper documents the lead up to the successful development of Guadalcanal's Gold Ridge mine proving that the Solomon Island Government can work successfully with international mining companies and reach amicable deals. This partnership benefits a wide range of the local community, government at regional and national levels and the operating mining company.

Russell Maharaj presents two papers on construction aggregate minerals for FSM. Dr Maharaj's work is an excellent example of the vital importance of industrial minerals. Whilst gold and platinum are very 'pretty' and 'precious' it is the relatively low value bulk-minerals (often the Cinderella of the minerals world) which are most important to most people. These resources provide the basic building materials of roads, houses and wharfs to name but a few. It is essential that governments of Small Island States plan aggregate mineral development in a way which is in sympathy with fragile Pacific ecosystems.

Peter Gunn and colleagues and **Bina Singh** present a thematic suite of three papers which present and interpret recent airborne geophysical data for Fiji. The papers are a tremendous contribution to the understanding of the geological and tectonic development of Fiji and its related mineralisation. The geophysical interpretations have a wide variety of implications and applications including suggested revisions of accepted geological maps and models and a demonstration of the close causal links and associations between, for example, porphyry copper mineralisation, and the volcanic-plutonic-structural development of the Namosi area.

Mike Petterson and colleagues demonstrate how recent geotectonic models of Solomon Islands and related arc-oceanic collages which develop in close proximity to highly oblique subduction zones have fundamental significance for metallogeny and mineral exploration Programmes both in the Pacific and in older intra-continental terrains.

James Stratford presents a new interpretation of the geotectonic development of Fiji and the causal links with mineralisation. Dr Stratford shows that Fiji has developed through four major 'epochs' from >40Ma to the present day which correspond to: primitive arc development; Vityaz arc development; Vityaz arc breakup; and intra-plate activity. It was during epoch 3 (Vityaz arc breakup) in Miocene Recent times that the best known mineral deposits of Fiji were formed.

Howard Colley reviews the exploration methods associated with 38 exploration Programmes undertaken in Fiji between 1976 and 1998: two of these led to mine development or mine feasibility (Tuvatu and Mount Kasi). Panning has proven to be the most effective exploration method although Professor Colley highlights the benefits of other methods such as stream sediment surveys and geophysical exploration.

Mike Petterson and colleagues document the results of the recent geological survey of Makira, the last of the large Solomon islands to be mapped. Over 90% of Makira is underlain by a Cretaceous Tertiary basic-ultrabasic-carbonate assemblage of mixed oceanic provenance.

Phil White emphasises the importance to mineral exploration of understanding the effects of disequilibria and thermal overprinting in fossil and active hydrothermal systems. Progressive overprinting which increases the ambient temperature of long-lived hydrothermal systems (due to magma ingress for example) often leads to significant mineralisation. Dr White uses case studies from Indonesia and PNG to illustrate his remarkable theories.

Finally I cannot let the opportunity go by to pay tribute to our close friend and colleague, Jackson Lum who was taken away from us at the young age of 46 in April 2001. Jackson was the epitome of the gentleman-geologist: a true pioneer mineral explorer who won the hearts and minds of people from all over the Pacific. Jackson's demonstration of professional integrity and competence coupled with his high-level diplomacy and sensitivity skills and acumen are an example for us all. Jackson was a real ambassador for our science, our service, and our industry. Jackson will be sadly missed but at least he will have the consolation that his work will live on and stimulate research and exploration for decades to come. We pay tribute to you Jackson and thank you for your tremendous contribution to our science, our region, our world and our minds, and, most importantly, our hearts. May you rest in peace.

Compiler & Editor

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[1]Papers interpreting data acquired through the substantial AusAID-funded Fiji Airborne Geophsycial Survey are published with the permission of the Government of Fiji, Mineral Resources Department.

[2]The geophysical signatures paper which first appeared in the Australian Geological Survey Organisation's Preview Issue 76 (Oct/Nov 1998) is published with the permission of Geoscience Australia.

EMERGING CHALLENGES AND OPPORTUNITIES FOR PACIFIC BASIN MINERAL DEVELOPMENT

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ABSTRACT

As a result of strong economic growth and increasing metal demand within the Pacific region the size and the scope of the minerals industry has increased dramatically within the last decade. With this growth, however, have come an increased number of environmental, social and cultural issues that the industry must address in cooperation with individual governments as well as a large and expanding group of stakeholders.

This paper addresses many of the critical issues that exist, or are emerging, within the Pacific region that have, or will have, a major impact on the region's rapidly evolving mining industry in the 21st century. One of the most significant of these changes are changes in national policy and legislation that result in the flow of exploration and development expenditures to individual countries or regions; most recently to South America and in particular to Chile. Equally important is the allocation of significant decision making power and authority from national governments and industry to local government (through decentralisation) and diverse stakeholders (through people empowerment). Impacting on the above changes is the emergence of a large number of international treaties, agreements and guidelines, largely resulting from the efforts of environmental and social NGOs, which further impact on industry. The extent to which governments and industry are able to anticipate and respond to these changes will determine, to a large extent, the nature and scope of mineral development within the Pacific region in the 21st century.

The existing Asian economic crises and present and possible changes in the minerals industry of China will be major determinants of the growth of mineral demand within the Pacific region and, therefore, will strongly *impact* the scope of the mineral industry both in the near and longer term.

INTRODUCTION

During the last decade several major structural changes have significantly impacted both the world's mining industry and the nations in which industry operates. The most significant of these changes has been (a) geographic shifts in exploration and development expenditures; (b) changes in minerals policy and legislation; (c) reallocation of decision-making power and authority; (d) the emergence and dominance of social-cultural issues, (e) the emergence of global constraints and (f) the increased role of NGOs. Two additional issues that are having, and will continue to have, a major impact on the mining industry of the Pacific region specifically are the Asian economic crises and the mineral industry and policy of China.

The purpose of this paper is to discuss the above issues in terms of the main causes for the changes, how industry and government have, and will need to, adjust to these changes and their potential impact on the Asia Pacific mining industry in the 21st century.

Geographic shifts in exploration and development expenditures

Throughout the 1980s and the early 1990s mineral industry investment in exploration and development was overwhelmingly (approximately 70%) concentrated in the United States, Canada and Australia and predominately in gold and copper activities (Clark, 1994; Clark and Naito, 1997). In the early-to-mid 1990s, a dramatic shift began to occur in international exploration and development investment with major expenditures being concentrated in South America and in particular in Chile (Mining Journal, 1996a). The hallmarks of this shift, and the "opening up" of Chile, were the revision of Chile's investment laws and the resulting discovery and development of the Escondida Copper Deposit. The opening up of Chile very quickly led to similar changes in investment laws and increased exploration and development expenditure levels in other South America nations (Mining Journal, 1996b).

The experience of the Pacific region has been similar to that of South America in that periods of expanded exploration and development activity have been, and continue to be, closely correlated with changes in investment laws and significant discoveries. The discovery of the porphyry copper deposits of Bougainville, Ertzberg and Ok Tedi in the late 1960s and 1970s and the epithermal gold deposits of Porgera, Lihir and Misima in the 1980s all had a catalytic effect on exploration and development within the region. During the same period changes to the mining law of Papua New Guinea and the Contract of Work (COW) in Indonesia (Clark, 1997) created favorable investment regimes.

More recently, in Indonesia, the discovery of the Batu Hijau copper/gold deposit, the development of the Mount Muro gold deposit, and the expansion of the Ertzberg/Grazberg deposits and ironically even the infamous "Busang Debacle" have fueled a recent increase in exploration and development expenditures within Indonesia specifically and the region overall. Given the high level of exploration and the number of significant discoveries in Australia, Fiji, Indonesia, Papua New Guinea and the Philippines there is little doubt that the Pacific region will remain a focal point of mineral exploration and development well into the 21st century.

Conversely, anticipated increases in the levels of private sector investment in mineral exploration and development in Central and Northern Africa, Brazil, China, India, Central Asia and the Russian Far East remains highly problematic (Clark, 1995). Although these areas have both a large known, and perceived, mineral potential the uncertainty with respect to the stability and competitiveness of their present mineral investment regimes is a major deterrent to increased exploration and development expenditures.

Structural changes in mineral policy and legislation

As noted earlier, changes in mineral policy and legislation have been a major factor in increasing the scope and distribution mineral exploration and development investment. During the period 1985 to 1995 a total of approximately 75 nations made changes to national policy, legislation or implementing rules and regulations and of these over 35 enacted or made major revisions to both their mining and investment laws. In the Pacific region, during the last five years (1995 - 1999), new Mining Laws have been implemented in the China, Lao PDR, Mongolia, Myanmar, Philippines, Russia, and Vietnam.

According to (J C Clark, 1996) the majority of the changes in mineral policy and legislation have focused on creating a more liberal investment climate characterized by providing increased security of title, "one-stop" processing of applications, assurances for repatriation of profits, corporate management and equity control and more liberal fiscal regimes. The liberalisation of the fiscal regimes has been characterized by allowances for loss carry-forward, accelerated depreciation and duty-free import of equipment and supplies.

It is important to note that of all the issues being addressed by modern mining legislation, the issue of security of title remains the most difficult issue in most countries and, where not effectively dealt with, constitutes a major disincentive to mineral investment and development (Clark and Naito, 1997). Normally, security of title issues arise with respect to three main areas: (1) conflicting claims or unresolved ownership issues, (2) the direct transfer, under prescribed requirements, from an exploration licence to a mining licence, and (3) the conflict between public policy and land access/title which often establishes priorities for use that preclude mining. One of the most dramatic examples of the latter issue occurred recently in Australia with respect to the Lake Cowal development where the New South Wales government has vetoed a US$940 million proposed gold mine citing concerns for surrounding wetlands and bird life (Askew, 1998).

For the future it is to be anticipated that mineral policy and legislation can be expected to continue to be redrafted or modified to accommodate changes in fiscal regimes that would increase investment in the mining sector. They may, however, result in less flexibility in development negotiations. It is also anticipated that policy and legislation will be altered significantly to incorporate broader and/or more specific provisions with respect to environment and social-cultural responsibilities, particularly with respect to the creation of compliance funds, post-mining rehabilitation provisions and sustainable development.

Reallocation of decision-making power and authority

There should be little or no doubt within either governments or industry that there has been, and continues to be, a major shift in the "power" base of decision making, with respect to mineral resource development, in all countries. This is well exemplified by recent experiences at Mount Kare, Bougainville, Gold Ridge, Coronation Hill, Mabo Island, Ertzberg/Grazberg, Ok Tedi, Marcopper, Windy Craggy and Omani where local citizens and action groups have substantially altered development objectives of both government and industry.

This shift in "power and authority" is the result of two emerging trends, i.e., "people empowerment" and "decentralisation," both rather ill-defined terms but exceedingly powerful concepts for the people involved. In simplistic terms "people empowerment" refers to an increased role for local or indigenous communities in decision making whereas "decentralisation" refers primarily to a transfer of government fiscal and decision-making powers from the national government to the provincial or local government levels. The results of both trends are essentially the same, i.e., the success or failure of a mineral development is no longer primarily a joint decision by industry and government but a decision resulting from negotiations with a broad range of "stakeholders". An ancillary, but critical, aspect of people empowerment and decentralisation is that both changes normally result in a larger and larger portion of the net revenues, acquired by the nation from the development of its resources, being transferred to the local levels of government. As an example, under the *Local Government Act of the Philippines*, 35 percent of the net Government revenues from resource development are returned to the provincial, city and baranguay level. As a result, indigenous populations, local communities and local governments not only have vastly increased decision-making powers but also have significant economic power. From the perspective of the national government and industry, "people empowerment" and "decentralisation" present a new and broader set of concerns to be addressed. Failure to address these issues, as was the case in Indonesia and Papua New Guinea, can, in extreme circumstances, lead to civil unrest and changes of government.

From the perspective of the national government, the return of mining revenue to the provincial and lower levels of local government represents a loss of control over how the funds will be expended, a decrease of funds available for national programmes, and an increase in friction over the use of shared revenues for local versus national programmes.

From the perspective of industry, the return of revenues to the provincial level and lower levels of government is a mixed blessing. At the national level, the transfer of fiscal receipts to local governments may significantly reduce the leverage of industry with the national government. Conversely, at the provincial government level there is more money available that is specifically identifiable with the mining project; in most cases this is a distinct positive for the mining venture. Conversely, any downturn in the profitability of the mine is immediately translated to lower funding at the provincial level causing discontent and unfulfilled expectations: distinct negatives for industry.

The adaptation of government, industry, local government and other stakeholders to decentralisation and revenue sharing may require a considerable transition period before the working relationships between all of the parties can be outlined and, more importantly, accepted. To insure that this transformation is successful it is imperative that both industry and the national government recognise and accept the transformation of power and responsibility to local government units and develop new procedures to deal with a changing decision making environment. Central to achieving this goal will be increased transparency, dialogue and interaction, at all levels of government and with special interest groups, in the decision-making processes.

Emergence and dominance of social-cultural issues

Perhaps the greatest impact of decentralisation and people empowerment is the ever-increasing role that social and cultural issues now play in the overall decision-making process (Clark and Naito, 1997). The importance of these issues has been recognised by most major mining corporations for over two decades. However, even the most enlightened companies have not adequately understood or dealt with these issues.

Assessing the critical social-cultural issues associated with mineral development is both a complex and a constantly evolving task for which there are very few guidelines. The lack of generally acceptable guidelines arises from the time-honored, and generally correct, assertion that every area and every development is different. When this is coupled with the fact that the social and cultural assessment activities that need to be undertaken are substantial departures from the norm for most mining companies, it is easy to understand why difficulties arise and why they are so difficult to resolve.

The social-cultural impacts of individual mineral developments vary significantly, depending on the level of economic and social development already extant in the vicinity of the proposed mining development. This can range from the primitive levels of development that characterised the Ertzberg (Indonesia) and Ok Tedi (Papua New Guinea) mining areas to the advanced levels of development associated with many mines within established mining districts in Canada, the United States and Europe. As a general rule it can be asserted that cultural issues are more critical in areas of less development and social issues are more important in areas of more advanced development. A logical and important extension of this rule of thumb is that over the life of a mine in a remote area, the basic problems will move from cultural to social, i.e., social-cultural change is dynamic.

In general the major broad social-cultural issues that arise out of mineral development, and that industry must address (A L Clark, 1996), are those associated with (a) the impacts from environmental changes, (b) the disruption of societal organisation and cultural values, (c) inequitable income distribution, (d) unresolved land access and/or compensation issues, (d) relocation and migration adjustment problems (e) uneven distribution of government services and (f) the loss of local control over major decisions. In attempting to deal with impacts of the above issues it is important to recognise that the resulting social and cultural impacts are largely irreversible and that most arise because the process of change is rapid but the capacity to change is slow.

In dealing with the rapidly expanding scope and intensity of social-cultural issues an unmistakable trend is for industry to reduce its dependency on the national government in the resolution of such issues. Although government will, and should, continue to play an important role the emerging realities associated with people empowerment and decentralisation, as noted before, dictate a larger role of industry. Central to fulfilling this new role is that industry develop and implement use of new techniques such as social-cultural impact assessments (SCIA) and social-cultural compliance plans (SCCP) for mineral developments. Both the SCIA and the SCCP require that industry and government recognise and plan for social cultural changes throughout the life of the mine and that they also adopt and demonstrate flexibility and a continuing positive attitude toward the resolution of issues that arise. A programme of continuing dialogue and education with respect to the mines' activities and the efforts of industry to accommodate social-cultural change must be the cornerstone of these activities.

It is also critical to recognise, contrary to the conventional wisdom that has guided many mining companies in the past, that social-cultural costs will escalate, not decrease, over the life of the mine. These increasing costs must be recognised and accounted for in overall development planning.

Emergence of global constraints and the role of non-governmental organisations

Perhaps one of the least understood and most important issues facing the mining industry today is that of the myriad of global constraints, such as international treaties, agreements, voluntary guidelines and standards that are being impressed on both individual nations and industry. The chief sources of these global constraints are international lending and insuring agencies, international aid agencies, economic blocs, non-governmental organisations (NGOs) and corporate shareholders. Each of these groups, at any point in time, has a specific agenda with respect to the actions of the mineral industry; however, the majority are reacting directly or indirectly to environmental and social-cultural activism.

The number of NGOs that are focused solely on the mining industry is relatively small and, compared to many NGOs, are relatively poorly funded. They are however extremely effective in marshaling national and international opinion against the mining industry whenever the opportunity arises which is unfortunately all to often. This raises the question if the group is small and modestly funded why have they become so effective in their campaign against mineral development? A portion of the answer lies in recognising that the rapidly expanding NGO community is, in general, is increasingly better organized and coordinated at the local level; has instant communication internationally, in particular with the print media, through the Internet; have become much more knowledgeable about the industry at both a technical and managerial level and, most importantly, have focused their attention on setting or influencing the agenda of the above mentioned lending/insuring institutions, international conventions, trading blocs and corporate shareholders.

As a result of the above the NGOs have been particularly successful in both directly and indirectly developing and managing the international agenda The "Basel Convention" and the "Environmental Summit" in Rio de Janeiro, Brazil represent two obvious examples where NGOs played a pivotal role, in agenda setting which resulted in both positive and negative impacts on the international mineral industry.

Overall the mining industry has recognised the growth of global constraints but to date has been relatively unsuccessful in constructively influencing the global agenda for such constraints. As a result, the mining industry is faced with the task of becoming a more active participant in global decision making through the development of the same type of network that the NGOs employ in order to more effectively put forth its message to the groups which set the global agenda. Additionally, industry must establish, regardless of the difficulties, effective communication and cooperation with individual NGOs and adopt an expanded proactive approach in the development and acceptance of voluntary standards and codes of conduct, such as those exemplified by the "Berlin Guidelines," and "ISO – 14000."

Emerging issues impacting the region's mineral industry

A host of specific issues are having an effect on the minerals industry of the Asia-Pacific region which are of greater or lesser importance depending on the individual nations being most impacted. There are, however, at least two issues that are of overall interest to the region, i.e. the impact of the Asian economic crises and the changing role of China.

The Asian economic crises have already resulted in a number of fundamental changes in the individual nations of the Asia-Pacific region, the change in government of Indonesia being the most dramatic, and it is anticipated to result in even more changes as the individual nations and the region struggle to recover. According to the Clark (1998) the key impacts on the regions mining industry will arise from the linkages between economic growth and the ability of the industry to respond to changes in demand for mineral resources. These include:

1. a reduced demand for cement and iron and steel for infrastructure and for base metals in the building sector;

2. large-scale mine developments within the region that will most likely be delayed until the economy of the region improves.

3. Overall exploration within the region will decrease, particularly that undertaken by domestic and junior mining companies

4. Major importers, such as the Peoples Republic of China and major refining nations such as Australia, Japan and South Korea, may ultimately benefit significantly from lower prices and a more competitive industry.

5. Gold demand will soften as disposable capital within the Asian economies decreases and gold (including bank reserves) is sold onto the market resulting in a price decrease.

Regionally and internationally the ultimate impact of the Asian monetary crises will be determined by how long they persist and how long the recovery period for the region may be. Experts are divided on this issue but it is clear that the continuing problems, particularly with the Indonesian and the Japanese economies (the latter is the region's largest metal producer and consumer) suggests that the recovery may be slow.

The Role of China in the world's mineral industry, both as a producer and consumer, has steadily increased since the inception of China's "open door" policy and as a result of the nation's strong economic growth of approximately 9 percent per year over the last decade. According to Lennon (1998), China is the second largest consuming nation in the world for lead and zinc, the third largest in aluminium, copper and tin and ninth in nickel in 1997. Overall China presently accounts for 10 percent of world demand in all metals except for nickel. Alternatively China is the world's largest producer of tin and zinc, second in lead and fourth in copper and aluminium. In the majority of mineral commodities, except for copper and aluminium, China is either more or less self-sufficient or is a major exporter (zinc and rare earths).

Because China's consumption of metals on a per capita basis is very low (Johnson and Clark, 1987, Lennon, 1998) it can be anticipated that as per capita income rises metal consumption, and hence demand, will rise also. With a population in excess of 1.2 billion people the demand impact quite obviously may be very large if the level of economic growth continues to grow at present levels.

Future growth in China's metals demand depends on three major factors i.e. the impact of the Asian economic crises on China's economy, the success of the proposed reorganisation and/or privatisation of state-run corporations (particularly for the China Nonferrous Metals Industry Corporation-CNNC) and continued export growth of metal based products to the international marketplace. In turn, the future of much of Asia's mining industry depends on the success of China in addressing the above issues. There can be little doubt that a slowdown in the economic growth of China will have far reaching effects on the global and regional metal markets and de facto on worldwide mineral exploration and development.

SUMMARY AND CONCLUSIONS

During the last decade the Pacific mining industry has undergone a period of rapid expansion, regionally and internationally, to meet the increasing demand for metals brought about by the rapid economic growth of the majority of region's nations. Particularly important to the industry has been the dramatic increase in exploration and development in the Pacific (Australia, Fiji, Indonesia and the Philippines) as a result of the discovery of a number of **"**world-class**"** mineral deposits and the development of enabling legislation and policy.

With the rapid expansion and development the mining industry during the last decade has come the requirement for the industry to change dramatically in order to meet a number of new economic, environmental, social and cultural challenges. The most critical determinant of the success with which the industry addresses these new challenges will be the extent to which industry can adjust and accommodate the changing role of industry, government and diverse stakeholders in mineral development activities.

Within the Pacific area the present Asian Economic Crises and the economic development of China will have a major influence on both short-term and long-term mineral demand and, to a large extent determine the growth on the Pacific mining industry.

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MINING IN PAPUA NEW GUINEA

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ABSTRACT

Gold was first discovered on Sudest Island in 1880, and since this time mining has been an integral part of the economy. The early discoveries led to an ongoing exploration and development for both mineral and petroleum resources which continues to the present day. Initially, attention was focussed on alluvial and high-grade hard rock gold targets on a relatively small scale. The major investment in mining came with the development of alluvial gold dredging operations at Wau and Bulolo in the 1930s. Apart from a short break during the second world war the dredging operations continued until 1965 when they closed down due to a combination of depressed gold prices and exhaustion of the available resources.

The first major hard-rock discovery to be developed was the Panguna copper deposit on Bougainville Island. It was first discovered in 1964 during a worldwide exploration effort targeted at the identification of copper resources. This period saw not only the discovery of Panguna but also the Ok Tedi, Frieda and Yanderra porphyry copper deposits. With the development of the Bougainville copper mine in 1972 Papua New Guinea entered an era of large-scale hard-rock metalliferous mining. The subsequent development of the Ok Tedi copper mine in the early eighties and the Misima and Porgera gold mines in the late eighties further expanded both the scale and scope of mining operations in Papua New Guinea. The nineties has seen the development of three more gold mines, the large Lihir mine, the Tolukuma mine and the Wapolu gold mine. In addition to the developed operations there are two more granted mining leases awaiting development at Mt Sinivit in East New Britain and at Simberi Island in the Tabar Group near Lihir.

In addition to the existing mines and two granted permits there are a significant number of other prospects that are likely to be developed at some time in the future. The advanced projects include Ramu Nickel, Morobe Gold, and the Frieda Copper Project. Less advanced but highly prospective exploration projects include the Awfi gold and copper prospect and the Mt Kare gold prospect.

The purpose of this paper is to provide an overview of the status of the mining and exploration sector in Papua New Guinea and to provide some insight into what the future holds by way of potential new developments over the next few years.

INTRODUCTION

Mining is one of the most significant contributors to the economy of Papua New Guinea. The mining industry has a relatively short history, which is primarily a reflection of the very recent geographical exploration of the country. The first significant discovery of gold was on Sudest Island in 1888 and other islands in the Louisiade Archipelago. Since this time the mining industry has been an integral part of the economy. The early discoveries led to an ongoing exploration and development effort, which continues to the present day. Initially, attention was focussed on alluvial and high grade hard rock gold targets on a reasonably small scale, mainly in the Papuan region controlled by the British authorities up until 1914. The New Guinea region was under German colonial administration until 1914 and was not open for prospecting until after the establishment of the Australian administration in 1914. The early discoveries were mostly in the islands and coastal regions of Papua. Early discoveries and developments included the Umuna and Kulumalia underground workings on Misima Island, the Kulumadau mine on Woodlark Island, and several small copper mines at Laloki near Port Moresby. The discovery of gold near Wau in 1922 by William 'Sharkeye' Park triggered the first significant exploration of the New Guinea mainland. The discovery of Edie Creek followed in 1926 with the development of the Edie Creek, Karuka and Day Dawn mines.

The first major investment in mining came with the development of alluvial gold dredging operations in the Wau-Bulolo area in the 1930s. The Bulolo Gold Dredging Company operated up to a total of eight dredges in the Bulolo Valley form 1932 to 1965. Apart from a short break during World War II the dredging operations continued until 1965, when they closed down due to a combination of depressed gold prices and exhaustion of the available resources. At their peak, the dredging operations recovered up to 250,000 ounces of gold per year from a total of six dredges.

The first major hard rock discovery to be developed was the Panguna copper deposit on Bougainville Island. It was first discovered in 1962 and seriously explored in 1964 during a world wide exploration effort targeted at the identification of copper resources. This period saw not only the discovery of Panguna but also the Ok Tedi, Frieda River and Yanderra copper deposits.

With the development of the Bougainville copper mine in 1972 Papua New Guinea entered an era of large-scale hard rock metalliferous mining. The development of the Ok Tedi copper mine in 1984 and later the Misima, Porgera, Tolukuma and Lihir gold mines have resulted in a further extension of both the scale and scope of mining operations in Papua New Guinea.

In addition to the mining projects currently in operation, there are a significant number of other identified resources which may be developed in the short to medium term (Table 1). As a result of these potential future developments, the contribution currently made by the mining industry to the national economy is likely to continue well into the future.

The contribution of the mining industry to the economy is significant and multifaceted. The government receives significant taxation, royalty, duty, and dividend revenues from the industry. Mineral exports account for the majority of total exports and therefore the majority of foreign exchange earnings. Employment is generated both directly by mining and exploration companies and also indirectly through service suppliers and companies. The non-mining private sector also benefits from spin off business activity. The industry has contributed to infrastructure development in areas of otherwise trackless jungle. The early exploration of many of the remote areas of Papua New Guinea has to a large extent been fuelled by the search for minerals and oil.

THE MINING INDUSTRY IN PAPUA NEW GUINEA

The industry today

The mining industry in Papua New Guinea revolves around a small number of very large projects. There are currently four large-scale mines and one medium-scale mine in production. The large-scale operations are the Ok Tedi, Porgera, Misima and Lihir mines. In addition to the producing mines there is the large scale Bougainville Copper mine at which operations are currently suspended. Production rates at all of these operations are large by world standards. Ok Tedi rates as the eighth largest copper producer in the world with Porgera and Lihir rating in the top ten gold producers in the world. At the time of its closure, Bougainville Copper Ltd also rated in the top five copper mines in the world.

Over the last few years there has been a movement towards the development of smaller scale mining operations. To date this has resulted in the successful development of the Tolukuma gold mine in Central Province and the granting of three other mining leases for smaller scale gold mines.

Copper production has varied from a high of 207,000 tonnes per year in 1992 to a low of 111,500 tonnes in 1997. The average production of just under 200,000 tonnes per year places Papua New Guinea as the ninth largest copper producer in the world.

Gold production from all mines has varied considerably over the last ten years from a high of 71 tonnes in 1992 to a low of 48 tonnes in 1997. Papua New Guinea ranked number 10 in the world as a gold producer in 1995 although this position slipped in 1997 as a result of production losses caused by the severe El Nino drought. Commencement of full-scale production from Lihir (approximately 20 tonnes per year) in 1998 pushed Papua New Guinea back up to a total gold production rate of 60 tonnes per year in 1998 and a further increase to 68 tonnes is expected in 1999. This would place Papua New Guinea into the position of eighth largest gold producer in the world. Combined production from all likely sources in the next ten years could result in production rates in excess of 90 tonnes per year.

Contribution to the national economy

Table 1. Sector contributions to economic activity – percentage share.

	EXPORTS %	GDP %	EMPLOYMENT %
	1998	1998(Est)	1990
Agriculture/Forestry/Fisheries	30.2	30.5	30.0
Mining and Petroleum	69.8	25.2	2.4
Manufacturing	–	7.6	8.3
Electricity	–	1.4	0.9
Construction	–	5.1	13.8
Wholesale, Retail Trade	–	7.7	8.5
Transport	–	4.8	8.5
Business Services	–	0.9	5.1
Other Services	–	16.7	22.9
Total	100.0	100.0	100.0

The mining industry in Papua New Guinea has played a pivotal role in the development of the economy and the country as a whole, and will continue to do so for many years to come. Since the 1890s, mining and petroleum exploration efforts have often been the cause of the establishment of basic contact and infrastructure development in many remote areas. With the development of larger scale operations this contribution to the economy has dramatically increased. Mining has today emerged as the primary exporter of Papua New Guinea produce and a significant contributor to Gross Domestic Product (GDP). Mineral product exports accounted for 46.6% of total exports in 1998, and when combined with petroleum exports jointly account for 69.8% of total exports. Mining and petroleum were the second largest contributor to GDP in 1998 after agriculture (*Table 1*). Mining and petroleum contributed 25.2% of total GDP in 1998. This percentage is expected to increase in the immediate future with the achievement of full scale gold production from Lihir, expansion of oil production from the Gobe and Moran Oil Projects, as well as a possible gas pipeline to Queensland.

Table 2. PNG mineral production 1987 - 1998.

YEAR	GOLD (kg)	SILVER (kg)	COPPER (tonnes)
1987	34,903	62,224	217,699
1988	34,593	68,915	218,642
1989	25,380	92,507	203,825
1990	32,323	112,327	170,221
1991	59,810	123,630	204,459
1992	69,241	93,108	193,359
1993	60,096	96,017	203,184
1994	58,654	77,758	206,368
1995	51,701	65,153	212,737
1996	51,573	59,036	186,665
1997	48,482	49,165	111,515
1998	61,357	58,033	152,200

Exports

Table 2 and *Table 3* present mineral and petroleum production and export statistics for the period 1987 to 1998. In Kina terms there has been more than a doubling in the value of both gold and copper production over the period. Copper production reached a peak in 1988 when Ok Tedi and Bougainville were in simultaneous production, only to fall in 1989 with the closure of the Bougainville mine. The general upward trend in gold production is expected for at least the next ten years as new mines are developed.

Table 3. Mineral and petroleum exports by value: K(million) F O B.

Year	Copper	Gold	Silver	Oil	Total
1985	164.2	318.8	6.9		489.9
1986	156.0	398.5	6.7		561.2
1987	281.9	422.9	10.1		714.9
1988	446.9	405.1	9.5		861.5
1989	344.9	316.9	14.3		676.1
1990	349.2	393.2	15.1		757.5
1991	323.8	666.9	14.6		1005.3
1992	313.5	745.9	10.7	301.4	1371.5
1993	256.3	681.6	12.1	817.8	1767.8
1994	367.4	702.3	10.3	702.7	1782.7
1995	754.5	840.1	13.1	827.7	2435.4
1996	387.0	773.6	10.1	1073.9	2244.6
1997	259.8	718.7	8.2	852.2	1838.9
1998	395.7	1227.8	15.5	813.1	2452.1

Source - Bank of PNG Quarterly Economic Bulletin.

The significant decline in 1997 mineral export figures occurred as a result of the prolonged El Nino drought in Papua New Guinea. This caused operations at the Ok Tedi mine to be suspended due to low river levels in the Fly River. The Fly River is the logistics lifeline for the Ok Tedi operation, used for shipping fuel and supplies into the mine site, and for shipping copper concentrate out. In the 1997 calendar year, mine and mill operations were suspended for a period of over five months. This situation led to a significant reduction in copper and gold exports in 1997. Ok Tedi is not only a significant producer of copper but also a large producer of gold as a co-product in its copper concentrate. In normal operating years gold production from Ok Tedi averages 15 tonnes.

Table 4. Total exports by value: K(million) F O B.

Year	Total Minerals	Agriculture	Forest Products	Marine Products	Other	Total Exports	Mineral& Petroleum Share %
1985	489.9	330.2	67.3	12.1	26.7	926.2	52.9
1986	561.2	331.9	74.7	7.9	25.1	1000.8	56.1
1987	714.9	268.9	110.9	11.0	17.5	1123.2	63.6
1988	861.5	255.2	97.5	7.5	34.4	1256.1	68.6
1989	676.1	270.1	96.2	8.1	61.1	1111.6	60.8
1990	757.5	204.6	79.6	8.2	72.5	1122.4	67.5
1991	1005.3	180.9	90.2	10.4	80.0	1390.5	72.3
1992	1371.5	203.1	148.2	9.3	110.0	1862.6	73.6
1993	1767.8	270.1	410.4	7.8	71.2	2527.3	69.9
1994	1782.7	374.6	494.4	10.3	0	2662.0	67.0
1995	2435.4	498.0	449.7	16.7	0	3399.8	71.6
1996	2244.6	573.7	467.3	10.4	0	3296.0	68.1
1997	1838.9	770.3	409.3	9.5	0	3051.6	60.3
1998	2452.1	846.5	170.9	41.5	0	3511.0	69.8

Source - Bank of PNG Quarterly Economic Bulletin.

The drought also impacted copper and gold production figures in 1998, with full production at Ok Tedi not being re-established until the end of the first quarter 1998.

Table 4 presents comparative statistics on the export performance of the main industry sectors in Papua New Guinea. The contribution of mineral and petroleum products to total exports has increased from 53 percent of total exports in 1985 to nearly 72 percent in 1995. It experienced a slight reduction in 1996 to 68.1% primarily as a result of weakness in the world copper market and a slight decline in gold exports. 1997 figures show a significant decline with mineral and petroleum exports account for only 60.3% of total exports due to the drought. 1998 saw an increase in mineral product exports to 69.8% as a result of a return to full production by all mining operations. Mine production figures for 1998 are presented in *Table 5*.

Table 5. Papua New Guinea mine production 1998.

MINE	GOLD (kg)	SILVER (kg)	COPPER (tonnes)
Ok Tedi	12,860	26,084	151,556
Porgera	22,606	2,849	
Misima	5,783	18,120	
Lihir	14,734	413	
Tolukuma	2,362	10,304	
Small Scale Miners	1,948	170	

Source – Department of Mineral Resources Quarterly Report.

Linkages to the non-mining economy

As a result of the very localised impact mines have on their economic, physical and social environment, as well as low labour intensity, mines are often referred to as enclave developments. There is the perception that linkages to the outside business community are poor. This does not mean that the general economy does not benefit from the operations, rather that the direct impact is localised. The claim that mining is isolated from the rest of the economy requires careful examination. The contribution of mining to downstream business and employment opportunities in associated industries, contractors and retailers in Papua New Guinea has not been quantified. It is, however, known to be significant as evident by the severe dislocation of businesses in many parts of the country following the suspension of mining operations at Bougainville.

Exploration expenditure in the economy

Mineral and petroleum exploration budgets have contributed in a major way to economic growth over the last 20 years. During the period 1988 to 1990 combined Mineral and Petroleum exploration expenditures reached a peak of K281 million per year, and averaged K225 million per year. Mineral exploration accounted for close to K70 million in 1988. Over the period 1988 to 1992 exploration expenditures progressively declined and stabilised at a rate of around K40 million per year thereafter. Exploration expenditures in 1997 totaled K46.7 million. *Table 6* and *Figure 1* provide a summary of exploration expenditure and exploration licensing activity over the period 1987 to the present. At the end of 1998 there were 156 Exploration licences in force and a further 42 applications pending covering a total area of 97,803km^2. The exploration expenditure figures presented in *Table 7* are broken down into grassroots and advanced exploration. Advanced exploration refers to those projects which have sufficiently identified the characteristics of a mineral resource to undertake order of magnitude development studies.

Table 6. PNG mineral export statistics 1988 - 1998.

Year	Gold (kg)	Export Value millions		Copper t.	Export Value millions	
		Kina	US$		Kina	US$
1988	31,874	378.3	312.6	218,700	500.9	414.0
1989	18,811	287.9	176.3	204,000	482.8	295.6
1990	31,021	361.0	343.4	170,200	398.5	379.2
1991	58,749	748.3	712.8	204,500	444.7	423.6
1992	68,327	745.9	765.0	193,359	313.5	320.0
1993	58,690	681.6	690.0	203,184	256.3	260.0
1994	58,654	702.3	600.0	206,329	367.4	310.0
1995	51,701	840.1	630.0	212,737	745.5	560.0
1996	51,573	773.6	580.0	186,665	387.0	290.0
1997	48,482	718.7	395.0	111,515	259.8	143.0
1998	61,357	1141.0	543.1	152,200	629.7	299.7

Note: US$ export values are calculated from year-end exchange rates of Kina to US$.

The situation reflected in Figure 1 does not illustrate the full picture with respect to exploration expenditures. The Kina figures mask the impact of the declining value of the Kina against the US Dollar since 1994. *Figure 2* presents exploration expenditures in US Dollars.

Ongoing mineral exploration is essential to the future well-being of the economy. Without exploration there would be no new mineral discoveries and the mining industry would be a short to medium term temporary industry. The time period from discovery to production is variable but often quite long. From discovery to the commencement of production at Panguna was eight years, which for a mine of that scale is very short. By contrast Ok Tedi was discovered in 1968 and did not reach development until 1984. Likewise, the Frieda copper deposit was discovered in 1967 and has still yet to be developed. Lihir was discovered in 1983 and finally reached production in 1997. This long gestation period demonstrates that the mines of the next decade must be in the

Table 7. PNG exploration statistics 1987 - 1997.

Year	Grassroots Exploration (K millions)	Advanced Exploration (K millions)	Total (K millions)	Number of Els
1987	24.0	25.9	49.9	195
1988	27.5	41.2	68.7	217
1989	24.1	40.2	64.3	167
1990	19.8	36.5	56.3	135
1991	16.8	33.9	50.7	112
1992	11.9	26.9	38.8	99
1993	8.6	32.0	40.6	89
1994	17.5	27.0	44.5	108
1995	12.8	33.1	45.9	108
1996	11.3	30.6	41.9	105
1997	14.6	32.1	46.7	125
1998	11.26	19.91	31.2	116

Source – Department of Mineral Resources Quarterly Report.

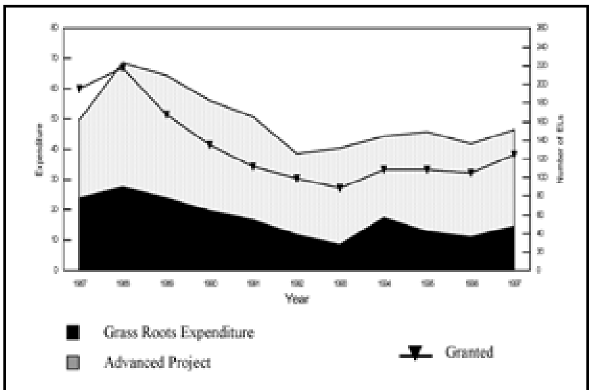

Figure 1. Mineral Exploration Expenditure 1987 - 1997 (K millions).

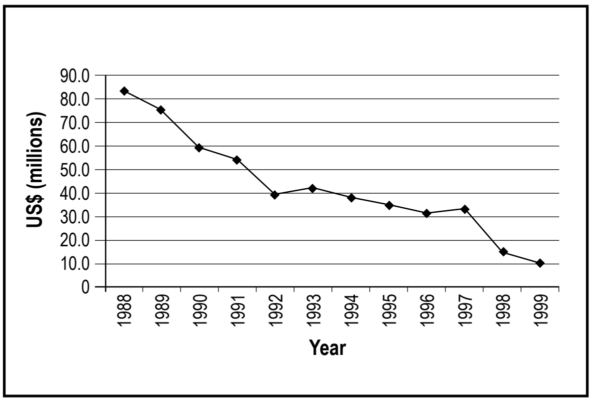

Figure 2. Exploration Expenditure in Papua New Guinea (US$) 1999 estimated.

process of discovery now. The decline in grassroots exploration in Papua New Guinea since 1988 and the change in focus to advanced projects is a cause for concern for the long-term future of the industry.

MINING PROJECTS

Lihir

The Lihir mine completed construction in late 1997 on Lihir Island in New Ireland Province 590km north east of the mainland of Papua New Guinea. Lihir Gold Limited is a publicly listed company with the principal shareholders being: Southern Gold (Rio Tinto 75% and Vengold 25%) holding 22.8%; Niugini Mining Ltd, 17.1%, Mineral Resources Lihir; 10.3% (8.5% of which is on behalf of the people of Lihir); Vengold Inc, 6.8%; with the balance of 43% held by private and institutional investors. The mine is managed and operated by the Lihir Management Company, a wholly owned subsidiary of Rio Tinto Ltd.

Mining is by open-pit methods, with a production rate of 2.85 Mt of ore per year to the mill. The current 37-year mine-life plans for mining in the pit to take place over a 15-year period with high-grade ore being fed direct to the mill. Low-grade ore is being stockpiled for later reclamation and processing over the 22-year period following the cessation of open-pit mining operations.

Apart from a small tonnage of surficial oxide material, the Lihir ore body is refractory with a high sulphide content. Metallurgical treatment is by whole-ore pressure oxidation followed by CIL for gold recovery.

Commissioning commenced in May 1997 with 1998 being the first full year of production. Gold output reached 519,824 ounces for the year despite some downtime caused by problems with the pressure oxidation autoclave brick linings. Relining of the autoclaves will continue into 1999 and is likely to have some effect on 1999 production.

The Lihir project presents the developers with some unique challenges with the reserve lying within an active geothermal area and immediately adjacent to the ocean. At the end of 1998 the base of the open-pit was already over 30 metres below sea level. A major well-point de-watering system is in place along the coastline and is reported by the company to be operating successfully. Rock temperatures in a significant proportion of the ore exceed 100 degrees Celsius and special explosives and detonating cord are required for blasting at these high temperatures. To date these challenges appear manageable and have not caused any delays in development.

Throughout 1998 the company constructed a new 300tpd oxygen plant to supplement existing oxygen capacity. This was commissioned in the first quarter of 1999 and is expected to increase gold production by an average of 100,000 oz of gold per year over the following two years. Expansion plans are also under consideration to increase production to over 1 million ounces per year.

Ore reserves at the end of 1998 were 96.3 million tonnes, grading 3.81g/t gold for a total of 11.8 million ounces. Total resources are 500Mt grading 2.65g/t gold for a total of 42.6 million ounces.

Ok Tedi

The Ok Tedi mine is a large porphyry copper deposit in a very remote area of the Star Mountains of the Western Province of Papua New Guinea. It lies some 18 km east of the border with the Indonesian province of Irian Jaya. The mine lies at an altitude of 2000 m in a very high rainfall area receiving between 8.5 and 10.5metres of rain per year.

Ok Tedi Mining Limited (OTML) is owned 52% by BHP, 27.5% by the PNG Government, 18% by Inmet Mining Corporation of Canada and 2.5% by the project area traditional landowners.

Total mine production averages 235,000 tonnes per day of which 80,000 to 85,000 tonnes per day is ore treated through the mill.

The El Nino drought of 1997 saw mine production severely reduced due to transportation difficulties on the Fly River for a period of over six months. Copper concentrate produced in the 1997 calendar year contained a total of 111,515 tonnes of copper, 8,182kg of gold and 15,846kg of silver. Of this, a significant amount remained stockpiled at the river port of Kiunga or at the mine until the drought finally broke in February 1998. The mine had returned to full production by the end of March 1998. Total production for the 1998 calendar year was 12,860kg of gold, 26,084kg of silver and 151,556 tonnes of copper in concentrate.

OTML has received some controversial press coverage over the last few years concerning the disposal of tailings and waste rock into the Ok Tedi and Fly River system. Monitoring and research continues in order to reach a greater understanding of the environmental impact of the mining project on the river systems. In late 1996 OTML had identified its preferred waste management option involving the dredging of mine derived sediments out of the Ok Tedi River. The mobilisation of the dredger to the dredging site in the Lower Ok Tedi River was significantly delayed as a result of the prolonged drought causing river levels to be too low for the dredger to be mobilised up river. Trial dredging commenced in March 1998 and operated successfully up until the end of the year producing sand from the river at a rate of 17 million tonnes per year. A major review of the success of the dredging trial is being carried out and a decision on whether dredging is a viable environmental option for the future is to be assessed around mid 1999.

Ore reserves as at the end of May 1998 were 343.9Mt at 0.88% Cu and 0.92g/t Au.

Porgera

The Porgera gold mine lies in Enga Province in the Highlands of Papua New Guinea. The mine commenced production as an underground mine in 1990 and has subsequently made the transition to an open-pit. The underground operation ceased in October 1997 and currently ore is derived solely from the open-pit operation. Based on current ore reserves, open-pit mining operations are scheduled to be complete around 2010. Gold production will continue until at least 2015 from low grade stockpiles. The open-pit mining rate is currently 210,000 tonnes per day of ore and waste.

The mine has produced close to 8.3 million ounces of gold since commissioning in 1990 with a peak annual production in 1992 of 46.2 tonnes of gold (1.48 million ounces). Production rates for the remainder of the mine life are expected to be in the range 600,000 to 800,000 ounces of gold per year. Gold production is from a refractory gold ore body where sub-microscopic gold is bound within pyrite grains. The gold recovery circuit includes flotation of the sulphide minerals followed by pressure oxidation, leaching and conventional CIP gold extraction. The mill has a throughput capacity of 17,000 tonnes of ore per day.

Placer Dome has acquired a 50 percent shareholding in the operation through its takeover of both Highlands Gold Ltd and Placer Pacific Ltd. Goldfields (RGC) Ltd holds 25 percent, Orogen Minerals holds 20 percent, and the Porgera landowners and Enga Provincial Government, 5 percent.

Production in 1998 was 726,806 oz (22,606kg) of gold and 98,614 oz (2,850kg) of silver.

The Porgera Joint Venture announced a 12 percent upgrading of ore reserves in 1998 and exploration is continuing to identify additional ore. Proved and probable ore reserves as at June 30, 1998 were 104Mt at 3.6g/t Au containing 12 million ounces of gold.

Misima

The Misima mine is located on Misima Island in the Milne Bay Province in eastern Papua New Guinea. The mine is an open-pit gold mine, which has on average produced over 300,000 ounces of gold per year. The mine commenced operations in 1989 and has to date produced some 88.2 tonnes (2.8 million ounces) of gold and 472.9 tonnes (15.2 million ounces) of silver. The mine works a low-grade ore body but is able to maintain low operating costs due to its strategic location in an island setting, adjacent to the coast. Gold and silver are produced from a conventional CIP gold processing plant.

Ownership of Misima Mines Pty Limited is Placer Dome 80 percent, and Orogen Minerals Ltd 20 percent.

Gold production declined from an average of 330,000 oz (10,300kg) over the years 1990 to 1995 to 186,000 oz (5,788kg) in 1998. Silver also declined from an average 1.9 Moz (60,000kg) per year from 1990 to 1995 to 590,000 oz (18,366kg) in 1998. These reductions were forecast and occurred primarily as a result of a combination of harder ore and lower head grades as the mine approaches the end of its life. Present indications are that open-pit operations will continue until mid 2000 with processing of low-grade stockpiles continuing until 2005.

Ore reserves as at December 1998 were 29.8 Mt grading 0.9 g/t Au and 9.2g/t Ag at a 0.7g/t gold equivalent cutoff.

Tolukuma

The Tolukuma resource was discovered in 1986 by Newmont Exploration and was ultimately developed by Dome Resources Ltd with first gold production in December 1995. The mine lies in the Central Province, 100 km north of Port Moresby in the rugged Owen Stanley Mountains. Access is only by helicopter and all mine activities are helicopter supported.

Gold production commenced in December 1995 at a rate of 100,000 tonnes of ore and 50,000 ounces of gold per annum. Production in 1998 totaled 76,000 ounces of gold and 331,000 oz of silver. The ore is free milling and treated with a conventional CIL plant followed by Inco process tailings detoxification.

The mine initially operated as a small open-pit and in 1997 commenced underground mining operations. Head grade from the open-pit for the years it operated averaged 15.5g/t Au and

49.4g/t Ag. By mid 1997 all ore production was being derived from the newly developed underground mine. Underground head grades for 1998 averaged 21.6g/t Au and 164.0g/t Ag.

The mine life was initially estimated to be 5 years, however exploration activities surrounding the known mineable reserves have been positive, and potential exists to extend the mine life by several years.

Reserves and resources as at the end of 1998 were 909,000 tonnes at an average grade of 21.9g/t gold and 93.0g/t silver.

Wapolu

The Wapolu gold mine is located on Fergusson Island in the Milne Bay Province. The resource was discovered in 1985 and finally developed in 1995. A mining lease was granted to Union Mining NL for a combined heap leach/vat leach and CIL gold mining project. Mineable reserves were initially estimated to be 1.6 million tonnes at 2.4 g/t gold. The estimated mine life was 3 to 4 years at a planned production rate of 34,000 ounces per year.

Construction commenced mid 1995 and production started towards the end of 1995. Commissioning and production problems continued into 1996 with heap leach proving unsuccessful. Vat leach was also attempted but the high clay content of the ore resulted in slow percolation and low production rates.

The mine ceased operations in 1997 and was decommissioned and rehabilitated. The area surrounding the old mine site contains potential for the identification of more resources and exploration activities are targeted to identify sufficient resources to undertake a larger scale operation.

Simberi

The Simberi gold project lies in the Tabar Islands some 40km northwest of Lihir. It was granted a Mining Lease in December 1996 for the development of a medium scale gold mine treating oxide ore overlying a sulphide resource of unknown size. The project is owned by Nord Pacific and proposes to produce 40,000oz of gold per annum for 5 years.

Oxide ore reserves were last assessed in August 1996 as 4.4Mt grading 1.54g/t Au. This ore reserve is based on a zero stripping ratio and a 0.5g/t Au cut-off.

The project remains on hold as a result of depressed gold prices. Exploration is ongoing and it is expected that the project will be developed in the near future.

Mt Sinivit (Wild Dog)

The Mt Sinivit mining lease (previously known as Wild Dog) lies in East New Britain Province some 75 km from Rabaul. This is planned to be a small scale open-pit mine to produce 10,000 ounces of gold per year. Ore reserves are 306,000 tonnes grading 4.0g/t Au. Initial development activities were halted due to the depressed gold price and are not expected to recommence until there is a significant shift in gold price to above US $350 per ounce.

Bougainville

The Bougainville Copper Project commenced operations in 1972 and was producing at a rate of 166,000 tonnes of copper and 450,000 ounces of gold per year at the time of its forced closure in 1989. Over its operating life it produced 3 million tonnes of copper and 305 tonnes (9.7 million ounces) of gold in concentrate.

The mine was forced to close in May 1989 following an armed rebellion by disgruntled mine area landowners. Although there are significant moves towards a peaceful resolution of the conflict on the Island there is no time frame for recommissioning of mining operations on the island.

The suspension of operations at the *Panguna* mine in 1989 was a major blow to the economy of Papua New Guinea. At the time of its closure the mine accounted for nearly 10 percent of GDP, 36 percent of export earnings and 18 percent of government revenue.

Access to the mine site on Bougainville to enable a detailed review of the mine and its infrastructure is still not possible. When conditions on Bougainville permit, Bougainville Copper Ltd (BCL) intends to review the costs of reopening the mine. Preconditions to reopening the mine necessarily include the restoration of political stability on the island, and a clear statement from the Bougainville community in favour of re-establishment of mining operations. Resumption of production would take approximately 2 years from the complete restoration of stability on the island and would be subject to an assessment of the economic viability of resumed operations.

Bougainville Copper Limited is owned 53.6 percent by Rio Tinto, public shareholders 27.3 percent and the PNG Government 19.1 percent.

Remaining ore reserves are 691Mt at 0.4 percent Cu and 0.47g/t Au, sufficient for a mine life of 15 to 16 years at the production rate prevailing prior to closure.

FUTURE PROSPECTS

Papua New Guinea is still considered to be under-explored and highly prospective for the discovery of new mineral deposits. There are a significant number of deposits which have already been discovered but not yet developed. These include both large and small-scale deposits which are likely to be exploited in the years to come as infrastructure development and commodity prices enhance their economic viability. The following is an outline of some of these potential future developments. Summary information on future developments is detailed in Table 8.

Frieda copper

A large porphyry copper deposit was first discovered at Frieda River near the border of the East Sepik and West Sepik Provinces in the 1960s. In 1987 Highlands Gold Ltd (now Highlands Pacific Ltd) took over the exploration licence and embarked on an aggressive exploration and metallurgical testing programme to develop a mining project based on the Nena and Frieda deposits. In 1997, Cyprus-Amax Inc entered the joint venture and has become the manager of the Frieda exploration project.

The total porphyry copper resource is estimated to be in excess of 1000 million tonnes at 0.5 percent copper and 0.3g/t gold. The high sulphidation Nena resource, which lies adjacent to the porphyry system, is 60Mt grading 2.0 percent copper and 0.6g/t gold with an additional oxide gold cap of 14.5Mt grading 1.4g/t gold.

A mining pre-feasibility study was completed by Highlands Pacific in early 1996 resulting in a proposed development strategy including a leach, solvent extraction and electro-winning circuit to produce LME grade A copper. Estimated capital cost of the project was US$1.6 billion, whilst operating costs were projected to be in the lowest quartile of the global cost curve. Exploration on the site is ongoing with the project being progressed towards feasibility by a joint venture consortium led by Cyprus Amax Inc.

Ramu Nickel

The Ramu Nickel Cobalt project is located in Madang Province. This project is based on a lateritic nickel occurrence discovered in 1962. Highlands Gold Ltd (now Highlands Pacific Ltd) took up the area in 1990 and has undertaken both resource and metallurgical studies. Total measured and indicated resources are currently estimated at 72.2Mt grading 1.0 percent Ni and 0.1 percent Co. Inferred resources add another 71Mt, bringing the total to 143Mt grading 1.0 percent Nickel and 0.1 percent Cobalt.

A bankable feasibility study was completed in December 1998 and demonstrated attractive rates of return on investment and low overall operating costs. The feasibility study and a proposal for development and environmental plan have been submitted to the PNG Government for approval. It is anticipated that government approvals will be received in the third quarter 1999 with construction commencing late 1999 or early 2000.

Morobe gold

The Morobe gold project lies in the Wau area of Morobe Province. Wau is the site where the first large-scale discovery of gold took place in Papua New Guinea in 1923. The project comprises three principal prospects, the Hidden Valley, Kaveroi Creek, and Hamata prospects. The ground adjacent to the three identified targets is also highly prospective.

The Morobe Gold project took a major step forward in 1996 as a result of the amalgamation of the Rio Tinto Hidden Valley Kaveroi Creek prospect with the adjacent Goldfields RGC Hamata prospect into a single project. The combination of the three prospects under one project significantly enhances the viability of mine development. Exploration activities were aggressively advanced throughout 1997 leading to the preparation of a pre-feasibility study presented in early 1998.

A new joint venture company comprising Aurora Gold Ltd and the Commonwealth Development Corporation gained control of the project in 1998. Evaluation of the prospects continues with a feasibility study planned for presentation around mid 2000.

Wafi

Rio Tinto holds the exploration licences over an advanced exploration prospect at Wafi situated in the Morobe Province near Lae. The prospect has two distinct mineral occurrences. A porphyry copper prospect has been drilled out giving a resource of 100Mt grading 1.27 percent copper and 0.67g/t Au. An epithermal gold prospect on the same tenement contains in the order of 26.1Mt grading 3.5g/t Au. Recent drilling by Rio Tinto has identified a new high grade zone, which has significantly expanded these resources, but no new resource estimate is as yet available.

Mount Kare

Located in the Enga Province of PNG the Mount Kare gold mining project has had a short but colourful history. It was the location of a significant landowner gold rush in 1988 which is reputed to have produced nearly 1 million ounces of gold.

Exploration of the hard rock potential of the Mt Kare area has continued through 1998 by a joint venture comprising Carpenter Pacific Resources of Australia and Madison Enterprises of Canada. Drilling results to date are encouraging with uncut identified resources of 20.4Mt grading

Table 8. Current and future mineral production estimates.*

Mine	Commodity	Rate	Value K mill/yr	Start year	Mine Life yrs
CURRENTLY PRODUCING MINES					
Ok Tedi	Copper (t) Gold (oz)	190,000 500,000	570 350	1984	25
Misima	Gold (oz)	200,000	140	1988	14
Porgera	Gold (oz)	750,000	525	1989	18
Tolukuma	Gold (oz)	60,000	42	1995	5
Lihir	Gold (oz)	600,000	420	1997	40
Alluvial Gold	Gold (oz)	60-100,000	42-70	1880	??
FUTURE DEVELOPMENTS					
Ramu	Nickel (t) Cobalt (t)	33,000 2,800	580 175	2001	30-40
Morobe Gold	Gold (oz)	300,000	210	2001	15
Nena Frieda	Copper (t) Gold (oz)	220,000 365,000	660 255	2005	20
Wafi	Gold (oz) Copper (t)	200,000 100,000	140 300	2005 2010	10
Simberi	Gold (oz)	40,000	28	2000	5
Woodlark	Gold (oz)	50,000	35	2000	7
Mt Sinivit	Gold (oz)	10,000	7	2000	4
Laloki	Copper (t) Zinc (t) Gold (oz)	4000 1300 15,000	12 1.8 10.5	2002	4
FUTURE RESTORATION ?					
Bougainville	Copper (t) Gold (oz)	160,000 350,000	480 245	2005?	12

Price assumptions: Gold = K 700 /oz Copper K 3000 / tonne NSR.

*These are Dept of Mineral Resources estimates only and may not reflect company policy.

5.6g/t gold and 28.7g/t silver at a cutoff grade of 1g/t Au. Drilling is ongoing and further increases in resources are expected.

The geology of the area has significant similarities to the Porgera mine which lies some 11 km to the north east on what appears to be a structural trend.

Other prospects

Several promising small mining ventures are in the advanced stages of feasibility studies. The Kainantu Gold project in the Eastern Highlands is also the focus of a new exploration programme following announcement of a joint venture between Highlands Pacific Ltd and Nippon Mining of Japan. On the outskirts of Port Moresby at Laloki lies a small massive sulphide/copper/gold/zinc prospect which is being evaluated for possible development. The Woodlark Island gold prospect has completed a mining feasibility study but with currently depressed gold prices further reserves are required to justify development.

New prospects which have been identified in the recent past which appear interesting include the Left May River copper/zinc/gold massive sulphide occurrence near the Frieda River Project, and the Crater Mountain Gold discovery.

Sea-floor mineral exploration

Of considerable interest has been the granting of Exploration Licences covering two offshore areas in the Manus Basin to Nautilus Minerals Corporation. The licences cover known areas of sea-floor massive sulphide mineralisation, (VMS black smoker deposits). The mineralisation in the Manus Basin is associated with andesitic and dacitic source rocks with high gold, silver, copper and zinc grades and low lead grades. Average copper and gold grades for 59 samples collected to date from the Pacmanus deposit are 9.9 percent copper and 15g/t gold. Grades from 24 samples from the Suzette deposit average 15.3 percent copper and 21g/t gold.

These areas lie in water depths of around 1600 metres and raise interesting possibilities for the future of sea-floor mining within Papua New Guinea's territorial waters. Offshore mining technology has to date been focussed on either shallow water diamonds or very deep water (>5000m) manganese nodules. New technologies for the exploration and mining of these deposits will be required and perhaps provide the greatest challenge for the project. A research cruise to the area will soon be testing the effectiveness of a remotely operated drill rig for testing the grade and thickness of the deposits.

Small-scale alluvial gold mining

Small scale alluvial gold miners produced over 62,000oz of gold in 1998. This is primarily from hand method operations although there are a small number of mechanised operations in production. A new government extension service for small scale miners commenced in 1998 and it is hoped that production from this sector will continue to increase over the next few years.

Undiscovered resources

Papua New Guinea is considered to be geologically highly prospective for new mineral discoveries. Its geological setting on the "Pacific ring of fire" makes it highly favourable for further discoveries of large scale porphyry copper/gold and epithermal gold deposits. There are also large areas of ultramafic rocks which are prospective for lateritic nickel deposits in many parts of the country. The country remains relatively unexplored compared to Australia, and holds promise of many more discoveries in the future. The major limiting factor to future discoveries is the difficult logistics of working in remote and rugged country as well as some difficulties with land access resulting from the customary land tenure system.

FUTURE ECONOMIC CONTRIBUTIONS FROM THE MINING INDUSTRY

With production from currently operating mines and expected future production from new mines in the medium term, some preliminary estimates of the future value of mineral production can be made. The currently very low commodity prices for both gold and copper do not encourage new developments at an early stage.

Gold

Gold production is expected to increase over the next decade with new production coming from a number of both large and small operations. Large-scale gold developments such as Morobe are expected to add to the increased gold production resulting from the ramping up of Lihir. In addition to the new gold mines, production of gold as a by-product of copper mining from the Frieda Copper deposit is also expected to contribute to gold exports before 2010. The Wafi Zone A gold prospect and the Mt Kare prospect also have significant potential for development as future gold mines.

A number of small to medium scale mines such as Woodlark, Kainantu, Simberi and Sinivit could also add to the total. Production from these new mines will more than offset the expected slight decline in gold production resulting from the closure of the Misima mine around 2005.

The small scale alluvial gold mining sector is also set to make significant contributions to gold production from both hand and mechanised alluvial gold mines around the country. Total gold production from this sector is expected to increase to in excess of 2.5 tonnes (80,000oz) per year by the year 2000.

A large unknown with respect to future gold production levels is whether operations are ever re-established at the suspended Panguna mine on Bougainville Island. Bougainville Copper Ltd was not only a major copper producer but also exported a large quantity of gold each year in the copper concentrate. The average gold production from BCL over the last five years of operations was close to 15 tonnes (480,000oz) per year.

Copper

Production from Ok Tedi is expected to continue at current levels through to at least 2010. Copper production is expected to rise with the commissioning of a new mine at Frieda River in the West Sepik Province by the Cyprus-Amax, Highlands Pacific joint venture. Copper production is currently estimated to commence at a rate of 220,000 tonnes per year. The development of the Wafi copper-gold resource is also possible in the medium to long term. Production from Wafi is unlikely before the year 2010. An additional small source of copper production is the small scale Laloki copper prospect near Port Moresby. This mine would also produce small quantities of zinc, gold and silver.

In the event that the Bougainville copper mine is re-commissioned, a significant increase in copper production would occur. Production from BCL, if re-established, is likely to be at a rate of 150,000 to 175,000 tonnes per year.

Nickel and cobalt

Nickel production from the Marum deposit in the Ramu Valley is potentially a new commodity for Papua New Guinea, diversifying the industry base away from the current strong copper and gold bias. In addition to nickel the Marum deposit has by-product cobalt which would add to the value of production. The deposit also contains chromite but this does not at present appear to be economic to exploit. The project developer, Highlands Pacific Ltd, has completed a feasibility study into developing the resource and has applied for project approvals from the Government of Papua New Guinea. Production is projected to commence in 2001 at a rate of 33,000 tonnes of Nickel and 2,800 tonnes of Cobalt per year.

Implications for government revenue

As a result of an increase in the number of mining developments, government revenues from the sector are expected to increase over the next decade. All tax revenues from the mining industry are directed to the Mineral Resources Stabilisation Fund which is a fund administered by the Bank of Papua New Guinea (Central Bank) in order to smooth the effects of mining related revenue collection on the economy. Direct tax revenues from the mining and petroleum sector over the period 1993 to 1998 have averaged over K300 million per year (Bank of PNG, 1999). These revenue streams should be able to be maintained by new projects coming on stream to replace those reaching the end of their productive lives. The low commodity prices currently being experienced are likely to damage on company profitability and therefore reduce direct taxation in the 1999 year.

Non-fiscal benefits to the Papua New Guinea economy.

All mining projects require the establishment of basic infrastructure in the area of the mine development. This is often a cost carried by the mine developer in order to ensure the effective operation of the mine. This is especially so in remote areas where basic infrastructure is generally non-existent. The infrastructure developments usually last well beyond the life of the mine and provide centres for economic development into the future. In addition, mining companies are allowed to develop non-mine related infrastructure under a tax credit scheme. This is currently seen as an effective way of delivering infrastructure in remote areas which the government finds difficult to service.

Employment opportunities will also increase significantly with the proposed mine developments. Direct employment in the mining industry could double over the next decade and employment in mining related service industries will follow suit.

CONCLUSIONS

The mining sector remains the driving force behind the Papua New Guinea economy. The current contribution provided by the industry is expected to continue in the medium to long term with the likely establishment of several new mineral developments over the next five to ten years. The direct effect of these new developments on the economy will be significant in terms of both increases in GDP, exports and foreign exchange as well government revenue.

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MINING AND COMMUNITY ISSUES IN FIJI

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ABSTRACT

Mining has proved itself to be an important contributor to national development in countries that are endowed with mineral resources, where such mineral resources are amenable to viable and sustainable development. In certain cases, it has even been the key element in kick-starting national economic development for such less developed countries (LDCs) as Papua New Guinea in the Pacific Basin.

With the incorporation of sustainable development issues in the international mining industry, the impact of mining on local communities, and especially on the local indigenous communities in these LDCs, has developed as arguably the most important issue regarding the sustainability of mining operations and projects. In recent years, such communities have been considerably empowered so that the sustainability and viability of mining operations is increasingly becoming contingent on their support and consent, rather than on investment conditions and the comparative advantages that a mineral-endowed country might possess. This empowerment has also come about at a time when LDC governments have taken a backseat in carrying out their responsibilities as a sovereign power, whilst grappling with the issues to do with trade liberalisation, globalisation of national economies and the move to privatise public utilities and companies. Fiji is no exception, and this paper highlights some of the community issues that have recently been incorporated into the policy formulation stage in an attempt to ensure a sustainable and beneficial mining sector for Fiji in the years ahead.

1.0 REVIEW OF COMMUNITY ISSUES IN MINING

1.1 Segregation and dislocation

The establishment of Fiji's colonial capitalist economy in 1874 ensured that indigenous Fijians; who would later be recognised under statutory authority as owning approximately 84% of all land in Fiji, remained in their villages under the authority of customary law. A unique aspect of this policy was that native Fijians would be taxed by the production of commodities such as copra and other food crops, and at the same time, the Native Labour Ordinances indirectly ensured that indigenous Fijians would not fully participate in commercial-type labour. Labour was then being recruited from Melanesia (Solomon Islands); and later still, from Polynesia (Samoa, Ellice Islands). The Colonial Sugar Refining Company (CSR) and the colonial government of the day then sought to recruit indentured labourers from India to work in the canefields, and so arose the importation of Indian indentured labourers to Fiji, and which would later form the nexus of Fiji's present Indian community. The effect of this labour policy on the indigenous communities involved, was not unique in the region, as highlighted by Connell and Howitt (1991):

> *"In the Australasian region, even at sites such as Vatukoula (Fiji) and Panguna (PNG), where mines were established when colonial governments had little concern with indigenous land rights, social and regional equity, environmental management and sustainable development, some individuals and groups have benefited from access to new services and resources. Such benefits, however, have been far from unequivocal. Dispossession, displacement, marginalisation, and alienation in periods of rapid change precipitated by minerals-based industrialisation have produced, and continue to produce, a legacy of sometimes tragic dimensions for many previously isolated indigenous groups. Seeds of optimism for the future for indigenous groups in the region are difficult to find, but they do exist."*

Gold was first discovered in Fiji at Mt. Kasi in Vanua Levu in the 1920s, and facing difficulties in recruiting the indentured Indian labourers from the cane fields to assist in the development of the mine, the Yanawai Mining Development Company soon pressured the colonial administration into circumventing the Labour Ordinances so as to recruit Fijian labourers from surrounding villages near the mine site (Plange, 1991).

Later amendments to the Labour Ordinances of the colonial government would greatly assist the development of the Tavua Goldfields; which would later be known as the Emperor Gold Mines. An ad hoc labour migration policy developed, where indigenous Fijians from all over Fiji were convinced that being employed at the Emperor Gold Mines would not only be good for the colonial government, but also for the church, and be part of satisfying customary obligations to the *vanua*. Indigenous Fijians embraced this as a novelty at first, but this soon wore off when the community was segregated into racial groups and a hierarchy formed in which the indigenous Fijians were placed at the bottom (Emberson-Bain, 1994).

What would be deemed now as inhumane working conditions underground only added fuel to the burning centre of discontent and resentment amongst the Fijian miners and their families. The colonial labour policies, to a large degree, ensured that the mining community in Vatukoula would remain segregated. This provided the legacy of militant unionism that began to confront the mining company at Vatukoula on industrial relations issues at the operations. It could also be argued that this signified a means of indirectly rebelling against the colonial system and the Fijian customary hierarchy that supported the labour policies that had brought about segregation and dislocation within their respective communities. Customary obligations ensured that Fijians remained subservient to this system of segregation until the enactment of the 1942 Industrial Association Act, and the subsequent formation of mining unionism at Vatukoula in 1947. Fijian labour at the mine finally had an independent voice that could be heard above the inhibitions brought about by customary obligations as well as the enforced subservience of the indigenous population by the colonial government's Labour Ordinances.

1.2 Property and Mineral Rights – Problems of Defining Ownership

As with most indigenous peoples around the world, Fijians have a special relationship with land and natural resources. Although land ownership is a western concept, most indigenous peoples identify land as a birthright rather than something to be demarcated, registered and owned. There is an emphasis on collective rather than individual ownership, and on non-perpertuity ownership so that land must be passed on from generation to generation.

Here in Fiji, the definition of the landowning unit or *mataqali*, was created as part of the colonial policy of defining land ownership amongst indigenous communities so as to then derive land titles and the consequent administration and control of land tenure. The Fijian concept of land ownership and its associated rights was thus formed, and this was facilitated by the creation of the Native Lands Trust Board (NLTB) which was tasked under statutory mandate to broker and administer rents, leases and compensation for any developments on native land on behalf of its native landowners. The formation of the Native Lands Commission (NLC) and the now defunct Native Lands Development Commission (NLDC) soon followed so as to register all customary land boundaries and identify landowning units or *mataqali*.

Although inalienable rights were granted to these landowning units with regards to land surface rights, all subsurface rights which encompassed mineral rights, were granted to the Crown, and later, to the State. This would be a sticking point amongst landowning units who viewed land ownership and its associated rights as encompassing everything above, on and below the land surface. The enforced definition of land ownership and rights to such ownership amongst indigenous Fijians, who had viewed land and other natural resources as their birthright, now had to be redefined under the western concepts of land ownership so that boundaries were established where previously none had existed.

Confusion over surface and subsurface land rights now exists amongst landowners. According to customary law, there is no such distinction and that the delineation of surface boundaries only represents the observable customary land boundaries which extend from the earth's core; through these surface boundaries and projected upwards into space. The newly amended Fiji Constitution of 1998 has not further clarified these distinctions, and especially with regards to the payment of mineral royalties and compensation for damages to land from mineral development activities. This is to be reconciled to the fact that community expectations and perceptions regarding land ownership and empowerment in decision-making at the national level, have increased dramatically in the last decade or so.

2.0 STRATEGIC ISSUES INVOLVING MINING AND THE COMMUNITY

2.1 Changing expectations and perceptions

With community empowerment, has arisen the problems of rising and different expectations and perceptions by the community, over their role in mineral exploration and development activities, and what is expected of the mineral explorer or developer. This is particular important at both intra- and inter-generational levels, since these expectations and perceptions are changing over time, as highlighted in the discussions on landowner issues at the Tuvatu prospect, the Mt. Kasi mine and the Namosi prospect. Without any guidelines being set by government, communities and the developer will set the levels for participation and involvement in mining projects, as prominent in PNG. This could bode ill for mining investors and developers in that they may be forced to take on the role of governments in equitably distributing wealth created. They also may face problems of settling definite and specific agreements with local communities brought about by the high levels negotiations associated with mineral exploration and development activities. The changing expectations and perceptions of communities, their empowerment, and the decreasing input of governments, may make mineral exploration difficult unless agreements and statutes can be established to manage these.

2.2 Security of tenure and property rights

One of the difficulties faced by LDCs that are endowed with mineral wealth is the reconciliation of customary land ownership law and statutory law so that the extent and rights of land ownership can be established. Although 84% of land in Fiji is registered as Native Land under the Native Land Trust Board (NLTB), there have been instances where the ownership of such land as determined by the Native Lands Commission (NLC), has been challenged in court, especially when relating to the rightful head of the landowning unit or *mataqali*. A major difficulty in reconciling ownership under both customary and statutory law has been in the process of surveying land boundaries under NLC guidelines. Under customary law, land boundaries were determined by natural topographical land features rather than by straight lines on topographical maps as in statutory law. This has meant by either an increase or decrease in landholding by adjacent landowning units, which has caused a degree of resentment amongst residents. A major landowner issue in Fiji has then been resentment caused by identification of mineralised ground within such boundaries.

The other associated complication has been in the re-distribution of benefits from mining within and amongst landowning units. In Mt. Kasi, the landowning unit (*Mataqali Naveitokaki*) that had the majority of ground which was covered by the mining lease, sought to keep most of the benefits of employment, business development and direct payments of compensation to themselves, only to result in not only poor management of such benefits but also differences amongst the members of the *mataqali* with regards to the sharing of such benefits amongst themselves. There was also a changing perception of what these benefits should entail, and this was often confused with compensation for damages from mining activities. There was a belief amongst landowners that the minerals belonged to the *mataqali* rather than the State as stipulated under the Mining Act.

2.3 Compensation for damages and mineral royalty

As discussed earlier in 1.2, land has a profound impact on the culture, belief and social systems of indigenous peoples, especially in the Pacific Basin. When developers and other external parties want to develop such land contrary to customary land tenure, an opportunity cost is paid to landowners, to compensate them for the loss of opportunity in using such land, or for the loss of pristine land and its instrinsic value. The past few decades have seen the expansion of the definition of such compensation from the opportunity cost principle, to encompass all benefits derived from such development. This has also caused the development of evaluative techniques such as contingent valuation to be used in the derivation of compensation. Debate as to how to compensate still rages on, and here in Fiji, the payment of mineral royalty has even been included as benefits within the compensation framework under Fiji's newly promulgated Constitution.

A compensation policy is close to being completed in Fiji, which deals with compensation arising from damages to the natural and social environment as a result of mineral exploration and development activities. Within this compensation policy, both fiscal and non-fiscal benefits are emphasised, especially in the context of sustainable development. It has been recognised in PNG that compensation is best managed and distributed by the customary/traditional social structures that exist among local and/or indigenous communities. Royalty also plays an important role in ensuring that sustainable economic benefits can be derived for future generations. The distribution of these benefits must also be clearly defined, and be a function of national development policies; the riskiness of the project; and the management of the distribution of such payments. Further to this has been the importance of the setting up of trust funds or accounts to provide the mechanism for collecting such payments for future use.

2.4 Occupational and public health and safety

Mining related accidents, and especially those that result in the loss of life, only serve to reinforce the perception that mining is a risky and dangerous endeavor. On a grander scale, the failures of tailings dams pose an even greater risk to public safety as well as to the environment. Waste management, especially with regards to tailings management and retention at the mine site, possess a complex set of problems; not only for the community, but also for regulators and the developer. The recent litigations involving the Ok Tedi tailings dam failure points to such complexities, especially when the rewards for such litigation could be abnormally high.

The other major public health risk is from mine pollution; whether it be noise, dust, air or water pollution. In the absence of any standards for pollution monitoring, or permits for pollution, there is a real danger of unmitigated public health risk. The longstanding complaints from the surrounding community about sulphur dioxide emissions from the mill stack at Emperor Gold Mines, has all the hallmarks of becoming a political issue at this time, given the high level of emotions involved from vested-interest groups. Water pollution from mine waste discharges into the waterways of the Nasivi River at EGM and the Yanawai River at Mt. Kasi always seems to raise emotional responses from such groups. The absence of proper regulatory stipulations in the Mining Act at this time could also lead to further litigation as in the Ok Tedi case. It is hoped that with the proposed discussion paper on the restructuring of Fiji's mining legislative framework and the subsequent amendments to the mining and supporting statutes, that the settling of such contractual obligations under Common Law proceedings, will be minimised or averted altogether. Participation, collaboration and transparency between all stakeholders is therefore critical in engendering a long-lasting partnership that ensures that mining becomes safe for those who work in mines, as well as for the communities that depend on it and/or are close to it. Such participation and collaboration must then be underwritten by government statutory and other legal stipulations.

3.0 CHANGES IN MINING DEVELOPMENT POLICIES

3.1 International trends

Dr. Allen Clark's conference paper titled **"Emerging Challenges and Opportunities for Pacific Basin Development in the 21st Century"** provides valuable insights into the latest developments in mineral policies in the Pacific region. For the purpose of this paper, I will deal with only two of these. Firstly, the packaging of mineral development policies and the subsequent amendments to mining statutes that are meant to attract and to retain mineral investors in host countries that are endowed with mineral wealth, such as Fiji (case in point), Papua New Guinea, the Philippines and other key Asian countries in the Asia-Pacific region. The second development that I would like to highlight in this context, is the empowering of local communities in the decision-making process of allowing mineral exploration and development to take place. This is distinct from the past practice of the sovereign power attracting investors based on a country's comparative and competitive advantages in the international minerals industry.

3.2 Fiji's minerals policy

In 1996, the Fijian Government formulated an Investment Policy Statement (IPS) to provide investment guidelines to investors for different sectors of Fiji's economy. The IPS then pre-empted the formulation of a Minerals Policy for the mining sector.

By the beginning of 1997, Fiji's first Minerals Policy was approved by Cabinet. Although it was constrained by the poor status of policy and statutory linkages and synergies that are fundamental to creating a national and holistic approach to policy development, it nevertheless provided the basis for a more internationally competitive investment guidelines for mineral investors and for the minerals sector in Fiji. It was clearly recognised that amendments to the Constitution in terms of mineral rights and ownership, and also to the relevant statutes such as the Mining Act and the proposed Sustainable Development Bill, had to take place so as to not only create the relevant synergies, but also differentiate investment promotion from regulation. The Minerals Policy thus covered the following areas and their respective aims:

- *Security of tenure and property rights*: To provide definition and clarification of rights under the Mining Act in terms of exploration and mining licenses, in conjunction with those statutes administered by the Native Land Trust Board, the Lands Department and the Native Lands Commission.

- *Sustainable development*: To introduce the concept of sustainable development into a general policy framework that addressed environmental, economic and social issues.
- *Social and cultural issues*: To provide a mechanism for integrating social and cultural issues to ensure that the community's interests and well being are foremost.
- *Fiscal Policy*: To formulate a fiscal policy that was internationally competitive, and yet based on Fiji's comparative and competitive advantages.
- *Labour and employment issues*: To introduce concepts of human resource management into the employment and training of the local labour force in the minerals industry.
- *Mineral exploration and mining procedures*: To provide stable, transparent and simple procedures in the administration of the Mining Act with regards to exploration and mining activities under licence.

The strategy to then realise the potential of Fiji's mining sector not only included the formulation and implementation of the Minerals Policy, but also the promotion of Fiji's minerals prospectivity. With the assistance of Japanese and Australian aid, a series of resource assessment and geophysical surveys were conducted; the most notable product of these endeavors has been the packaging of very high quality data sets on Fiji's geophysical signatures from airborne studies. It is unfortunate that the effort by the Fiji Government to expand the sector has coincided with the current depressed mineral commodities market, the advent of the Asian economic crisis and the turmoil in the international currency markets.

3.3 Proposed changes to the current mining legislative framework

Fiji's Mining Act and associated statutes[1] have required major amendments over the past 2-3 decades to keep up with changes in the international minerals industry. The outdated statutes are not only restricted in terms of *scope*, but also in terms of *application*. This is particularly prominent in the following areas, which modern-day mining legislation and policy have been able to encompass:

- The principles of occupational health and safety to do with *Duty of Care* and the varying forms of regulation (prescriptive, self- and co-regulation);
- The technological advances in mining, to do with mechanisation of work;
- The administration of mining licences and tenements in a very competitive and volatile industry where the competition for investment funds is high, especially during periods of low mineral commodity prices;
- The sustainable development paradigm; and
- The Socio-economic implications of mineral exploration and development, including the introduction of impact and management studies.

With the assistance of the AusAid Institutional Programme for the Mineral Resources Department, a major legislative review programme has just produced a *Discussion (Green) Paper* entitled *"Proposals for a New Legislative Framework to Promote and Regulate Mining in Fiji"*[2] that is being circulated to all stakeholders. This highlights changes to legislation that will incorporate the above elements. With consensus from the social partners (Government, employees, employers, landowners, any other stakeholders), this paper should then form a *position (white) paper* which will then allow the amendments to the Mining Act and related statutes to be endorsed by Cabinet.

Some key areas in the current Mining Act that have been identified as requiring extensive amendments and/or modifications are:

- *Mining tenement administration*

  The history of mining legislation in Fiji dates back to 1908 when the Mining Ordinance was enacted for the express purpose of making provision for the systematic prospecting of minerals and the organizing of mining ventures amongst mineral prospectors. It was framed to grant to prospectors and miners the *security of tenure* and *exclusive exploration and exploitation rights* that they sought. However, the proprietary rights of owners of land were also protected, to ensure that the interests of the public were adequately protected, and that mineral lands were not tied up in the hands of speculators. The Mining Ordinances were later amended and replaced by the Mining

[1] Explosives Act, Quarries Act, Petroleum Act, Sustainable Development Bill

[2] Discussion Paper (1998).

Act and its set of regulations; the former dealt with the issues of rights of access, property rights, and security of tenure with regards to mineral prospecting and development, and the latter outlined the *prescriptive regulations* of mining operations, as enforced by the Director of Mines and the Inspectors of Mines.

New proposals aim to provide a more robust and competitive mining tenement administration system that streamlines the process of issuing such licenses, based on the characteristics of mineral investment strategies and the needs of mineral investors – i.e. *market-driven* approach. The proposals also utilise some of the recent innovations that have proven effective in Australia recently in this regard.

- *Compensation and royalty*

  The strategy here is to streamline the constitutional requirements with regards to compensation and royalty, so as to have a direct connection with the stipulations of the Mining Act. This is to be based on the world-wide interpretation of compensation and royalty justifications and sharing between governments, landowners and developers, and to be fine-tuned to Fiji's conditions. A special committee is close to completing a Compensation Policy that not only reviews the statutory requirements for compensation for damages from mineral exploration and development activities, but also provides mechanisms for ascertaining and evaluating compensation.

- *Socio-economic and environmental issues*

These two issues were not addressed in the current Mining Act. The underlying principle is that all the areas that are impacted upon by mineral exploration and development and/or the stipulations of the Mining Act, should be within the Mining Act as the principal regulating statute for the industry. This is based on the fact that *mineral exploration and development impact cannot be totally dis-associated from the actual activity of mineral exploration or development*. This consideration also takes into account the issues of *Sustainable Development* and *Social Justice*.

- *Occupational health & safety in mines*

The amended mining statutes are designed to cover all OH&S issues at the mines, and to apply these issues in a way that is both *relevant* and *adequate* for Fiji's mining industry. Although the Health and Safety at Work Act highlights the principles of OH&S to be applied to industrial workplaces in Fiji, it does not focus on the specific applications of OH&S that are relevant to the mining workplace. The first draft of the amendments to the Mining Regulations and the Explosives Act have recently been completed by the Fiji Mines Inspectorate, and these amendments will be reviewed by the social partners as well as experts from abroad. These amendments are substantive to say the least, and incorporate trends in the regulation of the international mining industry, regarding OH&S principles. The amendments have concentrated on:

(a) An extended scope in the coverage of OH&S issues at the mines associated with technological advances in the industry;

(b) The recognition of the principle of *duty of care*[3] of mine managers in the application of OH&S issues a the mines;

(c) The application of *self-regulation, co-regulation or prescriptive regulation* at the mines in a form that is compatible with Fiji's mining industry;

(d) The recognition of the importance of *safety and risk management systems* at the mines, whereby the role of the mines inspector will be expected to change from one of *regulator* to one of *safety management auditor*; and

(e) International trends that determine the competitiveness of Fiji's mining sector.

In recent years, the use of Manager's Rules[4], as a set of *de facto* OH&S regulations at the mines, has superceded the current Mining Regulations and placed the Mine Manager in the front seat of OH&S management.

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[3] This guiding principle has been applied extensively in OH&S issues around the world, and especially in the mining industry by the ILO Convention 176 titled **"**Safety & Health In Mines**"**. The Conventions sets out the liabilities as to who is responsible for worker and workplace safety, and the roles of the employer and employee in this regard.

[4] Manager's Rules are sets of work standards that ensure that accountability and competency in all mining activities not specifically covered by the Mining Regulations, are adequately addressed at the mining workplace, with particular emphasis on occupational health and safety issues. Work standards range from the procedures for the usage of machinery to guidelines for performing a particular task in mining operations. Their formulation involves the submission of work standards by the mine operator to the Mines Inspector, who vets and then approves it for use. This inherently promotes self-regulation of mining operations, and makes for a more responsible mine operator.

4.0 SUSTAINABLE DEVELOPMENT ISSUES FOR MINING

4.1 The role of government

Government has many important roles or responsibilities. These include good governance; the equitable re-distribution of wealth; the provision of a level playing field in which both the public and private sectors can be competitive and efficient; and the provision of social and physical infrastructure and the accompanying policies that ensure the development of the community in general.

Areas of conflict that have recently arisen with regards to these roles and responsibilities include, firstly, the issue of *sovereignty* over minerals and how the Constitution and other statutes define *ownership of minerals*. With the recent trend of empowerment of indigenous landowners, governments seem to have taken a backseat in defining clear and stable guidelines for development that is focused on the community rather than the developer. There is also a growing conflict between customary law, constitutional and statutory stipulations in this matter. In the case of royalties, for instance, instead of landowners having a *beneficial interest* only based on the definition of what royalty is being paid for, landowners are now claiming royalties[5] that should only be claimed by the State as the owner of all minerals. The Fiji Government has been remiss in not providing a proper definition of *what* royalties are being paid for and under *what conditions*, as reflected in the recent Constitutional amendments to the 1990 Constitution.

The other issue is the important aspect of political input into development projects, especially its impact on the local communities. There are many examples in the Pacific Basin of mining projects having being commissioned or mothballed as a result of some degree of political meddling. Mt. Kasi in Fiji is a prime example. Here, the government commissioned a mining project as a means of arresting the then declining investment trend in Fiji, especially in terms of foreign direct investment (FDI). This is a key area that regulators and national planners need to be aware of due to the many vested-interest groups involved and how they can influence development decisions. NGOs have also taken up an important role as watchdogs in this regard.

[5] Royalty has been generally defined as the price paid by a developer in exploiting or capitalising on a country's mineral wealth, whereas compensation is paid for permanent damage or negative impacts caused by mineral exploration and development activities.

4.2 Community empowerment and building a partnership

Mining companies and mineral developers are well advised to initiate involvement and consultation with local communities from the very beginning of mineral exploration. This is a key step to building up the *trust account* from which the developer and the government can draw from when conflicts at or about the mining operation arise. The basic tenets of trust, respect and goodwill continue to remain key elements of this, especially since:

- local communities and indigenous landowners, although uneducated by western standards, are nevertheless highly intelligent. Underestimating this important factor may lead to distrust and even violent confrontation and alienation amongst stakeholders,
- have long memories of developers or governments that promise but do not deliver,
- may look towards non-monetary benefits rather than the over-emphasises monetary benefits of governments and developers.

4.3 Strategic issues before, during and after mining

The importance placed on social impact studies has also been emphasised in conjunction with environmental impact studies, especially since the most important asset (being human resources) in the area of development is affected. This also requires a strategic approach to liaison between all stakeholders, which should then present the basis for a comprehensive database of information for social and environmental impact studies, and primarily as *baseline data and information* on any mining project.

With regards to mine closure and mine decommissioning, the key element is partnership between stakeholders, and early planning so as to ensure sustainability at the outset. The 3 Ps[6] (*project*, *process* and *performance*) are words that best describe the mine closure strategy besides *partnership*. *Project* refers to the impacts and effects of the project closure on stakeholders; *Process* refers to strategies formulated that ensure that mine closure has the least negative impact on all stakeholders and yet has sustainability factored-in; and *performance* refers to actual implementation and achievement of the strategic objectives of the mine closure and decommissioning plan. In this regard, probably

[6] Conference Papers (1998).

the most critical aspect of mine closure planning is ensuring that such planning and strategies are formulated at the Feasibility Study stage, and that implementation begins when the mine is commissioned. The use of social and environmental baseline studies becomes highly important in the planning and implementation of mine closure and decommissioning strategies.

Probably the most negative and visible impact of mining activities has been in the area of waste management or the lack of it. This is evidenced in the range of tailings dams failures that have happened in the past (e.g. Marcopper in the Philipines, Ok Tedi in PNG), which have caused *negative impacts* on the local communities and the local environments. The disastrous impact on wildlife (e.g. fish deaths) result from tailings dam failures and mine construction activities e.g. Mt. Kasi Mine in Fiji. There must be a more intensive tailings dams management strategy in place and appropriate risk mitigation strategies. These could include other options for tailings storage and the redesigning of mineral processing methods to produce inert tailings for safer storage. Best practice, due diligence assessment and risk management are all key elements required in safeguarding against such catastrophes.

5.0 CONCLUSION

Community issues are emerging as probably the most critical aspect of resource development in mineral-endowed countries like Fiji, especially when Sustainable Development principles are factored-in to such development. Mining has been viewed by the larger community, as a destructive development. This has been reinforced by the fact that it involves the exploitation of a non-renewable resource, and has some negative impacts on the environment and community upon which it encroaches. The benefits of mining have often not been assessed and publicly stated. The trend of continuing community empowerment in natural resource development has meant a re-definition of the traditional roles of governments, developers and such communities. What is emerging is a progression towards more transparency in decision-making. This has been caused by community empowerment that has been hard won after catastrophic events induced by mining activities have resulted in community retaliation, as well as by a more participative and collaborative approach between the parties in decision-making.

The challenge for these partners in Fiji is to clarify their role in the process and to agree on the rules of participation. These rules must be underwritten by stable and transparent constitutional, statutory and policy frameworks that work together to produce the goals for the sustainable development of natural and/or non-renewable resources. Critical amongst these frameworks is the proper identification of landowners in terms of native land ownership under the Native Lands registry and the rights associated with such land ownership. These rights may have to be further defined under the Native Lands Act under the mandate of the Native Lands Trust Board (NLTB). Secondly, a proper legislative and policy framework must be developed and administered by the government to regulate the process of such development based on the ethos of Sustainable Development; this must yet allow the equitable generation and redistribution of the benefits of such development at minimal cost to all stakeholders and the natural environment. Anything less could mean discontent and resentment from the communities affected by such natural resource development, and eventually may lead to curtailment of such development, or in the first instance, lack of development.

Based on the lessons learnt from the two mining operations at Emperor Gold Mines and Mt. Kasi Mine, a proper framework and partnership for mining development in Fiji is being formulated and tested, at a time of very low mineral commodity prices. This has been reinforced by lessons learnt from other countries like Papua New Guinea. What remains is the development of a platform for mutual trust and respect between the government, the developer and the communities involved, to ensure a lasting partnership that is the basis for Sustainable Development initiatives.

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KEY FIJIAN WORDS

Vanua : Encompasses the Fijian indigenous concepts of land and its associated linkages to the customary structures of beliefs, belonging, identification and other issues that are a part of the Fijian social and cultural fabric.

Mataqali : Fijian landowning unit.

AN OVERVIEW OF MINERAL EXPLORATION AND ITS RECENT TREND IN SOLOMON ISLANDS

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ABSTRACT

Solomon Islands has a total land mass of approximately 28,369 km^2 within a sea area of some 1,632,964 km^2. Its economy is narrowly based on a few agricultural commodities and natural resources such as fish and timber and is endeavoring to sustain a fast growing population of around 360,000 plus (1994 projection). It is part of the Circum-Pacific metalogenic belt or part of the commonly called **"**Pacific Ring of Fire**"**. The geology of Solomon Islands varies in age from Recent to Cretaceous and is described as **"**a fractured arc**"** composed mainly of oceanic basalt basement, calc-alkaline volcanics and sedimentary cover. The double chain of islands that comprises Solomon Islands is aligned in a North-west - South-east direction, are located on the Pacific side of the collision zone between the Indo-Australian Plate in the south and the Pacific Plate in the north. A knowledge of minerals has existed since the islands were discovered in 1568, but it was not until the 1930s before any form of mineral prospecting began. Exploration waxed and waned over the decades. There exists a legislative framework for mineral matters called the Mines and Minerals Act 1990. A number of mineral occurrence discoveries were made up to 1990. However none has so far proved to be economically viable except the recently proven Gold Ridge gold deposit. There is still a lot to be known about the mineral resources of Solomon Islands. With the recent success of the Gold Ridge Project, mineral exploration interest in Solomon Islands has recently been experienced to be on an encouraging rise.

1.0 INTRODUCTION

Solomon Islands is a double chain of islands located to the east of Papua New Guinea (PNG) extending on a northwest to the south-east direction for up to 1500 km in length and lies between latitudes 6 and 11 degrees south and longitude 156 and 165 degrees east (Figure 1). The group consists of six main islands of sizes up to the excess of 5000 km^2 plus numerous small ones. The total land mass is approximately 29 000 km^2.

Solomon Islands (before it became independent in 1978) was originally termed the British Solomon Islands Protectorate (BSIP). Upon independence Solomon Islands adopted a parliamentary democracy government system. The executive arm of the Government is the National Cabinet headed by the Prime Minister who chooses its ministers. The legislature is a single chamber National Parliament composed of 50 Members of Parliament. The Head of State is the Governor General, representing the Queen as Head of the Commonwealth.

The main exports are copra, palm oil, cocoa, tuna and timber. Mineral exports play a very low key role but the establishment of the Gold Ridge mine which started producing gold in August of 1998 will, hopefully, reverse this trend.

The islands of Solomon Islands are geotechnically located in the Circum-Pacific Belt, stretching in a south-easterly direction from PNG in the north through Vanuatu, Fiji and New Zealand in the South.

2.0 GENERAL GEOLOGICAL SETTING AND GEOLOGY

The greater part of the Solomon Islands archipelago forms a linear double chain of islands, oriented in the north-east to south-west direction. Solomon Islands is part of the Greater Melanesian Arc System which marks the collision zone between the Australian and Pacific Plates. At present the Australian plate is subducting under the Pacific plate, and has been doing so for approximately the past 12my.

The Solomon islands are a subaerial tip of an upstanding topographic Block, the Solomon islands Block, which is bounded by two trenches, a discontinuous trench lies on the Coral Sea side (south-west) of the arc and another, although poorly defined, series of trenches lies on the north-east side (Vitiaz trench) of the arc towards the Pacific. The Santa Cruz island group in the east belong structurally to the New Hebrides Arc.

Most of the area is seismically active. The geology can be described in terms of three distinctive elements: 1) oceanic basement; 2) calc-alkaline plutonic- volcanic crust and 3) volcaniclastic and non-volcanic sedimentary cover.

The basement is made of oceanic basalts and cognate intrusions of ultrabasic rocks, dolerites and gabbros generally considered as upraised ocean floor. The calc-alkaline volcanics form andesitic cones and volcanic lithosomes, the earliest dated as Oligocene (Suta volcanics) and the latest as Plio-Pleistocene (e.g. New Georgia) and Recent (e.g. Savo). Large intrusive bodies are also present (e.g. the Koloula and Poha diorite complexes, Guadalcanal) which show porphyry copper mineralisation. Andesitic volcanics can carry hydrothermal gold veins.

The sedimentary cover comprises up to 5000 m of varied sediments which lie unconformably on the basement. The earliest sediments are assigned to the Upper Cretaceous. Greywackes and associated lithologies form the greater part of the successions, although there are extensive developments of Miocene and Pliestocene reefal limestones. From the Pliocene onwards volcaniclastic sediments become an increasingly important component.

Solomon Islands is not a simple arc system but represents a collage of crustal terranes with discrete and complex geological histories. This fact was recognised by, Coleman (1965, 1966 and 1970) and Hackman (1973), who divided this region into four distinct geological provinces. Their provinces are, Central, Pacific, Volcanic and the Atoll Provinces. The Central Province is characterized by variably metamorphosed Tertiary sea floor and remnants of the north-east facing arc sequence that grew during the early to middle Tertiary above the then south-west plunging Pacific Plate .

The Pacific Province appears to be an uplifted and largely unmetamorphosed portion of the OJP, and forms the basement of Malaita, Ramos, Ulawa, and the north-east part of Santa Isabel.

The Volcanic Province, which extends along the south-west flank of the Central Province is an island arc sequence composed of volcanic and intrusive rocks and active volcanoes of Pliocene to recent age.

The Atoll Province, consists of upraised coral atolls.

However subsequent mapping and geochemical investigations have shown that this Province Model is over a simplification of the tectonic processes which affected this region. An alternative model was proposed by Petterson, 1995, which incorporates findings of recent work, and subdivides the Solomon Islands into five distinct terranes on the basis of basement age and composition and subsequent arc development.

3.0 MINERAL EXPLORATION

Mineral occurences were known to be present in the islands since their discovery in 1568 by a Spaniash explorer, Alvaro de Mendana who found gold nuggets upon landing at a river mouth on the north coast of Guadalcanal Island. Having found the existence of gold, the islands were (mistakenly) named after the great King Solomon of the Bible.

It was not until the early 1930s before mineral prospecting began to flourish on the discovery of gold in the Gold Ridge area, Guadalcanal. A syndicate was formed and with numerous other lease holders began prospecting in the area. All activity abruptly ceased when fighting reached the islands during the WWII in 1942.

It was in 1953 before systematic prospecting and geological investigations began again when the first government geologist (J C Grover) was appointed to the local administration. During that time there was a lack of knowledge about the geology of Solomon Islands. Many scientific advances were made as reconnaissance traverses began on New Georgia, Santa Isabel, and on Guadalcanal. However, systematic mapping did not begin until 1963 which led to the discovery of: 1) a nickel-bearing laterite capping ultramafic rocks at several localities throughout Solomon Islands: 2) phosphate on Bellona; and 3) Hanesavo manganese which attracted a few reconnaissance prospecting mining companies. The geological map of the Islands was published nine years after the arrival of the first geologist.

In 1965 UNDP began an aerial geophysical survey project for the islands (A B Electric Malmletning, ABEM). Radiometric, magnetic and electro-magnetic methods were used. The survey was conducted in 1966. Regional gravity survey and routine seismological survey were conducted earlier on by the BSIP Geological Survey. Among other achievements, the UNDP survey was responsible for the discovery of the Rennell Island Bauxite deposit (25.2 mt of 48% Al_2O_3) and the Koloula copper mineralisation.

The islands experienced a rush by exploration companies in the early 1970s which led to most of the islands under reconnaissance permits and other specific areas under detailed prospecting licences. Discouraging results again reduced exploration to a low level in the mid 1970s. Prospecting activity remained low up to the early to mid 1980s.

In 1982, the Solomon Islands government called for tenders from international companies for the detailed evaluation of the Gold Ridge primary gold deposit, which ranked as one of the most attractive undeveloped gold prospects in the region at that time. Amoco Minerals of the USA won the tender and commenced work under a three years prospecting licence in 1983. Arimco of Australia continued the work at Gold Ridge until it relinquished the prospect in 1993 due to internal corporate changes within the company. The prospect was raised to a feasibility study stage at the time of withdrawal.

This opening of work in the country by Amoco and the availability of results of the geological and geochemical mapping work by the BSIP Geological Survey in the mid 1970s for the Western Solomons has prompted interest in other gold prospects in the country resulting in an increase in exploration activities. Important gold discoveries in neigbouring PNG contributed to a peak level of exploration activity in 1986, especially to search for epithermal gold. Unfortunately this peak did not last and in 1987, a waning of activity began partly in response to the international stock market difficulties and partly in response to internal problems relating to land access. Nevertheless much of the country remained covered by applications and licences. The downward trend established in 1987 continued until 1994 when the Gold Ridge deposit was placed on international tender for the third time. A subsequent submission of a feasibility study report for the Gold Ridge deposit in 1996 and the granting of a mining lease to Gold Ridge Mining Limited in March of 1997 reversed the downward trend.

As of November 1997, a total of 28 prospecting licences existed in the entire country, one mining lease, and 12 prospecting licence applications pending for consideration. As of September 1998, eleven (11) prospecting licences were unfortunately relinquished by Acabit exploration of Canada.

4.0 MINERAL OCCURRENCES

The mineral occurrences in Solomon Islands can be grouped into three categories by age and association: 1) oceanic basement association; 2) calc-alcaline association and, 3) residual deposits.

Numerous indications of mineral occurrences have been noted in almost all islands as a result of geological and mineral exploration work during past decades. A mineral occurrence map was produced in 1978: an update of this publication is now overdue.

4.1 The oceanic basement association

This includes all mineral occurrences found in basalts, gabbros, metamorphic rocks and ultramafic rocks of the pre-Oligocene basements. Mineralisation occurs as sulphides in small veins, dessiminations and stockworks in the basement basalts and metamorphic rocks, as exhalative products (manganese oxides), and as silicates in ultrmafic bodies.

4.2 The calc-alkaline association

This includes mineral occurrences associated with andesitic volcanics and their parent dioritic stocks (e.g. New Georgia and Western Guadalcanal). Mineralisation occurs as sulphide stockworks of porphyry-copper style (e.g. Koloula, Guadalcanal), as sulphides in the andesites and volcanic porphyries (e.g. Gallego and Umasani volcanics), and as hydrothermal epithermal mineralisation in altered, reworked andesitic pyroclastics (Gold Ridge, Guadalcanal).

4.3 Residual deposits

Residual deposits formed either by mechanical accumulation or chemical weathering during the Quaternary. Mineral occurrences include: bauxitic clays on upraised limestones (e.g. Rennell and Vaghena); as laterite from calc-alkaline volcanics and volcanic rocks; oceanic phosphates on raised atolls (e.g Bellona), and volcanic sublimates, chiefly sulphur occurring in fumerolic areas (e.g. Savo).

4.4 Other minerals

Industrial minerals are known to exist principally as limestones for possible cement manufacture, volcanic ash with pozzoline properties and sand

and river gravels used for construction purposes. There is still need for much more exploration in this category.

No hydrocarbons are known to exist in Solomon Islands but recent work in Fiji and Tonga may suggest that possible occurrences remain to be discovered. Four large offshore Basins occur in Solomon Islands. Recent interpretation of geophysical data by SOPAC of one of the Basins has revealed the existence of fossil reefal like structures within the sediment successions which are favourable reservoirs for hydrocarbons.

5.0 MINING POTENTIAL AND FUTURE OUTLOOK

Metallic mineralisation has been confirmed to exist in the country, although none of the known occurrences warrants exploitation to date except for the well known Gold Ridge epithermal gold deposit which has now been developed and produced its first gold ore as of 12 August 1998. The successful Gold Ridge mine development has generated mineral exploration interest in Solomon Islands, thereby boosting exploration expenditure and increasing the chances of new economical mineral deposit discoveries.

The Gold Ridge deposit gold reserves now stand at 1.36M oz (a recent increase by 98,000 oz: 35 percent increase of the original 1996 feasibility report). This is a result of a successful subsequent drilling programme around one of the known deposits. The mine is expected to have a 10 year mine lifetime and, with the current continued aggressive exploratory work, it may be extended.

Prior to the eventual establishment of a mine at Gold Ridge, the only form of mining was undertaken by individual alluvial gold panning by local people downstream of Gold Ridge which, for decades produced some 40 to 80 kg of gold annually (except from 1985 to 1987 when Zanex, an Australian Mining company undertook alluvial gold mining at Chovohio, downstream of Gold Ridge). With the advent of a mine at Gold Ridge, alluvial gold production has declined.

Although the Gold Ridge Mine is a small to medium scale one by world standards, it plays a significant role in the economic development of Solomon Islands. It is expected that 100,000 oz (or more) gold will be produced annually for at least 10 years. This development has stimulated increased activities from other economic sectors especially in the service and consumable sectors.

Some mineral prospects in the country have been well prospected and their reserves calculated. This includes the lateritic nickel deposits of Eastern Santa Isabel which is now intended to be placed out for international tender.

6.0 MINERAL LEGISLATION/ POLICY

The ownership of minerals is vested in the people and Government of Solomon Islands. The Mines and Minerals Act 1990 with its subsequent Regulations of 1996 govern all mineral and mining matters in Solomon Islands.

Permitting legislation is needed to be considered for mineral exploration in Solomon Islands, such as the Foreign Investment Act and the Lands and Titles Ordinance.

There is, as yet, no formal established mineral fiscal policy in place for Solomon Islands although past and present governments gave priority on the development of mineral resources. The current highly successful, negotiated fiscal measures now under operation for the Gold Ridge Mine between the Government, Local People and the company will form the basis for a national mineral fiscal policy for Solomon Islands.

7.0 CONCLUSIONS

The generally limited results of the exploration work carried out to date in the Solomon Islands (with the exception of the long-awaited Gold Ridge Mine) are disappointing but do not, in any way indicate a low national mineral prospectivity situation. On the contrary, the Solomon Islands is highly prospectable and new thinking with respect to deposit models and exploration will inevitably lead to new major discoveries. The islands remain largely undeveloped and unexplored by modern methods.

The Government of Solomon Islands will endeavour to maintain and improve current levels of exploration by finding amicable ways to assist companies accessing customary land, instigating proper permitting legislation, devloping stable government mineral and fiscal policies, and ensuring government capacity and capability.

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ASSESSMENT OF CORAL FOR CONSTRUCTION IN THE FEDERATED STATES OF MICRONESIA

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ABSTRACT

This paper presents the results of engineering-geological assessment of dredged coral reef rubble from Pohnpei Island, FSM for construction. Over 51 dredge sites were mapped. Disturbed samples were collected from dredge sites and assessed from petrography, composition, granulometry, Atterberg limits, water absorption, porosity, void ratio, dry and wet densities and unconfined compressive strength following American Society for Testing Material guidelines. More than 70% of dredged rubble is abraded and angular sand and gravel, consisting of coral, foraminifera tests and mollusc shells, with water absorption of 3 to 30%; porosity of 6 to 23%; void ratio of 0.06 to 0.30; dry and wet density of 1.88 to 2.50 kg/m^3 and 2.06 to 2.70 kg/m^3 respectively, with an unconfined compressive strength less than 50MPa. This suggests that this aggregate can be highly susceptible to failure under heavy static and dynamic loads, both in-situ and at fill and reclamation sites.

1. INTRODUCTION

Coasts in the Pacific Island Countries (PICs) are used for a variety of purposes, ranging from social and recreational to industrial activities. The relatively large ocean and maritime space in each of the PICs makes development impossible without some influence (positive or negative) on the coast and shorefront. For this reason, shorefront and coastline development must be pursued in a carefully planned manner, so as to minimise negative impact of development activities.

One of the main uses of coasts in PICs and in the Federated States of Micronesia (FSM) is coral reef dredging and mining of marine aggregate. This includes a mixture of carbonate sand, gravel, cobble and boulders, which comprise dead coral skeletons, live coral heads and massive coral skeletons (e.g. *Montstrea* spp). Coral reef mining has, for many years, been the main source of construction aggregate for the building industry in PICs. Reef carbonates are used in four major activities. These are: for fill and land reclamation in wetlands; housing and tourism development; construction of coastal protection structures (like seawalls, groynes, revetments, breakwaters, gabion baskets and bio-engineering protection); promenades and infrastructure facilities (like coastal roads); and construction of industrial facilities and residential buildings.

In coral reef and atoll environments, like those in FSM, mining of reef carbonates and extraction from storm ridge deposits, carbonate sandbanks, coral heads, reef rubble and reef sands and gravel is a multi-million-dollar economic activity. Marine carbonates are mined from reef crests, back-reefs and lagoons, in water usually less than 10 m deep. Common species of corals, which are mined, are *Montastrea* spp., in addition to *Acropora* spp., and *Porites* spp. Finely abraded gravel and sand are mined from shallow lagoons, in commercial quantities. These finer materials contain many branching corals, especially *Acropora* spp., molluscs, benthic foraminifera, *Halimeda* spp., *Rhodophyta* spp. and echinoderm test fragments.

Mining satisfies the demand for building aggregate, especially for domestic housing, which has evolved from the traditional thatched and palm dwellings, to concrete and mortar structures. In addition, much aggregate is required for the commercial building industry, and for construction of critical facilities, such as airports, roadways and bridges. With changing societal trends in the region, which show a departure from traditional buildings (bures and canoe houses) to concrete and mortar structures, and the demand for new homes, constructed facilities and civil infrastructure, there is an ever growing demand for building aggregate. Consequently, there has been a

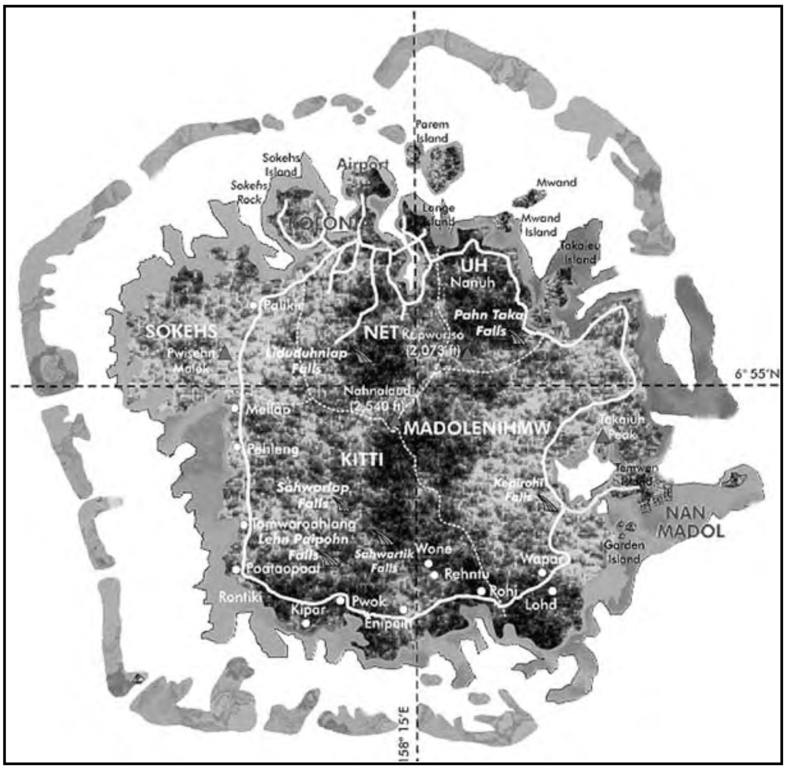

Figure 1. Map of Pohnpei Island, FSM, showing dredge sites (stars).

corresponding increase in dredging and mining of coral reef ecosystems to satisfy this demand in the construction industry. However, reef carbonates can be subject to early and premature engineering failure if they are of low quality, subject to large loads and not improved in engineered facilities. These can lead to premature failures, increase failure frequency of structures and increase risk at constructed facilities. This paper examines the geotechnics of modern reef carbonate and its implications for use as engineering construction material, with examples from, Pohnpei Island, FSM (Figure 1).

2. METHODOLOGY

Major dredging sites were mapped on Pohnpei Island, FSM. Twenty samples of dredged material were collected and tested in the laboratory for composition, granulometry, Atterberg limits, dry and wet density, porosity, water absorption, void ratio and unconfined compressive strength following American Society for Testing material (ASTM (2000)) guidelines. Site investigations were also conducted at 60 sites, to examine field aggregate geotechnical properties. The data was then used to assess the suitability of the representative reef carbonates for engineering construction.

3. RESULTS

Most dredging and mining of reef aggregates takes place in water depths of less than 10 m deep, and in most cases, between 5 and 10 m. These sites are lagoonal/ back-reef. Most excavation takes place by using hydraulic back hoe and dragline excavators. Figure 1 shows major extraction sites, which number 51, of which 47 are dredge sites, with 14 active areas (Maharaj (2001)). These sites represent dredging activities over the past two decades. Dredge material from these sites have several common characteristics. Twenty samples show that 50 - 70% of these aggregates are made up of coral skeletons, especially branching *Acropora* spp. and *Porites* spp. corals. These aggregate are light grey to white, non-plastic, angular, poorly graded, abraded and pitted with cavities. They consist of 50 - 70% gravel particles, with mixtures of carbonate, skeletal sands and less than 10% oolitic particles. Gravel fragments contain calcareous algae encrustation and spirulid worm tubes. Samples can be classified as ASTM (2000) GP class or poorly graded gravel and gravel-sand mixture, with little or no fines. Carbonate gravel is a major component of dredged aggregate and consists largely of coral fragments, mollusc skeletons, echinoderm tests and crustacean skeletons. *Halimeda* spp. and benthic macro-foraminifera tests are significant constituents of dredged sands in shallow lagoons and comprise up to 80% of dredged lagoon sands. These particles are typically flat, with high aspect and low surface area/volume ratios. They are usually of coarse sand to fine gravel size, with nominal particle diameter between 0.50 - 4.00 mm. These flaky particles are very porous, with high void ratios and are light, with specific gravity of less than 2.60.

Particles are uncemented and are not recrystallised. Branching coral fragments are cylindrical, while massive species are generally composed of rounded to sub-rounded particles. Boulders are usually sub-rounded massive coral species, but sometimes branching and irregular *Acropora* spp. These are denser. Carbonate mud is a minor fraction of dredged material, usually less than 15% of the bulk material.

Table 1 presents some laboratory test data on coral gravel particles from dredged sediments, while Figures 2 - 6% relationships between the various geotechnical parameters. From these data, samples have high water absorption, averaging 7.89%, but can be up to 29% in porous particles, with a corresponding high porosity and void ratio, averaging 12.81% and 0.15 respectively. These cause dry and wet densities to show similar trends. Dry density tends to decrease with increase in void ratio and porosity, while wet density show a similar trend when examined in relation to water absorption (Figures 3 - 5). Wet densities of fragments averaged 2420 kg/m^3, but some samples had densities as low as 2060 kg/m^3. Few samples had relatively high dry densities, owing to their high porosity and void ratio. Those more dense samples had dry densities approaching that of the mineral calcite, about 2700 kg/m^3 e.g. PA/K13 (Table 1). Water absorption and porosity show similar trends, except for sample PA/K 9 (Figure 2), while wet densities mimic dry density (Figure 6).

Table 1. Some geotechnical properties of dredged coral gravel.

Sample number (%)	Water absorption	Porosity (%) (e)	Void ratio (kg/m^3)	Dry density (kg/m^3)	Wet density
PA/K 1	4.6	6.25	0.06	2270	2370
PA/K 2	2.75	6.66	0.07	2420	2490
PA/K 3	1.85	6.25	0.06	2700	2750
PA/K 4	3.5	16.66	0.2	2350	2430
PA/K 5	6.04	12.5	0.14	2270	2410
PA/K 6	3.1	5.55	0.06	2510	2580
PA/K 7	7.33	21.43	0.27	2140	2300
PA/K 8	9.82	18.18	0.22	2040	2360
PA/K 9	29.9	12.5	0.14	1920	2500
PA/K 10	9.41	22.22	0.28	1880	2060
PA/K 11	4.62	6.23	0.06	2260	2360
PA/K 12	4.6	6.67	0.07	2420	2480
PA/K 13	1.83	6.3	0.06	2710	2750
PA/K 14	3.51	16.5	0.2	2330	2430
PA/K 15	6.04	12.52	0.14	2300	2400
PA/K 16	3.11	5.6	0.06	2500	2570
PA/K 17	7.32	21.33	0.27	2420	2310
PA/K 18	9.39	18.18	0.22	2040	2350
PA/K 19	29.7	12.6	0.14	1910	2540
PA/K 20	9.44	22.12	0.28	1850	2040
Average	7.893	12.8125	0.15	2262	2424

4. DISCUSSION

Modern reef carbonates from Pohnpei Island are of high porosity and void ratio, low dry and wet density, with low specific gravity (less than 2.60) and are of low compressive and impact strength. If used to construct concrete and rigid structures, or as engineering fill and pavement base courses, they can performs poorly and fail under static or dynamic loads due to particle crushing. In areas of high seismicity, like the Southwest Pacific (Maharaj (2001)), engineered sites built with this material are highly susceptible to structural collapse under large-magnitude cyclic strain and earthquake loads. These material are also highly susceptible to grain crushing and decrease in void ratio or structural collapse, under isotropic consolidation and shear, due to the high aspect ratio and flakiness and low strength of particles (Maharaj (1995)). These can result in differential foundation settlement under structural and/or "live" load.

Marine aggregates also contain harmful magnesium, chloride and sulphate ions (found in high concentrations in tropical seawater). These ions can

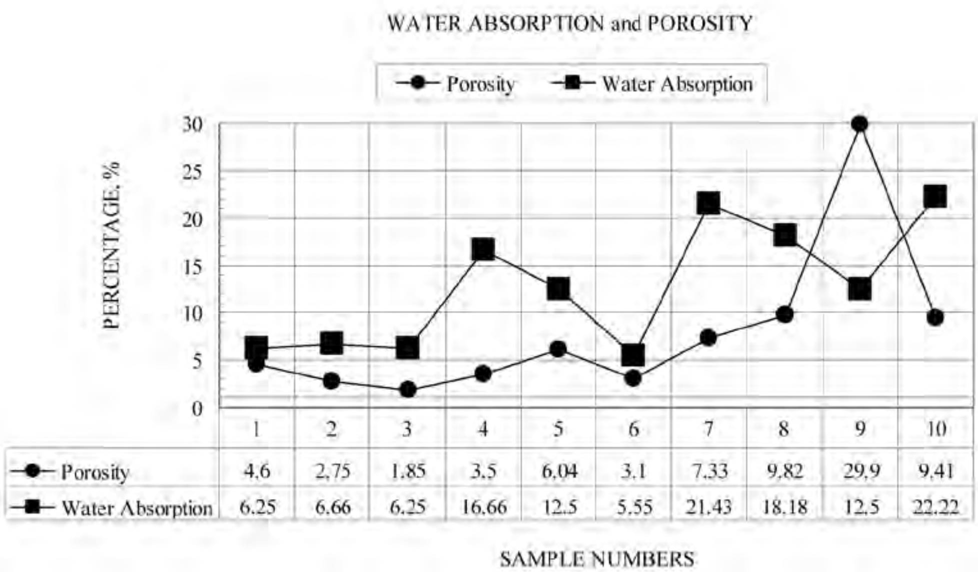

Figure 2. Graphical plot of water absorption and porosity for coral gravel samples.

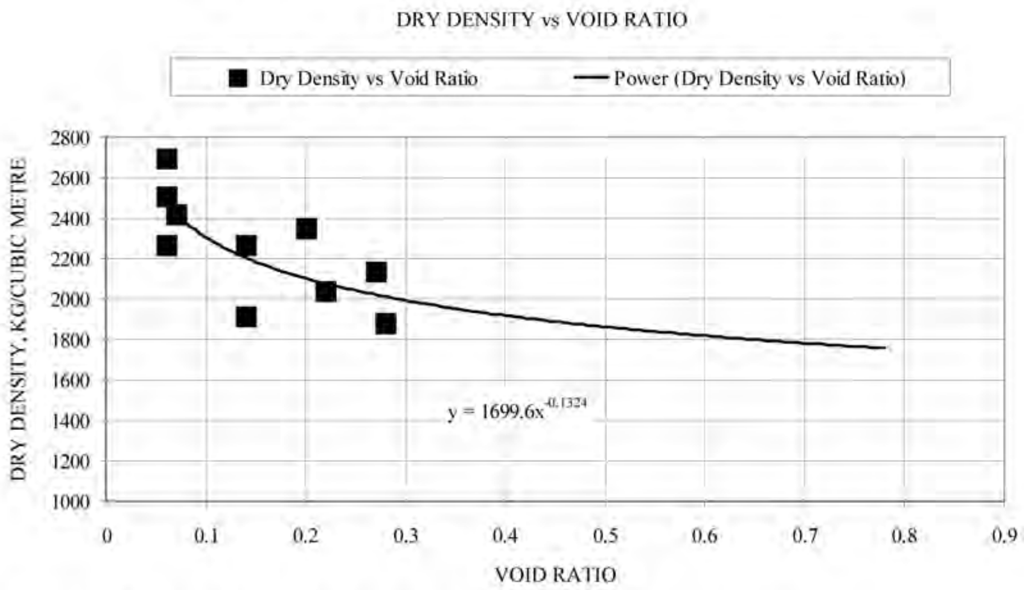

Figure 3. Graphical plot of dry density vs void ratio for coral gravel samples.

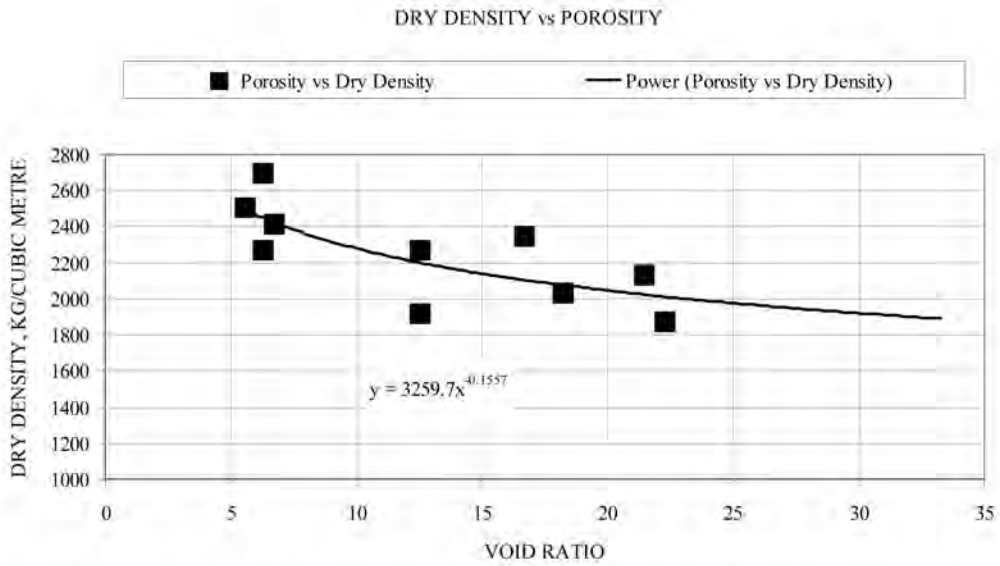

Figure 4. Graphical plot of dry density vs porosity for coral gravel samples.

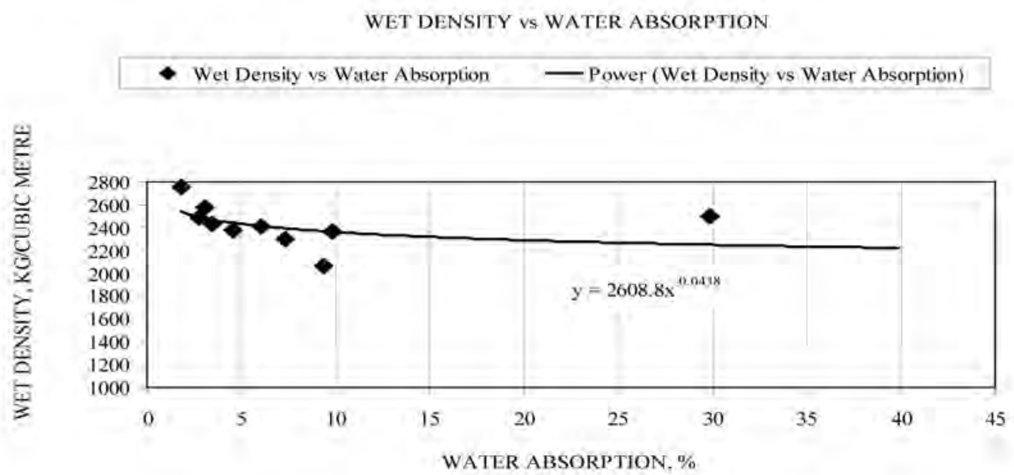

Figure 5. Graphical plot of wet density vs water absorption for coral gravel samples.

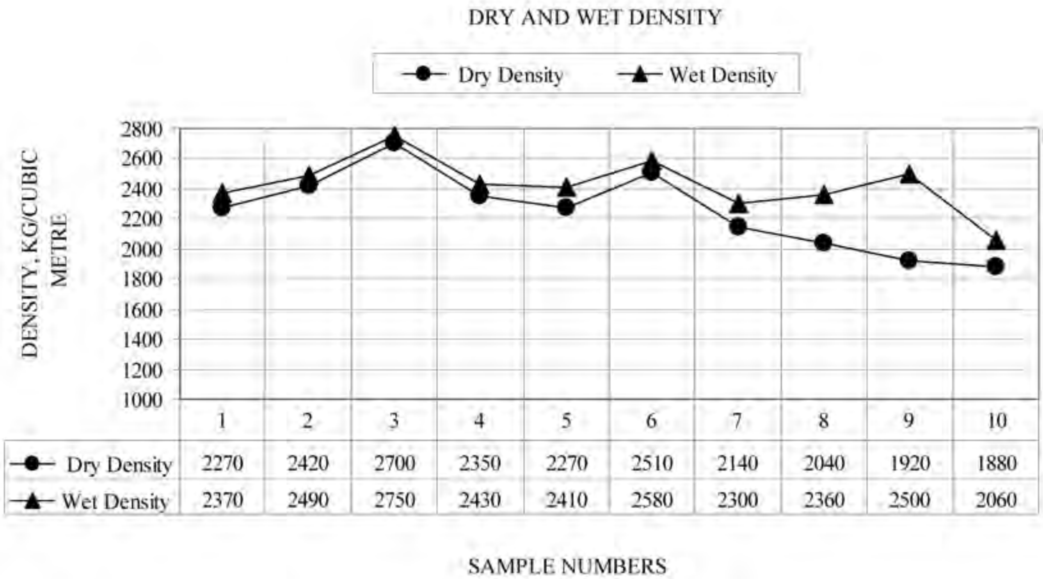

Figure 6. Graphical plot of dry density and wet density for coral gravel samples.

cause harmful chemical reactions with cement and un-coated steel, if marine aggregate is unwashed, and used in steel-reinforced concrete. This is more likely where the concrete is porous and designed using Portland cement (ASTM Type-I designation). Chloride ions also decrease the passivity of steel in concrete, and increases the susceptibility of steel-reinforcing bars (rebars) to corrosion, in steel-reinforced concrete (Geological Society of London (1991)). This type of corrosion of rebars can cause swelling of the outer corroded films of rebars, by as much as 400%. Such swelling results in high tensile stresses in cast concrete, which cracks, because of its low tensile strength. Tension cracks produced by this process cause further ingress of moisture and air, causing further oxidation of rebars and additional cracking. In addition, sulphate ions can also react with calcium rich cement and leads to precipitation of an expansive sulphate called ettringite and magnesium silicate hydrates. These also lead to swelling within the concrete, causing tensile stresses, cracking and spalling. Chemical reactions like those described above, in this high pH (11 - 14) and moisture-rich environment can result in deterioration of cement-aggregate and steel-aggregate-cement binding reactions in concrete. This can ultimately lead to spalling of concrete and collapse of the concrete structures. Steel-reinforced concrete cast with these aggregates in PICs, usually show ferrous oxide and hydroxide staining (Maharaj (2001)), due to rapid oxidation of the steel, in cracked concrete, and due to chemical attack by chloride ions usually present in these marine aggregates along the coast.

5. CONCLUSIONS

Reefs represent a major source of aggregate for the construction engineering industry in south PICs like FSM. Aggregates in these areas are almost entirely reef carbonates, with more than 50-70 % coral gravel, skeletal sands and minor amounts of fines. These constituents are angular, with high aspect and void ratios, high porosity and are of low density and strength. Consequently, they can fail under static/dead structural loads and cyclic strain. Reef carbonates also contain sea salts from seawater, notable chloride and sulphates. Consequently, they are of generally low quality for the construction industry. Where they must be used in construction, due to the unavailability of alternative sources of geomaterial or engineered composites, this aggregate must be initially washed to remove sea salt, and will require additives to improve its strength depending on the desired engineering application. In addition, amendments to, and modifications of design criteria need to be prescribed and made to improve on the (inherent low) quality of this aggregate when used in critical engineering structures and facilities. This will facilitate the optimum performance of constructed facilities built with these aggregates and therefore, reduce the risk and likelihood of their failure through engineering time.

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ASSESSMENT OF VOLCANIC ROCK FOR CONSTRUCTION IN THE FEDERATED STATES OF MICRONESIA

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ABSTRACT

Geological and geotechnical assessment of volcanic rocks from Pohnpei Island, FSM has revealed several sources of good quality construction aggregate. These are basic volcanics, which includes fine-grained, high-density, columnar, olivine basalt, with good impact and strength characteristics. Blocks have very low fracture frequency with low levels of impurities and weathered products with good outcrops on accessible coastal slopes. They can therefore be quarried, using columnar cooling joints as natural planes of weakness for blasting and excavation. Based on geotechnical properties, these rocks can be used in hydraulic scour structures, rock fill, structural concrete, unbound pavements; bituminous pavement, road sub-bases and mortar or concrete Blocks.

1. INTRODUCTION

This paper presents the results of an onshore aggregate assessment for Pohnpei Island, Federated States of Micronesia (FSM). The purpose of this study is to assess the availability and suitability of the various rocks as sources of construction engineering material. The study area is Pohnpei Island, which is 375 km^2 and is located between latitudes, 6° 5′ and 5°5′ North; and longitudes, 157° 5′ and 158° 5′ East (Figure 1). It is roughly circular, with an average diameter of 17 km, a circumference of 120 km, and surrounded by a 0.5 and 7 km wide barrier reef (Maharaj (1999)).

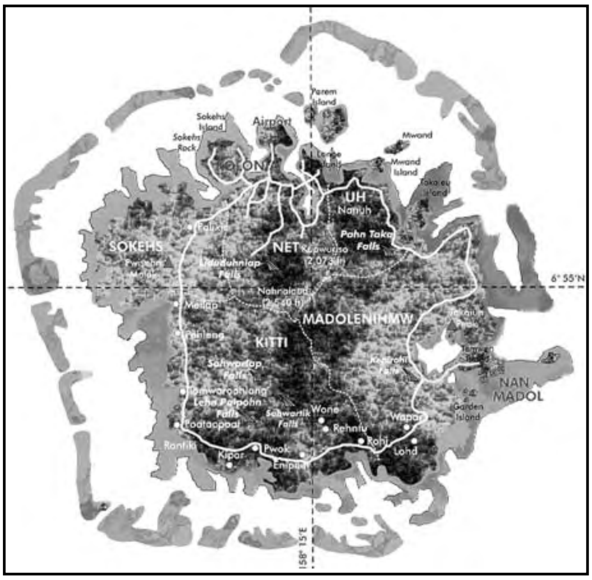

Figure 1. Map of Pohnpei Island, FSM.

2. METHODOLOGY

Information was collected from a literature review, field surveys, and laboratory testing of selected rock samples. Published information, is relatively rare, since the geology of Pohnpei Island has not been the subject of many studies. Bibliographic entries were surveyed in American Geological Institute international GeoRef database.

Site surveys were conducted around the periphery/ coastal areas of Pohnpei Island. This was largely done because upland areas are densely forested, have steep slopes and are subject to deforestation and severe soil erosion. Consequently, quarrying and aggregate mining in these upland areas can result in additional degradation of watersheds, and upland areas. Therefore, aggregate extraction in these sensitive upland areas should be restricted.

Rock exposures in Sokehs, Madolenihmw and Kitti Districts were examined (Figure 1). In addition, two quarry sites were visited. One of these is an operational site, APSCO Inc., while the other is an abandoned site. Both are in the Sokehs District.

Rocks were described from field outcrops, following the American Society for Testing Materials (ASTM, 1999) guidelines. Field rock properties noted were, rock type, Block shape and angularity, flakiness, Block size, colour, texture, structure, state of weathering, strength characteristics, fracture characteristics, and presence of fines and coatings. In addition, petrographic properties were described, as they relate to material properties and performance criteria.

20 rock samples, 40 kg of crushed rock (with particle diameters of 2.50 cm and 4.00 cm), and about 15 kg of crushed volcanic sand were collected at APSCO Inc. quarry operations, Pohnpei. Sample collection procedures conform to guidelines of ASTM (1999). Emphasis was placed on collection and examination of the more competent, columnar, olivine basalt from the Sokehs Districts, which is potentially more suitable for construction. Laboratory testing conformed to guidelines of the ASTM (1999) and included water absorption, dry density, wet density and specific gravity for 20 gravel samples; granulometry of ten volcanic sand samples; 25 L-Type Schmidt hammer rebound/unconfined compressive strength tests; and petrography of 25 rock samples.

3. RESULTS

(Note that geochemical analyses are given in Table 1)

3.1 General geology

The island of Pohnpei is a major locus of alkalic basaltic volcanism in the Equatorial Pacific and along the Caroline Ridge, a diffuse linear submarine feature, which separates the east and the west Caroline Basins from the Marianas Basin (Maharaj, 1999). Pohnpei Island forms part of an eroded, basaltic shield volcano, and is about 4 - 8 million years old. It is part of the Senyavin Islands, which consist of three islands, with Pohnpei being the topmost part of an eroded volcanic edifice (Maharaj, 1999). Basaltic volcanism has resulted in the deposition of lava flows and pyroclastic rocks (agglomerate and tuff breccias). Dykes of basaltic composition are also found on the island. However, owing to the dense vegetation cover and intense weathering in vegetated areas, geological mapping of the entire island has been limited.

3.2 Rock composition and physical characteristics

The rocks of Pohnpei Island are largely alkali/basic basaltic volcanic lava, and were formed by magmatic separation and crystal differentiation, from parental olivine basaltic magmas. The main rock types are, olivine basalts, nepheline basalts, nepheline basanites, and trachyandesite to trachytes. However, olivine basalt and basanite are the most common. Most rocks are aphyric or sparsely aphyric, with less than 10% phenocrysts. Where phenocrysts occur, they are largely olivine, pyroxenes (especially clinopyroxenes), titanomagnetite and/or micro-phenocrysts of plagioclase. These are embedded in a fine-grained groundmass of olivine, clinopyroxenes, plagioclase, opaque minerals, potassic oligoclase and accessory minerals. Nepheline may or may not be present within the groundmass. Some samples also contain augite phenocrysts while titanoaugite is found in many samples. Other minerals include phenocrysts of orthoclase, magnetite and apatite. Amygdales of plagioclase, anorthoclase, olivine and apatite are present (Table 1).

Olivine basalt is the most common lithology and is dark grey to grey-black in fresh samples, composed primarily of olivine and augite, in a feldspar

Table 1. Mineral composition of major rocks (Maharaj, 1999).

Major minerals	% of each mineral in the different rock types			
	Olivine basalt	Nepheline basalt	Nepheline basanite	Trachydensite and trachyte
Quartz	–	–	–	3-13
Orthoclase	5-11	–	6-9	14-23
Albite	16-22	–	10-23	34-61
Anorthite	16-32	13-23	19-23	4-18
Leucite	–	2-6	3-5	–
Nepheline	1-9	7-12	5-20	9
Carbon	–	–	–	1-4
Wollastonite	3-9	9-16	12-19	6
Enstatite	2-7	7-12	8-14	1-5
Ferrosilite	1-3	0.13-3	2-4	0.5
Forsterite	4-13	16-23	9-17	–
Fayalite	2-7	0.2-3	4-7	–
Calcium orthosilicate	–	0.7-8	–	–
Magnetite	4-9	6-10	3-8	1-6
Ilemnite	5-8	5-8	5-7	1-4
Haematite	–	–	–	0.5-1
Apatite	1-3	2	1-2	0.34

groundmass. Many outcrops consist of columnar basalts, with side dimensions of 25 - 50 cm. There is very little sign of weathering, generally less than 5%. However, some exposures show concentric ferrous oxide films, sometimes up to 3 cm deep. Crushed samples are very angular, with sharp edges, due to the largely fine texture. No discontinuities are visible in mesoscale samples or large Blocks.

3.3 Olivine basalt

Samples contain 4.9 – 18%, euhedral to subhedral olivine (forsterite and fayalite) phenocrysts. Some of these crystals are microphenocrysts (< 5 mm). Other major minerals include orthoclase, albite, anorthite, diopside, hypersthene, magnetite, illemnite and apatite. Samples are usually fine to very fine-grained and blue-grey in colour. They can however be fine to medium grained. Rare microphenocrysts of titanaugite and labradorite, in an equigranular, holocrystalline groundmass (+80% intergranular texture) of titanaugite, olivine, plagioclase, potassic oligoclase, titanomagnetite, nepheline, labradorite, olivine, titanomagnetite, ilmenite, sphene, nepheline, potassic oligoclase, accessory apatite and tiny unidentifiable crystallites. Fresh lavender-coloured titanaugite and titano-magnetite are also found. Clinopyroxene phenocrysts exhibit strong optical zonation with trains of tiny opaque inclusions often arranged parallel to optical zones in the crystal.

3.4 Nepheline basalt

Samples contain phenocrysts of olivine and magnetite and with a partly glassy groundmass. Major minerals include anorthite, leucite, nepheline, olivine, pyroxenes, magnetite and illemnite. The clinopyroxene phenocrysts exhibit patchy optical zonation. Samples are usually blue-grey to dark grey and fine medium grained, with a slight resinous lustre in fine-grained specimens and are sometimes massive. They contain large olivine and titanaugite crystals. These crystals can be 3 - 6 mm across. The matrix is usually dense.

Table 2. Petrochemistry of major rocks (Maharaj. 1999).

Major oxides	% of each oxide in the different rock types			
	Olivine basalt	Nepheline basalt	Nepheline basanite	Trachydensite and trachyte
SiO_2	42.94-45.54	35.29-35.87	40.36-44.56	51.25-62.58
TiO_2	2.90-3.80	3.05-4.01	2.64-3.64	0.41-1.70
Al_2O_3	11.55-18.77	10.61	10.38-15.54	19.13-19.36
Fe_2O_3	3.03-5.61	11.51	2.07-5.66	1.95-2.64
FeO	7.80-9.630	4.39-6.23	6.82-10.38	0.66-3.16
MnO	0.15-0.22	6.53-7.90	0.17-0.21	0.17-0.22
MgO	5.47-11.62	0.16	5.70-14.38	0.48-1.98
CaO	7.87-11.16	14.18-15.98	8.65-14.38	1.05-6.87
Na_2O	1.98-3.83	13.07-13.46	1.96-4.32	5.15-7.23
K_2O	0.82-1.66	1.63-2.65	0.99-1.62	2.45-3.90
H_2O^+	0.95-3.47	0.48-1.25	0.59-1.43	1.15-2.55
H_2O^-	0.14-1.11	1.65-2.56	0.11-0.65	0.72-1.07
P_2O_5	0.40-1.26	1.20-2.10	0.30-0.49	0.08-0.20

3.5 Nepheline basanite

Samples contain phenocrysts of olivine, magnetite and titanaugite. The groundmass is largely composed of nepheline, plagioclase and titanaugite. Samples are usually dark grey, and medium-coarse grain. They are sometimes gabbroic in appearance, with large olivine and titanaugite crystals. These crystals can be 3 - 6 mm across. The matrix is usually dense in samples. In some samples, it was not possible to differentiate between phenocrysts and groundmass.

3.6 Trachyandesite and trachyte

Trachyandesite samples contain phenocrysts of magnetite, sphene, aegerine-augite and sodalite, with significant amounts of feldspar. Nepheline is also common. Samples are dark grey, and medium grain. They are usually compact, with a slight resinous lustre.

Trachyte samples contain phenocrysts of anothoclase, aegerine, aegerine-augite, sodalite, with lesser amounts of magnetite and sphene, in a groundmass largely composed of anorthoclase and plagioclase (up to 75%). Samples are green-grey and of medium texture, sometimes with a resinous lustre.

3.7 Geotechnical properties

Geotechnical properties were evaluated for only olivine basalt. Dry and wet density tests of rock samples were 3000 - 3200 kg/m^3 and 3100 - 3376 kg/m^3 respectively. Water absorption varied between 0.19 - 0.59%, averaging 0.415%, with specific gravity between 2.90 - 3.50. Olivine basalt is of good integrity, with less than 5% of the Blocks surveyed containing mesoscopic fractures. Quarried Blocks also contain less than 10% impurities. L-Type Schmidt Hammer rebound for Blocks were greater than 48, and up to 52, with uniaxial compressive strength of 62 - 66 MPa (Table 3).

Table 3. Geotechnical properties of olivine basalt from twenty-five samples.

Geotechnical Parameters	Range	Average
Water Absorption (%)	0.19-0.59	0.4135
Dry Density (kg/m^3)	3000-3200	3111
Wet Density (kg/m^3)	3100-3376	3127
L-Type Schmidt Hammer Rebound	48-52	50
Uniaxial Compressive Strength (MPa)	62-66	64

The granulometry of ten crushed volcanic sands are shown in Figure 2. Samples have average D_{10}, D_{30}, D_{50}, D_{60} and D_{75} of 3 mm, 3.5 mm, 4 mm, 5 mm and 6 mm respectively. The average Coefficient of Uniformity (C_u) was 1.6, while the average Coefficient of Curvature (C_c) was 0.81. The samples were all poorly graded sands with gravel, and were classified as SP, based on C_u and C_c following ASTM (1999) classification.

4. DISCUSSION

Petrography and geological structure influence rock strength, durability, and engineering behaviour and performance. The ability of geomaterials to withstand erosion or it's potential for use in engineering construction is also influenced by petrography and geotechnical properties. In this context, geotechnical performance can be interpreted as the ability of the rock to withstand physical, chemical and biological stresses, and its ability to retain physical and mechanical integrity and properties, while resisting degradation over engineering time. Engineering time, in this context, refers to the average lifespan of typical constructed facilities, which varies between 50 and 75 years.

The relatively high percentage of heavy minerals and metallic oxides in the volcanic rocks of Pohnpei are key factors, which influence rock density. Most of the rocks show high percentages of olivine, magnetite, ilmenite, haematite, apatite and pyroxene, minerals of high specific gravity, greater than 3.27. The high specific gravity and density are good properties, and reflect compact and high Block strength. In addition, these lithologies are fine-grained, which also contributes to high bond strength between mineral grains, high density, low porosity and low water absorption. These produce good, medium Schmidt hammer rebound/hardness, and good, medium compressive strength, based on rock engineering classification (Li, 2000), which are satisfactory for construction purposes (Smith and Collins, 1993). This is particularly true for the columnar olivine basalt. In addition, many steep outcrops contain few pervasive tectonic discontinuities, other than columnar cooling joints and therefore, contain sound Blocks. Further, based on low fracture frequency, good Block integrity, high density and the presence of high specific gravity minerals, quarried Blocks are likely to be of high impact/dynamic strengths and high abrasion resistance (Latham, 1998). Consequently, these geomaterials are very good for use in fluvial and coastal hydraulic scour structures (Smith, 1999); rip-rap revetments; rock fill and structural concrete (if crushed to appropriate grades); in unbound pavement construction; and in bituminous pavement and road sub-bases, if crushed and cohesion improved, e.g. by the addition of fines.

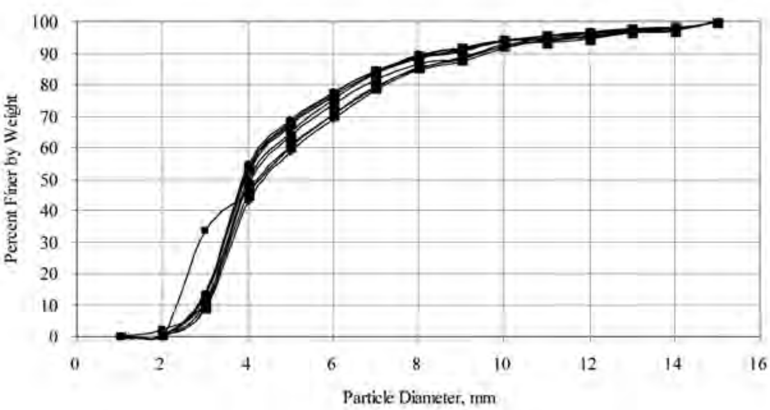

Figure 2. Cumulative grading curves for ten crushed olivine basalt sands.

Crushed volcanic sand also shows consistent grading, and is well suited for use in concrete and flexible, bituminous pavements, since they are derived from the same, competent olivine basalt source rock. All fractions are suitable for use in gravel-cement concrete mixtures, while the finer sand portion would be best suited for flexible bituminous pavements. Despite the angular nature of the crushed products, and lower surface area/volume ratio compared with more rounded equivalents, the crushed product can achieve a sufficiently high density, in cement mixtures, if properly compacted during their application in cement works. In addition, these sands have a relatively low flakiness ratio. Crushed volcanic sands of this grading may not produce good quality mortar, as they are too coarse, which can produce a rather porous, low-density mixture. For mortar application, these sands should be further crushed to an equivalent D_{50} of about 0.5 - 0.6 mm (Smith and Collins, 1993) to reduce porosity, increase density, and ultimate strength. This recommendation is particularly applicable for application of these sands in concrete Blocks, where high density, low porosity and high compressive strength are desirable.

5. CONCLUSIONS

Geological and geotechnical assessment of quarried volcanic rocks from Pohnpei Island, FSM, have revealed several sources of good quality construction aggregate. These are largely alkali basic volcanic rocks, which include high density, fine grain, columnar, olivine basalt. This olivine basalt has good Schmidt hammer impact/rebound values and good compressive strength characteristics. Less than 5% of Blocks contain mesoscopic fractures or weathered products in outcrops. Further outcrops are found on accessible, coastal slopes. They can be therefore be quarried, using cooling columnar joints as natural planes of weakness for blasting and excavation. Based on geotechnical properties, these rocks can be used in hydraulic scour structures, rock fill, structural concrete, unbound pavements and road sub-bases and mortar and concrete Blocks.

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THE FIJI AIRBORNE GEOPHYSICAL SURVEY PROJECT

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ABSTRACT

The Fiji Airborne Geophysical Survey Project of 1997 acquired airborne magnetic and gamma-ray spectrometric and digital elevation data over virtually all of the Fiji land mass and a significant proportion of the areas immediately offshore from Viti Levu and Vanua Levu. Analyses of these data has allowed a reappraisal of the geology and mineral potential of Fiji. The areal distributions of surface volcanicastic, volcanic and sedimentary units are generally well defined by textural assemblages in first vertical derivative images of the magnetic data and by images of radioelement concentrations. While the magnetic effects of surface volcanic material dominate the magnetic responses over large portions of onshore Fiji, upward continuation processing of the magnetic data suppresses such effects to the extent that the magnetic responses of underlying large intrusive bodies, many of which do not outcrop, can be identified. The intrusive bodies, which tend to occur in regularly spaced alignments and which apparently formed as a result of classic subduction processes, form the foundations of the Fiji crust. The association of these intrusions with overlying volcanic edifices can be deduced, in many cases, on the basis of geological correlations. Many of the magnetic features interpreted as indicating intrusive bodies, have central magnetic lows that are interpreted to correlate with volcanic vents. One line of intrusions occurs across the north of Viti Levu. These intrusions correspond to the localities of known volcanic centres at Vuda, Tuvatu (Navilawa), Vatukoula (Tavua) and Rakiraki. The colo-plutonic suite is imaged as a large series of magnetic bodies extending across the south of Viti Levu. Previously unknown intrusions have been identified on Vanua Levu. Various known mineral deposits have been shown to overlie buried magnetic intrutions and the definition of previously unknown intrusions suggests areas where future exploration should be concentrated. No obvious correlations can be made between the geology and structure of Viti Levu and Vanua Levu. These islands appear to have formed separately on either side of a major transform fault zone whose trace is indicated by alignments of intrusive centres. The airborne data has been used to provide refinements of the 1:250 000 scale geological maps of Fiji. The geophysical data is generally consistent with previous geological mappings of Viti Levu however the data indicates that major revisions of the existing geological maps of Vanua Levu are required. Any future geological mapping in Fiji should involve ground truthing of the geophysical responses.

INTRODUCTION

The Fiji Airborne Geophysical Survey Project, conducted during 1997, acquired airborne magnetic and gamma-ray spectrometric data and digital elevation data over the bulk of the Fiji land mass together with significant parts of offshore Fiji. Figure 1 shows the present-day tectonic setting in Fiji in Western Pacific. Figure 2 shows the areas surveyed. The objective of the survey was to provide a database to stimulate mineral and petroleum exploration in Fiji as well as to aid geological mapping, land-use studies, geohazard evaluations and groundwater exploration in Fiji.

The project was funded by the Australian Agency for International Development (AusAID). The Fiji Mineral Resource Department (MRD) has responsibility for the archiving, distribution and the ongoing usage of the results of the project. The Australia Geological Survey Organisation (AGSO), acting as project managers under contract to AusAID, designed and supervised the survey. The airborne geophysical contractor Kevron Pty. Ltd. performed the acquisition and processing components of the project. Data from the survey became publicly available on June 2, 1998 from the MRD.

AGSO, as part of its contractual obligations to AusAID produced interpretations of the project results. The AGSO report (Gunn et al., 1998a) delineates surface solid geology and major subsurface features indicated by the geophysical data. The primary outputs of the interpretation were 1:250 000 maps products for Viti Levu, Vanua Levu, Yasawa, North Lau, Kadavu and Moala. Figure 1 indicates the outline of these sheet areas. A 1:500 000 synthesis of the interpretation covering the entire region and a separate 1:500 000 scale image of the total magnetic intensity with superimposed depths to offshore magnetic sources were also produced. This paper describes the data acquired and summarises the main results of the interpretation.

OVERVIEW OF THE GEOLOGICAL SETTING OF FIJI

Detailed summarises of the known geology of Fiji are given by Rodda and Lum (1990), Rodda (1994) and Colley and Flint (1995). The islands of Fiji are located on a western Pacific volcanic belt comprised of an island arc chain containing Tonga, Fiji, Vanuatu, the Solomon Islands and extending to Papua New Guinea (Figure 1). These islands were created by subduction along the boundary between the Pacific plate and the Australia-India plate. The island nation of Fiji, which is comprised of two main islands, Viti Levu and Vanua Levu, the Yasawa chain of islands, the Lau group of islands, the island of Kadavu and numerous smaller islands (see Figure 2), has had complex tectonic history. As shown in Figure 3A, subduction in the vicinity of Fiji was originally from the east from the now extinct Vitiaz Trench, and it is likely that during this initial phase of induction that most of the main islands of Fiji were formed as a results of intrusive and volcanic activity arising from magma formation above the downgoing plate. The original simple two-dimensional geometry of Fiji was disrupted approximately 10 million years ago when the direction of the subduction was reversed and the actual location of the subduction moved to the west of the island chain. As illustrated in Figure 3B this was associated with the commencement of back-arc spreading in the North Fiji Basin and the Lau Basin as well as the development of the Hunter Fracture Zone, a major strike slip fault that may be associated with limited subduction. The tectonic situation illustrated in Figure 3B is thought

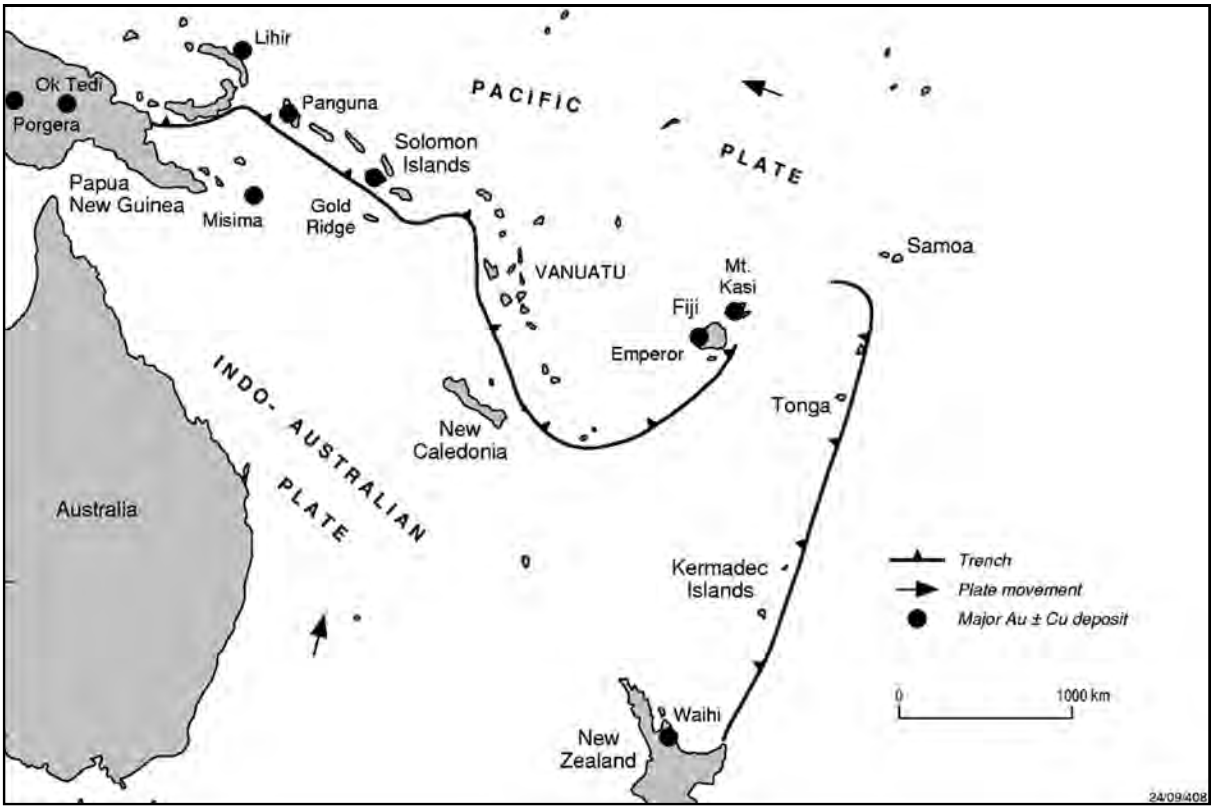


Figure 1. Location of Fiji showing its plate tectonic setting.

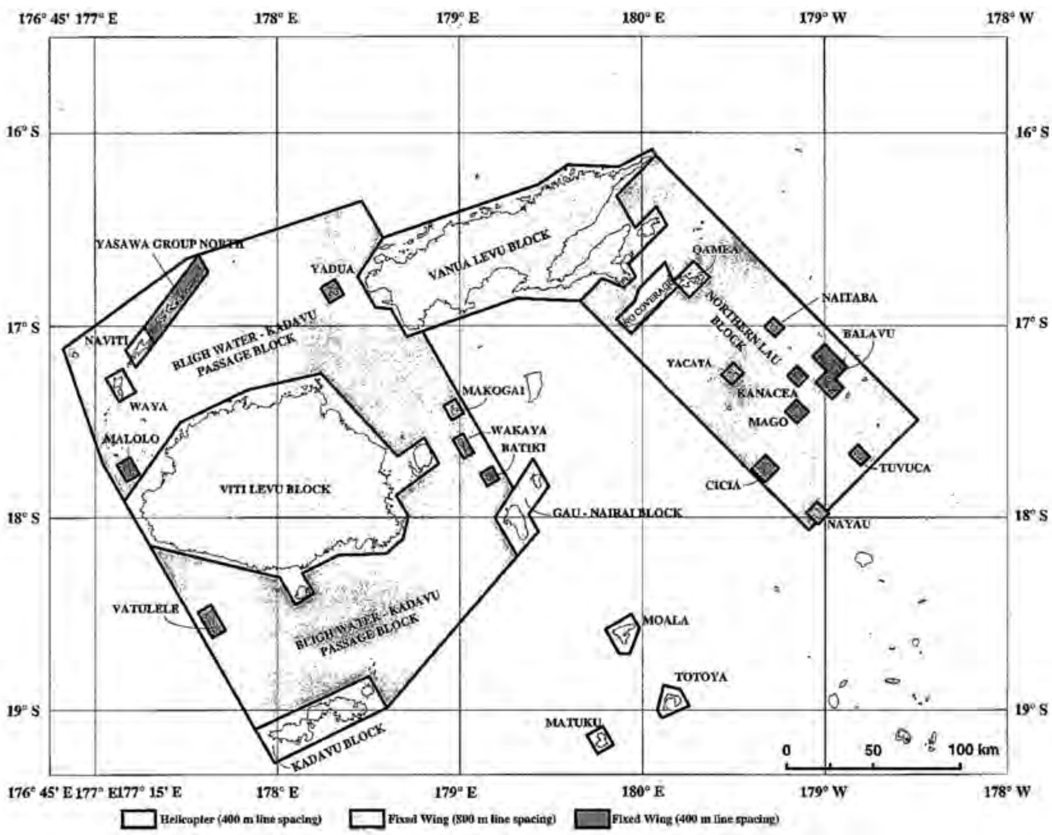


Figure 2. Principal islands of Fiji showing the coverage of the Fiji Airborne Geophysical Survey Project.

to have cause significant anticlockwise rotation of Viti Levu.

The development of the geological units of Fiji appears to have followed the relatively simple and logical sequence to be expected in the development of an island arc system albeit with overprints probably resulting from the reversal of the direction of plate subduction. Figure 4 shows a commonly accepted model for the development of an island arc system with magma generated from a slab of subducted oceanic crust and lithosphere rising towards the surface where it eventually solidifies to create batholitic granitoid intrusive bodies varying in composition from gabbro to granite. Stratovolcanoes developed over some of these rising intrusions, erupted lavas and pyroclastic material which contributed to building the rock mass of which island arc systems are comprised. Contemporaneous sills and dykes were injected into the country rock. Erosion of the lavas and pyroclastic material and their underlying intrusives creates a sedimentary matrix which also adds to the building of the island arc system. In the western Pacific, coral reefs contributed limestone to the sedimentary pile. Ophiolite slices were added to the igneous/sedimentary island arc system as a result of the detachment of slices of oceanic crust at the point of subduction. The intrusive centres which developed above the downgoing plate however manifest themselves as a semi-continuous line of discrete intrusions rather than as a continuos elongated intrusion. Figure 5 illustrates the relationship that may occur between an intrusion and a stratovolcano in an island arc system. In the example illustrated, a significant volcanic crater-Basin has formed. Such features are not ubiquitous and the intrusion may not form a volcano or the surface indications of an underlying intrusion may be restricted to isolated localised vents. Vents of volcanoes may also be plugged by bodies of solidified magma.

Compression associated with the subduction process may result in localised high pressure metamorphism and the development of thrust faults which may have a strike-slip components. High temperature metamorphism may be caused by heat associated with the ascending igneous plutons.

The significance of Figure 5 is not restricted to indicating how volcanic piles are related to underlying intrusions because the figure also indicates how two very important types of mineral deposits, namely porphyry copper-gold

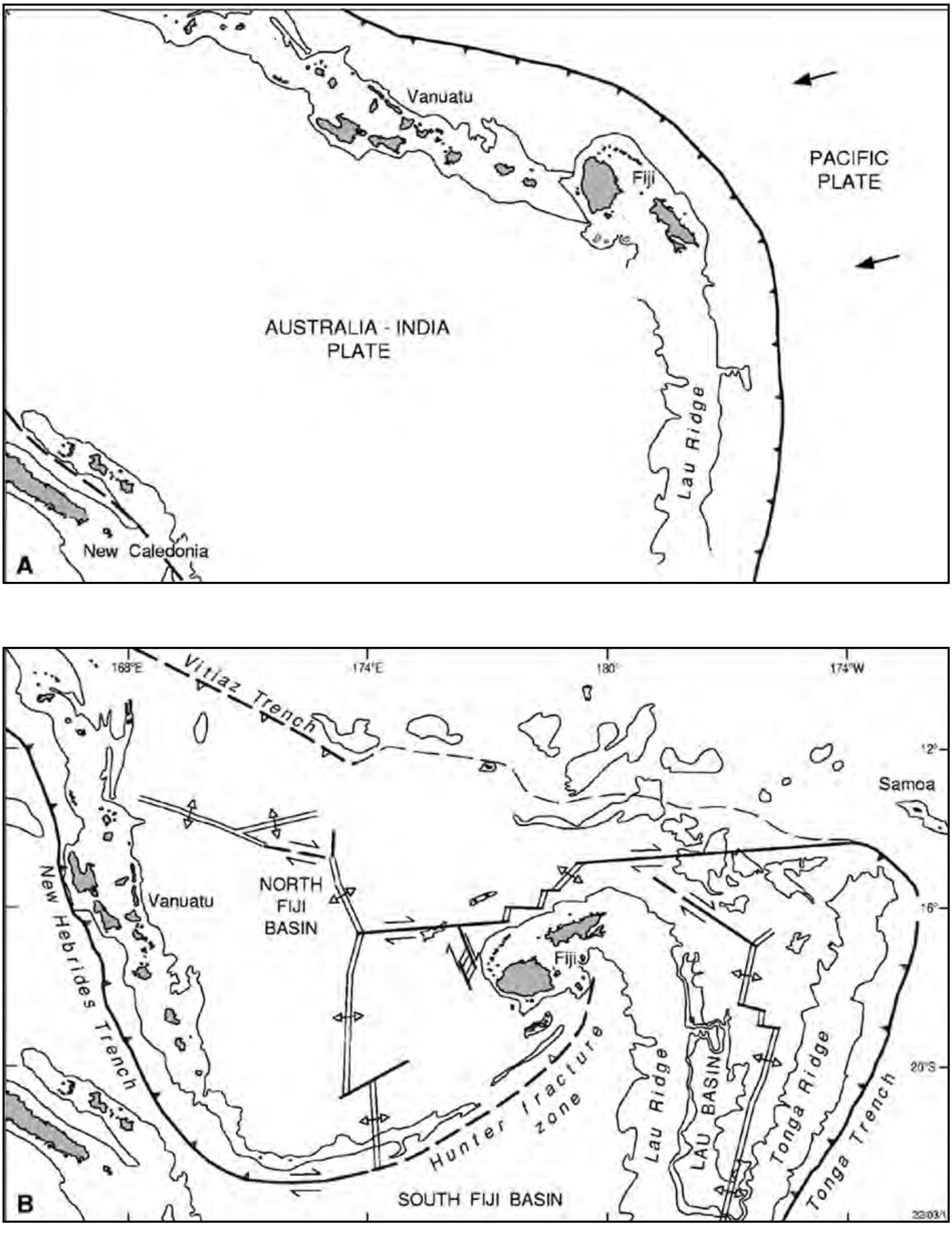


Figure 3. Plate tectonic configurations in the vicinity of Fiji. A is approximately 10 Ma. B is present. The direction of subduction has reversed.

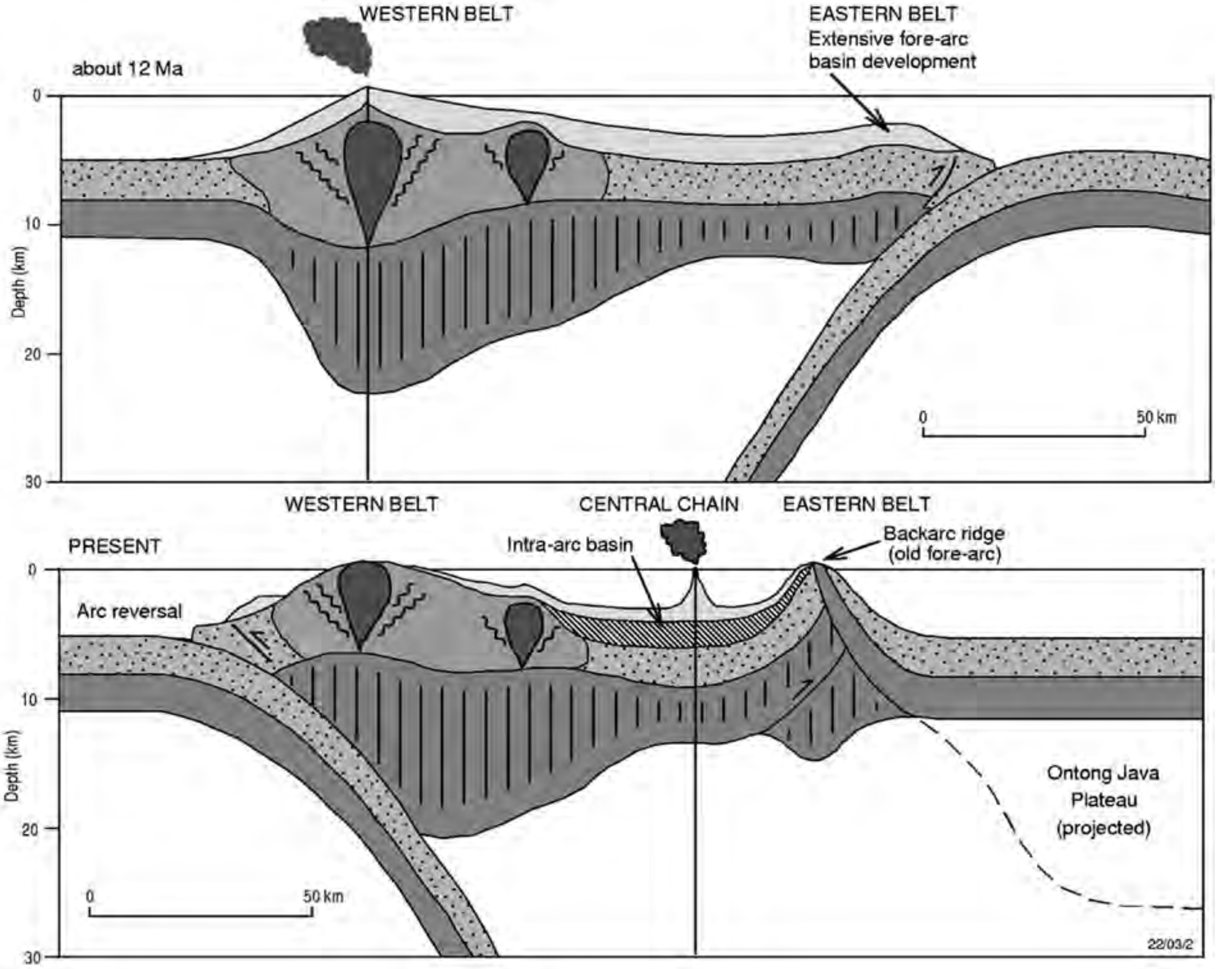


Figure 4. Model for subduction. This diagram is based on the situation occurring in Vanuatu which is better known than in Fiji. It is presented because a similar situation may have occurred in Fiji.

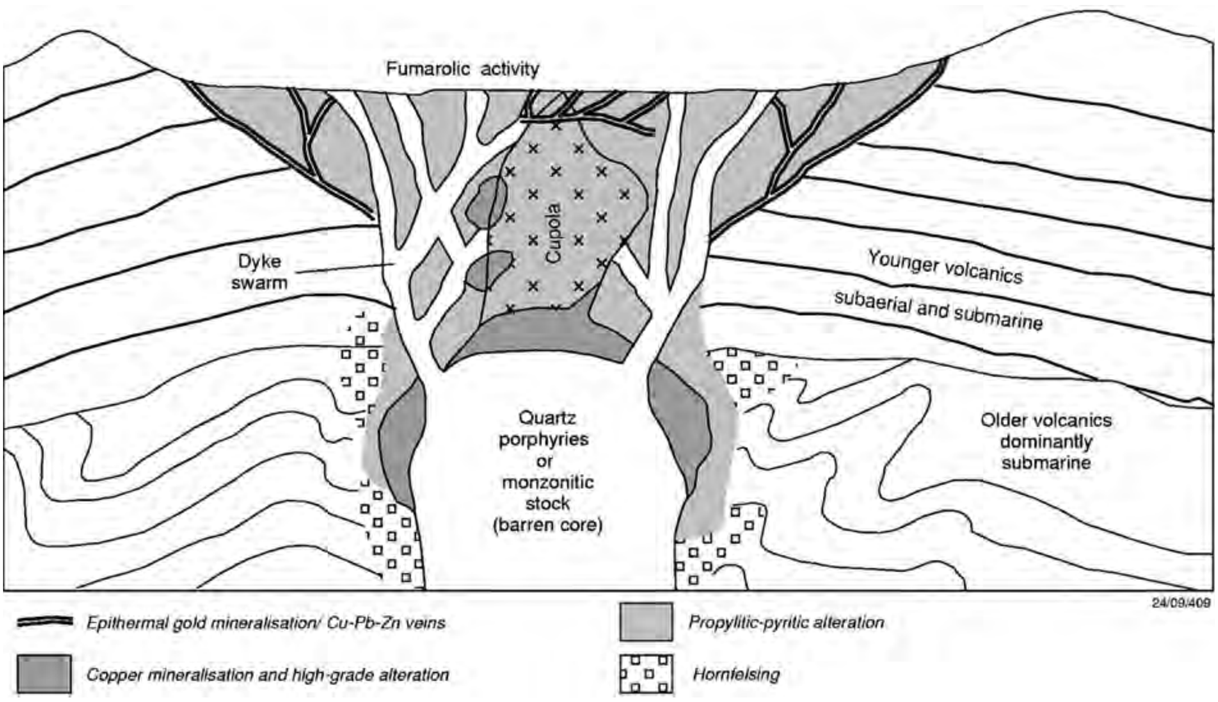


Figure 5. Relationship between intrusions and stratovolcanoes in island arc systems and the development of porphyry copper-gold and epithermal gold deposits (after Colley and Flint, 1995).

and epithermal gold deposits, may be related to intrusive volcanic systems in island arc systems. Copper and gold mineralisation may be precipated on the flanks of, and within, the intrusive body by mineralising solutions which have ascended in association with the intrusion. Such mineral accumulations, which are typically disseminated in nature but which may have large tonnages, are referred to as porphyry copper-gold deposits. Mineralised solutions may also rise above the level of the intrusive body by means of small vents and fracture systems. If this happens, gold mineralisation may be precipitated in vein systems above the intrusion. Such mineralisation is referred to as epithermal gold.

SPECIFICATIONS OF DATA ACQUISITION AND PROJECT OUTPUTS

The data were recorded using a fixed-wing twin-engine aircraft over offshore areas and low-lying islands (approximately 80 000 kilometres) and by two helicopters over the rugged terrain of the major islands (approximately 80 000 kilometres). The survey elevation was 80 meters above the land and sea. The helicopter lines had a spacing of 400 meters and were oriented 330 degrees from true north and tie lines have a spacing of 4000 meters oriented 60 degrees east of true north. The fixed wing aircraft had a line spacing of 800 meters over water and 400 meters over the islands with tie line spacings at ten times the line spacing. For all the fixed wing surveying except over the northern Lau group islands the line and tie line orientations were the same as for the helicopter. Over the northern Lau Group the traverse line oriented at 45 degrees due to the different orientation of geology of this island chain.

The radiometric (gamma-ray spectrometer) data were acquired with a 33 litre crystal over the full spectrum of 256 channels.

The simultaneous recording of GPS elevations of the survey aircraft and the ground clearance as measured by a radar altimeter allowed the production of a digital elevation model.

The acquisition contractor, Kevron Pty. Ltd., produced the following images and maps which are available for purchase as a data package:

Point-located digital data:

- total magnetic intensity, as measured and reduced to the pole (microlevelled)
- terrain clearance and terrain height
- total count-air absorbed dose rate nGh-1
- equivalent potassium percentage
- equivalent uranium ppm
- equivalent thorium ppm

Gridded digital data:

- total magnetic intensity, as measured and, reduced to the pole
- first vertical derivative of total magnetic intensity reduced to the pole
- digital elevation model
- total count air absorbed dose rate nGh-1
- equivalent potassium percentage
- equivalent uranium ppm
- equivalent thorium ppm

Image maps (covering the areas indicated in Figure 2):

- total magnetic intensity reduced to the pole, north sunangle (colour)
- 1st vertical derivative, reduced to the pole, north sunangle (grey scale)
- 1st vertical derivative, reduced to the pole in greyscale (north sunangle) superimposed over TMI in colour with no illumination (colour)
- 1st derivative, reduced to the pole, east sunangle (colour)
- total radiometric count rate (colour)
- potassium colour
- digital elevation model with a NE sun angle (colour)

Contour maps:

- total magnetic intensity reduced to the pole contours
- total count-air absorbed dose rate nGh-1 contours
- equivalent potassium percentage contours
- equivalent uranium ppm contours
- equivalent thorium ppm contours
- digital elevation model (meters) contours

Flight-path maps

INTERPRETATION METHODOLOGY

The information used for the interpretation comprised geophysical digital image and map products and the result of previous 1:50 000 scale geological mapping, of Fiji. These data were supplemented by more recent geological summaries and revisions described by Rodda and Lum (1990), Rodda (1994) and Colley and Flint (1995). A gravity coverage of Viti Levu was also available in a digital format (JICA-MMAJ, 1992).

The interpretation was performed by creating a computerised Geographical Information System (GIS) using MapInfo software. Layers of all appropriate geophysical parameters were installed in the GIS and then, by a process of comparison with previously mapped geological boundaries, the previously mapped geology was confirmed or revised. Where appropriate, previously unrecognised geological features were identified and their outlines incorporated into a definitive version of the interpretation. The interpretation also identified and delineated major subsurface intrusive features and magnetic bodies in the offshore areas.

The GIS used for the interpretation contained a wide range of images of the geophysical data. This was considered essential as no one images conveys all the information contained in the data. Additional images to those produced by Kevron Pty.Ltd. were produced using mathematical transformation routines in the INTREPID processing software and the actual enhancements of these additional images was done using the ER Mapper imaging system before the products were incorporated into the GIS.

The images used were:

Total magnetic intensity, reduced to the pole, in colour, with a north-directed sun illumination (Figure 6): This image, by being reduced to the pole, corrects for the asymmetry of magnetic anomalies caused by induction of the Earth's magnetic field which has the relatively low magnetic inclination of 40 degrees in the vicinity of Fiji. The fact that, after the reduction to the pole process, most anomalies consisted of a central positive peak suggests that remanent magnetisation is not an important factor in Fiji and the use of the reduction to the pole transformation is justified. The colour of the image allows relative amplitudes to the estimated and the north-directed sun angle illumination enhances east west trending geological features.

Total magnetic intensity, reduced to the pole, in colour, with no illumination: This image allows a clearer definition of major anomaly outlines than the illuminated version of the same data.

Analytic signal of the total magnetic intensity, in colour, non-illuminated. This image shows positive peaks over anomaly source positions regardless of the direction of magnetisation of the sources (Roest et al., 1992). It is useful for identifying remanent magnetisation because where remanence is insignificant the analytic signal indicates peaks in the same position as the reduced to the pole data.

Total magnetic intensity, reduced to the pole, continued upwards 500 meters, with no illumination (Figure 7): This is a version of the field as it would be observed 500 metres above the ground surface instead of 80 meters as it is originally recorded. This image suppresses the magnetic effects of small and thin near surface magnetic features of large magnetic features such as magnetic igneous intrusions.

First vertical derivatives of the total magnetic intensity, reduced to the pole, in colour with north and east illumination: Vertical gradient images enhance fine detail and suppress broad magnetic anomalies. The first vertical derivative image often resolves the magnetic effects of bodies whose anomalies coalesce in total intensity images. The first vertical derivative images of Fiji suppress the magnetic effects of deep magnetic intrusions and thereby allow easier mapping of surface features. The north illumination image enhances subtle features trending in the east-west direction. The east illumination enhances subtle features trending features trending in the north south direction.

First vertical derivative of the total magnetic intensity reduced to the pole, with greyscale illumination from the north and east directions:. The advantage of greyscale illumination is that it often allows the human eye to resolve finer detail than is possible in illuminated colour images.

First vertical derivative of the total magnetic intensity reduced to the pole with no illumination: Positive anomaly components appear in white. This quality often facilitates the tracing of anomaly boundaries.

First vertical derivative of total magnetic intensity reduced to the pole with greyscale illumination from the north, superimposed a non-illuminated colour image of the total magnetic intensity reduced to the pole: This image allows a combined analysis of total magnetic and vertical gradient data. Often the total magnetic intensity image in such situations illustrates the gross geology, and the vertical gradient component illustrates fine geological detail.

Colour ternary image of the equivalent potassium, uranium and thorium ground concentration (Figure

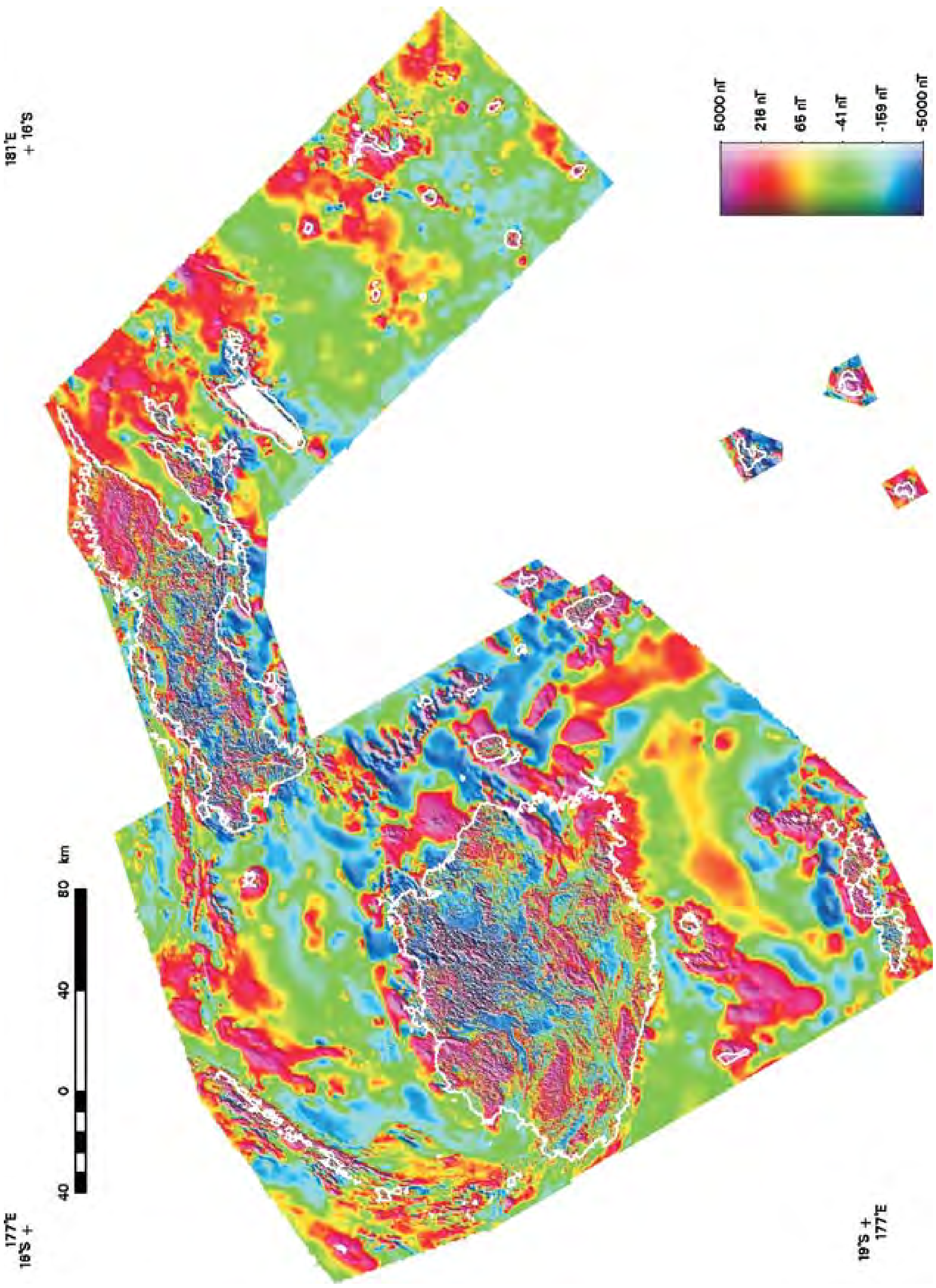


Figure 6. Image of total magnetic intensity of the Fiji region reduced to the pole.

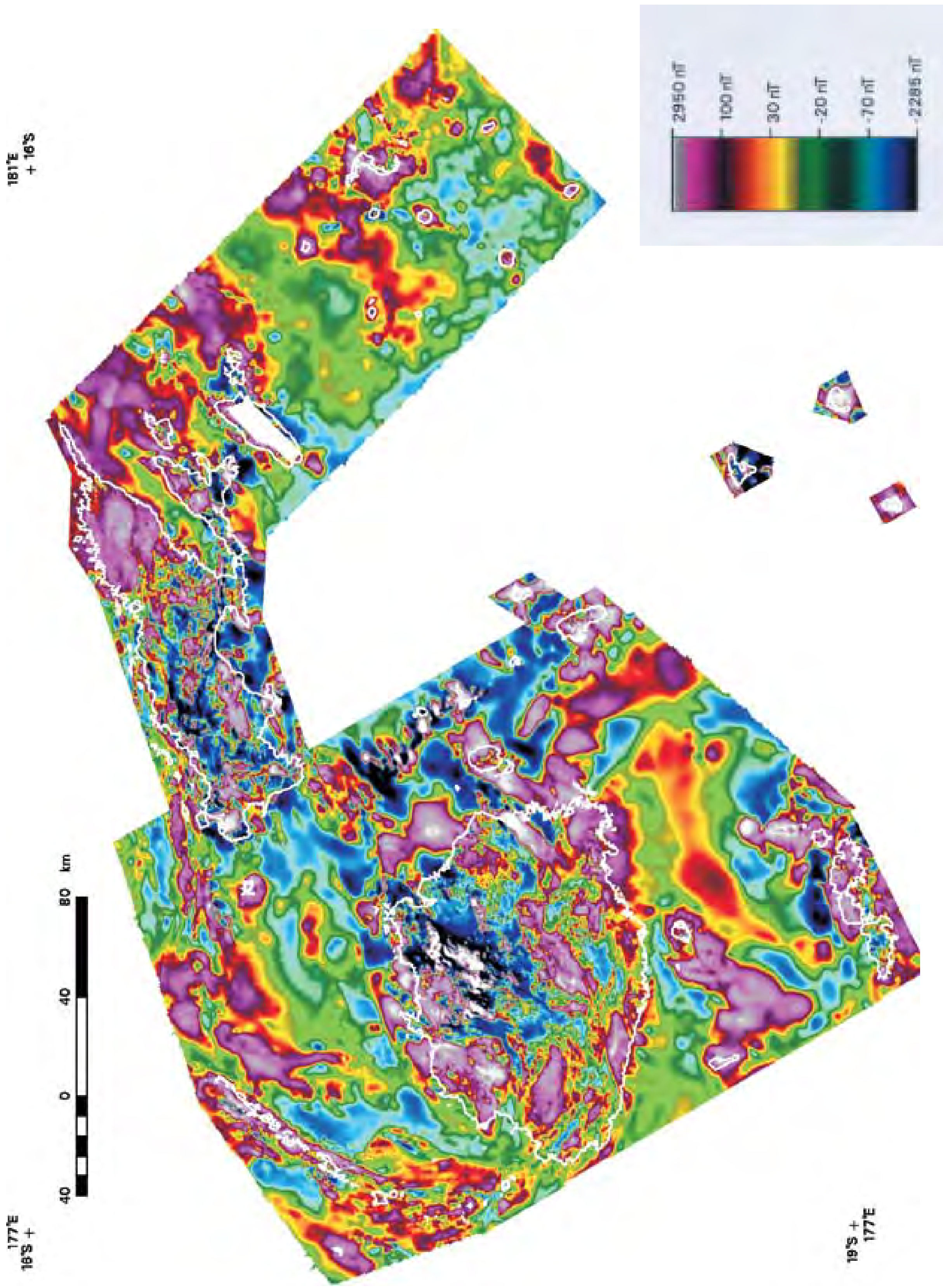


Figure 7. Total magnetic intensity, reduced to the pole, continued upwards 500 metres

8): This image gives a combined representation of the potassium, uranium and thorium ground element concentrations. The counts for all three radioelements are normalised and the red areas indicate areas of relatively high potassium concentrations. Relative high concentrations of uranium are indicated in blue and areas of relative high concentrations of thorium are indicated in green. Areas where all three radioelements are at their maxima appear in white and areas where all three radioelements are at their minima appear black. The ternary image is an excellent tool for mapping surface geology.

Colour images (non-illuminated) of the equivalent potassium, uranium and thorium ground concentrations: These images which map the equivalent ground potassium uranium and thorium concentrations are excellent tools for mapping surface geology. The potassium image is useful for indicating localised areas of potassic alteration which may be associated with mineral deposits.

Colour image (non-illuminated) of the potassium over thorium ratio: This image can be useful for enhancing alteration effects associated with mineralisation.

North illuminated and non-illuminated colour images of the digital elevation (Figure 9): These images allow studies of the topography of Fiji. The images are useful for identifying circular topographic features caused by calderas, topographic shapes relating to differential erosion over differing types of geology and linear features related to faulting. The topographic data is essential for identifying radiometric responses related to differential weathering and sediment transport.

Non-illuminated colour image of the medium wavelength gravity anomalies over Viti Levu: This image, based on data from the JICA-MMAJ (1992) gravity survey proved useful for identifying gravity anomalies associated with major subsurface intrusions.

Hard copy contours of the magnetic intensity, the ground radioelement concentrations and the digital elevations were also available for inspection.

The depths to offshore magnetic sources were computed using AutoMag software which is a module of the Model Vision package, developed by Encom Technology Pty. Ltd. The method analyses profile data and estimates depths to magnetic edges and the tops of vertical sheets. The technique is based on a publication by Naudy (1971). Gunn (1997) give a summary description of its usage. In situations were circular anomalies occurred in the offshore areas direct forward modelling was used to compute the source depths.

Figure 10 shows a reduction of the 1:500 000 scale composite interpretation map.

The interpretation map shows:

- outlines of areas of different surface geology, with the interior of each area colour-coded to indicate its geological identification. The geological identification in colour is supported by an abbreviation. The colour and the abbreviation can be referred to a geological legend. Each identified area is marked with abbreviations indicating the prime geophysical parameters that have been used to map it.
- subsurface extents of intrusions (shown as stippled areas onshore and as shaded areas offshore)
- probable and possible locations of volcanic vents
- outlines of offshore magnetic features distinguishing between intrusions, lava flows and sedimentary features
- depths to offshore magnetic features (omitted in this paper for reason of scale)
- faults, differentiated into major and minor faults
- locations of offshore wells
- locations of major mineral deposits (co-ordinates supplied by MRD)
- magnetic trends and lineaments
- indications of remanently magnetised bodies

FEATURES IDENTIFIED IN THE GEOPHYSICAL RESULTS

The interpretation process identified characteristic geophysical responses corresponding to the rock units which comprise Fiji. These can be categorised as follows:

Horizontal and sub-horizontal iavas, sills and pyroclastic rocks: The magnetic responses of the various lava flows and pyroclastics rock known on Fiji consist of erratic assemblages of high frequency anomalies. Such responses are typical of volcanic rocks flows by virtue of the fact that different portions of the units cool at different rates producing crystal of different sizes with different magnetic properties. The erratic magnetic responses of the various known lava flows appears to be compounded by many of the lava flows being interfingered with pyroclastic

Figure 8. Ternary gamma-ray spectrometric image RGB (K-Th-U) of the Fiji Region.

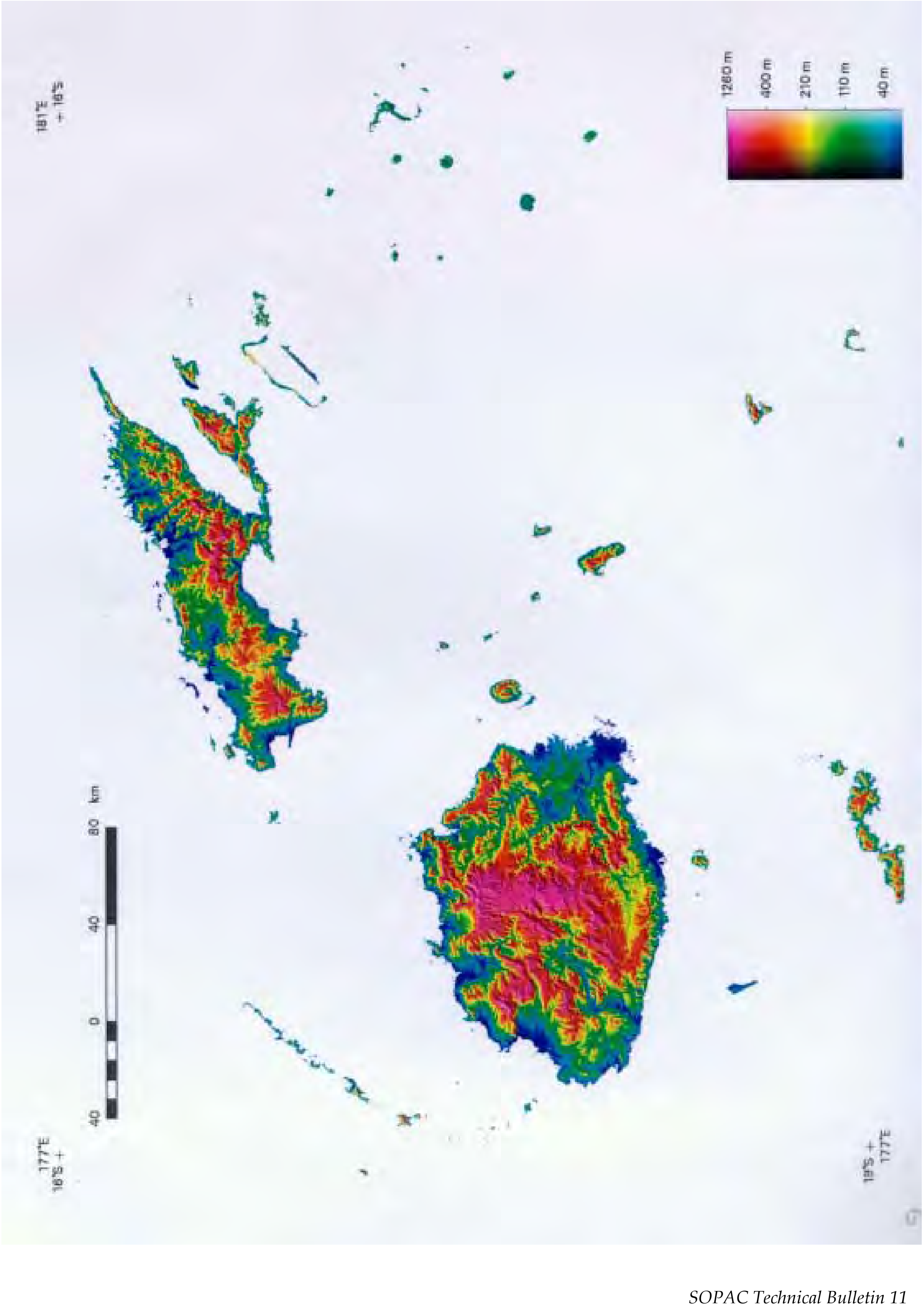
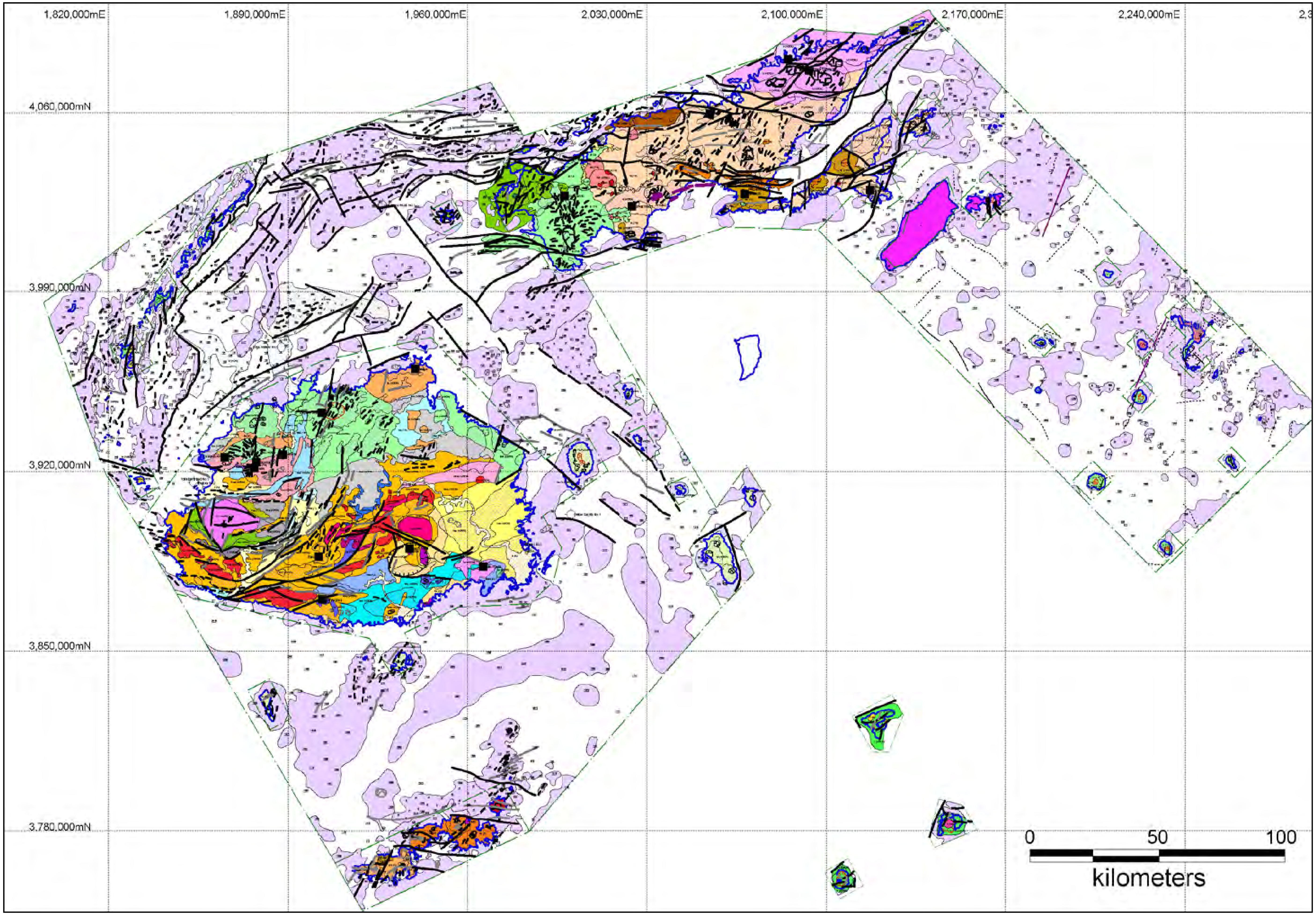


Figure 9. Digital elevation image of Fiji.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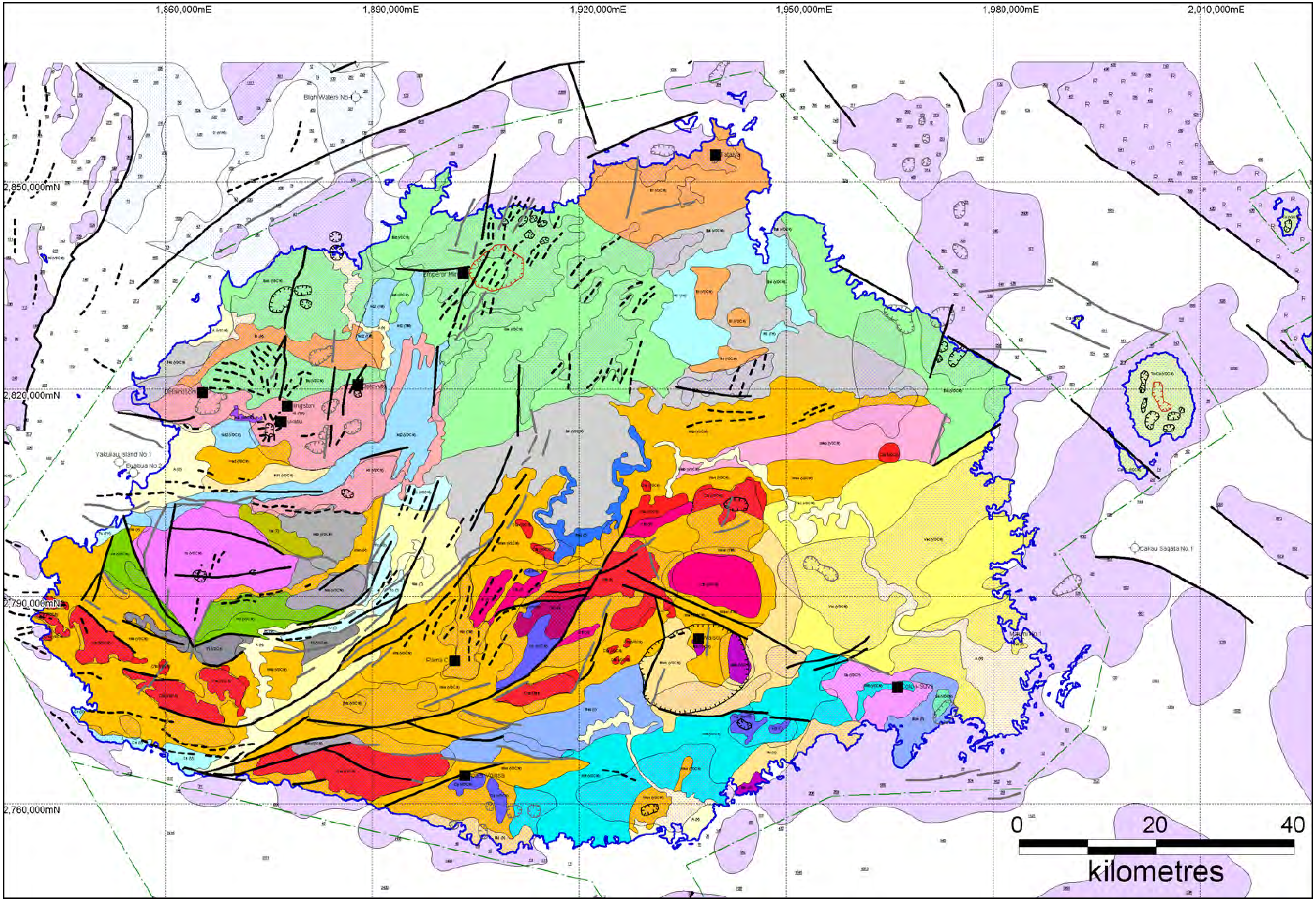
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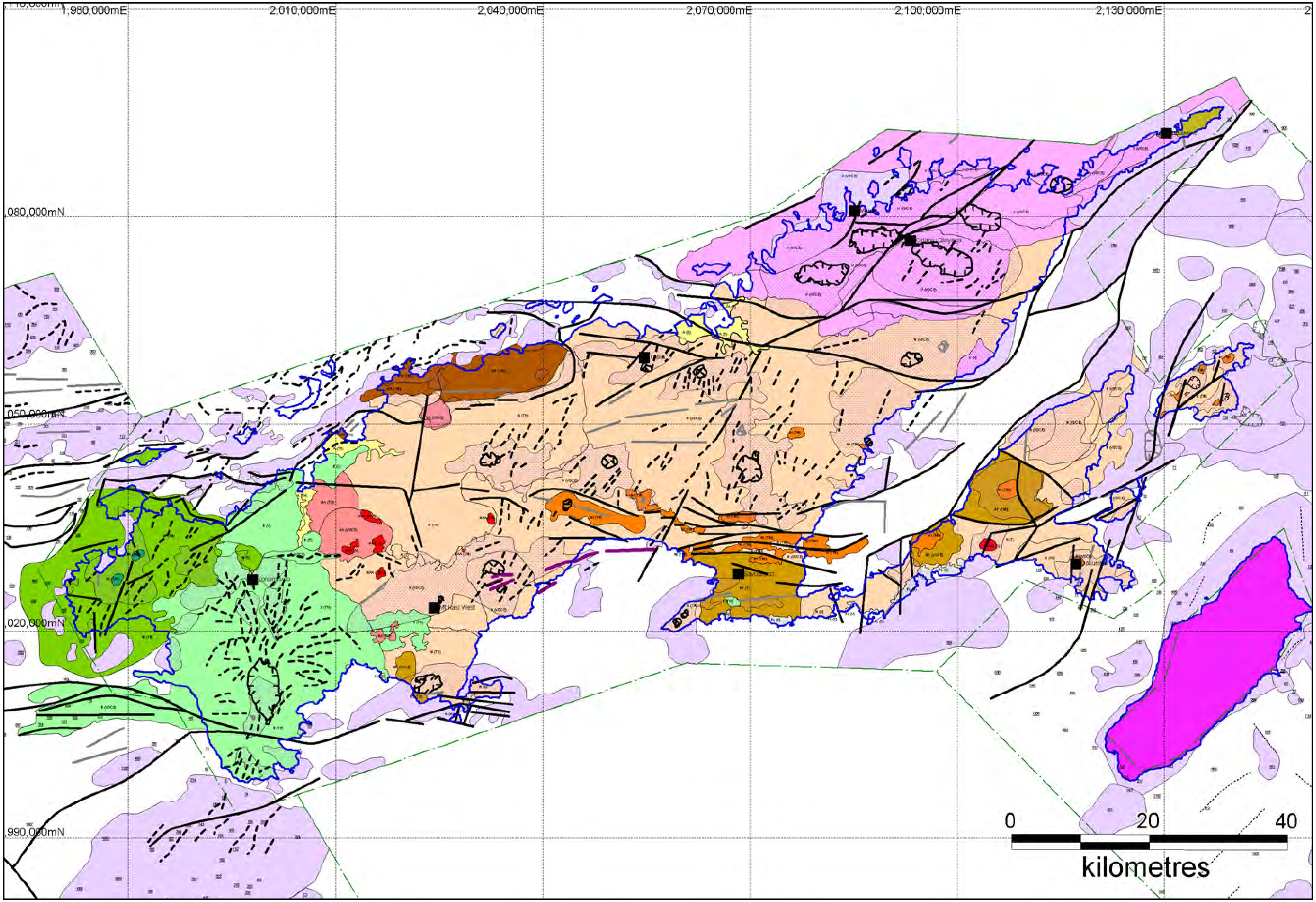
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LEGEND

VITI LEVU

A — Alluvium, beach sand, etc

Verata Sedimentary Group
Vnk — Nakuai Beds
Vno — Naqua Sandstone

Ba Volcanic Group
Bnk — Nakarotubu Basalt
Bvt — Vatia Andesite
Bky — Koroyanitu Volcanics Products
Bnm — Namosau Volcanics

Br — Rokavukavu Basalt
Bs — Saru Formation

Buv — Upper Vuda Beds
Bvk — Vatukoro Greywacke

Bmv — Muanisavu Sill

Cu — Cuvu Sedimentary Group

Koroimavua Volcanic Group
Ks — Sabeto Volcanics
Knv — Naviawa Stock

Navosa Sedimentary Group
Nvs — Sandstone, mudstone
Nvt — Tamanua Formation
Nva — Andesite Pyroclastic Rocks

Nadi Sedimentary Group
Nd2 — Sandstone
Nd1 — Andesite Pyroclastic Rocks

Ra Sedimentary Group
Rb — Baroku Sandstone

Medrausucu Group
Mam — Suva Marl
Mrs — Naveri Mudstone

Mnm — Namosi Andesite
Mv — Veisari Sandstone
Ms — Sirua Conglomerate

Mm — Mau Andesite
MWk — Wainikaro Stock
Ma — Diorite

Tuva Group
Tt — Takaro Conglomerate
Tc — Coi Sandstone

Colo Plutonic Suite
Ctl — Tonalite, Diorite (High magnetisation - low potassium)
Cts — Tonalite, Diorite (Low magnetisation - high potassium)
Ctc — Tonalite, Diorite (High magnetisation - high potassium)
Cg — Gabbro

Savura Volcanic Group
Sv — Vago Volcanics
Sn — Nasinu Basalt

Wainimala Group Wnm — Namalavu conglomerate
Wtt — Tuvutau Greywacke

W — Volcanics
Wa — Volcanics (High magnetisation)
Wnm — Namalavu Conglomerate
Wnu — Nubuonabota Volcanics
Wnuc — Nubuonabota Volcanics (contact metamorphosed)
Wta — Tari Formation
Wla — Lawalevu Sandstone
Wtv — Tawavatu Tuff
Wnd — Nadele Breccia
Wnb — Nabu Formation

Web — Wainbuka Trachyte
Wd — Dakadaka Basalt

Yavuna Group
Yvs — Yavuna Stock
Yv — Yavuna Volcanics

OFFSHORE REGION
B — Basalt (Reversed magnetism)
D — Detrital magnetite

VANUA LEVU

A — Alluvium
PL — Pliocene Conglomerate/Marl
T — Taveuni Alkali Basalt

Bua Volcanic Group
B — Bua Volcanic Group

Uluikamili Volcanic Group
UL — Uluikamili Volcanic Group

Nararo Volcanic Group
NA — Nararo Volcanic Group
NAA — Nararo Volcanic Group Andesite

Natewa Volcanic Group
N — Natewa Volcanic Group
NI — Natewa Volcanic Group Intrusive
NR — Natewa Volcanic Group Naravai Volcanics
NF — Natewa Volcanic Group Flow

Monkey Face Volcanic Group
M — Monkey Face Volcanic Group
MI — Monkey Face Volcanic Group Intrusive

Udu Volcanic Group
U — Udu Volcanic Group

KADAVU

A — Alluvium
P — Pumiceous Lava
BA — Biotite Andesite
F — Lava Flow
LB — Lava Flows and Breccias
OA — Ono Andesite
AA — Augite Andesite
B — Basalt
S — Silicified Rocks

NORTH LAU ISLAND GROUP

Tl — Tokalau Limestone Group
K — Korobasaga Volcanic Group
L — Lau Volcanic Group

YASAWA ISLAND GROUP

Yca — Calc-alkaline volcanics

MOALA / TOTOYA / MATUKU ISLANDS

H — Hornblende Andesite
T — Trachyte Flows
I — Intrusion (Highly magnetised)
V — Basic to Intermediate Volcanics

ISLANDS SOUTH AND EAST OF VITI LEVU

Sh — Shoshonitic Volcanics
Th Ca — Tholeiitic Volcanics to Calc-alkaline Volcanics
Ca — Calc-alkaline Volcanics

Intrusive Magnetic source - onshore (Subsurface)
Intrusive Magnetic source - offshore (probably subsurface)
R — Intrusive Magnetic source - offshore (Remanent magnetisation)

Only major subsurface intrusive features are indicated

Subdivisions of these units have been identified where they have distinctive geophysical responses. The geophysical parameter(s) on which such subdivisions are based are shown in brackets using the abbreviations listed in the Summary Explanatory Notes.

Major Fault
Minor Fault
Exploration Well
Lineament / Trend
Dyke
Probable Volcanic Vent
Possible Volcanic Vent
Caldera/Volcanic vent
Calculated depth to magnetic source (metres below S.L.)
Mineral Deposit
Nominal Survey Boundary

rock units which dominate much of Fiji's volcanic output and which themselves have irregular magnetism. Not all volcanic units are strongly magnetic. The amplitude of the total magnetic intensity field in the vicinity of the volcanic rocks flows is not very diagnostic of their extents and frequently the field amplitude is primarily caused by an underlying magnetic intrusion with the result that the observed field is the sum of the erratic high frequency effects of the horizontal lava flow and the broad high amplitude field of the underlying intrusion. Experience has shown that the best method of using magnetic data to delineate the extent of volcanic flows in such situations is to use an image which emphasises the high frequency character of the data and which suppressed the effects of the broader magnetic features. Computed first vertical derivative (vertical gradient) images achieve this and have been used to map areas of common textural character which are considered to define the extents of the various volcanic and pyroclastic units.

The airborne gamma-ray spectrometric (radiometric) data, by virtue of the fact that it is mapping responses emanating from the top 30 centimetres of earth material, is extremely useful in mapping rock units that occur on the ground surface without the confusing additional effects of deeper sources. The radiometric data maps the ground concentrations of three radioelements namely potassium, uranium and thorium. In practice it has been found that different volcanic units have different radioelement responses which allow them to be readily mapped using the radiometric data. Bedrock radiometric responses however are modified by weathering and transport of weathered products. Weathering and transport are commonly related to topography and correlations with the digital elevation model were indispensable to determine which radiometric responses mapped in situ bedrock and which responses mapped weathered and transported products. Such effects are particularly evident over the shoshonitic volcanic rocks emanating from the Tavua caldera. Over flat, high altitude areas, potassium appears to have been leached from these volcanic rocks and these areas correspond to lower potassium counts. The areas of steep slopes, where rapid erosion exposes fresh rock, correspond to high potassium counts.

Major igneous intrusions: Several major igneous intrusions, notably those belonging to the Colo Plutonic Suite, have been mapped using surface outcrop. The total magnetic intensity data shows that these intrusions correlate with intense magnetic anomalies which are significantly broader than the mapped outcrop. This phenomenon suggests that these intrusions have a significant subsurface extent beneath the sedimentary and volcanic rocks that cover the area surrounding their outcrop. The processing technique known as "upward continuation" has been applied to the total magnetic intensity data to compute the magnetic field as it would be observed at 500 meters above the ground surface in contrast to the ground clearance of 80 metres on which it was actually recorded. This has the effect of suppressing the magnetic effects of surface horizontal magnetic units such as volcanic and pyroclastic units while having very little effect on the magnetic responses of large intrusive features. The upward continuation process effectively filters out surficial magnetic features and allows the definition of the full extent of the large magnetic intrusions which underlie Fiji.

The large magnetic anomalies evident in images of the upward continued field are thought to be primarily due to intrusive features. It is possible that thick volcanic piles associated with such intrusions could be contributing some magnetic effect even in the upward continued field however this is considered unlikely as the mapped volcanic units of Fiji consists primarily of pyroclastic rocks. As intrusive features may widen in depth, subjective judgement has to be applied when tracing their boundaries. The inflection of the total magnetic intensity field has generally been used to outline such features as this gives a good approximation to the steepest portions of the source body.

The total magnetic field over the offshore areas shows anomalies similar to the upward continued field over the onshore areas. Many of the offshore anomalies are thought to indicate intrusive centres similar to those occurring onshore.

It should be noted that not all igneous intrusions are magnetic. Major non-magnetic igneous intrusions have been geologically mapped in Fiji. Where they outcrop such bodies can often be mapped using radiometric data. They can be variably mapped using magnetic data by studying the terminations of magnetic units which they cut and by identifying magnetic aureoles related to their intrusion.

Steeply dipping igneous units: Zone of intense linear anomalies, such as are associated with the Yasawa Group and the area between the northern end of the Yasawa Group and Vanua Levu have the form of anomalies caused by steeply dipping magnetic sheets. The source rocks of such units are most likely to be volcanic flows although mafic dykes and fragments of ophiolite material can cause similar anomalies. Anomaly inflections of the total magnetic field have been used to outline the inferred sources of these anomalies.

Sedimentary rock units: Sedimentary rocks generally have weak magnetic responses. This is due to the fact that even though they may be derived from the weathering of magnetic source rocks, magnetic minerals such as magnetite, which cause the magnetic responses of the source rocks, are normally oxidised to non-magnetic hematite during the weathering process. Some sedimentary units in Fiji have a weak magnetic character which can be mapped using textural characteristics defined in vertical gradient images. In situations where magnetic volcanic units flank non-magnetic sedimentary units, the absence of a magnetic response can be used to map the sedimentary unit.

In general, however, the radiometric data provides a superior mapping tool for the delineation of surface sedimentary units in Fiji than the magnetic data as the radioelement concentrations of potassium, uranium and thorium normally give distinctive signatures for the different units.

Alluvium in valleys commonly gives an elevated potassium count due to the accumulation of potassium leached out of adjacent country rock.

KEY RESULTS OF THE INTERPRETATION

General geological framework

The picture of Fiji that has emerged from the interpretation, which is entirely consistent with previous idea of its island arc origin, is that of an assemblage of linear belts of mainly buried, major igneous intrusions. These are interpreted as relicts of the magma chambers that fed volcanic vents which erupted the lavas and pyroclastic material that cover so much of the exposed Fiji land mass. Erosion products of exposed igneous intrusions and their volcanic daughter products, combined with a limited amount of carbonated sedimentation, have created the sedimentary matrix around the intrusive centres.

Probably the most significant finding of the interpretation is the recognition that the majority of the large igneous intrusions are magnetic bodies. Although the magnetic effects of many of these intrusions are obscured by the high frequency effects of near surface volcanic and pyroclastic material, the upward continuation process provides an excellent image of the major intrusive centres that have resulted in the creation of Fiji.

The interpretation of the large magnetic anomalies in the upward continued data as corresponding to major igneous intrusions, is supported by the following facts:

i. A known line of volcanic centres in northern Vanua Levu (Vuda, Navilawa, Tavua, and Rakiraki), which correspond to discrete major gravity anomalies indicating underlying intrusions (Colley and Flint (1995), Figure 12), all correspond to major magnetic anomalies in the upward continued data.

ii. Outcrops of the majority of the intrusions of the Colo Plutonic Suite overly major magnetic anomalies in the upward continued data which are significantly more laterally extensive than the area of the outcrops.

iii. Many (probably the majority) of volcanic centres recognised from geological mapping overlie the peak of the large magnetic anomalies in the upward continued data thereby implying that they are vents related to deep intrusions indicated by the magnetic anomalies.

At least two of the mapped outcrops of the Colo Plutonic Suite intrusions are associated with significant radiometric anomalies but are not associated with major magnetic anomalies. This fact implies that the intrusions of Fiji are not invariably magnetic and it is thus possible that non-magnetic subsurface intrusions may not have been detected by the survey. It is nevertheless believed that the majority of the intrusive centres in Fiji are magnetic and are evident in the upward continued data.

Geological mapping aspects

Mapping of individual volcanic and pyroclastic units is not always as simple as indicated in the previous sections. This is because different volcanic units do not always have distinctly different geophysical characteristics. It is possible that volcanic products from contemporaneous separate volcanic systems may interleave and add to the complexity. It is obvious that considerable difficulty exists with the field identification of different volcanic units. This difficulty is clear from 1:50 000 scale geological maps of the Natewa Volcanic Group on Vanua Levu where very little continuity or conformity exists between the maps of different geologists. Even on Vanua Levu it is clear that significant revisions are continually occurring. This is demonstrated by differences in maps published by Rodda (1994) and earlier 1:50 000 scale geology published for Fiji.

Given the above difficulties with the field identification of volcanic units, the geophysical interpretation has, by necessity, attempted to produce a compromise mapping of volcanic units, which is consistent with what appear to be most confidently defined geologically mapped units. In several situations the geophysical interpretation has identified areas of distinctive geophysical character that have not been recognised as discrete geological units. Such areas require ground evaluation as they may correspond to previously unknown units. It should also be accepted that the interpretation may not have recognised all the possible subdivisions geophysical responses over the volcanic area and that further detailed study of the geophysical results, combined with detailed ground checking, is likely to significantly increase the detail of the interpretation.

Similar comments can be applied to the use of the geophysical data to map sedimentary units, however the problems are not as severe as the different sedimentary units generally have distinctive radioelement concentrations. The most useful radioelement for mapping the various sedimentary units varies considerably from area to area and it has always proved worth while to study separate images of each radioelement, as well as ternary image in order to optimally delineate different units.

Interpretations over many of the smaller islands have generally been confined to identifying underlying igneous intrusions, volcanic vents, areas of volcanic rocks and obvious faults. It should be accepted that further detailed study of the data covering these areas could produce more detailed interpretations.

Faults systems have been identified from linear discontinuities and offset in anomalies. It is possible that some features identified as faults are simply linear geological contacts between different rock units rather than true faults. For the onshore areas, faults have only been indicated where they are likely to occur at or close to the ground surface. It should be appreciated that where magnetic data has been used to identify a fault, the fault will not necessarily manifest itself on the ground surface if a cover of non-magnetic material overlies the magnetic unit deposited after the episode of faulting.

Linear magnetic features that do not appear to be faults have been identified as "lineament/trends". These may be mapping bedding or joint systems.

The magnetic data indicates that some of the geological units that outcrop on land continue offshore. Areas where this occurs, notably at the eastern end of Viti Levu have generally not been shown in the interpretation as it is not clear that they outcrop on the seafloor. It is likely that most areas they will be covered by non-magnetic sediments. The interpretation has not identified all the minor magnetic sources in the offshore areas.

Specific comments on the various island groups

Viti Levu

The geology of Viti Levu, as interpreted, is largely consistent with previous mappings of the surface geology. The most significant findings are:

1. Definition of a significantly greater development of intrusives of the Colo Plutonic Suite than indicated by surface mapping. It is noted that the split in a line of intrusives of the Colo Plutonic Suite in southwestern Viti Levu suggests a process of limited back-arc spreading. It may be significant that the intrusive centre associated with the Namosi porphyry copper-gold deposits is located in this "opening" in the Colo plutonic Suite. Not all the Colo Plutonic Suite intrusions mapped using surface geology are magnetic. A notable exception is the large circular intrusion located at 178 degrees 10 minutes east, 17 degrees 55 minutes south. This intrusion is also different from the majority of the Colo Plutonic Suite intrusives in that it has an elevated potassium anomaly. An annular magnetic anomaly surrounding the potassium anomaly suggests a well developed zone of contact metamorphism. Another mapped Colo Plutonic Suite intrusion lacking a magnetic anomaly but associated with elevated potassium counts is located at 177 degrees 55 minutes east, 17 degrees, 55 minutes south (the Wainivalau Stock).
2. Identification of the subsurface line of magnetic intrusions in northern Viti Levu, which coincide with gravity highs, and which are probably the source of the epithermal gold deposits at Vatukola, Navilawa (Tuvatu), Vuda and Rakiraki. These intrusions appear to have sourced shoshonitic lavas. Another line of intrusions just north of these features appears to have sourced calc-alkaline lavas.
3. Identifications of a major magnetic intrusion beneath the Yavuna Group.
4. Delineation of major fault systems concave towards the northwest which appear to have accommodated an anticlockwise rotation of Viti Levu.

Vanua Levu and adjacent islands

While the geophysical interpretation has produced surface mappings that are broadly consistent with existing surface geological mappings of Vanua Levu, the geophysical interpretation has given significant new insights into the geology and structure of the island. The most significant facets of this interpretation are:

1. Intrusions have been identified beneath all volcanic groups on the island. These intrusions are interpreted as being relics of the magma chambers from which the volcanic rocks originated. Vents allowing the ascent of the volcanic rocks have been variably recognised as intrusive plugs, magnetic lows, ring type magnetic anomalies and areas of high potassium counts apparently due to potassic alteration.

2. Several, predominantly east west trending fault systems traverse Vanua Levu. A limited amount of igneous activity is associated with this faulting, which the pattern of the fault traces suggests may have involved considerable transcurrent movements which may be related to motion along the Fiji Fracture Zone.

3. As it has proved extremely difficult to reconcile all the previously mapped subdivisions of the Natewa Volcanic Group with the geophysical results the geophysical interpretation has provided new subdivisions based on geophysical character. These geophysically mapped units require field verifications as they are likely to provide the basis for new geological mapping.

Kadavu

Kadavu has been interpreted as a series of volcanic flows overlying feeder intrusions. The interpretation has been able to identify various discrete intrusions and in many cases the vent systems from which the volcanic rocks emanated have been identified. An offshore intrusion, which is a northeastern continuation of the Kadavu system, exhibits a clear line of magnetic lows along its crest. These have been interpreted as a line of vents above the intrusion. Well defined fault systems have been mapped in the area.

The northern Lau Group

The magnetic field over the northern Lau Group indicated that the islands in the area are surface manifestations of volcanic/igneous complexes. Few coherent alignments of igneous centres can be identified. Several northeasterly trending, reversely magnetised, dyke systems can be noted correlating with alignments of islands. It is difficult to determine exactly where the igneous complexes of the northern Lau area merge with the more coherent pattern of igneous intrusions associated with the Udu Volcanic Group of northeastern Vanua Levu. If a junction had to be drawn between these two provinces the most probable position would be along the trend of the island Taveuni, which together with several offshore igneous intrusions evident in the magnetic data, may have been intruded along a fault system which forms a boundary between Vanua Levu and the Lau Group. This causes negative magnetic anomalies and is evidence that these features posses significant remanent magnetisation.

The Yasawa Island Chain and the Mamanuca Island Group

The interpretation of the area of the Yasawa Island Chain and the Mamanuca Island Group has posed more challenges than other areas of Fiji because the geology of the area is obviously so different from the rest of Fiji and so little of the area actually outcrops. Rodda and Lum (1990) describe the Yasawa Islands as largely composed of primarily basaltic volcanic rocks intruded by gabbro dykes trending along the axis of the island chain. Significant thrusting and transcurrent movement has been identified. The possibility that the rocks could be ophiolite fragments has already been mentioned. Because of the complexity of the area, the interpretation has concentrated on defining the main assemblages of magnetic rock material and the major obvious fault systems. A very detailed analysis of the magnetic data combined with correlations with field geology is required to refine the interpretation.

Economic geology aspects

In a separate publication relating to the interpretation of the data from the Fiji Airborne Geophysical Survey Project, Gunn et al. (this volume) have documented how the localities of known epithermal gold deposits on Vanua Levu are characterised by distinctive composite magnetic, radiometric and topographic signatures. These reflect the existence of underlying intrusions, potassic alteration associated with mineralising processes, the existence of vents above the intrusion and fracture systems which appear to have controlled the positions where mineralisation has been concentrated.

The Namosi porphyry copper system (Colley and Flint, 1995) corresponds to a distinct circular ternary radiometric anomaly (white) which corresponds to a diffuse, but distinct, circular assemblage of minor magnetic anomalies. The radiometric anomaly however continues to the east of the intrusive features as a result of andesite lavas in this area giving a similar response. The discontinuous annular magnetic anomaly surrounding the intrusion may be reflecting the effects of contact metamorphism. No corresponding major magnetic intrusive can be identified as corresponding to this feature although some significant internal magnetic highs appear to indicate diorite stocks. The Namosi response is thus significantly different to the response of the epithermal deposits described above.

The use of the airborne geophysical data to identify intrusive centres and map associated vent systems, fracture patterns and areas of possible potassic alteration should significantly aid the identification of areas in Fiji where exploration efforts for porphyry copper-gold and epithermal gold deposits should be concentrated.

Offshore areas

Several types of magnetic anomalies dominate the offshore areas. These are:

1. Broad magnetic anomalies with ovoid shapes which appear similar to the anomalies in the upward continued data over the onshore areas inferred to be due to large intrusive and volcanic complexes. This conclusion is supported by the fact that many such features appear to form the "roots" of volcanic centres manifesting themselves as isolated islands such as Beqa, Vatulele, Yadua, Ovalau and all the islands in the northern Lau Group area.

2. The area immediately north and west of Vanua Levu contains a series of narrow linear anomalies which continues to the Yasawa Group. These anomalies have the form of being inclined due to thin sheets of steeply dipping magnetic material. Fault patterns interpreted as associated with these magnetic sheets suggest that thrusting and possible transcurrent movement has been associated with the emplacement of these magnetic sheets. Such movements may be related to original subduction down the Vitiaz Trench and subsequent strike-slip movement along the Fiji Fracture Zone. The magnetic sheets could be comprised of volcanic and ophiolitic material. It should be noted that Rodda and Lum (1990) have noted similarities between the Yasawa Group lithologies of Maewo and Pentecost Island in Vanuatu which contain volcanic and ophiolite fragments emplaced by subduction down the Vitiaz Trench.

3. The alignment of islands formed by Makogai, Wakaya, Batiki, Gau, Moala and Totoya suggests that they are igneous centres developed along a fracture zone. This idea is supported by the aeromagnetic data which shows that igneous activity along this line is even more extensive than indicated by the islands. A characteristic of this igneous activity is that it is obvious that significant remanent magnetism is associated with these intrusions because, in contrast with the majority of the magnetic anomalies in Fiji, these exhibit significant negative components after the reduction to the pole transformation. This commonality of alignment and remanent magnetisation strongly reinforces the idea of a structurally related origin for these islands and their associated igneous rocks.

Sedimentary Basins

The offshore aeromagnetic survey covered the Bligh Waters, Bau and Suva sedimentary Basins. The stratigraphy and hydrocarbon potential of these Basins has been described by Rodd (1993) and Johnson (1994). The primary mapping method used for sedimentary Basins was to determine the depths to the various magnetic sources adjacent to, within, and beneath the Basins. This is a basic technique used for studying Basins. It is generally assumed that depths to large magnetic igneous intrusions beneath sedimentary Basins give estimates of the thickness of overlying non-magnetic sediments and thereby allows the gross geometry of the Basin to be estimated. It is possible that the magnetic intrusions do not reach the floor of the Basin or the intrusion is actually intruded into the sediment section. Care should be exercised when using depth estimates to intrusive features for mapping Basin geometries. It is also possible that intrasedimentary units such as volcanic flows and still occur and depths to these units will obviously not map the Basin geometry. Depth to magnetic sources estimated for offshore magnetic anomalies are indicated on the interpretation maps. These are shown as depths below sea level. Water depths must be subtracted from these figures to obtain sediment thicknesses.

From the depth estimates to magnetic sources obtained for the offshore areas of Fiji, it does not appear that any new significant, previously unknown sedimentary Basins have been identified.

Localised magnetic culminations in the various Basins could indicate shallow intrusive features which have acted as loci for reef growth. If this is so, they warrant attention in any hydrocarbon exploration programme. Not all such culminations have been identified in the interpretation maps and if this concept is to be followed, it is recommended that a detailed re-examination of the magnetic data be made.

Tectonic and structural aspects

While the magnetic data has been useful for delineating the geometry of magnetic units in Fiji, these mappings are not readily interpretable in plate tectonic terms. Superposition of several episodes of intrusion appears to have occurred. Tectonic episodes and structural features suggested by the interpretation, and not mentioned in the previous discussions, are:

1. No direct geological connection between Viti Levu and Vanua Levu is apparent.
2. The Yasawa Island Chain and its offshore equivalents appears to have had their southern end bent towards the southeast.
3. A significant anticlockwise rotation of Viti Levu relative to the Yasawa Group appears to have occurred. Major arcuate faults (concave to the northeast) appear to have accommodated strains in Viti Levu during the rotation of Viti Levu.
4. The line of intrusion on the Makogai-Totoya trend may mark the deformed trace of an ancient fault offsetting the islands of Viti Levu and Vanua Levu. This feature may have accommodated anticlockwise rotation of Viti Levu.
5. If Yasawa Group equivalents were emplaced along a subduction zone west of Vanua Levu, the Bligh Waters Basin May have originated as a forearc Basin. The morphology of this Basin however appears to have been enhanced by the anticlockwise rotation of Viti Levu associated with overthrusting from the northern side of the Basin.
6. Major east west fault systems traversing Vanua Levu appear to have a significant strike slip component.
7. There is no obvious break between the geology of the Lau Group and the geology of Vanua Levu, although a change of character can be noted along the trend of Taveuni.
8. Kadavu appears to be the product of an isolated assemblage of intrusive centres with Beqa and Vatulele Islands being due to similar assemblages albeit of a different age. As postulated by previous authors, these linear belts of intrusions may be related to subduction along the Hunter Fracture Zone following the reversal of subduction which manifests itself so clearly in Vanuatu to the northwest.

CONCLUDING REMARKS

The airborne geophysical dataset covering Fiji contains a wealth of geological information. It must be accepted that such datasets can be progressively interpreted in increasing detail and that any interpretations of the data may require modification as new geological data becomes available. This paper has merely highlighted some of the significant features indicated by the data. Further detail studies of the results of the Fiji Airborne Geophysical Survey Project are likely to significantly enhance the geological knowledge of Fiji at both local and trigonal scales.

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MAGNETIC, RADIOMETRIC AND GRAVITY SIGNATURES OF LOCALITIES OF EPITHERMAL GOLD DEPOSITS IN FIJI

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ABSTRACT

Fiji contains several epithermal gold deposits and by studying the geophysical responses in the vicinity of these deposits it is possible to identify a set of geophysical characteristics which indicate localities where such deposits may be located. Epithermal gold deposits are formed above intrusive stocks resulting from subduction processes. The source intrusions for the deposits are normally covered by lavas and pyroclastic rocks and the irregular magnetic effects of these units obscure the magnetic effects of the intrusions. In Fiji however the source intrusions can be recognised as causing gravity highs and magnetic highs in upward-continued magnetic data in which the magnetic effects of volcanic rocks were suppressed. Vents associated with the intrusions can be recognised as magnetic lows which sometimes contain a central high. Some vents and calderas can be recognised in digital elevation data. Increased potassium concentrations can be interpreted to indicate potassic alteration associated with mineralising processes. Fractures that may localise epithermal deposits can be recognised in the magnetic data and enhancements of the data such as produced by derivative operations.

INTRODUCTION

On 2 June 1998 the results of the Australian Agency for International Development (AusAID)-funded Fiji Airborne Geophysical Survey Project were released. This project, which involved the acquisition of approximately 160 000 line kilometres of aeromagnetic, airborne gamma-ray spectrometric and digital elevation data, was designed and managed by the Australian Geological Survey Organisation (AGSO). The data were acquired 80 m above the land and sea surface with 400 m line spacings onshore and 800 m spacings offshore. The Australian company Kevron Pty Ltd was contracted to perform the acquisition and processing. The primary objectives of the survey were to provide databases to stimulate mineral and hydrocarbon exploration in Fiji and to allow refinements to the geological mapping of Fiji. AGSO produced 1:250 000 scale interpretations of the data which revised and extended the known geology of Fiji and identified areas considered to have enhanced potential for mineral and hydrocarbon prospectivity. The Fiji Mineral Resources Department (MRD) is the Fiji Government agency responsible for the archiving, distribution and ongoing usage of the products of the project.

During AGSO's interpretation it was noted that localities of known epithermal gold occurrences in Fiji have distinctive geophysical signatures that can be recognised in the airborne geophysical data. The object of this paper is to present and explain these signatures as it is considered that they can be used as templates to identify localities prospective for undiscovered epithermal gold deposits both in Fiji and other areas with similar geological settings.

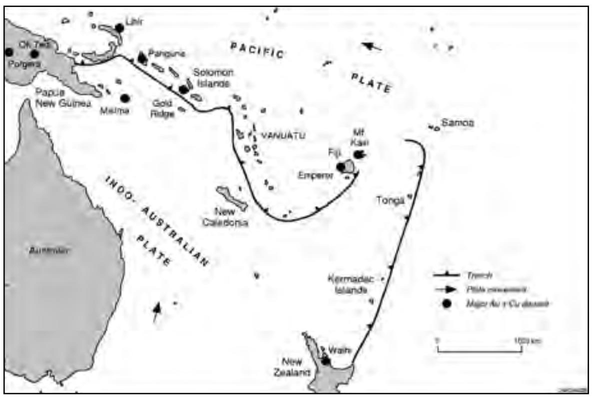


Figure 1. Location of Fiji.

BACKGROUND INFORMATION ON THE GEOLOGY OF FIJI EPITHERMAL GOLD DEPOSITS

Figure 1 shows that Fiji is located along the circum-Pacific **'**Ring of Fire**'** which is the intrusive/ volcanic belt hosting most of the larger epithermal gold and porphyry copper gold deposits in the world. The igneous activity in this belt is the result of subduction processes. In the case of Fiji the present geometry of subducting plates has been complicated by a reversal of the subduction process associated with the developing of the spreading centre in the North Fiji Basin. Figure 2 shows inferred plate tectonic reconstructions which explain the development of the island arc systems which comprise Fiji and its environs.

Figure 3a shows the commonly accepted model for the developments of island arc systems. The model involves the development of stratovolcanoes above intrusive plutons resulting from thermal processes associated with subduction of oceanic crust. Detachment of oceanic crust at the point of initial subduction can preserve slices of oceanic crust as ophiolite wedges. Figure 3a illustrates the situation inferred in Vanuatu, the island arc system adjacent to Fiji, prior to arc reversal in the area. Figure 3b illustrates the present situation in Vanuatu that has resulted from a reversal of the subduction direction. It should be noted that a new line of intrusive centres is being developed above

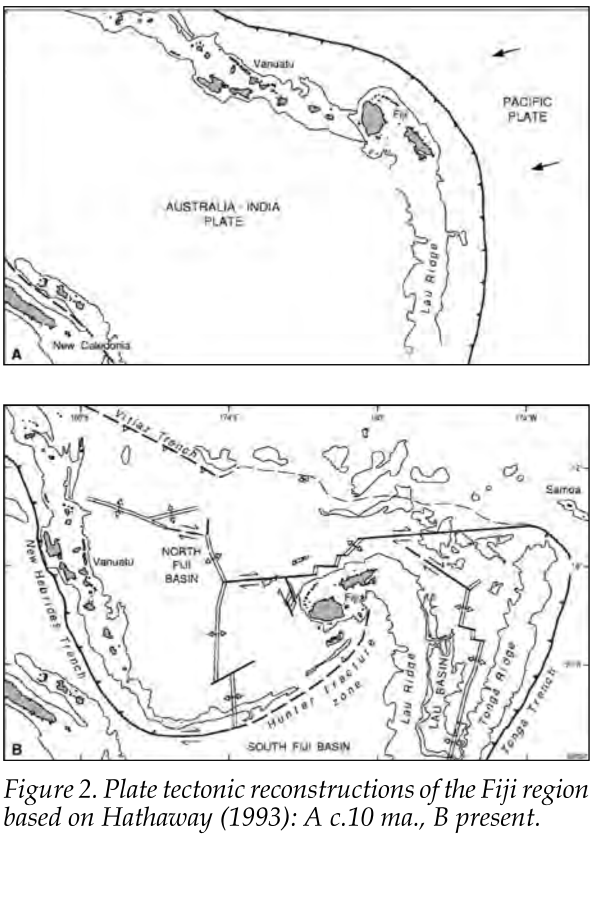


Figure 2. Plate tectonic reconstructions of the Fiji region based on Hathaway (1993): A c.10 ma., B present.

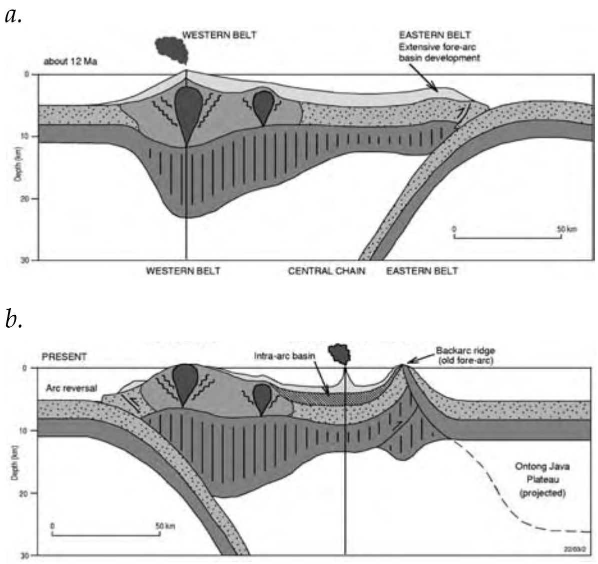


Figure 3. Sections illustrating the evolution of the Vanuatu island arc system.

the now subducting sheet. It is probable that the development of Fiji has followed a similar process, albeit one that has been complicated by a degree of rotation associated with the opening of the North Fiji Basin.

It is important to understand how the above, basically simple, processes lead to the geological development of island-arc complexes such as those that comprise the islands of Fiji. Central to this understanding is the fact that the main building units of these complexes are the intrusive plutons and their associated volcanic products. These systems build the island-arc systems on a floor of ocean crust. The plutonic systems and their associated volcanic products tend to occur in alignments parallel to subduction zones and to show petrologic differentiation that ranges from the tholeiitic series closest to the point where subduction commences through the calc-alkaline series to the alkali series most distal from the point of subduction. Figure 4 shows a model for an island arc intrusive volcanic complex. This consists of an intrusive stock, which does not reach the surface, overlain by a vent system through which lavas and pyroclastic material are transmitted to the surface where they are deposited in a series of sub-horizontal layers around the vent in a manner that can form a stratovolcano. Dykes, sills and volcanic plugs may be intruded into the section above the intrusive stock. Erosion of the volcanic and intrusive material creates the primary source of sedimentary rocks in island arc systems although reef growth sometimes contributes substantial carbonate components. The simple system described above can however be complicated by metamorphism due to burial and thermal effects and pressure associated with the interactions of different plates along the subduction zone. These plate interactions can also result in folding, faulting, tilting and uplift. Overprinting of intrusive and volcanic episodes and extension can further complicate the geological assemblages of island arc systems. Despite this complexity, it is commonly possible to identify relatively simple geological situations similar to the one illustrated in Figure 3a and to use this recognition as a basis for geological and geophysical interpretations.

Figure 4, after Colley an Flint (1995), illustrates a model showing how porphyry copper-gold and epithermal gold deposits can be genetically related to the intrusions that build island arc systems. It should however be noted that, while Figure 4 indicates the development of a stratovolcano, such features are not an essential component in the development of epithermal gold and porphyry copper-gold deposits. These deposits can be formed without the actual development of a volcano. Disseminated copper and gold mineralisation may be precipitated from fluids associated with the emplacement of the intrusive stock in the country rock above, flanking and in the upper portions of the stock. Such porphyry copper-gold deposits cannot be economically mined unless extensive erosion of the overlying volcanic material occurs. Magmatic gases and hydrothermal fluids ascending above the intrusive stock, via fractures and fumaroles, may mix with meteoric or connate fluids to precipitate gold in what are termed epithermal deposits. Some epithermal gold deposits are spatially associated with a central vent above an intrusive stock and some are located in fractures or small local vents which are proximal to, but not necessarily vertically above, the intrusive stock. Porphyry copper-gold and epithermal gold deposits tend to be associated with calc-alkaline and alkaline suites of rocks. Fiji contains several known porphyry copper and epithermal gold deposits (Colley and Flint, 1995). This is expected given Fiji's island arc setting.

The system illustrated in Figure 4 is simple and idealised. Despite the fact that rock associations in such systems are frequently considerably more complex, especially when multiple phases of intrusion occur, the model of Figure 4 is appropriate for understanding the likely geophysical responses of the units comprising the system illustrated and for the subsequent recognition of such responses in Fiji. These responses are discussed in the following section in the context of how they can be used to identify localities where epithermal gold deposits may occur.

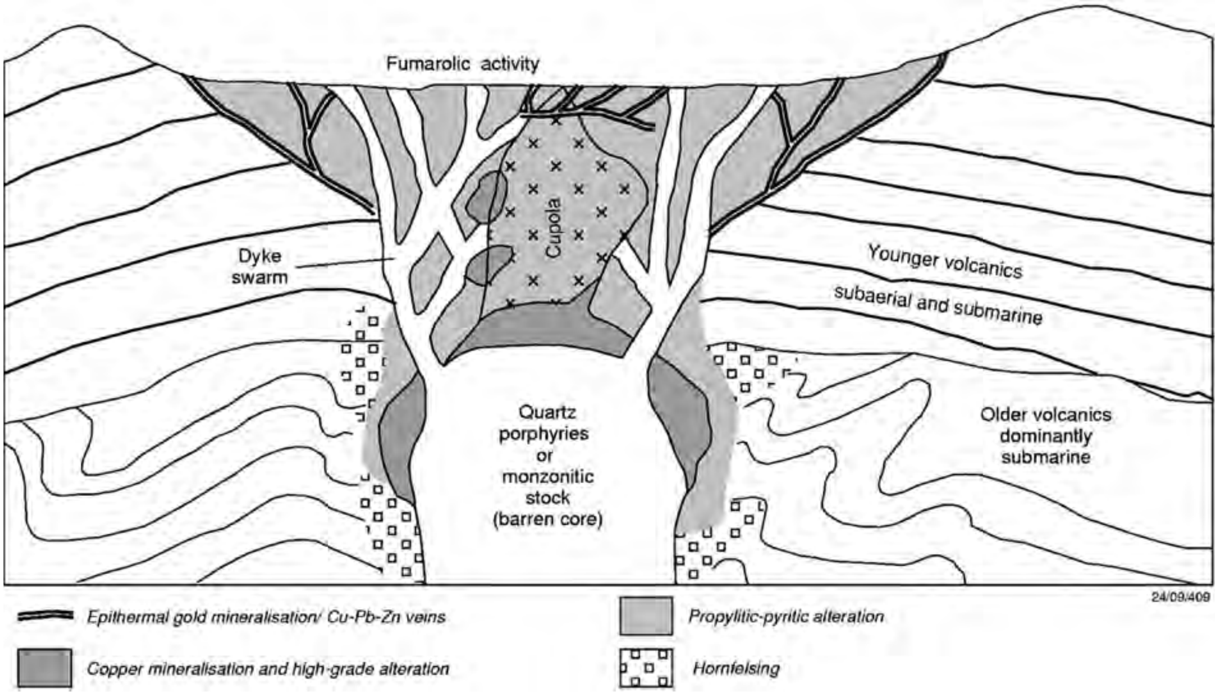


Figure 4. Geological setting of epithermal gold and porphyry copper-gold deposits (after Colley and Flint, 1995).

EXPECTED REGIONAL GEOPHYSICAL RESPONSES OF INTRUSIVE VOLCANIC SYSTEMS THAT MAY HOST EPITHERMAL GOLD DEPOSITS

The components of the model of Figure 4 and their possible geophysical responses are as follows.

The intrusive stock

This may be magnetic and thereby cause a discrete magnetic anomaly. If multiple phases of superimposed intrusion occur, this anomaly may exhibit concentric zoning or even more complex subdivisions. As the plan sections of such intrusions tend to be circular or ellipsoidal, the observed anomalies commonly have such outlines as well. Contact metasomatic effects may produce a magnetic annulus, due to magnetite concentrations in the country rock surrounding the intrusion. The intrusions do not always contain significant concentrations of magnetite and it is possible that they will be imaged as magnetic lows relative to adjacent country rock if the country rock contains greater concentrations of magnetic minerals. Destruction of magnetite by alteration processes associated with fluid flow may create local magnetic lows in the magnetic responses of the intrusions and the country rock.

The intrusion of stock-like bodies is an essential factor in the formation of most epithermal gold deposits. The identification of such intrusions in a particular area at depth is thus a favourable regional indicator for the possibility of an overlying epithermal gold deposit. It is important however that erosion has not stripped off the cover sequence, such as genetically related volcanic and pyroclastic rocks, in which any epithermal gold deposit is likely to be located. Such erosion is not completely negative from an exploration viewpoint as it may expose rocks with porphyry copper potential.

The volcanic system

This consists of the assemblage of volcanic and pyroclastic rocks together with any dykes and sills developed in volcanoes above the intrusive stocks. Figure 4 shows such a volcano consisting of a central vent that has resulted in the formation of a caldera. It is possible to have multiple vents. Calderas are not always formed. If calderas do form they tend to be circular. Vents may contain plugs of solidified volcanic material such as that illustrated in Figure 4. Vents may also be associated with the formation of ring dykes and radial fracture systems.

The volcanic and pyroclastic material ejected from the volcano (shown as 'younger volcanics subaerial and submarine' in Figure 4) consists of irregular (both in thickness and in plan) superimposed sheets of volcanic rocks such as lavas, tuffs and agglomerate. The magnetic characteristics of these units are extremely variable due to different cooling histories and compositions at different localities. Often it is only possible to outline such units in the magnetic data on the basis of their textural character rather than their bulk magnetic response. Airborne spectrometric gamma-ray responses (ternary, potassium, thorium and uranium) are however extremely useful for mapping the surface outlines of exposed volcanic units on the basis of variations in their radioelement concentrations.

Vents are commonly evident as magnetic lows. There are several possibilities for their response. It may simply be due to a physical hole. It could be due to the destruction of magnetite in and around the vent system due to alteration processes. It could also be due to the magnetic effects of a plug of weakly magnetic or reversely magnetised rock in the vent. Some vents are marked by central magnetic highs which are due to plugs of magnetic rock. These central highs are often surrounded by magnetic lows which may be caused by the factors listed above. Ring dykes can add doughnut-shaped magnetic highs to the magnetic signatures of vent systems. If a caldera is developed it will be visible in digital elevation models unless its topographic expression is destroyed by erosion.

The identification of a vent system associated with calc-alkaline or alkaline volcanic rocks allows exploration efforts for epithermal gold deposits to be focussed in the locality of the vent.

The epithermal gold deposits

These do not have a direct geophysical expression. Specific localities where such deposits may have formed can however be indicated by airborne geophysical data. As shown in Figure 4 such deposits are developed in vein systems in, or proximal to, volcanic vents. These veins are the result of precipitation of gold from fluids that have ascended from the underlying stock via fractures and faults. Such fractures and faults can be visible in airborne magnetic data by virtue of displacements of magnetic units and destruction of magnetite by mineralising fluids and weathering along the plane of the fault or fracture.

Alteration processes may locally enhance the potassium content in the country rock adjacent to epithermal gold deposits and such elevated local potassium concentrations can often be recognised in images of potassium values determined from the gamma-ray spectrometric data.

SPECIFIC SIGNATURES OF EPITHERMAL GOLD DEPOSITS OBSERVED IN FIJI

Figure 5 shows an image of the total magnetic intensity field of Fiji as recorded during the Fiji Airborne Geophysical survey project. The data of this image has been reduced to the pole to correct for polarity effects caused by induction in the Earth's magnetic field which has an inclination of 38.87° in the vicinity of Fiji. The production of an analytic signal image (Roest et al., 1992), in which highs indicate the correct spatial position of magnetic sources regardless of magnetic remanence effects indicates that, while some magnetic units in Fiji are significantly magnetised by remanence, the majority are not. The reduced-to-the-pole image of Fiji can generally be regarded as imaging the geometries of magnetic sources according to the principles of magnetic induction as applying in a situation with a vertical inducing field. Therefore the image is giving a good general indication of the positions and shapes of the magnetic sources of the area.

A detailed description of the AGSO 1:250 000 scale interpretation of these data is given by Gunn et al., (1998). They conclude that, apart from the linear anomalies in the north-west extremity of the survey area, which are likely to be due to slices of ophiolitic rocks, virtually all the magnetic responses observed are due to intrusive/volcanic complexes such as described in the preceding sections. Several linear belts of intrusive centres and associated volcanic centres of different ages and petrological characteristics have been indentified. These belts are not immediately apparent in the magnetic image of Figure 5 as the intrusions are mainly buried beneath a cover of volcanic and sedimentary rocks. An appreciation that the intrusive/volcanic complexes comprising this belt have geometries

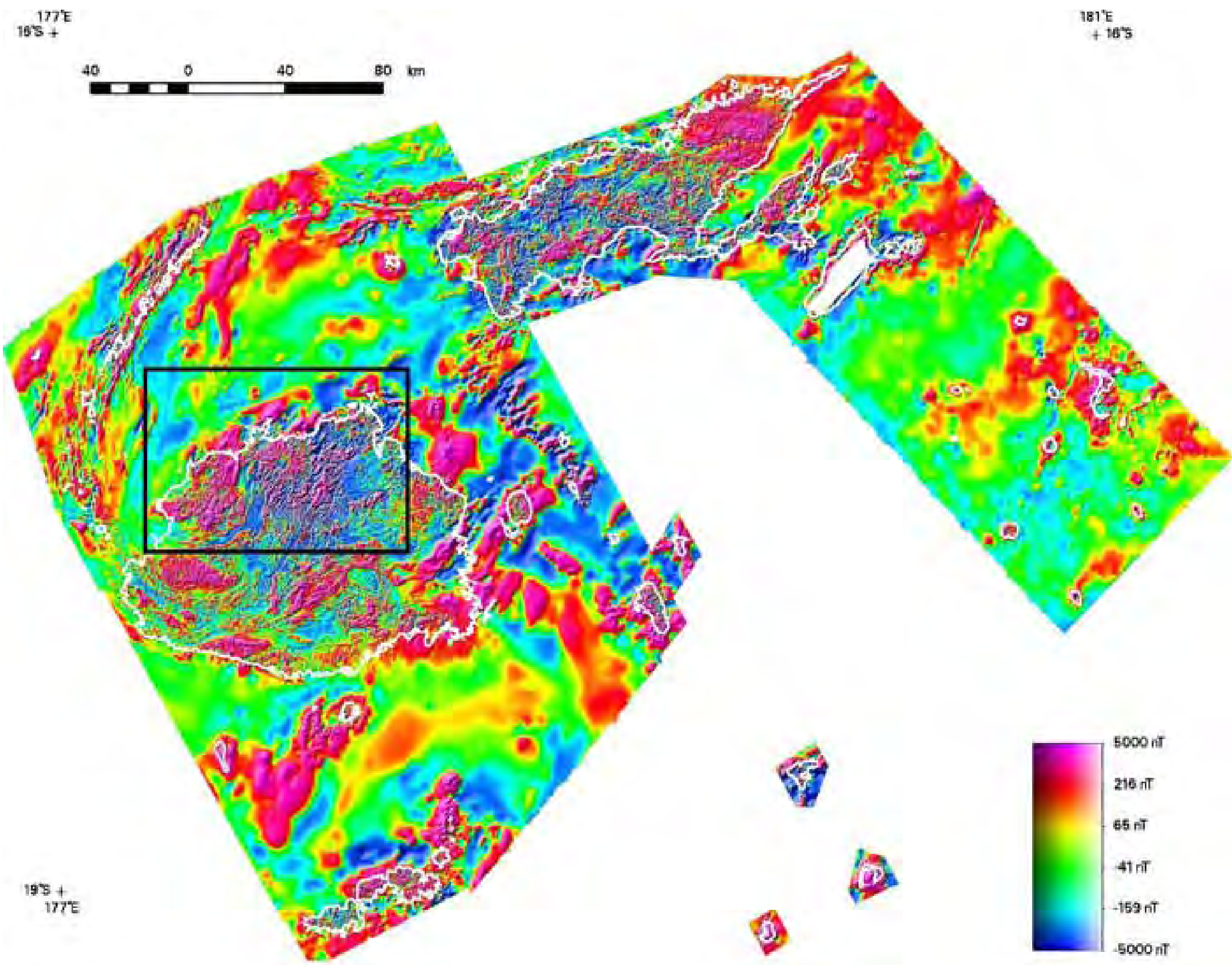


Figure 5. Image of total magnetic intensity field reduced to the pole for the Fiji region. The area detailed in Figure 6 is outlined.

and geology conforming to the model of Figure 4 has allowed the selection of processing routines to enhance and identify the responses of these centres. The following discussion details the imaging and interpretation of one such linear belt of intrusive/ volcanic complexes which has been identified along the northern margin of Viti Levu, the largest island of the Fiji Group of islands. Colley and Flint (1995) document several epithermal gold deposits occurring along the zone. The locations of these deposits, namely Vuda, Tuvatu, Vatukoula and Rakiraki, which are hosted by shoshonitic volcanic assemblages, are shown in Figure 6. Vatukoula is a major deposit originally containing approximately 8 million ounces of gold. The Tuvatu deposit is currently undergoing a feasibility study.

The geophysical indicators of the intrusive/ volcanic systems that formed these deposits are as follows:

Gravity data (Figure 6a). The data from this image corresponds to the gravity contours of Figure 12 of Colley and Flint (1995) and represents terrain-corrected Bouguer gravity data processed to suppress long wavelength and shallow source over Viti Levu. The acquisition and processing of these data is described by the Metal Mining Agency of Japan (1993). The significance of these results is that isolated gravity highs appear to be indicating the gravity effects of deep, dense, intrusions beneath the epithermal gold deposits.

Total magnetic intensity (Figure 6b). This image, which has been illuminated from the west, does not clearly indicate the magnetic effects of the intrusive bodies indicated by the gravity data. The image of Figure 6a is dominated by the erratic high frequency magnetic effects of the shoshonitic volcanic assemblages which host the epithermal gold deposits. The magnetic effects of the underlying intrusions are only evident in this image by vague general increases in the field values in the vicinity of the intrusions. The image of Figure 6b shows the high frequency magnetic effects of the surface and near-surface volcanic material superimposed on the broader magnetic effects of the buried intrusions. It is only when the effects of the volcanic material are removed by a filtering process, such as the upward continuation illustrated in Figure 6c, that the magnetic responses of the buried intrusions become obvious. While the image of Figure 6b can be used to map individual volcanic units, the vertical gradient image of the magnetic field (Figure 6d) proved more useful for this task.

By carefully inspecting the image of Figure 6b it is possible to identify features expected to be characteristic of the localities of epithermal gold deposits. The Vuda vent system appears as a circular magnetic low containing a central high. The Tuvatu epithermal deposit appears to be located in an east west trending fault adjacent to a small circular magnetic high with a central low which collectively may be indicating a vent. The Vatukoula deposit is located adjacent to the Tavua Caldera in a locality where east-west trending and north-east trending faults indicated in the data appear to intersect. The Tavua Caldera is evident as a magnetic low.

Upward continued total magnetic intensity (Figure 6c). When a magnetic field is recalculated at a higher level the magnetic effects of thin discontinuous and sub-horizontal magnetic sources are suppressed relative to the magnetic effects of bodies with significant width and depth extent. In the image of Figure 6c where the field data has been computed at a level of 500 m above the ground surface (in contrast to the field shown in Figure 6b which was measured 80 m above the ground surface) the magnetic effects of the surface volcanic material have been suppressed to the extent that three major magnetic anomalies corresponding to the gravity anomalies in northern Viti Levu have become evident. It appears that the intrusive bodies underlying the Vuda, Tuvatu, Vatukoula and Rakiraki epithermal gold deposits are both dense and magnetic relative to the material into which they are intruded.

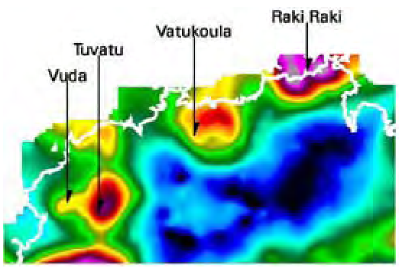
The upward continuation data shows a distinct magnetic low corresponding to the vent system manifesting as the Tavua Caldera. The intrusive centre associated with the Rakiraki epithermal system shows a similar (albeit offshore) central low. No clear central low is associated with the intrusion underlying the Vuda and Tuvatu deposits, however both the gravity and upward continued magnetic data indicate an elongation of this feature and it is possible that it sources several relatively smaller vents such as those associated with the Vuda and Tuvatu areas rather than a major single vent such as the one causing the Tavua Caldera.

Vertical gradient of the total magnetic intensity (Figure 6d). The vertical gradient processing has enhanced the magnetic effect of high frequency magnetic anomalies relative to the effects of broad low frequency magnetic anomalies such as are caused by deeper sources. The processing of Figure 6d is particularly useful for the mapping of individual volcanic units on the basis of textural characteristics. The vertical gradient processing also simplifies the recognition of fine detail such as fault and fracture systems. Vent systems such as Vuda, Tuvatu and Tavua which have surface expressions can be recognised in the derivative data.

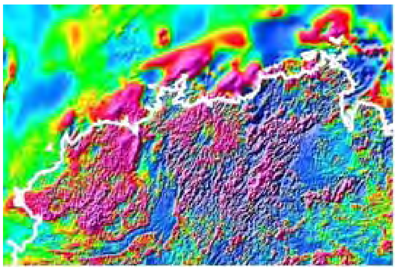
Ternary radiometric image (Figure 6e). The ternary gamma-ray image is an excellent tool for the mapping of surface geology if care is taken to identify effects caused by variations in weathering and areas where transported material has been superimposed on bedrock. The image of Figure 6e shows that the areas corresponding to the Vuda, Tuvatu and Tavua vents have elevated counts in all radioelements. The principal vent in the Rakiraki area is offshore so no comments are possible for this area.

Potassium image (Figure 6f). In the image of the equivalent potassium ground radioelement concentrations of Figure 6f it can be noted that the vicinities of the Vuda, Tuvatu and Tavua vents all correspond to localised areas with potassium values amongst the highest evident in the data. These can be assumed to be due to potassic alteration caused by fluids associated with the formation of the epithermal gold deposits.

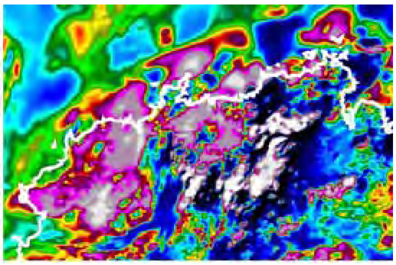
Digital elevation (Figure 6g). The Tavua Caldera is clearly evident in the digital elevation image of Figure 6g. None of the other epithermal gold deposits being considered has an obvious topographic expression.



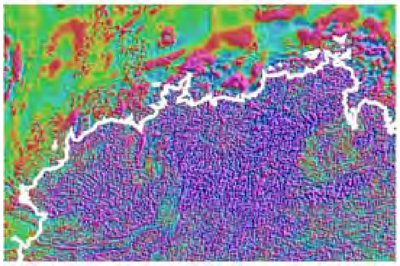
a. Intermediate wavelength gravity field.



b. Total magnetic intensity reduced to the pole, illuminated from the west.

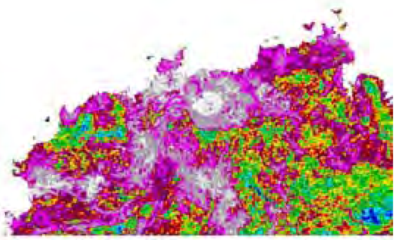


c. Total magnetic intensity continued upwards to 500 metres.

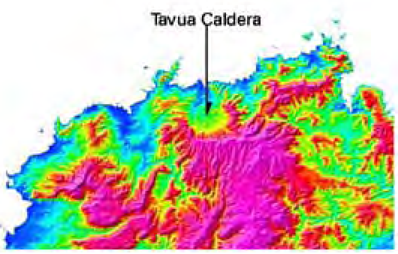


d. First vertical derivative of total magnetic intensity.

e. Ternary gamma-ray spectrometric image (white high).

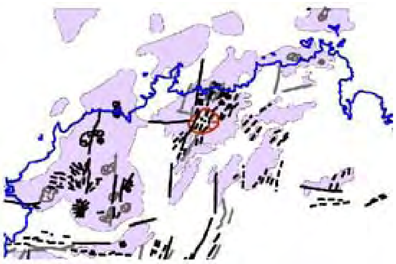


f. Equivalent potassium concentrations (white high).



g. Digital elevation.

h. Detail from the surface solid geology interpretation of Gunn et. al. (1998). Different volcanic units, structure and vents have been identified.



i. Detail from the interpretation of Gunn et. al. (1998) showing locations of major subsurface intrusive stocks.

Figure 6. Details of the belt of intrusive/volcanic complexes associated with epithermal gold deposits in northern Viti Levu. The locations of the deposits (Vuda, Tuvatu, Vatukoula and Rakiraki) are indicated in several images.

GEOPHYSICAL INTERPRETATION

The following images summarise the geological interpretation of the geophysical data:

Surface solid geology (Figure 6h). Figure 6h shows a detail from the solid geology interpretation of the geophysical data produced by Gunn et al. (1998). The interpretation has distinguished different volcanic flows, structure and localities of vents.

Positions of major subsurface intrusions (Figure 6i). Figure 6i, a detail from the interpretation of Gunn et al. (1998), indicates the outlines of subsurface intrusions that have not reached the surface.

It appears significant that the intrusive centres that appear to be sourcing the epithermal deposits under discussion occur in a line and at regular spacings. It could be envisioned that they have resulted from the contemporaneous ascent of magma in a series of regularly spaced convection cells formed above a subducting plate of oceanic lithosphere. Some workers have raised the possibility importance of major transform faults in the localisation of epithermal gold deposits. Such features are not markedly evident in the area being considered although a significant north-east-trending fault zone does appear to intersect the Tavua Caldera.

CONCLUDING REMARKS

This paper has discussed geophysical responses associated with epithermal gold deposits in a limited area of Fiji. The area presented has the greatest known concentration of such deposits and is best documented in terms of such deposits. The airborne geophysical data of the Fiji Airborne Geophysical Survey Project contains response in other areas of Fiji, not known to contain epithermal gold deposits, which are similar to the responses noted to be associated with the known deposits.

ACKNOWLEDGEMENTS

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INTERPRETATION OF AEROMAGNETIC AND RADIOMETRIC SIGNATURES OF THE NAMOSI AREA, VITI LEVU, FIJI

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ABSTRACT

The Namosi area, on the island of Viti Levu in the Republic of Fiji, represents an island arc complex. The bulk of the rocks exhibit intense aeromagnetic and radiometric signatures and are interpreted to be of igneous origin being either volcanic, intrusive or derived from volcanic or intrusive rocks. Analysis of airborne magnetic, radiometric and digital elevation datasets show the Namosi area is host to a major volcano-plutonic complex with magnetite-bearing oxidised intrusions. This complex is interpreted as a major eruptive centre associated with the Namosi porphyry copper-gold deposits. The general distribution of the stratigraphic units of the volcanic complex suggests that it could have been a stratovolcano, now largely dissected by erosion.

Geology of the Namosi area, as interpreted, is largely consistent with previous mapping of the surface geology although a significantly greater development of intrusives of the Colo Plutonic Suite has been defined by the airborne geophysics than indicated by surface mapping. The majority of these large igneous intrusions are magnetic (presumably I-type) bodies. This study also shows that not all Colo Plutonic Suite intrusions mapped using surface geology are magnetic. These low-magnetic intensity Colo Plutonics, are associated with significant gamma-ray anomalies.

Offshore aeromagnetic results indicate the existence of major structures, which were interpreted to be part of the Colo Plutonic Suite. Furthermore, fault systems were identified from linear discontinuities and offsets in anomalies. The interpretation supports earlier findings that dominantly north-east - south-west and north-west - south-east trending faults occur in the Namosi area. Interpretation of the airborne geophysical data has demonstrated the presence of various geological features that had not previously been detected or were poorly defined by earlier work. This study, therefore, has highlighted several factors that may be useful in future exploration for porphyry copper-gold mineralisation in the Fijian (or similar) environment.

INTRODUCTION

The Namosi district is located in the headwaters of the Waidina River, approximately 30 km west-north-west of Suva, on the island of Viti Levu (Figure 1). Most of the area is uninhabited and undeveloped and is covered by dense tropical rainforest. Annual rainfall exceeds 5000 mm. The topography is rugged with elevations ranging from less than 100 m above sea level to approximately 1400 m (Royle et al., 1979).

In recent years there has been significant advances in the understanding of the geology and tectonic setting of porphyry copper-gold deposits. It has been realised that porphyry copper-gold deposits are strongly correlated with volcanic activity, particularly sub-volcanic stocks (Sillitoe and Bonham, 1984).

The Namosi area represents an island arc complex of calc-alkaline andesite flows and pyroclastics (the Medrausucu Group) which overlie weakly metamorphosed andesitic to basic basement rocks (Wainimala Group). Porphyritic intrusions invade both the Wainimala and Medrausucu groups. The gross structure, geology and mutual stratigraphic relationship of the volcanic rocks have been interpreted as representing a dissected stratovolcanic sequence (Royle et al., 1979).

The Namosi porphyry prospect hosts a volcanic, epi-mesothermal style mineralisation. The major porphyry-copper prospects are at Waisoi, Waivaka, Wainibama and Wainiwi. There are also a number of polymetallic vein and skarn systems around the periphery of these prospects. The latter are not strictly disseminated-type deposits but are closely associated with the porphyry copper prospects (Colley and Flint, 1995).

Different levels of erosion within volcanic centers in the Namosi district allow the construction of a volcanic model, which shows the relationship between porphyry-style and epithermal-style mineralisation (Colley and Flint, 1995).

There have been strong structural influences on the location and extent of mineralisation. Previous work (Colley and Flint, 1995; Ellis, 1996; Rodda, 1976; Royle et al. 1979) have identified probable structural controls on most of the deposits.

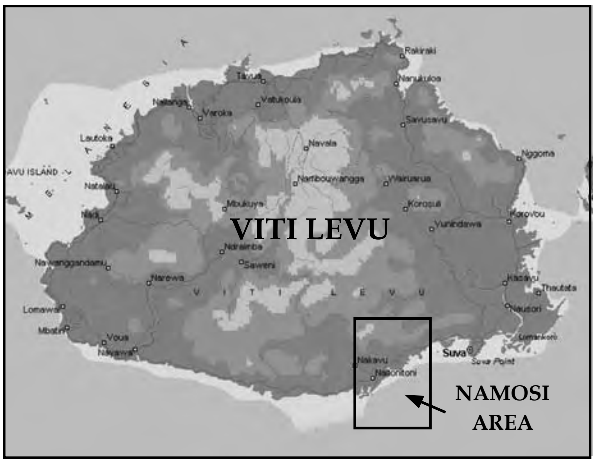

Figure 1. Locality map of the Namosi area, Southern Viti Levu, Fiji.

THE FIJI AIRBORNE GEOPHYSICAL SURVEY

The airborne geophysical survey of the Fiji Islands was commissioned by the Commonwealth of Australia, represented by the Australian Agency for International Development (AusAID), for the Government of Fiji as part of the Australian Government's bilateral aid programme to Fiji.

Most of the studies undertaken in the Namosi area have largely concentrated on the Waisoi porphyry copper deposit. There is very little published work on the geology, mineralisation and structural setting of the Namosi area on a regional scale.

The airborne magnetic and radiometric survey funded by AusAID is the first regional and systematic airborne geophysical survey undertaken in the Namosi area. The acquisition of geophysical data has made it possible to provide a cost-effective modelling of the structure and geology of the rugged Namosi terrain. The primary objective of the project was to make available a comprehensive data set of airborne magnetic, radiometric and digital elevation data that covers the Fiji landmass and adjacent sedimentary Basins. In addition to this, a dataset that would stimulate mineral and petroleum exploration in Fiji and provide a basis for ongoing geological, hydrogeological, geohazard, geothermal, landuse, and environmental studies in Fiji.

The Australian Geological Survey (AGSO), acted as project managers under contract to AusAID and designed and supervised the survey. A contractor, Kevron Pty Ltd of Perth, utilising its subsidiary companies, Kevron Geophysics Pty Ltd and Geoinstruments Pty Ltd, performed the data acquisition and processing.

The survey area covered the bulk of the Fiji landmass (excluding a number of small islands) and a significant area of the surrounding waters.

DATA ACQUISITION

Data acquisition involved collection of airborne magnetic, radiometric and digital elevation data over the land areas of the survey. Only magnetic data was acquired over the offshore areas, as water is not conducive to producing a radiometric response.

The data were acquired during the favorable weather season, between April and October, 1997. Several airborne acquisition systems were used simultaneously. The offshore areas were surveyed with a fixed wing airplane. Areas of rugged topography were surveyed with a helicopter-mounted system in order to maintain a constant ground clearance. The helicopter coverage was extended a small distance offshore in many cases. This was done to avoid having an artefact in the data caused by the join between the fixed wing and helicopter coverage. The 400 m-line spacing was maintained for all helicopter coverage. To maintain data quality throughout the survey, stringent survey specification and calibration procedures were adopted. These specifications were established by AGSO in conjunction with the contractors.

METHODOLOGY

Interpretation of the Namosi airborne geophysical data was performed by creating a computerised Geographical Information System (GIS) using MapInfo 4.5 software. The GIS contained a wide range of images of geophysical data which were produced in the Intrepid processing software. These images were enhanced using the Earth Resources Mapper (ERMapper) 5.5 imaging system.

Previously mapped geology (Figure 2) was confirmed or revised once layers of all appropriate geophysical parameters were installed in the GIS. Where appropriate, previously unrecognised geological features were identified and their outlines incorporated into a definitive version of the interpretation. Finally, hard copies of all the various images, which conform to Fiji National standards, were produced.

In many situations, a degree of generalisation and educated guesswork was applied to position boundaries. The interpretation map, therefore, should be regarded as a basis for future refinement of geological mapping of the Namosi area based on detailed geological mapping and ground truthing of the various anomalies detected by the geophysical survey.

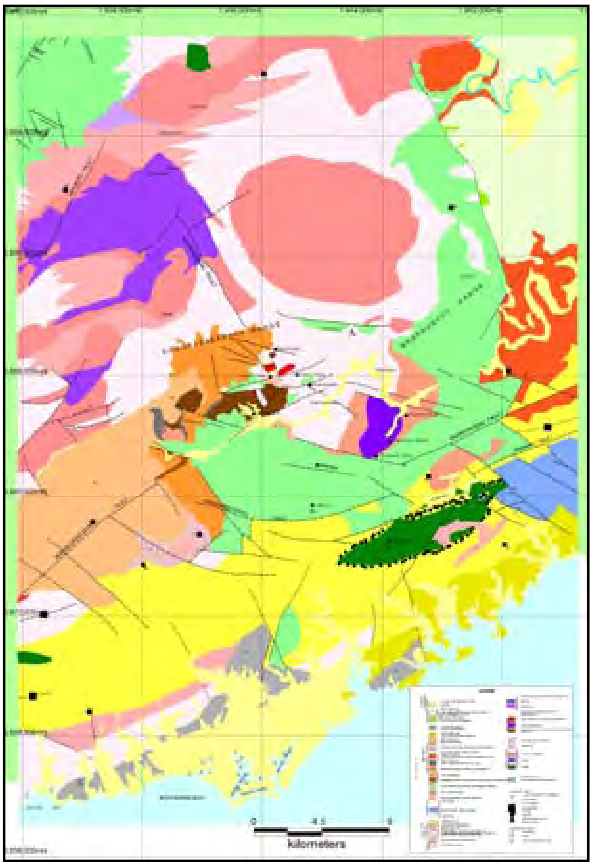

Figure 2. Geology of Namosi.

GEOPHYSICAL INTERPRETATION

Total magnetic intensity images

Basic interpretation of the aeromagnetic data set was performed on various images of the total magnetic intensity (TMI) data set reduced to the pole.

It was assumed that there is no remanent magnetisation in the Namosi area. If there was a significant amount of remanence, smearings of anomalies would have occurred in the transformed maps (MacLeod *et al.,*1993). No such smearing is obvious in the reduced-to-the-pole images of the Namosi area, so it is highly probable that no significant remanence is present.

The reduced to the pole, TMI image of the Namosi area (Figure 3) shows an assemblage of magnetic and non-magnetic units, faulted magnetic rock units and linear magnetic highs. Boundaries to the assemblages were drawn in such a way as to encompass all the anomalies that appeared to be associated in character and spatial distribution.

For the large discrete isolated magnetic anomalies, the boundaries were traced where the edge of the anomaly was estimated to be. For the narrow anomalies the source is represented by only a line.

The high-intensity magnetic anomalies were interpreted to be associated with the Namosi Andesite (Medrausucu Group) and the Colo-Plutonic Suite. It is possible that part of the Colo-Plutonic Suite exists in the offshore high magnetic anomalous zones as well. The extremely high-intensity magnetic responses within the Namosi Andesite are interpreted as representing the Namosi Andesite magnetic signature.

Linear north-west trending magnetic highs are interpreted as faults. The discontinuous nature of the linear magnetic highs may be due to variable destruction of magnetic minerals in the fault plane.

The sub-circular feature at the centre of the project area (labeled A in Figure 3) was interpreted to be associated with a deeply eroded volcanic complex, within which occurs several porphyritic intrusives of diorite and tonalite composition. The subcircular feature labelled B, was interpreted to be the tonalite/trondhjemite pluton (Rodda,1976) of the Colo Plutonic Suite. Several magnetic lows, (Figure 3) corresponds with the distribution of Wainimala and Medrausucu Groups (Waidina Sandstone and Navua Mudstone).

Vertical gradient images

Vertical gradients of magnetic fields represent magnetic fields in which regional effects and interference effects between adjacent anomalies have been suppressed. Therefore, the first vertical derivative images were used to provide optimum resolution of near-surface magnetic contacts.

Several versions of the vertical derivative of the TMI, reduced to the pole images were used for interpretation of the Namosi dataset.

The greyscale image of the first vertical derivative, with no illumination (Figure 4) shows significant structural detail, which is not obvious in the TMI image. Figure 5, shows the greyscale image of first vertical derivative, with a north-east illumination, which has been applied to emphasise north-westerly contacts shown by previous geological work.

Various other sunangles were applied to identify prominent north-west, north-east, north-north-west and east-west trending lineaments.

These lineaments are not visible on the TMI image, as they are associated with magnetic lows. These lineaments are probably faults that are associated with magnetic lows being caused by weathering along the fault planes, which consequently results in magnetic minerals being oxidised to non-magnetic minerals.

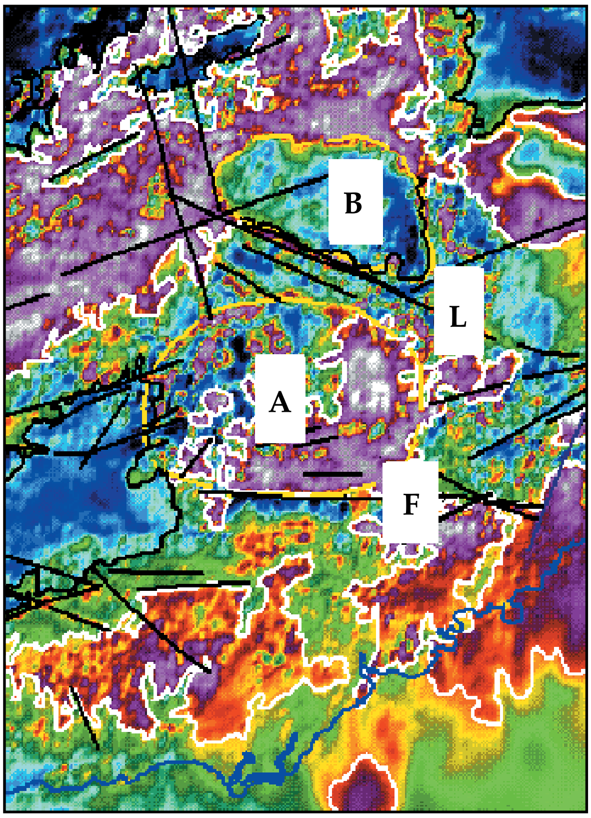

Figure 3. Reduced-to-pole, total magnetic intensity image of the Namosi Area, showing magnetic units (white and red areas) and non magnetic units (blue and green areas), faulted magnetic rock units (F), and linear magnetic highs (L).

Upward-continued images

The process of upward-continuation is useful for suppressing the effects of shallow anomalies when detail on deeper anomalies is required. The upward continued model to 500 m of the total magnetic intensity image (Figure 6) was used to distinguish between magnetic sources of effectively infinite depth and depth-limited sources. The broad magnetic anomalies in Figure 6 could possibly be due to intrusive features that have a significant subsurface extent.

Radiometric images

Different aspects of the gross geology are respectively imaged by different gamma-ray spectrometry images. Lava flows and pyroclastic units have different radioelement responses which allow them to be readily mapped using the radiometric data.

For e.g, the potassium count image (Figure 7) distinguishes most of the major rock units. That is the Colo Plutonic Suite intrusions, Medrausucu Group volcanic rocks and Wainimala Group sedimentary rocks.

The K image highlights high-K (red) and low-K anomalous areas. The high K areas correspond to the evolved, K-rich calc-alkaline magmatic centres. The low K areas correspond to volcanic rocks which have lower K counts due to K leaching.

Furthermore, areas of steep slopes where rapid erosion exposes fresh rock, correspond to high K counts.

Gravity images

Gravity data are commonly used to delineate the position of boundaries at deeper levels than aeromagnetic data can, as they contain contributions from the whole crust/lithosphere.

Gravity data acquired by the Metal Mining Agency of Japan (MMAJ, 1992), over the study area (Figure 8) images the existence of an annular structure near the Namosi porphyry copper deposit.

These gravimetric structures were interpreted by MMAJ (1992) to reflect magmatic intrusions in the area.

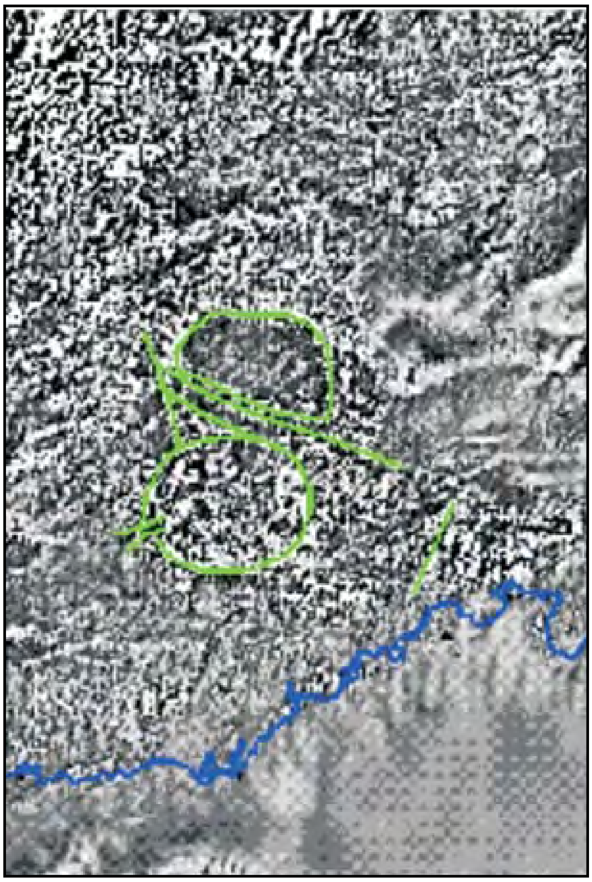

Figure 4. 1VD greyscale image of the Namosi area, showing interpreted structures.

The porphyry copper prospects, however, do not have a distinctive gravitational signature. This is probably due to the limited density contrast between the andesitic country rock and mineralised porphyritic intrusions.

Digital Elevation Models (DEM)

The DEM data set is useful for correlating topography with magnetic and radiometric features, which assisted interpretation. Figure 9 shows a superimposed relative potassium count over DEM. Areas of higher altitude have generally higher potassium contents. Also obvious in this image is a river truncating the interpreted volcanic centre. This image distinctly shows the deeply eroded volcanic complex and a dome-like structure that was interpreted to be the Wainivalau Stock.

GEOPHYSICAL INTERPRETATION MAP

The geophysical interpretation map (Figure 10) is a portrayal of the features identified from the aeromagnetic, radiometric and DEM data in the context of the best available geological control. The interpretation shows two distinct circular morphological features, which can be distinguished clearly in both the magnetic and the radiometric data. These two features show enrichment in all 3 radioactive elements, potassium, uranium and thorium.

The structure in the south has been interpreted to be a deeply eroded volcanic complex. Within this complex are a number of high-intensity magnetic units, interpreted to be intrusive rocks, which possibly represent original volcanic conduits. The ring-like structure to the north of the interpreted volcanic centre correlates well with the Wainivalau Stock (Rodda, 1976), of the Colo Plutonic Suite. Gamma-ray spectrometric data for the Namosi area shows that potassium content is generally high. The most dominant structural features are east-north-east - west-south-west trends predominate with antithetic north-north-west trends.

CONCLUSIONS

On the basis of the geophysical evidence, there is little doubt that the Namosi area is part of a major volcanic event. Although direct evidence of a caldera has been lost by uplift and erosion, the

Figure 5. 1VD greyscale image of the Namosi area, with a north-east sunangle, showing prominent north-west and north-east trending lineaments.

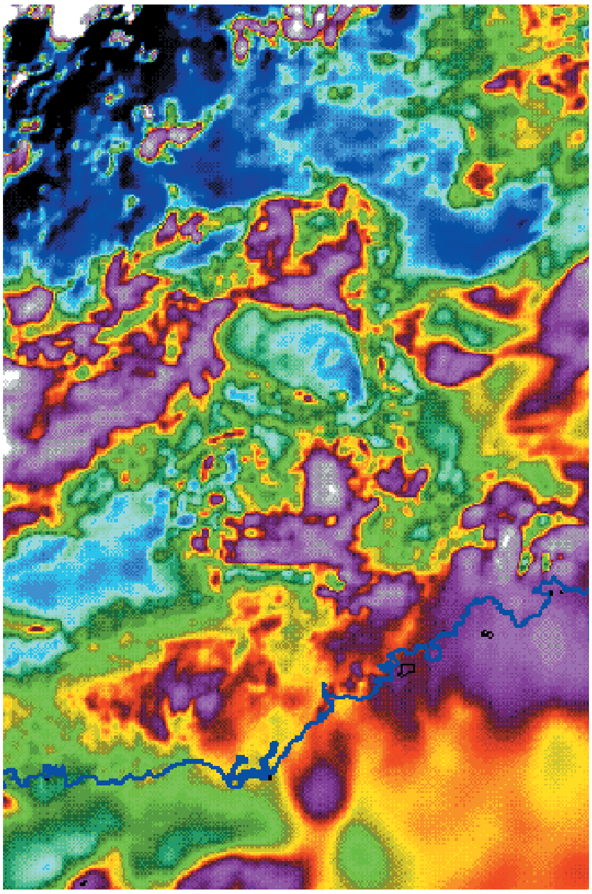

Figure 6. Total magnetic intensity 'continued upwards' to 500 m. Histogram equalised, COMTAL LUT, black low, white high.

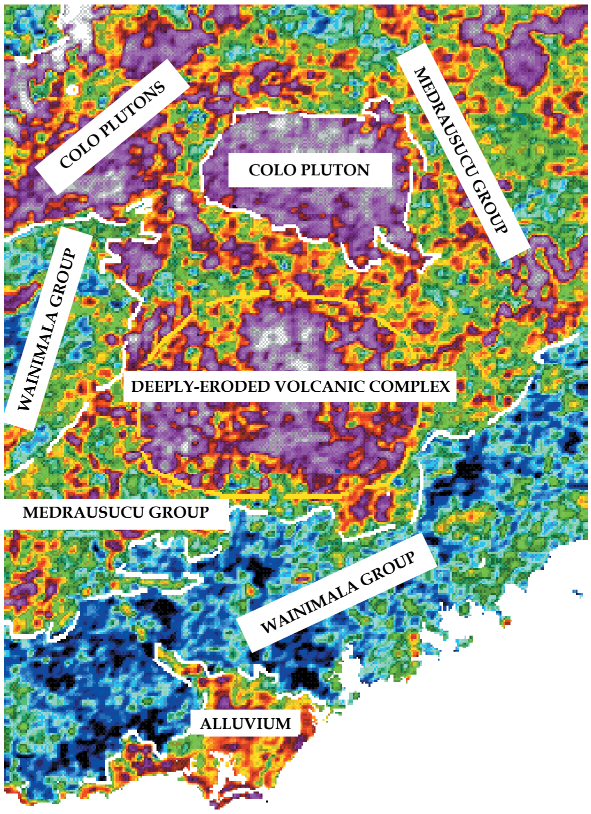

Figure 7. K image of the Namosi area distinguishing major rock units.

geophysical evidence presented here suggests that there is at least one major eruptive centre within the Namosi area.

The predominance of intrusive rather than extrusive lithologies indicates that the current level of exposure is within the root zone of the volcanic complex. The arcuate features have geometries similar to that expected, and indeed observed, in caldera structures in both ancient and modern volcano-plutonic centres.

The porphyry copper deposits, Waivaka, Waisoi and Wainabama are clearly hosted by an eroded stratovolcano sequence. This model is supported by the andesitic volcanic rocks in the Namosi area.

It is probable that volcanic type porphyry copper deposits occur in the Medrausucu Group. On the other hand, the Colo Plutonic Suite hosts plutonic type porphyry mineralisation. Skarn-type deposits formed by contact metamorphic effects between the Colo Plutonic Suite and limestones of the Wainimala Group.

Previously, authors (Colley and Flint, 1995; Ellis, 1996; Rodda, 1976; Royle et al., 1979), have described geological systems which conform to a caldera-type model but no definitive volcanic centre has previously been identified. This is because their descriptions have been largely based on the results of surface mapping which is only able to identify exposed rocks.

The geophysical data made it possible to delineate intrusive bodies beneath the surface, hence providing a more comprehensive picture of the model described above. Furthermore, this interpretation also demonstrates that known porphyry-copper-gold deposits in Fiji are probably genetically linked to magmatic provinces.

The airborne geophysical dataset contains a wealth of geological information. It must be accepted that the interpretations described here are based on subjective judgements, which although based on sound physical and geological principles, may not be correct. The interpretation is nevertheless considered to provide significant new insights into the geology, structure and mineral prospectivity of the Namosi area.

ACKNOWLEDGEMENT

I thank Tariq Rahiman for reviewing this paper and helping to improve the final product.

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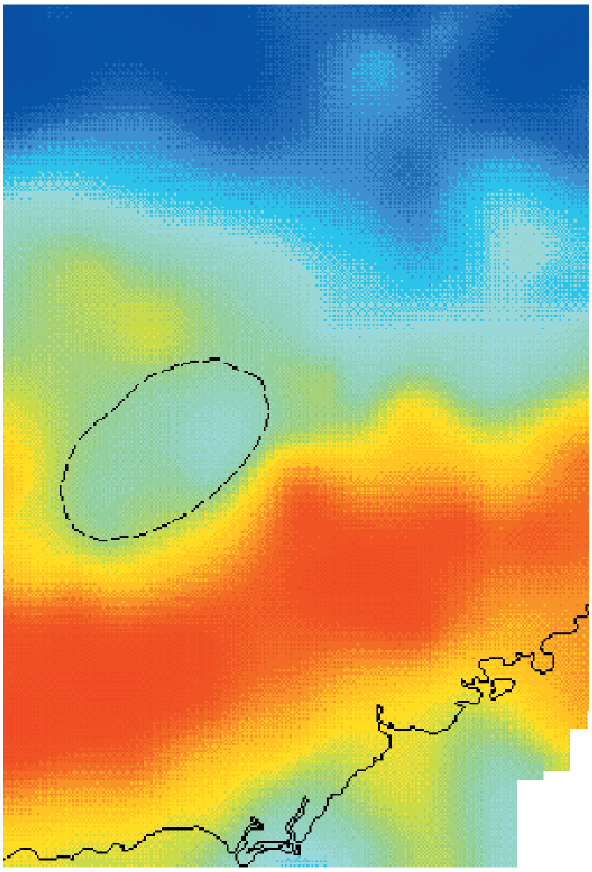

Figure 8. Gravity image of the Namosi area (MMAJ, 1992) showing annular structure which probably corresponds to the centre of the volcanic complex.

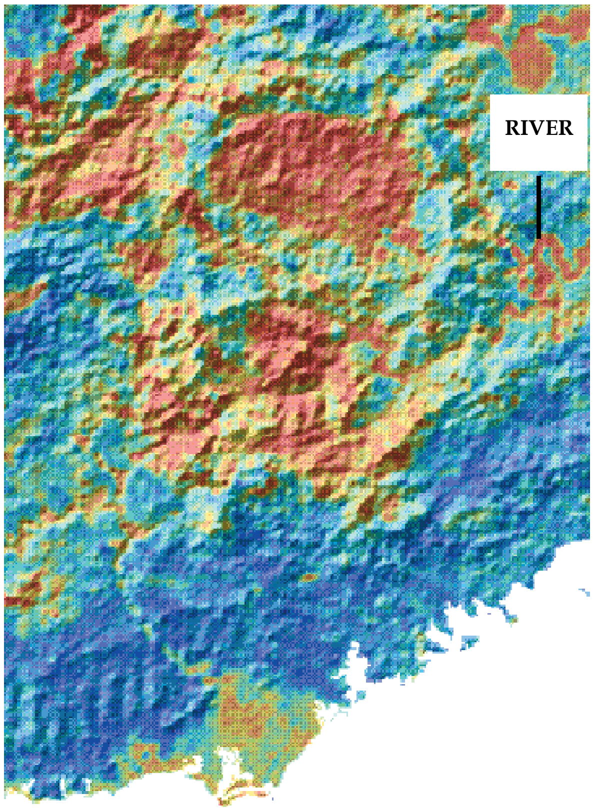

Figure 9. K image of the Namosi area draped over the digital elevation model.

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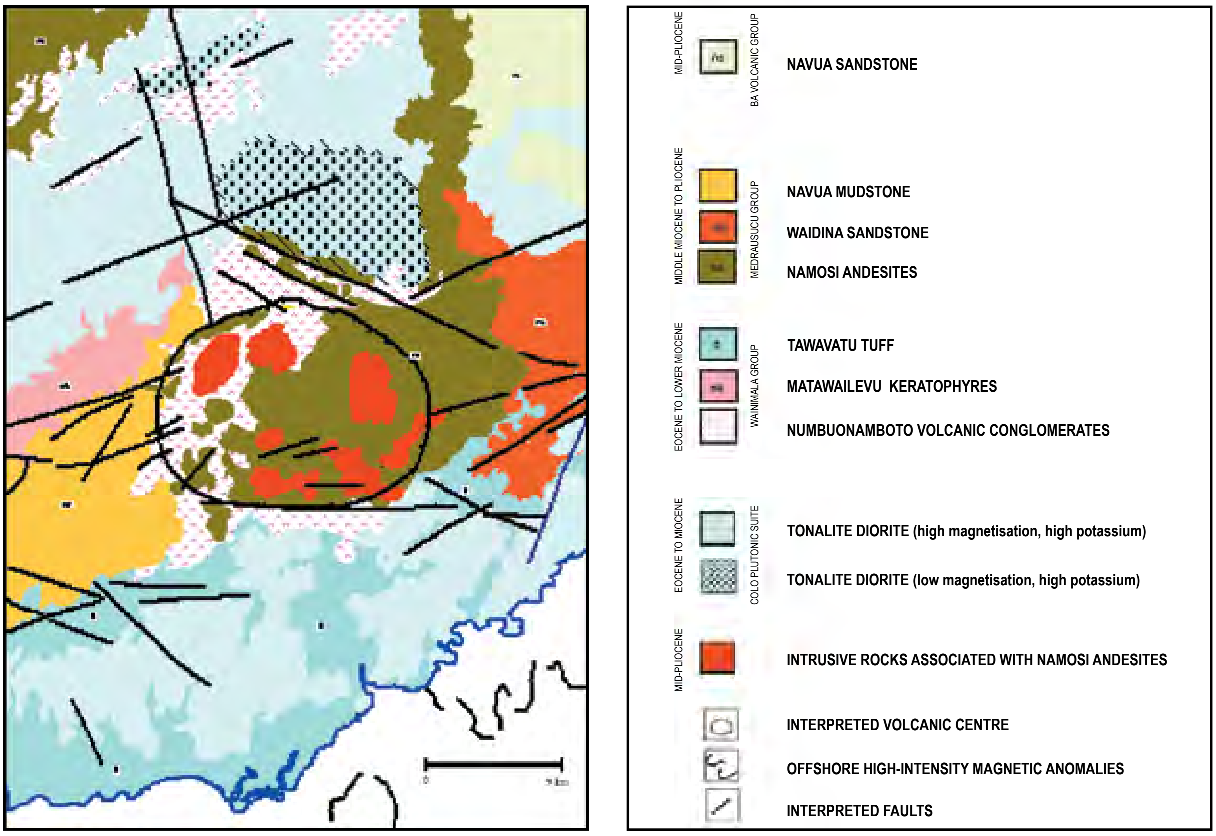

Figure 10. Geophysical interpretation map.

APPLICATION OF TERRAIN MODELLING OF THE SOLOMON ISLANDS, SOUTHWEST PACIFIC, TO THE METALLOGENESIS AND MINERAL EXPLORATION IN COMPOSITE ARC-OCEAN FLOOR TERRAIN COLLAGES

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ABSTRACT

The Solomon Islands are a complex collage of crustal units or terrains (herein termed the 'Solomon Block') which have formed and accreted within an intra-oceanic environment since Cretaceous times. A new subdivision of the Solomon Block into five terrains on the basis of basement lithology and geochemistry, age and respective development (or lack thereof) of younger arc-dominated supracrustal sequences has been recently published by Petterson et al. (in press). The most fundamental terrain division divides Cretaceous-dominated basaltic basement sequences into: 1) a plume-related Ontong Java Plateau terrain (OJPT) which includes Malaita, Ulawa and northern Santa Isabel; 2) a 'normal' ocean-ridge-related south Solomon MORB (mid ocean ridge basalt) terrain (SSMT) which includes Choiseul and Guadalcanal, and; 3) a hybrid 'Makira Terrain' which has both MORB and plume/plateau affinities. The OJPT formed as an integral part of the massive Ontong Java Plateau (OJP), at c. 122 Ma and 90 Ma, was subsequently affected by Eocene Oligocene alkaline and alnoitic magmatism, and was unaffected by subsequent arc development. The SSMT initially formed within a 'normal' ocean ridge environment which produced a MORB-like basaltic basement, through which two stages of arc crustal growth subsequently developed from the Eocene onwards. The Makira terrain records the intermingling of basalts with plume/plateau and MORB affinities from c. 90 Ma to c. 30 Ma, and a contribution from Early Miocene to present day arc growth.

Two distinct stages of arc growth occurred within the Solomon Block: stage 1, from the Eocene to the Early Miocene, and stage 2, from the Late Miocene to the present day. Stage 1 arc growth created the basement of the central part of the Solomon Block (the Central Solomon terrain: CST), which includes the Shortland, Florida and south Santa Isabel islands. Stage 2 arc growth led to crustal growth in the west and south (the New Georgia terrain or NGT) which includes Savo and the New Georgia and Russell islands. Both stages of arc growth also added new material to pre-existing crustal units within other terrains.

The value of modelling the Solomon Block on a 'terrain' model basis is that it allows a geological framework to be established which is set within a modern context and reflects the dynamic tectonic evolution and crustal accretion of the Solomon Islands.

The Southwest Pacific has long been a region which has been affected by oblique collision tectonics which have produced composite transform-convergent tectonic zones (CTCs). CTC zones may be tens to >100 km wide and comprise a complex network of highly fractured crust which is broken into discrete crustal Blocks bounded by boundary (arc) parallel and boundary (arc) normal structures. CTC zones are dominated by strike slip and transpressional tectonics. Individual fault Blocks may be uplifted; undergo subsidence; rotate; or translate. Fault Blocks may form exotic terranes which are translated over tens or

hundreds of kilometres. The CTC fault architecture fundamentally controls the shape and location of phenomena such as pull-apart and strike slip Basins; islands; and volcanoes. The highly fractured nature of CTC zones provides numerous pathways and zones of extension/free space which may tap and channel metal rich fluids and control the final positions of mineral deposits.

A combined application of terrain and CTC-type tectonic modelling has profound implications and applications for metallogenesis from both a generic, predictive, metallogenetic and exploration standpoint, and on a more localised, site- or problem-specific scale.

There are a number of key features of the geo-tectonic model which are particularly relevant to metallogenesis. These are:

The Solomon Block is not a simple arc. It is a collage of arc, ocean plateau and hybrid-ocean floor terrains. It is not therefore appropriate to evaluate the mineral potential of the Solomon Block purely in terms of arc- or ocean-floor-related metallogenetic models.

The geotectonic model defines, more precisely than previous models, which islands belong to which type of terrain. This information is most valuable for and applicable to planning and focusing mineral-exploration Programmes.

The arc terrains can be subdivided into those areas which have grown only during the present period of arc growth and those which formed during an earlier stage of arc development and have been modified by the latest period of arc growth. The older arc terrains have been through at least two major periods of major hydrothermal activity linked to arc growth, and may therefore have an increased potential for mineralisation. Relative uplift within arc terrains influences the likely mode of mineralisation: e.g. epithermal deposits may be expected in the less uplifted and eroded parts of arc terrains (e.g. West Guadalcanal and Gold Ridge) whilst porphyry-copper-type mineralised intrusive bodies and/or mesothermal mineralisation is to be expected in more uplifted regions (e.g. Koloula, south Guadalcanal). The Recent to present-day arc hosts numerous sites of vigorous hydrothermal activity. A combined volcano-structural-mineralisation model for areas dominated by the young arc is invaluable to mineral-exploration Programmes. The Gallego Volcanics of west Guadalcanal is one area where such a model is applicable.

Ocean plateaus can theoretically concentrate platinum-group elements (PGEs): an example of a flood-basalt-related PGE-rich deposit occurs in Noril'sk, northern Siberia. The Ontong Java Plateau (OJP) is the largest ocean plateau in the world, and parts of the OJP have been obducted to produce the islands Malaita, northern Santa Isabel, Ulawa, and part of Makira. The PGE potential of the OJP is, as yet, unknown. The OJP is thick enough to be intruded by alnoite pipes which have potential for garnet, ilmenite, and possibly diamond mineralisation. The structural controls on alnoite intrusion are now well known on Malaita, and the existence of as-yet-undiscovered alnoite pipes is suspected. Furthermore, areas of elevated levels of Ag and Pb concentrations in Malaitan stream sediments which are cover-sediment hosted, and structurally and magmatically controlled have been identified.

Major terrain boundaries within the Solomon Block mark the sites of intra-Block obduction and collision, and can mark the sites of deep-level mafic and ultramafic bodies (e.g. on Santa Isabel), which are known to be associated with elevated levels of Ni and Cr. Similarly, uplifted areas of the present forearc such as in southern Makira and Guadalcanal may expose other deep-level mafic/u-mafic complexes.

METALLOGENESIS IN A COMPOSITE ARC–OCEANIC TERRAIN SUBJECT TO STRIKE-SLIP AND TRANSPRESSIONAL TECTONICS AND OBLIQUE PLATE COLLISION

The objective of this paper is to highlight key aspects of the geology and structure of the Solomon Islands, and to use this evidence to build up a model of intra-oceanic-arc to ocean-floor accretion which has profound implications for metallogenesis and mineral exploration within terrain composites formed in environments similar to the Southwest Pacific. This paper does not aim to give a comprehensive account of the geology and structure of the Solomon Islands readers are referred to papers such as Coleman (1991), Ryan and Coleman (1992), Petterson et al (1997) and Petterson et al (in press) for further details.

The main thesis of this paper is that present-day Solomon Islands is a geological entity which has formed as a result of the accretion of a number of distinct crustal units which themselves originally formed within a variety of geological environments. Plate movements have brought these various crustal units together as an accreted amalgam. Much of this crustal accretion has occurred within oblique plate collisional environments which have resulted in stress partitioning with two orthogonal stress vectors: one parallel to plate boundaries which results in strike-slip tectonics; and one normal to plate boundaries which results in compressional tectonics. The interplay between these orthogonal stress vectors within transpressional tectonic environments has led to such varied tectonic phenomena as: translation of geological terranes (sensu stricto) over tens or hundreds of kilometres; rotation of discrete fault Blocks; formation of intra-arc and intra-oceanic Basins; etc (e.g. Ryan and Coleman, 1992).

The consequences of this dynamic terrain - strike slip accretionary model for Solomon Islands (and similar geological environments) are far reaching for metallogenesis and mineral exploration. For example, it becomes very important to identify which type of terrain you are considering for mineral exploration. A single-minded approach to exploration within young-arc, old-arc, and ocean-plateau terrains may not be the most effective way of locating mineral deposits. Transpressional accretion tectonics provides many structural conduits which allow the ingress of deep-seated magmas and metal-rich brines to surface or near-surface levels. An understanding of this tectonic-structural style will greatly assist theoretical modelling of metallogenesis, constrain expected models for deposit type and style, and focus mineral exploration Programmes, both regional and local. Variable rotations of individual fault Blocks will erode the crust to different levels or bury different parts of the crust under a young sediment fill. Thus within a few tens of kilometres it is theoretically possible to be dealing with young arc terrains dissected to a few hundred metres and exposing epithermal gold deposits, then more highly dissected arc terrains which expose porphyry copper deposits, and then cross a major uplifted crustal Block which exposes mesothermal deposits and/or deep-seated ultramafic bodies which host economic deposits of nickel and chromium.

This paper is structured into three main sections which deal with: 1) the terrain model of Solomon Islands; 2) tectonics at oblique collisional boundaries; and 3) applications of 1) and 2) to metallogenesis and mineral exploration.

Tectonic setting of Solomon Islands

Figure 1 and the inset to Figure 2 summarise the geographical location and tectonic setting of Solomon Islands. The Solomon Islands are situated between longitudes 156° E and 168°E and latitudes 12°S and 7°S, forming part of the present-day Greater Melanesian arc system stretching from Papua New Guinea in the north-west through the Solomons and Vanuatu to Fiji in the east; Greater Melanesia is situated to the north and north-east of Australia.

The bulk of the Solomon Islands land mass forms a double chain of islands. The larger islands are named New Georgia, Choiseul, Santa Isabel, Guadalcanal, Malaita, and Makira (formerly San Cristobal). To the east lie the Santa Cruz islands which form the northern end of the Vanuatuan arc. The Solomon Islands form an upstanding topographic high (the Solomon Block) sandwiched between the north-west - trending north Solomon, or Vityaz trench to the north-east and the New Britain-San Cristobal trenches to the south-west. The Alaska-sized Ontong Java Plateau (OJP) lies to the north of Solomon Islands, with detached parts of the OJP forming the Malaita anticlinorium (which includes the islands Malaita, Ulawa and the bulk of Santa Isabel see below). South of the Solomon Islands are situated the Woodlark, Solomon Sea and Coral Sea ocean Basins and assorted ocean plateaus such as the Louisiade Plateau.

The Solomon Islands are situated at the margins of the Australian and Pacific plates with the Australian plate moving north-eastwards at c. 7 cm/year and the Pacific plate moving north-

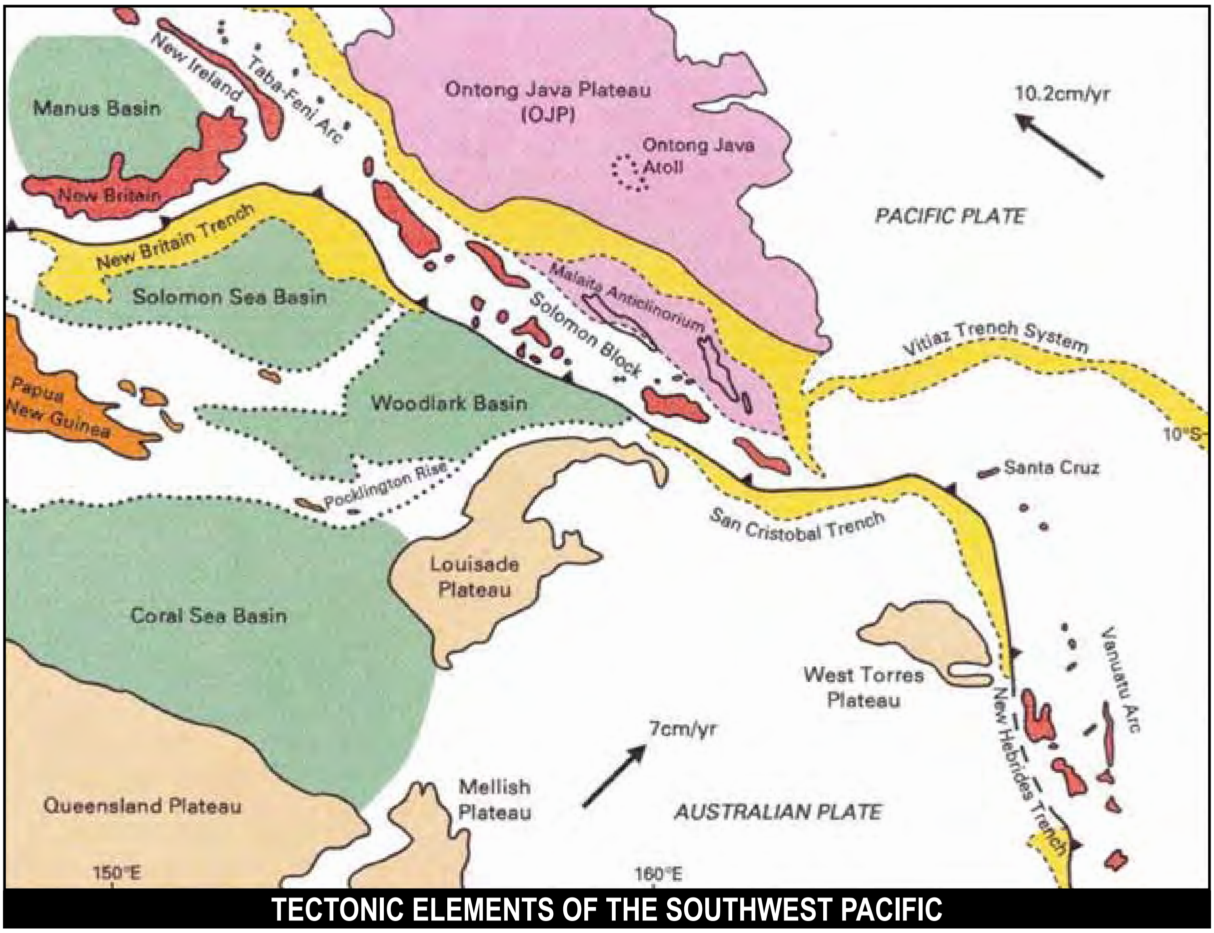

Figure 1. Tectonic elements of the Solomon Islands region of the Southwest Pacific. The Solomon Islands, Bougainville and the Taba-Feni islands define a north-west - trending crustal high, termed the 'Solomon Block', bounded to the north and south by the Vityaz (north Solomon), and New Britain-San Cristobal trench systems. The Alaska-sized Ontong Java Plateau (OJP) is in collsion with the Solomon Block with detached parts of the OJP forming the Malaita anticlinorium. South of the Solomon Islands are a number of oceanic Basins and ocean plateaus. Acknowledgements to Elsevier Publications. Diagram first published in Petterson et al., (in press [a]).

westwards at >10 cm/year (Figure 1). This highly oblique collision results in the Australian plate subducting beneath the Pacific plate forming well-defined Wadati-Benioff zones in the vicinity of the New Britain and San Cristobal trenches. A Benioff zone and ocean trench are much less well defined south of New Georgia, where the young (<5 Ma) Woodlark ocean is presently subducting. The north Solomon or Vityaz trench is thought to be a relic of southward subduction of the Pacific plate beneath the Australian plate from the Eocene to before 8 - 12 Ma (e.g. Kroenke, 1984), which remains active to the present day in a local, intermittent fashion. Details of specific aspects of the tectonics of Solomon Islands are given below. More comprehensive reviews of the tectonic setting are given in Kroenke (1984) and Petterson et al (in press.).

The terrain model for the Solomon Islands

The current terrain model of Petterson (1995) and Petterson et al (in press) is a development of the province model of Coleman (e.g. Coleman, 1966) who first recognised that the present island archipelago of Solomon Islands is not a simple one-terrain geological entity. Coleman originally recognised four discrete 'provinces' which he termed the Pacific, Central, Volcanic, and Atoll provinces. Subsequent systematic geological mapping of the main islands of the Solomon archipelago by the British Geological Survey during the 1970s through to the 1990s, together with newly acquired geochemical and geophysical data pertaining to the islands and their oceanic environs, has enabled Coleman's province model to be re-cast in modern geodynamic terms. It should be noted

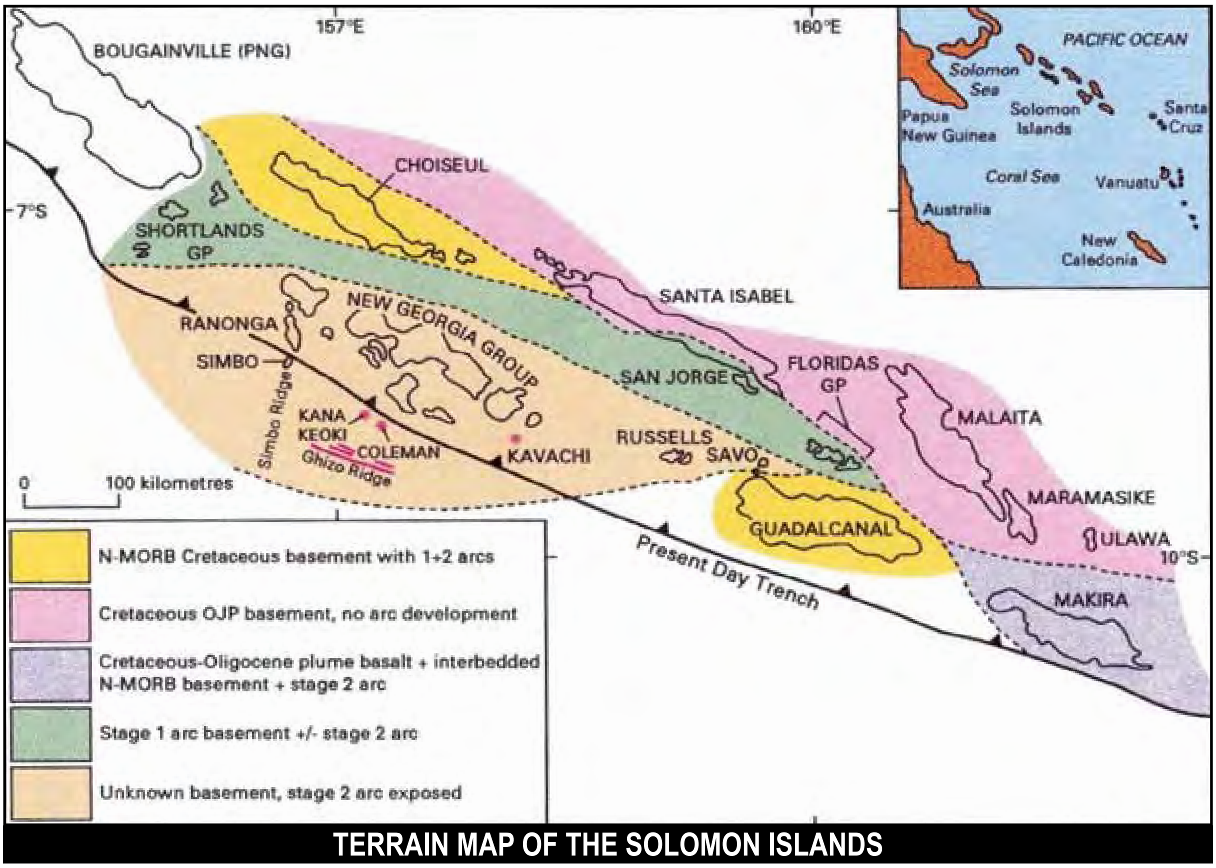

Figure 2. Five distinctive terrains are recognised within Solomon Islands. The Ontong Java Plateau terrain formed mainly during the Cretaceous and is a detached part of the Ontong Java plateau. The islands Choiseul and Guadalcanal form the South Solomon MORB terrain which comprises Cretaceous ocean-basalt basement sequences with additions from both stage 1 (Eocene to early Miocene) and stage 2 (Late Miocene to present) arcs. Makira is a Cretaceous Oligocene oceanic terrain which has been affected by the stage 2 arc. The Shortland and Florida islands and southern Santa Isabel compose the Central Solomon terrain which formed during arc stage 1 and underwent variable development during arc stage 2. The boundary between the Central Solomon and Ontong Java terrains is a true terrane boundary called the Kia-Korighole-Kaipito fault (or KKK). The New Georgia and Russell islands, together with Savo and Kana Keoki-Coleman seamounts and related structures compose the Late Miocene to present day stage 2 arc. Acknowledgements to Elsevier Publications. Diagram first published in Petterson et al., (in press [a]).

that this paper will use both the terms 'terrane' and 'terrain'. 'Terrane' is used in the sense that discrete crustal Blocks with unique geological histories are separated from other distinct 'terranes' by terrane boundaries. The term 'terrain' is used more loosely in the sense that discrete crustal Blocks may have unique characteristics, but may share some things in common with neighbouring terrains. 'Terrain' boundaries may not be (as yet) clearly defined.

The new subdivision of the Solomon Block has been made on the basis of: 1) basement geology; 2) age constraints (radiometric and stratigraphic); 3) geochemistry, in particular the trace element and isotope (where known) composition of basement basalts; and 4) respective development (or lack thereof) of younger arc-dominated supracrustal sequences. Figure 2 summarises the new geo-tectonic subdivision of Solomon Islands; five distinct 'terrains' have been recognised and are briefly described below.

The most fundamental terrain division divides Cretaceous-dominated basaltic basement sequences into: 1) a plume-related Ontong Java Plateau terrain (OJPT) which includes Malaita, Ulawa, and northern Santa Isabel, north of the Kia-Kaipito-Korighole fault (KKK see Figures 2 and 3); 2) a 'normal' ocean-ridge-related South Solomon MORB terrain (SSMT) which includes Choiseul and Guadalcanal; and 3) a hybrid 'Makira Terrain' which has both MORB and plume/plateau affinities.

Ontong Java Plateau Terrain (OJPT)

The OJPT (Figure 2) formed as an integral part of the massive Ontong Java Plateau (OJP), at c. 122 Ma and 90 Ma (Petterson et al., 1997, Neal et al., 1997). The OJP resulted from the surfacing of a large plume head which had originated deep within the Earth's mantle, possibly at the core-

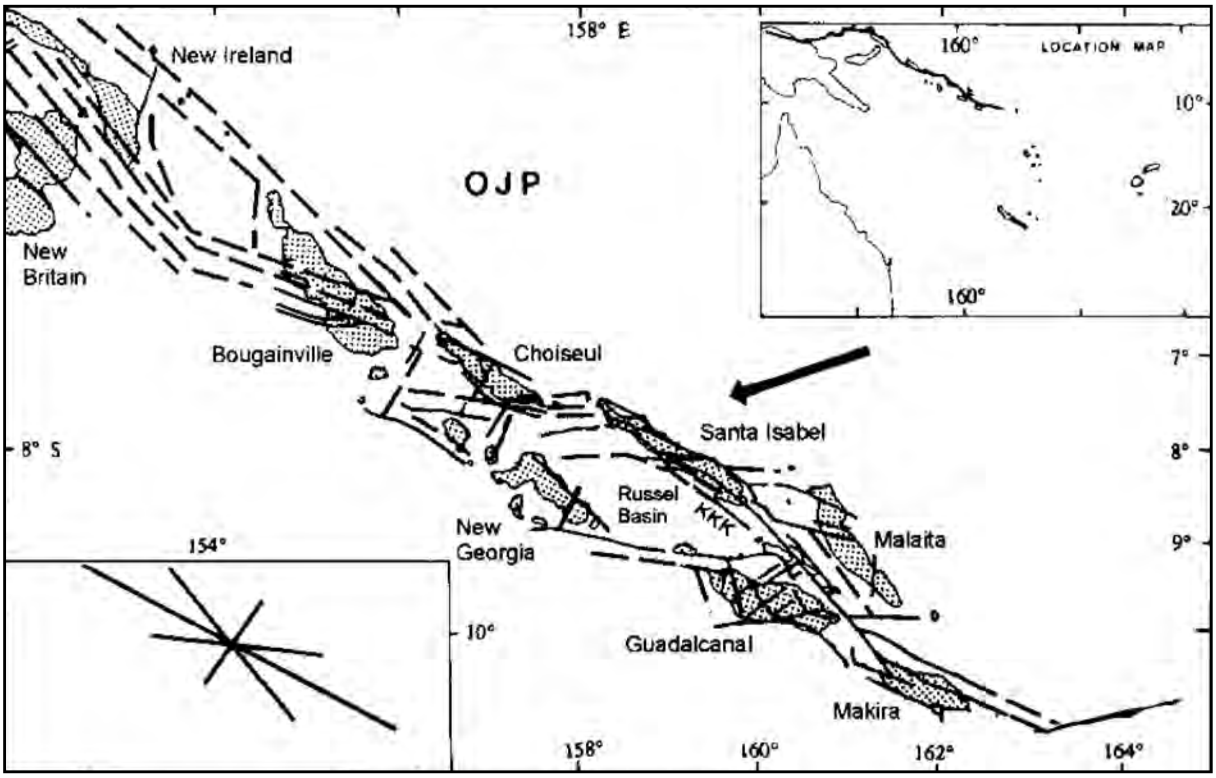

Figure 3. General and simplified fault architecture of the Solomon Islands region illustrating the predominance of faults that are boundary (arc) parallel to sub-parallel and boundary (arc) normal. This basic fault architecture governs the shape of individual islands, the locations of magmatism, the position of pull-apart and strike-slip sedimentary Basin; and Mineralisation. See text for details. Acknowledgements to Elsevier Publications; diagram originally published in Coleman (1991).

Key: KKK – Kia-Korighole-Kaipito fault system; large arrow - Pacific/Australian plate-convergence vector; NB - New Britain; NI - New Ireland; B - Bougainville; C - Choiseul; NG - New Georgia; S - Shortland Basin; SI - Santa Isabel; R - Russell Basin; G - Guadalcanal; M - Malaita; SC - San Cristobal (Makira); OJP - Ontong Java Plateau. Lower inset: relative proportions of major fault trends.

mantle boundary. The Cretaceous plume caused large-scale, high-volume mantle melting and the eruption of immense volumes of basalt magma over a relatively short period of time. Since its formation the OJP has passively drifted as part of the Pacific plate until its collision with the Solomon Block. Thus it is important to understand that the OJPT is *not* an arc sequence in any shape or form, although it is spatially associated with crustal units which are dominated by arc sequences. The OJPT comprises an ocean crustal sequence of plume-related basalts and related basic intrusive rocks with overlying deep-sea pelagic limestone and chert sediments. The OJP has been affected by periods of extension, particularly since the Eocene, possibly as a consequence of the OJP overriding hotspot plumes (such as the Raratongan or Samoan hot spot) which have resulted in alkaline and alnoitic magmatism during the Eocene and Oligocene respectively, and increased sedimentation within localised Basins. The OJPT has been unaffected by subsequent arc development. For further details, see Petterson et al (1997).

The OJP began colliding with the Solomon Block around 20 - 25 Ma, but only began to forcefully collide at around 4 Ma. The main compressional to transpressional event occurred between 4 and 2 Ma and resulted in the accretion of the OJPT with the Solomon terrain collage. The accretion process occurred through the delamination of an upper crustal flake of the OJP which was thrust towards the north-east, with increased coupling between the OJP and the Solomon Islands causing the Solomon arc to overthrust the OJP. The surface expression of this bounding fault between the OJPT and the rest of the Solomon Block crops out on Santa Isabel as the Kia-Kaipito-Korighole Fault (KKK see Figures 2 and 3), which is a true terrane boundary and is a major arc-parallel strike-slip structure (see section below). Between the north Solomon trench and the KKK is the Malaita anticlinorium (or the OJPT see Figures 1 and 2) which rises above sea level to form the islands Malaita, Maramasike and Ulawa, and the bulk of Santa Isabel, and represents obducted and accreted Ontong Java Plateau. The OJP is probably still accreting with the Solomon Block, with the region of active accretion presently located north of Choiseul (P. Mann, pers. comm.).

South Solomon MORB Terrain (SSMT)

The South Solomon MORB terrain (SSMT) comprises the islands Guadalcanal and Choiseul (Figure 2). The SSMT initially formed within a 'normal' ocean-ridge environment which produced a MORB like basaltic basement through which two stages of arc crustal growth subsequently developed from the Eocene onwards (see below). Cretaceous basement sequences on both Choiseul and Guadalcanal are dominated by basalts with a trace element geochemical composition typical of 'normal' mid-ocean-ridge basalts (Petterson et al., in press). As well as basaltic lavas the basement sequences include basic dykes, sills, and gabbros, pelagic limestones and cherts and ultramafic bodies. Thus the basement geology of the SSMT reflects a non-arc oceanic origin. However, unlike the OJPT the SSMT, basement geology was subsequently modified by two periods of arc growth which have produced sequences dominated by basic andesite to rhyolite volcanic and inrusive rocks, large volumes of volcaniclastic-rich sediments such as turbidites, and interbedded limestones.

Makira Terrain

The Makira terrain (Figure 2) records the intermingling of basalts with plume/plateau and MORB affinities aged between c. 90 Ma and c. 30 Ma, and a contribution from Upper Miocene to present-day arc growth. Trace-element compositions of interbedded basalts from Makira are bi-modal in their composition with about one third of analysed samples having MORB-like affinities and the remaining two-thirds having compositions identical to OJP lavas (Petterson et al., in press). Unpublished Ar-Ar ages of Makiran basalts have yielded ages of 98 - 90 Ma, 63 Ma, and 33 - 35 Ma (R. A. Duncan, unpublished data). Makira is subdivisible into a basement complex (which composes around 90% of the island) dominated by basalts, dolerites, basic dykes, gabbros, and ultramafic sheets with local sediments such as limestones, cherts, sandstones, and basalt breccias; and a cover sequence which consists of sandstones, basalt breccias, basalts, and arc related dacite dykes, together with raised-beach, coralline and mangrove-swamp deposits. The arc-related dacite dykes are most likely related to the present stage of arc activity, although they have not been dated. Makira is a highly dissected and uplifted composite oceanic-arc terrain. Readers are referred to Petterson et al. (in press (b)) for further details.

The Central Solomon Terrain (CST)

The Central Solomon Terrain (CST) includes the islands Santa Isabel (south of the KKK), the Shortland Islands and the Florida Islands (see Figure 2). This terrain formed originally from the Eocene onwards and includes contributions from both stages of Solomon arc growth (see below). Basement sequences are arc-like, oceanic, and ophiolitic in character and dominated by arc basalts, basic dykes, gabbros, ultrabasic rocks, and more evolved andesitic-dacitic rocks. The present-day stage of arc growth has added to parts of the CST; for example the Mboli beds of the Florida islands are a sequence of? Late Oligocene to Pliocene crystal-rich turbiditic sediments and andesitic lavas (Taylor et al., 1977). Readers are referred to Neef and Plimer (1979) and Plimer and Neef (1980) for further details.

The New Georgia Terrain (NGT)

The New Georgia Terrain (NGT) includes the islands of the New Georgia Group, together with the Russell Islands, Savo, and submarine calc alkaline volcanoes such as the Coleman and Kana Keoki seamounts, Kavachi, and the Ghizo and Simbo ridges south of the main New Georgia island group (Figure 2). These islands have no known old basement and have formed during the present stage of arc growth. The NGT is dominated by arc volcanic rocks which range in composition from relatively primitive high-Mg picrites to calc-alkaline basalts, andesites and dacites. Arc volcanic rocks are extruded as lavas and pyroclastic flow and fall deposits, with co-volcanic intrusive dykes, stocks, and plutons. Associated with the crystalline extrusive and intrusive arc rocks are reworked crystal-rich sediments. Readers are directed to Dunkley (1986) for further details of the geology of the NGT.

The subduction of young (<5 Ma), hot, oceanic lithosphere belonging to the Woodlark Basin at the SSTS is another tectonic feature which has influenced the development of the Solomon Block, particularly the NGT. Woodlark Basin subduction has resulted in a sequence of tectonic phenomena including: the production of unusual magma compositions (e.g. `Na-Ti rich basalts, and an abundance of picrites); an anomalously small arc trench gap between the New Britain and San Cristobal trenches and the Quaternary Recent arc front; calc-alkaline arc growth within the downgoing Woodlark Basin lithospheric plate as a consequence of calc-alkaline magma transfer along leaky north-east - trending faults; rapid fore-arc uplift; and rapid infilling of intra-arc Basins, (e.g. Crook and Taylor, 1994).

Two Stages of Arc Growth: 1) Eocene to Lower Miocene, and 2) Late Miocene to present

Two distinct stages of arc growth occurred within the Solomon Block, from the Eocene to the Early Miocene (stage 1) and the Late Miocene to the present day (stage 2). These stages of arc growth have made contributions to all Solomon terrains with the exception of the OJPT. Stage 1 arc growth created the basement of the Central Solomon Terrain, and made contributions to the pre-existing oceanic basement of the South Solomon MORB terrain. Stage 2 arc processes generated the young, juvenile New Georgia Terrain and have made contributions to the SSMT, CST and Makira terrains. The first stage of arc development is linked to south-directed subduction at the Vityaz/North Solomon trench (e.g. Kroenke, 1984). The present-day, second stage of arc growth is genetically associated with north-directed subduction at the New Britain/San Cristobal trenches, which possibly began as late as 8 Ma in the Solomon Islands region (Petterson et al., in press (a)).

Geological Evolution of Solomon Islands

The new terrain model of Petterson et al. (in press (a)) enables a dynamic interpretation of the development of the Solomon Islands terrain collage. The main conclusions of the terrain model are as follows. 1) five distinctive terrains have been identified based on a wide range of criteria and evidence. 2) These terrains all have unique geological histories and stages of development. 3) Some terrains (e.g. the OJPT) record entirely oceanic events and have been totally unaffected by arc growth in the Southwest Pacific. 4) Some terrains (e.g. the NGT) are entirely arc-like in character. 5) Three of the Solomon terrains (the SSMT, CST, and Makira Terrain) have a hybrid, composite and complex history, which in simple terms has involved an early period of oceanic basaltic development followed by arc crustal additions. 6) Terrain boundaries are as yet poorly defined, with the exception of the KKK which is a true terrane boundary separating the Cretaceous oceanic Ontong Java Plateau terrain from the arc-like Eocene and younger Central Solomon terrain. The KKK has a surface expression on Santa Isabel (Figures 2 and 3) and has also been defined by seismic surveys in the offshore environment (Coleman, 1991 see Figure 3): for example the trace of the KKK extends to immediately north of the Florida Islands. 7) Terrains such as the SSMT which may once have formed continuous crustal units are now separated by other terrains (for the SSMT, the CST), indicating that significant strike-slip crustal movements have taken place. 8) The subduction of the young and relatively hot and buoyant Woodlark Basin has had a profound influence on the development of the Solomon terrrain collage. 9) The present-day Solomon Islands represents the amalgamation of crustal Blocks formed in ocean-plateau, ocean-ridge and island-arc environments.

Tectonics at Oblique Convergent-Transform-Composite (CTC) Plate Margins

Convergent-Transform-Composite (CTC) plate margins (Figure 4) are defined by Coleman (1991) and Ryan and Coleman (1992) as zones of accommodation, tens to >100 km wide, which border highly oblique convergent plate margins, comprise a large number of discrete fault Blocks which jostle, rotate, and translate (possibly for tens to hundreds of kilometres), and are strongly affected by strike-slip, transpressional, and trans-tensional tectonic forces. Examples of CTC zones include the Melanesian boundary from Tonga to Helmaheras, the Aleutian Islands plate boundary, and the Philippine Fault System.

CTC zones are strongly affected by strike slip faults and transpression in other words fault and fold-forming tectonic processes are partitioned into vectors which are parallel to the plate boundary (are arc-parallel) and those which are orthogonal to the plate boundary (are arc-normal). Factors such as the angle of subduction, the nature and thickness of the overriding plate, and the rate and obliquity of convergence, are all important factors in controlling the tectonics related to a specific locality. CTC zones are dominated by strike-slip fault movements and can contain a high density of closely spaced strike-slip faults.

Figure 4 illustrates the main aspects of a hypothetical CTC zone. The plan view of a CTC zone illustrates the general setting showing a sinuous plate boundary with a variable amount of oblique convergence (increasing from west to east). Simple shear-dominated tectonics breaks up the crust in the overriding plate into a series of discrete fault Blocks which are translated sinistrally in a

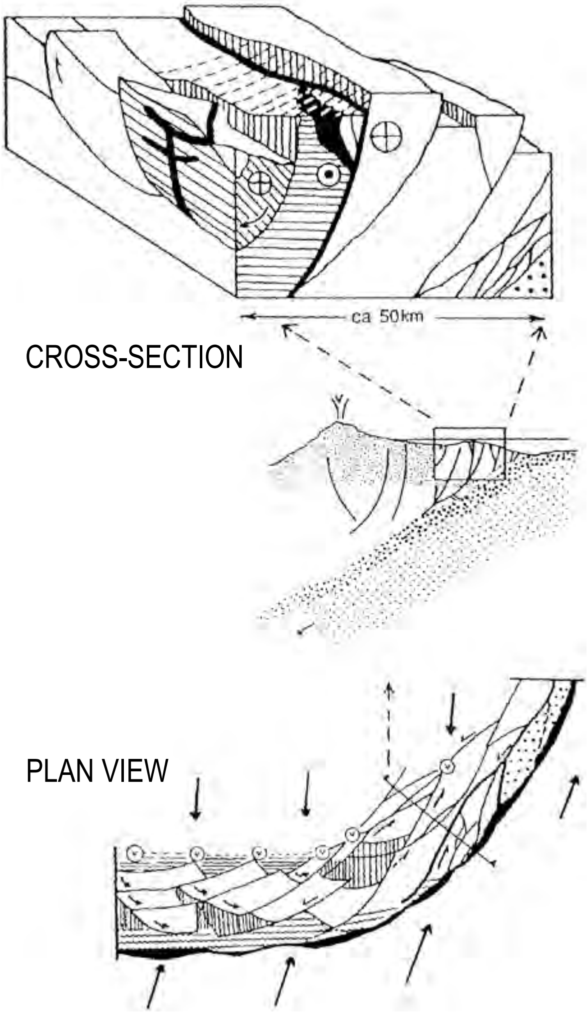

Figure 4. Cartoon of convergence with arc build-up and increasingly oblique angle of attack. The trench is in sinuous black; encircled **v** *is a volcano. Bottom: plan view shows rotation, shearing and Blocks with increased strike-slip fracturing as obliquity increases. Horizontal lines suggest summit or inner forearc Basins, vertical lines Basins of the pull-apart type, wavey lines near the trench are elements of the accretionary prism. The heavy line suggests the current master fault system. Individual Blocks may be carried along the transform complex outboard of the master fault, for example, dotted Block. Heavy bar is the approximate line of the section above: this is a profile of the arc with deep strike-slip fracturing - part is enlarged as the Block diagram. These profiles stress the undulations in the fracture surfaces both in plan and in profile. Relative motion on these surfaces produces vertical and horizontal movement of Blocks and also rotation and tilting. Transtensional and transpressional situations arise along fractures and provide 'plumbing' for diapiric convective hydrothermal systems with caps enriched in metals. These caps can be concealed by debris from a ramped Block (centre) or tilted to give a misleading outcrop pattern (left) or even removed from the root stock.*

conveyor-belt fashion. Fault Blocks are rotated and sheared as well as translated. The cross-section across the CTC zone depicts relative rotation of discrete fault Blocks, opening of listric faults, the fracturing of the overriding plate and the formation of pull-apart sedimentary Basins.

This CTC zone style of tectonics results in a highly fractured and allochthonous crustal structure. The fault Blocks may break up geological outcrop patterns, making it difficult to make sense of mapping data on a regional scale. Variable fault rotation, uplift and subsidence may result in the creation of a series of grabens and horst Blocks, with a highly variably dissected terrain: for example some Blocks may be uplifted and erode to mid-crustal levels, whilst others may subside and be buried under ore by younger sediments. Originally coherent autochthonous arc terranes may be split and disrupted, with exotic terranes being allochthonously accreted to the disrupted arc.

Fault formation and Block rotation can create local extensional pull-apart structures which act as conduits to mid- and lower-crustal, and possibly even mantle depths. These conduits can channel magma migration and related hydrothermal fluids and control the loci and structural position of plutons, volcanoes, and mineral deposits. Fault patterns can be complex with braided and/or anastamosing geometries, and sudden changes in fault trends producing extensional re-entrant structures: such geometries can create a large number of intersecting structural nodes and conduits, and a high density of fractures. The most active 'master fault systems' change with time as local tectonic conditions change the large number of boundary-parallel and boundary-normal faults allows tectonic stress to be activated as required on a number of different fault systems. Individual fault systems may be highly active for only certain periods of time, and remain dormant at other times. Rhombohedral pull-apart and strike-slip sedimentary Basins are common and can contain thick, intra-Basin sediment fills. Sedimentation rates can be rapid as Blocks are uplifted and eroded within the local environment.

Examples of CTC zone tectonics in the Solomon Islands

The Solomon Islands has been very strongly influenced by oblique collisional tectonism for at least the past 8 - 10 Ma and probably for a much greater period, possibly extending back to the first known collisional event during the Eocene.

Regional fault geometries

Figure 3 illustrates some of the key regional structures known in the Solomon Islands region. The major faults exhibit a linear to arcuate geometry with predominant north-west and north-east trends. Subsidiary fault trends include north-north-west and east-south-east. The most important known fault system is the Kia-Korighole-Kaipito (KKK) fault system which is broadly an arc/boundary-parallel structure although it has a somewhat complex and sinuous geometry in detail. The larger fault structures are parallel to the KKK. Much shorter faults are either normal or subtend a high angle to the arc/plate boundary, and cross-cut many of the islands. These shorter arc-normal faults appear to have strong controls on the location of disparate geological phenomena, for example volcanoes and mineral deposits (see below for further details). As a fault network, the arc-parallel and arc-normal structures have determined the geometric architecture of Solomon Islands across a spectrum of scales. For example, the actual shapes of the larger islands are strongly influenced by the fault geometry, with the island long axes paralleling the arc-parallel faults and the short axes (western and eastern island coastlines) paralleling the arc-normal faults. Similarly, Figure 5 shows the location of the main intra-island submarine Basins of the Solomon Block (e.g. Iron Bottom Sound Basin, Indispensable Basin, Russell Basin). Basin geometries strongly reflect the gross controlling fault architecture with long axes and short axes paralleling the arc-parallel and arc-normal structures respectively. Many of the Basins are rhombohedral trans-tensional pull-apart, and/or strike-slip Basins (e.g. Auzende et al. 1994). Finally, it is also likely that the bounding faults between the terrains of Figure 2, as well as other, as yet unrecognised terrain boundaries, will be compatible with the gross fault geometry of the Solomon Block.

Island Structural Geometries

Figures 6, 7, and 8 illustrate the key fault trends for the islands Makira, Malaita, and New Georgia respectively. These data have been obtained from recent geological surveys of the islands (Dunkley, 1986, Petterson et al., 1997, Petterson et al., in press [b]).

A remarkable pattern emerges of fault geometries (and fold geometries for Malaita and Makira) which closely reflect the large-scale fault geometry of the Solomon Block. On a more local scale, specific island fault architectures reflect their respective positions within the Solomon Block, indicating that local tectonic factors are important in addition

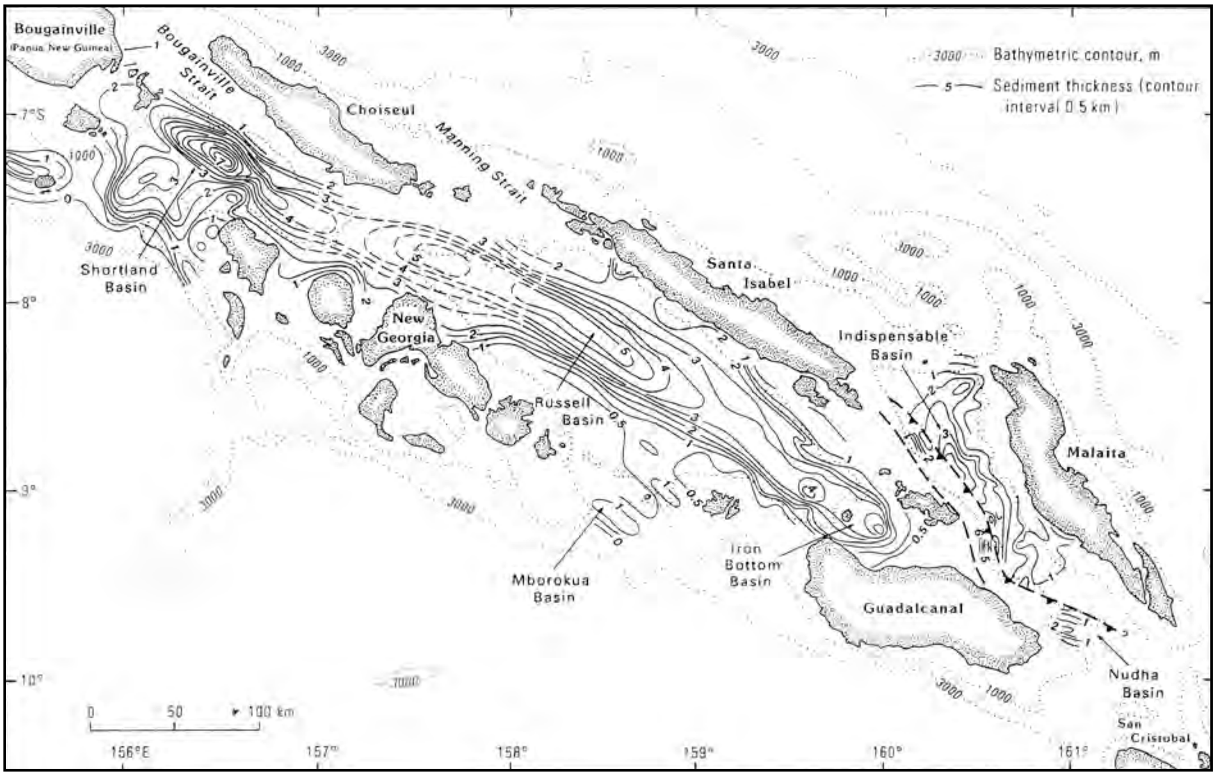

Figure 5. Main intra-Solomon Block pull-apart and strike-slip sedimentary Basins. Acknowledgements to Ministry of Natural Resources, Solomon Islands. Figure originally published in Coleman (1989).

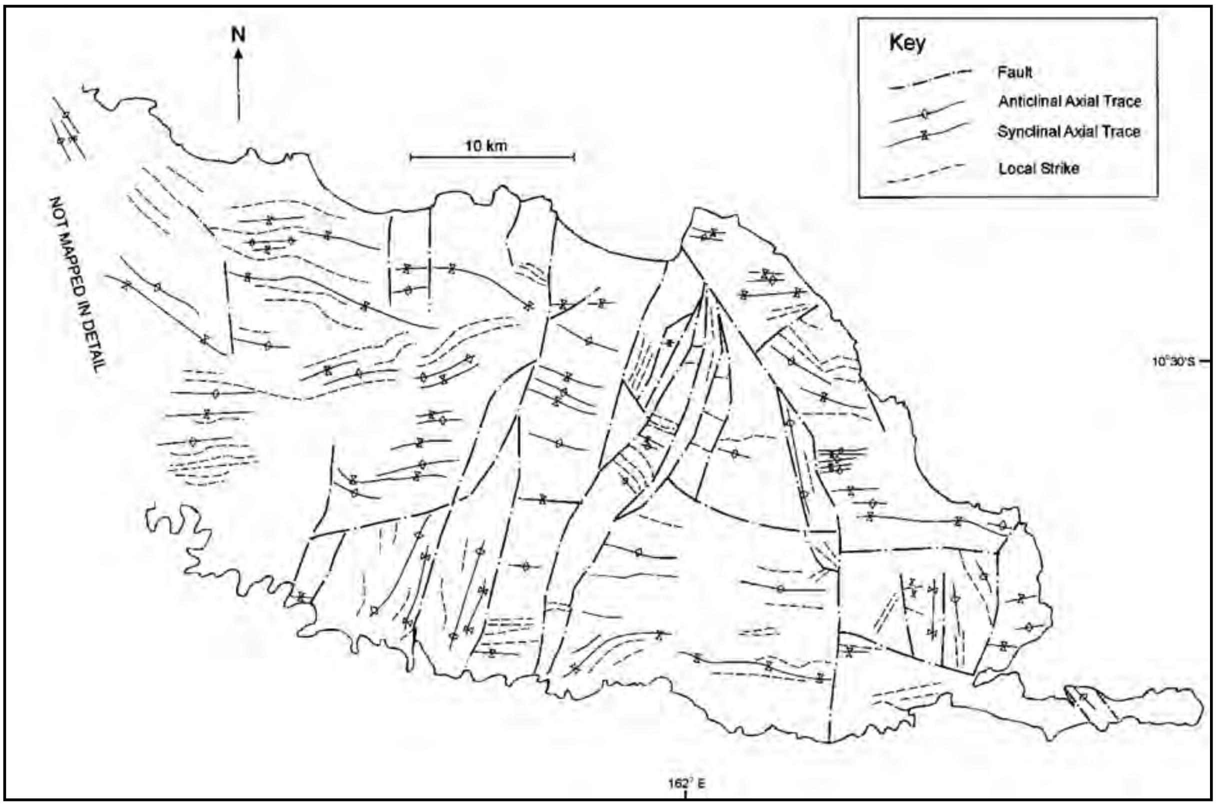

Figure 6. Key structural architecture of Makira (San Cristobal). Island-wide structures are dominated by east-west arc-parallel and north-south arc-normal faults and fold traces. See text for further details. Acknowledgements SOPAC. Diagram originally published in Petterson et al (in press [b]).

to the gross tectonic controls. For example, New Georgia is situated adjacent to a strongly oriented north-west - south-east plate boundary and is most strongly affected by arc-parallel north-west - trending faults (Figure 8). However north-east - trending arc-normal faults exert strong controls on the actual shape of island coastlines and the loci of individual volcanoes. Quaternary volcano edifice collapse is strongly controlled by arc-normal and arc-parallel structures (P. Dunkley, pers. comm.). Makira is situated at a re-entrant in the San Cristobal trench whose trend changes from north-west to more west. Figure 6 demonstrates that fault and axial-trace trends on Makira are predominantly east-west to east-north-east - south-south-west and north - south to north-north-east - south-south-west, reflecting the changing obliquity of the Melanesian plate boundary in this area. Finally, Malaita is affected by three main structural trends: arc-normal faults trending north-east, arc-parallel north-west - south-east folds and faults, and more east-trending faults. The Malaitan structures reflect a 4 - 2 Ma transpressive event which resulted in north-east - south-west compression and fold axes with north-west trends. The transpressive to strike-slip nature of this event also produced structures which were discordant to the predominant structural grain and are more east in their trends (Petterson et al., 1997).

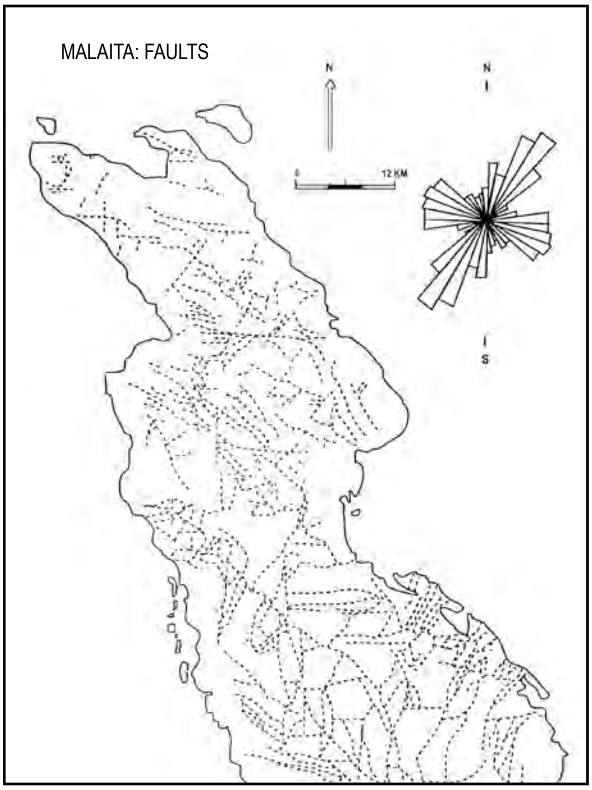

Figure 7. Fault patterns on Malaita illustrating predominant north-east; and east trends. See text for details. Acknowledgements to Elsevier Publications. Figure originally published in Petterson et al.,. (1997).

Thus the conclusion of both a whole-Solomon-Block structural analysis, and an individual island structural analysis, is that the Solomon Islands' geological development has been very strongly influenced by oblique, convergent-transform-collisional zone tectonics. Strike-slip and transpressional deformation styles have predominated and produced a highly fractured and heterogeneous crustal accretionary Block. Structural controls can be demonsstrated at all scales. Metallogenic modellers and mineral explorationists ignore the basic geological and structural template at their peril. In the section below we will explore some examples of how the principles described in the sections above can be applied with an economic geology standpoint.

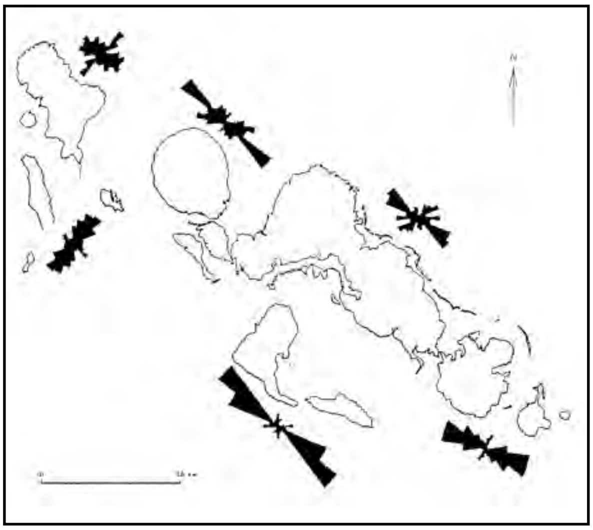

Figure 8. Fracture patterns in the New Georgia Group showing predominant north-west and north-east fracture trends. See text for details. Acknowledgements British Geological Survey. Figure first published in Dunkley (1986).

APPLICATION OF TERRAIN AND OBLIQUE-COLLISIONAL TECTONIC MODELS TO METALLOGENESIS AND MINERAL EXPLORATION

Recognise your terrain

The most fundamental application of the terrain model is to be aware of the complex nature of crustal Blocks which owe their genesis to tectonic environments found in the Southwest Pacific. Thus a particular Block of land which an individual company may hold for an exploration licence may well stretch across a number of terrains, depending on the size of the licence area and the scale of individual crustal subunits within a terrain collage. Some groundwork must be done regarding recognition of terrains and terrain boundaries, as these are fundamental controls on the location of mineral deposits. Each terrain then needs to be characterised e.g. is the terrain predominantly an arc or continental or cratonic or ocean-plateau terrain ...etc?

To each terrain its own strategy

Once terrains have been identified and boundaries delimited, appropriate mineral-exploration (or metallogenetic-modelling) strategies must be employed. For example, in the case of Solomon Islands the Ontong Java Plateau terrain (OJPT) would not be the best place to look for porphyry-copper deposits, or the New Georgia terrain for diamonds. However the OJPT could possibly be the place where diamondiferous alnoite pipes may occur, or there may be zones of platinum-group-element enrichment related to the large-scale basaltic outpourings which generated the OJPT. Similarly, parts of the South Solomon MORB terrain (SSMT) have been through two cycles of arc development and have had two phases of fluid infiltration and vigorous hydrothermal activity theoretically these could be the best places to look for epithermal, or porphyry-copper, or volcanic hosted mineralisation.

Once the theoretical potential of mineralisation styles and the initial mineral target evaluation for each terrain have been assessed, appropriate exploration strategies must be employed. These strategies will depend on climate, vegetation cover, access and rock exposure, as well as more theoretical factors.

Exploration expectation psychology

A properly and appropriately evaluated exploration programme which has been designed in the full cognisance of the implications of terrain tectonics will have a significant effect on the expectation psychology. Many exploration Programmes are terminated prematurely because of fundamental misunderstandings of the local geology and structure, and/or because they have been poorly designed. For example, in past years exploration companies may have gone into the Solomon Islands with a 'single model mentality' i.e. that the Solomon Islands is an island arc and nothing else. This misguided psychology results in inappropriate exploration strategies and possibly even the search for non-existent mineral targets. This approach can often lead to early disillusionment and the premature termination of an exploration programme. We suggest that mineral exploration accompanies adopt the opposite expectation psychology i.e. that they do their homework, evaluate the complexity of the terrain collage, and target accordingly. If this approach is adopted, any subsequent exploration data can be slotted into an already developed exploration model which will be constantly refined with new data. Gross differences in exploration results across the terrane collage can be more easily understood, and promising mineralisation areas can be more easily defined.

STRUCTURAL CONTROLS ON THE LOCATION OF MAGMATISM AND MAGMATISM-RELATED MINERALISATION

Perhaps the most readily demonstrable application of the combined terrain/CTC-zone tectonic model is in explaining the distribution of arc volcanoes and magmatic centres in Solomon Islands. There are no arc volcanoes or related arc rocks on northern Santa Isabel or Malaita for example, because these are a detached part of the Ontong Java plateau.

The distribution of Miocene - Recent arc volcanoes within the New Georgia terrain can readily be explained by reference to Figure 9. Figure 9 is taken from Crook and Taylor (1994) and illustrates the structure of the Woodlark Basin and the location of Miocene - Recent volcanoes in New Georgia, Choiseul, the Russell Islands, Savo, and Guadalcanal. Magnetic anomalies within the Woodlark Basin are off-set by north-south transform faults: this fault system geometry is superimposed on the usual arc parallel and arc-normal trends. Volcanic centres north of the trench lie along north-west - south-east and north-east - south-west axes. For example the long axis of the New Georgia island chain parallels the trench, whilst the volcanic lines through Vella Lavella to Choiseul, through Vangunu, through Kavachi and Nggatokae, and through west Guadalcanal to Savo all trend north-east to north-north-east. South of the trench, volcanic lines are also sub-parallel to the trench (i.e. the Kana Keoki - Coleman seamounts and the Ghizo ridge), whilst others are more north - south (such as the Simbo ridge). Thus all major volcanic lines and trends are readily explainable

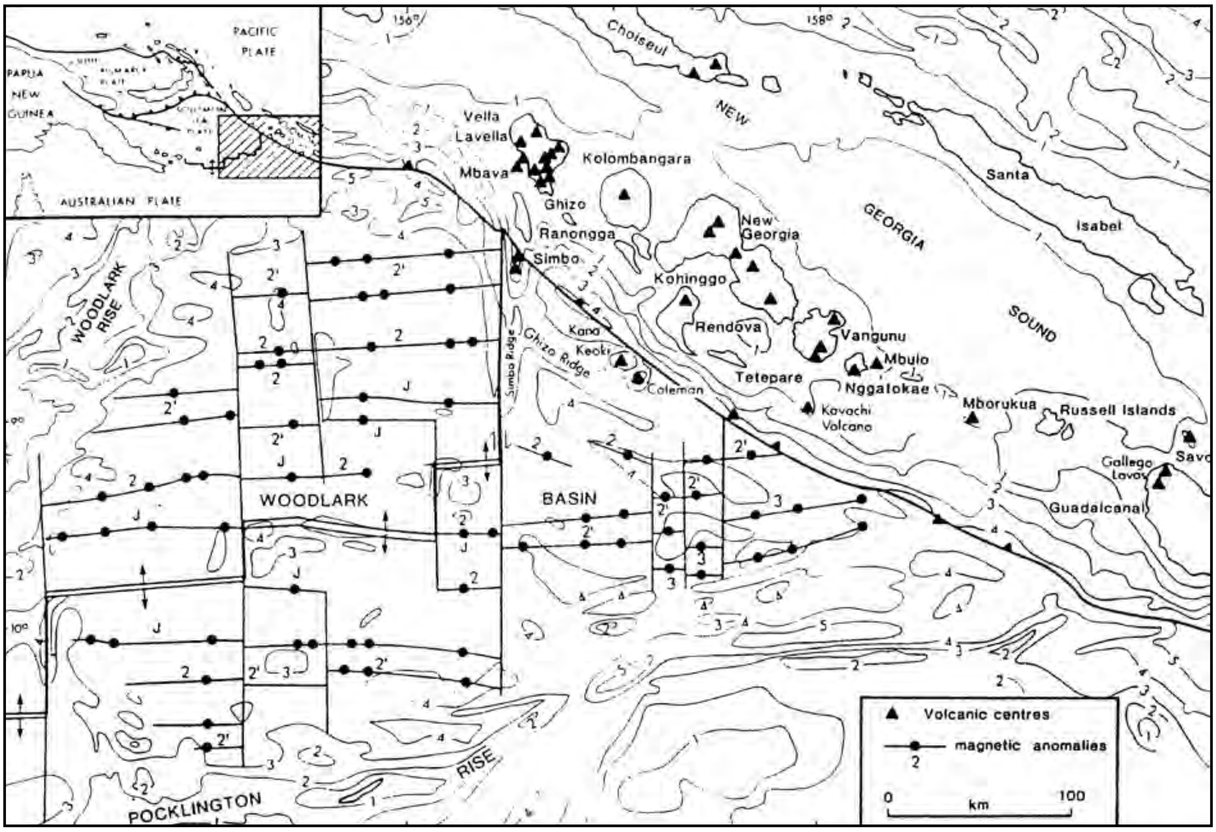

Figure 9. Tectonic features of the Woodlark Basin. Note the north - south transform faults which have displaced the east-west trending magnetic anomalies. Subduction of the Woodlark Basin has resulted in major uplift of the New Georgia - Guadalcanal - Makira frontal Solomon arc. The highly fractured nature of the Solomon arc, combining with leaky transform faults within the Woodlark Basin, has allowed the ingress of calc-alkaline magmas originating beneath New Georgia to be channelled south of the New Georgia trench and form calc-alkaline edifices such as the Coleman and Kana Keoki seamounts and the Ghizo and Simbo ridges. Acknowledgements to Kluwer Publications. Figure originally published in Crook and Taylor (1994).

in terms of the terrain-CTC-zone tectonic model. The model also predicts a high density of fractures, with fracture intersection nodes being particularly important as sites of extension and magma ingress. This phenomenon has had a profound influence on the magmatism of the Woodlark Basin, with calc-alkaline magmas originating within the mantle wedge to the north of the New Georgia trench being tapped by arc-normal and north - south Woodlark Basin fractures, which then channel these arc magmas southwards across the oceanic trench to form arc volcanoes on the downgoing Woodlark plate.

Figure 10 is a geological map of west Guadalcanal which again illustrates the very close relationship between terrain, structure and magmatism. A number of Miocene - Recent volcanoes are located in west Guadalcanal, forming the Gallego volcanics (e.g. Hackman, 1980). These volcanic centres include (from south to north) Tiaro Bay Cone Peak, Marende, Talalu, Gallego, Komambulu, Popori, Paru and Esperance and culminate in the presently active volcanic edifice of Savo, situated to the north-north-east of west Guadalcanal (Petterson et al., in press, [c]). Photogeological and mapped geological lineaments trend north-north-east, south-east, and east, again reflecting arc-parallel and arc-normal structures with additional local structural trends. In the case of west Guadalacanal and Savo, arc-normal structures have clearly been fundamental in creating conduits, pathways and space for the subsequent sites of volcanoes and related intrusions. The fault architecture of west Guadalcanal has helped to develop a locally dense network of volcanoes.

The genetic links between arc volcanism, the sites of arc volcanoes, and magmatically related arc mineralisation are well established. Volcanoes, magma chambers, and sub-volcanic plutons are the heat source for vigorous hydrothermal cells. These hydrothermal cells can leach metallic elements from a large volume of repository crustal rock and concentrate high value metals in brines. Metals in solution may be re-deposited in economic concentrations at sites where there is sufficient space and local thermodynamic conditions are conducive to mineral precipitation.

Figure 11 demonstrates the effects of present-day hydrothermal activity: Figures 11a and 11b are from Savo, illustrating solfataric vents and wholesale hydrothermal alteration, with large volumes of dacitic Block and ash deposits and other arc rocks and deposits having undergone extensive degradation with the formation of argillic and related alteration zones. Figure 11c is a photograph of Kavachi during one of its regular eruptive cycles. During these times Kavachi forms a low island and displays Surtseyan-type behaviour with large amounts of water-rock interaction. Such interaction produces high volumes of steam and results in highly explosive phreatic volcanism. Most of the present-day Solomon volcanoes developed initially within a submarine setting, like the Kavachi, Kana Keoki, and Coleman seamounts of the present day. Potentially mineralising hydrothermal cells are highly active for a large part of the active lifetime of the volcanoes, *and* for protracted periods after the volcanoes have become extinct

West Guadalcanal is an example of an area which theoretically is highly prospectable. This area hosts almost 30 individual volcanic centres and domes, each of which has a hydrothermal cell associated with it. The volcanoes are structurally linked and a dense fracture network exists, increasing the opportunities for mineralising fluids to interact with different structural sites, and thus optimising the opportunities for mineralisation. The volcanoes have produced large volumes of highly permeable Block and ash deposits which have the potential to allow ready access to fluid flow and could host syn-volcanic or post volcanic, stratabound and/or epithermal-type deposits. The magma composition of the Gallego volcanics can vary between basalt and rhyolite with a modal composition of acid andesite to dacite. The Gallego volcanoes have variable exhumation histories: Gallego and Komambulu volcanoes are quite deeply dissected, whilst Tiaro Bay has subsided and undergone caldera collapse, and Esperence retains youthful volcanic characteristics. This variable dissection may increase the opportunities for finding a range of mineral deposits from syn-volcanic, strata-bound deposits, to epithermal deposits which were deposited at less than 1000 m, and possibly even deeper deposits. Dispersal trains for alteration zones may be quite short as their geochemical signatures are quickly swamped by large volumes of easily eroded tephra deposits which flank the volcanic massifs.

Another positive characteristic of West Guadalcanal is the fact that it may well have undergone two stages of arc growth. The basement to north-west Guadalacanal is not well known and two scenarios are possible: 1) it is juvenile and has formed entirely since the Late Miocene; and 2) it formed during the Eocene to Lower Miocene. Our terrain model implies the latter possibility, as the Gallego volcanic field is structurally adjacent to the Oligocene to early Miocene Poha diorite (e.g. Hackman, 1980). If our interpretation is correct, it would increase the possibility of mineralisation in western Guadalcanal. Many Pacific mineral deposits are located in areas where young arc volcanoes and

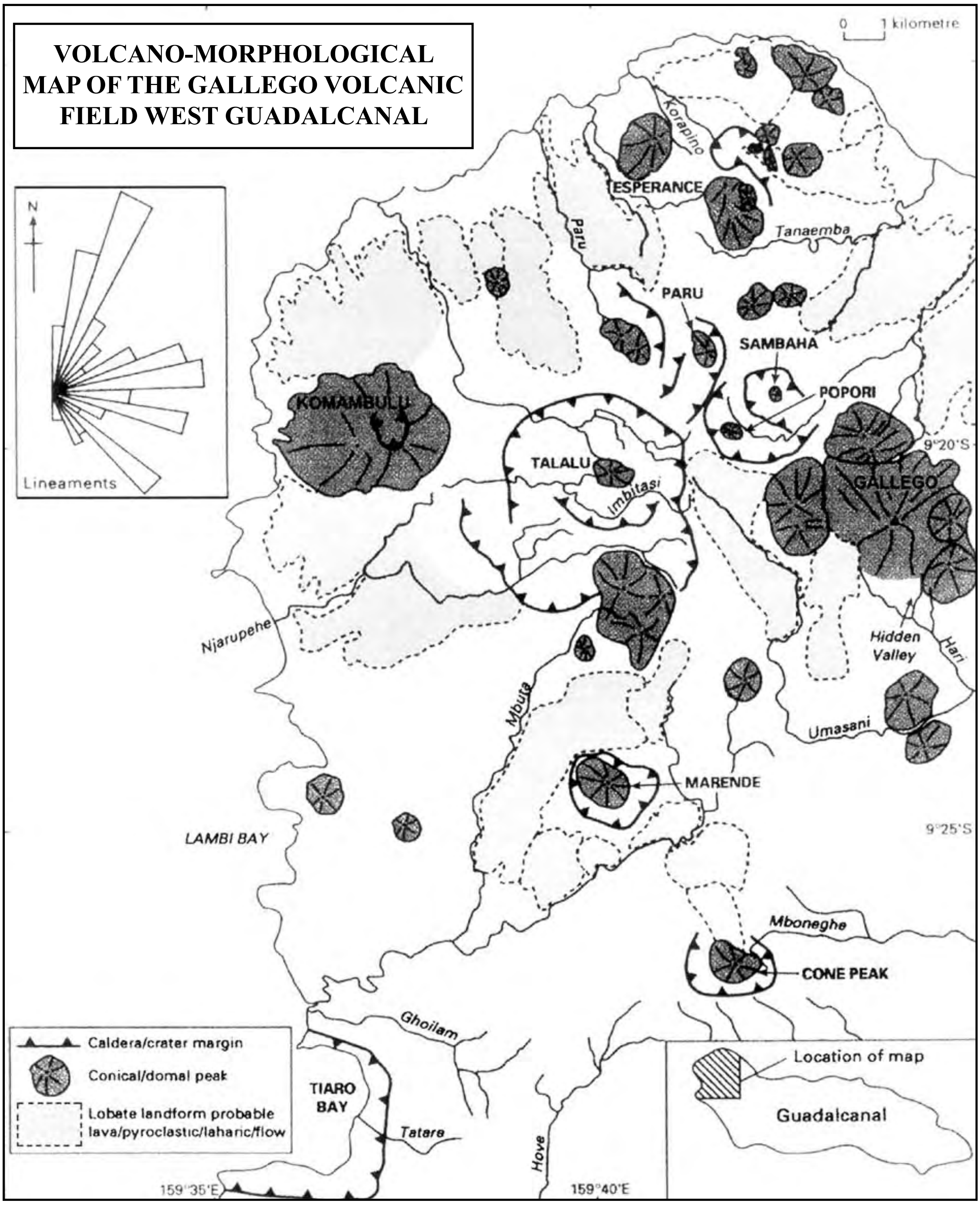

Figure 10. Location of major volcanic and volcanic-dome edifices in western Guadalcanal. Magmatism is strongly controlled by north-north-east and east trending lineaments. See text for details.

related intrusions are built upon pre-existing arc crust. Examples of this geological relationship include: Pangunu on Bougainville; many deposits in the Philippines; and Koloula and Gold Ridge in central Guadalcanal (Coleman, 1991).

Gold Ridge and Koloula mineralisation; Central and Southern Guadalcanal

A first-class example of mineralisation being linked to younger magmatism within older arc-composite terrains, and exhibiting strong structural control, is the Gold Ridge–Koloula line in central and southern Guadalcanal.

Gold mineralisation at the now active Gold Ridge mine, central Guadalcanal, is hosted within a Lower Pliocene, coarse, rudaceous volcaniclastic facies. Mineralisation is defined as being of a high-temperature, low-sulphidation nature and is characterised by a gold-pyrite association within quartz-calcite veins which are themselves within illite-carbonate-quartz-pyrite alteration zones (James et al., 1997). Geological mapping by Hackman and others (e.g. Hackman, 1980), together with stream-sediment geochemical sampling surveys (Qopoto et al., 1994), and recent mineral-exploration studies (James et al., 1997), suggest that the main mineral deposit is strongly structurally controlled, particularly by arc-normal structures. Stream-sediment geochemical anomalies are confined to rivers which drain the relatively small area of the Gold Ridge volcanics (only around 5 km^2). The stream-sediment-anomaly evidence underlines the strongly fault-controlled distribution of the Gold Ridge mineralisation, and is an example of how the combined terrain-CTC model can be readily applied to local mineral-exploration programmes.

Porphyry-copper mineralisation is hosted at Koloula, southern Guadalcanal, within a 4.5 - 2.4 Ma intrusive complex consisting of 26 different intrusive phases. The complex ranges in composition between leucogabbro (with associated olivine pyroxenite), diorite, quartz diorite, tonalite, trondhjemite, and aplite. Hydrothermal alteration has produced a number of alteration systems which display alkali feldspar - quartz, magnetite-actinolite; potassic, and propylitic styles of alteration as well as a number of sub-zones and overgrowth alteration phases. Some of this alteration is associated with copper mineralisation, best developed within chloritic fractures and quartz veins. The Koloula complex is strongly affected by west-north-west - east-south-east and north-north-east - south-south-west faults. The arc-parallel west-north-west faults have been dated in the sense that they displace 4.5 - 2.4 Ma intrusive rocks, and appear to be older than the arc-normal north-north-east - trending faults which offset 2 Ma and younger intrusive rocks. Readers are referred to Chivas (1978) and Chivas and McDougall (1978) for further details.

Thus the combined evidence from Koloula, Gold Ridge and west Guadalcanal implies that mineralisation may be associated with: 1) Upper Miocene to Recent volcanic-plutonic centres, particularly those which intrude into and extrude onto older arc-composite crust; or 2) arc-normal faults and possibly with nodal intersections between arc normal and arc-parallel fault systems. Further, 3) Mineralisation may be hosted by highly porous epiclastic or primary pyroclastic volcanic deposits which have been affected by hydrothermal alteration. Mineralisation may be syn-genetic or epigenetic epithermal-disseminated. 4) Deeper-level mineralisation may be porphyry copper in style, genetically linked to sub-volcanic intrusive complexes. 5) Other possible mineral associations could include sedimentary-exhalative/volcanic-associated massive sulphide deposits. 6) Extrapolating these asociations and applying the terrain model it would suggest that younger magmas which interact with older arc crust within the Central Solomon or South Solomon MORB terrains are highly prospectable areas. Similarly, juvenile magmatic centres within the New Georgia terrain must also have a high level of prospectability: one recent mineralisation find which is currently being explored is located on the island of Vangunu within the NGT (Donn Tolia, pers. comm.).

Extrapolation of known mineral deposits

Once a mineral resource has been found, has been proven to be of economic value and is being actively worked, it is normal procedure to instigate a detailed local mineral-exploration programme to identify possible extensions to the known mineral reserve. The current terrain model helps in two ways.

Firstly, the regional structural architecture is normally reflected at all scales, including the local scale. Thus, possible mineral-body extensions along arc-normal and/or arc-parallel structures, and nodal intersections between these two fracture sets, could be explored in the first instance. Possible local structural divergence from the general structural template should also be investigated. This analysis may even be helpful on an extremely localised micro-scale level within a mine for grade

A

B

C

Figure 11.

(a) Hydrothermally altered valley close to the central crater, Savo, Solomon Islands. Note the high degree of rock degradation.

(b) Hydrothermal-solfatoric vent and hydrothermally degraded valley side, Savo.

(c) The volcano Kavachi which surfaces above sea level during eruptive cycles. Note the highly explosive Surtseyan – phreatic activity and the water-magma interaction.

evaluation: we suggest that mineralising fluid pathways are strongly structurally controlled, and once the key mineralising veins have been identified it may be possible to predict local extensions to the mineralized vein systems.

Secondly, the mineral deposit may well have been physically split into two or more parts by terrain and strike-slip tectonics. This will manifest itself on a local scale, as for example a high-grade deposit abruptly terminating at a faulted boundary. Thus it is most important to develop the local geological model as far as possible, and look for possible correlative terrains to the one in which the present working mine is situated. Depending on the age of the deposit, the correlative allochthonous terrain(s) which contains the 'other half' of the mineral deposits could have been translated by tens of metres to tens of kilometres or even further. In general, the younger the deposit, the closer the sister allochthonous terrain. It is most important in this scenario to evaluate fault motions, i.e. are they essentially horizontal or is there a significant vertical component? The sister terrain is more likely to be found if horizontal tectonism has prevailed.

Relative crustal erosion levels

A knowledge of the relative structural position within the crust is important in evaluating the economic feasibility of using terrains. A knowledge of the terrain model together with a knowledge of the local geology can provide a first-approximation answer to this problem.

For example, in the case of the Solomon Block, the proximity of a particular crustal unit to the New Britain-San Cristobal trench system is closely linked to relative uplift. Subduction of the young, warm, and buoyant Woodlark Basin has led to the major uplift of the southern parts of the New Georgia islands, Guadalcanal, and Makira. On Makira only the roots of an arc remain recent mapping has located only a relatively small number of dacite dykes which are possibly feeders to a much more extensive magmatic-arc system. Similarly, in southern Guadalcanal, extensive fore-arc uplift has resulted in the erosion of the supracrustal arc cover sequence, exposing the plutonic roots to the former arc volcanoes. In both the examples of Makira and south Guadalcanal it is probable that any epithermal mineralisation which may have existed has now been eroded (could any related placer deposits be located?) and deeper-level porphyry-copper or mesothermal mineral systems may be more likely targets. In contrast, western Guadalcanal has experienced only moderate denudation, and upper crustal sequences remain intact.

Fault Blocks can subside as well as be uplifted, and many potential mineral sites may be buried in post-subsidence rift-sediment sequences. The potential for 'blind deposits' must be borne in mind.

Terrain boundaries

Deep crustal ophiolitic or purely oceanic ultramafic bodies may be exposed close to thrusted and uplifted regions adjacent to terrain boundaries and highly uplifted crustal Blocks. Examples of this include the line of ultramafic bodies which mark the hanging wall of the KKK on Santa Isabel, and exhumed ultramafic bodies in southern Guadalcanal. Ultramafic complexes may be the source of orthomagmatic Ni-Cr deposits or Ni-Cr placer deposits. The island of San Jorge located close to south-east Santa Isabel is an example of this type of mineral association.

Ontong Java plateau terrains

Mineral-exploration targets within the entirely oceanic terrains of Solomon Islands have tended to concentrate on alnoite pipes. The main reason for this is the potential for diamond formation within these structures which originated within the deep lithosphere. The alnoites are also associated with a host of other minerals including garnet and ilmenite. Recent mapping on Malaita has demonstrated strong structural controls on alnoite intrusion, extrusion of alkaline basalts, Basin formation and sedimentation, and moderate Ag and Pb geochemical anomalies (Mahoa and Petterson, 1995) which may reflect sedimentary exhalative-type mineralisation. The predominant controlling structures trend north-west (Petterson et al., 1997).

It should also be remembered that the Ontong Java plateau is the product of very high-volume effusion of basalt lava and related intrusive basic rocks. The OJP is the size of Alaska and 40 km thick, and was erupted predominantly within two discrete eruptive cycles at c. 122 Ma and 90 Ma (Neal et al., 1997). Such large-scale eruptions are the product of large plumes which may originate at the core-plume boundary and which, in theory, may contain significant concentrations of platinum-group elements.

Geochemical controls

It is beyond the scope of this paper to discuss how igneous rock composition affects the chemistry and syle of mineralisation. However it is well established that there are genetic links between, for example, intrusion composition and mineralisation, even within Solomon Islands and Bougainville/ Panguna (e.g. Chivas, 1978, Coleman, 1991, James et al., 1997). A knowledge of the geochemical composition of intrusive complexes and extrusive volcanic regions can further refine the combined terrain-CTC model and produce an even more promising mineral target evaluation model.

CONCLUSIONS

Table 1 is a simplified summary of theoretical mineral associations within Solomon Islands and their local structural and geological controls.

1) The Southwest Pacific region has been dominated by oblique collisional tectonics for a long period of time. Strike-slip and transpressional tectonism has been the norm probably since the Eocene, and certainly since the Late Miocene.

2) Oblique-collisional tectonics has resulted in a high density of boundary-parallel and boundary-normal faults which control the structural architecture of the region. Discrete fault Blocks may be uplifted, rotated, downthrown, or translated. Fractured arc and oceanic crust, relative uplift and subsidence of crustal Blocks, translation of exotic crustal units, and the formation of pull-apart and strike-slip Basins are some of the resulting tectonic phenomena.

3) At least five distinct terrains have been recognised within Solomon Islands. These terrains range from entirely oceanic units formed by large-scale plume-related basaltic outpourings, to purely arc terrains formed since the Late Miocene, to more-complex and composite terrains with oceanic dominated basement and subsequent arc-related crustal development.

4) Combining the terrain and oblique-collisional modelling is a powerful way of assessing mineral potential in regions of the earth's crust which have accreted in a fashion similar to the Southwest Pacific. The combined models can predict the most likely structural and geographical positions of mineral deposits and form a basis for metallogenetic modelling. This principle is true on a large regional scale and on a small individual mine scale. Consideration of igneous rock geochemistry can increase the effectiveness of this mineralisation assessment model.

5) It is most important that mineral explorationists are aware of terrain tectonics, can define terrain types and terrain boundaries, and make mineral-potential assessment studies and design mineral-exploration Programmes using the terrain model as a fundamental guide. Terrain tectonics profoundly influences the distribution of mineral deposits, and also exposes a range of crustal depths which in turn host different types of deposit (e.g. epithermal versus porphyry copper versus mesothermal deposits).

6) This paper suggests that there are some highly prospectable areas within the Solomon Islands, including volcanic-exhalative, epithermal and porphyry-copper-type deposits within composite arc-oceanic and more-juvenile arc terrains, and possible platinum-group-element and alnoite-related mineralisations within the oceanic Ontong Java Plateau terrains.

Table 1. Simplified summary of mineral potential of discrete terrains within the Solomon Islands.

Terrain or sub-terrain	Islands	Structural/geological controls	Possible mineralisation	Qualitative index of prospectability
Ontong Java	Malaita, Ulawa, northern Santa Isabel	OJP related basalt terrain. Deep sourced alnoite pipes + alkali basalts. Pelagic cover, Basin formation. north-west - south-east structural grain, local discordance.	Alnoite related garnet ilmenite ?diamond association. ?Possible platinum group element Mineralisation. Oceanic sedex Mineralisation linked to alk. Basalt centres + Basin formation.	Moderate
Plateau Terrain KKK Terrane Boundary	Santa Isabel + off-shore extrapolations	Central Solomon terrain overthrusting OJP	Ni-Cr-Cu. Cyprus type ophiolitic and ultramafic Mineralisation associations.	High
South Solomon MORB terrain & Central Solomon terrain	South Santa Isabel, Choiseul, Guadalcanal, Shortlands, Floridas	Highly fractured crust cut by arc–parallel and arc–normal faults High variability in crustal exposure levels. Complex composite crustal sequences.	Epithermal gold. Porphyry Copper. Local mesothermal associations. Ophiolitic & ultramafic associations. Volcanic-hosted massive sulphides.	Very High
New Georgia terrain	New Georgia island Group, Russells, Savo	Arc front dominated by arc – normal & arc – parallel structures. Clusters of arc volcanoes with associated plutons and volcanic cover sequences.	Epithermal gold. Volcanic hosted massive sulphides. Porphyry Copper in deeply eroded parts.	High to Very High
Makira terrain	Makira	Composite oceanic basement with local stage 2 arc development. East-west and north-south faulting. Deeply dissected in south.	Oceanic basement associated Mineralisation. Ultramafic associated Ni and Cr. Possible mesothermal arc Mineralisation.	Moderate

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MINERALISATION EPOCHS WITHIN THE FIJI PLATFORM AND THEIR RELATIONSHIP TO CRUSTAL DEVELOPMENT

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ABSTRACT

Four distinct periods (epochs) in the development of the Fiji Platform have been identified. These epochs are related to changes in tectonic development and are reflected in the spatial and temporal distribution of various styles of mineralisation presently found across the Fiji Platform. Epoch 1 includes the oldest rocks in Fiji (Yavuna Group) which formed in a primitive island arc setting. No significant areas of mineralisation are known from this time. Epoch 2 includes rocks formed during the main period of activity along the Vitiaz arc from the Early Oligocene to the Late Miocene. Mineralisation during this epoch is subdivided into island arc exhalative Mn and base metal deposits (Wainimala Group), and later vein Au and skarn deposits related to a period of major plutonism (Colo Plutonic Suite). Epoch 3 includes rocks formed during a period of complex tectonic and volcanic activity from the latest Miocene to the Late Pliocene. The main mineralisation types formed at this time were porphyry copper and several types of Au deposits. The most significant known mineral deposits in Fiji were formed during epoch 3. Epoch 4 includes Late Pliocene to Recent rocks, with mineralisation mainly restricted to residual deposits derived from the weathering of pre-existing rocks. The geological history and associated mineralisation of the Fiji Platform reflects the complex evolution of a single crustal Block in response to an evolving tectonic setting. This area therefore provides a useful insight into the complexities that may be encountered in older areas where the original relationships between rock suites may be uncertain or obscured.

INTRODUCTION

It is well known that certain types of mineralisation are commonly associated with particular tectonic settings (Mitchell and Garson, 1981). Knowledge of the tectonic history of a particular group of rocks is therefore of great assistance in determining potential exploration targets within a particular region. The tectonic evolution of the Fiji Platform can be defined from the characteristics of a number of rock suites presently exposed across the platform. As will be seen, particular types of mineralisation tend to be associated with each of these various rock suites.

It can be said, with the possible exception of the oldest exposed rocks on Viti Levu (Yavuna Group), that the rocks suites presently exposed on the Fiji Platform are all related to the evolution of a single crustal Block in response to its changing regional tectonism. The Fiji Platform therefore shows most variation in terms of temporal metallogenic evolution, and hence the use of the term epochs. In areas to the west of the Fiji Platform, such as the Solomon Islands, individual metallogenic terrains have been identified which may have a similar age, but which originated as discrete crustal units and were subsequently amalgamated through transpressional tectonics (Solomon Islands Petterson and others, 1998; 1999). This situation differs from that inferred for the Fiji Platform.

Regional geology

Most islands that comprise the Fiji archipelago, are located on the Fiji Platform (Figure 1). This platform (Rodda, 1994) also contains the two largest islands of Viti Levu and Vanua Levu. The oldest rocks on the Fiji Platform are those of the Yavuna Group on Viti Levu (Figure 2), which comprise a

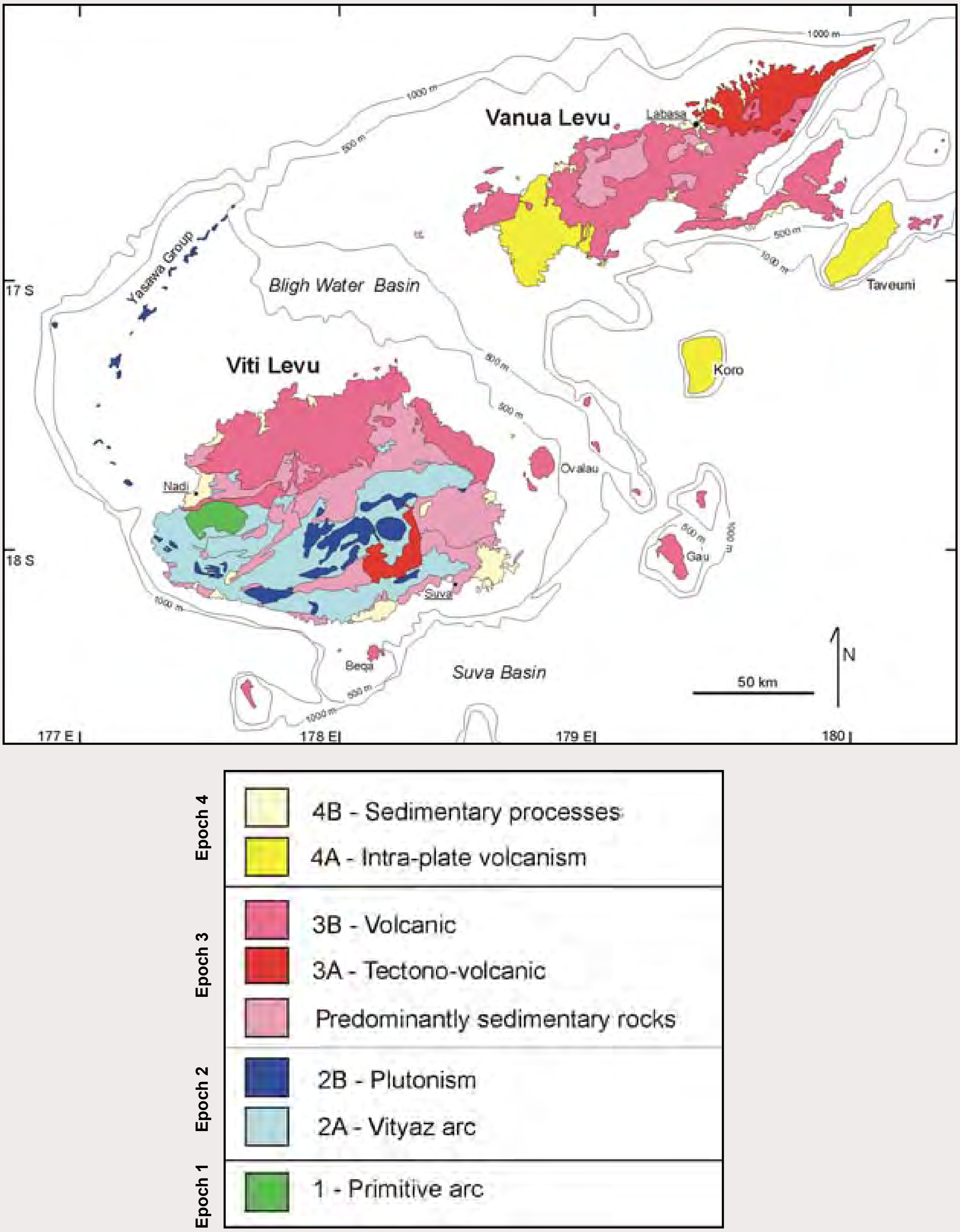


Figure 1. Geology of the Fiji Platform (after Hathway, 1993; Hathway and Colley, 1994; Rodda, 1994) showing the relative location of the various epochs (identified by number) across the Fiji Platform. Note that the sedimentary rocks of epoch 3 have been separated from the predominantly volcanic rocks of the same epoch. 3AV = Namosi Andesite, Udu Volcanic Group. 3B = Koroimavua Volcanic Group (except Vatutu Sandstone), Ba Volcanic Group (except Vatukoro Greywacke), Macuadrove Supergroup on Vanua Levu (except Dreketi Basin and some smaller sedimentary Basins). The Tuva Group is here placed in epoch 2A because it is a predominantly sedimentary suite and it formed just prior to the Tuva deformational event, which is taken as the boundary between epochs 2 and 3. It is however much younger (8 Ma) than the other sedimentary suites in epoch 2 (Wainimala Group 32 - 14 Ma).

fragment of a Late Eocene to Early Oligocene arc volcanic suite (Hathway, 1992; 1994; Hathway and Colley, 1994). The Yavuna Group comprises the basement on which the younger Wainimala arc was formed. The Wainimala Group is widespread across Viti Levu (Hirst, 1965; Band, 1968; Rodda, 1976; Hathway, 1994; Hathway and Colley, 1994). This unit is a remnant of activity along the Vityaz arc, a north-east-facing system located along the Australian - Indian plate boundary and active from at least the Oligocene to the Late Miocene (Falvey, 1978; Gill and others, 1984; Hathway, 1994) (Figure 3). The Colo Plutonic Suite was intruded during the Middle to Late Miocene (12 to 8 - 7 Ma - Hathway, 1993; Rodda, 1994). These rocks represent a period of intense but otherwise

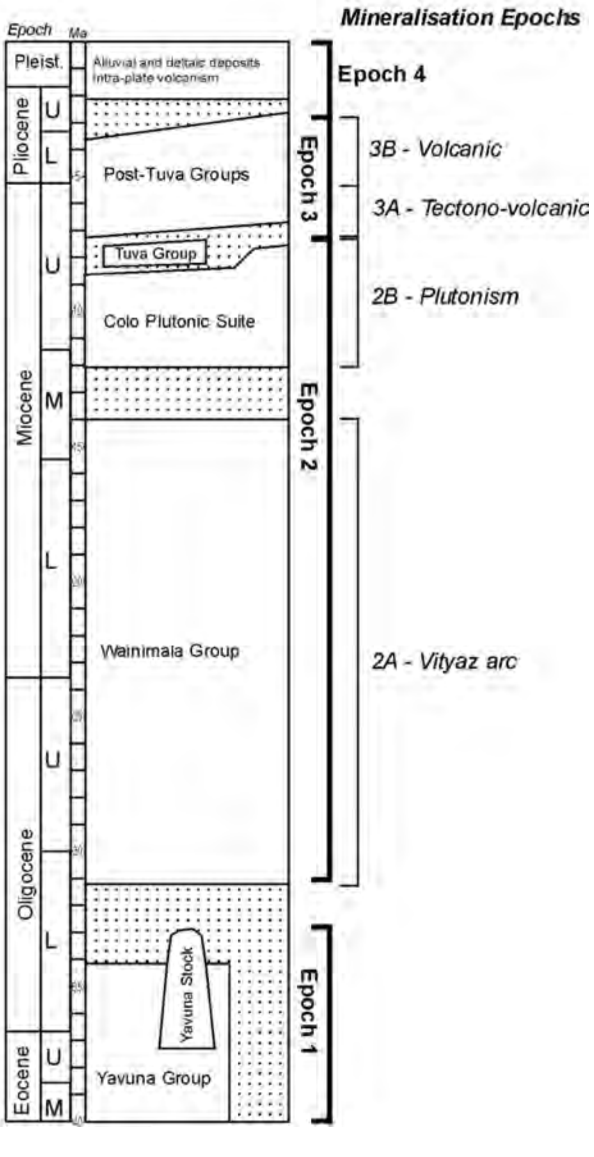


Figure 2. Stratigraphic column for Viti Levu showing the temporal distribution of epochs across the Fiji Platform (after Hathway, 1993; Hathway and Colley, 1994; Rodda, 1994).

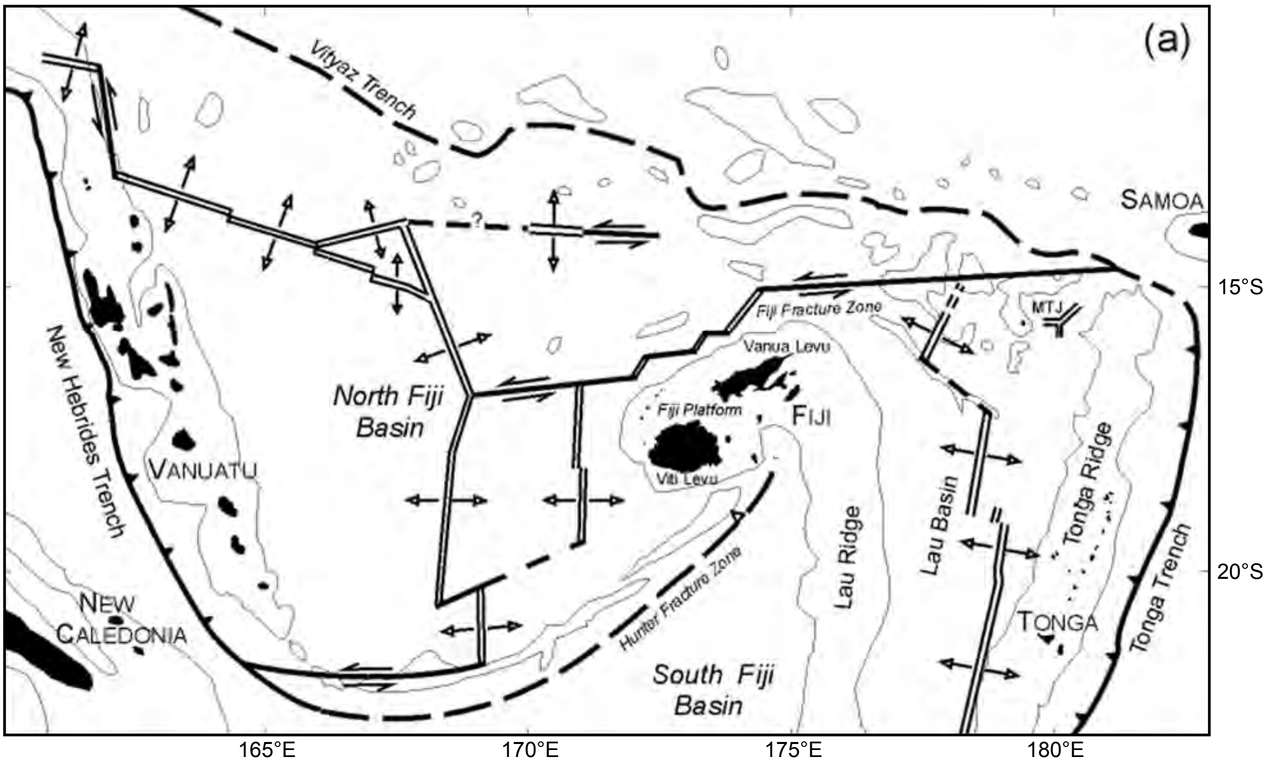
normal Vityaz arc activity (Gill, 1987). Following deposition of the Tuva Group in the earlier part of the Late Miocene (8 - 7 Ma) a Late Miocene phase of complex folding and faulting effected both the Wainimala and Tuva Groups prior to deposition of the first of the younger rock suites (Hathway and Colley, 1994).

Rocks formed after the Tuva deformational event include several significant sequences on Viti Levu, and all the rocks presently exposed on Vanua Levu. This deformational event was probably related to continued sundering of the Vityaz arc between the Fiji and New Hebrides sectors, initiation of forearc rifting in front of the Fiji Platform (Auzende et al., 1995), and the commencement of major sinistral rotation of the platform (Mallahof and others, 1982; Hathway, 1993).

The first rocks formed on Viti Levu following the Tuva deformation are predominantly sedimentary sequences deposited in strike-slip Basins that formed in response to the rotation of the platform at this time (Hathway, 1993). From around 6.5 Ma onward, the percentage of volcanic rocks in the sequence on Viti Levu increases with the appearance of the Namosi Andesite and the Koroimavua Volcanic Group in the latest Miocene, and the Ba Volcanic Group in the Early Pliocene. The volcanic record on Viti Levu ceases at around 3.7 Ma (Rodda, 1994).

Upper Miocene to Lower Pliocene rocks on Vanua Levu are all part of the Macuadrove Supergroup (Hindle, 1976; Rodda, 1994) which consists of four volcanic-dominated groups. The oldest of these groups is the Udu Volcanic Group in the north-east of the island (Rickard, 1970). Other units include the Monkey Face Volcanic Group in the south-west, and the Nararo and Natewa Volcanic Groups elsewhere across the island. Significant scope remains for resolution of the volcanic stratigraphy on this island.

The youngest volcanic rocks on the Fiji Platform are Upper Pliocene to Recent alkalic volcanic rocks of the Bua Volcanic Group on Vanua Levu (Hindle and Colley, 1981), and the Koro and Taveuni Volcanic Groups (Rodda, 1994) on nearby islands (Figure 1). The composition of these volcanic rocks reflects a non-arc intra-plate (Gill and Whelan, 1989a; 1989b) origin, suggesting that by about 3 Ma the Fiji Platform had moved away from the source of arc magma. This change in composition marks the final dissociation of the Fiji Platform from the old Vityaz arc system. This period also saw major uplift across the Fiji Platform (Rodda, 1994) which led to the resultant poor Late Pliocene sedimentary record presently found on both main islands.



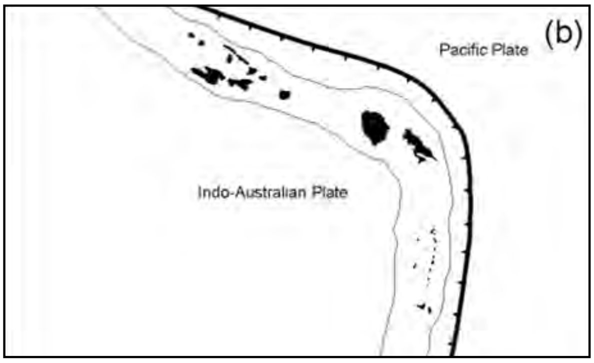


Figure 3. (a) Present day plate tectonic setting for Fiji and surrounding areas (after Hathway, 1993, Auzende et al., 1995). (b) Appearance of the Vityaz arc, after opening of the South Fiji Basin and prior to the breakup of the North Fiji Basin (after Hathway, 1993) during Early to Middle Miocene. Present day land masses for Vanuatu, Fiji and Tonga have been included for reference, information for New Caledonia has not been included.

MINERALISATION TYPES

The data used in this paper comes from several published sources (Colley, 1976; Colley and Greenbaum, 1980; Colley and Flint, 1995). Colley and Flint (1995) used six main categories to describe the styles of metallic mineralisation across the Fiji Platform (Table 1). The physical distribution of these mineralisation styles across the Fiji Platform is outlined in Figure 1 with statistical information given in Tables 2 and 3.

Primary gold

Type A1 – This category includes the large epithermal mineralisation systems such as Vatukoula and Mt Kasi, as well as the numerous smaller deposits and prospects. These deposits can be broadly characterised as complex Au-Ag (±/Te) epithermal vein systems primarily, although not exclusively, hosted in volcanic rock suites (Colley and Flint, 1995). Both low-sulphidation (Emperor) and high-sulphidation (Mt Kasi) examples are present (Figure 4). Type A1 deposits have presently only been found in association with Pliocene calc-alkaline to alkalic (shoshonitic) volcanic rock suites. The position of many of the Pliocene volcanic centres and associated mineralisation, shows a degree of structural control on mineralisation with most deposits situated along the north-east - south-west oriented Viti Levu Lineament (Gill and Whelan, 1989a; Setterfield and others, 1991; Colley and Flint, 1995). Based on the size of previous discoveries, type A1 deposits appear to hold the greatest potential for future resource development, particularly on Vanua Levu.

Type A2 – This category includes gold deposits that show the characteristics of both epithermal and porphyry type mineralisation. The elemental assemblage is typically Au-Ag-Cu-Zn (Colley and

Flint, 1995). These deposits reflect a complex interplay between parts of what may have been the same mineralising system as it evolved over time. There is no clear distinction between type A1 and A2 deposits, and separation is made here on the basis of deposit mineralogy, which may only reflect differences in the depth of the present exposure of individual deposits. This appears to be the case at Vatukoula where porphyry-type mineralisation has been inferred to occur at depth (Anderson and others, 1987) in this complex Type A1 deposit. While no type A2 deposits are currently being mined there is real potential for future exploitation of these types of deposits, particularly at Tuvatu in western Viti Levu (A-Izzeddin, 1998).

Table 1. Mineralisation styles present across the Fiji Platform. Information adapted from Colley and Flint (1995). The code letters are used throughout the text and appear on the figures. MS = massive sulphides.

Types	Sub-types	Code
Primary gold	Epithermal Au-Ag (+/-Te) Epithermal Au + base metals Vein Au (plutonic)	A1 A2 B
Disseminated Base Metals	Porphyry Cu-Au ?Porphyry -related (Cu, Zn)	C1 C2
Skarn	Skarn Cu, Zn, Au Skarn Fe (now residual)	D1 D2
Polymetallic MS and vein	Cu-Zn VMS Cu-Zn-Pb VMS	E1 E2
Manganese deposits	Exhalative Mn	F
Residual and placer	Residual Al Placer and eluvial Au Placer Fe (Iron sand)	G1 G2 G3

Table 2. The distribution of individual mineral deposits and prospects across all of Fiji (from Colley and Flint, 1995). No weighting is given for the size of individual deposits. The gaps in the dataset for Vanua Levu are due to the absence of rocks from epochs 1 and 2 on this island. "Other islands" includes deposits found on the Mananuca, Yasawa and Lomaiviti island groups on the Fiji Platform, and the Lau island group and Kadavu which are not part of the platform sequence. Deposit-types G2 and G3 are not listed in this table because of difficulty in differentiating specific resources.

Code	Viti Levu	Vanua Levu	Other islands	Total	% Total
A1	15	30	6	59	29
A2	13	6	-	19	11
B	10	-	-	10	6
C1	13	-	-	13	7
C2	4	1	3	8	4
D1	12	-	-	12	7
D2	4	-	-	4	2
E1	17	7	-	24	13
E2	7	2	-	9	5
F	15	2	-	17	10
G1	1	9	1	11	6

Type B – This category includes the numerous vein gold deposits hosted within the Lower Oligocene Middle Miocene Wainimala Group and mostly associated with the intrusion of the Colo Plutonic Suite (Colley and Flint, 1995). Type B deposits are characterised by gossans and polymetallic-Au veins hosted in Wainimala Group rocks that are often situated close to small Colo stocks. These deposits are usually older than type A1 and A2 deposits.

Disseminated deposits

Given the common occurrence of these types of deposits in island arcs further west (Papua New Guinea, Philippines), the presence of porphyry copper deposits on the Fiji Platform is not unexpected. There are two major occurrences of these types of disseminated deposits.

Type C1 – These are the volcanic-associated deposits of Colley and Flint (1995). They are found across the Fiji Platform in rocks usually less than 6.5 Ma old. The Late Miocene Pliocene was a time for the development of many large porphyry Cu-Au deposits across the western Pacific (Titley and Heidrick, 1978; Sillitoe, 1997). The largest known resource of this type in Fiji are the deposits around Namosi in south-eastern Viti Levu (Figure 4). The low grade of the Namosi deposits may delay development of this resource in the near future (Leonard, 1998). The potential for locating new type C1 deposits on the Fiji Platform exists where ever there are sufficient quantities of Miocene or younger arc volcanic rocks.

Table 3. Distribution of mineral deposits and prospects within individual epochs of the Fiji Platform, regardless of deposit type. Data from Colley and Flint (1995). Mineral deposits from Lau and Kadavu are not included here.

Epoch	Viti Levu	Vanua Levu	Other islands	Total	% Total
4B	2	9	1	12	7
4A	–	–	–	–	0
3B	23	30	2	55	31
3A	16	18	–	24	19
2B	23	–	2	25	14
2A	47	–	2	49	29
1	–	–	–	–	0

There is probably some overlap between the formation of type C1 and type A2 deposits, with these deposits representing parts of a general porphyry-type mineralising system. These deposits are separated here on the basis that type A2 are sought primarily for Au, while in type C1 deposits both Cu-Au are the primary exploration targets.

Type C2 – This category includes the plutonic-associated deposits of (Colley and Flint, 1995). In contrast to type C1 deposits they are usually associated with older rock suites (Colo Plutonic Suite). These deposits often have features that reflect a porphyry-type origin, although with no clear evidence of an actual porphyry system (Colley and Flint, 1995).

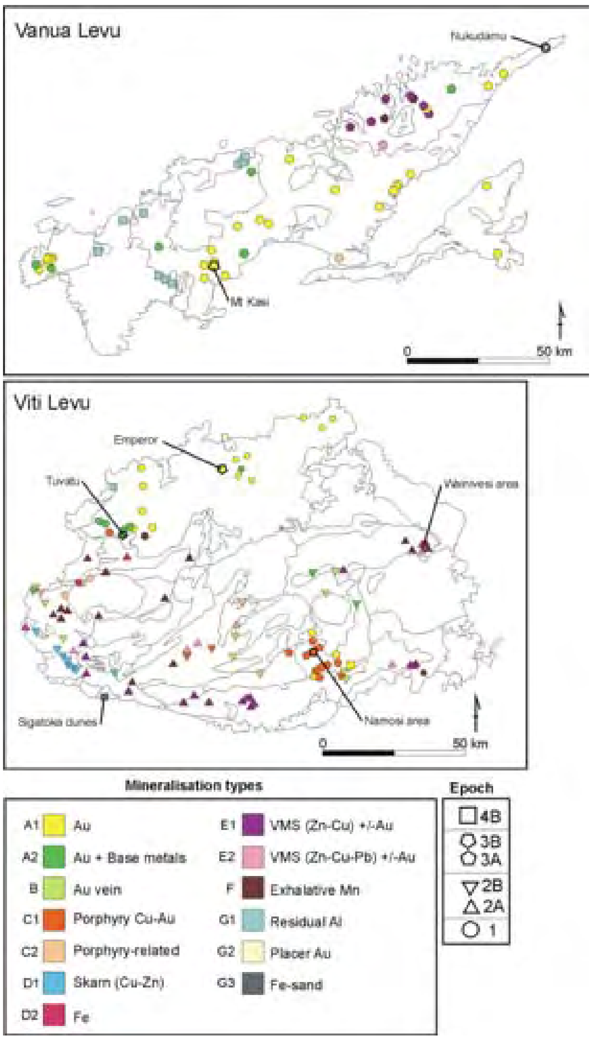


Figure 4. The location of the known mineral deposits and prospects on the (a) Viti Levu and (b) Vanua Levu (after Colley and Flint, 1995) with regard to mineralisation type (Table 1) and epoch. Lines on the maps are the epoch and unit boundaries shown on Figure 1.

Skarn deposits

Type D1 – With the large number of intrusions (Colo Plutonic Suite) and weathered volcanic centres it is not surprising that a number of skarn deposits are found across the Fiji Platform. Most of these deposits typically have a Cu-Fe±Zn mineralogy. Cu-Fe skarn mineralogy is common in island arc settings (Einaudi and Burt, 1982), although the predominance of Cu, and the presence of tonalites as host rocks is possibly unusual.

Type D2 – Several massive iron deposits are found on Viti Levu. The iron is thought to have a magmatic pyrometasomatic origin associated with a skarn-type environment (Colley and Flint, 1995). It should be noted that all these deposits, some of which have previously been mined, are presently found as residual concentrations of boulders occurring as either thin sheets on overlying bedrock (Tuveriki), or as boulders within creeks (Wainavola Creek). They are separated from the Type G3 iron sand deposits because of their close spatial association with the original source rocks.

Polymetallic massive sulphide and vein deposits

Type E1 - Numerous volcanic massive sulphide (VMS) type deposits are scattered across both main islands (Colley and Flint, 1995; Colley and Rice, 1975; 1978). One deposit (Nukudamu) has been mined (Figure 4). The preserved remnants of these deposits include both the exhalative (Vunivesi), and feeder portions (Wainikoro) of the VMS mineralising system (Colley, 1976; Colley and Flint, 1995). There are significant differences between the revised model for formation of Kuroko-type deposits (Ohmoto and Skinner, 1983) and the VMS deposits on the Fiji Platform (Colley and Flint, 1995). Type E1 deposits are defined as those with an economic mineral assemblage consisting of Zn-Cu-Pb.

Type E2 - The only apparent difference between type E1 and type E2 deposits is that type E2 deposits contain a more limited economic mineral assemblage consisting of only Zn-Cu. Genesis of these deposits is otherwise thought to be similar to that of type E1.

Manganese deposits

Type F – The largest Mn deposits on the Fiji Platform are stratabound exhalative deposits within the Wainimala Group, found mainly in western Viti Levu. These deposits appear to have formed as a result of shallow submarine thermal-spring activity during a period of waning volcanism (Colley and Flint, 1995). Some younger Mn deposits are hosted in Late Miocene to Pliocene volcanic rocks in eastern Viti Levu and on Vanua Levu. Residual Mn deposits are also known from some offshore islands of the Fiji Platform, and from the Lau group of islands (Colley and Flint, 1995) to the south of the Fiji Platform (Figure 3).

Residual and placer deposits

Type G1 – Most bauxite found across the Fiji Platform occurs as gibbsitic nodules in lateritic clays (Colley and Flint, 1995). Climate does not appear to play a major role in the development of this bauxite as deposits occur on both the wet and dry sides of the main islands. Most bauxite is developed on either basaltic or less commonly andesitic basement rocks.

Type G2 – Placer and eluvial gold occurs in several places across the Fiji Platform. Detrital Au in known from the Tavua (Nasivi), Ba and Rewa River deltas (Colley and Flint, 1995), the apparent absence of follow-up studies suggest these concentrations may not be economic, although recent work at Tavua (Wong and others, 1999) may help to better define these resources. Mt Kasi contains the only eluvial gold deposit to have been mined, estimates of the relative size of the eluvial portion of this deposit range from 30 - 60% of the total tonnage (Colley and Flint, 1995).

Placer mineralisation in small islands faces the inherent problems of relatively small source area, short drainage systems and small off shore storage areas that tend to limit the potential size of any deposit. Nevertheless, Type G1 deposits remain a potential resource for (lower cost) metallic mining operations, although stringent environmental monitoring would be required to ensure the protection of these often fragile environmental regions.

Type G3 – The best known iron sand deposits are found at the mouth of the Sigatoka River in the Sigatoka Dunes area. Estimates of reserves of magnetic minerals appear sub-economic and with no significant gold found with the ferrous minerals (Colley and Flint, 1995). Iron sand resources have also been examined in the Ba River delta.

EPOCH ANALYSIS

The types of mineralisation described above are often restricted to particular lithologies. In some cases these lithologies are also restricted to a particular time period, giving rise to the epoch concept for describing the distribution of mineralisation. Four metallogenic epochs are described below, several of which have significant subdivisions.

Epoch 1 - Primitive arc (+40 -34 Ma)

This epoch includes the rocks of the Yavuna Group which are presently found only in south-western Viti Levu (Hathway, 1992; 1994; Hathway and Colley, 1994). This unit is thought to have formed during the early stages of development of an intra-oceanic island arc (Hathway and Colley, 1994). The relationship between this unit and the younger sequences on the Fiji Platform is uncertain and this may be the only truly separate terrain presently exposed on the Fiji Platform.

No significant sites of metallic mineralisation have presently been reported from this terrain, although there are reports of accessory Ni-Co sulphides and Au in gabbros and ‘primitive’ basalts (Colley and Flint, 1995). Any mineralisation during this epoch is likely to be that associated with primitive oceanic island arcs. As these particular settings do not tend to be associated with significant mineralisation (Mitchell and Garson, 1981), this may not be a particularly prospective terrain. If however, interpretations of mineral deposits in primitive island arcs are revised, or mineral deposits are found in similarly aged arc rocks in countries along strike, this terrain may warrant a more detailed examination.

Lower Middle Eocene basaltic extrusive, pyroclastic rocks and dykes are reported from the island of ‘Eua and from drill holes across Tonga Ridge (Cunningham and Anscombe, 1985; Tappin, 1993). Middle Eocene rhyolites have also been found at the bottom of ODP drill holes in the Tonga forearc suggesting rocks of this age form the basement to parts of the Tonga islands. The Upper Eocene sequence on ‘Eua consists primarily of carbonates (Cunningham and Ascombe, 1985). Significant mineralisation has not been reported from the Eocene rocks on ‘Eua. An Early Oligocene break in the stratigraphic record on the Tonga Ridge (Tappin, 1993), occurs at a similar time to the unconformity between the Yavuna Group and the Wainimala Group on the Fiji Platform (Hathway and Colley, 1993). This hiatus is taken as the boundary between terrain 1 and 2 on the Fiji Platform. The cause of this apparently regional unconformity may be related the initial opening of the South Fiji Basin (Malahoff and others, 1982; Herzer and Exon, 1985).

The only Eocene Early Oligocene rocks presently known from Vanuatu are limestone and basalt clasts in Miocene volcaniclastics (Carney and others, 1985). Rocks of equivalent age and tectonic origin to epoch 1 may be present as (unexposed) basement for some of the New Hebrides arc (Carney and MacFarlane, 1978; Carney and others, 1985).

According to Colley and Flint (1995), the first phase of the metallogenic evolution of the Fiji Platform is the early arc stage (34 - 12 Ma). However this period is younger than bulk of the Yavuna Group so that their early arc stage appears to include only the Wainimala Group, which has it own distinct sequence of mineralising events. As the Yavuna Group has uncertain affinities to the Wainimala Group, this terrain is separated from the younger rocks because of its more primitive arc geochemistry and uncertain tectonic relationship to the younger rocks presently found on the Fiji Platform.

Epoch 2 - Melanesian arc (32 - 7.5 Ma)

This epoch incorporates rocks that formed during the main period of activity of the continuous Vityaz arc. Two main suites are recognised within this epoch on Viti Levu (2A and 2B1). Rocks of similar age but uncertain affinities to those on Viti Levu are reported from the Yasawa islands (2B2). There is no record of rocks associated with this terrain on Vanua Levu.

Epoch 2A – Vityaz arc (32 - 14 Ma) - The main stratigraphic unit associated with this epoch is the Wainimala Group, which is located primarily on Viti Levu, but also on some of the offshore islands in the Mamanuca and Yasawa island groups. Different sections of the arc, including arc edifice and back arc Basin assemblages, have been recognised within this group in south-western Viti Levu (Hathway, 1994), although elsewhere on Viti Levu such detailed stratigraphic work is yet to be undertaken. The Savura Volcanic Group in south-eastern Viti Levu (Rodda, 1994) is of similar age to younger Wainimala Group strata, although the relationship to the Wainimala Group is uncertain.

The youngest rocks included in epoch 2 are those of the Tuva Group (Hathway and Colley, 1994), which are the first sedimentary rocks preserved after the cessation of the Wainimala Group strata at 14 Ma. They are not included within the younger epoch 2B as they are significantly different in character from the plutonic rocks of that epoch. No mineralisation has been reported from this suite of rocks.

Epoch 2B1 - Plutonism (12 - 7 Ma) - The Colo Plutonic Suite represents a period of enhanced plutonism in this sector of the Melanesian arc. There is a break in the stratigraphic record on Viti Levu between the end of the Wainimala Group and the intrusion of the Colo Plutonic Suite. Initial interpretation of these rocks suggested their appearance signified a major orogenic episode (Colo Orogeny Rodda and Kronke, 1984). More recent geochemical studies suggest these rocks are part of an intense but otherwise normal period of Vityaz arc volcanism (Gill, 1987). The intensity of arc volcanism indicated by the Colo rocks could be related to initial opening of the North Fiji Basin and partial sundering of the Vityaz arc that may have started as early as 12 Ma (Auzende and others, 1995).

Epoch 2B2 - Yasawa arc (8 - 7 Ma) - Volcanism on the Yasawa Islands occurred at the same time as Colo plutonism on the main island. The relationship of the Yasawa Volcanic Group (Rodda and Lum, 1990) to previous and subsequent geological events is complex. The boundary between epochs 2B and 3A may be gradual in the area around the Yasawa Islands (at the western edge of the platform). Mineralisation in the Yasawa Islands (Waya) appears to occur primarily within rocks equivalent to the Wainimala Group (epoch 2A) which are older than rocks of epoch 2B2.

Summary

Mineralisation is very common within this epoch, although no major deposits are currently being exploited. Most primary mineralisation associated with epoch 2A is that related to exhalative-type mineralising systems, including polymetallic-VMS (type E) and manganese (type F). Wainimala Group rocks are commonly the host rocks for younger deposits associated with epoch 2B1. Mineral deposits from epoch 2B1 are typically those associated with intrusive bodies, including vein gold (type B), skarn (type D) and some disseminated base metal deposits (type C2). Epoch 2 is equivalent to both the early arc (Wainimala Group) and mature arc (Colo Plutonic suite) phases of Colley and Flint (1995). No significant areas of mineralisation have presently been found to be directly associated with the Upper Miocene Yasawa Volcanic Group (epoch 2B2).

Elsewhere in the region surface exposures of rocks of equivalent age those of epoch 2 occur in the Noumuka Group of islands and on ʻEua in Tonga (Cunningham and Anscombe, 1985). Lithologies exposed here are primarily Miocene volcaniclastic sandstones and some carbonates. Drilling across the Tonga Platform indicates there are significant thicknesses of Late Oligocene to Middle Miocene volcaniclastic rocks with an equivalent age to that of the Wainimala Group (e.g. Tappin, 1993). Latest Oligocene to Late Miocene rocks are also present on Vanuatu (Carney and others, 1985), where they contain more volcanic lithologies that are seen on the Tonga Platform. While exploration has been undertaken as yet no significant mineral deposits have been reported from Vanuatu (Hutchison, 1998).

Epoch 3 - Arc breakup (7.5 - 3 Ma)

This epoch includes rocks formed during the final breakup of the Vityaz arc. The boundary between epoch 2 and 3 on Viti Levu may be gradational, and it is taken as those rocks formed after the Tuva deformational event. This event that occurred at around 7.5 Ma (Hathway, 1993) and it deformed all existing rock units (Yavuna, Wainimala and Tuva Groups) on Viti Levu. This epoch also marks the start of the stratigraphic record on Vanua Levu with the appearance of the Udu Volcanic Group (Rodda, 1994). Two subdivisions can be recognised during this complex phase of final arc development and break-up.

Epoch 3A - Tectono-volcanic (7.5 - 5.5 Ma) - Tectonism played a major role in influencing the deposition of rock units formed at this time. Sedimentary rocks were dominant on Viti Levu, although all sedimentary Basins contain intercalated volcanic rocks. These calc-alkaline (Gill, 1987) volcanic rocks occur as either relatively minor parts of the sequence, such as those within the Navosa and Ra Sedimentary Groups (Hathway and Colley, 1994; Hirst, 1965), or as major units such as the Namosi Andesite (Band, 1968; Rodda, 1976) in the Medrausucu Group. The Namosi Andesite is associated with major type C1 porphyry copper deposits. The record on Vanua Levu is initially dominated by the predominantly dacitic volcanic rocks of the Udu Volcanic Group which are associated with type E deposits (Rickard, 1970).

The presence of significant sedimentary sequences make it possible to further differentiate prospective areas on the epoch map (Figure 1). As most significant mineral deposits on the Fiji Platform appear to be associated with volcanic rocks, it may be advantageous to separate the predominantly sedimentary portions of this epoch to better define potential targets. This of course does not rule out the possibility that the sedimentary sequences may still host metallic mineral deposits associated adjacent volcanism

Epoch 3B - Volcanic (5.5-3 Ma) - From approximately 5.5 Ma onward, volcanic rocks dominated the stratigraphic record of the Fiji Platform (Rodda, 1994) particularly on Vanua Levu. Epoch 3B also sees the first appearance of shoshonitic rocks in the Koroimavua Volcanic Group and later in the Ba Volcanic Group from 5.6 Ma onward (Gill and Whelan, 1989a; Hathway, 1993). The incoming of shoshonitic rocks indicates unusual process occurring in the arc (Gill and Whelan, 1989a) possibly those related to the final break-up of the Vityaz arc. The commencement of opening of the Lau Basin to the east from 6 Ma onward (Hawkins, 1995) may have also contributed to the break-up of this section of the Vityaz arc.

Sedimentary rocks continued to be deposited in south-eastern Viti Levu (Medrausucu Group/ Verata Group) and in intra-arc Basins on both main islands (Vatukoro Greywacke, Vatutu Sandstone, "Dreketi Basin"). Many of the smaller volcanic islands across the Fiji Platform also formed at this time (Beqa). Arc-related volcanism across the platform ceased at around 3 Ma (Gill and Whelan, 1989a; 1989b).

Summary

Mineralisation during epoch 3A is that typically associated with island arc settings (types E and C), although mineralisation during epoch 3B appears have been the result of unusual conditions associated with the rapid breakup of the arc, which would account for the presence of the shoshonitic rocks. Epoch 3B contains a number of the Type A1 and A2 deposits including the most significant known mineral deposits on the Fiji Platform. Both the Emperor and Mt Kasi mines were formed at this time. It should be noted that in some cases (Emperor) mineralisation may significantly post-date formation of the host sequences (Setterfield and others, 1992).

Epoch 4 – Intra-plate (3 - 0 Ma)

With continued opening of the North Fiji Basin, the Fiji Platform moved further away from the active plate boundary, causing a cessation in island arc volcanic activity and the commencement of intra-plate alkaline volcanism (Gill and Whelan, 1989). The two subdivisions of this epoch are based on the origin of the deposits. The age of these suites is overlapping.

Epoch 4A – Intra-plate volcanism (3-0 Ma) - The largest single volcanic events associated with this epoch were the formation of the Seatura Volcano on Vanua Levu (Hindle and Colley, 1981), and the large islands of Koro and Taveuni (Rodda, 1994) to the north-east of Viti Levu. All volcanism on the

Fiji Platform during this period is of the alkaline intra-plate type (Gill and Whelan, 1989b).

Epoch 4B – Sedimentary processes (3 - 0 Ma)

Most clastic rock units preserved at this time are shallow marine to deltaic sediments deposited close the coasts of the main islands (Rodda, 1994). There is a degree of overlap between sedimentary sequences in south-eastern Viti Levu that were deposited across the boundary between epochs 3B and 4A.

Summary

No significant mineralisation has been associated with the alkalic volcanism of epoch 4A. However there is some mineralisation associated with the Pliocene to Recent (Whelan and others, 1985) arc-volcanic rocks on Kadavu (Colley and Flint, 1995; Wheller, 1998) to the south of the Fiji Platform. Mineralisation associated with epoch 4 on the Fiji Platform is restricted to type D2, and G residual and alluvial deposits formed by the reworking of the older "hard rock" deposits.

CONCLUSION

With the possible exception of the Yavuna Group, the rock suites present on the Fiji Platform all formed atop a single crustal Block. This might initially suggest that the geological evolution of Fiji Platform was relatively simple, possibly dominated by a single long-lived subduction system. In reality the geology of the Fiji Platform is much more complex. While the early history of the platform was indeed dominated by island arc volcanism, this was followed by a period of Block rotation during the Late Miocene where structural forces were dominant. A later episode of arc volcanism includes shoshonitic rocks which suggests that the tectonic setting of the platform at this time differed from that of the earlier arc phase. The Fiji Platform is presently under the influence of predominantly structural plate movements with occasional bursts of intra-plate alkaline volcanism.

The complex temporal evolution of the Fiji Platform is reflected in the distribution of many different rock units and in the distribution of mineral deposits. This temporal complexity has implications for the interpretation of ancient rock suites during regional exploration programmes. It shows that individual crustal Blocks may have a complex geological history, and even include a number of rock suites formed in different tectonic settings. So if exposure is poor and it is not possible to locate the terrane bounding fault, the presence of suites from different tectonic settings close to one another need not necessarily indicate the presence of a terrane boundary. Care should therefore be taken to ensure "terranes" that may be fragments of the same Block, but at different stages in its evolution, as identified as such during field mapping. Recognition of this fact will greatly aid in understanding the geological evolution of a region.

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A REVIEW OF MINERAL EXPLORATION PROGRAMMES IN FIJI: IMPLICATIONS FOR PROSPECTING IN THE SOUTHWEST PACIFIC

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ABSTRACT

A review of 38 exploration Programmes carried out in Fiji between 1976 and 1990 reveals a heavy reliance on geochemical prospecting. Principal targets in the exploration Programmes were deposits of epithermal gold, porphyry copper and volcanic massive sulphides. Early stages in the exploration were characterised by collection of rock chip samples and stream sediments; panned concentrates were also collected in around half the exploration Programmes. Historically panning has been very successful and all Fiji's major gold occurrences were discovered by this method. Follow-up soil geochemical surveys were conducted in 70% of the licences along surveyed grids and in pits and trenches. Channel sampling of rock was also common at this stage. Of 12 Programmes progressing to the drilling stage five had targets solely defined by geochemical prospecting. The survey shows that BLEG (bulk leach extractable gold) sampling and analysis is no more effective than traditional panning methods and that regional geochemistry is of limited value in targetting potentially mineralised districts.

Geophysical exploration methods, principally magnetic, electromagnetic (EM) and induced polarisation (IP) surveys, were employed in about 30% of the Programmes, usually at an advanced stage of exploration and commonly after drilling had commenced. Interpretation of EM and IP results was hampered by tropical-weathering clays giving long decay times which masked potential sulphide responses. The limited efficacy of geophysical methods led to a much greater reliance in the initial stages of exploration on geochemistry and geological mapping to define drill targets.

In all the exploration Programmes significant areas of hydrothermal alteration were located indicating that in volcanic terrains such alteration is the norm around volcanic centres. Of the 38 Programmes, two (Tuvatu and Mt Kasi) progressed to the mining or mine feasibility stage. This survey of exploration Programmes and the distribution of known prospects indicates that the rugged interior of Viti Levu, and to a lesser extent Vanua Levu, is still poorly explored. In particular exploration techniques applied so far appear to have limited potential for discovering mineral occurrences in larger river systems where there are significant alluvial deposits. The survey also indicates that the biggest challenge facing exploration geologists is not to locate areas of hydrothermal alteration and sulphide mineralisation, but to devise methods that can differentiate productive ground from barren hydrothermal ground in volcanic centres.

INTRODUCTION

In the last three decades or so there has been a considerable amount of exploration in Fiji with porphyry copper being the principal target in the 1970s and epithermal gold the target from the mid 1980s. For significant periods of time virtually all the major islands were covered by exploration licences and there was little free ground for the late-comers. With such a stampede of exploration there is a tendency to think that there is little left to do. However, this review and analysis will show that there are large areas for which we have very limited knowledge and even well-studied areas can turn up surprises. This is best illustrated by the Tuvatu prospect in western Viti Levu which on current expectations could turn out to be a significant gold deposit. The area around Tuvatu has been the subject of intense exploration with prospecting dating back to the turn of century but it was not until 1988 that a local prospector working for a small exploration company made the initial discovery of the Tuvatu lodes.

This paper provides a very brief historical review of exploration methods employed in Fiji in the current century and a more detailed analysis of 38 exploration Programmes carried out in the period between 1976 and 1990. The emphasis is on the exploration methods that have been used to define drilling targets. Data from the detailed surveys were gathered while the author was reviewing exploration company reports in the preparation of the memoir on the Metallic Mineral Deposits of Fiji (Colley and Flint 1995). Further details on the mines and prospects mentioned in this paper are provided in the memoir. An outline of the geological terrains is shown in Figure 1 and the relationship between mineral deposits and terrains is given elsewhere in this volume (see Stratford). The one significant feature to point out is that most of the known deposits in Fiji are found within terrains 3AV and 3BV (Figure 1) which are dominated by Late Miocene volcanic rocks and associated volcaniclastic sediments and a period of mild deformation and crustal extension; the so-called 'Colo Orogeny' (see Colley & Greenbaum 1980). Figure 2 illustrates the distribution of prospects in Fiji and indicates deposit types and relationship to the 'orogenic' event.

BRIEF HISTORICAL REVIEW

Prior to the 1950s the accepted method for exploration was to carry out geological prospecting and panning. Prospectors were looking for 'colours' in the pan, mineralised and altered float in the streams and obvious in situ signs of mineralisation such as silicification, quartz veining and gossan development. A number of major prospects were discovered and mining began at Vatukoula, Mt Kasi, Wainivesi and Colo-i-Suva but only Vatukoula proved to be viable in the longer term.

In the 1950s further exploration was aided by the creation of the Geological Survey of Fiji and the commencement of a comprehensive geological mapping programme at a scale of 1:50,000. This regional mapping programme continued for about 20 years and the major benefit for exploration was that mineralisation could now be viewed in a detailed geological context leading to a better understanding of deposit formation. During the early years of the Geological Survey, geophysical technques, principally magnetic and self-potential(SP) methods, were introduced to Fiji for the first time. Much of this early work was carried out in collaboration with Emperor Mines of Vatukoula. The geophysical approach had modest success in defining new massive sulphide targets, particularly in drier climatic zones (e.g. north-east Vanua Levu).

The next significant milestone in promoting exploration was the initiation by the Geological Survey in 1966 of a regional 1:50,000 geochemical mapping programme designed to provide multi-element analysis of stream sediments from all the major islands in Fiji. This work was boosted in 1968 when the Fiji Government and Barringer Fiji Ltd formed a joint venture to complete the regional geochemical survey and also provide regional aeromagnetic and radiophase surveys. The geophysical surveys were completed by 1970 and the geochemical surveys by 1972. Companies prospecting in Fiji from 1972 onwards have had access to a substantial Government database that includes map coverage of the major islands for regional geology, geochemistry and airborne geophysics. The next advance was the funding provided by a consortium of exploration companies for the Mineral Resources Department to acquire side-looking airborne radar imagery (SLAR) of Vanua levu and Viti Levu. This imagery proved to be very useful for picking out major structural features and delineating eroded volcanic centres in terrain where conventional aerial photographic interpretation was commonly hampered by cloud cover and dense vegetation.

Table 1 presents details of the discovery methods for 53 of the more important prospects in Fiji; most of these were discovered prior to 1976. This table indicates the success of a 'geological' approach to prospecting which generally involves mapping and sampling ,principally along creek traverses, of in situ rock and float; this approach commonly also included panning. Geophysical methods were mainly successful in helping to define structural extensions of known deposits.

In the 1990s a further milestone in exploration has been reached with detailed geophysical and geochemical surveys showing a progressive change of focus from the regional to the district scale. This programme was conducted through a Japanese aid programme in which JICA-MMAJ (Japanese International Cooperation Agency-Metal Mining Agency of Japan) carried out regional gravity and aeromagnetic surveys on Viti Levu followed up with detailed geophysical, geochemical and

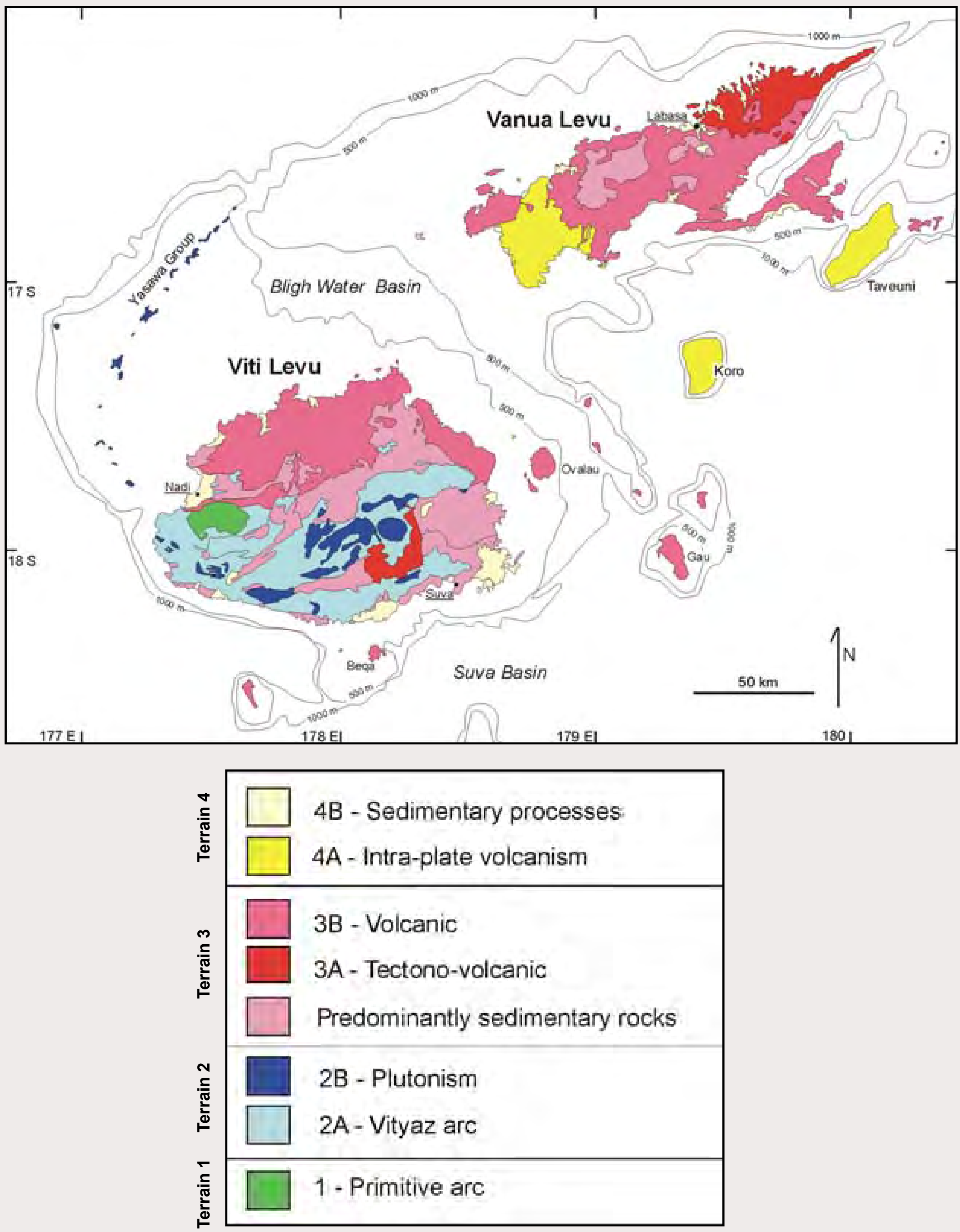

Figure 1. The geology of the Fiji Platform showing the major types of terrain (taken from Stratford (this volume) where a fuller caption is provided).

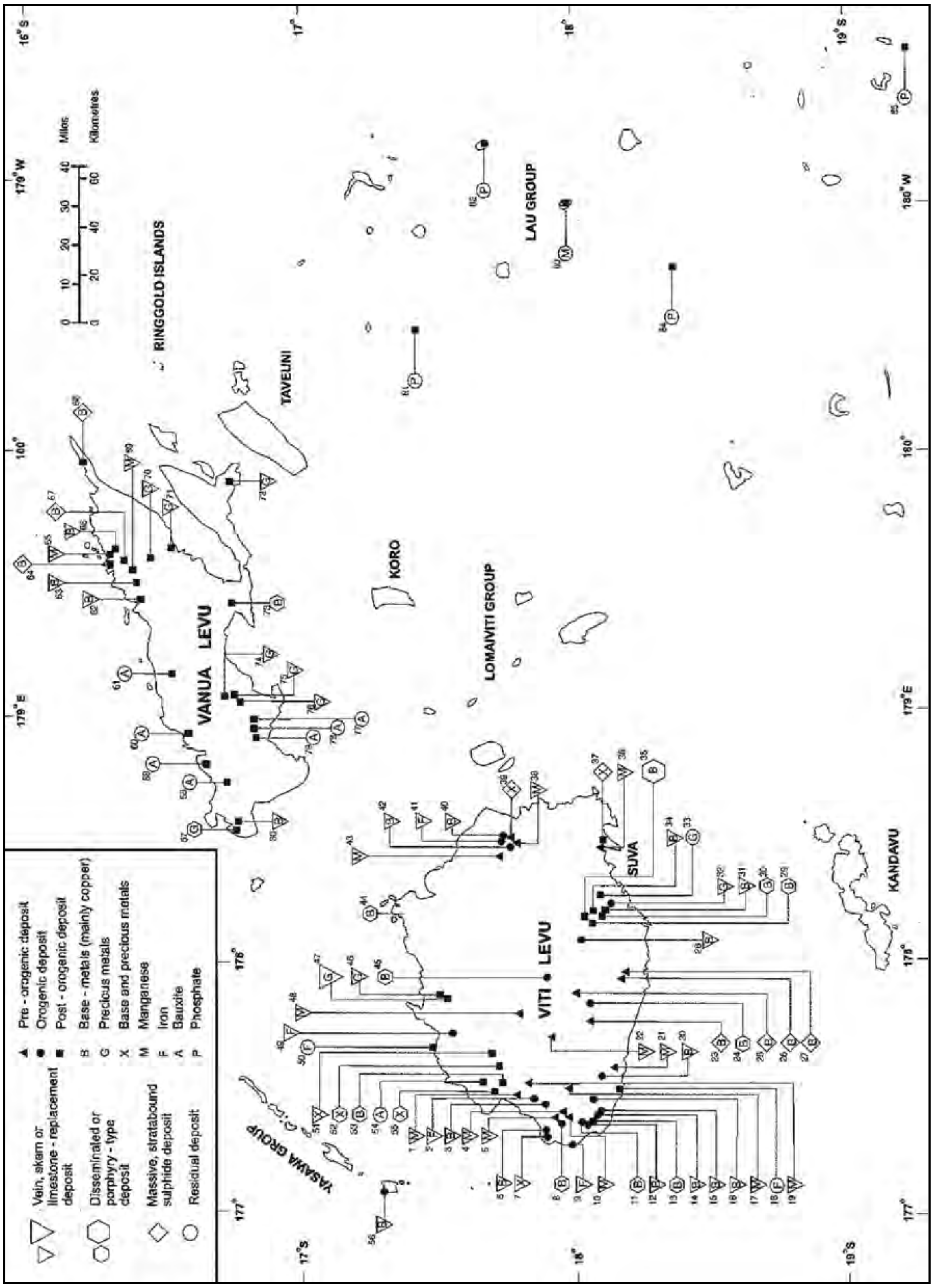

Figure 2. Location of major prospects in Fiji (adapted from Colley and Greenbaum, 1980). Prospects mentioned in the text are numbered as follows: Banana Creek (52), Ciriniu (66), Colo-I-Suva (37), Dakuniba (72), Faddy's (7), Koroisa (8), Mouta (64), Mt Kasi (75), Nailaga (49), Peni's Farm (46), Rakiraki (44), Rama Creek (24), Savudrodro (73), Tau (9), Tuvatu (52), Udu (68), Vatukoula (47), Vudibasoga (61), Waimanu river (33), Wainabama (29), Wainikoro (67), Wainivesi (39), Waisoi (35). Note the uneven distribution of prospects with seemingly barren areas in the centres of Viti Levu and Vanua Levu.

Table 1. Discovery method for major mineral occurrences in Fiji.

METHOD	NUMBER OF DISCOVERIES
Geological mapping and traversing	36
Geochemical prospecting	12
Geophysical prospecting	5*

*all extensions of known deposits

geological work on potential prospect areas. A feature of this survey was the manner in which geophysical surveys were used to gain a greater understanding of the general subsurface geology rather than focusing exclusively on potential mineralised structures. More recently this emphasis on understanding regional subsurface geology has continued with further airborne regional aeromagnetic and radiometric surveys (K, Th, U) provided through an AusAid programme. Details of this latest geophysical work are documented by Gunn et al. elsewhere in this volume.

In addition to the comprehensive map coverage referred to above the Mineral Resources Department of Fiji (formerly the Geological Survey) maintains a well-referenced archive of open file reports on exploration company activities and has published a number of memoirs which summarise these activities (Houtz and Phillips 1963: Colley 1976: and Colley and Flint 1995).

EXPLORATION PROGRAMMES

Exploration Programmes can use both geochemical and geophysical exploration techniques and it is important that these be viewed as complementary rather than representing alternative approaches to discovering mineral deposits. In ideal conditions the two approaches can give different sets of information: geochemical methods reveal the types of metals in the deposit and an indication of ore grade; geophysical methods outline the size, shape and subsurface depth of a potential orebody. However, in the real world ideal conditions are not common and so one method tends to gain favour over the other as the principal approach to exploration. In general terms geochemical exploration works best in rugged, wet terrains where rapid erosion and weathering vigorously attack the potential orebody releasing metal ions and ore particles into groundwater, soils, and drainage sediments; it tends not to work well in flat areas with sluggish drainage, arctic and tundra areas where water is frozen for much of the year, or in areas that have a thick superficial cover of transported material (e.g. glacial till). Geophysical methods tend to work best in drier and less rugged terrains where complications arising from the presence of abundant water and correcting for varying elevation are minimised.

Construction of exploration Programmes in Fiji follows, with one notable exception, a pattern that is widely-quoted in textbooks on mineral exploration and a typical programme employs the following methods:

- stream sediment sampling
- mapping and sampling of float and in situ rock
- soil sampling of a surveyed grid
- ground magnetic survey (optional) and
- pitting and trenching.

POINT OF MAJOR DECISION ON THE NEED FOR FURTHER PROSPECTING

Diamond drilling and/or reverse circulation drilling

Geophysical surveys

The exception is the time when geophysical surveys are carried out. As will be pointed out later there are considerable problems in conducting geophysical exploration in Fiji at the prospect stage, consequently a significant number of exploration Programmes do not use geophysical methods. However, as the recent AusAid programme has shown the use of geophysics can be very valuable aid in the regional analysis of geology. Where geophysical surveys are used to investigate a prospect then commonly it is at the stage when drilling is being carried out. Company reports studied in this investigation indicate that the use of geophysical prospecting is not normally considered in the initial design of the programme but occurs at an advanced stage when field geologists are under pressure to come up with a subsurface geological model and core data are not sufficient to give subsurface continuity to such a model.

Figure 3 provides an analysis of the exploration methods adopted in 38 licence areas in Fiji during the period 1976 to 1990 and Tables 2 and 3 illustrate case histories for two of Fiji's most important prospects. This analysis and the case histories indicate the overwhelming reliance on a geochemical approach in the initial stages of exploration and that drill targets are invariably located by soil geochemistry coupled with geological mapping of the survey

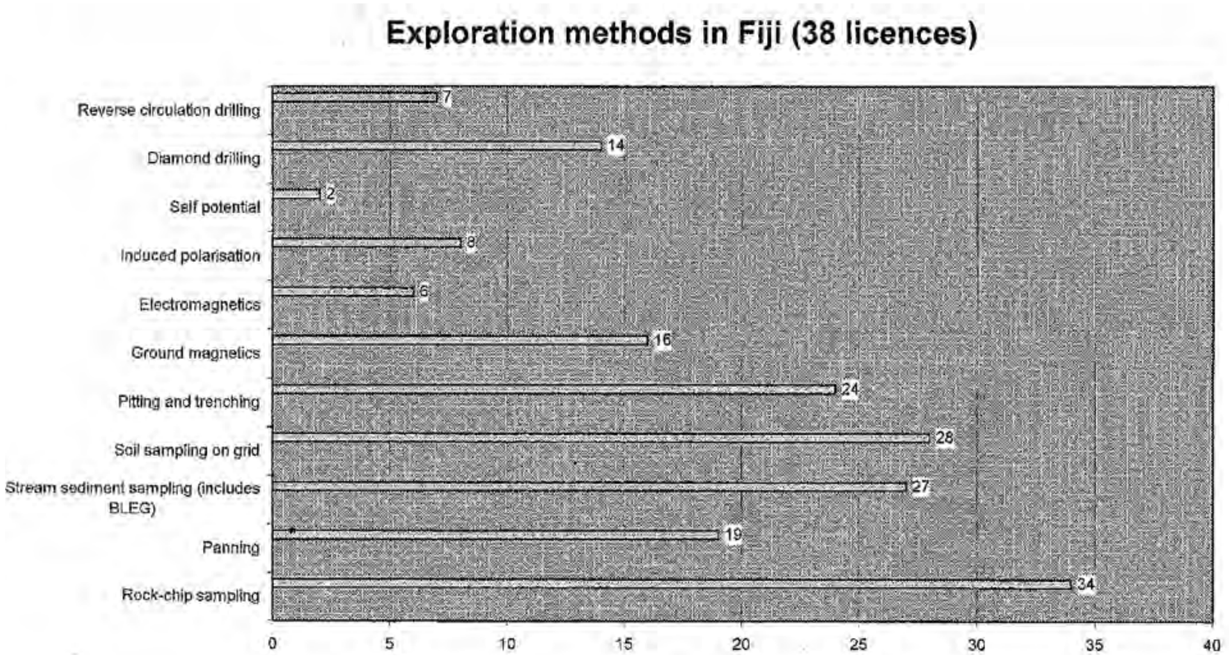

Figure 3. Graph illustrating the extent of application of common exploration techniques in 38 licence areas investigated in Fiji between 1976 and 1990.

Table 2. Case study – Waisoi Creek, Namosi.

Location	Waisoi Creek, Namosi district, south-east Viti Levu, Fiji.
Geology	Eroded andesitic volcanic centre(s) with exposure of dioritic subvolcanic intrusions and 'windows' through to underlying basic andesitic 'basement' rocks.
Prospect type	Porphyry copper deposit with low Au and Mo contents.
Discovery methods	Gold prospecting in the 1930s noted occurrence of quartz-sulphide veining in the Namosi region; Geological Survey regional mapping of the Namosi district in the early 1960s reported in the Waisoi drainage propylitic alteration over several km^2 , malachite staining and quartz vein stockworks; Government invited bids for prospecting licence in 1968 and over the next 3 years the target zone in Waisoi creek is defined by geochemical stream sediment survey (some 2000 samples) and follow-up soil surveys.
Geochemical prospecting	Effective because high rainfall produces long geochemical dispersion trains (3 km with up to x 12 background values), however, soil anomalies (up to 0.65% Cu) sometimes masked by barren material brought down by numerous landslides in rugged terrain (see Figure 5).
Geophysical prospecting	Of limited use because interpretation of induced polarisation and other electrical surveys compromised by abundance of groundwater and deep-weathered lateritic clays; strongly magnetic host-rocks complicate interpretation of aeromagnetic and ground magnetic surveys, however, classic 'doughnut-shaped' magnetic anomalies are partially developed.
Drilling targets	Soil anomalies with ^{3} 5000 ppm Cu over 2 km^2; drilling of about 40 km of diamond drilling between 1972 and 1976 estimates 590 million tonnes of ore at grade of 0.47% Cu. Further drilling in the 1990s on newly surveyed geochemical anomalies and IP, SP and magnetic targets gives revised estimate of 930 million tonnes at 0.43% Cu, 0.14 g/t Au and 50ppm Mo. Altogether about 62 km of drilling has been carried out at the prospect.
Evaluation	Pre-feasibility studies in 1978 - 1980 concluded that the prospect was subeconomic given the current demand and price for copper; the pre-feasibility studies of 1991 - 1992 have not been followed up.

Table 3. Case Study – Udu Mine.

Location	Nukudamu Creek, Udu Peninsula, north-east Vanua Levu, Fiji
Geology	Flank succession of submarine volcano consisting of massive rhyodacitic pumiceous breccias, pumiceous and calcareous volcanic sediments and a small intrusion of quartz-plagioclase porphyritic rhyolite.
Prospect type	Volcanic-hosted massive sulphide with close affinities to kuroko-type mineralisation.
Discovery methods	Found in 1959 by local prospector locating gossan covering an area 750 x 30 metres.
Geochemical prospecting	Survey by Imperial College, London in 1962 - 1963 sampled stream sediments, tidal flats, soils, rocks and vegetation (see Figure 4). Anomalies found in all sample types with soils proving most effective with Cu values up to x 20 background. Tidal flat anomaly extended for 1.5 km north-east of prospect. Stream sediment sampling severely hampered by: very short length of streams (usually less than 1 km), pronounced dry season with no water flows, and stagnant pools with accumulation of organic matter.
Geophysical prospecting	IP and other electrical methods compromised by deep lateritic clays and intense argillic alteration. Gravity surveys detecting massive sulphide lenses to depths of 130 metres owing to strong density contrast between ore and pumiceous host-rocks.
Drilling targets	Between 1962 - 1969 Banno Brothers sank 381 DDHs (20 km of drilling), however, recovery was less than 5% in 60% of the holes owing to very poor drilling techniques in difficult ground. Drill holes targetted mainly by geological intuition and interpretation (e.g. drilling beneath surface gossan). The last hundred or so holes had good recovery and drill targets included geophysical and geochemical anomalies
Evaluation	Initial tonnage estimate based on suspect drilling programme was 3.5M tonnes. Soon after mining commenced in 1968 this was revised downwards to 150,000 tonnes as the original deposit model was found to be wildly inaccurate (see Figure 9). The mine closed in late 1968 having produced 32,500 tonnes of concentrate containing 6% Cu and 6.7% Zn. Further evaluation for Au was carried out in by Geopacific in 1990 with the drilling of 4 DDH through massive sulphide lenses, however, values were found to be subeconomic.

grid. The only popular geophysical method in use in the early stages is ground magnetics, even so this was employed in less than half the licence areas. The indication in company reports is that the use of ground magnetics at an early stage is more an aid in interpreting the geology of deeply weathered terrain than in defining mineral targets. Of the 38 licence areas only three used a geophysical method to define a drill target. At the drilling stage diamond drilling was preferred and in only three licence areas was reverse circulation drilling used exclusively. In a number of licence areas where both diamond and reverse circulation drilling were employed it was commonly difficult to reconcile the assay results gained from core and chips even when the respective holes were in close proximity.

GEOCHEMICAL PROSPECTING

For convenience stream sediment panning will be included in this section although in Fiji this method is primarily used for mineralogical identification rather than chemical analysis.

Drainage surveys

Generally speaking geochemical methods work well in Fiji's rugged terrain where there is considerable rainfall and rapid erosion. Large targets such as porphyry coppers commonly have stream sediment dispersion trains up to 3 km in length with distal anomaly values between x 2 and x 4 background. Massive sulphide targets usually give dispersion trains under 1km with anomaly values having an erratic range from x 2 to x 10 background. During the search for epithermal gold targets in the 1980s a number of companies employed a bulk leach extractable gold (BLEG) sampling procedure. This generally involved wet sieving of 5 to 10 kg samples on site and analysis of the -80 mesh fraction and in some cases flocculation and analysis of the fines. No major new prospects were discovered using the BLEG approach but it did have modest success in confirming known mineralisation. For example at the Rama Creek prospect, very low value BLEG anomalies led to follow-up rock chip sampling and assay which gave values of up to 125g/t Ag. In a small number of licence areas BLEG sampling and panning were carried out concurrently and it was found that panning was as effective as the

BLEG approach. This, coupled with the historical success in Fiji of panning for locating major prospects, suggests that panning might be the preferred option for rapid, cheap reconnaissance surveys of drainages for gold mineralisation. A further advantage is that panning surveys can be carried out by locally-hired samplers following a minimum of training. In most areas of Fiji, the basic to intermediate bedrock types produce a black 'tail' in the pan that is dominated by magnetite, ilmenite and pyroxene, consequently gold 'colours' in the pan are easily spotted. In coastal locations extension of drainage anomalies into tidal flats has been recorded most notably in tidal flats of the Ba river delta and by the Udu mine at Nukudamu (Figure 4).

Problems

Although stream sediment surveys have a good success record in locating mineralisation analysis of company reports show areas in which these surveys have limited application. Particular problems include the following:

- rapid dilution of anomalies in major rivers through the masking of anomalies by unmineralised alluvium
- masking of anomalies by unmineralised landslip material in the upper drainages
- choking of drainages with unmineralised soil in cultivated areas.

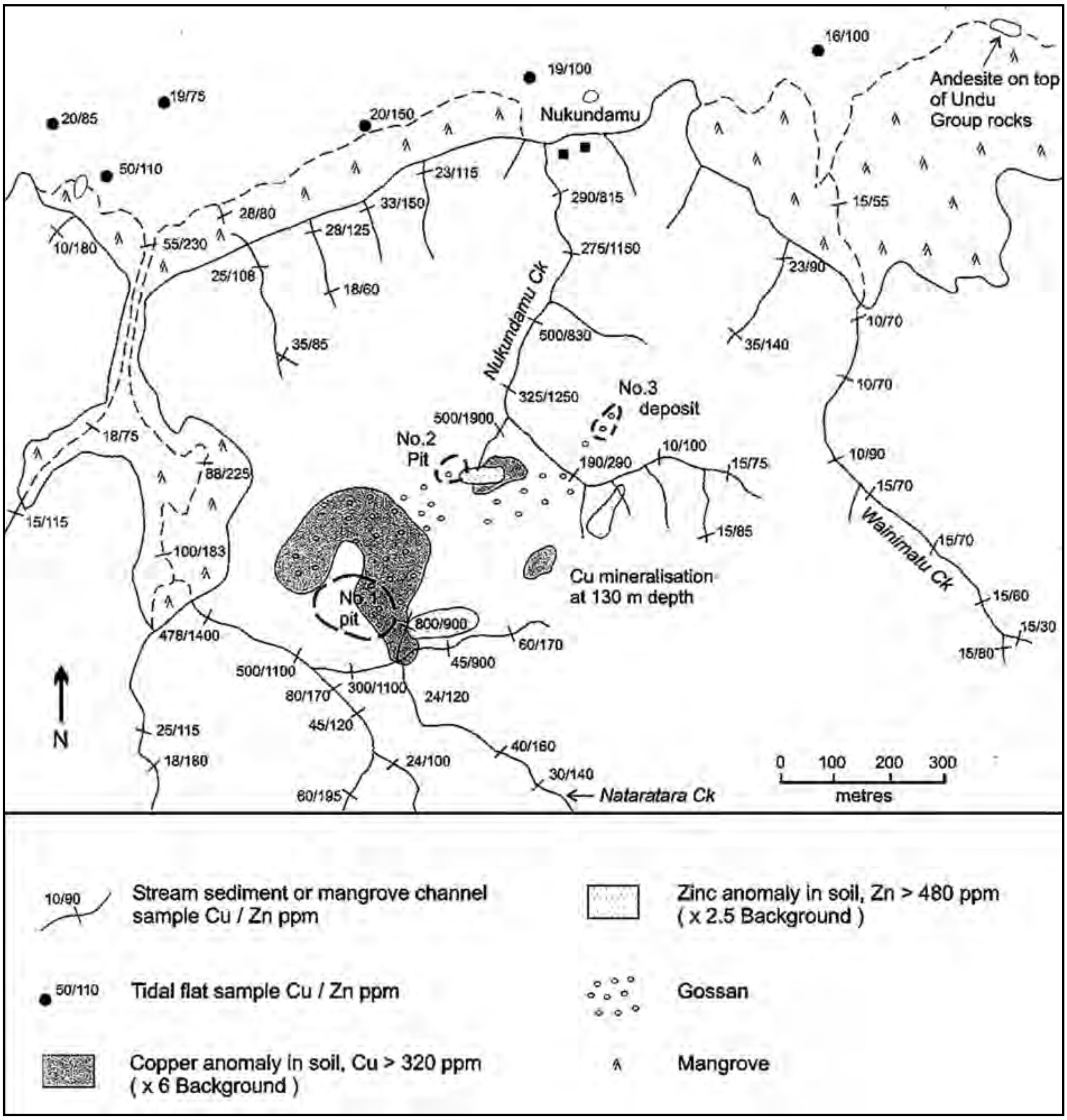

Figure 4. Geochemical survey of the Nukudamu coast by Imperial College, London in 1962 - 63.

These factors are commonly combined in valleys of the larger rivers and are so acute as to render drainage sampling almost useless. For example, in the Namosi district (Figure 5) virtually all the anomalies are confined to the upper parts of drainages and the major Waidina river valley is apparently barren. This pattern of anomaly distribution is repeated in many other areas giving the impression that almost all the major river valleys in Fiji are devoid of mineralisation. If this is a true distribution then it is statistically quite remarkable, however, it is far more likely that the distribution reflects the limitations of conventional geochemical sampling in larger drainages. This particular problem was encountered in the investigation of the Savudrodro prospect near Savusavu (Colley 1981). Geochemical expression in stream sediments was masked by unmineralised alluvial cover, however, drilling through the cover revealed strongly altered and moderately mineralised bedrock. In view of the problems posed by alluvial cover it is probably not an exaggeration to say that that at the present time the majority of major river valleys in Fiji should be regarded as unexplored ground.

Soil surveys

A review of the theoretical concepts that explain metal distribution in soil profiles is beyond the scope of this short paper and readers are referred to standard texts on exploration geochemistry (e.g. Evans 1995; Rose, Hawkes & Webb, 1979). However, it will be useful to outline some basic principles:

- The A horizon of the soil profile is dominated by decaying organic matter which produces organic acids.
- As the organic acid moves down through the profile in groundwater it leaches metal from the upper part of the B horizon so sampling of this metal depleted zone is avoided.
- Normally the metals in solution are precipitated out on to clays and iron oxides in the lower part of the B horizon. This enhances the metal content making it the ideal level for soil sampling.
- The C horizon is where bedrock is breaking down and it at this point that mineralised material is released from the bedrock into the soil. Again this can be a useful level for sampling though the metal values may be lower than in the B horizon just above.
- The final important point to consider is that the soil profile in rugged tropical terrain is not static. The weathering front is moving continuously down into fresh bedrock and material is being removed at the top of the soil profile through such mechanisms as downslope soil creep and sheetwash during and after heavy rainstorms.

Figure 3 indicates the heavy reliance placed on soil geochemistry in defining drill targets and this trust is generally well justified as drilling of soil targets has proved significant mineralisation in many licence areas. However successful application of soil geochemistry is not without problems, these relate principally to anomaly size, the depth of sampling, and using pathfinder elements.

Anomaly size

At the Waisoi porphyry copper prospect the soil copper anomaly covered a very large area of approximately 2700 m x 1800 m (Leggo, 1977) and the difficulty at the initial drilling stage was to pick out targets in this very extensive anomaly. The situation was also complicated by landslipping of unmineralised material across the Waisoi prospect (Figure 6). At the opposite end of the scale the Tuvatu gold prospect, which on current expectations could develop into a significant gold mine, had a single spot anomaly of 1.4g/t Au. This was within a grid with 44,000 metres of line and 876 sample stations. This anomaly was ignored by the initial licence holders because their preferred target was a porphyry copper and so they focussed on a much larger copper anomaly (>500ppm Cu values) just to the north of the gold anomaly. Follow-up work in 1988, some 10 years after the initial survey, by a new licence holder located gold-bearing veins in the vicinity of the spot gold anomaly. The Tuvatu experience suggests that any gold anomaly in a soil survey, no matter how small and isolated, is worth some form of follow up.

Sampling depth

Company reports indicate that generally field crews prefer to sample at some pre-determined depth after carrying out rather cursory orientation sampling through the soil profile in the target zone. The sample depth is usually between 0.75 and 1.0 metres and is commonly reported as representing the C or C/B horizon. Given that the C horizon is commonly many metres thick, this arbitrary approach has proved surprisingly successful in defining copper anomalies in soils over porphyry copper prospects. However, there is some evidence to suggest that a more detailed orientation survey

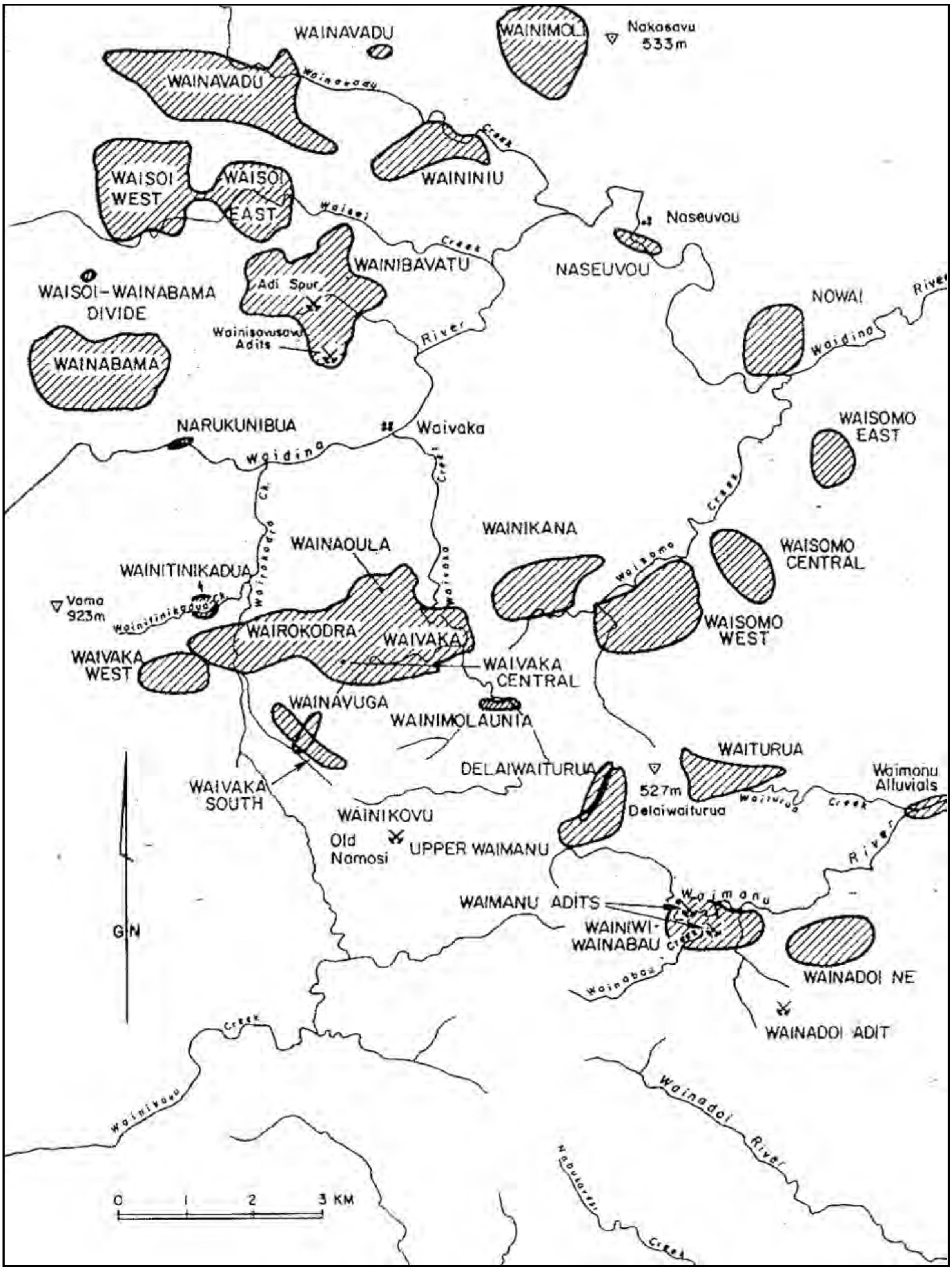

Figure 5. Map of the Namosi district showing the distribution of copper anomalies (shaded areas), note the absence of anomalies along the Waindina river.

is required for gold prospects. For example, at the Vudibasoga prospect in Vanua Levu initial soil sampling either of the A or A/B horizon between 0.5 and 0.8 metres recorded only one spot gold anomaly. A second survey, taking samples from over 2 metres depth in the B/C or C horizon, proved a much bigger anomaly with a strike length of 500 metres and gold values of up to 2.2g/t. As a general rule it would appear that sampling of the C or B/C horizon in Fiji does yield more reliable results. This is to be expected given the considerable depth of weathering and high mobility of elements in the upper soil horizons owing to the abundance of acids produced by organic decay. Sampling at the B/C horizon may present technical problems as this may be many metres below the surface and require power auger drilling to reach the sampling level.

Hg as a pathfinder element

On a number of occasions exploration for extensions of the Vatukoula mine in the Tavua Caldera has employed the analysis of Hg as a pathfinder element for Au. In the most recent survey 220 samples taken from the A horizon showed no significant anomalies. This repeats the results of work carried out in the 1960s in the Tavua Caldera where again the use of Hg as a pathfinder had little

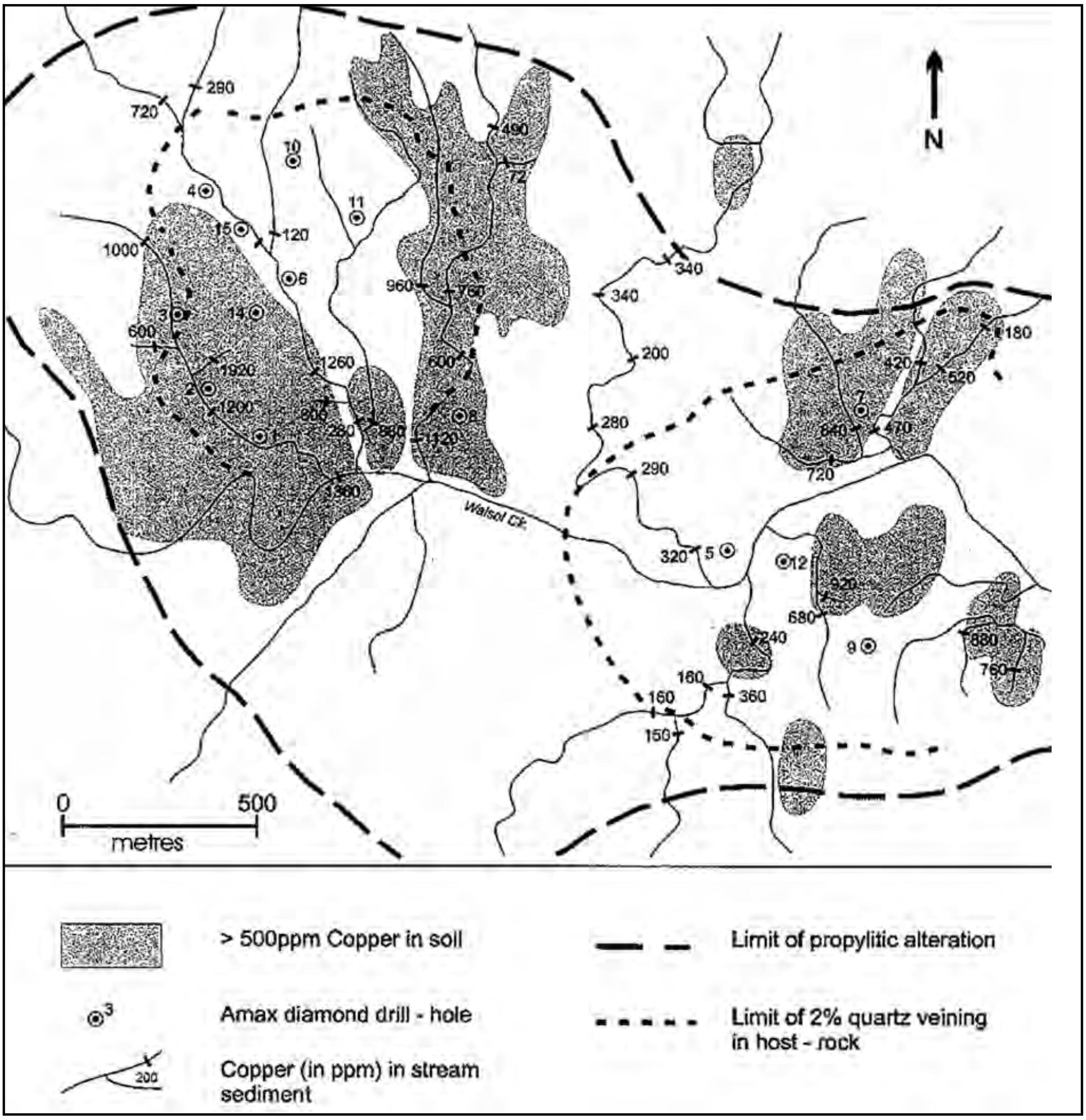

Figure 6. Map of the Waisoi prospect in the Namosi district showing how the soil copper anomaly is cut by barren ground developed on a landslip.

success (Williams, 1965). Interestingly electron microprobe studies by the author have shown that pyrite associated with gold mineralisation at Vatukoula does carry a trace of Hg so further investigation and testing of the use of Hg as a pathfinder could have potential benefit. Another potential pathfinder element worthy of further investigation is As. Again at Vatukoula gold is commonly associated with As-bearing pyrite or arsenopyrite. Analysis of As in samples has been carried out in a number of surveys but has not been assessed as a pathfinder because the samples have also been analysed for Au and Ag and anomalous zones are determined using these elements.

GEOPHYSICAL PROSPECTING

Conventional wisdom holds that geophysical prospecting does not work well in wet, tropical climates. In Fiji this is more or less true for those Programmes using geophysical methods at the prospect prior to drilling. In most cases it is very difficult to model what is invariably very noisy data in a manner that convincingly matches existing geological maps and other data. However if geophysical methods are used at the drilling stage a more rigorous subsurface geological control can be applied and significant anomalies can be detected within the noisy background. Even with the drawbacks it should be appreciated that application of geophysical methods is more or less essential for subsurface geological modelling of prospect size and shape and defining targets for deeper drilling.

Problems

The major problems for geophysical surveying in Fiji are:

- rugged terrain requiring complex correction of raw data for variable elevation
- an abundance of subsurface water (water, like copper sulphide minerals is a good conductor of electricity)
- deep tropical weathering of highly variable thickness (e.g. at Waisoi from 40 m to 300 m) with surveys passing rapidly from weathered to unweathered rock each of which can have a markedly different geophysical signature
- highly conductive clay-rich overburden which can mimic the response of sulphide mineralisation in electrical surveys
- very long decay times for induced polarisation signals again mimicking the response from sulphide mineralisation
- strong magnetic signals from the basic to andesitic country rock which make it difficult to detect magnetic orebodies.

Despite these difficulties geophysical prospecting, as shown below, has been successful in a number of exploration Programmes and indeed for one method, self-potential surveying, the wet, tropical climate is ideal. In these conditions the chemical weathering of sulphide orebodies is rapid and the production of positively charged metallic ions effectively turns the orebody into a giant battery producing its own detectable electrical current.

Magnetic surveys

Magnetite is by far the most magnetic mineral and if it is present it will normally dominate the response in a magnetic survey. In Fiji magnetic anomalies related to mineralisation may occur as lows, highs, or as linear anomalies. Magnetic *lows* are related to the destruction by hydrothermal alteration of magnetite in the host rock and such lows have been detected at the Waisoi porphyry copper prospect and at the Cirianiu gold prospect in Vanua Levu. Magnetic *highs* have helped to define copper mineralisation at the Wainabama prospect in the Namosi district. This prospect is regarded as the product of a low-sulphidation porphyry system where the lack of sulphur in an environment dominated by Fe-rich ore fluids leads to the development of magnetite rather than pyrite as the common accessory mineral. At Wainabama magnetite can be seen as a selvage to copper-sulphide bearing quartz veins. Unfortunately interpretation of magnetic anomalies in the Namosi district is complicated because the basal Namosi conglomerate contains numerous magnetite-bearing gabbroic cobbles and this rock unit generates magnetic highs. Magnetite highs have also helped to locate subsurface magnetite skarn occurrences in the Wainivesi district and at Tau in western Viti Levu. In both these areas similar anomalous highs are also produced by basic dykes and other intrusives, however, these may be distinguished by the *linear* nature of the anomaly. In rare instances linear anomalies may relate to mineralisation, for example, the Au-bearing Cowboy Vein at Vudibasoga has produced a linear magnetic high.

Electrical surveys

The long decay times resulting from an abundance of clays produced by tropical weathering has severely hampered the use of IP (induced polarisation) in many surveys. Nevertheless *chargeability lows* have defined gossan and a pyritic halo at Waisoi. The most successful application though is the mapping of *resistivity highs* during IP and CSAMT (controlled source audio-frequency magneto-tellurics) surveys. At a number of prospects: Koroisa, Wainikoro, Dakuniba, and Cirianiu resistivity highs have located major silicified structures carrying significant mineralisation. The most recent success is at Mt Kasi mine where resistivity highs in a CSAMT survey have identified silicified zones at depth which have been interpreted as upflow and outflow zones of a Au-bearing hot spring system. Finally it should be noted that self-potential (SP) surveys proved successful in the late 1950s in defining the subsurface characteristics of shallowly-buried massive sulphide mineralisation at prospects such as Wainivesi mine, Udu mine and Mouta. Given this response a potential method for exploring for massive sulphides is to use the CST (constant separation traversing) resistivity surveying as this mimics an enhanced SP response.

Gravity surveys

Gravity surveys have rarely been employed by exploration companies because the small size of orebodies means they rarely produce a significant gravity anomaly. However, a gravity survey did succeed in defining massive sulphide mineralisation at a depth of 130 m, subsequently proved by drilling, at the abandoned Udu mine in north-east Vanua Levu. The occurrence of very dense, massive sulphide mineralisation in the exceptionally low density, pumiceous dacitic-rhyolitic host rocks of the Udu Group offers the best opportunity in Fiji for applying gravity methods. More recently gravity was used in the JICA-MMAJ survey of the Rakiraki area to assist in defining volcanic centres in the Rakiraki district (Figure 7). The success of this approach indicates that there may be scope for employing gravity surveys to map eroded volcanic structures elsewhere in Fiji.

FLUID INCLUSION STUDIES

The study of fluid inclusions provides a very useful tool for mineral exploration. Although a thorough review is beyond the scope of this paper, and readers are referred to standard texts such as Shepherd et al. 1985, it will be useful to outline some of the key findings arising from fluid inclusion investigations:

- Measurements of fluid temperatures and salinities give an indication of the type of ore-forming system (e.g. porphyry systems tend to have high temperature phase with homogenisation temperatures (T_h) at >400°C and high salinity indicative of magmatically-derived ore fluids; epithermal systems tend to lower temperatures, T_h <300°C, and low salinities indicating ore fluids with a meteoric water component.)
- The chemistry of the fluids can give an indication of the fluid's capacity to carry ore metals, generally speaking the higher the salinity the more metal that can be carried.
- Studies can also reveal the possibility of rapid precipitation of metals from solutions through such phenomena as boiling and effervescence of ore fluids caused by pressure decreases as fluids rise to the surface, and/or mixing of two fluid types (e.g. hot ore fluid with cool groundwater or seawater.)
- Finally fluid inclusion characteristics can be used to distinguish barren vein systems from productive ones.

The value of fluid inclusion studies became apparent during the upsurge in exploration for epithermal gold deposits in the 1980s because of the ability to predict fluid boiling which can lead to bonanza grades of ore. During the boom in exploration for epithermal gold in Fiji at this time a number of companies commissioned fluid inclusion studies. With one or two notable exceptions (e.g. Mt.Kasi, Vatukoula) these studies cannot be considered as reliable. The main problem is that studies were restricted to simple measurements on no more than 3 or 4 inclusions. For reliable results measurement of upwards of 50 inclusions are needed to support the case for boiling of ore fluids. The inclusions should belong to the same generation of quartz veining, have similar homogenisation temperatures (T_h) but show variable liquid-vapour ratios. Establishing the different types and generations of inclusions is generally a slow and tedious business involving the measurement of several hundred inclusions. To determine the depth of boiling with a reasonable degree of accuracy inclusion studies need to produce carefully constructed boiling point curves and/or to produce isochore plots of H_2O and CO_2. The commissioned work generally did not show this degree of detailed analysis. There is good research work on Fijian deposits to indicate that fluid inclusion studies can be extremely useful in modelling hydrothermal events. For example the work by Ahmad et al., 1987 at Vatukoula has produced detailed boiling point curves correlated to mine levels (Figure 8) which allow geologists to locate potential high-grade zones. However, to gain such detailed results Ahmad studied inclusions from 37 different vein samples and made several hundred measurements of inclusions in the course of completing a PhD study (Ahmad 1979). This highlights the tensions that arise for exploration companies commissioning fluid inclusion studies: should they speculate on a very small number of measurements that can be done quickly? Or should they support more detailed research work that may take a number of months or years to be completed.

NEW DISCOVERIES AND THEIR DISTRIBUTION

Table 4 lists some of the more significant discoveries made during the period 1976 to 1990. Given the strong international focus on gold targets during this period it is not surprising that the new discoveries are either epithermal or porphyry-related gold deposits. The table also indicates the continuing success of a geological-geochemical approach to prospecting in Fiji with all these new discoveries having a good geochemical response. Figure 2, which includes both the older and new prospect locations, shows that distribution is uneven with the rugged interiors of Viti Levu and Vanua Levu appearing to be barren. In addition all the major rivers (e.g. Ba, Nadi, Sigatoka, Navua, Waindina, Wainimala) appear to be devoid of mineralisation. Such a distribution does not make statistical sense and rather than lacking mineralisation it is much more likely that these interior areas and the larger rivers have not been studied sufficiently and could contain sites of significant mineralisation.

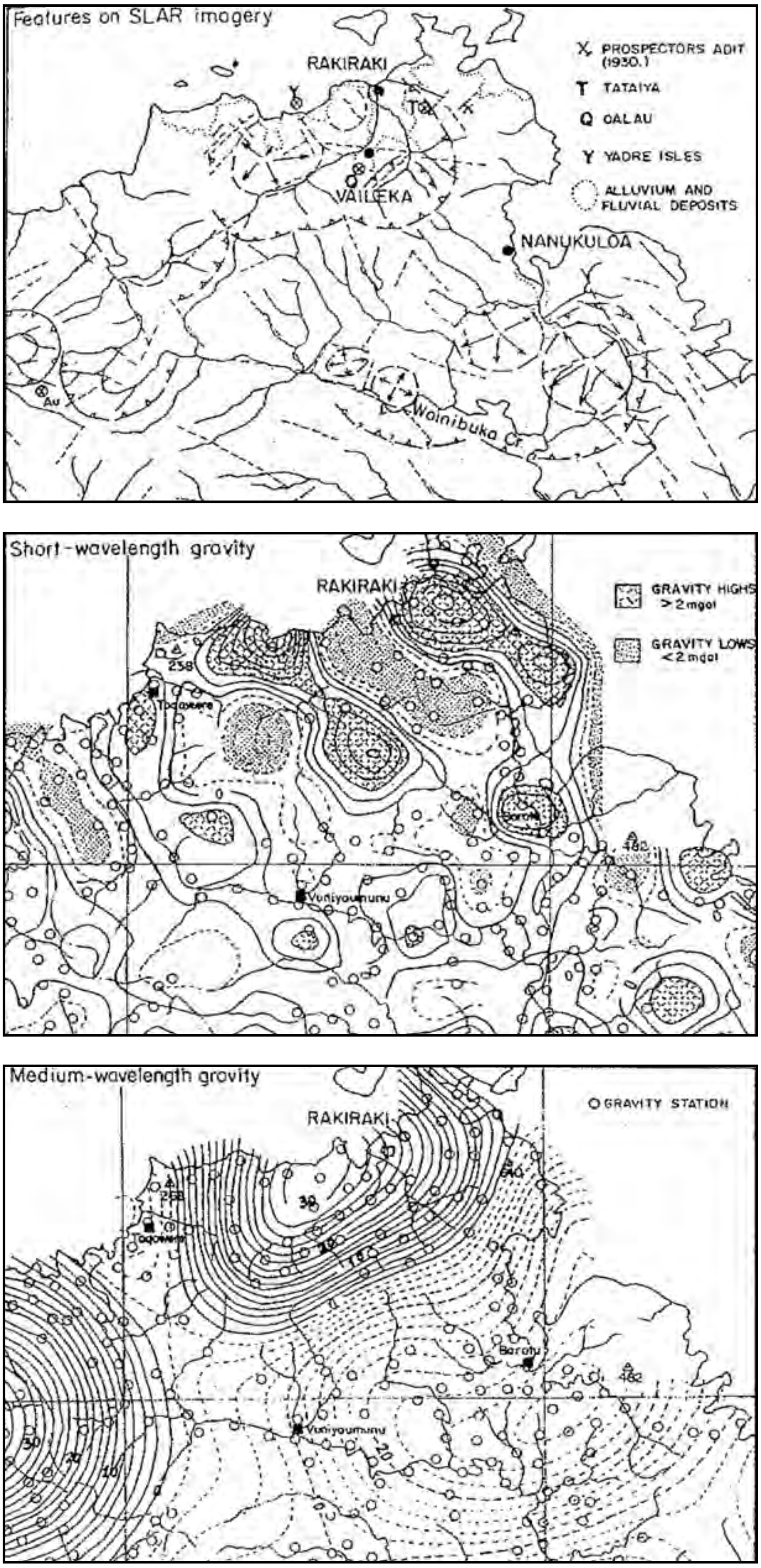

Figure 7. The MMAJ modelling of the Rakiraki volcanic centre using SLAR imagery and gravity data.

SUGGESTIONS FOR FUTURE EXPLORATION

It would be misleading to try to define an ideal exploration prgramme for use in Fiji and other islands of the Southwest Pacific principally because different types of mineral target demand differing approaches. However, it is possible to summarise the effectiveness of different exploration techniques and Table 5 gives suggestion for applying the various exploration approaches.

Further conclusions from this survey of exploration practice in Fiji can be framed in a series of recommendations for future exploration.

- Reconnaissance exploration of the rugged, poorly known interiors of Viti Levu and Vanua Levu would best be achieved by a regional programme of stream sediment panning. Panning located almost all the major gold prospects in Fiji and it has the advantage of being a relatively rapid and cheap method of exploration. Members of the local population could be trained as panners to carry out the work for commercial organisations or through a government initiative.

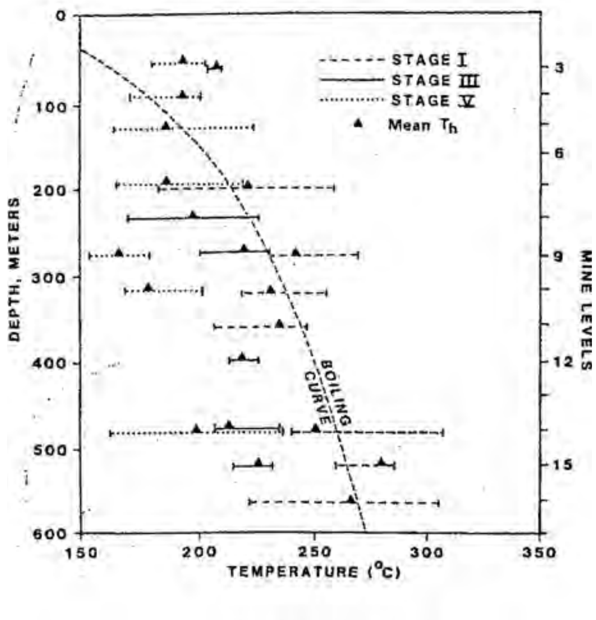

Figure 8. Variation in homogenisation temperatures (T_h) for different vein generations at Vatukoula mine and the predicted boiling point curve (from Ahmad et al., 1987).

Table 4. Significant new discoveries 1976 - 1990.

Prospect name	Method of discovery	Deposit type
Tuvatu, north-west Viti Levu (52)	Au spot anomaly on soil grid	Au-qtz veins possibly associated with Kingston Cu-Au porphyry system
Banana Creek, north-west Viti Levu (52)	Stream sediment geochemistry	As above
Nailaga, north-west Viti Levu (49)	Stream sediment geochemistry, magnetic low	Argillic-phyllic alteration within a shoshonitic volcanic centre
Rakiraki, north-east Viti Levu (44)	Panning, gravity modelling,soil geochemistry	Au-qtz-calcite veins in Rakiraki tholeiitic volcanic centre
Peni's Farm, north Viti Levu (46)	Soil geochemistry, trenching	Epithermal Au-qtz veins assoc1ated with Tavua caldera
Faddy's, south-west Viti Levu (7)	Gossan, soil & rock chip geochemistry	Au-qtz veins of unknown affinity
Mt Kasi, south-west Vanua Levu (75)	Soil geochemistry	Epithermal Au-qtz-baryte veins
Cirianiu, north-east Vanua Levu (66)	Side-looking radar, soil geochemistry, magnetic lows	Epithermal Au-qtz veins
Vudibasoga, north-west Vanua Levu (61)	Float prospecting, soil geochemistry	Epithermal Au-qtz veins

Numbers in brackets refer to deposit location in Figure 2.

- Exploration of the larger river systems is needed and will require an approach that is more reliant on geophysical prospecting. The survey could adopt the methods used by the JICA-MMAJ in their prospecting in northern Viti Levu with detailed magnetic and gravity surveys defining target geological structures (e.g. vein systems), masked by alluvial cover. In addition where there are spot gold anomalies or pan colours larger scale dredging to sample deep alluvial levels might also help to define a target. Investigation of the only known alluvial target in Fiji in the Waimanu river (33) revealed that the best gold grades were at deep levels within the alluvium.

- Better modelling of volcanic and intrusive centres can now be achieved by using, in addition to conventional geological maps, SLAR imagery and geophysical data produced by the JICA-MMAJ* and AusAID survey Programmes. Gunn et al. elsewhere in this volume show how gravity and magnetic data can be used to give a better definition of intrusive centres. Allied to this academic studies could focus on modern volcanic facies analysis to help determine the extent of eruptive centres and style of volcanism. Setterfield et al. (1991) have demonstrated the value of such an approach in modelling the evolution of the Tavua caldera.

- At advanced stages of exploration there needs to be a more considered approach in using petrographic studies particularly investigation of fluid inclusions with measurements being taken on a sufficient number of samples to be statistically valid. Rather than aiding basic exploration the approach would be better used to determine if significant events

Table 5. A summary of applicability of exploration techniques.

Exploration method	Application in Southwest Pacific terrains
Stream sediment	Excellent reconnaissance technique for detecting shallowly buried or surface mineralisation, particularly effective in the search for porphyry-style mineralisation.
Panning	Still one of the most reliable ways of locating exposed gold mineralisation with the bonus that gold colours are easy to spot in the dark tail that typifies panning in basic-andesitic terrains.
BLEG	No real advantage over panning unless target is subsurface, unexposed gold deposit.
Rock chip	Owing to the high mobility of metals in a wet, tropical environment no advantage in using primary geochemical methods until a more advanced stage of exploration (e.g. pitting, trenching and drilling)
Soil	Overall the most reliable way of defining drilling targets owing to the mobility of metallic elements in the soil profile and general absence of masking overburden apart from landslips in very rugged areas. Displacement of anomalies downslope due to soil creep is a common feature.
Magnetic	Aeromagnetic surveys may help to locate eroded volcanic centres in heavily forested terrain. Ground magnetic surveys probably most effective in outlining areas of hydrothermal alteration where magnetic lows indicate destruction of magnetite in the host rocks.
Resistivity	Resistivity highs can indicate major quartz vein structures.
Induced polarisation	Has proved of limited use owing to abundance of groundwater and weathering clays and resultant very long IP decay times.
Gravity	Gravity surveys can help to delimit volcanic centres and direct use for locating orebodies limited to the search for dense massive sulphide bodies in low density rhyodacitic terrains.
Self potential	Has proved reliable in detecting surface and near surface massive sulphide bodies.
Gossan	Good gossans generally only found in areas with marked dry season and over massive sulphide bodies.
Fluid inclusions	Useful at a very advanced stage of exploration on to assist in describing an ore deposit model and the potential for ore bonanzas through fluid boiling.

*Japan International Co-operation Agency/Metal Mining Agency of Japan (e.g. boiling) have occurred. Additionally academic studies comparing fluid inclusions in hydrothermally-altered barren ground and productive areas may aid understanding as to why there is a world-class gold deposit at Vatukoula and essentially barren hydothermal ground in numerous other volcanic centres of similar age and rock types.

To conclude it is suggested that future exploration in Fiji could be best achieved through a combination of local, commercial and academic initiatives. Government or aid agency funded panning campaigns could deliver reconnaissance surveys in the rugged interiors, commercial interests may best be focussed on applying geophysical prospecting in the major river valleys and academic research projects could focus on investigating fluid phases in barren and productive centres and on elucidating the volcanic stratigraphy of prospective districts.

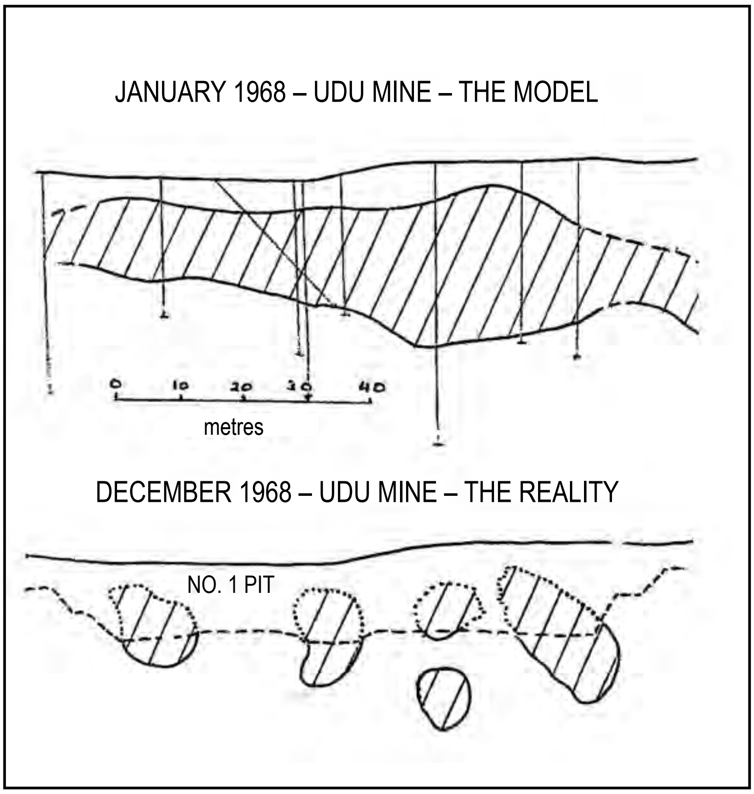

Figure 9. Comparison of the predicted ore horizon (shaded) at Udu mine, based on drilling and the favoured mdel for Kuroko-type mineral deposits, and actual extent of ore lenses revealed by opencast mining.

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A FIRST GEOLOGICAL MAP OF MAKIRA, SOLOMON ISLANDS: STRATIGRAPHY, STRUCTURE AND TECTONIC IMPLICATIONS

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ABSTRACT

This report presents the first ever comprehensive account of the geology of Makira (formerly San Cristobal). Makira is the last large island of the Solomon Islands archipelago to be systematically geologically mapped at a scale of 1: 50000.

Makira is readily sub-divisible into the Makira Basement Complex (MBC) and the unconformably overlying Makira Cover Sequence (MCS). Currently available Ar -Ar whole rock radiometric age data indicates a Cretaceous Oligocene (c. 98 Ma -34 Ma) for the Makira Basement Complex. The Harigha Sandstone Group, a unit within the Makira Cover Sequence has yielded Mid Miocene Early Pliocene foraminiferal ages.

The Makira Basement Complex forms the great bulk of the volume of Makira (probably c. 90%) of which basaltic lithologies comprise >65%, and locally almost 100% of the sequence. The Makira Basement Complex comprises basalt and dolerite sheets and minor dykes with gabbroic and ultramafic sheets and intrusions (herein termed the Wairahiti Volcanic Group or WVG) with interbedded sedimentary limestones, cherts, sandstones, and basaltic breccias (herein termed the Waihaoru Sedimentary Group or WSG). The Wairahito Volcanic Group comprises a sequence of basalt, dolerite and gabbro sheets and dykes with local ultramafic sills and intrusions. A cumulate thickness is difficult to estimate as there are few regional stratigraphic units which can be used for correlation purposes; however geological cross-sections suggest a minimum thickness of 2 km. The Waihaoru Sedimentary Group rocks have a wedge or lens like morphology, with a local thickness maximum region which quickly pinches out along strike. Individual beds can attain considerable (tens to >100 m) thickness locally. Monolithic basaltic breccias are particularly common within the WSG in the north of Makira. There are no diagnostic stratigraphical units within the basement which crop out on a regional basis, making cross-island correlation very difficult.

The Makira Cover Sequence comprises two main rock groups and an uppermost Quaternary Recent sequence of alluvium, raised reef, beach, and mangrove swamp deposits. The Upper Miocene Lower Pliocene Harigha Sandstone Group (HSG) comprises a varied sequence of weak to moderately cemented poorly to moderately sorted, soft, and sometimes chalk-like, calcareous sandstones and siltstones with occasional interbedded basaltic sheets. The HSG is at least 100 m thick. The Kahua Breccia Group (KBG) comprises monolithic basalt breccias and bi-lithic basalt-limestone breccias which locally grade into coarse, poorly sorted sandstones and interbedded basalt sheets. The KBG is at least 100 - 200 m thick.

Dacite dykes cut the basement at a number of localities. The dykes are several metres to ?tens of metres thick, fine to medium grained and leucocratic, with phenocrysts to microphenocrysts of hornblende, pyroxene, and feldspar (plagioclase and alkali feldspar) set in a fine grained felsic groundmass. Flow textures and accessory zircon crystals are common. The relationship of the dacite dykes to the cover sequence is uncertain. Many dykes strike north-north-east, parallel to the predominant extensional fault trend. The dacite dykes are evidence for a period of arc formation on Makira: corroboratory evidence is provided by Jeffrey et al., 1975, who document possible arc derived epiclastic sediments which crop out in the Arosi peninsular, in western Makira. The intermediate to acid volcanic and volcaniclastic rocks comprise the Makira Arc Group, which is post Oligocene (? Miocene Pliocene) in age.

Compressive folding, extensional faulting, and unconformity structures are all present on Makira. The island is divisible into a number of fault Blocks of varying size with north-north-east - south-south-west and east west extensional fault structures separating discrete fault Blocks. The density of faulting is greatest in the central, southern and eastern part of the island: western Makira appears to be the least affected by faulting, and contains the largest individual fault Blocks by area. Faults are visible on all scales: from island wide structures to outcrop and smaller scales. Within an individual fault Block there is a consistency to the structure: for example within western Makira it is possible to trace individual fold axes and lithological units for 10 - 15 km along strike. Between many fault Blocks, particularly in central Makira there is often an abrupt 90° change in strike trend from east-south-east to north-north-east indicating that there has been significant fault Block rotation. Fold trends are predominantly east west to east-south-east - west-south-west, with localised north-north-east - south-south-west trends, except within local fault Blocks as described above. Fold geometry is essentially open and gentle: the degree of shortening is limited. The faulting and folding pattern of Makira can be most easily explained by the highly oblique collision between the Australian and Pacific plates (e.g. Petterson et al., 1997) which induces a predominant transpressive stress regime with resulting north south compression and east - west sinistral shear. The interplay between the two dominant stresses (i.e. simple shear versus compression) appears to be highly complex with one dominating over the other at certain times and both acting simultaneously at other times. There have been at least two periods of transpression and uplift separated by a period of localised extension and localised Basin formation dated at Mid Miocene 00Early Pliocene.

The unconformity between the cover and basement sequences has some intriguing characteristics. Structural cross-sections suggest that the cover sequence has formed within small extensional ?pull-apart Basins, with bounding listric, extensional, growth faults, and which received sediment from rivers draining the surrounding uplifted highlands of Makira. Basalt magma was extruded within these small Basins. Despite apparent fault control on the Basin margins the cover sequence exhibits a highly irregular surface contact relationship with the cover sequence suggesting that the youngest sediments overlapped the edge of the Basin and were deposited irregularly on top of the basement. Some fold structures cut straight across the unconformity suggesting that at least some folding has occurred in the relatively recent past.

Makira appears to be most uplifted towards the south where the highest ridges are located. The major watershed of Makira (which trends east west) is located only some 5 - 10 km north of the southern coast and separates relatively long north-flowing rivers from relatively short south-flowing rivers. The present drainage pattern reflects relatively recent uplift and tilting to the north in response to Makira's present forearc position. This uplift has stripped Makira of the bulk of its deep-sea pelagic and arc rocks. The gross uplift and northwards tilting of Makira has a close analogue with Guadalcanal which exhibits a very similar structural style.

The geochronological age structure of the Makiran basement is uncertain as there is poor stratigraphical control across the island. Theoretically the oldest rocks should be exposed in the most uplifted southern part of the island (this is the case in Guadalcanal for example where there is better geological control). There is some support for this theoretical notion

from unpublished preliminary Ar-Ar age dating results which have yielded plateau ages of c. 90 Ma from basalt samples taken from the Matangarighi river (south-east Makira); c. 55 - 67 Ma from basalt samples taken from the upper Wairahito river (central east Makira); 2); and c. 33 - 35 Ma from basalt samples taken from northern Makira.

It is possible to subdivide Makiran basalt samples on the basis of varying Zr/Nb ratios and Nb concentrations. The bulk of Makiran basalt samples are compositionally most similar to Ontong Java plateau basalts, but a significant number of samples are more akin to 'normal' ocean floor basalts (e.g. Makira 'MORB') or alkaline ocean island basalts.

A geo-tectonic model of Makira is proposed which proposes that the Makiran basement represents the episodic accretion of oceanic basalts and sediments from the Cretaceous to the Oligocene from a range of oceanic environments. This composite basaltic terrain underwent compression and uplift during post-Oligocene/pre-Mid Miocene times culminating in the formation of an island Block. The uplifted island underwent extension/ gravitational collapse and erosion which produced a series of local submarine Basins into which were deposited basaltic and limestone clastic sediments. An arc developed on Makira, probably after 8 Ma. Since Late Pliocene times Makira has been subject to intense fore arc transpression.

INTRODUCTION AND SCOPE OF PAPER

This paper presents the first island-wide comprehensive account of the geology of Makira (formerly known as San Cristobal). The systematic geological survey of Makira is still ongoing and will finish in either 1998 or 1999. This report is a preliminary summary of field investigations which took place between 1994 and 1997. The paper proposes a stratigraphic and structural framework for Makira and a preliminary geo-tectonic model.

This paper builds on the work of people who have made field investigations of makira in former times, most notably: Grover, 1958, Pudsey-Dawson et al., 1958, Thompson and Pudsey-Dawson, 1958, Coleman, 1965, and Jeffrey et al., 1975.

TECTONIC SETTING OF MAKIRA

The geographical and tectonic setting of Makira is presented in Figures 1 and 2. Makira is the most south-eastern of the double chain of larger islands which form the bulk of the land mass of the Solomon Islands archipelago, Southwest Pacific.

The Solomon Islands comprise an upraised Block bounded to the north-east by the Vitiaz (locally north Solomon) trench and to the south-west by the South Solomon (New Britain-San Cristobal) trench. The Solomon Block is a composite terrain collage (Figure 2, Petterson et al., in press) comprising terrains dominated by thick ocean plateau crust (the Ontong Java Plateau (OJP) Terrain); terrains formed predominantly during Eocene Lower Miocene stage 1 arc times (e.g. the Shortlands); and Upper Miocene Present day stage 2 arc times (e.g. the New Georgia Group); and terrains which are themselves composite oceanic/arc terrains (e.g. Guadalcanal). Makira is a somewhat unique island even in Solomon Island terms as it is a composite of a number of oceanic units with a stage 1 arc. The Solomon arc is part of the Greater Melanesian arc which includes the active arcs of New Britain and Vanuatu (Figure 1).

The Solomon Block is currently in collision with the Ontong Java Plateau (OJP) (Figure 1) and has been colliding with the OJP since around 20 Ma (Petterson et al., in press). The Woodlark Basin (Figure 1) is a young (< 5 Ma) ocean Basin which is being subducted at the South Solomon trench. The subduction of young, warm Woodlark Basin lithosphere has led to a range of tectonic phenomena including increased coupling between the Australian and Pacific plates, and the uplift of the Solomon forearc. The northern part of the Australian plate in the vicinity of Solomon Islands comprises a number of ocean Basins and plateaus. The collision between the Australian and Pacific plates is a highly oblique one with the Australian plate moving northeastwards at c. 7 cm/year and the Pacific plate moving west-north-west at >10 cm/year.

STRATIGRAPHICAL FRAMEWORK

A number of sections below describe the lithological characteristics of different units within the Makiran stratigraphy. It is useful to begin by outlining the larger scale geological framework

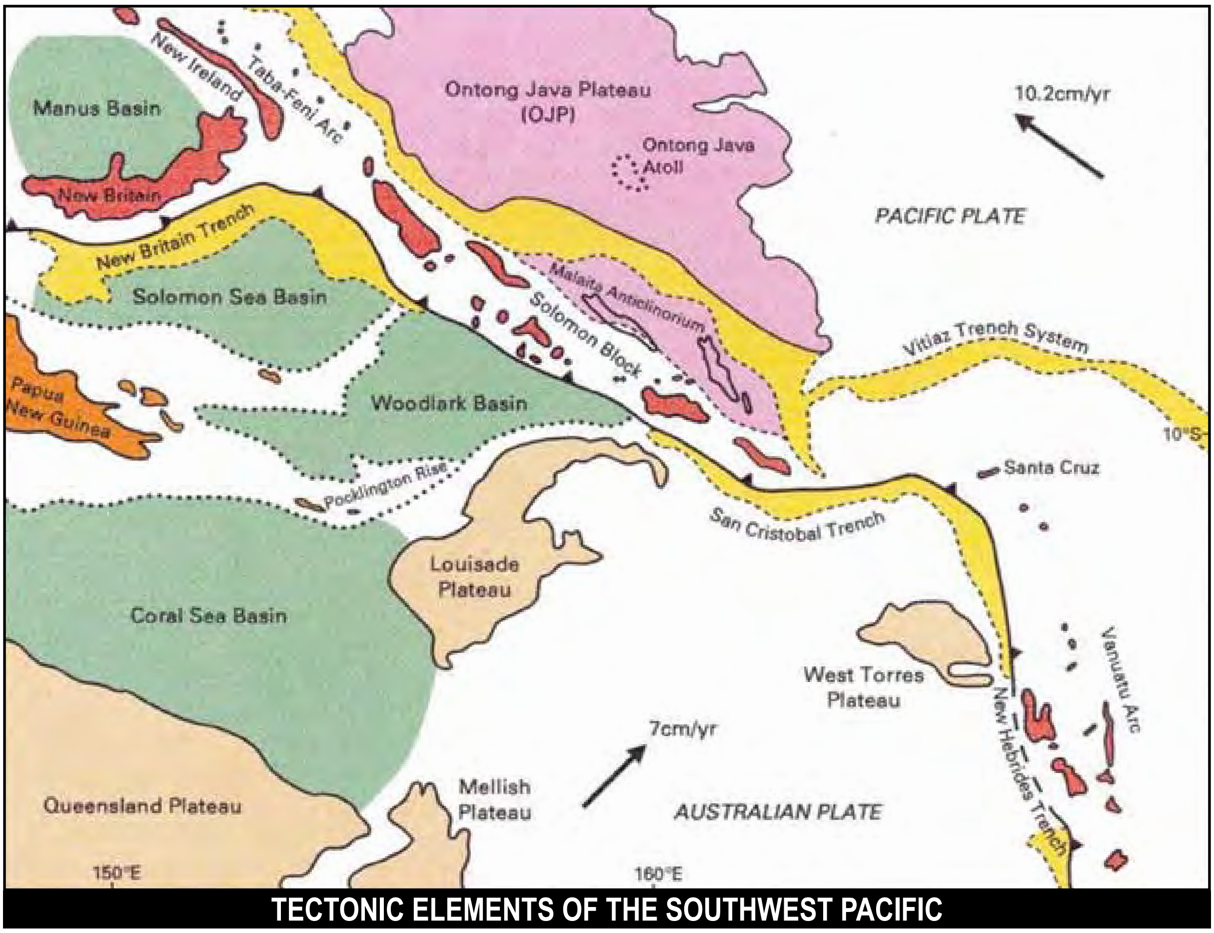

Figure 1. Tectonic Elements of the Southwest Pacific (reproduced by permission of Elsevier Publications). The Solomon Block contains the Solomon Island archipelago, which is bounded to the north by the Vitiaz (north Solomon) trench and to the south by the New Britain-San Cristobal (south Solomon) trenches respectively. The Solomon arc is part of the much larger Greater Melanesian arc which includes the islands of New Britain, Santa Cruz, and Vanuatu. The Ontong Java Plateau (OJP) is in collision with the Solomon Block, and the Malaita anticlinorium represents the obducted part of the OJP within the Solomon Block. A number of ocean Basins (some younger than 5 Ma) and plateaus are situated south of the Solomon Block. Solomon Islands is situated at the highly oblique collisional boundary between the Pacific and Australian plates.

(Table 1). The reader is referred to Figure 3 (geological map of Makira) while reading the following stratigraphical sections.

MAKIRA BASEMENT COMPLEX

Wairahito Volcanic Group

The Wairahito Volcanic Group is by far the most significant geological unit on Makira as it crops out over the bulk of the island (at least 65% of Makira is underlain by the Wairahito Volcanic Group). The WVG comprises a sequence of basalt, dolerite and gabbro sheets and dykes, with local ultramafic sills and intrusions. A cumulate thickness is difficult to estimate as there are few regional stratigraphic units which can be used for correlation purposes; however geological cross-sections suggest a minimum thickness of 2 - 4 km.

Typically the Wairahito Volcanic Group (WVG) is characterised by a monotonous sequence of basalt sheets with little interbedded sediment. Observed sheet thicknesses vary between 1 and 25 m and are typically of the order of 1 - 5 m. Basalt sheets are pillowed, non pillowed, or 'bulbous', the latter field term designating basalts which display poorly developed pillow structures. Some pillow lavas exhibit black glassy carapaces to pillow structures; individual pillow diameters measure between 10 and 150 cm and occasionally display 'mother and baby' pillow structures with larger (>1 m diameter) pillows being interconnected with smaller pillows. Most basalt sheets are well jointed with joint systems oriented at least parallel and normal to sheet margins.

Basalt grain size varies between very fine grained and medium to coarse. The most featureless lavas are massive aphanitic and fine grained. Other

Table 1. Stratigraphical framework model of Makira.

	COVER SEQUENCE (Formal Name: Makira Cover Sequence)
Recent & Quaternary deposits	(Alluvial sands and gravels; raised beach and beach deposits; mangrove deposits; coralline reef deposits)
Makira Arc Group ? Late Miocene – Pliocene)	(Dacite dykes and reworked arc volcaniclastic (post-Oligocene, deposits)
Kahua Breccia Group (post – Oligocene,? Mid Miocene to Early Pliocene)	(Monolithic basalt and bi-lithic basalt/limestone breccias with sandstones and basalt lavas)
Harigha Sandstone Group (Mid Miocene – Early Pliocene)	(weak – moderately cemented calcareous sandstones & siltstones with occasional basalt lavas)
Unconformity	
	BASEMENT SEQUENCE (Formal name: Makira Basement Complex)
	STRATIGRAPHICAL UNITS
Wairahito Volcanic Group (Cretaceous – Oligocene)	(pillowed and non pillowed basaltic to gabbroic sheets, and ultramafic rocks)
Waihaoru Sedimentary Group (Cretaceous – Oligocene)	(Limestones, basalt breccias, cherts, sandstones, mainly interbedded within the Wairahito Volcanic Group)

sheets contain feldspar ± pyroxene laths up to 1.5 - >3 mm long, the latter displaying ophitic doleritic textures. Occasional examples of 'orbicular' basalt were observed with circular to ovate 'orbicles'/ spherules of coarse dolerite to gabbro set in a fine grained basalt groundmass. The thickest sheets display the coarsest facies of basalt/dolerite. One locality within the Huni River (north-east Makira) contains an example of rhythmic layering with repeated coarser gabbroic layers up to 1 cm thick set within a medium fine- grained groundmass.

Examples of interdigitating and wedging of individual basalt sheets were observed at several localities. Basalt-basalt contacts with little or no inter-sheet sediment are common indicating local rapid effusion of lavas/sills. Other areas contain thin to thick inter-sheet sediments indicating periods of quiescence with respect to basalt effusion. Rubbly bases and tops to basalt sheets are locally present.

The WVG basalts are invariably altered to some degree. At one extreme the basalts are affected by a high density of shear zones with an individual shear zone typically measuring c. 1 m. Within shear zones the basalts display a greenschist epidote chlorite mineralogy, and shear related fabrics. Chlorite ± quartz ± haematite ± calcite veining is not uncommon within any part of the WVG, although the extent and density of veining is highly variable. Vein systems are best developed close to major shear or fault structures. Individual veins range up to 2 cm wide.

In thin section the variation in basalt is predominantly related to grain size. The finest grained basalts are micro- to crypto-crystalline and may contain the occasional micro phenocryst. Medium grained basalts tend to be subhedral- to euhedral-equigranular to inequigranular when glomerocrysts of larger gabbroic grade porphyritic pyroxenes and feldspars, set in a medium grained groundmass. The coarsest dolerites and gabbros tend to be euhedral to subhedral granular. All except the finest grade rocks are holocrystalline to slightly hypocrystalline: green to brown partly devitrified glass with occasional perlitic cracks is a common interstitial phase. The mineralogy is remarkably simple with plagioclase and clinopyroxene forming the great bulk of thin sections (usually >85%) most usually in approximately equal proportions, with accompanying interstitial opaque minerals and brown-green glass. In the medium–coarser grained rocks the larger pyroxene phenocrysts tend to display an ophitic to sub ophitic texture.

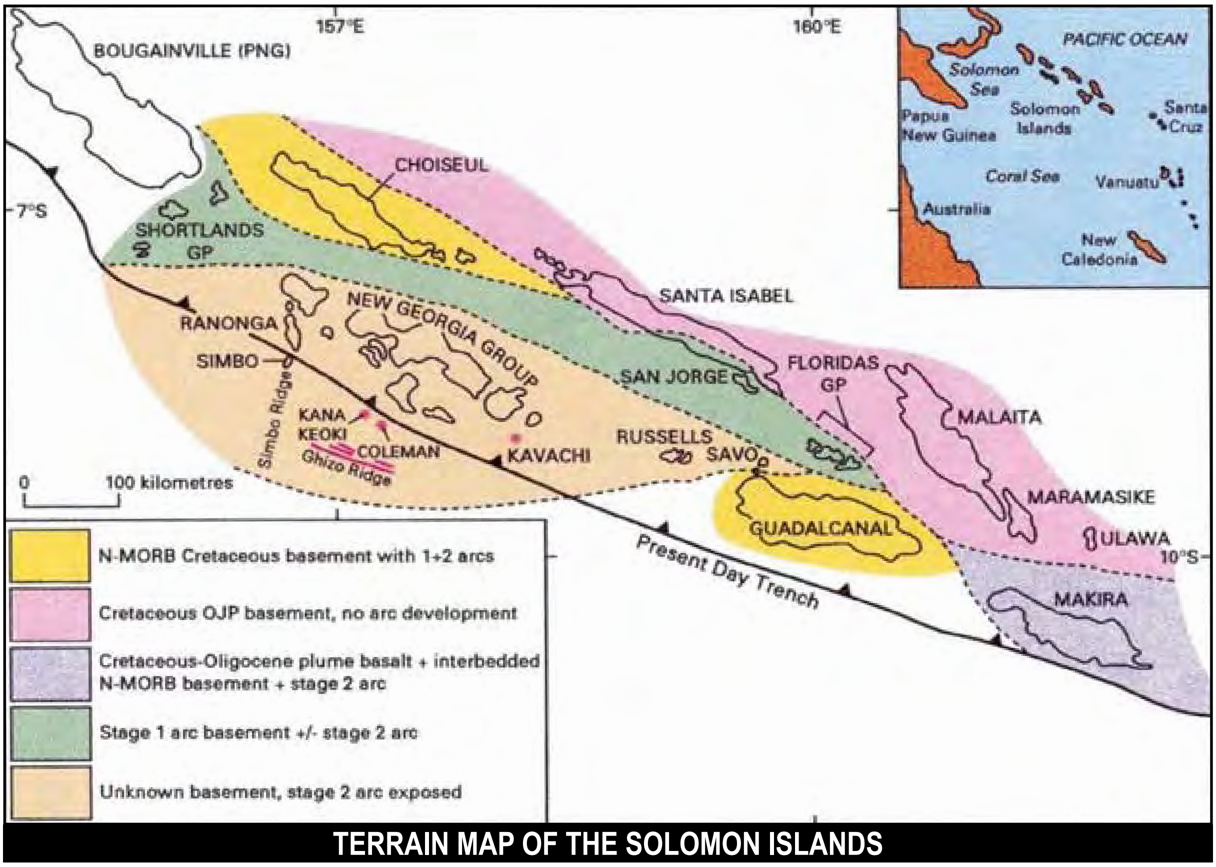

Figure 2. Terrain map of the Solomon Islands (reproduced by permission of Elsevier Publications). Solomon Islands can be subdivided on the basis of age and geochemistry of the basement geology and the relative development, or lack of development, of two major stages of arc growth: stage 1 (Eocene to Lower Miocene); stage 2 (Upper Miocene to present day) respectively. Makira forms a unique terrain with a varied oceanic basement and some evidence of stage 2 arc growth.

Occasionally olivine and orthopyroxene is present: in one section the modal abundance of olivine was 5 - 10%. The plagioclase crystals display random to variolitic and sub-variolitic textures. In most medium and coarse grained sections the pyroxenes and plagioclase crystals display random, intricate, interlocking textures. Many thin sections display variable alteration, most notably within the mafic minerals which are altered to chlorite and/or actinolite. Chlorite, quartz, and calcite veins are common.

A number of ultramafic units crop out within the Makira Basement Complex, most notably in the hills south of Kahua Point in north-east Makira. Unfortunately no large outcrops of ultramafic material were observed in any river traverses, but examples of ultramafic units have been encountered as smaller scale sheets or sills and as float material. The Kahua Point Ultramafic body appears to be a sizeable body, measuring some 5 x 1.5 km, has a distinctive expression on aerial photographs, and supports a depleted bush cover relative to typical Makiran rainforest. Serpentinite is the most common ultramafic rock encountered; most samples examined are serpentinised to some degree and have a greasy feel and smooth lustre. Rarer examples of fresher pyroxenite and peridotite were also encountered.

Only a small number of ultramafic thin sections were studied. Of these some are completely serpentinised. The few slides which contain relict minerals and textures display coarse grained granular textures with interlocking euhedral to subhedral olivine, clinopyroxene and orthopyroxene crystals with interstitial opaques.

A number of basalt samples have been dated by Dr R Duncan using the whole rock Ar-Ar radiometric dating method. It is beyond the scope of this paper to discuss these results in detail, particularly as the results are, at present, preliminary results. However the analysed samples have yielded a broad spectrum of ages for basement basalts with three modal ages at circa 90 Ma, 60 Ma, and 30 Ma respectively, indicating a Cretaceous Oligocene age range for the Wairahito Volcanic Group, (see below for further details).

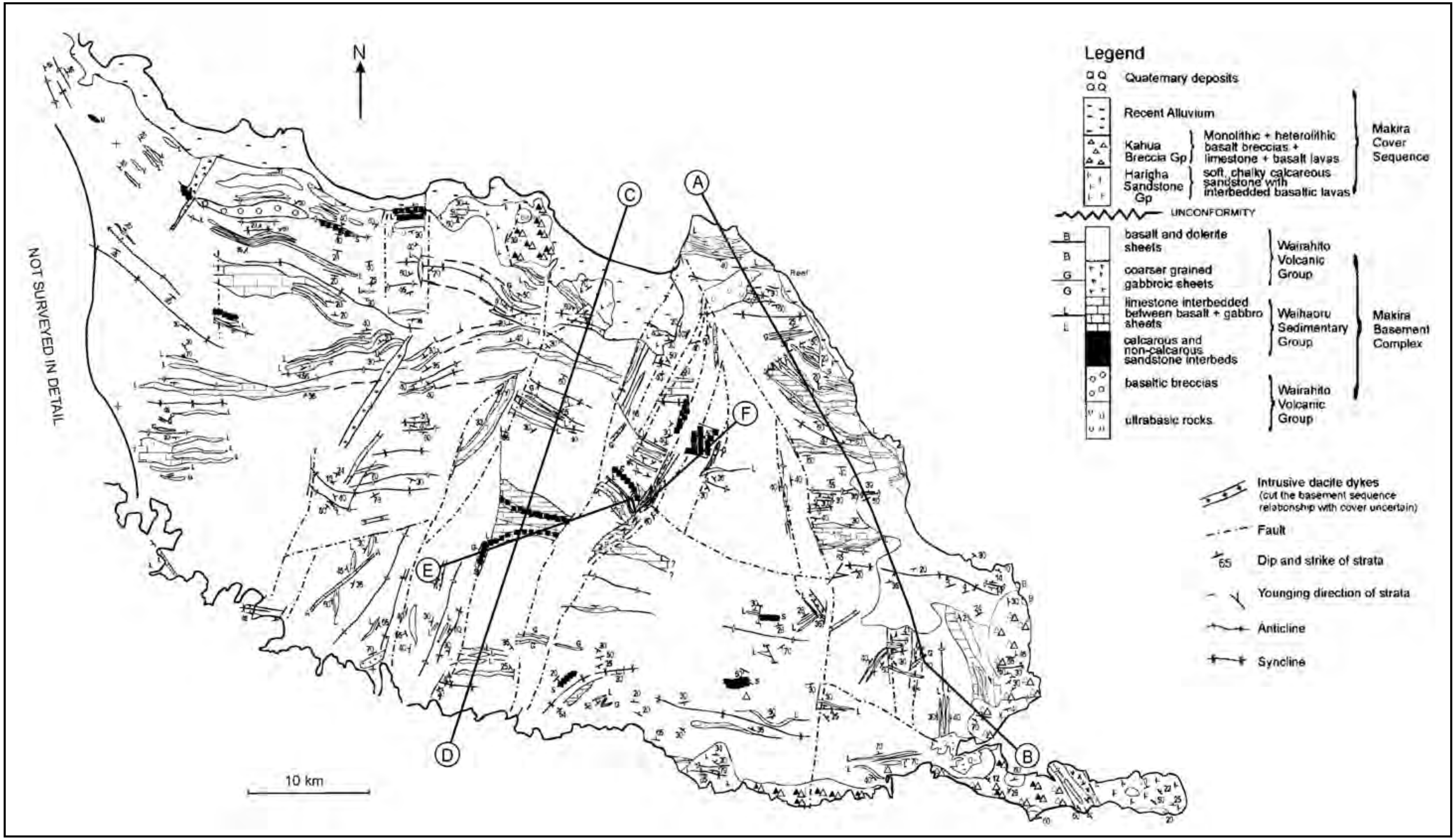

Figure 3. Geological map of Makira. Over 90% of Makira is underlain by a Cretaceous Oligocene oceanic basement comprising: 1) interbedded basalt, dolerite, gabbroic, and ultramafic sheets and a minor proportion of discordant intrusions (termed the Wairahito Volcanic Group); and an interleaved sedimentary assemblage of lithologies comprising pelagic limestones and cherts with basalt breccias and sandstones (the Waihaoru Sedimentary Group). The basement is unconformably overlain by the Mid Miocene Early Pliocene Harigha Sandstone, and Kahua Breccia Groups, and Quaternary to Recent alluvial and reef deposits. Intrusive dacite dykes of post Oligocene (?Upper Miocene Pliocene age) cut the basement. East west trending folds and north-north-east and east west faults dominate the structure of Makira. Locations of geological cross-sections shown in Figure 5 are indicated. See text for details.

Waihaoru Sedimentary Group

The Waihaoru Sedimentary Group (WSG) comprises a relatively diverse sequence of sedimentary lithologies within the Makira basement Complex. The WSG most commonly occurs as interbeds within the basalt dominated Wairahito Volcanic Group, but individual units can attain local thicknesses of tens of metres upwards to >100 m. There are three main facies of the WSG: cherts; limestones; and breccias. All WSG units have a wedge or lens like gross morphology/geometry, pinching out along strike from a thickness maximum location.

Cherts

Cherts are invariably interbedded within thicker limestones forming limestone – chert sequences, although occasionally limestones or cherts occur in isolation. Cherts usuallly occur as discrete beds or laminae or as nodules and concretions within thicker limestone units. Occasionally chert dominated Individual chert layers vary in thickness from a laminae/mm scale upwards to 40cm. Maximum total thicknesses of chert dominated deposits are in the order of several metres. The cherts are red or white, occasionally dark grey to black in colour, are fine to very fine grained and display a conchoidal fracture.

Only a small number of chert thin sections were examined. These sections are siltstones to mudstones with larger subrounded feldspar and pyroxene crystal – clasts set within a very fine grained dark to medium grey muddy matrix. Vague spherulitic ?radiolaria are locally present.

Limestones

Limestone dominated sediments are the most common lithology within the WSG. The limestones are white, red, pink, or grey, pelagic calcilutites and calcisilties and are interbedded within the basalt dominated WVG. Individual limestone units can attain local thicknesses of 40 – >100 m but are more usually between 5 and 10 m thick.

The limestones are usually hard and porcellainous, are parallel laminated to bedded and are invariably cut by an anastomosing network of calcite veins. The veins can occupy over 15% of the rock by volume with individual veins attaining thicknesses of 1 - 5 mm. In general the limestones are well jointed, can display karstic weathering features, and although are commonly reasonably pure calcareous lutites they can locally grade into darker coloured, more non-calcareous mudstone-rich sequences, and/or contain thin laminae of dark mudstone material.

Parallel lamination/bedding predominates but locally sedimentary structures such as flame and load structures, slump folding and contorted and disrupted bedding are present, suggesting that wet sediment loading and deformation occurred locally within rather active tectonic depositional environments (?such as submarine active half grabens).

All colours and facies of limestones contain foraminifera, although modal foraminiferal percentage values vary between trace amounts and 40% with 15 - 30% being more typical. The foraminifera are set within a groundmass of very fine grained, generally light coloured, lime mud. The grey limestones are laminated, even on a microscopic scale, with the laminae being defined by alternating colours (e.g. dark grey and light grey) of mudstone.

In thin section the limestones display a variable purity in terms of their calcareous mud content, grading between a pure white to pale grey calcareous-rich facies, and a dark grey, non-calacreous, mudstone-rich facies. The matrix of the limestones is very fine grained and difficult to resolve, even under the microscope. Most sections contains reasonably preserved foraminiferal tests which have a modal abundance of circa 10 - 50%.

Breccias

Breccia units are of two main types: monolithic basalt breccias and bi-lithic basalt-limestone breccias. More rarely some lithologies include almost monolithic limestone breccias. Breccia units tend to have local rather than regional significance: they are particularly important in the Waihaoru area of north-west Makira wher they form composite units with a total thickness of >200 m. More typically the breccias attain thicknesses of several metres to tens of metres.

The most common lithology is a poorly sorted monolithic basalt breccia with a high concentration of densely packed (occasionally clast supported), subangular to subrounded basaltic (± doleritic and gabbroic) clasts, with the larger clast sizes ranging between <1 cm to >2 m (on average between 1 and 15 cm), set within a dark mud to sand to gravel grade basaltic matrix. The breccias are usually interbedded with crystalline, non-brecciated basaltic lavas and sills, and occasionally grade into coarse sandstones. Bedding structures, where present, are usually weakly developed.

Bimodal basalt-limestone breccias display the same gross lithological characteristics as described for the basalt breccias. Basalt clasts are usually much more common than limestone clasts with 90% basalt to 10% limestone clast ratios predominating. More rarely limestone clasts may attain 50% of the total large clast population.

The breccias appear to be sedimentary in origin and suggest that submarine basalts and limestones were being eroded and redeposited together with available basaltic and calcareous detrital material within proximal environments. This suggests that submarine erosion and depositional processes were active, possibly adjacent to active ocean floor faults.

MAKIRA COVER SEQUENCE

Harigha Sandstone Group

The Harigha Sandstone Group (HSG) unconformably overlies the Makira Basement Complex, cropping out in north central, southern, and east-south-east Makira. The thickness of the HSG is unknown but is at least >100 m thick.

The Harigha Sandstone Group is a sandstone dominated clastic unit which also contains finer grained siltsones and mudstones and coarse, poorly sorted conglomerates. The most common lithofacies is a grey to pinkish white to dark grey, weakly to moderately cemented, porous, and usually calcareous sandstone. The sandstone units within the HSG are variably sorted: some are well sorted whilst others are poorly sorted pebbly sandstones. The sandstones are most commonly massive to bedded (thinly-, well- bedded facies are not uncommon) and heterolithic (with basalt, limestone and sandsone lithic clasts) clast supported, with a calcareous matrix. Clast shape varies between sub rounded and well rounded. Fine grained calcisiltite to lutite chalk-like facies are also occasionally present within the HSG.

The coarser conglomerate facies can contain individual clasts which have long axes ranging up to 30 cm, with a more usual 5 - 10 cm maximum long axis size, and typical long axis dimensions of 5 mm - 1 cm. The conglomerates are heterolithic and contain basalt, limestone and sandstone clasts. The conglomerates are matrix supported with the subrounded larger clasts embedded within a siltstone-sandstone matrix. Bedding structures tend to be poorly developed although the conglomerates occasionally grade into coarse sandstone units, and one exposure exhibited coarse-tail normally graded bedding with the maximum clast size grading from 7 cm at the base to 2 cm at the top of a graded unit.

Sedimentary structures are common and include: parallel bedding; clast imbrication; flame and load structures; rip up clasts of mudstone within a laminated sand/siltstone; erosional surfaces/ bases to channels; and slump folding. These structures would indicate a certain amount of soft sediment deformation, gravity sliding, and loading, as well as the presence of current activity and channeling. Johanna Resig (pers. comm.) has analysed a number of HSG samples for their fossil content. Preliminary conclusions of Dr Resig include: 1) the HSG contains both pelagic and benthic foraminifera which yield Late Miocene to Early Pliocene (11 - 3 Ma) ages; and 2) interpreted water depths of between 100 - 300 and 1000 - 3000 m for various foraminiferal genera and species. The presence of both pelagic, deep sea, and benthic, shallow marine foraminiferal fauna within the HSG can be explained by: 1) the existence of an HSG Basin and shelf with pene-contemporaneous lateral facies variations; or, 2) rapid variations in depth with time indicating temporal subsidence and uplift.

Basalt lavas and breccias are interbedded with the sandstones.

Kahua Breccia Group

The Kahua Breccia Group (KBG) crops out in the central-north, east, and south-east of Makira and unconformably overlies the Makira Basement Complex. The relationship of the KBG with the Harigha Sandstone Group remains unproven and the two units could be penecontemporaneous. The thickness of the Kahua Breccia Group is unknown but is at least 150 - 200 m.

The KBG is predominantly a sequence of heterolithic breccias and coarse lithic sandstones with occasional siltstones. Dominant clast lithologies include basalt and limestone with a basalt : limestone ratio of >1, and ranging up to 4. The breccias tend to be moderately bedded, with local graded bedding being occasionally present. Sorting is usually poor and the larger clasts are angular to sub angular in shape. The matrix material comprises mainly of sand and silt grade basalt and calcareous clasts. The KBG is generally weakly to moderately cemented.

Basalt lavas and breccias are present within the KBG.

Makira Arc Group

The Makira Arc Group (MAG) comprises a suite of andesitic to rhyodacitic rocks which occur either as dykes or larger scale plutons or reworked volcaniclastic material.

The most widely encountered lithology is andesitic to rhyodacitic dyke material. These acid dykes crop out in central, central-southern, and south-eastern Makira. The most common lithology is a leucocratic, grey to white, hornblende ± pyroxene-phyric dacite to rhyodacite. The hornblende phenocrysts are typically black and acicular to prismatic in shape, which range between 2 mm and 4 cm in length (usually 4 and 8 mm). Occasionally the crystals are aligned suggesting a degree of flow banding. The groundmass comprises a very fine grained, leucocratic, felsic, crypto-crystalline material. Some samples contain autoliths of mafic to ultramafic material, not unlike dacites described from Savo, (Petterson, 1995, in press). Mafic minerals comprise between 10% and 25% of the dacites and rhyodacites by volume.

Other crystalline lithologies described from various localities include: a hornblende-phyric, mesocratic micro-diorite; a diorite porphyry; and a medium grained diorite to granodiorite. The more basic lithotypes contain up to 30 - 40% mafic minerals by volume.

One of the frustrating things about piecing together the evidence for the full range of lithologies within the MAG is that the requisite lithologies have only occasionally been encountered at outcrop, and samples typically occur within the float material. It appears that the great bulk of the Makiran arc has been eroded and redeposited either within the present-day south Solomon trench or within submarine Basins to the north of Makira.

A small number of thin sections of the MAG were examined. Dykes from the Hao River are very fine grained. The groundmass occupies around 85 - 90% of the sections and comprises a leucocratic, felsic, microcrystalline to crypto-crystalline mass which is difficult to resolve. The remaining 10 - 15% of the sections comprise flow oriented laths of hornblende and pyroxene, the former occurring as acicular, lozenge, and rhombohedral shaped crystals. The Hao dyke rocks are probably dacitic to rhyodacitic in composition. One coarser grained rock from the Maghoha float is a medium grained hornblende -phyric acid andesite with relatively large patches of chlorite/actinolite possibly after pyroxene.

Jeffrey (1974) described a sequence of volcaniclastic sediments which crop out within a north - south trending graben situated in the Arosi peninsular of western Makira. This unit is termed the Waihada Volcanics which are a sequence of water laid tuffs, agglomerates, and assorted volcaniclastics, and have been assigned a Miocene age. The Waihada Volcanics include a varied sequence of lithologies such as: tuffs and volcanic breccias; hyaloclastite; pyroclastic deposits; tachylite; agglomerates; and cross laminated, reworked volcaniclastic sediments. Basalt dykes cut more acidic agglomeratic facies.

At the time of writing there are no available ages for any Makira Arc Group rocks. However the high silica, highly evolved nature of the rocks would suggest affinities with the second major stage of arc volcanism present within Solomon Islands which began during the Upper Miocene and continues to the present day (Petterson et al., in press, a). At the very least we can deduce that the MAG is post-Oligocene in age.

Recent to Quaternary deposits

There are a number of areas where Quaternary to Recent deposits blanket the solid geology of Makira. Most notably these areas include a northern, coast-parallel strip of land some 1 - 4 km wide dominated by alluvial and beach sand, silt, and gravel deposits and a thin (<1 km) eastern and south-eastern coast-parallel strip of land dominated by coralline reef deposits. The southern coast is an upraised, erosional coastline. Some low lying areas of the interior contain moderately thick mangrove deposits.

STRUCTURE OF MAKIRA

Makira has not proven to be an easy island to map or understand from a geological viewpoint. This is because of two main factors:

- There is a lack of island-wide distinct stratigraphical marker units. This makes correlation, even on a local scale, very difficult.
- Makira is structurally complex. Makira is presently being stretched by left lateral simple shear (see sections below) which has produced a number of large scale extensional faults with resulting fault rotation, particularly in central Makira. This brittle fault tectonics has produced a rather piecemeal geological and structural scenario (Figures 3 and 4): there is a degree of geological and structural continuity within one fault Block, but sudden changes occur across major fault structures.

Folding

Figure 4 illustrates the major fault axial trends and the local strike of distinctive stratigraphic units. The general regional fold axial and strike trend is east - west to east-south-east - west-south-west, and we take this trend as the local *orthogonal* trend to the maximum regional compressive stress direction. Figure 4 also illustrates that this regional picture is complicated by two main modifying tectonic controls: 1) extensional brittle fault movements have involved significant to substantial rotational movements which have modified the regional strike. In some cases (for example in central-eastern and central-southern Makira Figure 4) local fault rotations have changed the local strike from east-west to north-south; 2) sinistral (and local dextral) simple shear has produced a number of 'S' shaped fold axial trend morphologies indicating that the predominant north - south compression which resulted in the east - west regional strike had a left-lateral dominated shear component. In other words the predominant fold forming tectonic events were transpressional rather than pure orthogonal pure shear compression.

Faulting

Figures 3 and 4 highlight two main fault trends: north-north-east - south-south-west to north - south and east - west to west-north-west - east-south-east. Other minor fault trends include: north-east - south-west and north-north-west - south-south-east. The 'master' fault set appears to be the north-north-east - south-south-west trending structures which are large cross-island structures having strike-parallel dimensions of at least 30 km. As mentioned above these faults have a strong control on local outcrop patterns and structure and have a significant rotational component to their extensional movements. The east-west to east-south-east - west-south-west fault set are antithetic faults to the dominant north-north-east - south-south-west synthetic faults. The east - west antithetic faults also have a very significant rotational component to their movement tectonics and exert a strong control on local outcrop patterns and structure. The antithetic faults are much smaller structures with respect to the synthetic faults, extending over distances of 6 - 15 km.

The north-north-east - south-south-west and the east-west faults together produce a series of fault Blocks. We have identified approximately 15 major fault Blocks. The largest and least fragmented parts of Makira are in the west, whereas the smallest and most fragmented parts of Makira are in central-east Makira.

The density of faults and shears can be high on a local, outcrop scale. Most mapping traverses encountered locally deformed, sheared and highly faulted rocks. This relatively high density of faulting and shearing at a local scale probably reflects a combination of older, hydrothermal shear systems within the Cretaceous Oligocene oceanic basement, and more recent brittle tectonics.

GEOLOGICAL CROSS-SECTIONS

Figure 5 illustrates the general fold structure of Makira. Sections A - B and C - D respectively are simple north-south cross-sections across the eastern and central parts of Makira. Section E-F is a north-east - south-west section which crosses a number of fault Blocks in central Makira. All three sections bring out a number of features about the stratigraphy and structure: 1) the great bulk of the stratigraphy comprises basement basalts from the Makira Basement Complex; 2) ultramafic masses and younger andesitic dykes are intrusive bodies; 3) limestone and coarse gabbro/dolerite sheets may attain significant local thicknesses but are not laterally continuous: they pinch out in all directions. The Makira Cover sequence is unconformable on the Makira Basement Complex and its outcrop is controlled by listric, extensional growth faults. The unconfomity is not a simple one, as the plane of unconformity is itself folded and there is lateral continuity of some of the youngest fold structures between cover and basement. This suggests there have been at least two phases of folding separated by a period of extension, Basin formation, and deposition.

Section C–D is the simplest section as it is drawn through one contiguous fault Block. The folds have upright axial planes and are gentle to open folds, with a wavelength of 5 - 10 km. Most are symmetrical with a tendency to slight asymmetry indicating a possible northward fold vergence. The degree of shortening is relatively small: of the order of 10 - 18%.

Section A–B is a north - south section through easternmost Makira and crosses a number of fault Blocks. The folds are symmetrical, and gentle to open with upright axial planes, with a wavelength of c. 5 - 8 km. The amount of shortening within the basement is of the order of <10%. The cover sediments rest unconformably on the basement and are bounded by extensional listric faults which are modelled as variable in their angle of dip.

Section E–F subtends an angle of circa 45° to the regional strike and is used to illustrate the abrupt changes in dip across major faults and the rotational component of the brittle fault tectonics.

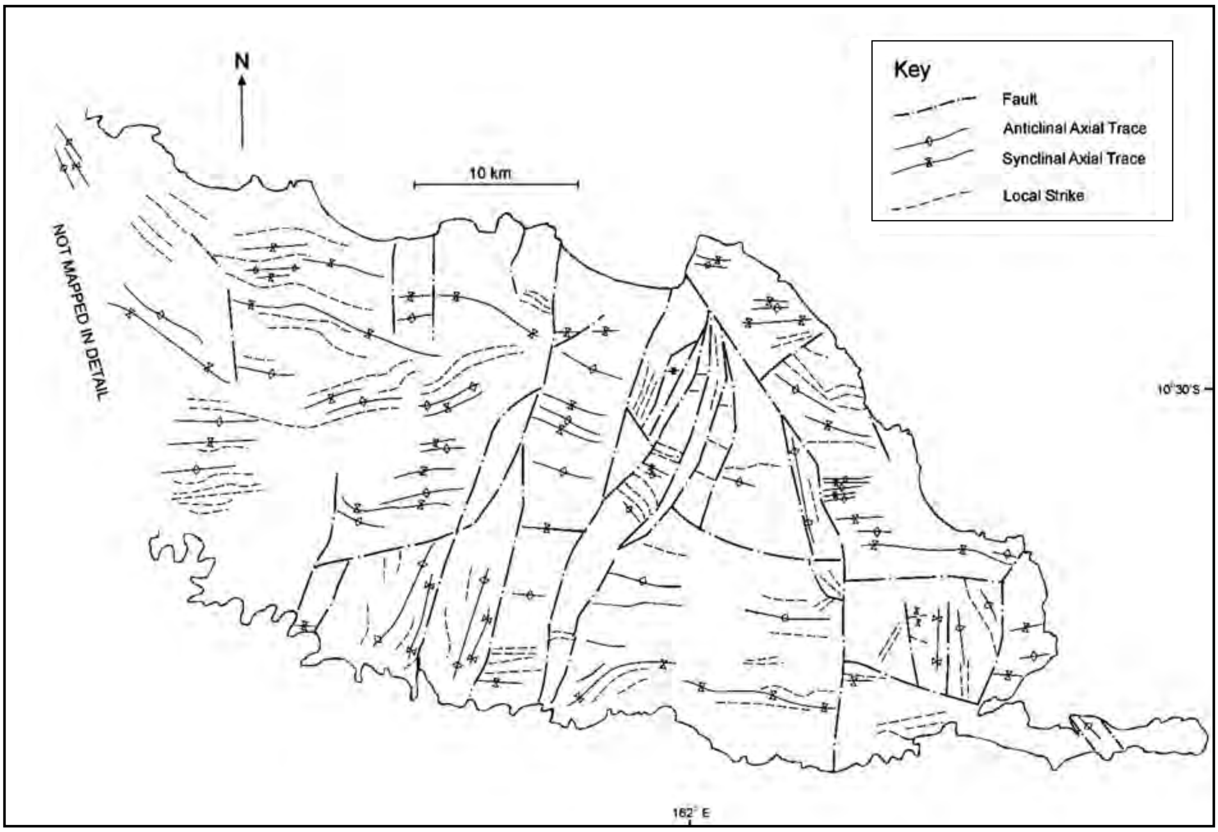

Figure 4. Structural map of Makira. Predominant east - west trending fold axes are locally discordant due to: 1) fault rotations which can produce local north - south trending fold axial planes; and 2) sinistral dominated shear causing sigmoidal axial fold trends. The interplay of north - south compression and left lateral shear has strongly affected the structural development of Makira.

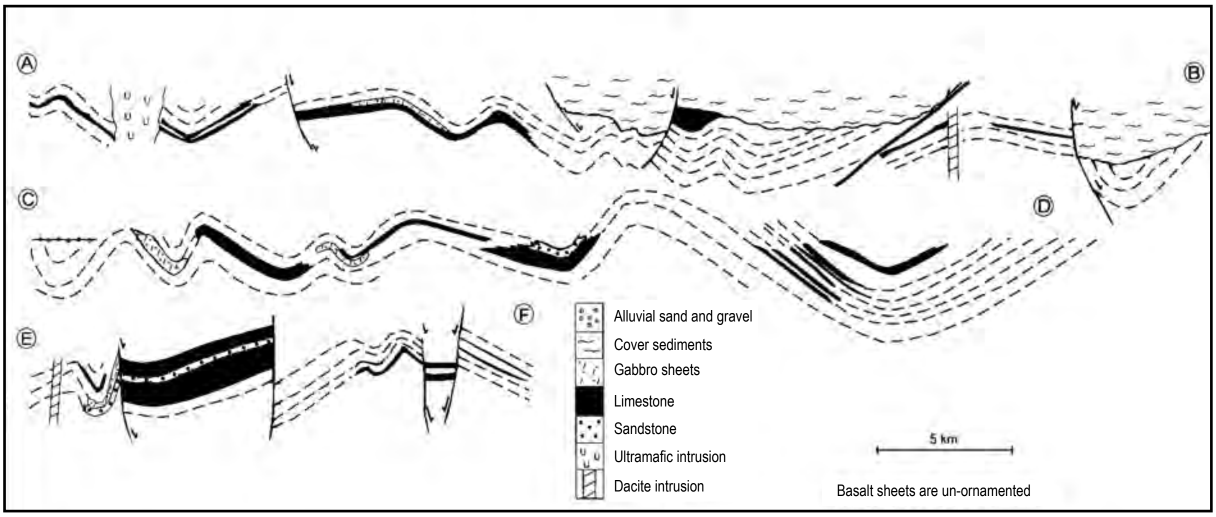

Figure 5. Geological cross-sections across Makira. Section C–D is the simplest section, which crosses central Makira and illustrates upright to slightly asymmetrical fold structures. Note the impersistence of limestone units which pinch out in both directions. Section A–B is drawn through eastern Makira and illustrates the Mid-Miocene to Early Pliocene Basin fill cover sequences which unconformably overlie the basement. Note the listric bounding growth faults and the folding of the plane of unconformity. Section E–F is an oblique dip section which illustrates sudden changes in dip across key fault Blocks.

Basement cover relationships

The geological map of Makira (Figure 3) demonstrates that the edge of the Makira Cover Sequence is locally highly oblique to the strike of the Makira Basement Complex, indicating an unconformable relationship. However, the unconformity is not a simple one. The continuity of the youngest fold axes between cover and basement, across the plane of unconformity indicates that both cover and basement have been folded by the most recent compressional events. Sensible geological cross-sections through both basement and cover units can only be drawn if their mutual geometrical relationships are modelled using Basin margin listric growth faults. The youngest sediments locally overlap the Basin margin faults producing the unconformable outcrop pattern present in Figure 3. We model the cover sediments as localised Basin fills. The Basins formed during Mid Miocene to Early Pliocene times after a post-Oligocene period of uplift and compression. The uplift/compressional event produced an uplifted rigid Block which gravitationally collapsed/extended in the south-east, and eroded to produce a considerable volume of basalt and limestone clastic material. This clastic material was quickly redeposited within proximal-medial shallow marine Basins (100 - 300 m deep) which deepened off shore into very deep water (>1000 m). Subsequent uplift during Upper Pliocene toRecent times has raised these shallow and deep water Basins and their respective deposits to a subaerial setting..

Structure and age variation across Makira

In terms of topography, Makira is characterised by a southern, coast-parallel backbone of ridges exceeding 1000 m above sea level which act as the major watershed. This major watershed is only 5 - 10 km north of the southern coastline and has influenced the development of relatively long, northward flowing rivers and short southward flowing rivers with steep long profiles. This is a similar situation to that of Guadalcanal and is due to the fact that both islands are within a frontal arc tectonic setting and have experienced signifcant uplift in Recent times, with the greatest uplift affecting areas closest to the south Solomon trench.

The uplift of the southern part of Makira could, in theory, bring older rocks to the surface: this is certainly the case in Guadalcanal where the oldest basement is exposed within the most uplifted southern regions (Hackman, 1980). It is unfortunate that the lack of stratigraphical control on Makira makes it difficult to make definitive statements concerning the age structure of Makira without the additional assistance of both isotopically and palaeontologically determined age data. It is for this reason that a number of samples have been sent to Drs Robert Duncan and Johanna Resig for isotopic/palaeontological age determination work respectively.

Figure 6 summarises recently determined Ar-Ar whole rock ages (R A Duncan, unpublished data). These data are provisional and should be treated with some caution. However, the limited data set does appear to suggest a geographical provincialism to the age of the Makira Basement Complex and a general younging to the north. The oldest ages of c. 98 - 92 Ma were determined from samples taken from south - eastern Makira (the Matangarighi area); samples from central Makira (Wairahito) have yielded Ar-Ar ages of between 67 and 52 Ma, and the youngest basement ages of c. 34 - 35 Ma have been determined from samples from northern Makira. This age pattern could be explained by: 1) a simple uplift model with the most uplifted southern regions exposing the oldest geology; or 2) a gradual northwards accretion of oceanic basement material with time, with major accretion events occurring periodically every 30 Ma or so.

Dr Johanna Resig has recently determined Mid Miocene Early Pliocene (c. 11 - 3 Ma) ages from foraminiferal dominated faunal assemblages present within the Harigha Sandstone Group, which is a constituent unit of the Makira Cover Sequence (Table 1).

Basalt geochemistry

Recently determined geochemical data on Makiran basalts is presented in Figures 6–9 inclusive. Figure 7 is a Nb-Zr plot, and Figure 8 a Nb-Zr/Nb plot of basalt samples from Malaita and Makira. Both illustrate the point that approximately two thirds of analysed samples from Makira plot within the Ontong Java Plateau (OJP) field, here represented by Malaitan basalts (which have identical compositions to the OJP, Petterson, 1995; Neal et al., 1997; Petterson et al., 1997) whilst approximatel.y one third of Makiran samples have higher Zr/Nb ratios (>25), more typical of N-MORB basalts. A small number of Makiran samples have high Nb concentrations and low Zr/Nb ratios (< 10) which reflect a more alkaline (e.g. Ocean Island) basalt composition: some samples from Malaita and Ulawa have an even more alkaline composition than those from Makira.

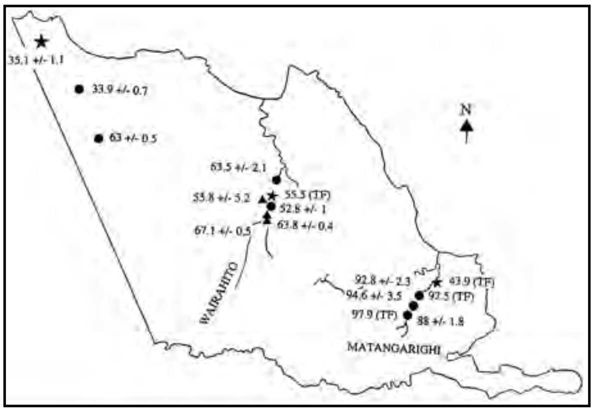

Figure 6. Map illustrating the currently available whole rock Ar-Ar radiometric data (R A Duncan, unpublished data). There is a clear age provincialism and younging-northwards trend. This figure also illustrates the stratigraphical interbedding of plateau lavas (circles); MORB lavas (stars) and alkaline basalts (triangles). Basalt classification is based on Zr/Nb ratios, see text for details.

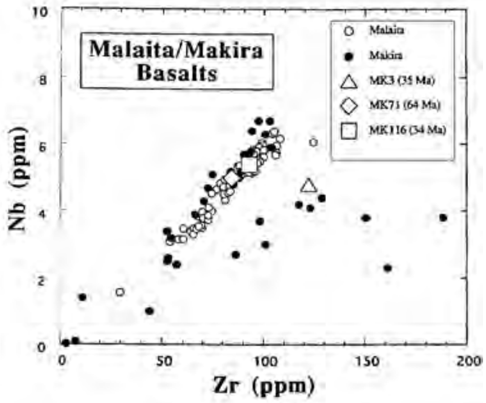

Figure 7. Nb-Zr scatter plot of Makiran basalts. Most Makiran basalts plot within the Ontong Java (OJP) field, here defined by basalts from Malaita. About a third of Makiran samples have higher Zr/Nb ratios more typical of N-MORB basalts.

Figure 9 illustrates the point that the available (limited) combined geochronological and geochemical data show that basalts with Zr/Nb ratios of circa 5 (alkaline basalt); 15 - 20 (plateau basalt); and >35 (MORB) were all simultaneously erupting between c. 70 and 45 Ma. Only plateau basalts have been dated at c. 90 and 34 Ma respectively. Figure 6 shows that within the Wairahiti area of Makira plateau, alkaline, and MORB basalts are all mutually interbedded, and all of an approximately penecontemporaneous age: this interbedded relationship is confirmed from undated samples taken from the Waihaoru river of north-west-central Makira (one dated sample here of 35.1 ± 1.1 Ma, Figure 6).

The implications of the combined geochronological, geochemical, and mapping datasets are profound for the structure and stratigraphy of Makira. The data suggests that Makira was a depocentre for the eruption of basalts from distinct source regions. It is beyond the scope of this paper to hypothesise on the petrogenetic origins of the three basalt types suffice to say that the plateau and alkaline basalts are plume related and *may* be genetically linked to the OJP basalts (particularly the older c. 90 Ma basalts); whilst the MORB basalts were more likely erupted within an ocean ridge tectonic setting. Whatever the ultimate origin of the basalts, it is evident that Makira has accreted episodically through time, amalgamating basaltic units from a range of oceanic tectonic environments.

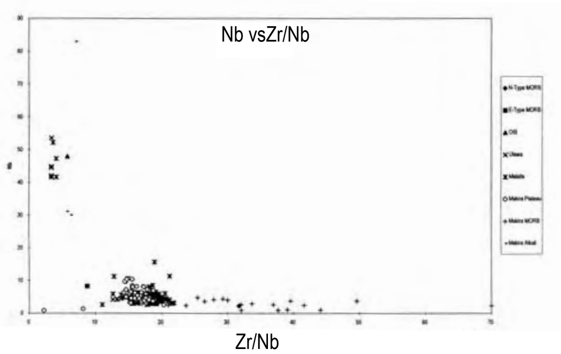

Figure 8. Nb-Zr/Nb scatter plot. Malaita (OJP) basalts and the bulk of Makiran basalts define a tightly constrained compositional field with Nb concentrations <13 ppm and Zr/Nb ratios between c. 10 and 23. Makira MORB samples have Zr/Nb ratios >24, up to 50. Makiran (and Ulawa and Malaitan) alkali basalts have low Zr/Nb ratios (<8) and relatively high (30 - 85) Nb concentrations.

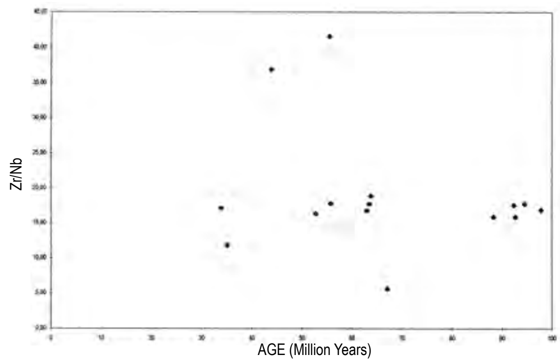

Figure 9. Scatter plot of Zr/Nb ratio with determined whole rock Ar-Ar age. Although the database is limited it shows that alkali, plateau, and MORB basalt magmas were available between c. 67 Ma and 48 Ma. The current database also suggests episodic accretion events at c. 88 - 98 Ma; 67 - 48 Ma; and 34/35 Ma respectively.

GEO-TECTONIC SYNTHESIS

Table 2 summarises the geological and tectonic evolution of Makira.

The Makira basement accreted somewhat episodically at c. 30 My intervals from around 100 Ma to 30 Ma. The relative volumes of these accretion events are difficult to assess at the present time. It appears that at least the c. 60 and c. 34/5 Ma events amalgamated basalts from plateau, ridge, and ocean island environments. The oldest event may only have amalgamated plateau basalts, although the database is limited. Most of the Makira basement records rapid effusion and accretion of basalt sheets, regardless of composition. However the basement also records localised periods of quiescence during which pelagic sediments were allowed to accumulate.

The basement was uplifted and folded between the Oligocene and the Mid Miocene. The tectonic cause of the uplift/compressional event is unknown but it is tempting to link this with the initial docking of the OJP with the stage 1 Solomon arc (Neal et al., 1997; Petterson et al., 1997). The Oligocene to pre-Mid Miocene compressional event resulted in an uplifted island which subsequently extended during Mid Miocene to early Pliocene times to produce localised extensional Basins. Basalt-limestone clastic sediments derived from the erosion of the uplifted island were transported by local fluvial systems into proximal-medial shallow marine Basins with water depths of 100 - 300 m, and which deepened offshore into deep water pelagic sediment dominated Basins with water depths of 1000 - 3000 m.

An arc developed on Makira. How extensive this arc was and what structures it formed is unknown. However the roots and reworked, redeposited sediments of the arc are locally preserved. The timing of the arc is problematical, but we suggest that it probably occurred during stage 2 arc , post -8 Ma times (Petterson et al., in press).

Since Late Pliocene times (c. 3 Ma) Makira has experienced a prolonged period of transpression and uplift. Figure 10 summarises some key plate movement and compressional vectors which have affected Makira during this period. The Australian plate is currently moving northeastwards and the Pacific plate is currently moving north - west wards giving a highly oblique plate collision. We know from structural studies on Malaita (Petterson et al., 1997) that the Malaita region experienced strong north-east - south-west compression between 4 and 2 Ma. Figure 1 shows the proximity of the

Table 2. Geo-Tectonic Evolution of Makira.

AGE	GEO-TECTONIC EVENT
Cretaceous – Oligocene (c. 100 - 30 Ma)	Accretion of basalt-dominated oceanic sequences from plateau, ocean ridge, and ocean island environments. Main accretion events at c. 90-100 Ma, 55 - 67 Ma, and 34 - 35 Ma. Deep sea pelagic sedimentation throughout.
Post-Oligocene, pre-Mid-Miocene (c. 30 - 12 Ma)	Compression and uplift. Formation of earliest east - west trending folds and uplifted island Block.
Post-Oligocene (?Miocene-Recent? <8 Ma)	Intrusion and extrusion of Arc material into and onto a basalt dominated basement.
Mid Miocene-Early Pliocene (11 - 3 Ma)	Collapse /extension of uplifted island Block in the south - east. Erosion of uplifted basalt-limestone basement. Formation of localised shallow submarine Basins. Deposition of locally derived basaltic and limestone clastic material within shallow marine Basins. Deep sea pelagic sedimentation persisting in deeper sea offshore Basins.
Late Pliocene-Present (3 - 0 Ma)	Transpressional tectonics within a forearc setting. Wedging of Makira between a north - east ward moving Australian plate, a north - west ward moving Pacific plate, and other transpressional vectors caused by impingement of Woodlark Basin, OJP, and Louisade Plateaus. Transpression causes east - west dominated folding, and left lateral, shear-induced normal faulting/fold axis kinking. Faulting most prevalent in central-east Makira. Makira is seismically very active at the present time, particularly in the west and south. Deposition of alluvial sediments and reef deposits.

Woodlark Basin and OJP and Louisade plateaus with respect to the Solomon Block. The interaction between the Woodlark Basin/Louisade Plateau the Solomon Block may have produced compressional to transpressional shear stress within the Makira region of the Pacific plate. Maps of recent seismic activity (e.g. Petterson, 1995) show Makira to be the most seismic large island within the Solomon archipelago, with the highest density of seismic events occurring in northwestern and southern Makira. Figure 10 models the large scale brittle fault pattern on Makira as resulting from a combination of north - south compression and west-north-west directed left lateral shear, resulting in a Riedel-shear type situation, forming north-north-east trending, predominant synthetic faults and east-north-east trending subsidiary antithetic faults.

This strong transpression has resulted in the piecemeal structural dissection of Makira, particularly in central-east Makira. Present day seismic activity may suggest that the maxima of the present day transpression is located in western Makira.

Prolonged uplift of Makira since post-Oligocene times has resulted in relatively deep erosion of the island and the loss of the bulk of the pelagic cover and arc sequences. The dominant north-flowing rivers have formed an alluvial plain in the north of the island (similar to the Guadalcanal plains, Hackman, 1980). Reef deposits are present in eastern Makira.

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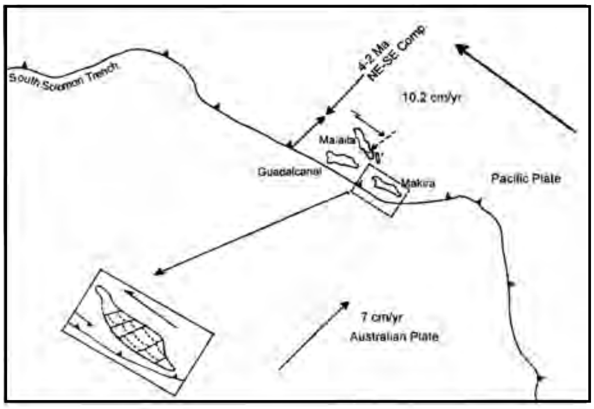

Figure 10. Makira is strongly affected by the highly discordant collision of the Australian and Pacific plates (solid vectors). Between c. 4 and 2 Ma the Malaitan area was affected by strong north-east - south-west directed compression caused by the collision and obduction of the Ontong Java Plateau. See text for discussion.

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DISEQUILIBRIUM, OVERPRINTING AND MINERALISATION IN HYDROTHERMAL SYSTEMS

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ABSTRACT

Disequilibrium is a temporary disturbance of a system that usually exists in a more or less steady state. Overprinting is the replacement of one mineral assemblage by another due to changes in physical and/or chemical conditions (temperature, pressure and/or chemistry). Recognising disequilibrium and overprinting in fossil hydrothermal systems can be important in mineral exploration, because some of the mechanisms that cause overprinting also cause mineralisation. It is also relevant when assessing the potential of geothermal fields for energy development, and in identifying geothermal hazards.

There is a close association between prograde overprinting and mineralisation where overprinting is due to renewed magmatism in a stable or waning hydrothermal system. Retrograde overprinting is associated with mineralisation where it is due to a sudden pressure drop following catastrophic unroofing of a hydrothermal system.

INTRODUCTION

Overprinting is the partial or complete replacement of one secondary (hydrothermal or metamorphic) mineral assemblage by a different assemblage, due to changes in physical and/or chemical conditions. In a stable system, reactions between fluids and rocks work to produce a secondary mineral assemblage that is in equilibrium both internally and with the fluid at the prevailing conditions, provided there is sufficient time and permeability. Note that permeability can be an important factor, as it may limit fluid rock interactions, such that low temperature phases persist metastably at higher temperatures.

Yet hydrothermal systems are seldom stable for long (in the geological sense), and when conditions change, then a new set of reactions will work to produce a new equilibrium assemblage. Such changes generally affect the fluid temperature, pH or chemistry, or possibly a combination of all three, and may be associated with mineralisation. Overprinting may be prograde (producing higher temperature and/or pressure assemblages), retrograde (producing lower temperature and/or pressure assemblages) or neither (due to differences in fluid chemistry or state, rather than temperature or pressure).

A brief disequilibrium event might produce very little mineralogical evidence of overprinting, whereas after a long-lived event and extensive overprinting, there may be no remnants of the prior assemblage(s) left. A brief disequilibrium event is best identified on the basis of vein or breccia matrix minerals that are not in equilibrium with other vein and alteration assemblages, and/or a distinct population of fluid inclusions (e.g. higher salinity and/or homogenisation temperatures). Because fluid inclusions reflect an instant in geological time, they better record brief events, whereas alteration mineralogy indicates long-term conditions. After extensive overprinting, usually some minerals from earlier assemblages are preserved because they are resistant to alteration or they are enclosed in a resistant mineral, while others may be recognisable from crystal pseudomorphs (e.g. chlorite after biotite). Prior generations of veining may be preserved (e.g. porphyry-style veins, or quartz pseudomorphs after platy calcite crystals). Fluid inclusion data may also preserve evidence of varied conditions during crystal growth; for example there may be two populations of fluid inclusions within a single vein as revealed by homogenisation and/or ice melting temperatures. (Note that two populations of inclusions are distinct from a wide spread within a single population, which could represent non-equilibrium trapping of a two-phase fluid).

The aims of this paper are to document the common occurrence of disequilibrium and overprinting in hydrothermal systems, using examples, and to examine the mechanisms by which overprinting and mineralisation are genetically linked. In some mineralised systems, it is not so much the general conditions, but the change in those conditions that is significant for mineralisation.

Stable geothermal systems

To understand the processes of overprinting, it is first necessary to understand the processes and conditions in stable hydrothermal systems. Hydrothermal systems comprise large convective cells in which groundwater is heated and ascends above a heat source (usually one or more intrusive bodies).

The boiling point of water increases with increasing pressure. Therefore, the boiling point at depth is higher than it is at the surface. Pressures in the shallow convective parts of active systems (typically to a depth of about 3 km) are controlled by hydrostatic effects (i.e. the pressure is determined by the weight of overlying water). Accordingly, below the water table temperatures can increase above 100°C. In many active systems, the temperature at a given depth is close to that which is predicted by a theoretical hydrostatic boiling point for depth gradient (Figure 1). This defines the limiting condition for water to be liquid at its boiling point: any pressure release at any point will cause it to boil. Gases dissolved in the water significantly lower the boiling point, whereas ionic solutes such as salts raise the boiling point slightly.

As hot water passes through a rock, certain elements including metals are dissolved. These are then precipitated elsewhere by processes such as fluid mixing, boiling, cooling and chemical reaction with host rocks. Where their deposition is sufficiently focused, various types of economic hydrothermal mineral deposits can form, including epithermal precious metal, volcanic hosted massive sulphide (VHMS), porphyry and skarn deposits.

At greater depth, and in other regions where permeability is low (e.g. in fine-grained sediments), fluids may be effectively isolated from the surface and prevented from convecting. Consequently, fluid pressures may exceed hydrostatic, and approach lithostatic (i.e. the pressure is determined by stresses in the overlying rock). Under lithostatic conditions, pressures increase more rapidly with depth and so water can exist at higher temperatures, though heat is transmitted by conductive rather than convective processes.

Hydrothermal eruptions are a relatively common occurrence within stable geothermal systems and do not require a major disequilibrium event. The amount of energy required to produce even a large hydrothermal eruption corresponds to between hours and months of the natural heat flux of a system. Thus, a large hydrothermal eruption will "leave no identifiable trace within the reservoir rocks in terms of hydrothermal alteration overprinting" (Browne and Lawless 2000).

PROGRADE OVERPRINTING

In hydrothermal systems, prograde overprinting usually results from a rise in temperature. A rise in temperature is often due to renewed magmatism (e.g. emplacement of a shallow intrusive body), but can also follow an increase in pressure. Pressure can increase if the water level is raised or if low permeability allows pressures to temporarily exceed hydrostatic conditions by confining water within the rock. If the water level is already close

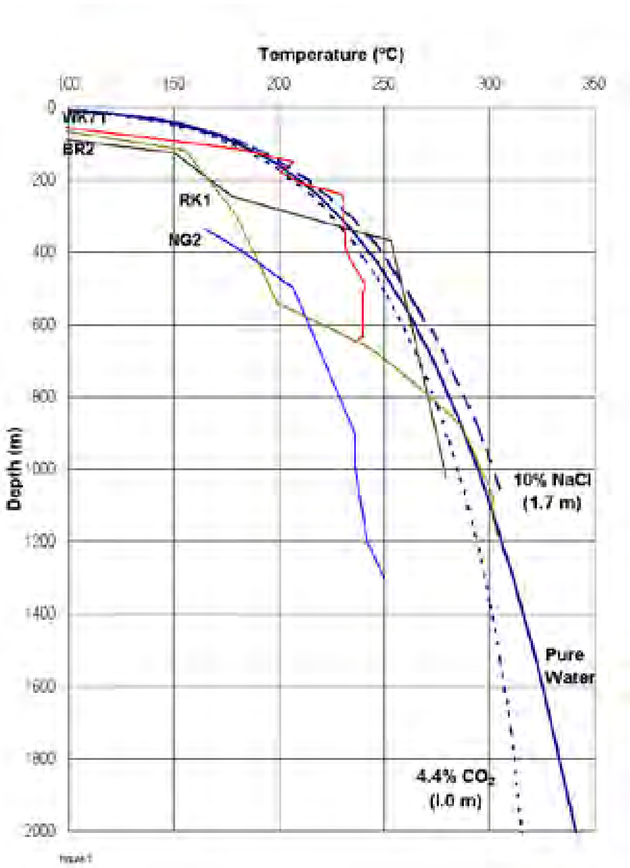

Figure 1. Temperature gradients in selected geothermal fields compared with a hydrostatic boiling point for depth gradient. The boiling point curve is after Haas (1971), and data for geothermal fields is from Grindley and Browne (1968) (BR2, Ohaaki), Steiner (1977) (WK71, Wairakei and RK1, Rotokawa) and Browne et al. (1981) (NG2, Ngawha).

to the surface, either the land must be submerged or more rock added at the surface by accumulation of material (as in submarine hydrothermal systems, tectonic depressions, and caldera Basins) for prograde overprinting to occur.

Renewed magmatism

Igneous activity has been documented from many active geothermal systems, including Suoh in southern Sumatra, Indonesia (1933) and Rotomahana in New Zealand (1886). The effects of renewed magmatism on a hydrothermal system are often overshadowed by the volcanic effects (e.g. Pinatubo, 1991), since the latter are commonly larger and more spectacular. However, the effects of renewed magmatism on a hydrothermal system can last much longer, as the examples here show.

Renewed magmatism in a hydrothermal system that is already close to a boiling point for depth gradient will raise the temperature above stable conditions (Figure 2). This will result in catastrophic magmatic-hydrothermal eruptions at the surface, and hydrothermal brecciation and boiling at depth (e.g. Browne and Lawless, 2000), until the system returns to a stable state. The sudden boiling and consequent loss of gas cause gold and other metals to deposit at depth, due to the destabilisation of bisulphide complexes. Briefly elevated temperatures may be recorded by minerals deposited within veins and breccia matrices during these events, and by the fluid inclusions within these minerals, though if the mobile phase is steam rather than water, it will contain few solutes and so cause little deposition. However, alteration assemblages take longer to form, and will generally record conditions after the hydrothermal system has returned to a stable temperature profile at or below boiling point for depth conditions. Therefore overprinting will only be preserved by the alteration assemblage if the stable temperature profile is significantly different after the renewed magmatism to what it was before. This may require elevation of the water table.

Renewed magmatism need not have catastrophic effects if a system remains below a boiling point for depth gradient. For example, prograde overprinting in the Kilauea East Rift Zone geothermal area (Hawaii, USA) is indicated by alteration assemblages that are not in equilibrium internally or with fluid inclusion data and measured downhole temperatures (Bargar et al., 1995). Minerals such as chalcedony, smectite and interlayered chlorite-smectite (which form below about 200°C) occur where temperatures are up to 350°C (together with high temperature phases

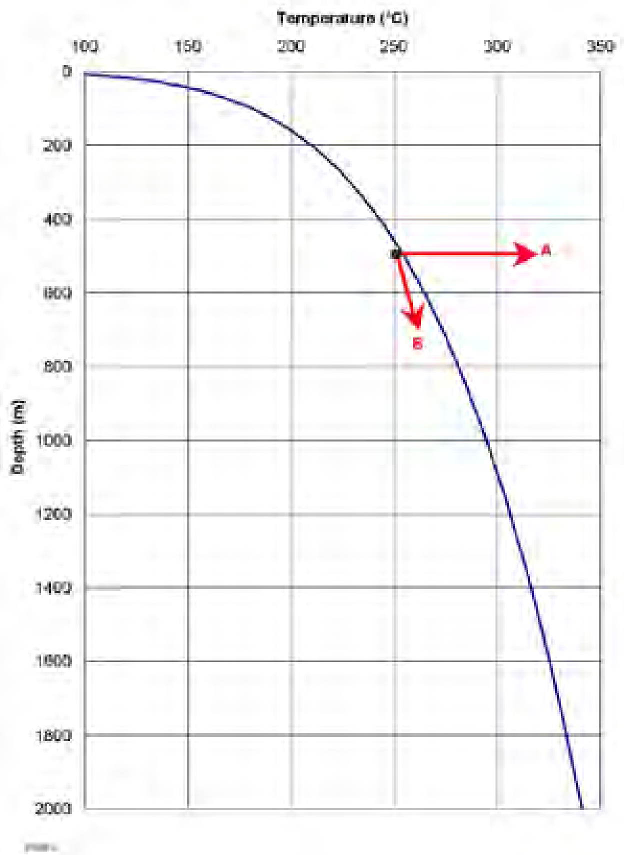

Figure 2. Temperature-depth plot illustrating the effects of renewed magmatism (A) and burial (B) on temperatures at depth in a hydrothermal system compared with a hydrostatic boiling point for depth gradient.

such as garnet, amphibole, biotite, epidote and talc at over 300°C), but the present temperature gradient is still mostly below boiling point for depth conditions. Vapour-rich fluid inclusions and bladed calcite crystals provide evidence of previous boiling, but little hydrothermal brecciation was reported by Bargar et al. (1995).

Suoh, Indonesia

The Suoh geothermal system is located within a pull-apart Basin near the southern end of the Sumatra Fault System. Boiling point for depth conditions prior to June 1933 were indicated by boiling springs, silica sinters, and fumaroles (Stehn 1934). On 25 June 1933, southern Sumatra was shaken by violent earthquakes, and then two weeks later, gas pressures in the hot springs and solfataras at Suoh increased. On July 10, two craters burst into violent activity, and between July 16 and 19, more than 100 vents opened, with eruptions issuing mud, stones, and steam from seven of these. The largest vent measured 2 km by 1.5 km. The most violent eruption observed ejected material to a height of over 1000 m, and others were heard 650 km away on Java (Stehn, 1934, van Padang, 1951). The floor of the Basin, an area of 32 km^2, was covered to an average thickness of 6 m (i.e. approximately 0.2 km^3 of material was erupted), causing the Semangka River to be diverted by several kilometres. By August 5, eruptive activity had virtually ended.

The eruption deposits comprise an unsorted muddy breccia, with clasts up to 0.5 m across of altered volcanic rocks, hydrothermal material including sinters, and unaltered hornblende dacite fragments, in a clay-rich matrix (P J White and J V Lawless, unpublished data). Near the largest vents, tree trunks are present at the base of the unit, and lie pointing away from the vents. The thickness and extent of the eruption deposits, and the fallen trees pointing away from the vents strongly suggest that much of this material was deposited from a base surge, as was proposed for a similar deposit formed during the 1886 eruption of Rotomahana, New Zealand (Nairn, 1979). Hydrothermal epidote in clasts indicates the eruptions excavated to at least 370 m below the surface, based on a minimum temperature of 240°C for epidote formation, a low-salinity fluid and boiling point for depth conditions (P J White and J V Lawless, unpublished data).

The scale of the Suoh eruptions is much larger than would be expected for purely hydrothermal eruptions, and the eruption products contain juvenile magmatic material (hornblende dacite). Thus, we may surmise that tectonic activity opened a fracture through which a fresh batch of magma ascended until it encountered the geothermal system. There the magma was quenched by the water, but caused flashing of hot water to steam, and explosive magmatic-phreatic eruptions. In less than one month these eruptions had ceased and system returned to a boiling point for depth profile, which it still maintains today. The Suoh geothermal system has not yet been drilled, but when (or if) it is, it will be interesting to see what overprinting and mineralisation might have occurred during one month of disequilibrium, and what evidence will remain in a fossil system.

Kelian, Indonesia

A similar event is believed to have occurred at about 20 Ma at Kelian in East Kalimantan, Indonesia, which is now the site of a large gold mine. A complex history of hydrothermal alteration, veining, brecciation and mineralisation has been documented for this deposit, with four partly overlapping stages recognised (van Leeuwen et al. (1990). Early (Stage I) propylitic (chlorite-carbonate-sericite-pyrite±epidote) alteration of andesite occurred at over 240°C (possibly 300°C). In Stage II, fracturing and sericite-quartz deposition (IIa) was followed by brecciation and deposition of adularia-sericite-quartz-pyrite with silver, arsenic and possibly minor gold (IIb). Stage II fluids were low salinity (<4 eq. wt% NaCl), moderately hot (270 to over 300°C) and periodically boiling. During Stage III, there was extensive brecciation and deposition of carbonates, quartz and sericite, together with base metals and gold. Fluids were hot (300 - 330°C), saline (>10 eq. wt% NaCl) and CO_2-rich, and there was extensive boiling. Stage IV comprises late carbonate-kaolinite overprinting, representing the encroachment of cool (200 - 250°C), acid (pH 3 - 5) fluids from the surface and periphery of the system.

It is considered that renewed magmatism during Stage III provided an input of heat and magmatic fluids, based on the high temperature, high salinity and relatively high gas content of the fluids (from fluid inclusion and mineral assemblage data) and their isotopic composition (van Leeuwen et al. 1990). This renewed magmatism coincided with the formation of a large breccia body, and deposition of the bulk of the gold and base metals (Davies et al. (1999). A similar mechanism has probably occurred in many other mineralised hydrothermal systems (Lawless, 1988), but the mineralogical consequences are commonly overlooked.

Accumulation of material

Prograde overprinting may also arise from more gradual changes, such as where the land surface is subsiding and material accumulating during the course of hydrothermal activity, or where there is a rising water table (due to climatic change, tectonic activity, etc.). Examples are submarine hydrothermal systems, and systems that are located within structural Basins or calderas in which epiclastic and/or pyroclastic deposits are accumulating. Even where sedimentation rates are very high, heating of this material is a gradual process, and will not in itself cause mineralisation. This is because the rate of temperature increase is generally less than the rate of burial relative to boiling point for depth conditions (Figure 2). Mineral deposits that form within calderas and in a submarine setting (e.g. volcanic hosted massive sulphide (VHMS) deposits) may preserve evidence of overprinting due to coeval burial, but in these cases overprinting is not related to the process of mineralisation.

RETROGRADE OVERPRINTING

Retrograde overprinting generally results from a temperature decline. A drop in temperature can occur due to gradual cooling during the waning stages of hydrothermal activity. Cooling at a given point can also occur following lowering of the water level. This may be due to climatic change, or the removal of a quantity of rock from the surface. There might be a gradual loss of material by erosion, or a sudden loss due to volcanic eruption or sector collapse.

Sector collapse

Major sector collapses have been recognised at many active geothermal fields, including Papandayan in West Java, Indonesia (1772), and Lihir in Papua New Guinea (prehistoric). Some sector collapse structures have in the past been mistakenly identified as calderas, but there are important differences between the two, in terms of their origins, the deposits produced, and their effects on a hydrothermal system. The differences between sector collapses and calderas are shown graphically in Figure 3.

A sector collapse is the *outward* (lateral) collapse of an entire sector of a volcano to produce a large debris avalanche. The amphitheatre at the head of the sector collapse is typically 1 - 3 km across and horseshoe shaped, with subparallel side walls (e.g. Siebert, 1984). The resulting debris avalanche is a coarse, unsorted epiclastic deposit that extends out as a tongue of debris with a hummocky surface. Historical examples of sector collapses have occurred at Bandai, Japan (1888), Bezymianny, Russia (1956), and Mt St Helens, USA (1980). It is only since the well-studied Mt St Helens event that sector collapses have been recognised as a common occurrence during the growth of large composite volcanoes (Ui et al., 2000). They have now been identified at more than 200 volcanoes worldwide (e.g. Tilling, 2000), and are particularly common on island volcanoes (e.g. Holcome and Searle, 1991) and large composite cones. Some sector collapses, including Mt St. Helens, take place during volcanic activity, but others occur during quiescence. During the 1980 sector collapse on Mt St Helens, some 2.5 km^3 of rock with a maximum thickness of over 500 m was removed from the mountain, leaving a large amphitheatre with a steep back slope (Voight et al., 1981). Other sector collapses on composite cones (including Shasta, USA and Colima, Mexico) have been much larger than this, involving volumes of over 20 km^3 (e.g. Ui et al., 2000). Landslides on oceanic islands have been even larger, with volumes of over 1000 km^3,

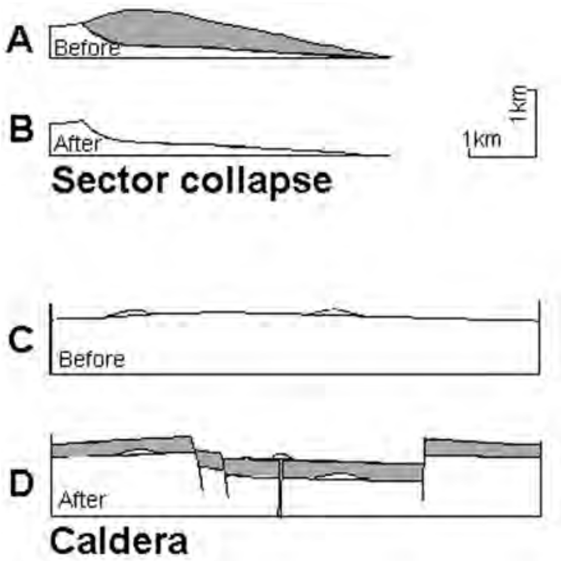

Figure 3. Schematic cross-sections highlighting the contrasting effects of sector collapse (A, B) and caldera formation (C, D). Shaded areas show material that is removed or added, respectively, during these events. The sector collapse is based on sections through Mt St. Helens before and after the 1980 event (from Siebert 1984). The scale applies only to A and B; calderas are generally larger.

and single events removing 10 to 20% of the total volcanic edifice (Holcome and Searle, 1991), though the largest of these are slow-moving slumps rather than debris avalanches.

In contrast, a caldera is a volcanic depression that forms by large-scale downward collapse of the ground surface above a magma chamber during or after an eruption. Calderas are typically semicircular to oval, and kilometres to tens of kilometres across. Caldera-forming eruptions produce pyroclastic flow, surge, and fall deposits, which are dominated by glassy juvenile material. The caldera Basin is often partially or completely infilled with eruption deposits, so that a point on the original land surface will be buried. Up to 50% of the erupted pyroclastic material may fall back into the caldera Basin, especially in the largest calderas, where it may be as much as 5 km thick (Lipman, 1984). As an example, a caldera measuring 6 by 7 km was formed during the 1883 eruption of Krakatau (Indonesia) which ejected some 18 km^3 of dacitic pyroclastics. Larger caldera forming eruptions can produce over 1000 km^3 of pyroclastic deposits (e.g. Ninkovich et al., 1978).

Removal of material from above a hydrothermal system by sector collapse will suddenly reduce the confining pressure, which may result in hydrothermal brecciation, boiling and mineralisation. The effects are similar to those of renewed magmatism, but with a different mechanism; decreased confining pressure rather than increased temperature (Figure 4). A sudden pressure drop can have the same effect on a hydrothermal system as sudden heating, pushing the system beyond boiling point for depth conditions. However, in this case the temperature will decrease rather than increase, causing retrograde overprinting. In contrast, a caldera-forming eruption will deposit material at the surface, leading to higher subsurface pressures, and thus prograde overprinting (Figure 4).

Lihir, Papua New Guinea

An example of mineralisation that can be attributed to the effects of sector collapse and retrograde overprinting is the giant Ladolam gold deposit on Lihir Island, Papua New Guinea. The Ladolam area was once the site of a large volcanic cone (Luise volcano), beneath which a porphyry system produced potassic and propylitic alteration (secondary K-feldspar, biotite, amphibole and magnetite) and incipient copper-molybdenum-gold mineralisation at depth, and argillic alteration above. A massive sector collapse of the weak clay-altered material between 0.15 and 0.35 Ma. instantaneously removed approximately 1000 m of cover to expose the top of the porphyry system (Moyle et al., 1990). The sudden large pressure drop that accompanied this collapse resulted in violent hydrothermal brecciation and boiling, and epithermal alteration and gold mineralisation overprinting the porphyry system (Moyle et al., 1990). The hydrothermal system eventually reached a new equilibrium that was consistent with the lower pressures, and remains in that state today, with active fumaroles and boiling springs occurring within the mineralised zone.

Moyle et al. (1990) described the large horseshoe shaped amphitheatre as a caldera, but offered two alternative explanations for its origin; explosive phreatomagmatism, or large scale cone failure. The latter option is favoured here, as it is more consistent with the geomorphology, the lack of a tuff ring or young pyroclastic deposits, horizontally extensive sulphidic breccias, exposed monzonitic intrusives, and low temperature overprinting high temperature alteration. More convincingly, coarse epiclastic debris avalanche deposits have recently been mapped for up to 45 km off to the eastern coast of the island (Herzig et al., 1994). It has been suggested that a significant portion of the Ladolam gold deposit may lie at the bottom of the ocean (Herzig et al., 1994), though this is not predicted by the above interpretation.

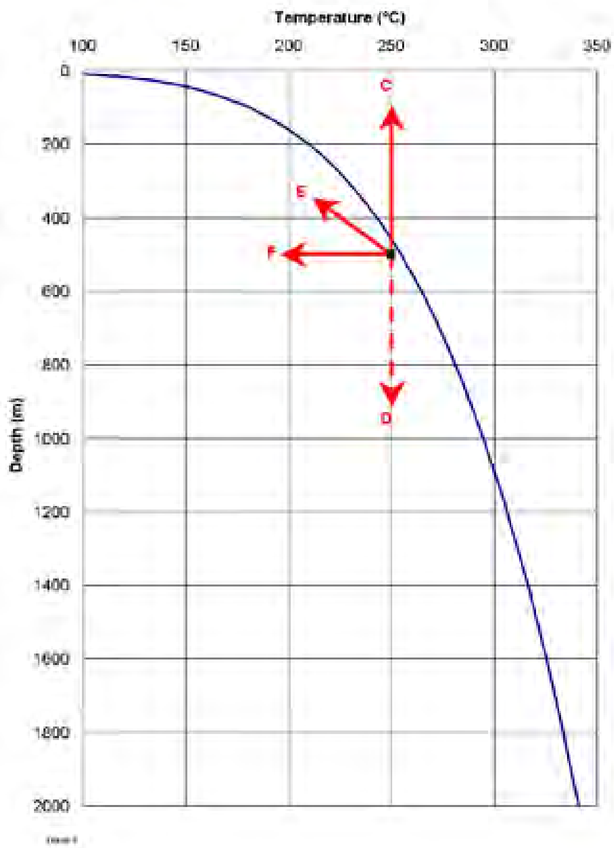

Figure 4. Temperature-depth plot illustrating the effects of sector collapse (C), caldera collapse (D), gradual erosion (E) and cooling (F) on a hydrothermal system, compared with a hydrostatic boiling point for depth gradient.

Erosion

Many hydrothermal systems are located in areas of active uplift and tectonism, and it is possible for a system to be uplifted and eroded to considerable depth over its lifetime. Areas of rapid erosion are of necessity steep, and hydrothermal systems in such areas are characterised by having a deep water level. Accordingly, gradual removal of material from the surface will have little impact on the deep hydrothermal system, and even a major landslide will not normally remove sufficient material to impact significantly. With the notable exception of sector collapses, as discussed above, erosion is normally a slow incremental process that will only gradually change the stability zone for each hydrothermal assemblage. The system will adjust accordingly and cause retrograde overprinting without ever exceeding boiling point for depth conditions (Figure 4).

Tongonan, Philippines

The active Tongonan geothermal system in the Philippines is an example of a system that has experienced considerable erosion over its lifetime (Leach et al., 1983). In one area, hydrothermal epidote (indicating temperatures over 240°C) occurs at a shallow level where current temperatures (from downhole measurements) are less than 150°C. An assumption of boiling point for depth conditions would imply at least 340 m of erosion, but based on the present temperature profile (deep water level and less than boiling point for depth conditions), it may have been much greater (Lawless, 1988).

Cooling

Gradual changes due to declining temperatures in a waning hydrothermal system will result in retrograde overprinting. Evidence of retrograde overprinting should therefore be common in fossil hydrothermal systems, since all have cooled. Indeed this is the case; for example, the platy calcite crystals that form in boiling zones are almost always pseudomorphed by quartz in epithermal deposits, except in systems that cooled too rapidly for this to occur (e.g. Golden Cross, New Zealand; Simpson et al., 1995, and Kelian, Indonesia; van Leeuwen et al 1990).

However, retrograde overprinting due to gradual cooling will generally not cause mineralisation. This is because lowering the temperature may change the stable mineral assemblage at a given point, but moves that point away from boiling point for depth conditions (Figure 4). Accordingly, processes like boiling and hydrothermal brecciation that might cause deposition of metals are less likely to occur. Mineralisation might occur due to fluid mixing as cool, oxidised peripheral fluids, which are often acid, encroach on the reduced, neutral pH fluids in the core of the system. However mineralisation at this stage is generally minor, though it might add to what was deposited during previous stages (e.g. Kelian; van Leeuwen et al., 1990).

Tectonic activity

Tectonic activity can cause sudden pressure changes that cause temporary disequilibrium in shallow hydrothermal systems. The tectonically induced pressure changes produce temperature and chemical changes, which are recorded by rhythmically banded epithermal veins (e.g. Waihi, New Zealand), though this is not necessarily the only origin of banded veins. This was examined by Bogie and Lawless (1999), who described dilation due to faulting causing a fluid pressure drop, inducing greater steam separation and a temperature drop, followed by heat transfer from the country rock to the fluid (e.g. Henley and Berger 2000), and eventually a return to equilibrium boiling point for depth conditions. These changes are accompanied by changes in the style of fluid movement (from laminar bubble flow to turbulent slug flow, then flow of steam and immobilisation of water, and back to laminar bubble flow) and mineral deposition. Gold and sulphides are deposited during the heat transfer stage when water is immobilised, which represents the time of greatest disequilibrium. Bogie and Lawless (1999) did not specify the magnitude of the pressure, temperature and chemical changes that occur, or their duration. However the temperature changes are probably quite small, and the changes in fluid chemistry much larger, based on the variable vein textures and mineralogy. The duration of these events is sufficient to produce fine banding within veins, but not enough to affect alteration assemblages in the host rocks.

In deeper hydrothermal systems, tectonic activity will generally have less effect, except where impermeable host rocks mean that fluid pressures can exceed hydrostatic, and approach lithostatic conditions. This may be the case at Porgera (Papua New Guinea), where mineralisation appears to result from repeated, sudden pressure fluctuations associated with tectonic activity in a deep, overpressured hydrothermal system. The Porgera gold deposit is associated with an alkaline intrusive complex that intrudes impermeable Cretaceous shales, and formed at an estimated depth of 2 - 3 km (Richards and Kerrich, 1993). Two stages of mineralisation are distinguished; Stage I phyllic alteration and base metal rich veins with quartz, pyrite, sphalerite, galena and carbonate, which locally constitute low grade ore, and Stage II (also known as Zone 7) high grade banded quartz-roscoelite-pyrite-gold veins associated with the Roamane Fault. The Roamane Fault was only active during Stage II and focused fluids during this stage (Munroe, 1995).

At a depth of 2 - 3 km, temperatures over 340°C are required for pure water to boil under hydrostatic conditions. The mineralising fluids at Porgera were CO_2-rich (Richards and Kerrich 1993, Cameron et al 1995), but even with 4.4 wt% (1 molal) dissolved CO_2 (and zero salinity), boiling at these depths requires temperatures in excess of 315°C. Homogenisation temperatures of Stage II fluid inclusions average about 145°C (Richards and Kerrich, 1993), and even after appropriate pressure corrections (about 20°C), the inferred trapping temperatures of 165°C are still well below boiling conditions (Figure 5). High pressures (approaching lithostatic) during mineralisation were inferred from near-critical fluid behaviour (Richards and Kerrich, 1993), extension fractures (Munroe 1995), and liquid CO_2 in fluid inclusions (Cameron et al., 1995). So, instead of being due to boiling, it is proposed that mineral deposition was caused by the sudden loss of dissolved gases when dilational movement of the Roamane Fault caused pressures to drop from near-lithostatic to near-hydrostatic (Figure 6). Pressure fluctuations between ~450 and ~250 bars were proposed by Richards and Kerrich (1993), but could have been greater than this (at 2 - 3 km depth, lithostatic pressures are about 550 - 850 bars, and hydrostatic pressures are 150 - 300 bars).

Cameron et al. (1995) considered that mineralisation was accompanied by cyclic variations of fluid composition and possibly pressure and temperature to produce the banded veins, but then argued that gold deposition was due to fluid mixing. It is considered here that these cyclic variations arose

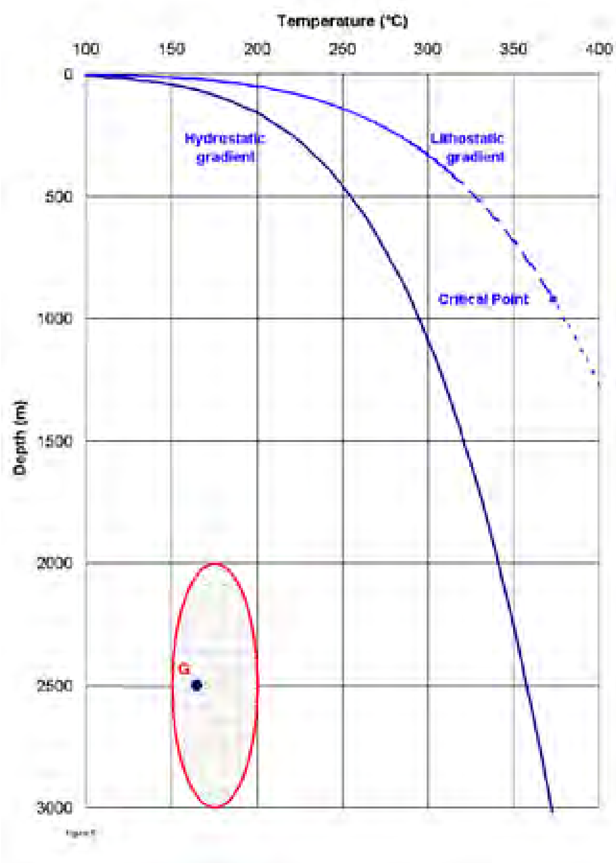

Figure 5. Temperature-depth plot showing inferred conditions during mineralisation at Porgera compared with a hydrostatic boiling point for depth gradient. Point G shows the most likely fluid composition, and the shaded area shows the possible range of conditions. Dilational faulting will not significantly affect either the temperature or depth.

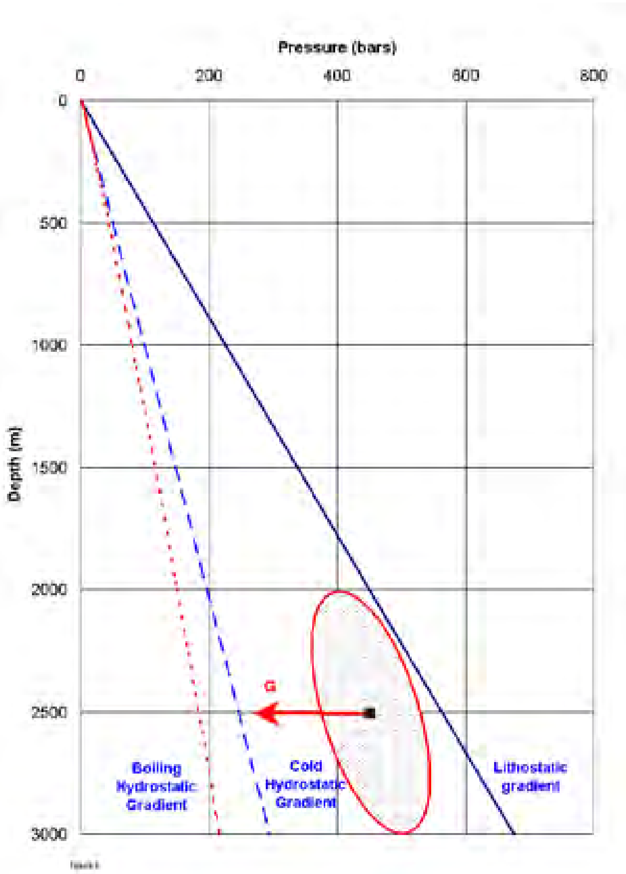

Figure 6. Pressure-depth plot showing inferred conditions during mineralisation at Porgera compared with lithostatic and hydrostatic pressure gradients. Point G shows the most likely fluid composition, and the shaded area shows the possible range of conditions. The arrow shows the likely effect of dilational faulting.

when suddenly lowered pressures due to periodic dilational fault movements caused adiabatic cooling and gas loss (*i.e.* phase separation by effervescence rather than boiling), changing the fluid composition (to less acid, more oxidised), and causing gold to deposit. Pressures built again once permeable channels were Blocked by mineral deposition and ductile deformation of the weak shales. Thus the two fluids postulated by Cameron et al. (1995) were present, but at different times, and mineralisation was not caused by mixing of these two fluids, but by one changing into the other due to loss of gas. Richards and Kerrich (1993) reported widespread overprinting of early propylitic assemblages, though it is uncertain to what extent this is due to the Stage II event. Short-lived disequilibrium events such as these typically cause very limited overprinting, and the varied fluid conditions are best indicated by vein mineralogy and textures.

OTHER OVERPRINTING

Overprinting may reflect changes in fluid chemistry, or changes from liquid-dominated to vapour-dominated conditions. However, these changes in themselves are not likely to cause mineralisation, except where they are associated with processes such as boiling or mixing of different fluids, rather than to the process of overprinting. For example, high and low-sulphidation epithermal systems are superimposed at Masupa Ria (Kalimantan, Indonesia), but mineralisation is restricted to quartz veins associated with the low-sulphidation event (Thompson et al., 1994).

CONCLUSIONS

Significant physical changes are common within the life cycle of a hydrothermal system. These changes often result in overprinting, and may also cause mineralisation, depending on the process(es) responsible for overprinting. Prograde overprinting may be closely tied to mineralisation where a hydrothermal system has been rejuvenated by renewed magmatism. Retrograde overprinting can be intimately associated with mineralisation where overprinting was due to rapidly decreased confining pressures, as may occur during sector collapse or extensional tectonism. Analysing fossil systems for evidence of overprinting and determining its cause may help in assessing the mineral potential of a system and locating mineralisation.

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