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Reducing Vulnerability of Pacific ACP States

TUVALU TECHNICAL REPORT – COASTAL CHANGE ANALYSIS USING MULTI-TEMPORAL IMAGE COMPARISONS – FUNAFUTI ATOLL

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Important Notice

This report has been produced with the financial assistance of the European Community; however, the views expressed herein must never be taken to reflect the official opinion of the European Community.

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EXECUTIVE SUMMARY

Shoreline change and processes were analysed on Funafuti Atoll by the comparison of digitally rectified 1941, 1943, 1984 aerial photographs with a 2003 IKONOS geo-referenced satellite image. Analysis of the digitally enhanced historical images also allowed the interpretation of past land and vegetation types, which in turn provides an insight into historical land forms on Funafuti.

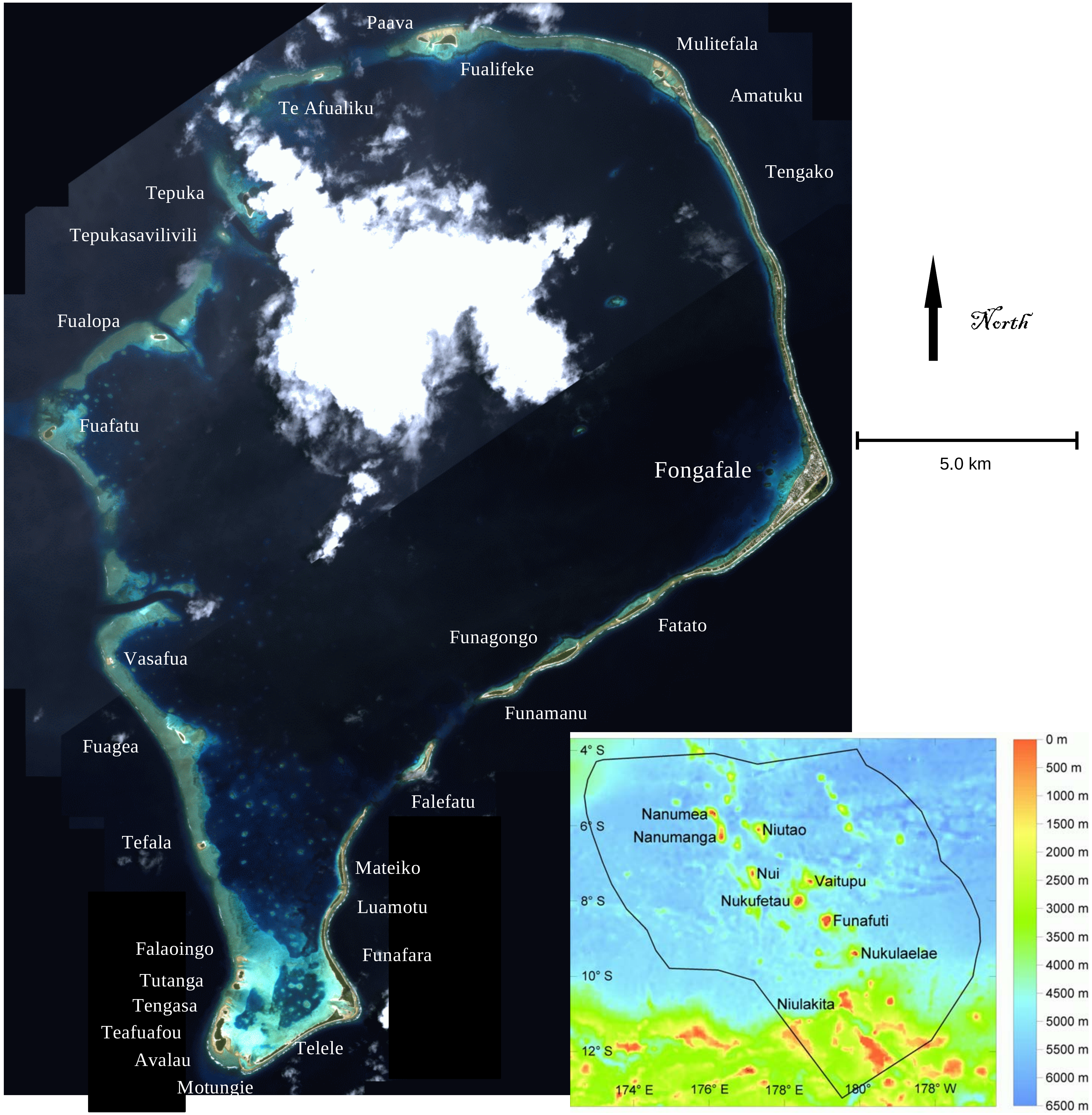
No evidence was found supporting suggestions that erosion on Fongafale's lagoon coast was more pronounced between 1984 and 2004 (coinciding with a pilot aggregate dredging programme in Funafuti Lagoon). Furthermore, this coast was found to have prograded westward by some 25 to 30 m since 1941 and the 1943 historical photos indicate that this was caused by active dredging, reclamation and infilling of the pre-war lagoon-side coastline.

It is likely that much of the present lagoon shoreline instability experienced in Fongafale is a continuing artefact of these profound changes made by the United States military effort through the early 1940's.

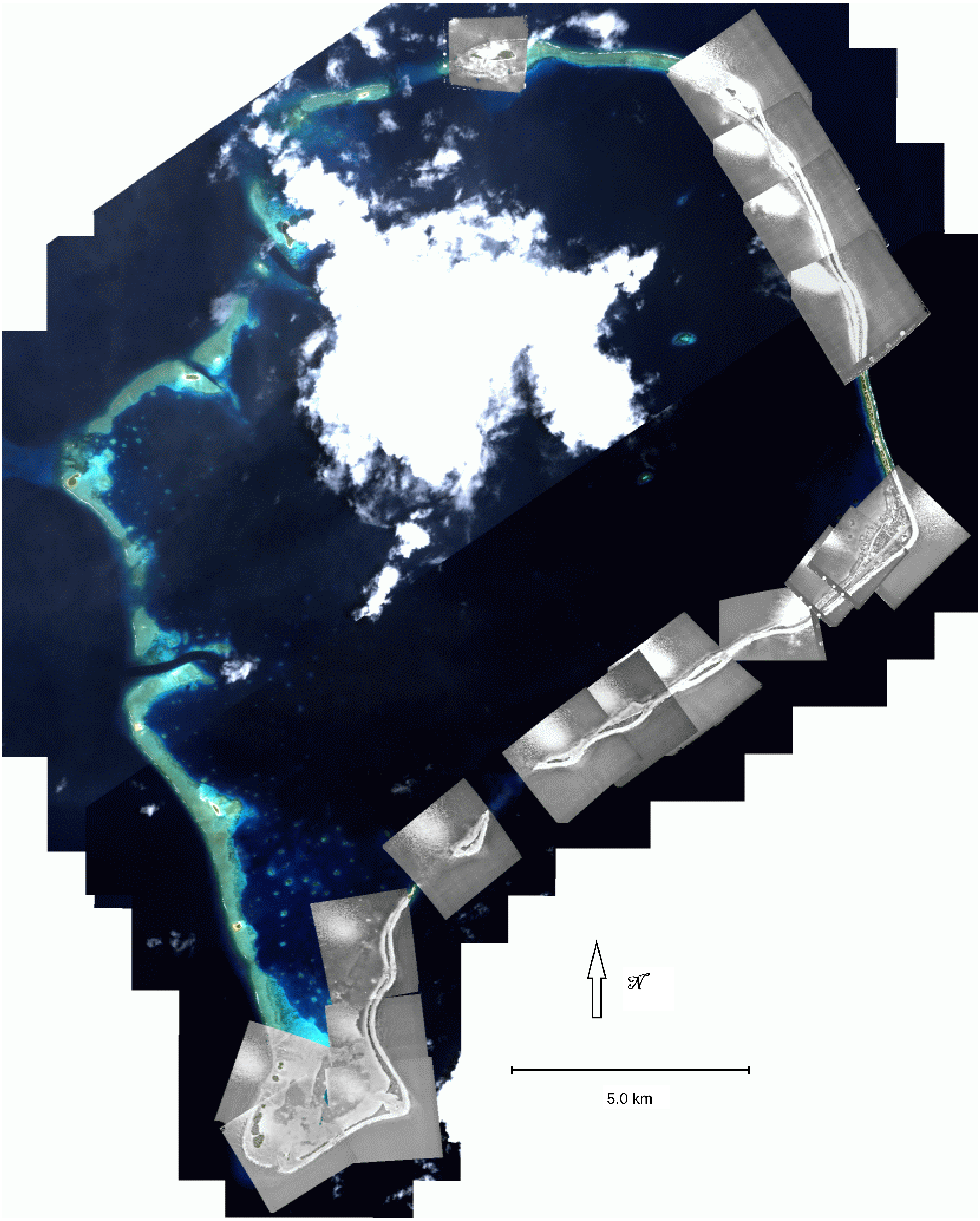
There is significant evidence of coastline shift in the islets of the western and northern reef systems during the period from 1984 to 2004. Groundtruthing of geomorphological and vegetation features of these islets similarly suggest continual, natural movement of these islet's soft shorelines.

Close analysis of land forms and vegetation patterns in early 1941 aerial photographs of Fongafale, show a strong likelihood that much of the area adjacent to the Fongafale airstrip is naturally low-lying and subject to regular seawater inundation.

Likewise, prior to the US military earthworks, a large inter-tidal brackish pond (Tafua Pond) extended well beyond the north-western edge of the present airstrip into what is now a housing area.



The 2004 IKONOS satellite image of Funafuti Atoll showing Fongafale and other smaller islets. Fongafale is the administrative centre of Tuvalu where all Government departments, medical facilities and international ports of entry are located. Inset map shows the relative position of Funafuti and the location of Tuvalu's territorial boundaries (Source: Smith and Sandwell, 1997).



In this figure the 2004 geo-referenced satellite image forms the backdrop upon which the scanned and geo-rectified 1984 aerial photographs have been overlaid. Note that not all islets and areas are covered due to the unavailability of photographs of these areas. It can be seen how this overlay technique will allow an easy and accurate comparison of coastal and landform change over time. Historical aerial photographs from 1941 and 1943 have also been overlaid in exactly the same manner giving an indication of change over the last 60 years. Additionally, future satellite images of Funafuti can be added to these layers to achieve ongoing monitoring of coastal change. It is also important to note that all images shown in this study are orientated identically to grid north (UTM WGS 84) and are available via the SOPAC Secretariat as geotiff files.

INTRODUCTION

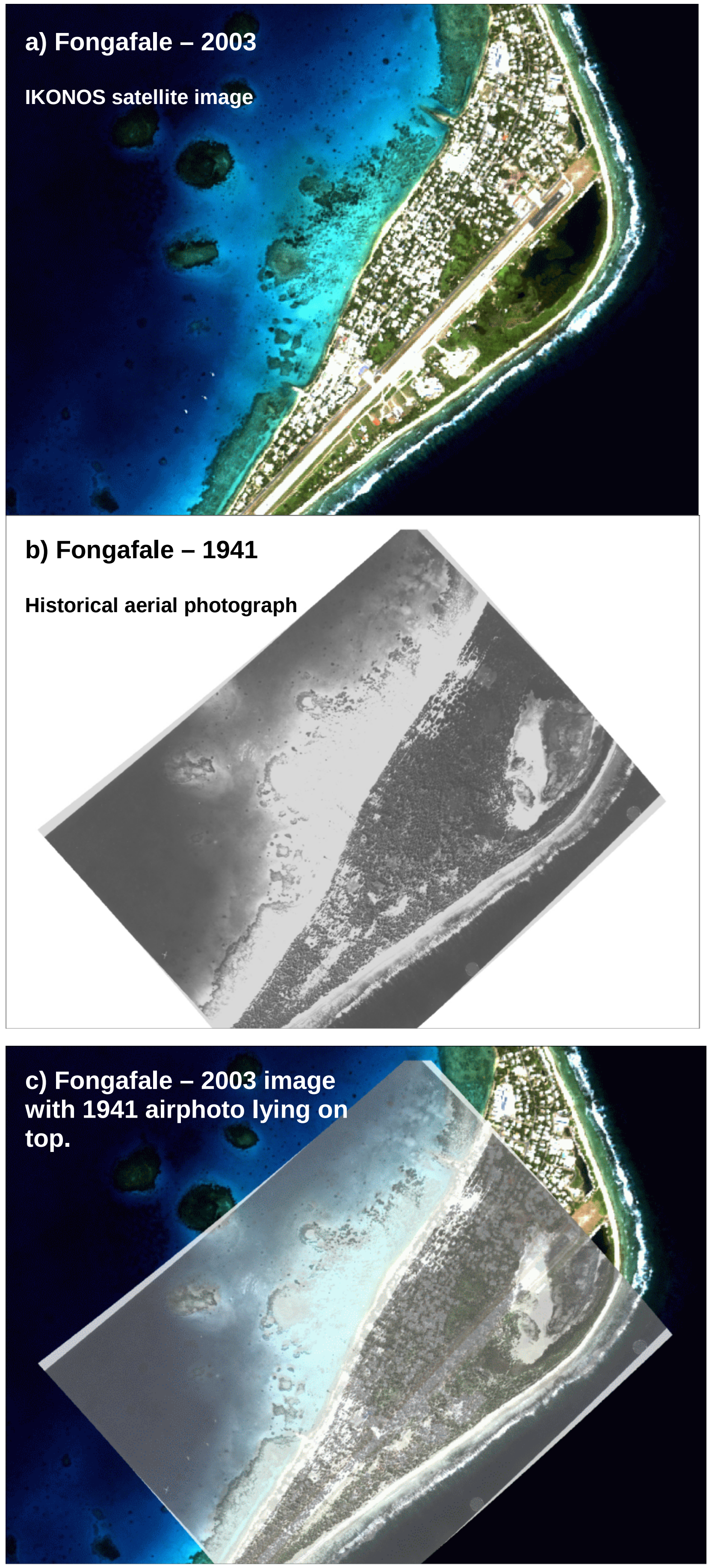
This work was initiated by the SOPAC / EU EDF Reducing Vulnerability of Pacific ACP States Project. Multi-temporal analysis of historical aerial photos and satellite images were utilised to address work tasks developed during the multi-stakeholder meeting between representatives of the SOPAC / EDF Project and the Tuvalu Government and community. These tasks are identified within the SOPAC / EDF Tuvalu work plan as; TV 1.1.2 (3.5.1); 1.2.5; 1.2.6 (3.5.2).

During a site visit by the author in September 2004 it became apparent that in order to address the aggregate supply issues on Funafuti there was a need to first address Government and community concerns regarding the potential of lagoon basin dredging to disturb coastal processes and possibly accelerate coastal erosion (Webb, 2004 [EU-SOPAC Project Report 36]). This perception appeared related to an earlier pilot dredging scheme undertaken in co-operation with SOPAC in the early 1990's. During the period that the pilot scheme was active it was widely held by the community that shoreline erosion increased on both the Fongafale Lagoon shore and on the islets of the western reef of Funafuti Lagoon. As a consequence dredging ceased and beach and land mining of aggregates resumed.

In order to conclusively address these concerns, a broad study of coastal change using multi-temporal analysis of historical aerial photos and satellite images was undertaken. This was completed with the intention of supporting existing information and quantifying coastline movement of the Fongafale lagoon-side shore. It also sought to characterise shoreline movement on the islets of the western reef. The use of a pre-war aerial photography of Fongafale (1941 – SOPAC Archives) also provided some useful insights into issues such as seawater flooding in the eastern Fongafale area (the vicinity of the Meteorological office).

Recent advances and better access to remote imagery and the potential to digitise and manipulate historical photographs has greatly improved methods of image multi-temporal (time series) comparison. The resulting photographic layers represent an extremely powerful and highly visual tool which can be readily used and understood at a technical and village extension level. The results of this study were very successfully presented to the Government, Funafuti Kaupule (Is. Council) and community elders and broader community using a laptop and projector and large overhead screen.

The critical failing of this presentation method is our inability to leave this information in a readily useable and accessible form for anyone but a select few, as only a small number of individuals possess computers of adequate power, software (capable of manipulating these images) or technical capacity to utilise these tools. This “pictorial” guide was produced in response to this need and is intended to provide information not only at a technical level but as a prompt for resource managers in a universally understood and useful medium.



METHODS

The digital rectification of images refers to the process of digitising (scanning hard copies of photographs) and then electronically manipulating these historical photographs so that they can be compared to current geo-referenced satellite images (geo-referencing refers to a layer of information embedded into a digitised image which allows the image to be precisely positioned in a GIS grid system – in this case UTM WGS 84). This process was undertaken using GIS and image manipulation software (MapInfo Professional 7.0® and ERDAS Imagine 8.4®).

Funafuti presents a particular challenge with this form of work since permanent reference points which can be commonly found in images from differing time periods only exist in recent times (survey points, permanent roads and buildings, etc.) and these features are often restricted to only small locations on any particular island (towns, etc.). This means that other persistent natural features on the land and in the shallow marine environment must be used.

A further limitation is the differing resolution or quality of images. Aerial photographs generally have better resolution than satellite images but older air photos may be similarly limited due to the state of technology at that time and the poor condition of negatives, etc. It should also be recognised that historical images were seldom acquired with the specific intention of use as a coastal management tool and as such, the flight angles and paths, exposure, coverage and elevation are often not optimum. Even so, these photographic records when compared as a time series, offer the best opportunity available to determine accurate rates and patterns of coastal change and processes over time.

The degree of error and therefore the reliability of this work is difficult to determine since easily accessed or surveyed reference points have not been used for much of this process (since they don't exist). Rather, this work has been reliant on an intimate knowledge of land, shore line and shallow marine forms and structures in these atoll environments. Groundtruthing and community discussion of the changes perceived from this work was also undertaken on two occasions during 2005 and as a general statement, there has been consistent agreement with the findings of the study. An estimate of accuracy is in the range of ± 5 m and is largely attributable to the 4 m resolution IKONOS image backdrop and the lack of known survey points in many locations.

*Figures **a**, **b** and **c** are an example of how images from different time periods can be laid over one another so that the changes over time can be easily detected. Note in this example that the lagoon reef patterns match extremely well over time, such persistent formations were used to geo-reference the historical aerial photographs. Lines can also be drawn along the coast from one time period and placed over the next to allow a better estimation of coastline shift over time. In this study the coastline is defined as the tree line since there is a strong contrast between the beach and vegetation. Coastal vegetation is also a valid indicator of the upper active beach zone since vegetation will only persist where the waves are not up rooting seedlings, etc. Care however is required in mangrove areas as strictly speaking mangroves lay below the shoreline. It should also be recognised that the vegetation can change quickly in response to weather (drought, wind, storms, etc.).*

MULTI-TEMPORAL ANALYSIS OF FUNAFUTI COASTS, 1984 – 2003

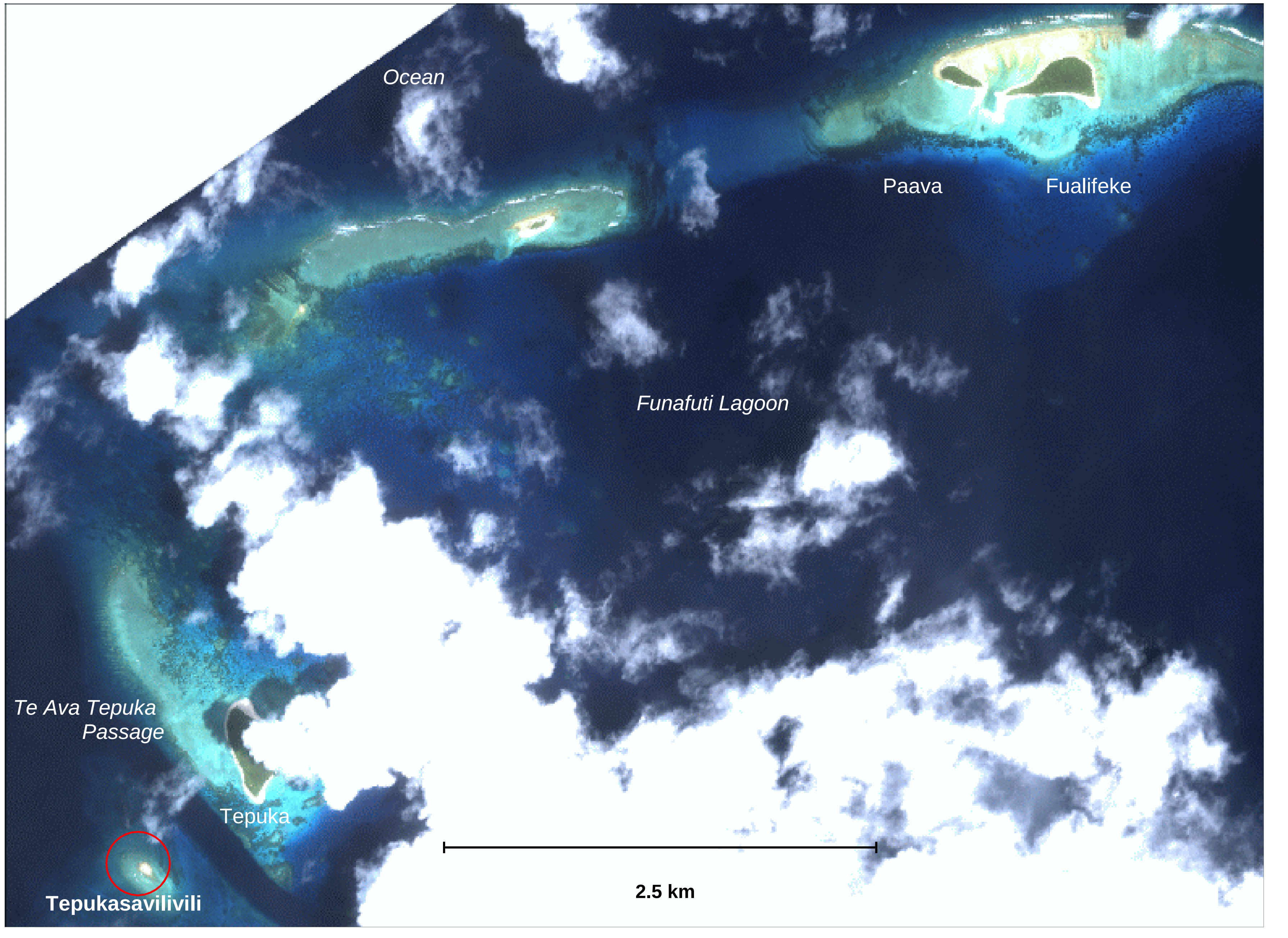
"Was the disappearance of the small islet in the western reef (Tebukasavilivili) related to the 1990's pilot lagoon aggregate dredging operation?"

Prior to 1990 *Tepukasavilivili* Islet was vegetated but is now simply an elevated rubble shoal, the central portion of which is slightly higher than the mean high water mark. Earlier aerial photographs of *Tepukasavilivili* and several other islets of the western reef were not available at the time of this work so multi-temporal analysis could not be undertaken. However, multi-temporal analysis of *Paava* and *Fualifeke* islets (approximately 6.5 km to the northeast) indicate that movement of these soft-shored islets can be significant and is likely to be controlled by prevailing climate patterns rather than any connection to the pilot dredging project. Indeed these two islets and many other shorelines in Funafuti show continuing movement even though dredging was halted over 10 years ago. Additionally, the distance between the location of the dredging activity (Fongafale – some 13 km from *Tepukasavilivili*) would strongly suggest there could be no possible connection between these events.

Shoreline movement is a common and natural feature of all soft coastlines including those of Funafuti. Beaches respond proportionately to more subtle seasonal weather change (small changes in wind speed, direction, duration, etc.) and dramatic change (cyclones and storms, El Niño). Much of the sand movement patterns on Tuvalu's shorelines is consistent with water movement generated by normal easterly, trade winds and as a result of tidal flow moving into and out of the lagoon. Therefore, it is expected that during a break in these predominant conditions, shoreline disturbance will occur (e.g. westerly gales, extreme ENSO events, etc.). Westerly storms are particularly disruptive in these islands, since they attack shorelines which are normally sheltered from the predominant easterly winds.

Tepukasavilivili Islet is located in a particularly vulnerable location with deeper waters surrounding the islet on all sides. This means its shorelines are not protected by the broader shallow reef flats (like those of neighbouring *Tepuka* – see image). This closer proximity to deeper waters (particularly the western ocean-side drop-off) suggests that during westerly gales or storms *Tepukasavilivili* would be in an extremely exposed position and vulnerable to wave overtopping and physical disturbance. Unlike *Paava* and *Fualifeke* islets, such a small islet simply can not absorb any significant change in its shorelines.

Paava and *Fualifeke* islets (see also next page) are good examples of ongoing soft shoreline movement. It is important to note that these islets do not have permanent inhabitants and little, if any, human disturbance of its shorelines has occurred. There is evidence of facilities built by the US military during the 1940's (mostly concrete footings, etc.) however, there is no evidence to suggest these have contributed to any of the shoreline changes discussed below. Analysis of the 1984 and 2003 images combined with groundtruthing in September 2004 indicate that the erosion currently occurring on these islets is approximately equivalent to the degree of accretion (accretion = shore-line build up or increase in land area).



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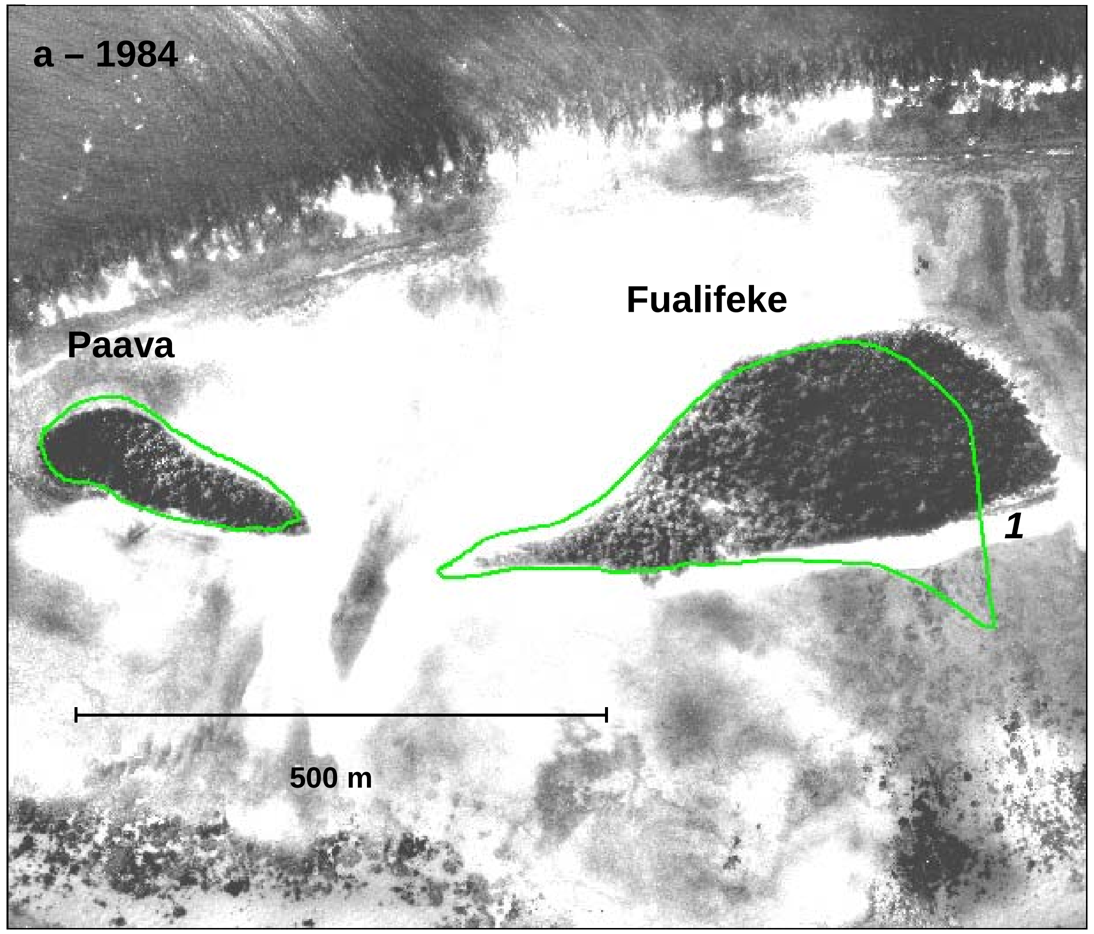
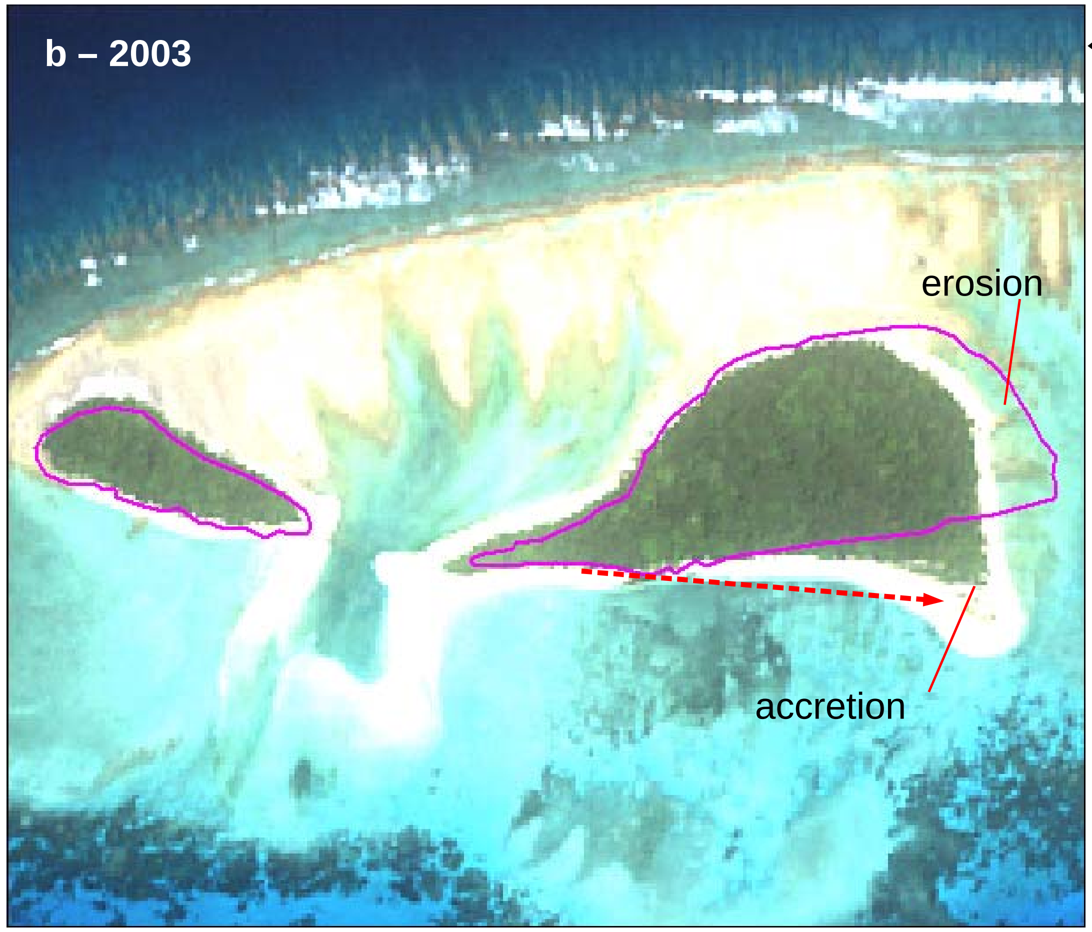
Location map showing the relative position and size of Tepukasavilivili Islet (red circle) and Paava and Fualifeke islets in the north western quarter of the atoll. Note Tepukasavilivili's comparatively exposed position without extensive, protective reef flats towards the west. (Note that Tepuka Islet is partially hidden behind cloud in this image).





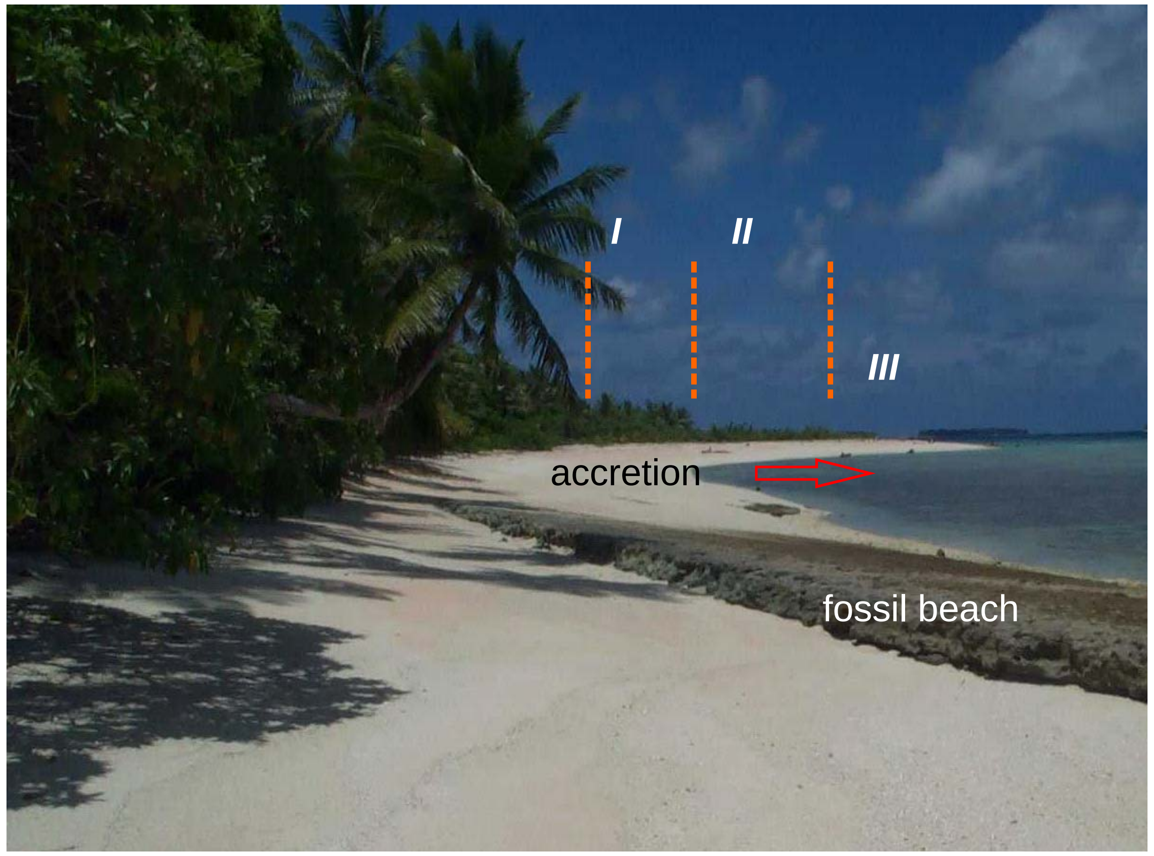
*A comparison between Paava and Fualifeke Islets in 1984 (**a**) and 2003 (**b**). The shoreline from each time period has also been superimposed over each image. (Note both images are of identical scale and orientation).*

*In 1984 Paava had an estimated land area of 1.48 Ha (**a**) and by 2003 has increased in size by approximately 10 % to 1.63 Ha (**b**). Fualifeke has experienced erosion on its eastern coast (approximately a 70 m retreat – see **a** and **b**) but most of this material has subsequently accreted as a an extension (approximately 110 m long) on the east end of the southern shore (see **a** and **b**). Despite the large change in these islet's shorelines it only represents a 3.5 % reduction in land area from 1984 to 2003.*

Since it is known that these are dynamic environments the small change in total area can not be considered a significant loss. However, it is strongly recommended that monitoring using remote sensing techniques is continued using higher resolution satellite imagery as this would allow more accurate measurement and reduce the margin of error.

The 1984 photograph (**a**) shows that the pattern of accretion at the eastern end of the southern Fualifeke Islet (**1**) was occurring since before 1984. The thin vegetation and lack of large trees (especially coconuts) in area (**1**) indicate that this land recently accreted. This trend has continued and was still apparent during the 2005 field trip.

In light of the apparently natural movement measured in Fualifeke Islet over the last 20 years it seems most likely that an exposed islet the size of Tepukasavilivili (only about 100 m^2 in 2003) would be extremely vulnerable if similar coastline shifts occurred.



*This photograph was taken in 2004 during the first groundtruthing mission. The photo looks east along the southern beach of Fualifeke towards the newly-accreted area (red line / arrow in figure **b**). Note in the fore-ground a fossil beach, which is further evidence of past sand movement on this shoreline. Note also the vegetation layers on the newly accreted spit. (**I**) represents coconut palms of approximately 10 years of age, (**II**) seedlings from 2 to 5 years and (**III**) very recently established seedlings < 2 years old. These clear stages in growth suggest that the deposition of viable coconuts occurs in similar pulses most probably related to weather events and it is also possible that the accretion and erosion also occurs in pulses. Additionally, the coconuts are thought to be deposited via lagoon-borne transport since the neighbouring juvenile stands are too young to bear fruit and evidence of human intervention (planting) was not apparent on this uninhabited islet.*

"Did Fongafale's coast erode because of the dredging project?"

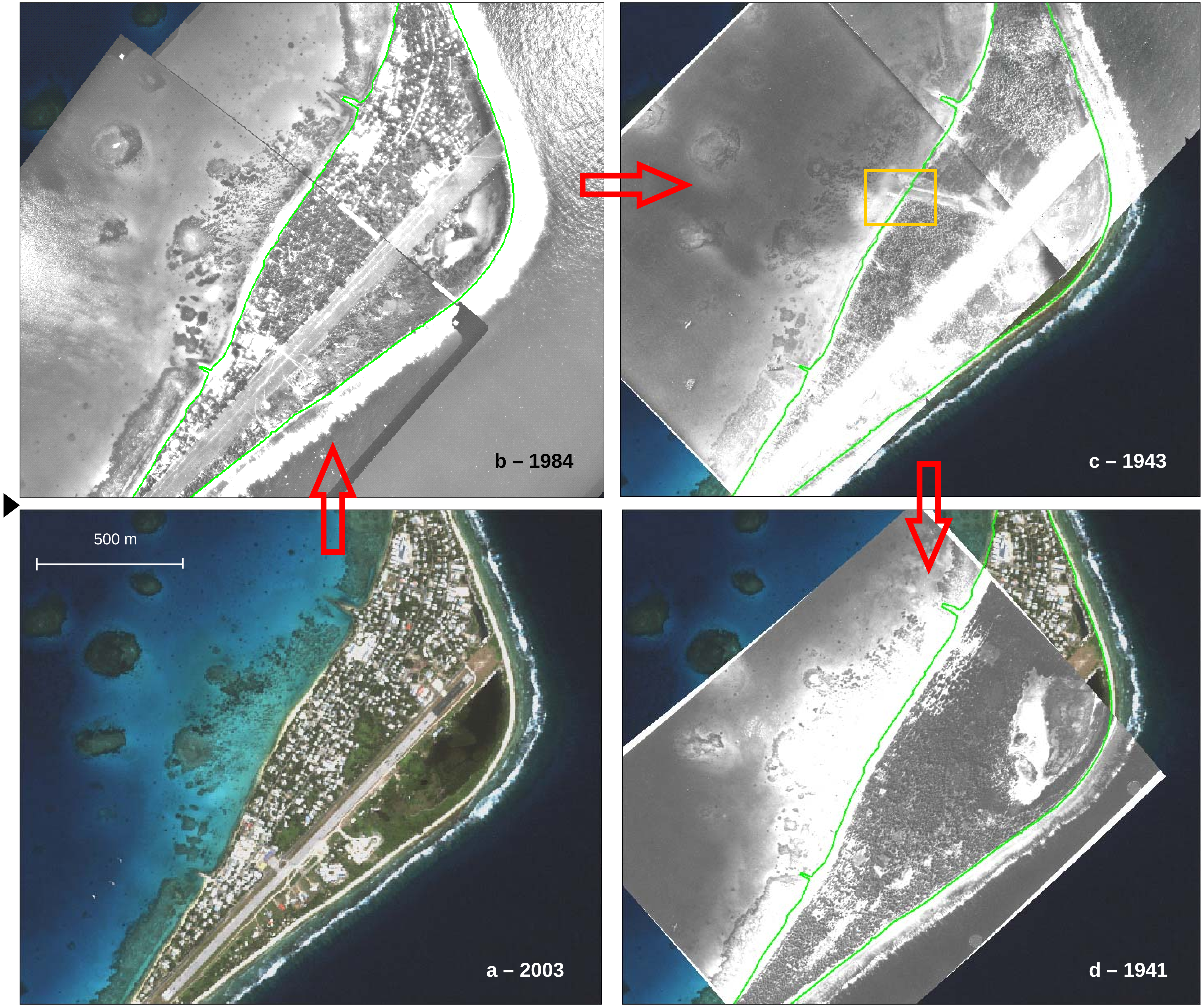
In order to assess whether there has been shoreline movement (erosion) on Fongafale's lagoon coast from the period 1990 to the present, image layers from 2003 (**a**) and 1984 (**b**) were compared. As can be seen there is essentially no detectable difference between the lagoon shoreline in 1984 and 2003 indicating that no consistent patterns of erosion or shoreline movement occurred over the last 20 years.

As earlier discussed, due to the 4 m resolution of the base satellite image small shoreline movements could not be reliably detected. However, the trend of coastline stability seen between 1984 and 2003 is also supported by beach profiling data covering the same period (1987 to 1998). This compilation of profiles by Woodward (1998) is potentially accurate to within millimetres.

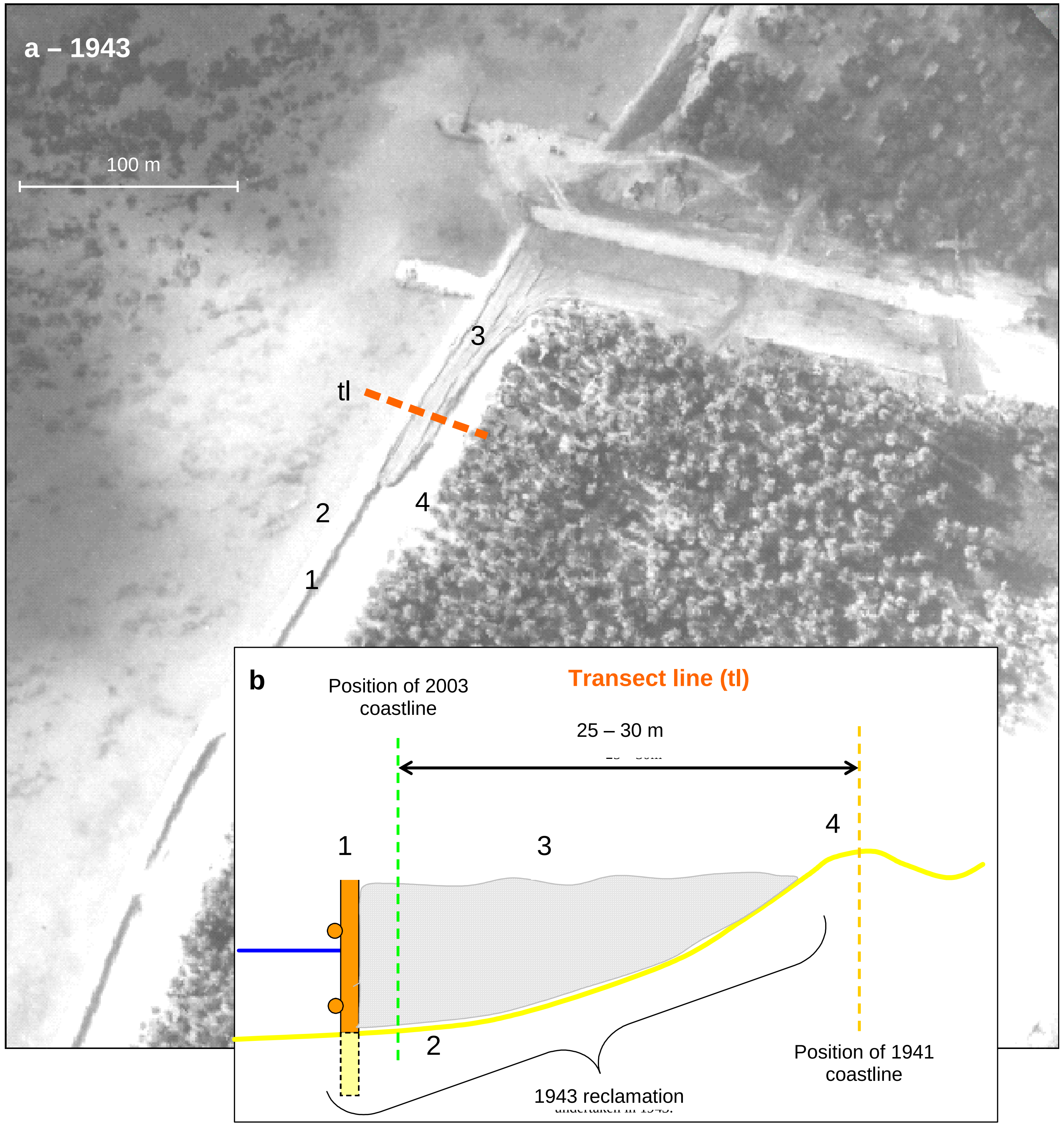
*Figures **a**, **b**, **c** and **d** show the sequence of geo-rectified historical images of Fongafale all with the present position of the coastline (2003 – green line) super-imposed over the top. (Note, all images are of identical scale).*

No difference can be detected between the overall position of the coastline in 2003 (**a**) and 1984 (**b**). However, additional work undertaken to determine longer term trends on this coast revealed obvious differences in the position of the coastline between 2003 and 1943 (**c**) and 1941 (**d**). It appears that Fongafale Lagoon coast has in fact prograded towards the lagoon some 25 to 30 m over the last 60 years.

Details of this change are shown on the following page with a close-up of the area marked by the orange square (**c**). (This series of images (**a** to **d**) are an excellent example of how consistent in size and shape some of the reef features can be over time. Such features allowed the accurate geo-referencing of the historical photographs).



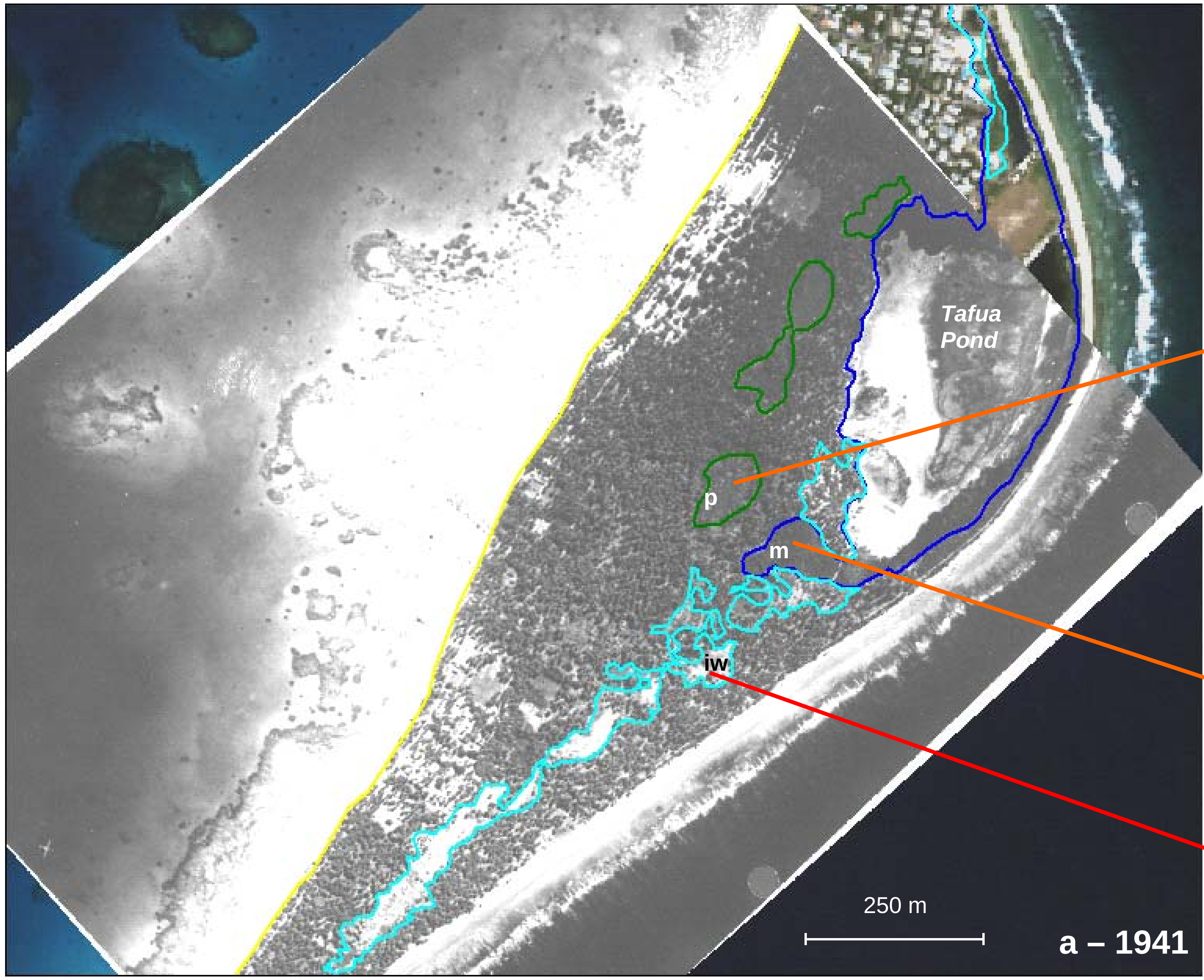
Additional work undertaken during this study to gain a better understanding of long-term coastal processes on Fongafale, graphically highlighted the massive impact that the engineering undertaken by the US military had on this shoreline (and other areas) of Fongafale (see also Xue and Malolonga, 1995). During WWII Funafuti Atoll played a short but important role as a staging post for the mounting of the US attack on Tarawa (Kiribati, Tuvalu's northern neighbour was at that time occupied by the Japanese – McQuarrie, 1994). Note that in 1941 (see previous page) there was little sign of disturbance on the land or shoreline but by 1943 the airstrip was complete and jetties and other structures can be seen along Fongafale's lagoon coast.

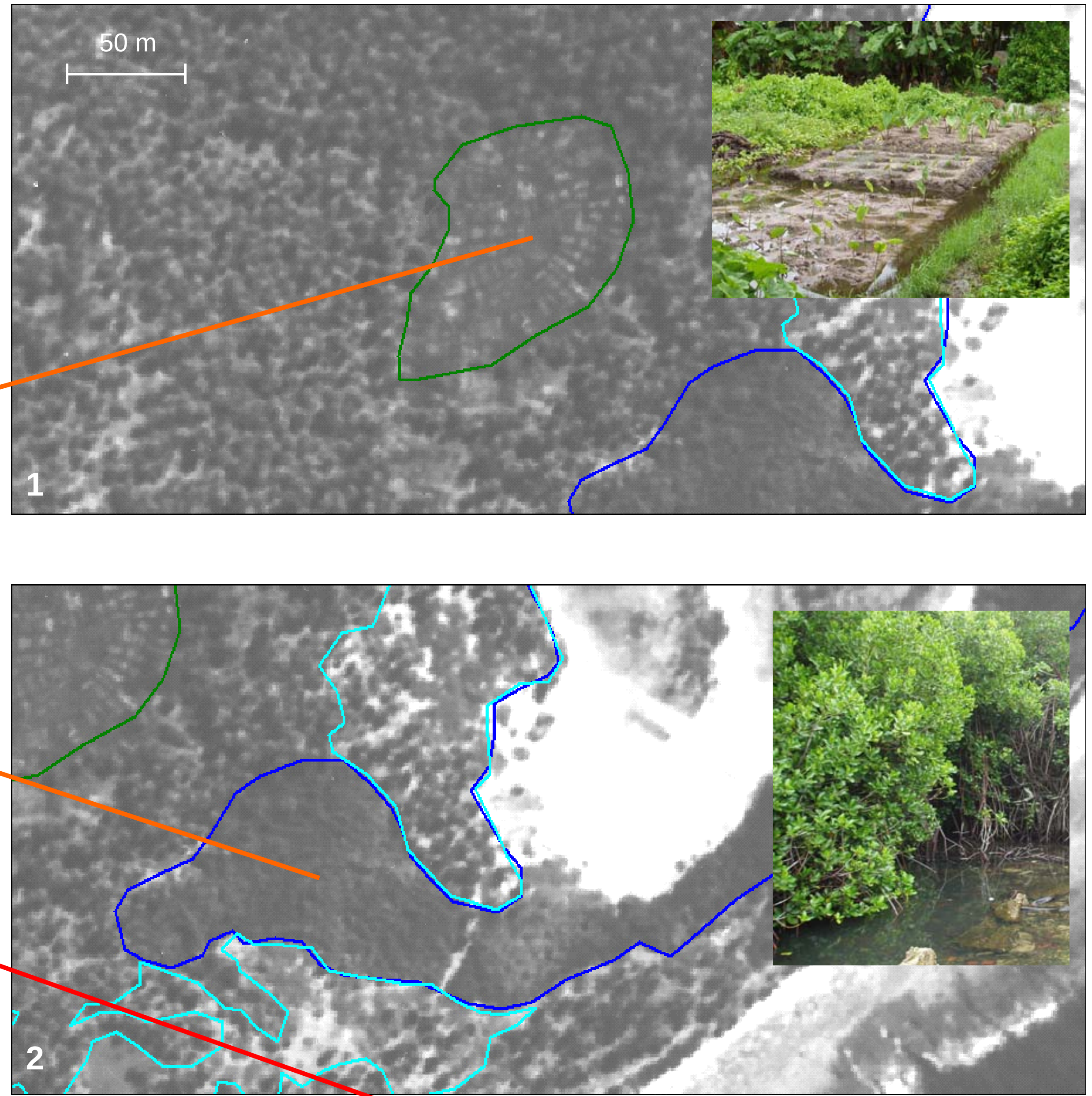


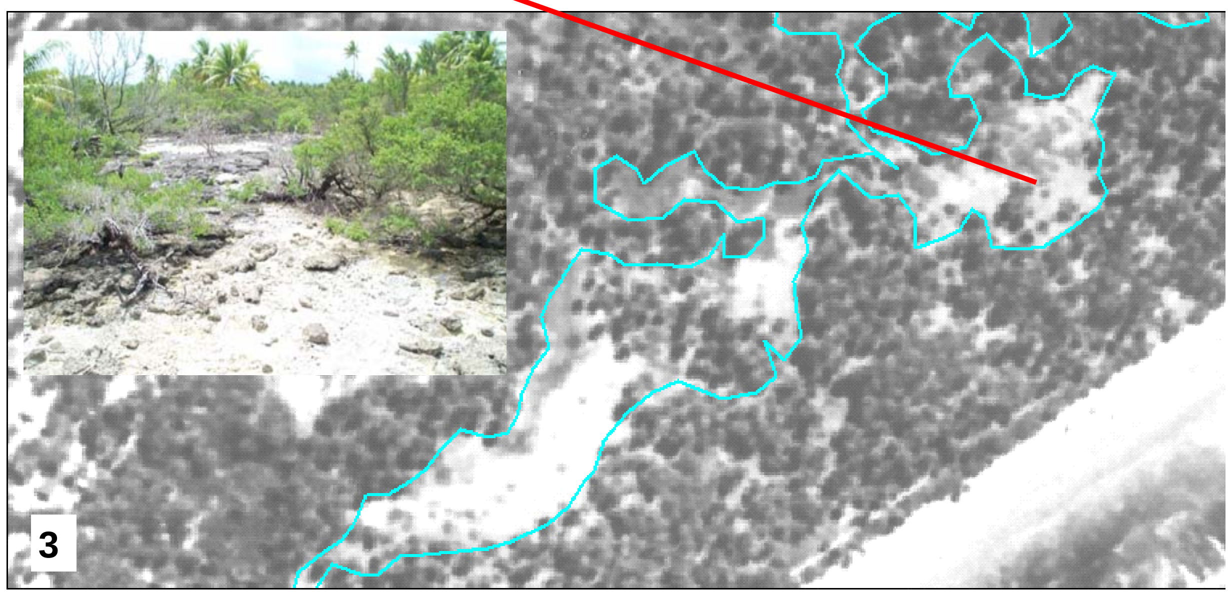
*This photograph (**c**) was taken in 1943 from the new reclaimed platform on Fongafale's lagoon foreshore (facing north). Note the sharp drop-off at the water's edge and the tops of coconut logs incorporated into the retaining wall can also be seen sticking out above the top seaward edge of the reclamation area. Such a retaining wall would have likely had a very short life span (less than 10 years) and would not have provided long-term protection to the reclaimed foreshore. As a result of the magnitude and inappropriate nature of the engineering effort of 1943, this coastline has suffered ongoing instability ever since. (Photograph (**c**) sourced from US Navy, National Archives Washington, USA, in McQuarrie, 1994).*

*This close-up of the 1943 aerial photograph (**a** – this is the area outlined in orange on the previous page – 1943 image) shows the active reclamation of the central area of Fongafale's lagoon coastline. The transect line (**tl**) is shown in the conceptual diagram (**b** – inset). The dark line running parallel to the coast (**1**) appears to be the retaining wall built at the toe of the original beach slope (**2**). The darker grey zone (**3**) is coral rubble fill brought in (from borrow pits elsewhere on Funafuti) to level the area between the retaining wall and original beach berm (**4** – at the time this aerial photograph was taken, this back-filling process only extended about 100 m south). In this way, Fongafale's lagoon-side coast was artificially extended some 25 to 30 m beyond the 1941 natural coastline (**4**).*

Additional to the reclamation of Fongafale's lagoon-side shore in 1943, the dredging of navigation channels was undertaken over much of the length of the foreshore and jetties and ramps were extended out into deeper waters (**a**). These disruptions left a legacy of coastal instability which remains a major feature of Fongafale's lagoon coast and has required constant effort by the community to protect this shoreline as many people and facilities are now positioned over the former reclamation area (see pg. 9). The changes brought about during WWII were not conceived with a view to long-term stability or the maintenance of natural coastal processes. As such, it is not surprising that wave over topping and localised flooding remain problems on this coastal fringe especially during westerly gales.

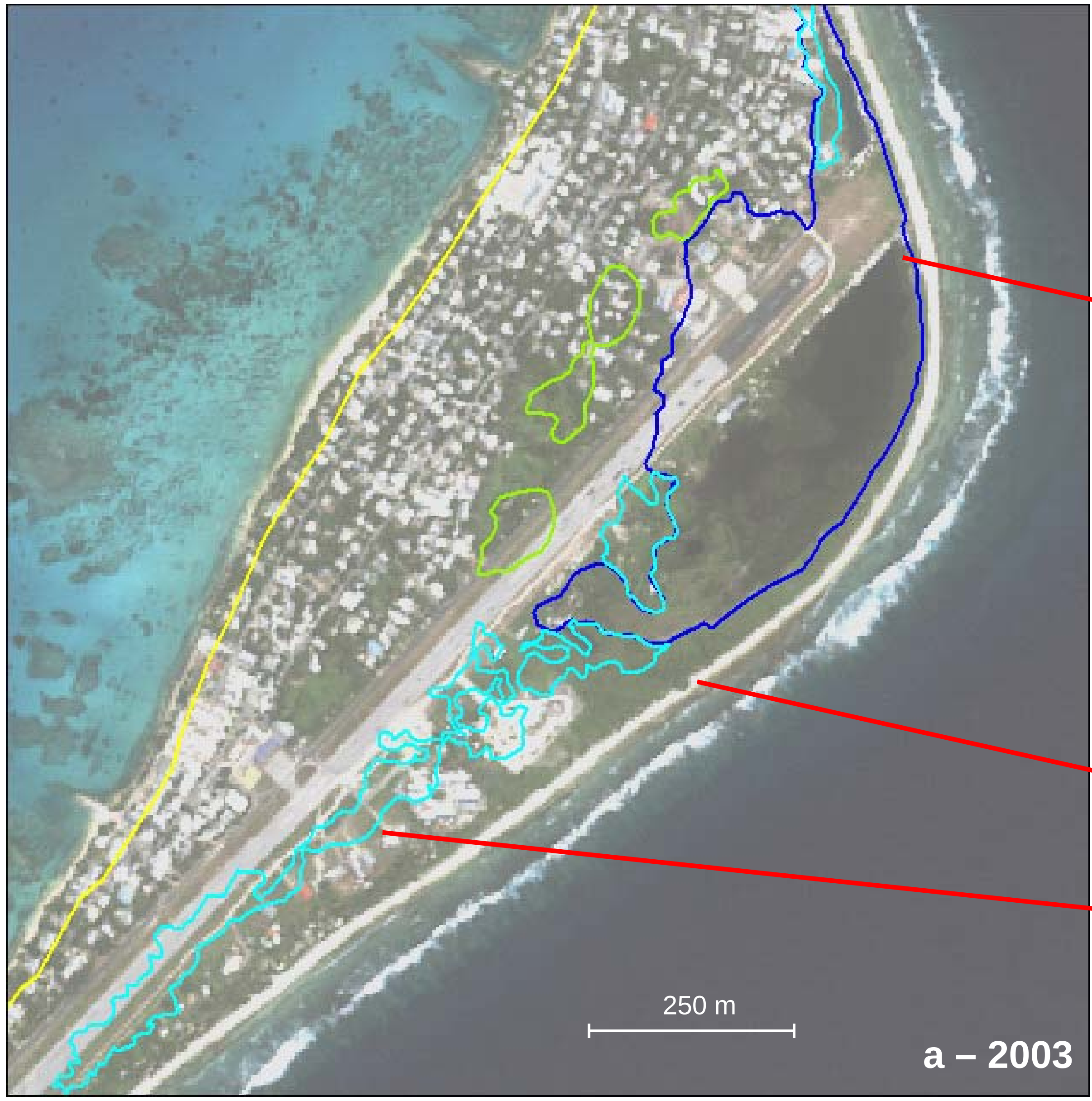


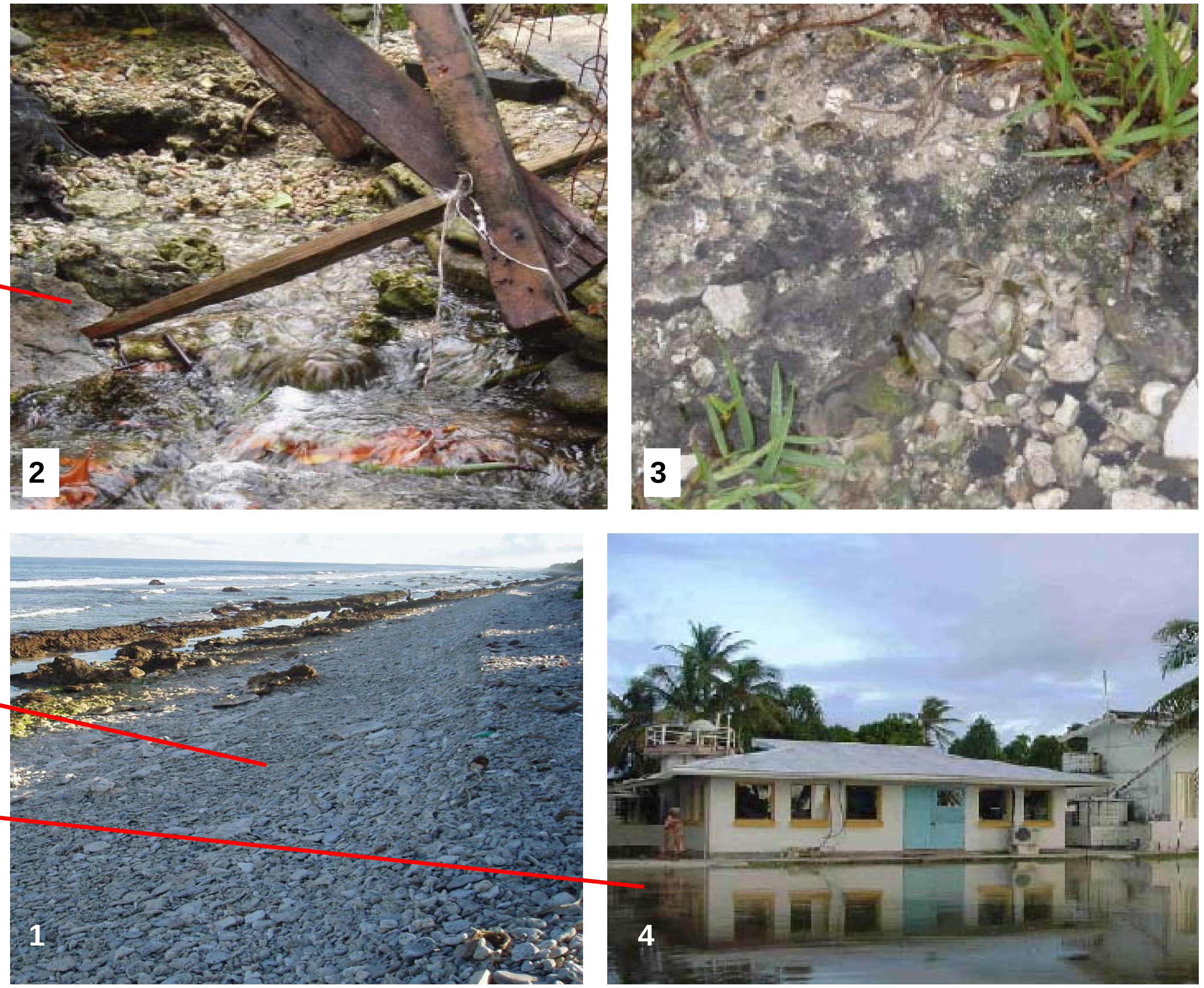




*Analysis of the digitised high-resolution 1941 aerial photograph (**a**) brought to light some features of interest regarding the present land-use pattern in Fongafale and partially addresses some of the additional issues which were raised as community concerns during the SOPAC-EU Project Tuvalu multi-stakeholder consultations in 2003.*

The features identified in (**a**) are further enhanced in the corresponding close-ups (figures **1**, **2** and **3** – all the same scale). To further assist the reader, photographs of the corresponding vegetation type are inset into the appropriate frame (all of these inset photographs were taken in existing Funafuti habitats during 2004 / 2005. The areas in dark blue (**m**) represent the former extent of Tafua Pond, a mostly sub-tidal brackish pond previously known for its excellent milkfish. Dark areas around the perimeter of the pond are mangrove (*Rhizophora stylosa* – "tongo"), which is an indication that the water in the pond at this time was predominantly marine and was strongly influenced by tidal flushing (as is the present pond). The light blue areas (**iw**) represent what appears to be low-lying ironwood thicket (*Pemphis acidula* – "ngie") which grows in the upper intertidal zone usually slightly higher than mangroves and again is strongly associated with regular marine flushing. The areas in green (**p**) appear to be low-lying areas dominated by freshwater conditions rather than saline. The most southern is divided into what is thought to be a large community swamp taro garden (*Cyrtosperma chamissionis* – "pulaka"). A **yellow line** has also been superimposed on figure (**a**) to highlight the position of the 1941 coastline.

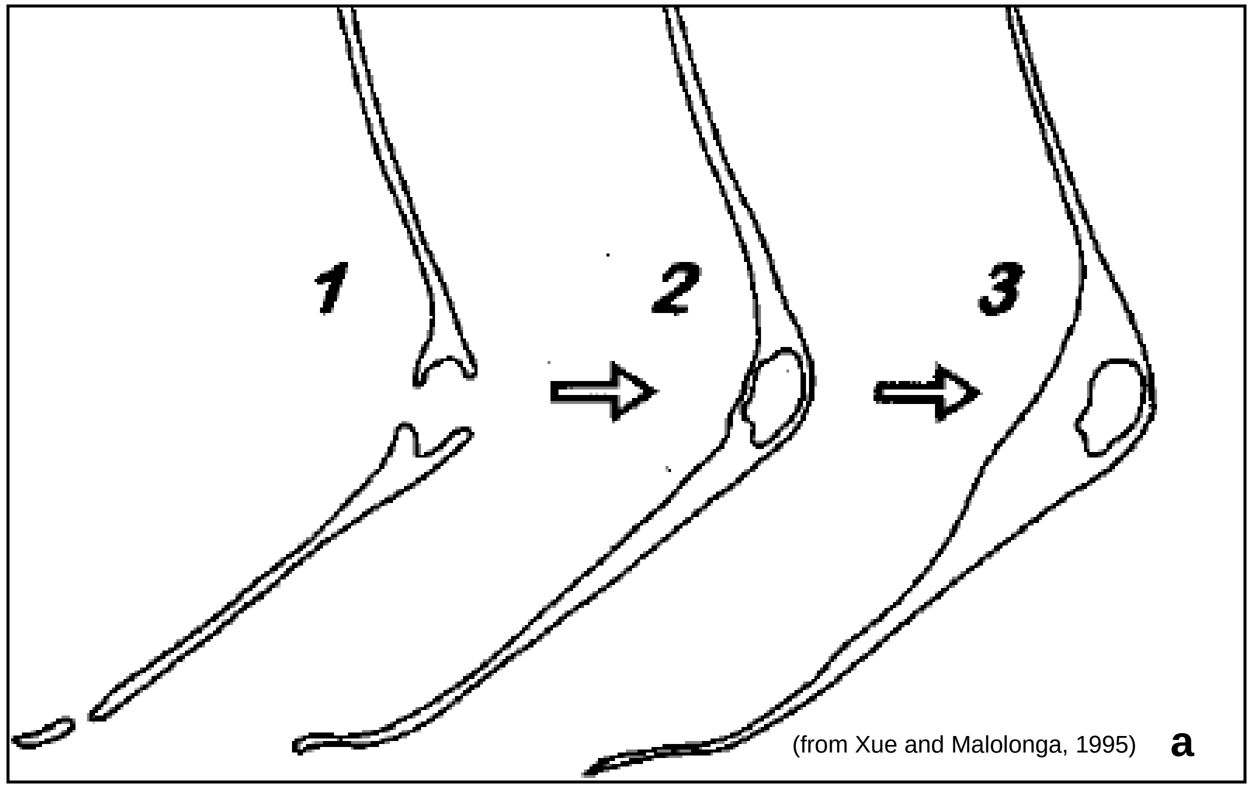




*In this figure the zones identified and outlined from the 1941 aerial photograph (page 8, figure a) have been superimposed over the 2003 satellite image. This allows us to see which areas and buildings in modern Fongafale maybe positioned in former low-lying or swampy ground (green, light blue and dark blue zones) and which buildings are positioned on the old reclaimed, disturbed lagoon foreshore (those areas west of the **yellow line**). It is interesting to note that the Meteorological Office and nearby areas on the eastern side of the airstrip are all positioned in or near what is identified in 1941 as upper inter-tidal ironwood thicket. This vegetation type (**light blue line**) occurs in the high inter-tidal zone and would have previously been subject to regular (at least 1 or 2 times a month) saltwater flooding. Similarly, the freshwater and/or brackish swampy zones (**green line**) correspond well with present taro pits and low lying areas which experience occasional flooding. Similarly, Tafua pond's former extent (**dark blue line**) was far greater and it appears to have extended west of the runway into what is now housing areas. The identification of these historically low-lying areas helps explain why some parts of Fongafale are vulnerable to saltwater flooding today.*

(Note that the satellite image colours have been faded in this figure to allow the zone lines to be clearly seen).

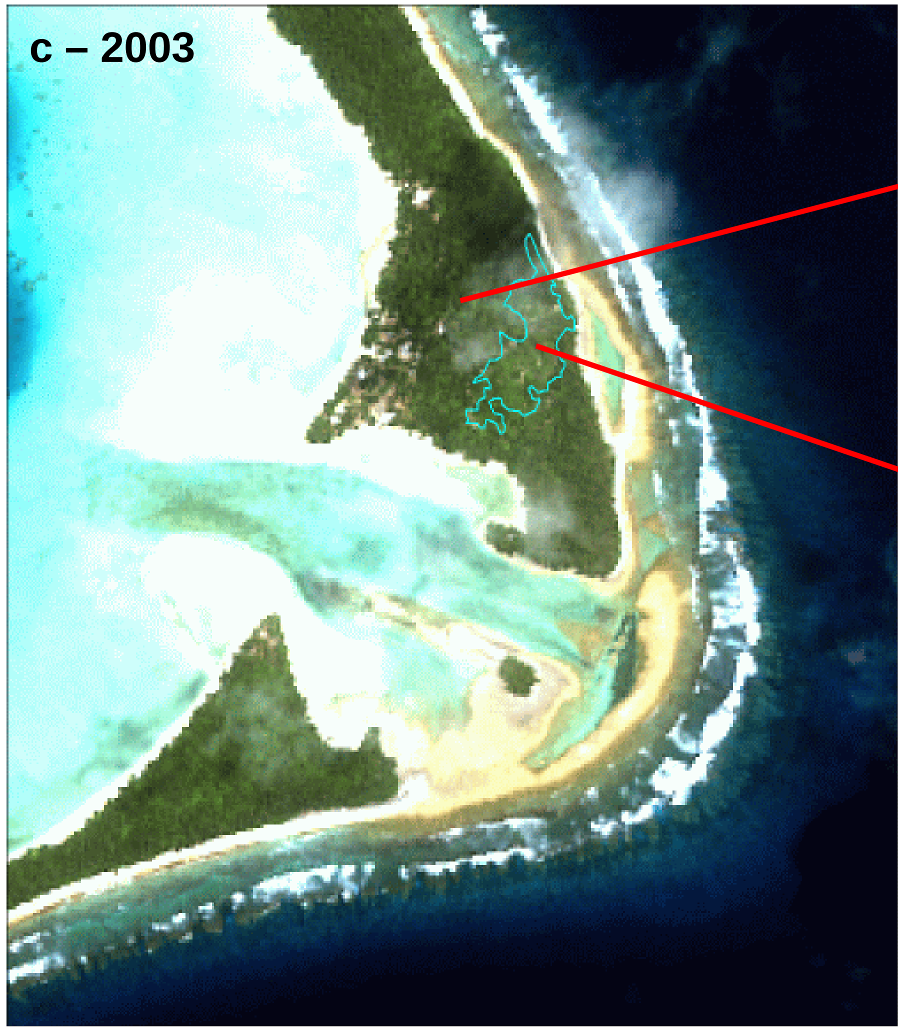
*Fongafale's ocean-side beach berm system is mostly composed of coral rubble, (**1**) marine waters can move through this material comparatively easily which explains how saltwater dependant habitats (mangrove and ironwood – both identified in the 1941 aerial photograph) have existed on Fongafale without any direct passage or channel to either the ocean or lagoon. Regular tidal flood and ebb cycles are also evident in today's Tafua pond environment and figure (**2**) shows marine water rushing through the beach berm barrier to the pond during high tide. Other areas east of the runway are also regularly inundated with marine waters and seawater springs (**3**) are evident in many areas during incoming spring tides. The Funafuti Meteorology Office which is built at the edge of a former inter-tidal ironwood habitat starts to flood when tides exceed 2.8 m (**4** – photograph kindly provided by the Tuvalu Meteorological Office).*

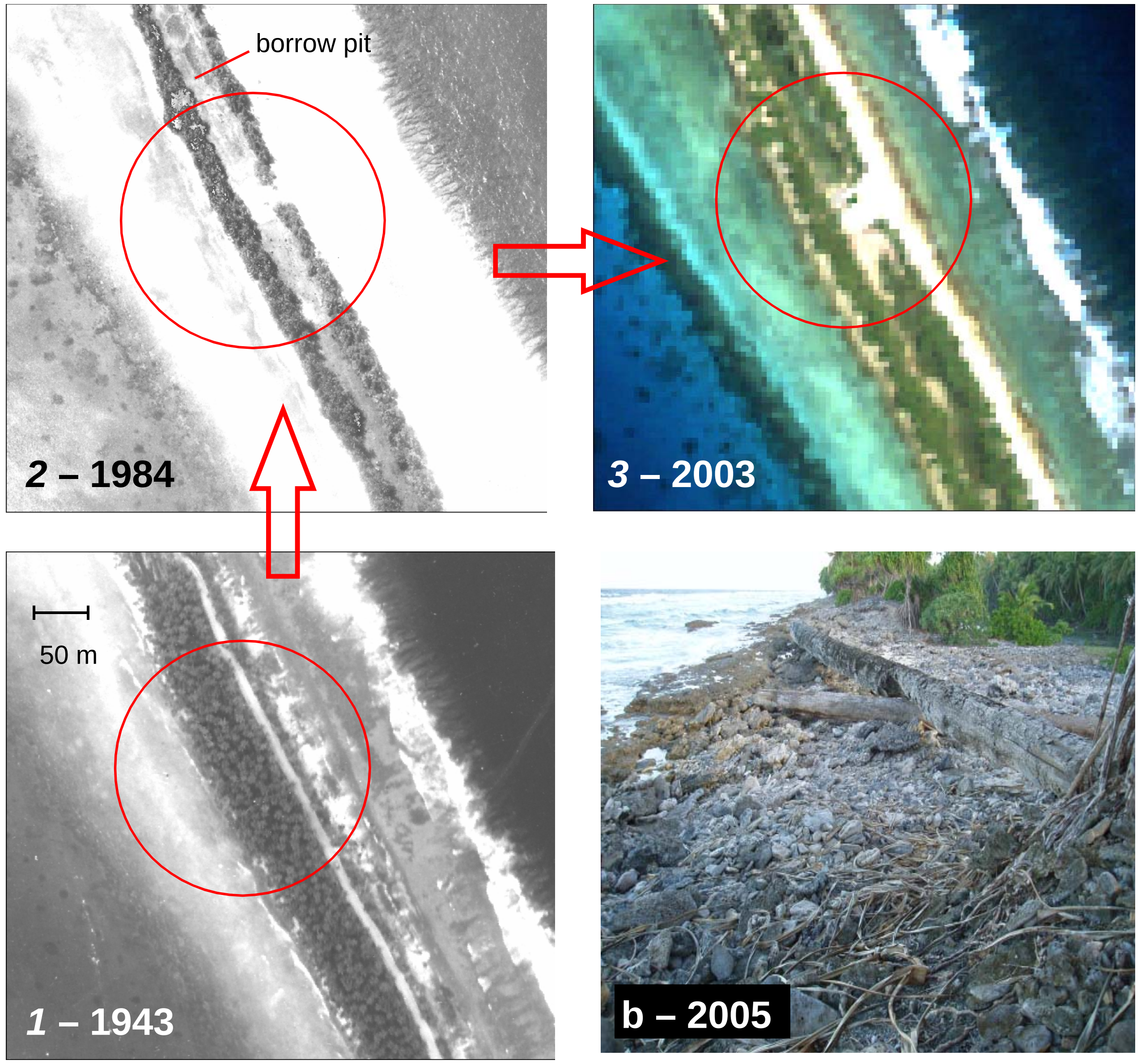


*A study of coastal processes by Xue and Malolonga (1995) identified Funafara Islet (see location map on pg.1) as an example of how the low-lying areas and land mass of Funafuti were formed (**a**). Note how in (**1**) Funafuti's formation was similar to Funafara (**b** and **c**) with a central channel separating the north and south arms. In (**2**) the arms have closed and by (**3**) accretion has widened the islet and isolated a low area (Tafua pond). The sparsely populated and intact vegetation systems of Funafara Islet also provides evidence that inter-tidal ironwood thickets (Pemphis acidula – "ngie") exists in the Funafuti environment without direct connecting passages to the lagoon or ocean environment and are reliant on saline groundwater percolation of seawater (such vegetation can only persist if the environment is regularly inundated with marine waters).*

Figures **b** and **c** show the comparative 1984 and 2003 images of this mostly undisturbed islet. The area outlined (**light blue**) is an ironwood thicket (**d**) which has no permanent connecting passage to the ocean or lagoon but rather is inundated on a regular basis by seawater which percolates through the rubble bank that forms the ocean-side beach head. Note that it is comparatively easy to identify the ironwood swamp in the 1984 aerial photograph (**b**).

Photograph (**d**) was taken during the second groundtruthing trip in 2005 and shows a typical ironwood thicket or saline swampy area in Funafara Islet. It is interesting to note that immediately west of this saline ironwood swamp was a transition to low-lying brackish / freshwater areas where swamp taro (**e**) was also growing (*Cyrtosperma chamissionis* – "pulaka"). The landform system of Funafara is assumed to be in a more or less pristine state and appears to mirror the pre-1943 environment of Funafuti. Furthermore, it is an indication that both saline and brackish flooding is a natural component of these islets. However, in view of the scale and nature of the 1943 US military engineering efforts on Funafuti the natural hydrological processes on this islet would have been irrevocably disturbed.





An additional coastal feature was also identified during this study which deserves attention. The 1943 US military engineering efforts on Fongafale required an estimated 644 700 m^3 of aggregate (estimate of aggregate needed to fill the present borrow pits – Gibb Australia 1985). Material for these works was extracted from borrow pits which remain a prominent feature of Fongafale and Tengako. Whilst the legacy of the borrow pits has remained a problem to the community (loss of land and associated opportune disruption of hydrology, ad hock rubbish dumping, etc.) in areas they also threaten the coastal integrity of the island. In the northern end of Tengako (**a**) the thin wall left between the beach berm and the inside edge of the borrow pit (approximately 5-m wide) collapsed inwards forming a "break through". This gap now permits ocean-side waves to penetrate into the borrow pit and will probably eventually threaten the lagoon-side beach. This multi-temporal image study tracked the gradual increase in size of this breakthrough (***1*** to ***3***) and groundtruthing revealed numerous areas on this coast where similar subsidence and breaches are likely to occur. Widespread collapse of the beach berm "wall" would be practically impossible to repair and would result in a dramatic change to Tengako's ocean-side coast and remaining land area.

▲

*The images **1**, **2** and **3** are close-ups of the area shown in **a** and are of identical scale and orientation. The 1943 aerial photograph (**1**) shows the island coastline intact, note that the vegetation in this area is consistent (mature coconut groves) and there is no indication that this is a particularly vulnerable coastal area prior to the commencement of earthworks later in the same year. The 1984 (**2**) aerial photograph graphically shows the borrow pit (central light grey band running the length of the island) and the breakthrough – white gap at this time approximately 18-m wide. By 2003 (**3**) the breakthrough is about 38-m wide and ground-truthing in 2005 (**b**) showed the gap to now be 44-m wide.*

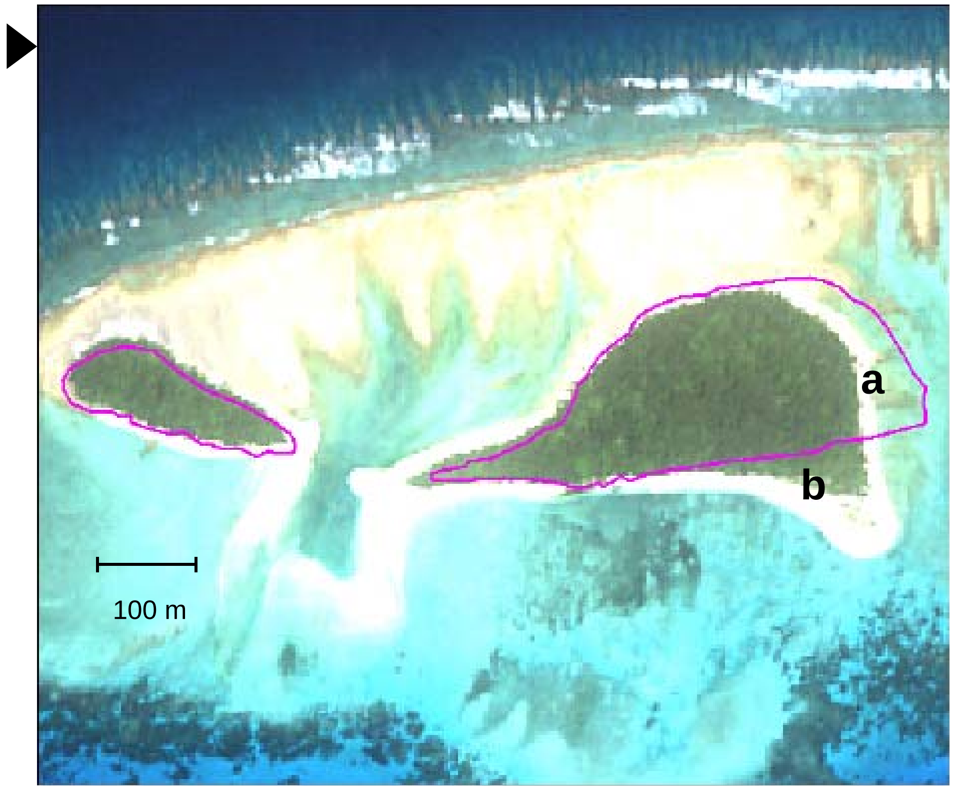
Each subsequent storm or high water event now freely enters the borrow pit edge within and it should be a matter of some urgency that the borrow pit in this northern area of Tengako be filled before this problem becomes unmanageable. The distance between the borrow pit and the ocean side beach berm is on average 5- to 8-m wide and there is evidence of wave wash over and the beginnings of beach berm collapse in many areas.

The following figures are a compilation of the islets of Funafuti and the coastal change which has been detected between 1984 and 2003. The images are presented in pairs which are of identical scale and orientation. Above is the colour 2003 satellite image over which the 1984 purple coastline has been superimposed. Below is the 1984 aerial photograph (black and white) which has the 2003 green coastline marked.

Change in shoreline position is obvious in some locations (such as Fualifeke to the right) however this should not necessarily be seen as unusual or in a negative light. As earlier mentioned the accuracy of this work is limited by the environment and particularly the 4-m resolution of the IKONOS satellite image. Since many of the islets are very small, distance of shoreline change in meters is not quoted; as changes less than 5 m could not be reliably reported. As such, change is quoted as a percentage change in total land area of each islet. This gives a clearer idea of any atoll-wide trends which may be present regarding shoreline movement (i.e. net erosion, net accretion or equilibrium). It is stressed however that error within the method remains a component of the measurements and it is prudent to consider changes of less than ± 5 % not to be significant without additional higher-resolution monitoring and/or ground truthing.

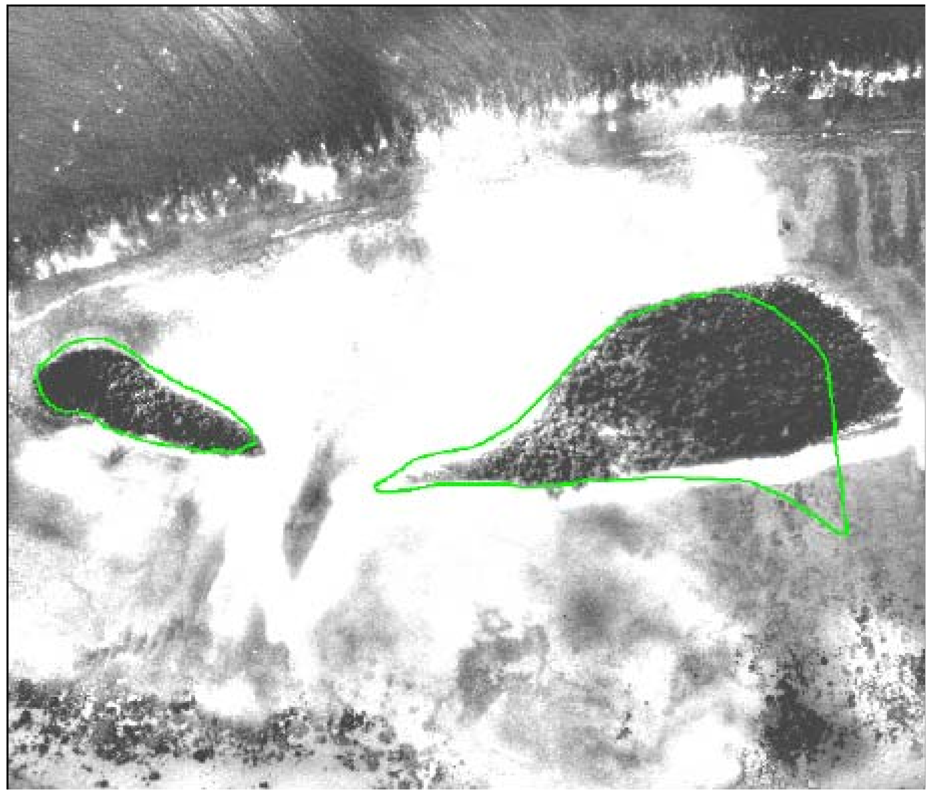
Additionally, a degree of natural variability must also be expected on these soft shores as such movement is a natural feature of these islets. Shoreline movement does not necessarily equate to a net reduction in size of a particular islet and Paava / Fualifeke are a good example of this. It is easy to see how the human perspective of shoreline processes in Fualifeke could present two entirely different stories if viewed in isolation. Land owner (**a –** see neighbouring image) who owns the eastern area of Fualifeke Islet would report his home and land was devastated by erosion, whereas landowner (**b**) would probably report nothing and quickly claim all of the newly-accreted area as his own! The truth is that there is no significant change in the overall land area of Fualifeke even though very significant shoreline shift has occurred. Considering the Fualifeke example, it is easy to understand how human perspectives could lead to incorrect generalisations about erosion on Fualifeke.

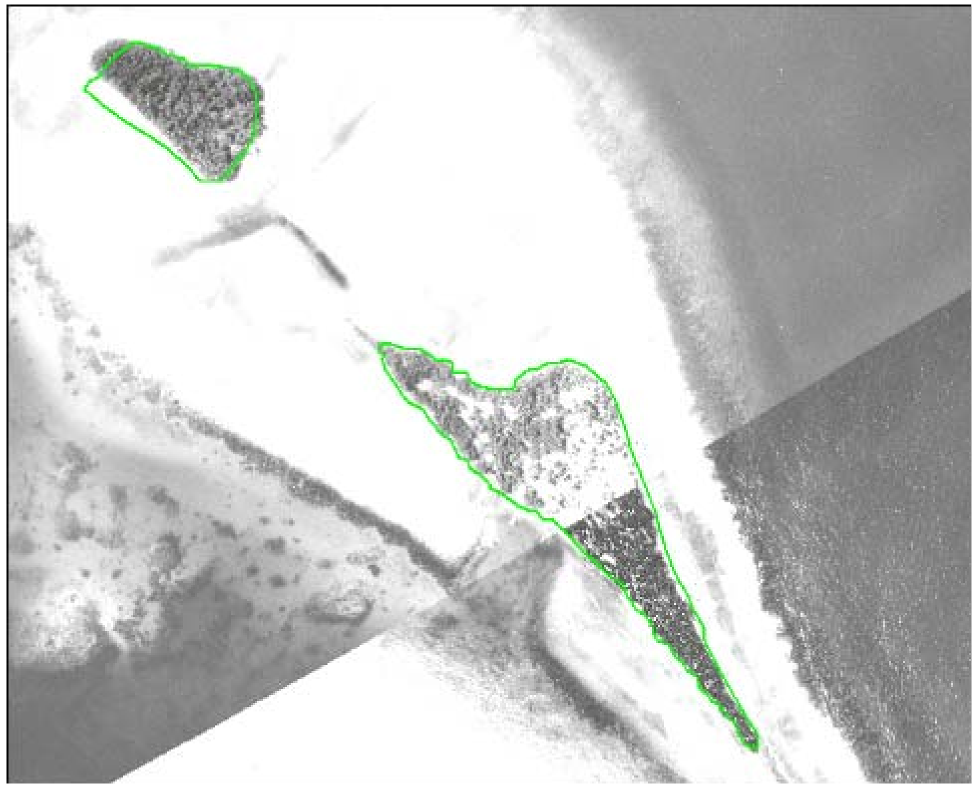
Whilst there are no permanent inhabitants of Fualifeke if time and money had been invested in building houses in the eastern quarter of the island, Fualifeke would have been the subject of erosion reports and many thousands of dollars would have been spent trying to build seawalls in an attempt to “protect” the islet. Fualifeke does not need to be protected, it simply needs to be recognised that there are limitations on how such an environments can be used by humans. This highlights the importance of good planning and coastal assessment before building as it is obvious that development in areas like Fualifeke’s east coast would result in disaster. This example also shows the importance of continued monitoring to enhance our understanding of natural shoreline shift.

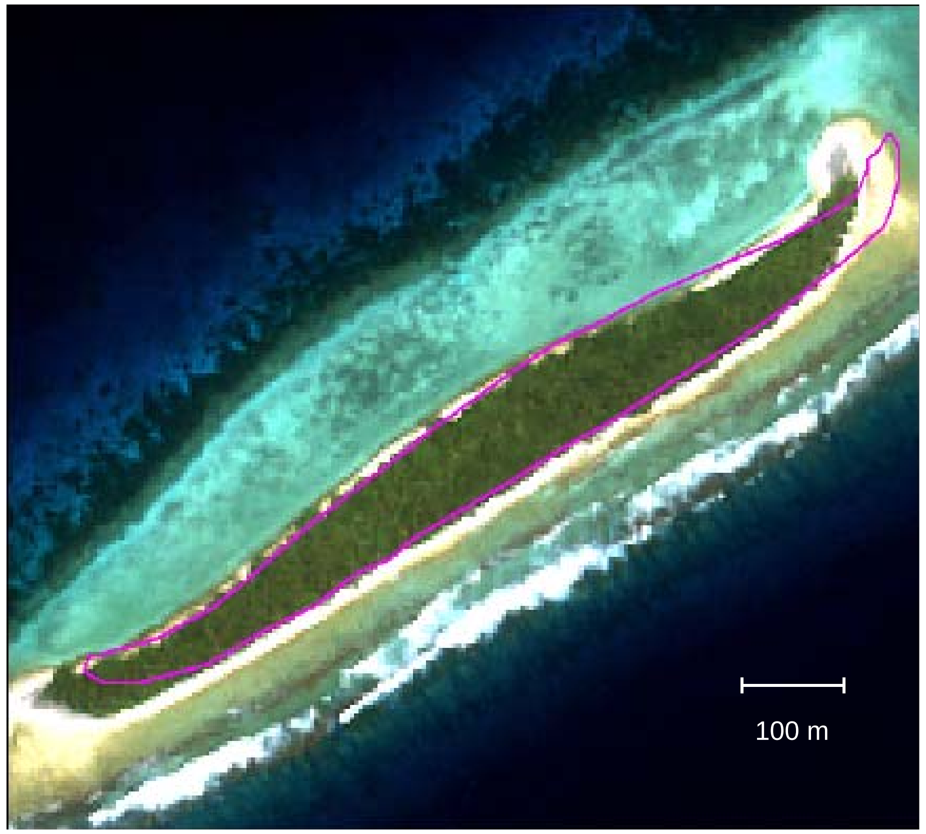


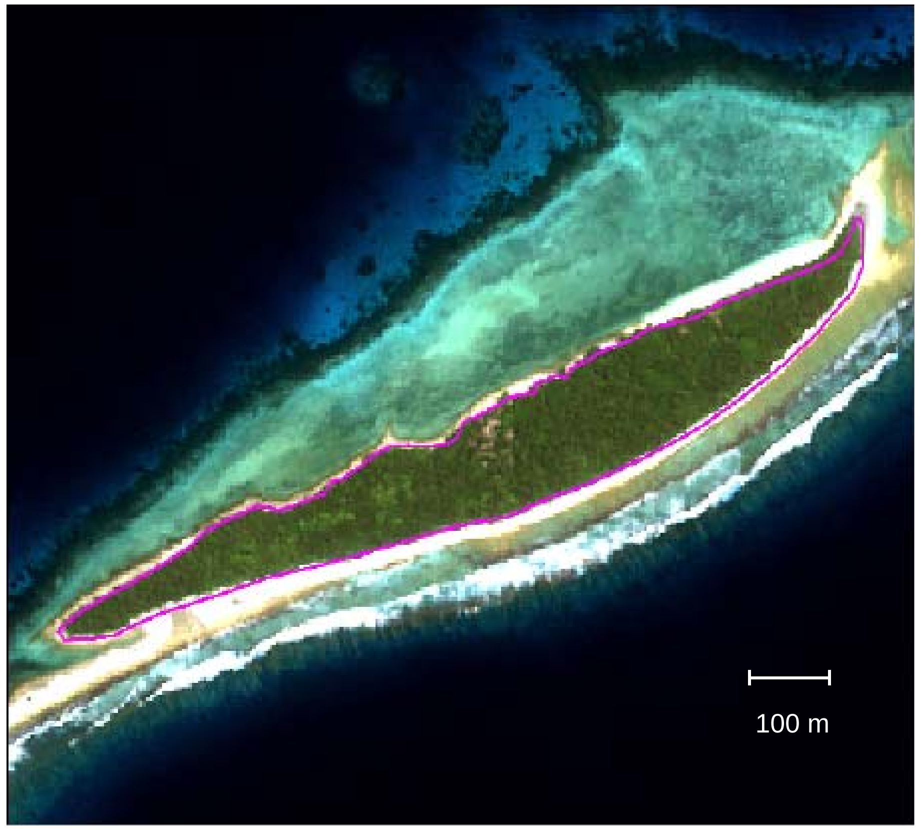
Paava 10.1 % increase
Fualifeke 3.4 % decrease

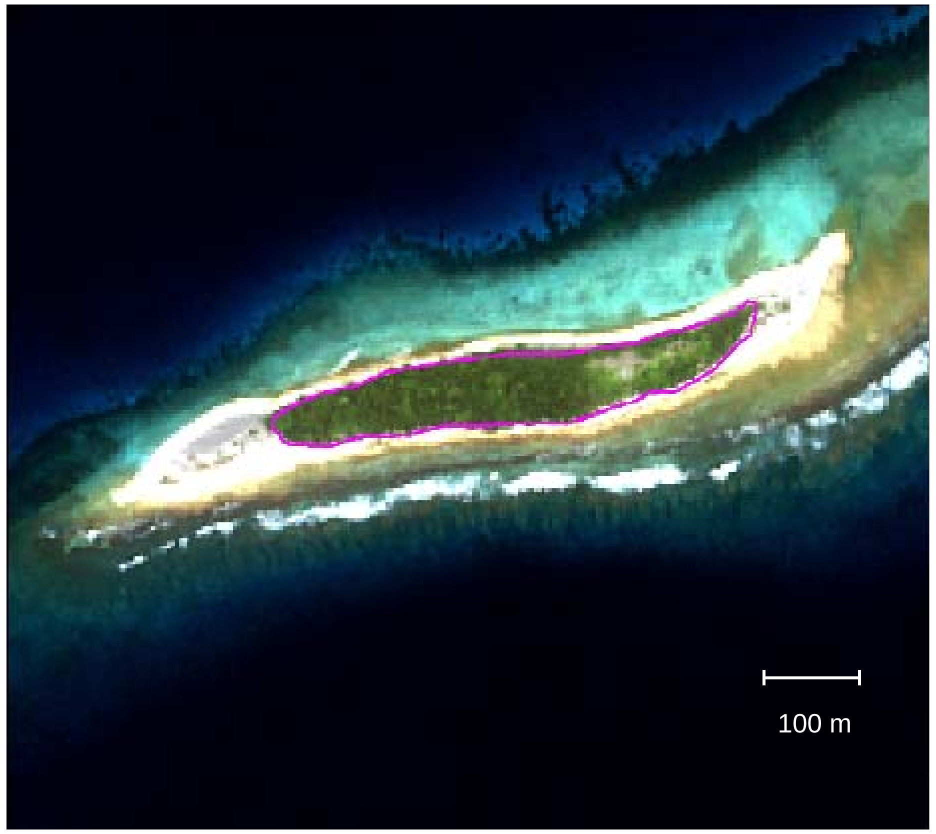
Mulitefala 0.8 % increase
Amatuku 4.6 % increase.











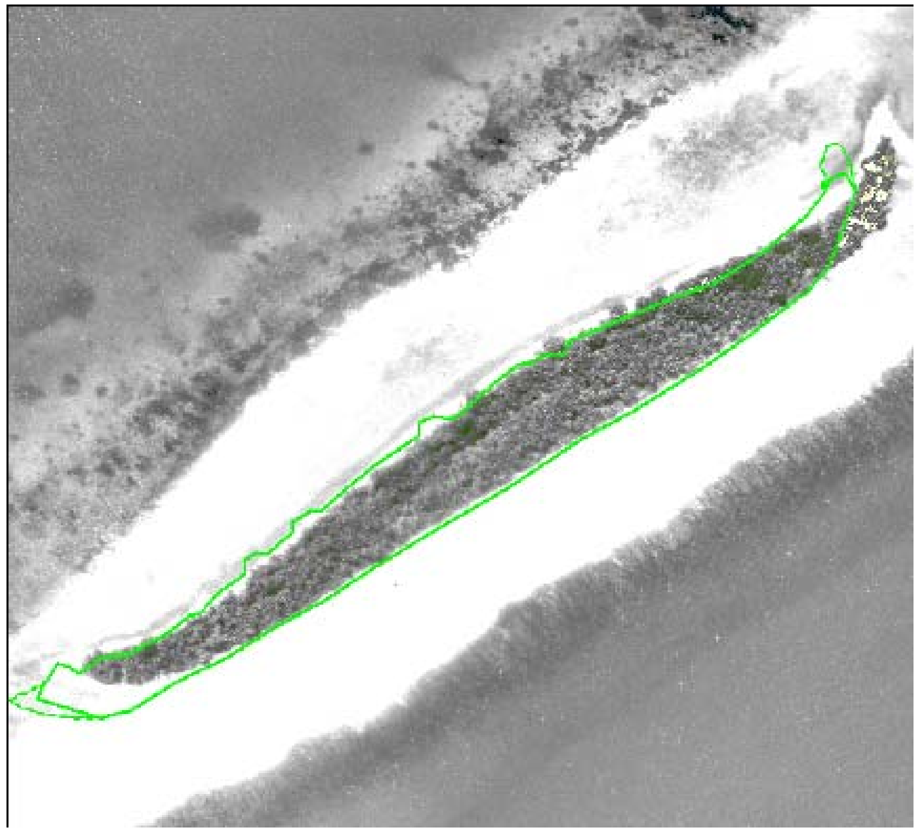
Fatato 8.6 % increase

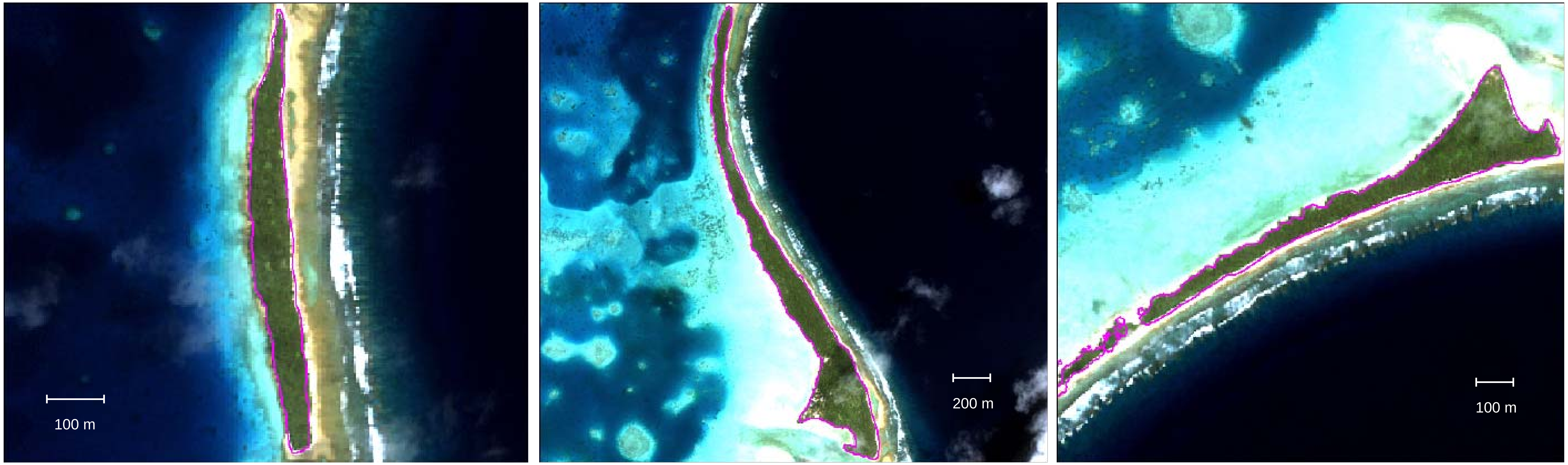
Including large rubble banks

Funagongo 1.0 % increase

Funamanu 28.2% increase

Including large rubble banks

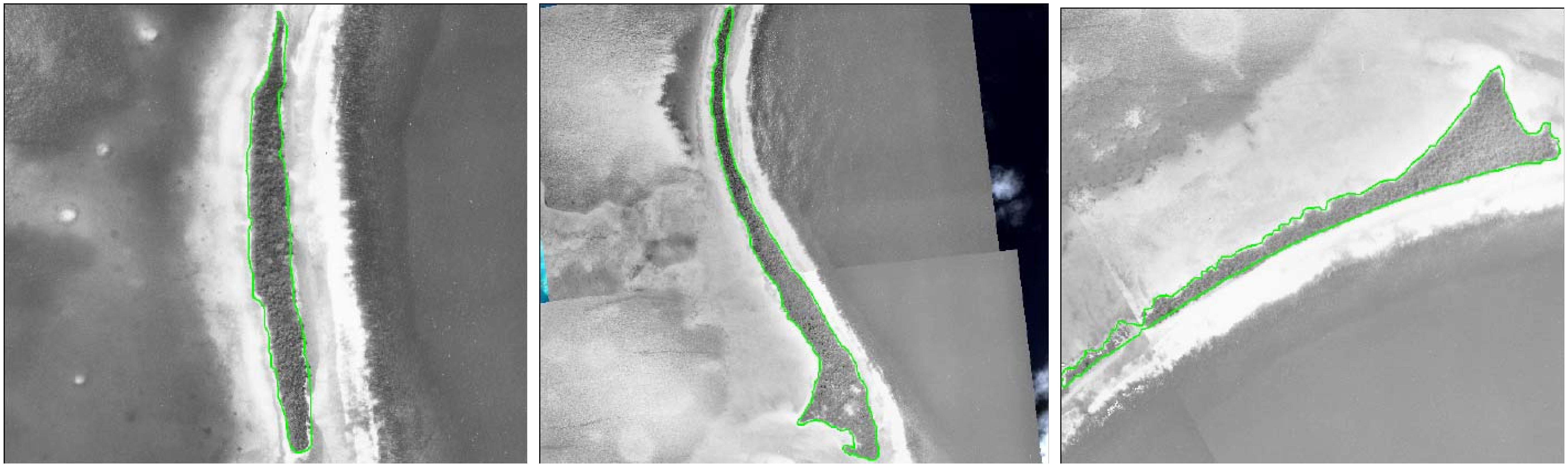


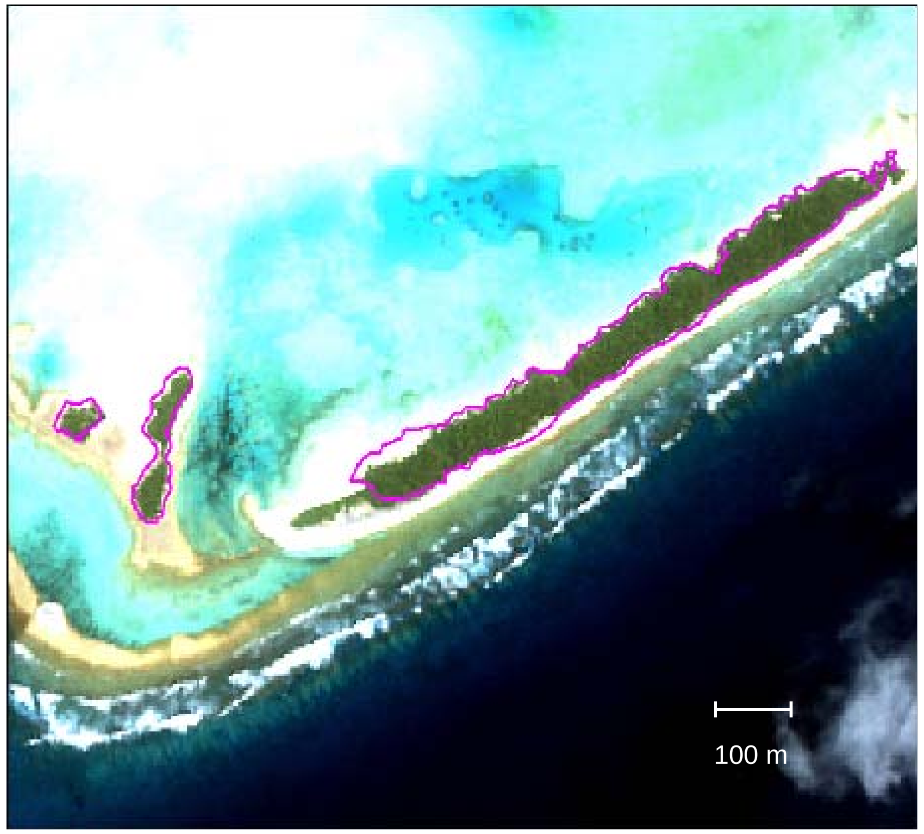


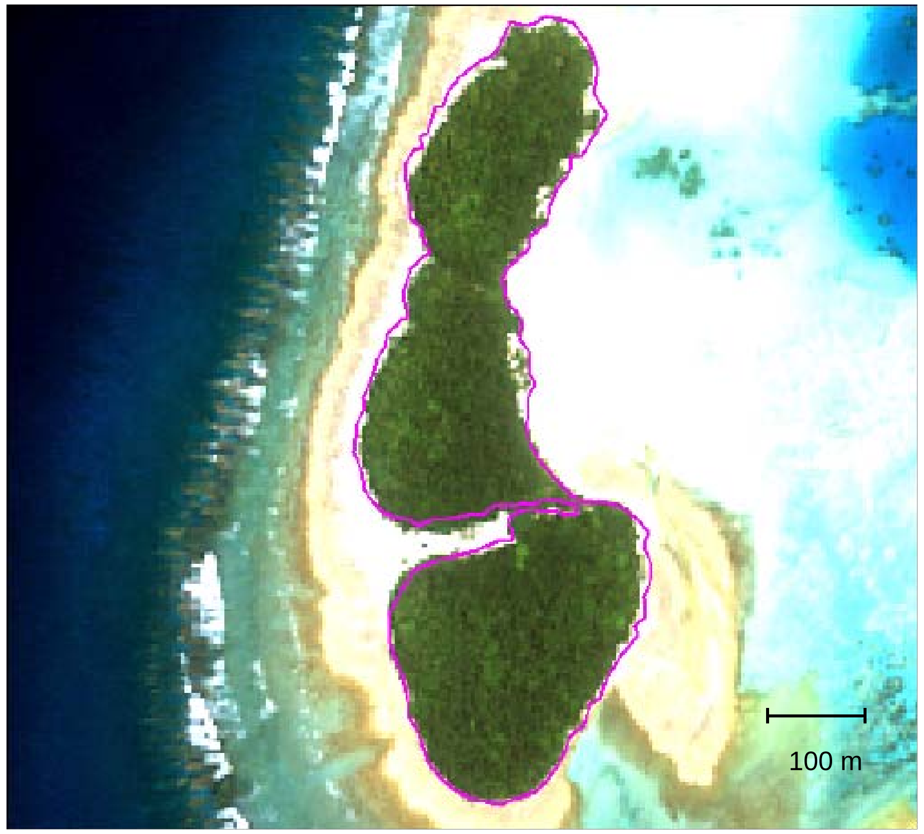
Mateiko 6.1 % increase

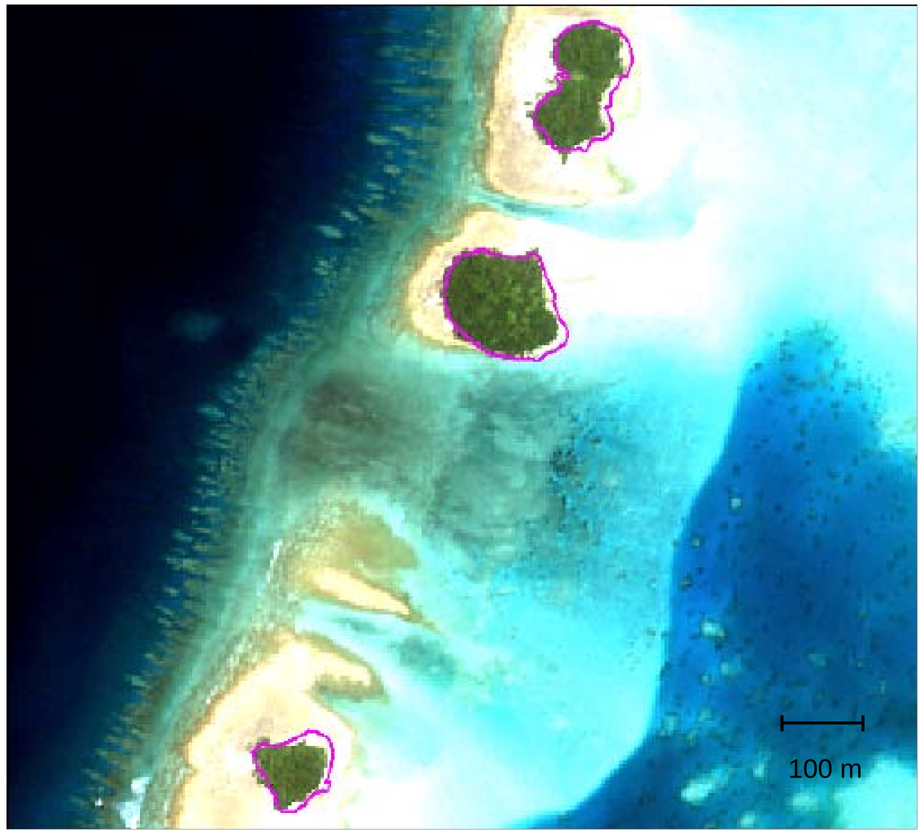
Funafara 3.6 % increase

Telele 0.5 % increase







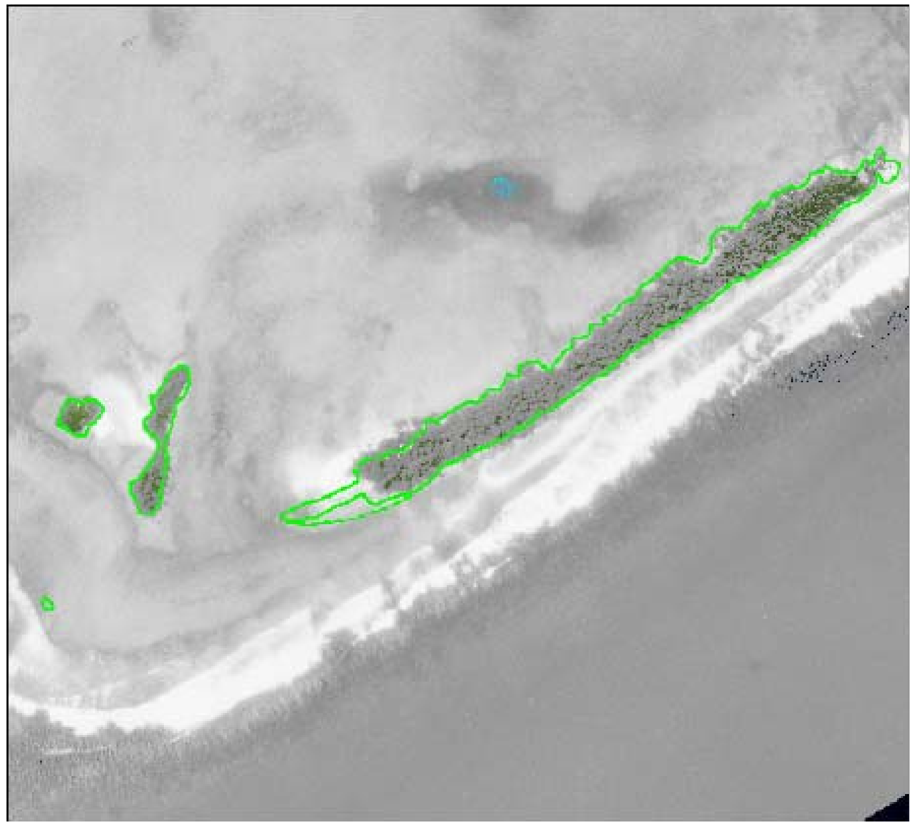


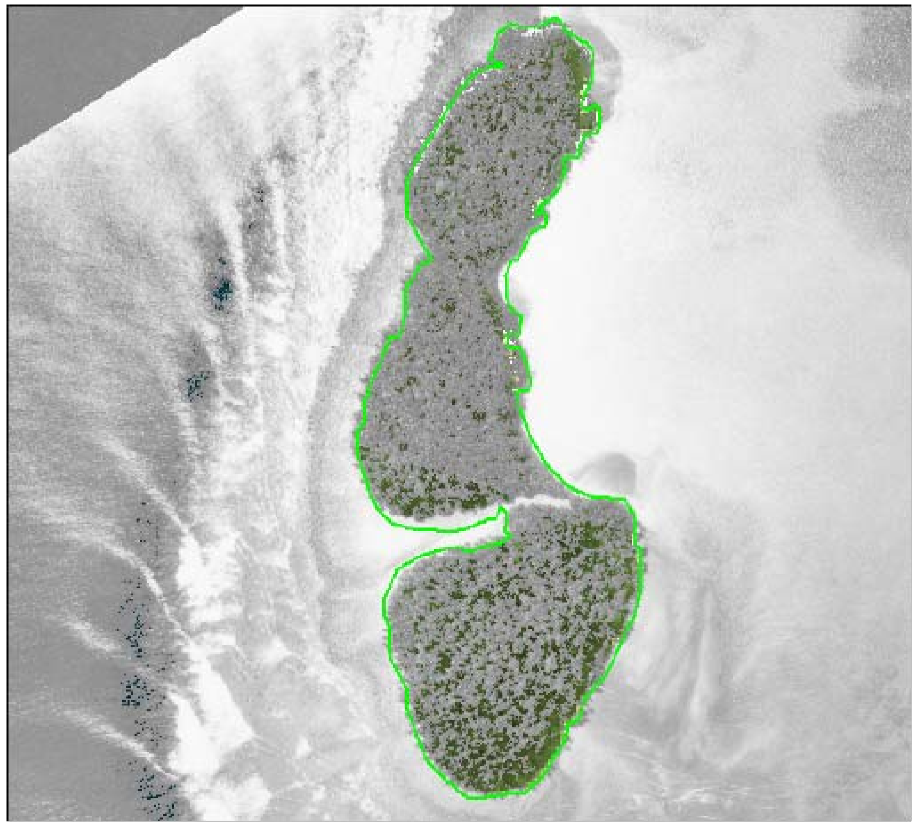
Motungie 1.0 % increase

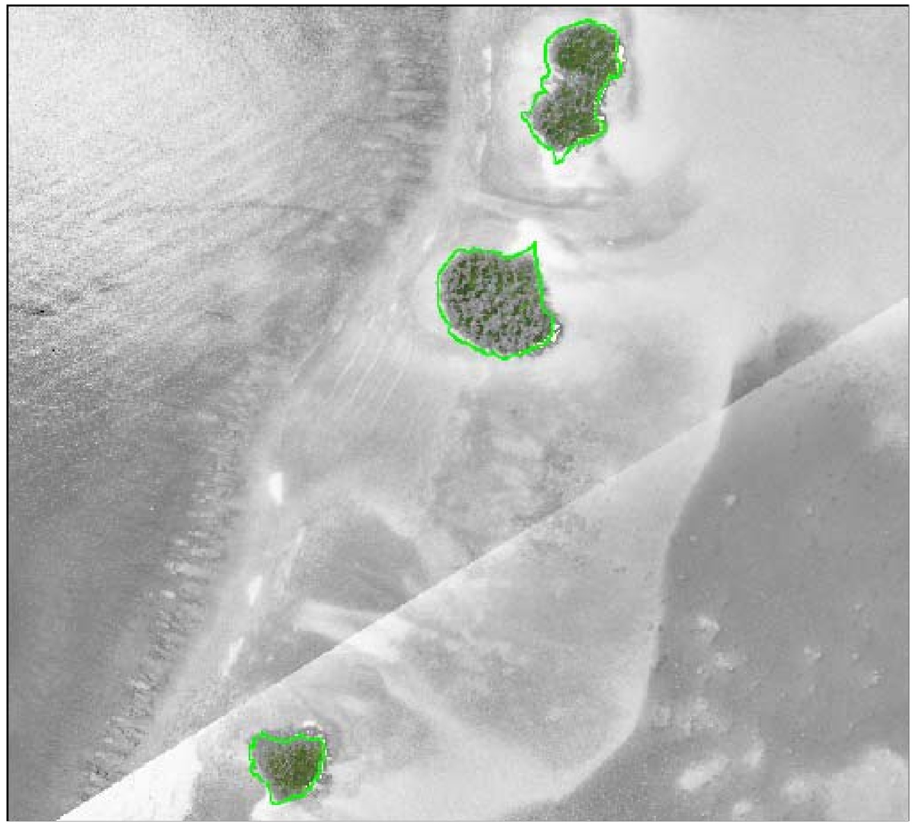
Including rubble banks and small islets

Avalau / Teafuafou 2.1 % decrease

Tengasu 14.0 % decrease
Tutanga 3.6 % decrease
Falaoingo 0.2 % decrease







The table below shows the comparative estimated land area of the uninhabited islets considered in this study. Overall these figures indicate there is no trend of either erosion of accretion on these islets and they have remained in a naturally dynamic state of stability during the interim period between 1984 and 2003. The overall change in area of approximately 2.8% (increase) cannot be considered a significant change in land area. Equally important, there is no evidence of an overall trend of net erosion or land area reduction between 1984 and 2003.

	Estimated area – 1984	**Estimated area – 2003**	**Change in area**
Islet	*Ha*	*Ha*	*Ha*
Paava	1.48	1.63	0.15
Fualifeke	6.85	6.61	– 0.24
Mulitefala	2.33	2.35	0.02
Amatuku	6.13	6.42	0.29
Fatato	5.11	5.54	0.44
Funagongo	10.66	10.76	0.10
Funamanu	2.99	3.83	0.84
Falefatu	3.23	3.66	0.43
Mateiko	4.25	4.51	0.26
Luamotu	1.80	1.74	– 0.06
Funafara	22.95	23.78	0.83
Telele	8.83	8.87	0.04
Motungie	4.97	5.03	0.05
Avalau/Teafuafou	12.14	11.89	– 0.25
Tengasa	0.68	0.59	– 0.10
Tutanga	1.66	1.60	– 0.06
Falaoingo	1.31	1.31	0.00
	Total area 1984	**Total area 2003**	**Total change**
Ha	**97.38**	**100.12**	**2.75**

Fongafale is an area of great community interest since it is the main urban centre of the island and also receives the greatest pressure on it's coastlines. The 2003 IKONOS image was not of sufficient resolution to adequately determine if the lagoon-side coast of Fongafale has moved in the period from 1984 to 2003. Similarly, analysis of total land area change on Fongafale showed only a 0.028% change (increase) from 1984 to 2003, this result simply confirms that any changes which have occurred are comparatively small and are below the detection limits of this study. As earlier discussed, lagoon beach profile data from the period 1987 to 1998 (Woodward, 1998) also confirms that overall, no significant shift has occurred on Fongafale's lagoon coast over the last 15 to 20 years. It is highly recommended that any future satellite image requisition be of sub-meter resolution (e.g. QuickBird imagery 0.9-m resolution) as this will allow the continued monitoring of this coast and will be better able to detect small changes.

It is obvious that some small islets (e.g. Funamanu and Fatato) have increased significantly in size. This is due to the build up of large cobble / gravel banks which are thought to be the remains of the cyclone rubble bank thrown up in the early 1970's. This has slowly moved landward and has been incorporated onto the shorelines and in places formed significant extensions to these islets.

Significant changes in the position of the lagoon shore of Fongafale was found to have occurred in the period from 1941 to 2003. In 1943 the US military artificially increased Fongafale's land area (approximately 8.5 % or 5.7 Ha) by the reclamation of the lagoon coastline by 25 to 30 m. As earlier discussed this effort was not undertaken with the view to retain natural shoreline processes and the reclamation and other associated nearshore works, have left a legacy of instability on this coast. Since this poorly reclaimed zone has long since been settled, it is not surprising that the community has the perception of this coast being vulnerable to wave wash over and erosion, especially during westerly gales (see also Xue and Malolonga, 1995). It is apparent that Fongafale's lagoon-side coast remains unstable and that it is still "recovering" from those works undertaken some 60 years ago. Superimposed over this long-term disturbance are the numerous efforts of shoreline residents to protect and / or further reclaim on their coastal fringe. In many cases such ad hoc coastal engineering can result in increasing vulnerability by further disturbing coastal processes. Also, land restrictions result in new buildings springing up on newly-reclaimed areas, these remain particularly vulnerable since local protection works tend to fail during bad weather.

This study also serves to show that even in the complete absence of human inhabitants and development, soft shorelines naturally fluctuate and move (= dynamic equilibrium). This is not a problem to the environment as it has occurred since long before the first human footprint marked these beaches. It is a problem which concerns the human use of the environment and highlights the great need for extremely careful consideration of planning, monitoring and use of these fragile atoll shores.

These uninhabited islets of Funafuti atoll, are excellent examples of natural shoreline movement. Note the differing stages of growth in the vegetation (centre cut-off between mature and young coconuts). This is clear evidence of how the islet has shifted over time.

These sloping rock platforms are fossil beaches. Whilst the example above is evidence of movement from the last 70 years or so, these naturally solidified beaches show that the shoreline of this islet has shifted continually for hundreds of years.

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