

# Interim Report on Studies of the $M_w \sim 7.9$ Earthquake of 3 May 2006, Kingdom of Tonga

## Participants

Phil Cummins  
James Whatman  
Anna-Lisa Lahtinen  
Geoscience Australia, Canberra, A.C.T., Australia

John Beavan  
Laura Wallace  
Geological and Nuclear Sciences, Wellington, New Zealand

Douglas Wiens  
Patrick Shore  
David Heeszel  
Washington University of St. Louis, Missouri, U.S.A.

Michael G. Bevis  
Eric Kendrick  
Ohio State University, Columbus, Ohio, U.S.A.

Frederick W. Taylor  
Jackson School of Geosciences  
The University of Texas at Austin  
Austin, Texas, U.S.A.

Tevita Malolo  
Kelepi Mafi  
Sione Nonu  
Tevita Fatai  
'Apai Moala  
Others to be named  
Ministry of Lands and Survey, Nuku'alofa, Kingdom of Tonga

Funded By  
Ministry of Lands and Survey, Kingdom of Tonga  
Geoscience Australia  
Geological and Nuclear Sciences, New Zealand  
The National Science Foundation, U.S.A.

## SUMMARY

The very large and rare  $M_w \sim 7.9$  Earthquake of 3 May 2006 in the Kingdom of Tonga aroused great interest among both Tongan scientists and their colleagues in Australia, New Zealand, and the United States. This earthquake was preceded by only one large event in the historical seismicity record for Tonga (April 30 1919) and perhaps two other large shallow earthquakes inferred from written records. Conventional wisdom was that the Tonga arc is of the “Marianas type” at which the subducting Pacific plate is very old and dense so that it sinks into the Earth’s asthenosphere along the Tonga trench by virtue of its great density. This process was believed to occur without elastic deformation of the forearc or large shallow earthquakes. However, if this assumption is wrong, then the Kingdom of Tonga may have much more potential for very large local earthquakes and tsunami than has been previously recognized. As has been discovered elsewhere, the historic record may be too short to provide a realistic assessment of the worst case scenario for earthquakes and tsunami. Given this realization the interested parties mounted an expedition to investigate the nature of this earthquake so as to provide a scientific basis for assessing the likelihood of future events of this size or even larger ones. The main risk is that if other events of this type occur they might generate large tsunami which are known to pose a much greater risk to people and property than the earthquake ground motion.

To investigate the earthquake we formed a collaborative research group of scientists from Australia, New Zealand, Tonga, and the United States. We brought in seven seismographs from Australia and the US to supplement the three-station network already in Tonga and eight GPS receivers primarily for the islands west of the earthquake epicenter. In addition, we made coastal observations to determine the regional pattern of subsidence associated with the earthquake. The GPS instruments can measure horizontal and vertical motion quite precisely, but only after the earthquake from the time of deployment onward, except for some sites on Tongatapu, Vava’u, and Lifuka that had been occupied by GPS receivers in the past.

Our survey located many earthquake aftershocks and established that the entire forearc platform from northernmost Ha’apai to points at least as far south as Nomuka and Telekevava’u subsided. Tofua did not subside measureably. At this time, most of the GPS data have not been processed. However, the small amount of processed GPS data show that Lifuka subsided by  $\sim 230$  mm, consistent with other observations. There is no hard evidence of pre-seismic subsidence or uplift from the coral observations unless it began less than one year before May 2006 in which case we would not be able to detect it.

Our preliminary conclusions regarding the focal mechanism of the earthquake have led some of us to favor an interpretation that it occurred along a steeply dipping reverse fault. If that is true, then it seems unlikely that the subsided islands will rebound to their previous levels. However, the nature of the

earthquake remains ambiguous at this time. We hope that access to the complete GPS data and further analysis of seismicity data may lead to firm conclusions regarding the nature of the earthquake. If the earthquake occurred on the interplate megathrust, then that implies that the observed subsidence was due to release of elastic strain. In that case, we expect to observe post-seismic uplift of the islands over the next months, years, or decades. We would expect that very similar events have occurred in the past and will occur in the future. If the event was on a steeply dipping reverse fault then we do not expect there to be much if any post-seismic uplift and the earthquake is likely to be an extremely rare event that may even be unique to this area.

We offer the following recommendations:

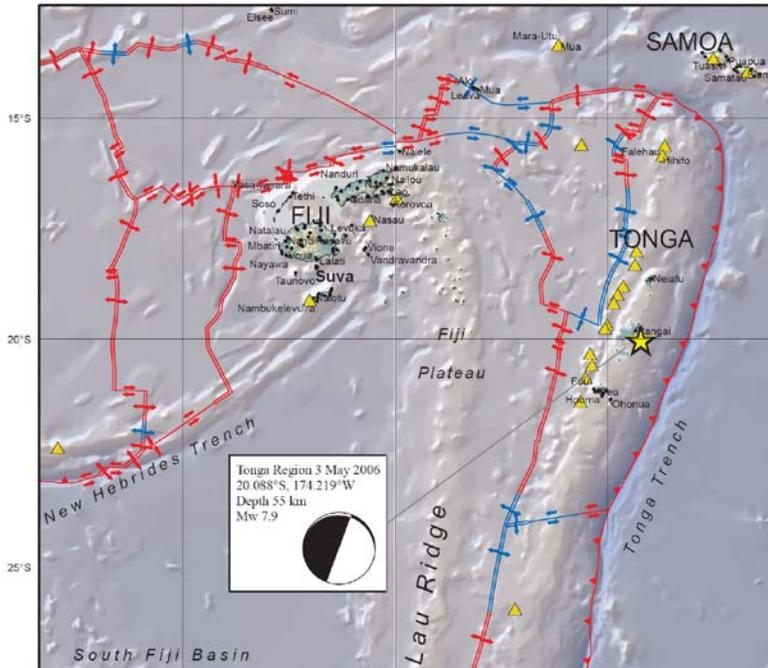
1. **Follow through with the study of the 2006 earthquake.** Data related to this event remain one of the best chances to understand whether megathrust rupture events do occur along the Tonga arc. Whatever, the origin of this event, we must consider whether it is something that can happen again if this earthquake could have been tsunamigenic.
2. **Support tsunami awareness, mitigation, and warning.** However, recognize that warning systems are relatively ineffective for locally generated tsunami and that earthquake and tsunami awareness are more effective for those cases.
3. **Provide geologic hindsight** by conducting paleotsunami and paleoseismic studies to determine if large earthquakes have caused significant vertical motions in Tonga in the past and whether tsunami even larger than the 1919 event have occurred.
4. **Monitor subduction-zone deformation.** Such measurements would document strain accumulation as indicators of future earthquake size and frequency.
5. **Discover additional written or oral records of past tsunamis.** Such records form the usual basis for estimating tsunami size, frequency, and potential impact.

## Introduction

Although it is true that the greatest earthquakes and tsunami are generated at convergent plate boundaries, it is believed that certain types of arc systems, termed the Marianas (and Tonga) type, accommodate subduction of oceanic plates without having very large shallow interplate thrusting earthquakes.



### M7.9 Tonga Region Earthquake of 3 May 2006



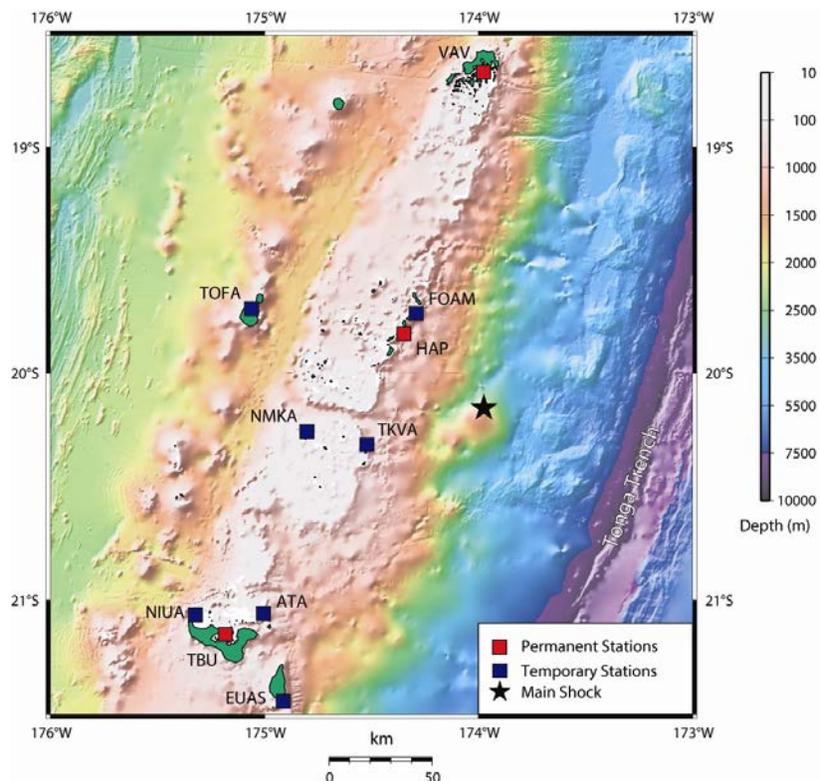
**Fig. 1. Map of the tectonic setting of the Tonga arc. GPS measurements show the fastest tectonic plate convergence rates on Earth along the northern Tonga trench. At Niuatoputapu, the Pacific plate converges and subducts beneath the Tonga forearc at ~25 cm/yr. The yellow star marks the USGS epicenter for the 3 May 2006 earthquake and the inset shows its focal mechanism.**

Therefore, there has been little concern that disastrous earthquakes would occur in the Marianas and Tonga arcs (Fig. 1). The basis of the belief that Tonga would not generate large shallow events is that geophysicists and geologists have classified the world's subduction zones in terms of their degree of interplate seismic coupling. According to Uyeda and Kanamori [1979] the two extremes are represented by Chile, the most seismogenic plate boundary on earth, and the Marianas and Tonga, where the subducting plate almost 'falls' into the mantle. After GPS measurements established that the Tonga island arc has by far the greatest rates of backarc spreading as well as plate convergence on Earth [Bevis et al., 1995], most geophysicists concluded that Tonga, rather than the Mariana, is actually the least seismically-coupled subduction zone in the world and, therefore, very unlikely to generate "great" shallow interplate megathrust earthquakes of the type that are the most destructive due to extremely violent and widespread ground motion and due to their propensity for generating very large tsunami.

On 3 May 2006 a great ( $M_w = 7.9$ ) shallow earthquake occurred between the Tonga trench and the Ha'apai Island group in southern Tonga (Fig. 1). The focal mechanism for its centroid moment tensor (CMT) *almost exactly* matches that expected for interplate convergence along the shallow interplate thrust zone, *i.e.*, a megathrust. If this interpretation is correct, this would be one of the most surprising earthquakes of the last twenty years, and it would require major rethinking on the mechanics of subduction as well as seismogenesis. If this was an interplate megathrust rupture event, then subduction of the Pacific plate beneath the Tonga arc has not proceeded largely by aseismic creep as has been thought. Instead, some unknown percentage of the slip has been stored as elastic strain or deformation within the island arc crust. Eventually, any such elastic strain is likely to be released, often as an earthquake. Another implication of this event if it is an interplate megathrust rupture event is that if it has happened once, then it can happen again, both in the location of the 3 May 2006 event and possibly to the north and south of that event.

However, all focal mechanisms are inherently ambiguous because seismological data about an earthquake nearly always offer two possible orientations for the coseismic fault plane. Thus, one explanation is that the event was an interplate megathrust rupture and the alternative explanation is that this event had a high angle fault plane

**Fig. 2. Map showing the sea floor topography of the Tonga arc and seismograph stations on the Tonga arc including those that existed prior to our 2006 project. Note the shallow forearc platform which is studded with shallow coral reefs and islands.**

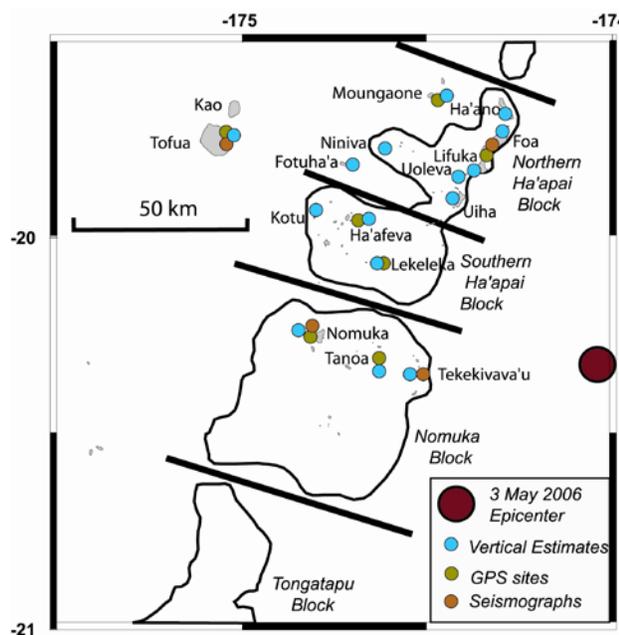


cutting deep into the Pacific plate lithosphere at a location beneath the Tonga arc east of the Ha'apai Islands. In this case the event would constitute a great plate-tearing event. Such plate tearing events are rare, especially in slabs experiencing downdip compression, and no such event has been subject to careful study using GPS and broadband seismic array. The hypocenter depth of ~55 km according to

the USGS provides some support for the tear hypothesis because the event appears deeper than the typical interplate megathrust rupture. The reports of significant subsidence in the Ha'apai Islands suggests that at least part of the fault slip extended into shallower depths. Data regarding the earthquake prior to our study did not allow us to decide between the two possible focal mechanisms for the event, but either way this is an extremely interesting and important earthquake.

To resolve the question of the 3 May 2006 focal mechanism and, thus, the nature of this earthquake and to be able to address the question of whether such large events may occur in the future, we proposed a rapid deployment of research-quality broadband seismographs, GPS instruments to measure post-seismic crustal motion, and observations of living coral colonies and coastal geomorphology to provide information on vertical crustal motions prior to the event and for places where GPS instruments were not deployed (Figs. 2 and 3).

**Fig. 3. Map of the Tonga forearc between the Vava'u and Tongatapu Groups shows islands where we deployed seismographs and GPS instruments and made observations of coastal subsidence or the absence of coastal subsidence. Of the sites visited on this map, only Tofua did not show**



**evidence of 2006 subsidence. The greatest amount of documented subsidence occurred at Telekivava'u, closest to epicenter as mapped**

the here.  
interim firm desire. been  
do not  
two

Unfortunately this report can not offer the conclusions that all of us The seismicity data have processed and considered. Unfortunately, the data provide a basis for clearly choosing which of the possible fault planes is

correct for the event. Seismologists prefer the interpretation that the rupture was a steeply dipping slab tearing event, but significant doubt remains. The coral and geomorphology indicate that virtually all of the Ha'apai, Kotu Group, and Nomuka Islands subsided, but subsidence of these islands would be expected for either of the two choices for focal mechanism. We hope that when the GPS data are available that they will enable us to determine a clear fault plane. Post-seismic

vertical and horizontal motions measured by the GPS instruments may provide a basis for comparison and contrast with motions following other megathrust rupture events that will provide a basis for a more definitive interpretation. It also is possible that future vertical motions that we will continue to measure using coral and GPS techniques will give us important information.

### **Fieldwork**

To conduct this study, scientists from Geoscience Australia, the Kingdom of Tonga, and the University of Texas, Washington University of St. Louis, and Ohio State University in the USA joined in the effort by contributing personnel, expertise, and instruments. Funds to conduct the work was provided by the Kingdom of Tonga, Geoscience Australia, and the US National Science Foundation.



**Fig. 4. GPS station in the foreground at Tofua Island with Kao Island in the distance. A seismograph station was located just to the left. This GPS mast, bolted into a lava flow remains in place as do all of the others. They can be re-occupied at any time in the future to determine the net amount of motion that has occurred since October 2006 when we removed the instruments.**

GPS stations existed at Tongatapu and Vava'u Tonga from the Southwest Pacific GPS Project of 1988-1997 and some additional ones had been established subsequently in Ha'apai. John Beavan had measurements from these sites made prior to May 2006. He contacted Tongan surveyors who reoccupied three sites in the weeks following the earthquake.

The US and Australian field participants met with Tongan colleagues in Nuku'alofa in mid-June 2006 as the seismographs and GPS instruments arrived from the USA and Australia by air cargo. After a few days of planning and preparations, the equipment and field personnel boarded the Church of Tonga vessel Langfouli for a voyage to the islands of Nomuka, Telekivava'u, Tano'a, Tofua, and Lifuka. We then used a smaller Ministry of Lands and Survey boat to visit Lekeleka, Ha'afeva, and Mo'unga'one Islands.

Seven seismographs were deployed including six semi-broadband and one broadband instruments. Three permanent SPANET stations at Tongatapu,

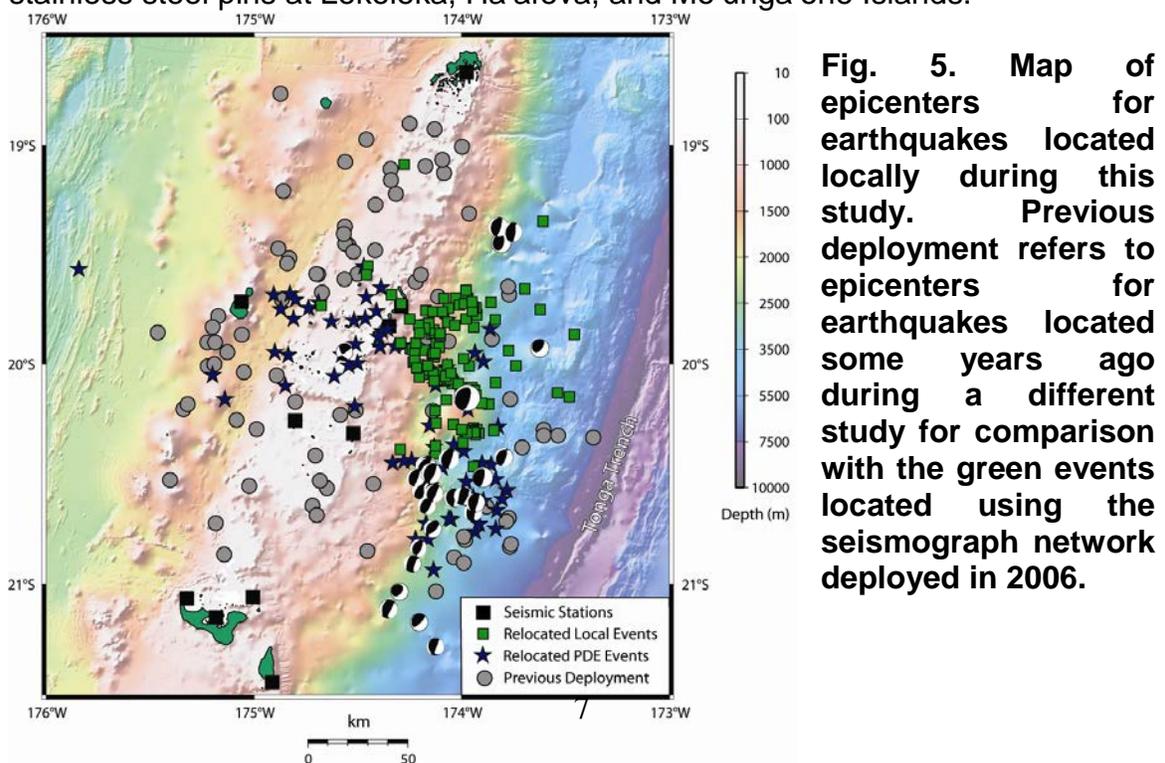
Lifuka, and Vava'u also provided data. Temporary stations were located at Eua, Tongatapu, Ata, Nomuka, Telekivav'au, Tofua, and Foa Islands. Thus, there was at least one broadband station in each major island group.

Figures 2, 3, and 4 show the deployment of GPS and seismographs on various of these islands. Continuously operating GPS stations were emplaced at Eua, Nomuka, Tanoa, Tofua, and Lifuka. These stations operated successfully from June until late October 2006. Temporary GPS stations were installed at Lekeleka, Ha'afeva, and Mo'unga'one Islands and operated for a few days.

At each site observations of living coral and coastal features allowed us to evaluate vertical tectonic deformation that occurred near the time of the earthquake but before deployment of the GPS instruments.

Much of the field team returned in October 2006 to remove the seismographs and continuous GPS instruments and to reoccupy the temporary GPS sites at Lekeleka, Ha'afeva, and Mo'unga'one. During each visit we also made observations of live coral and coastal morphology at the islands having GPS or seismographs plus several additional islands including the northernmost Ha'apai island of Ha'ano and some of the western islands in the northern Ha'apai Group such as Niniva.

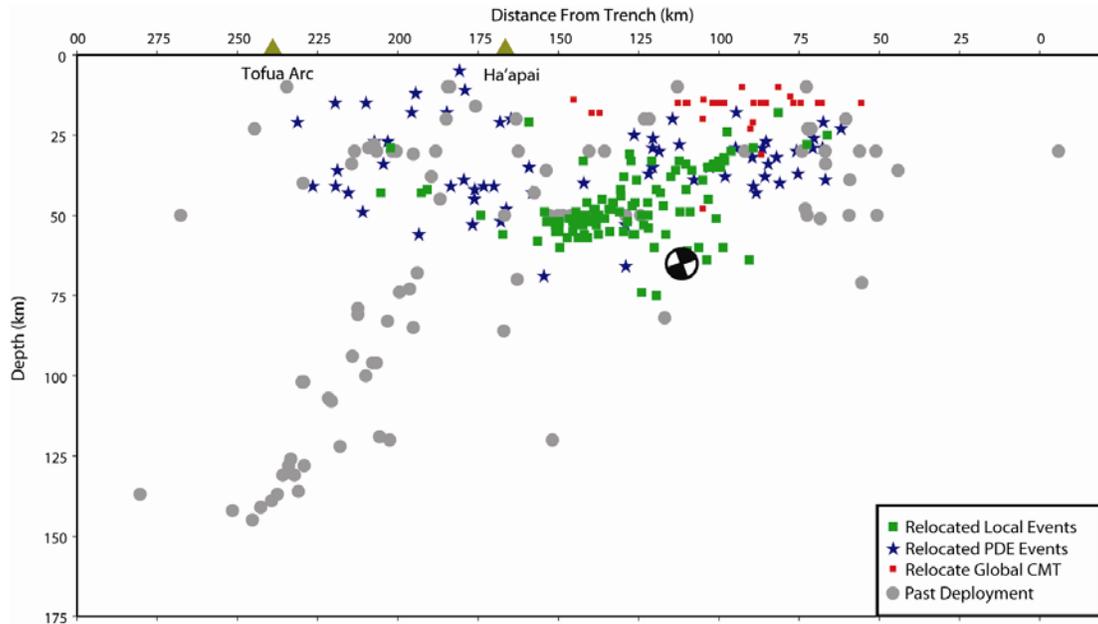
A third visit to Tonga in November 2007 provided additional observations of the coral record at several sites in the Vava'u group and again at Ha'ano and Lifuka in the Northern Ha'apai group. We hope to continue to make coral observations over subsequent years to monitor coral growth. If the GPS results and coral observations suggest that something valuable can be learned, it is possible that we can re-occupy the GPS stations in the future. The GPS masts at Eua, Nomuka, Tanoa, Tofua, and Lifuka will remain for future use as will the stainless steel pins at Lekeleka, Ha'afeva, and Mo'unga'one Islands.



**Fig. 5. Map of epicenters for earthquakes located locally during this study. Previous deployment refers to epicenters for earthquakes located some years ago during a different study for comparison with the green events located using the seismograph network deployed in 2006.**

## Results

We processed the seismicity data and determined precise locations using Joint Hypocentroidal Decomposition using a 1-D velocity model and leaving depths free (Figs. 5 & 6). The local PDE events from SPANET we relocated in



**Fig. 6. Earthquake hypocenters projected onto a West-to-East profile across the Tonga arc with the CMT for the main 3 May 2006 event plotted. Note that the aftershocks line up along a westward dipping trend that could be the interplate megathrust surface. However, the main shock hypocenter lies well below most of the aftershocks at ~55 km or even a little deeper. Generally, the maximum depth for interplate megathrust ruptures is ~40-50 km. This allows two interpretations. 1. The rupture extends between the main shock hypocenter and the cluster of aftershocks as a steeply dipping reverse fault. 2. The main shock hypocenter is near the base of a particularly deep megathrust rupture and the aftershocks are in the upper plate above rather than along the ruptured megathrust.**

the same manner. We relocated events recorded at stations outside our Tonga network using ISC phase data with depths controlled by assuming the CMT depth. Figure 5 shows a concentration of aftershocks offshore from Lifuka and nearby islands along the eastern margin of the forearc platform. Farther south, the aftershocks appear to be located closer to the trench. When projected into a profile across the arc, the aftershocks are located above the May 3 2006 hypocenter for the main event. These events appear to parallel the interplate megathrust which would potentially support an interpretation of a megathrust rupture event. However, the CMT hypocenter for the main shock lies well below

these aftershocks rather than among them (Fig. 6). Therefore, an interpretation of a steeply dipping rupture within the downgoing plate that extends upward into the base of the forearc is also possible. Thus, we are not yet prepared to make a definitive statement regarding the mechanism of this earthquake.

Preliminary GPS results from John Beavan for the temporary deployments at Tongatapu, Lifuka, and Vava'u are the only GPS data relating to the May 2006 event that are now available. There have been delays in processing the GPS data that we collected from June-October 2006. However, the good news is that all of the stations performed perfectly and the raw data exist and will give information on total vertical and horizontal motion from June through October 2006. The continuous GPS stations will not only give total net motion, but show exactly when it occurred, whether it was gradual and continuous or episodic, and whether the rate of motion changed over the course of the measurement interval if the motion was gradual.

Island	Site	N (mm)	N error (mm)	E (mm)	E error (mm)	Vertical (mm)	V error (mm)
Tongatapu	TGPU	27	5	66	8	23 (down)	16
Tongatapu	TONG	24	8	46	6	25 (up)	14
Lifuka	LFKA	227	8	375	6	231 (down)	22
Vava'u	VAVS	35	6	25	6	5 (down)	16

These GPS data show that Tongatapu and Vava'u were undergoing normal convergence with the Pacific plate over the time of the earthquake as would be expected. Their vertical motion from before until after the earthquake is insignificant. Thus, there is no evidence that there was any crustal motion at these stations that is directly related to the May 2006 earthquake. However, at Lifuka, there was a very large northeastward shift of the GPS station across the time interval that includes the earthquake. There data also show subsidence of about 227 mm at Lifuka. However, we do not know whether part of the horizontal and vertical motion at Lifuka and other islands occurred before and after as well as during the main shock.

Coastal observations at every island site from Ha'ano in northern Ha'apai to Telekivava'u in the south and at western forearc islands such as Nomuka, Kotu, and Niniva, all show clear evidence of coastal erosion that indicates subsidence of at least 10-20 cm (e.g., Figs. 7 & 8). Subsidence appears greatest at Telekivava'u and nearby islands and at the next island group to the north that includes Kotu and Lekeleka Island. Telekivava'u is undergoing severe coastal erosion and shoreline retreat of up to 10-15 m in places. A resident, Steven Gates, presented evidence based on photographs and observations of reef

exposure during low tides before and after the earthquake, that Telekevava'u had a total subsidence of ~0.5 m. When we arrived at Lekeleka, Sione Nonu noted the unusual turbidity of the water as we landed. We found trees being undermined and falling into the sea and the waves lapping against exposed red volcanic soil. Tofua Island is, however, different. It is the only one of the



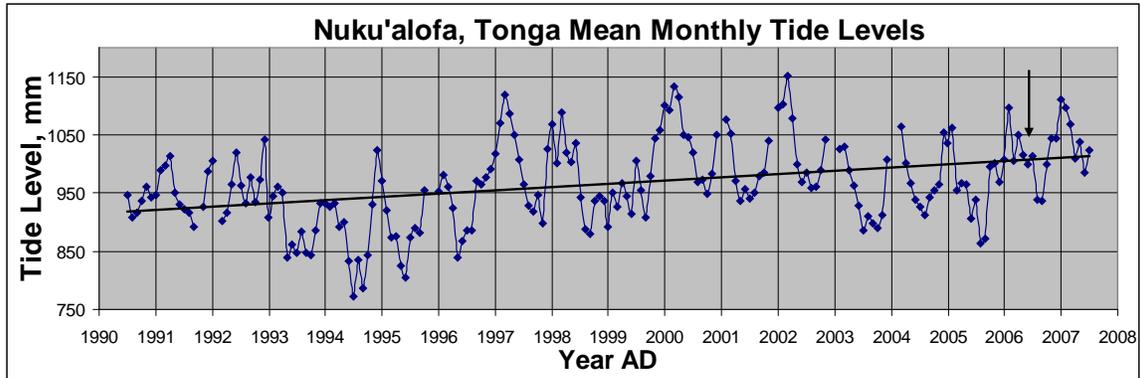
**Fig. 7. Photograph of severe coastal erosion at Telekivava'u Island to the east of Nomuka Island. Steven Gates who took this and many other photographs has convincing evidence that this island subsided ~0.5 m. However, he also has indications that subsidence began up to eight months before May 2006**

Ha'apai islands that had no detectable vertical motion during either of our two visits in June and October 2006. No coastal erosion has been observed at Vava'u or Tongatapu although there had been preliminary reports of coastal erosion at one islet in the Vava'u Group. We also note that the tide gauge at Nuku'alofa and the astronomical tide tables do not suggest that tide levels following the 2006 earthquake were significantly different than in preceding years (Fig. 9).



**Fig. 8. The fence along the shoreline at the hospital in Pangai, Lifuka Island is underwater during high tide. Coastal erosion is damaging buildings and infrastructure such as wharves and sea walls. 'Apai Moala visited this exact site in early June 2006 prior to our arrival and found high tide reaching behind the coconut trees which is about 1.5 to 2 m farther inland than when we visited in November 2007. This suggests that**

**Lifuka has rebounded from some greater maximum subsidence at the time 'Apai made his observations.**



**Fig. 9. Seaframe monthly mean sea level measured by tide gauge at Nuku'alofa, Tongatapu. This is the tide gauge closest to the earthquake and is not fully representative of sea level in the Ha'apai Group. This record shows a relative sea level rise for which the cause has not been resolved. However, it is sufficient to show that there was no large regional sea level rise following the 2006 event that might be misconstrued as tectonic subsidence. For example, at the time when Steven Gates first noticed anomalous coastal erosion at Telekivava'u Island in September 2005, the tide gauge record shows somewhat lower than average tide levels for 2005.**



**Fig. 10. *Porites* sp. Coral head near the northern end of Lifuka Island in June 2006. The corals were indeed about 25 cm below water level during low tide. This coral had grown upward from a very shallow sea floor until it had reached the highest possible level at which it could live. There its top surface died and it grew only horizontally. This and much larger such corals have acted as**

**natural tide gauges that show relative sea level stability for several decades preceding the 2006 earthquake and subsidence.**

It is clear that subsidence has occurred throughout the Ha'apai and Nomuka forearc platform, but there are clues that not all of the vertical motion was coseismic. At Telekevava'u, Steven Gates began to notice alarming coastal erosion beginning about September 2005, about eight months before the earthquake. The Nuku'alofa tide gauge record indicates lower than average

mean monthly tides in late 2006 rather than higher tides, so regional high tides are not a likely explanation. 'Apai Moala went to Lifuka in early June after the earthquake and observed high tide levels reaching about 1-2 m farther inland than the high tide marks during our visit there in October 2006 and November 2007. We did not visit that exact spot in June 2006.

Coral observations are valuable because corals behave as living tide gauges that have recorded some information about relative sea level changes that have occurred in the years before the 2006 earthquake. As with a tide gauge instrumental record, caution must be exercised as we interpret possible tectonic contributions to the record of relative sea level changes.

**Fig. 11. *Porites sp* coral at Ha'ano Island north of Lifuka Island as seen in November 2007. At this and other locations visited on Lifuka Island, corals have begun to grow upward in response to a rise in relative sea level. Note how this coral is beginning to grow inward over the previously dead surface as well as upward. Of course we interpret this relative sea level rise as tectonic subsidence associated with the May 2006 earthquake.**



Corals at all sites examined in the Ha'apai and Nomuka Island Groups indicate that there had been little or no net relative sea level change over the span of the most recent several decades (Fig. 10). This appeared to be the case also at the one site we visited on Tofua, although the smaller size of the corals limits the record of no significant relative sea level change to perhaps one or two decades. However, in November 2007, we examined living corals at Ha'ano and Lifuka and found that all corals have begun to grow upward in response to an upward shift in relative sea level that we interpret to be the subsidence associated with the May 2006 earthquake. However, corals have limitations (Fig. 11). For example, their records do not have sufficient resolution to allow us to confirm that Telekevava'u began to subside eight months before the May 2006 earthquake.

The living corals examined at several sites in the Vava'u Group also indicate that relative sea level stability had prevailed. However, beginning approximately 3-5 years ago, shallow-living corals at most sites began to grow upward (Fig. 12). This indicates a rise in relative sea level at Vava'u. This upgrowth is now about three cm, which is as fast as corals can grow. The relative sea level rise to which they are responding is at least this large. At this point we do not know whether this apparent relative sea level change may have tectonic implications.

**Fig. 12. Typical Porites sp. coral heads observed among the Vava'u Islands in November 2007. Most corals show several cm of upgrowth that began ~5 yr ago (note the wrist watch for scale). There is no evidence that this relative sea level rise is associated with the May 2006 event east of the Ha'apai Islands, but it is possible that this apparent rise in relative sea level**

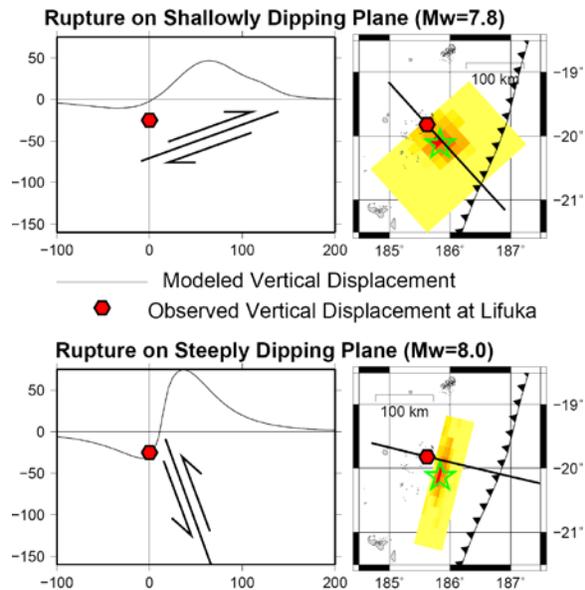


**has a tectonic cause. We intend to monitor coral growth and to inspect the GPS data from the Vava'u GPS stations for evidence of subsidence.**

### Discussion

Given the unprecedented occurrence of the great 2004 earthquake at Sumatra and now the May 2006 event in Tonga, we must not assume that Tonga or any other arc, for which the paleoseismic history is lacking, can not generate very large earthquakes. The 19 April 1919  $M_w \sim 8.2$  great earthquake near Vava'u is

**Fig. 13. Comparison of the expected vertical crustal displacement that would be associated with each of the two possible slip planes for the 3 May 2006 CMT. The upper one is the interplate megathrust. Uplift would occur between the Tonga forearc platform (where all the islands are) and the trench. All of the islands would subside, but only a few cm. The lower is for a steeply dipping reverse fault that would penetrate the downgoing plate. It might extend up into the forearc and it does generate greater subsidence for the islands of the forearc platform.**



another warning that Tonga can generate large earthquakes. Unlike the very small tsunami following the 2006 earthquake, the 1919 event generated a wave that is reported to have reached 2-3 m above sea level at Ha'apai and perhaps 20 m up the cliffs at Ha'alaufuli on the east coast of the main land mass of Vava'u. The old seismicity data and the tsunami reports suggest that it was a

shallow event, but its mechanism is not well constrained by the old data. In any case, these earthquakes suggest that scientists need to re-assess the potential for significant elastic strain accumulation across megathrusts in Mariana-Tonga type arcs. Although it is certain that most of the interplate slip does occur aseismically along the Tonga arc, if only a very small percentage of the rapid plate convergence at the Tonga arc is stored as elastic strain, then very large, if infrequent, earthquakes are possible. In fact, the historical record of seismicity for Tonga is so short, that we can not rule out the possibility that the past 200 years have been anomalous for the relative paucity of large shallow earthquakes.

The main issue regarding the 2006 earthquake is this: Was it or was it not caused by rupture on the interplate megathrust? If it was a steeply dipping reverse fault mainly within the downgoing plate, then we have no basis on which to suspect that such events occur very often. If it is such a plate breaking event then such events may occur occasionally, but they are not likely to generate tsunami unless they occur at shallow depths. If this was a reverse faulting event, then it is one of the largest examples known and future ones are not likely to be even this large. However, given the perspective provided by the 1919 and the 2006 events, we have to recognize that Tonga does have significant earthquake and tsunami potential even if the earthquakes occur only once per century.

On the other hand, if the April 2006 event was a megathrust rupture, then it is likely to be repeated and it is possible that past megathrust ruptures could have been significantly larger and more powerful and that future earthquakes could be very destructive. Unlike a plate breaking event, which we consider to be rare and nearly random, a megathrust fault can be regularly replenished with elastically stored energy from the very rapid convergence of the Pacific plate toward the Tonga arc.

The 3 May 2006 earthquake of Mw ~7.9 occurred in a location and at a depth that first suggested that it was an unusual megathrust rupture at an arc that had been considered uncoupled due to the age of the downgoing Pacific lithosphere and the existence of a rapidly opening back arc basin. Some seismologists believe that the evidence to date more strongly support a steeply dipping event within the downgoing plate. Perhaps that is the nature of the 1919 event as well. Our GPS work in Tonga since 1988 has revealed no evidence of elastic strain within the upper plate that would suggest that energy was being accumulated. This is consistent with the living coral evidence that shows an absence of relative sea level changes in the islands over the decades preceding the 2006 earthquake. However, it is possible that elastic strain accumulated in the Tonga forearc many decades ago and was stored until the dynamic balance between elastic strain and interplate slip on the megathrust became unstable and aseismic slip accelerated to generate the earthquake. It is possible that post-seismic motions recorded by the continuous GPS stations will provide insights into these possibilities when the data are available.

Geological studies have shown that Lifuka and other islands in Ha'apai and Nomuka have undergone negligible accumulation of vertical tectonic movement over the past ~100,000 years, so that any subsidence is not likely to be permanent. The same is true for the Tongatapu Group, including 'Eua. However, the Vava'u Group has been subsiding at a mean rate of ~0.5 mm/yr for many thousands of years. No one knows whether this subsidence occurs episodically or if it is constantly occurring.

If the recent subsidence of the Tonga forearc platform from northern Ha'apai to the Nomuka group was caused by elastic strain release along a megathrust rupture, then we can imagine two scenarios. 1. Aseismic slip at tectonic plate convergence rates has resumed and no further subsidence will occur. As soon as elastic strain begins to accumulate again in the upper plate, then the subsided islands, including Lifuka and its neighbors, will begin to uplift. 2. Following the earthquake, slip on the megathrust decelerated to aseismic rates but still faster than long-term plate convergence rates. In this case, there could be continued elastic strain release that would cause continued subsidence.

The first scenario is far more likely based on events at other arcs and the absence of evidence for continued subsidence. At Lifuka, there are hints that uplift may have begun to reduce the amount of total subsidence within weeks after the earthquake. In any case, the longer term evidence is that the forearc is not undergoing net subsidence except at Vava'u so that sooner or later, Lifuka, Telekivava'u and all the subsided islands will uplift back to their pre-earthquake positions. We may already have the data from our GPS sites that will show this to be the case.

If the earthquake was caused by a steeply dipping reverse fault then its energy source should not involve much if any elastic strain within the Tonga forearc. In that case, there is unlikely to be much if any postseismic uplift of the subsided areas. If the rupture extended into the upper plate thereby causing dropdown of the subsided islands then we can not imagine a scenario in which that the related subsidence could be recovered.

One desirable conclusion if the earthquake was on a steep reverse fault is that such an event would likely be extremely infrequent or even unique for the area. This is true because if it had occurred just a few times in the past few thousand years then the Holocene reefs and notches on the Ha'apai Islands would now be submerged. In fact the ancient reefs document the fact that there has been no net vertical deformation for many tens of thousands of years for most of Ha'apai and Nomuka. However, these reefs do not in any way contradict the idea that there can be repeated cycles of elastic strain accumulation and release such as would occur on repeated seismic ruptures of the main interplate megathrust fault system.

## **Recommendations**

We will continue to work with our data and attempt to resolve the question of the focal mechanism and the type of earthquake of 3 May 2006. Those attempts may or may not result in a fully unambiguous conclusion, but the results will guide us toward a better evaluation of seismic and tsunami risk in the Kingdom of Tonga. However, there are other steps that we suggest regardless of the outcome of this study. The experience of the 1919 and 2006 earthquakes in Tonga and other large earthquakes around the world show that the earthquake ground motion is rarely the direct cause for death and destruction except in highly urbanized areas. The much greater risk is from large tsunami. Thus, we recommend the following measures:

- 1. Follow through with the study of the 2006 earthquake.** Data related to this event remain one of the best chances to understand whether megathrust rupture events do occur along the Tonga arc. Whatever the origin of this event, we must consider whether it is something that can happen again if this earthquake could have been tsunamigenic.
- 2. Support tsunami awareness, mitigation, and warning.** However, recognize that warning systems are relatively ineffective for locally generated tsunami and that earthquake and tsunami awareness are more effective for those cases.
- 3. Provide geologic hindsight.** Earthquake and tsunami history needs to span thousands of years define the range of earthquake and tsunami sizes and recurrence intervals for each tsunami source in the probabilistic hazard assessment. Accordingly, paleotsunami studies on Tonga coastlines combined with other paleoseismic techniques have the potential to determine if large earthquakes have caused significant vertical motions in Tonga in the past and whether tsunami even larger than the 1919 event have occurred. It should be a priority to learn more about the geologic record of the 1919 tsunami and if it was only a very local event at one or two locations in Vava'u and Ha'apai..
- 4. Monitor subduction-zone deformation.** Such measurements are needed to constrain convergence rate and strain accumulation as indicators of future earthquake size and frequency. Sites exist and have already been measured to provide a base of information against which to compare future geodetic measurements in Tonga. We particularly should seek to determine if new elastic strain is beginning to accumulate on islands arcward of the 2006 rupture zone. The tectonic subsidence of Vava'u and the hint of a pulse of relative sea level rise lead us to recommend that the possibility of tectonic crustal motions at Vava'u be monitored carefully.
- 5. Discover additional written or oral records of past tsunamis.** Such records form the usual basis for estimating tsunami size, frequency, and potential impact. We have discovered a couple of accounts of past tsunami at Tongatapu, Ha'apai, and Vava'u, but there may be more information that could be extracted from traditional "myths" or stories that have their basis in actual tectonic events or tsunami.

## Conclusions

This is an interim report on the results of our collaborative study of the 3 May 2006 Mw 7.9 earthquake between the Tonga trench and the Ha'apai Islands. We are unable at this time to resolve the question of whether this event was produced by rupture on the main interplate megathrust fault system or by a steeply dipping reverse fault that broke into the downgoing Pacific plate underlying the inner trench slope portion of the Tonga forearc. What is clear to the scientists involved, however, is that Tonga can no longer be neglected as a possible source of very large shallow earthquakes and tsunamis. We must endeavor to understand the May 2006 event and its implications for local earthquakes and tsunamis and its scientific implications for our understanding of the potential for accumulation and release of elastic strain at Marianas-type arcs. Even if we conclude that the 2006 event occurred on a steep reverse fault, it was a very large and strong event. We need to determine if such events have happened in the past and if so do they pose a significant threat for ground motion and tsunamis.

## Appendix 1; Report of a tsunami associated with the Great 30 April 1919 earthquake near Vava'u, Kingdom of Tonga

Account contributed by geologist Allan Morton who presented a paper at the Geological Society of America meeting in 2003 entitled:

Evidence for large tsunamis in the Tongan Islands

Note: Wednesday falls on April 30, 1919 and Tuesday is April 30 1918.

In the biography of Iohani Wolfgramm, formerly of Ha'alaufuli, Vava'u is an account of a tsunami that came ashore at the nearby Otualea Beach (also known as Keitahi Beach). It was associated with a large earthquake that Iohani thought occurred in 1918 but was probably the large earthquake of April 30, 1919. His daughter, Tisina Wolfgramm Gerber of Salt Lake City, Utah, compiled this biography from audiotapes she made and transcribed. Following is an excerpt from his biography:

“Every Wednesday night at Ha'alaufuli the missionaries preached on the street corner. Salome [his mother whose maiden name was Salome Fo'ou Afu] went out with some neighbors to hear them. My Father [Charles Fredrick Wolfgramm], being very weary decided to put the children to bed early, and then retire himself. Soon after, there was a great earthquake. This was 1918. I remember being thrown from my bed. We children were tossed about the floor, as the earth beneath us shook violently. Hurrying to our feet, we all ran outside to see what was happening. The missionaries were still

preaching. Suddenly we heard a very loud noise coming from Otualea, our favorite beach. We discovered it to be a very big tidal wave, climbing nearly half way up the cliff. This was my first experience, witnessing a tidal wave, which was so devastating. It took with it, every single beach house. The sand was thrown to the deep part of the ocean; only rocks were left behind. Fish, sharks, and sea life of all kinds were thrown on the treetops. Coconut trees, and toa trees, were pulled out from their roots; wild flowers and vines were crushed against the rocks. All the sand had been washed away, and there were holes everywhere upon the seashore. All the people rushed to the beach, to see what had occurred. Children immediately envisioned using the holes for their individual swimming holes; they thought it amusing to see fish and shark hanging upon the trees. \_The Vava'u group of islands was of volcanic origin and the village was on the top of these high rocks. Fortunately, no lives were lost on the beach that night."