Aftershocks, Crustal Structure and Faulting along the Southern Side of the Central Highlands, Papua New Guinea

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ABSTRACT

A magnitude 7.5 earthquake struck Hela, Southern Highlands, Western Highlands and Enga Provinces of Papua New Guinea (PNG) on 26 February 2018 causing many deaths, injuries and landslides (see accompanying paper in this conference by McCue, Gibson and Love).

From 19 to 23 March a six-station accelerograph network was rolled out over a 100km length of the fault zone in the epicentral region of the mainshock and thousands of aftershocks were recorded at 200 samples/second continuously. Data were recorded on SD cards on site. The last large aftershock of the sequence, magnitude 6.3, occurred on 7 April so we returned to PNG to collect the data. Strong shaking was recorded on the two nearest accelerographs. The horizontal peak ground acceleration (pga) at right angles to the strike of the mainshock was in excess of 0.67g at a distance of 35km and strong shaking lasted more than 10 seconds. Fourier spectra of the 6 accelerograms show a strong shaking plateau from 0.5 to 1.5s period.

More than 100 of the larger aftershocks have been located using the aftershock network data alone and a modified crustal model originally developed for Gippsland Victoria. No pattern was observed in the aftershocks to indicate that the events occurred on a single planar structure.

Identification of the depth phase pP recorded on seismographs worldwide is compatible with a focal depth of 32km for the large aftershock on 7 April 2018. Our computed location puts the initiation of rupture at 24km depth. The small amplitude of surface waves compared with the body waves supports a lower crust rupture. Aftershock foci occurred over a depth range of near surface to about 40km, all within the crust. Planes dipping both to the SSW and NNE can be inferred.

Uplift along a short surface fault segment was photographed during our 2nd visit, damming the Tagari River. It could have been caused by any of the M6+ earthquakes in the sequence. Few cases of surface faulting have been observed in PNG which is surprising given the high rates of seismicity and number of tectonic plate boundaries where most surface faulting occurs.

INTRODUCTION

A magnitude 7.5 earthquake on the southern side of the Central Highlands of Papua New Guinea on 26 February at 17:44 UTC, killed more than 160 people in several provinces and injured many others. An aftershock of magnitude 6.0 killed 11 people on 4 March at 19:56 UTC, while another aftershock of magnitude 6.7 on 6 March at 14:13 UTC killed at least 25 more. A magnitude 6.3 aftershock killed another 4 people on April 7 at 05:48 UTC, more than a month after the first tremors hit the area.

A state of emergency in the four affected provinces was declared on 1 March due to the widespread damage, deaths and injuries, huge landslides and continuing aftershocks that destroyed subsistence gardens and fish and other food resources that lived in the rivers below.

During the period 19 – 23 March 2018 a network of 6 digital accelerographs was installed in the vicinity of the mainshock to monitor aftershocks both to enable better locations, especially focal depth, and to provide information on crustal structure below the deepest of the oil/gas drilling wells to the Moho. The data will inform the next building code update and provide useful design parameters for those companies needing to rebuild or design new structures.

THE FEBRUARY 2018 EARTHQUAKE, MAGNITUDE 7.5

Strong shaking, damage and felt reports At 3:44am on the morning of 26 February 2018 (17:44 UTC on 25 February) a very strong earthquake shook the Southern Highlands of Papua New Guinea. Occupants in oil/gas company camps between Moro and Komo reported shock and fear as their beds shot backwards and forwards across the room, cupboards rocked and toppled over and PVC water and waste pipes were broken. Residential blocks were badly damaged their foundations and access stairs collapsed, doors buckled, utility supplies were crippled necessitating closure and repatriation of flyin/flyout workers. Amazingly, given the large number of landslides, no oil or gas pipelines were breached. The other oil/gas producer Exxon reported similar problems in their camps but also damage to the Hides gas conditioning plant and closed down. Power transmission lines to Porgera from gas generators in the central highlands were destroyed by landslides so the mine had to cease production.

The average duration of strong shaking in the Moro region was reported as about a minute. The situation for the local villagers was dire; more than 160 deaths, many more injuries and people missing.

Several lightly reinforced buildings collapsed in Tari and Mendi due to the strong shaking causing loss of life and casualties, but the hospital at Tari, an old single-story timber framed building on a concrete slab seems to have suffered little damage. At least 26,000 people were displaced, and 275,000 people were in urgent need of emergency supplies such as food and clean water, over 544,000 people were reported affected by the quake, with half of them being targeted for assistance. The quake and its aftershocks caused panic and some damage in West Papua and, unusually, shaking was noticeable in northern Queensland and the Torres Strait islands.

The earthquake location, mechanism and faulting The mainshock location determined by various agencies is listed in Table 1. The onset of rupture, the focus (below the epicentre), was approximately in the centre of the aftershock zone and rupture propagated up, down and sideways at near the shear wave velocity of about 3km/s. With a fault length approaching 170km (the immediate aftershock zone from the USGS – see Figure 8 below) the duration of rupture and strong shaking was at least 30 seconds, but shaking was felt for considerably longer than that as surface waves propagate more slowly than 3km/s, and there are multiply reflected and refracted phases bouncing around.

Table 1 Locations of mainshock by different agencies

Date	Origin time	Latitude	Longitude	Focal depth km	Agency
2018 02 25	17:44:44	-6.070	142.754	15, 20, 25	USGS
	17:44:42	-6.098	142.751	17	GA
	17:44:44	-6.149	142.766	35	IRIS
	17:44:44	-6.08	142.79	30	ICSEM/EMSC
	17:44:42	-6.05	142.74	22	GEOFON
	17:44	-6.0	142.6	24	PMGO
Average depth				23.5	

The USGS mechanism (Figure 1), the moment tensor solution, was a pure thrust, the principal stress direction striking at 212° or NNE/SSW. The assumed fault strikes parallel to the Highlands at 293°, and its dip is 30° to the NNE, similar to most of the mechanisms found by Ripper and McCue (1983) for previous earthquakes in the Southern Highlands Seismic Zone

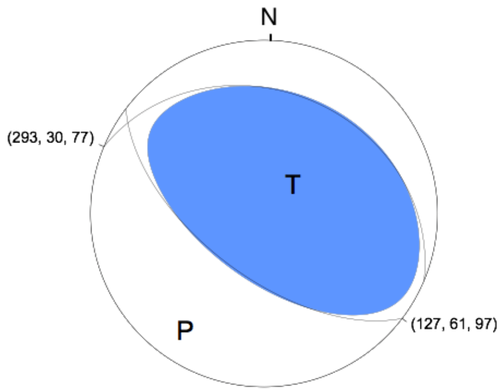

Figure 1 Focal mechanism of the mainshock by the USGS.

The focal depth modeled for the USGS moment tensor solution was 20km but estimates of focal depth varied from 15 to 35km between seismological agencies and 15 to 25 km for the USGS alone (Table 1).

It is surprising that few earthquakes in Papua New Guinea have been associated with surface faulting. Many of the earthquakes are offshore, the great shallow M8.1 earthquake on the Weitin Fault through southern New Ireland in 1981 is possibly the only exception prior to February 2018.

Figure 2 Air photo of blocked Tagari River, looking southward, the arrows marking the fault.

An interesting helicopter view at 142.9844°E, 6.3396°S, 28km west of Moro, shows a fault-blocked Tagari River (Figures 2) which has finally cut through and started draining the impounded water and mud. Getting there on the ground would be a major logistical exercise.

A satellite view in Figure 3 shows the same section of river at a smaller scale, the short fault segment, river blockage and offset quite clear. The strongly faulted terrain can be inferred.

Figure 3 Satellite image from Google Earth showing the 1km long fault offset along the Tagari River photographed from the helicopter in the previous figure.

The earthquake source was movement on a fault or, more probably, series of faults that failed under the unrelenting collision of the Australian and Pacific Plates, the former moving at about 7m per hundred years towards the NNE, the latter moving at 10m per hundred years towards the NW in the PNG region. A number of large shear-gouge fragments, sub-plates or continental fragments, separate the two plates in the Papua New Guinea region in this complex mega shear zone that has resulted from their collision over many millions of years. Koulali and others, 2015 summarise the kinematics in central and western Papua New Guinea.

Dow 1977, Craig and Warvakai 2009, Hill and others 2010, Davies 2012, and Holm and others, 2016 discuss the geology of the thrust belt through New Guinea. Thanks to their investigations, and dramatic topographic maps such as the Google map shown in Figure 4, the surface geology is reasonably well known but the underlying crustal structure of the Central Highland is largely unknown. The upper layer is the folded and faulted Darai Limestone in which the P-wave velocity is in the range 3.7 to 4km/s and its thickness 1.1 to 1.2km (Nelson and Turner, 2015). Craig and Warvakai (2009) quote a velocity of 4.6km/s. The depth to cratonic basement is not known but may be 3 to 7km in the vicinity of the earthquake. The depth to the Moho doesn't seem to have been measured or modelled.

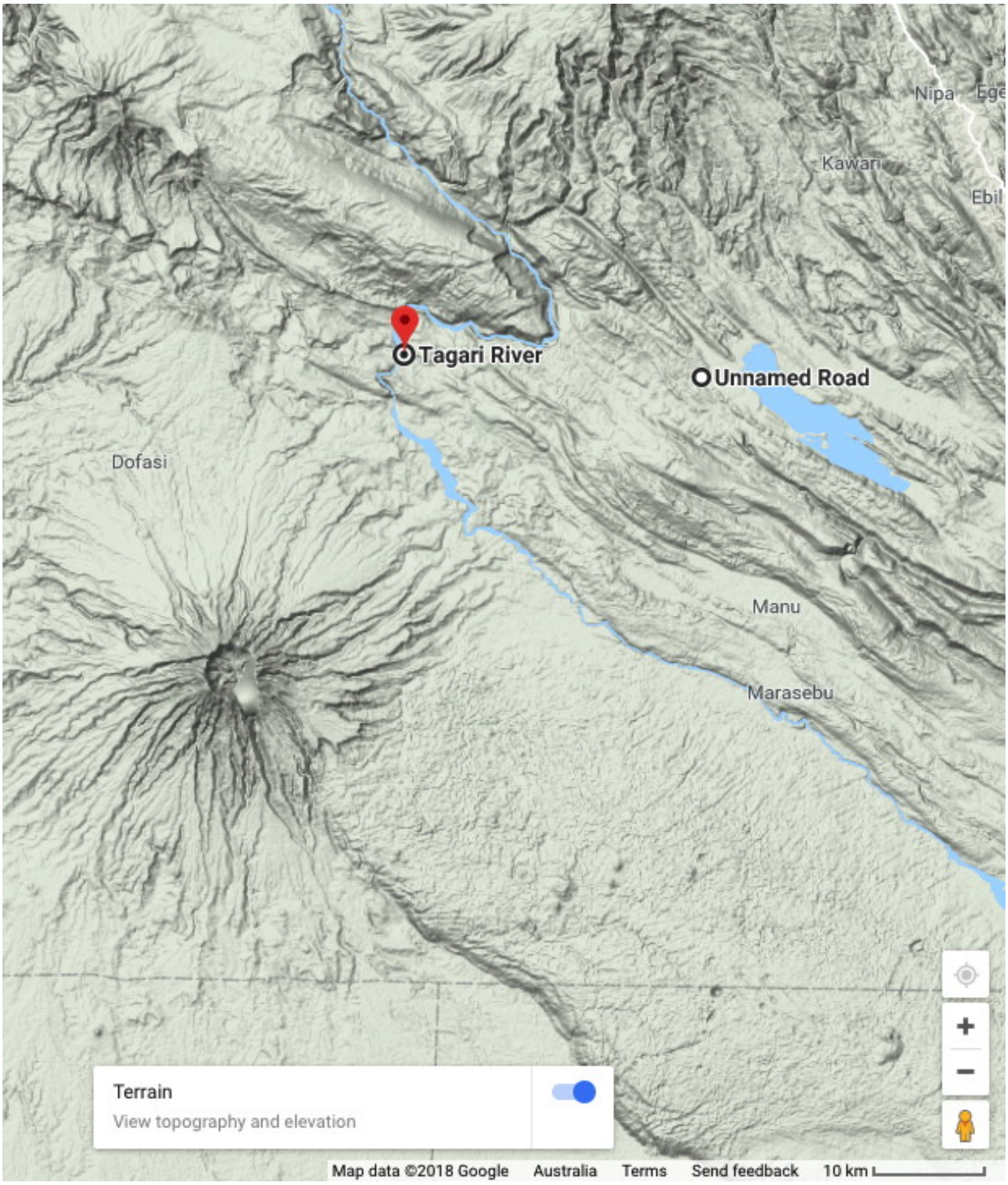

Figure 4 Google map showing the location of the fault-offset Tagari River, photographed and mapped in the previous 2 figures. The 'Unnamed Road' marker is at Moro Airfield and the flower structure southwest of Moro is the volcano Mount Bosavi.

CRUSTAL STRUCTURE

The long, continuous zone of shallow thrust-type earthquakes along the south side of the Central Highlands marks the northern boundary of the Australian Plate (Ripper and McCue, 1983). Wallace and others, 2004 and Koulali and others, 2015 also commented on the seismicity and plate geometry. A magnitude 7.5 earthquake occurred in the vicinity in 1922 followed by a magnitude 7 earthquake in 1954 (Everingham, 1974). On 25 June and 29 October 1976 major shallow magnitude 7 earthquakes occurred in Papua Province about 100km west of the border along the same earthquake zone. McCue (1981) reproduced aerial photographs taken by Mission Aviation Fellowship following the first earthquake. Loss of life, damage and landslides were on a similar scale to those in 2018.

The Central Highlands are being uplifted as a result of the collision of the Australian Plate to the South and the Pacific Plate to the north. The Highlands are underlain by thickened Australian continental crust. Consequently we tried a number of different Australian crustal models (Wilkie and Gibson, 1995) and finally adopted the Gippsland Victoria model as the one that gave the least standard error. Interestingly it has a 3km thick surficial low velocity layer comparable to the Darai Limestone duplex in the Lake Kutubu region near Moro.

With ongoing uplift of the Central Highlands the mountain root will deepen to attain isostatic equilibrium so the Moho is likely to be deeper than in Gippsland. We modified the model by increasing the Moho depth to 45km from 38km. None of the raypaths cross through the Moho in the hypocenter locations.

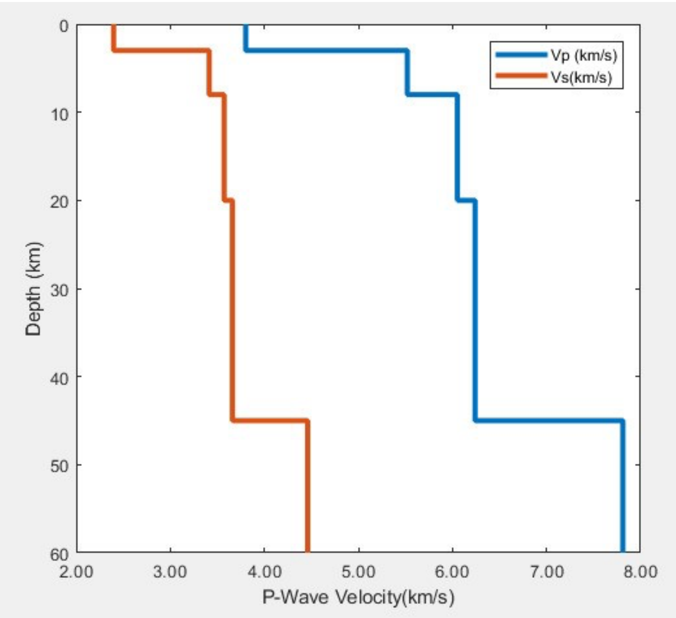

Figure 5 Modified Gippsland model, P and S velocities versus depth, used for aftershock locations (figure from Sinadinovski and others, this conference).

Earthquakes in Gippsland do not exhibit the same strong surface waves, Love waves, as have been observed on the accelerograms of shallow Central Highlands earthquakes so the model isn't perfect. Additionally the attenuation of shaking is much stronger in PNG than anywhere in Australia when felt areas are compared.

THE AFTERSHOCK STUDY

Seismology Research Centre staff in Melbourne assembled and tested six Gecko recorders and triaxial accelerographs http://www.src.com.au/seismographs-accelerographs-designed-by-seismologists/ to deploy above the aftershock zone to accurately locate aftershocks; their origin time, latitude, longitude and focal depth (point of initiation of rock rupture). Two deep-cycle 12V batteries powering each recorder were provided on site by Oil Search and were expected to last about 2 months.

The accelerographs were installed at Moro Airfield, Tari hospital, Nogoli, Mount Bosavi, Suabi and Ridge Camp, the Moro, Nogoli and Ridge Camp sites on Oil Search property. These are sensitive instruments powered by 12V batteries, with a GPS receiver so they have precisely the same timebase. We attempted to place an accelerograph at one of the three Mananga drill pads closer to the epicentral region but no secure housing could be found there. We opted instead to install the last recorder at Ridge Camp about 15km south of Moro where we were based.

Aftershocks were still being felt at the rate of one or two per day at the beginning of the deployment during the 19th – 23rd of March. The first 2 authors felt 3 or 4 small aftershocks over the week, a gentle rocking motion like those felt in Christchurch NZ in 2010 but unlike aftershocks at Tennant Ck NT or Eugowra NSW which were more shock like, a bang and rattle.

A site at Moro airport was the first installed, in a warehouse being used to temporarily house relief supplies, and even in this noisy environment aftershocks were being recorded at the rate of about ten per hour, most of them too small to be felt. We expected the aftershocks to get fewer and smaller and peter out over the following few months.

Figure 6 shows the mainshock-aftershock sequence with time, the red arrows show when the accelerograph deployment began and our data retrieval visit, fortunately capturing the last of the seven magnitude 6+ events. After the first 2 weeks the frequency of aftershocks has clearly diminished.

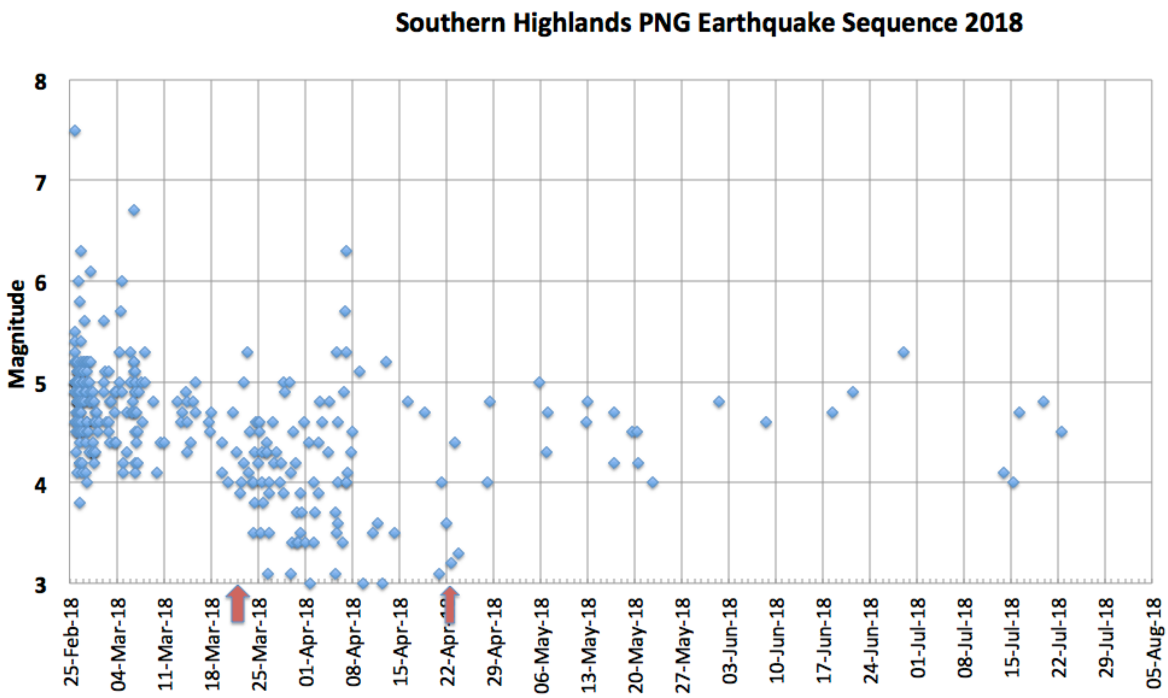

Figure 6 Mainshock date and aftershock progression with time, the numbers and size of earthquakes rapidly decreasing. The red arrows show times for which local network data are available.

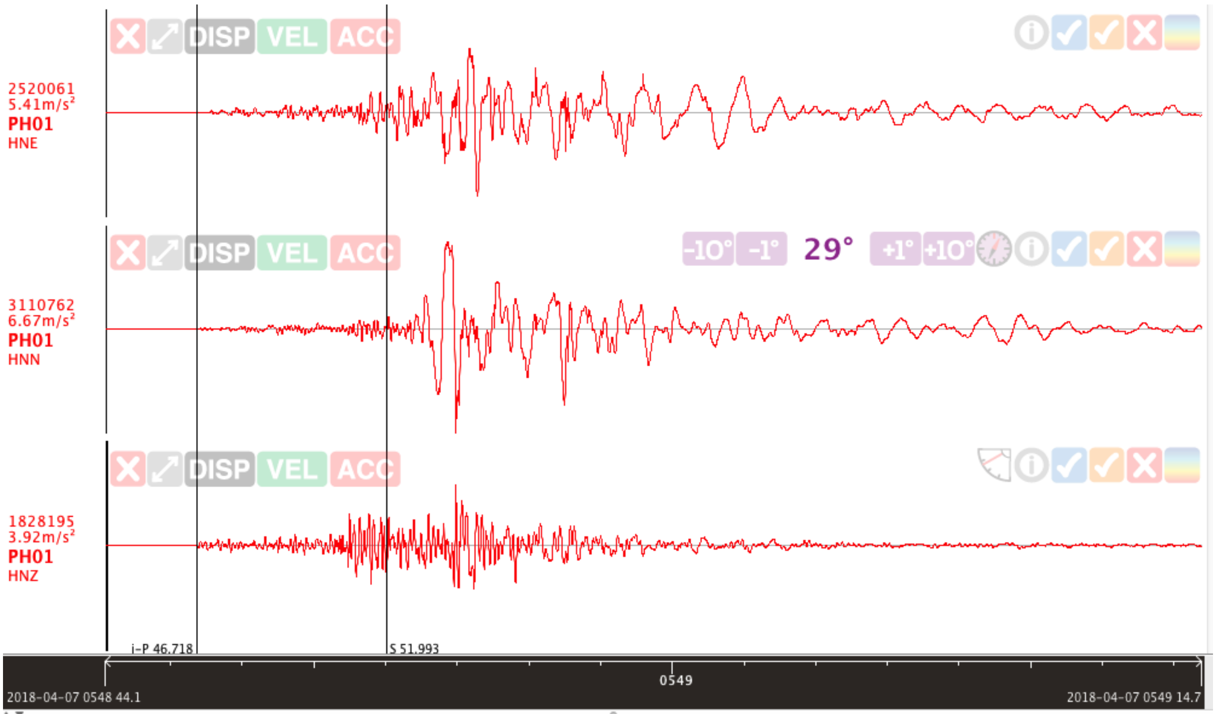

Figure 7 A record of the ground motion (acceleration) recorded at Tari Hospital during the large aftershock on 7 April 2018 but rotated 29° to the direction of maximum ground shaking (perpendicular to the strike of the faulting).

AFTERSHOCK LOCATIONS

There were apparently no foreshocks to the mainshock at 17:44UTC on 25 February (3:44am on 26th February local time). Aftershocks occur on the failed fault surfaces, their accurate location in 3 dimensions helps identify the faults, importantly their strike and dip. This can only be done using a network of seismographs strategically positioned above and around them. In this case the mainshock location was mapped using available worldwide seismograph network seismographs, the nearest stations 450 - 600km away in West Papua. Few of the PNG network data were available to USGS or Geoscience Australia. The critical focal depth was estimated variously at between 15 and 35km, hardly useful for answering some critical questions about the earthquake strong ground motion.

The aftershocks locations extend about 85km NNW and ESE from the epicentre along strike but their focal depths are uncertain, they form a cloud in the space between the surface and a depth of about 40km.

Figure 8 below shows the distribution of aftershocks recorded by the USGS in the first few weeks and the temporary aftershock recording stations. Suabi and Bosavi are on the Australian craton and the other 4 stations are on the thickened and uplifted ~3km thick fold belt sediments. The range-front fault is exposed by the topography north and east of Mt Bosavi the most prominent of several puzzling large shield volcanoes.

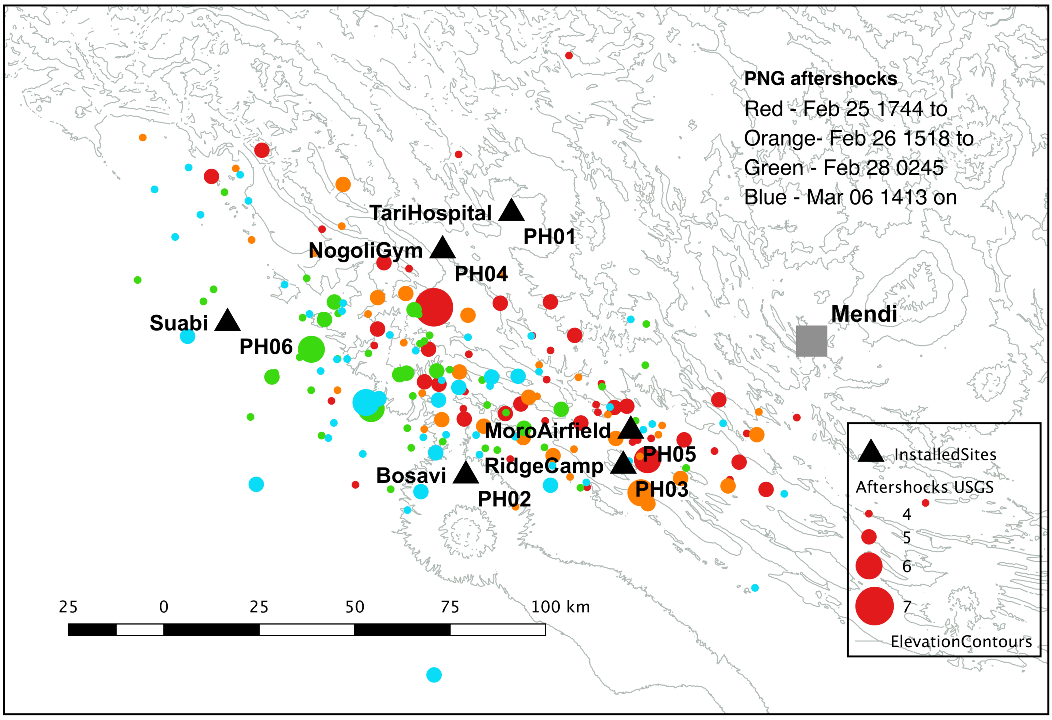

Figure 8 The aftershock monitoring stations (black triangles) plotted with the mainshock and early aftershocks (coloured dots, size proportional to magnitude) on a topographic map.

FOCAL DEPTH OF THE LARGE PNG AFTERSHOCK OF 7 APRIL 2018

Our reading of the P and S arrival times of the large aftershock on the 6 accelerographs yielded a focal depth of 24km using the modified Gippsland model.

Depth Phases Recorded Worldwide

Exploration drill holes and seismic reflection profiling expose a 3km deep layer consisting of thickened Darai Limestone overlying other lower velocity sediments but provide no information about the crustal layers below the sediments or the depth to Moho. There is obviously extensive layering based on the surface wave coda of all the earthquakes, much longer lasting and of higher amplitude than body waves P, or S, the latter hard to pick at times on the accelerograms.

To compare our computed focal depth with other measured values we examined waveforms of the earthquake at various regional distances from the USGS database to pick out depth phases pP and PcP. In the process, PcP was found to be insensitive to varying depths in the crust. pP, the P wave reflected from the surface of the crust above the focus is less ambiguous as it is the first of the subsequent phases after the original P wave arrival. It can only be confused with sP.

We also used a regional earthquake independently located by the USGS and clearly recorded on the accelerograph network to measure the upper mantle velocity Pn using the origin time from the USGS and the recorded time at Nogoli accelerograph station, as shown below.

Phase pP

Depth phase 2018 0407 at 0552 07.4			
	P	pP	pP-P (s)
CTAO	0552 07.05	0552 19.00	11.95
GUMO	0553 04.89	0553 17.90	13
WRAB	0552 22.07	0552 30.66	8.6
MBWA	0554 17.72	0554 28.15	10.4
PMG	0550 04.39		
average			11.0*

- corresponds to a focal depth of ~32km with the model we have used.

Phase PcP
Several stations such as Marble Bar show a characteristic PcP but the travel time is 10m 16.2s, about 1 minute longer than expected and the travel time is almost constant for all crustal depths so in this case it not a discriminating phase.

Phase Pn
We estimated the upper mantle velocity using travel times of a regional earthquake on 30 March 2018 at 0650 UTC. M 4.5 - 82km SSE of Angoram, Papua New Guinea.

The USGS solution using a global average model is:

Date and time 2018-03-30 at 06:50:03 (UTC)
Location 4.790°S 144.221°E
Depth 108.7 km.
The station gap was 62° and the nearest station MANU 4.2°, so the USGS epicentral location and computed focal depth are reasonably good (±10km).

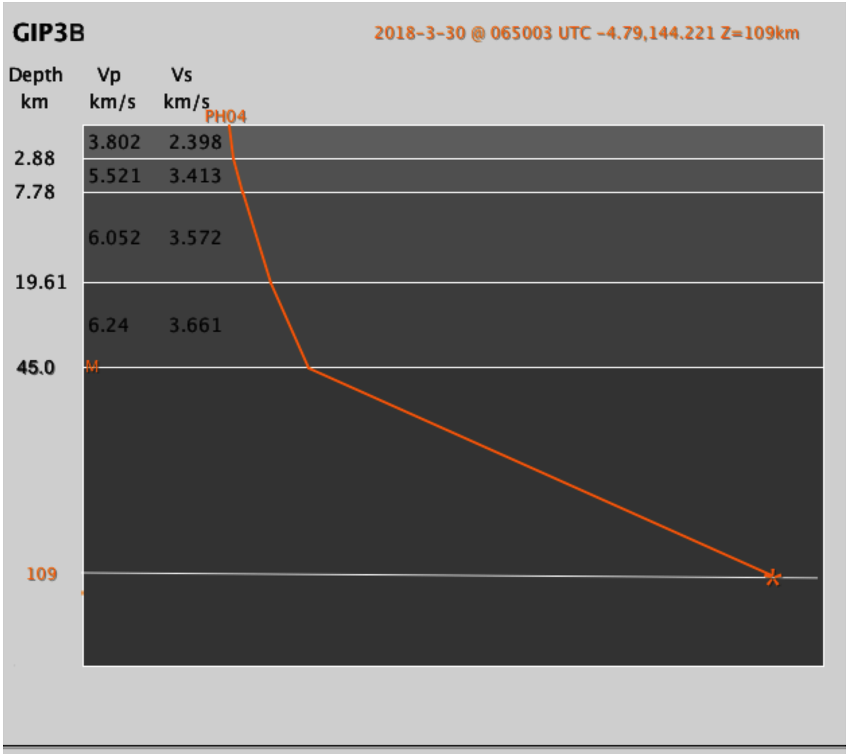

Figure 9 Model (not to scale) for checking the Moho velocity using the only regional earthquake well recorded at Nogoli (PH04) in the month of local recording, the focus more than 200km distant.

Table 1 P and S arrival times at the 6 temporary stations.

Station	Location		Altitude m	Distance km	P 0650	S 0650
PH01 Tari	142.950440°E	5.846570°S	1755	183.3	32.39	54.84
PH02 Bosavi	142.843064°E	6.464851°S	809	240.7	38.02	65.6
PH03 Ridge	143.213676°E	6.441845°S	1434	214.8	37.15	61.14
PH04 Nogoli	142.788324°E	5.934673°S	1344	203.4	35.03	60.85
PH05 Moro	143.231240°E	6.359247°S	940	206	35.81	61.27
PH06 Suabi	142.282045°E	6.105904°S	216	259.8	40.53	69.09

Using Snell's Law and a stepwise process with a steep final surface incidence angle (i=11° measured from the PH02 (Bosavi) record of the first motion of the regional earthquake on 30 March 2018), an upper mantle velocity of 7.8km/s was computed. The computed upper mantle velocity is quite sensitive to the velocity structure used in this procedure but this confirmed that the upper mantle P wave velocity is indeed similar to that in Gippsland, the velocity used in our model.

GROUND MOTION SPECTRA

The software package WAVES from SRC integrates the acceleration data into velocity and displacement waveforms, the velocity particularly useful for phase picking. It also plots Fourier spectra that are useful for picking the corner frequencies. In the case below in Figure 10 of the N29E component at Tari (PH01) the spectral amplitude is flat between 0.5s and 1.5s and drops off with higher frequency to the right and longer periods to the left. The flattening at long periods is probably due to strong surface waves.

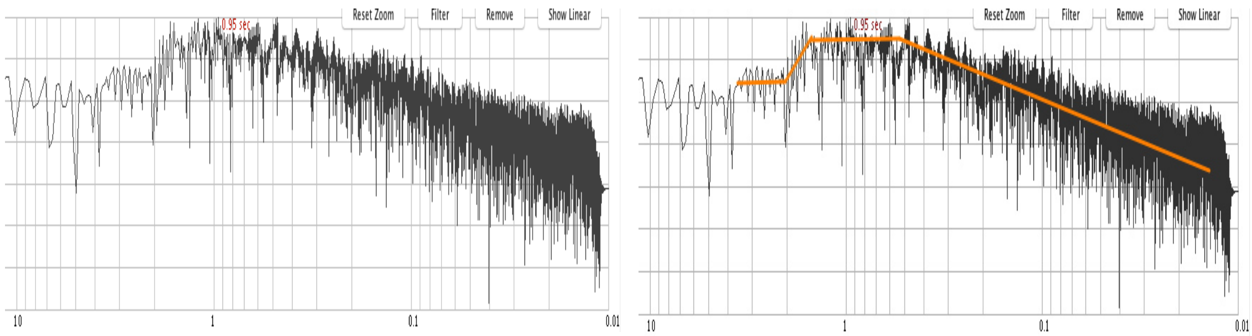

Figure 10 Fourier Spectra of the Tari Hospital ground acceleration time history, site PH01, the horizontal scale is period (sec), vertical is amplitude. Trend lines are added on the rhs figure.

The drop off at high frequency can be measured for comparison with the generally assumed value of -2.

DISCUSSION

We have used a proxy crustal model to locate aftershocks that occurred under the Central Highlands of PNG over a month from 19 March. No pattern in the aftershocks that might indicate a distinct fault system can be discerned, rather the whole region is being sheared, thickened and uplifted by crustal shortening as reflected in the geology. One of the few cases of active surface faulting was observed during an overflight by helicopter, on ground verification was impossible but a careful study of aerial photography using drones is bound to throw-up other cases that may be accessible on the ground.

In a separate tomographic study of the aftershocks (Sinadinovski and others this conference), 3D variations to the model have been explored with a view to revising the aftershock locations.

The records of the many aftershocks we have examined look alike, and are quite different from Australian earthquakes at the same distance. For one thing the dominant seismic wave frequency is lower in the Southern Highlands than at a typical Australian cratonic site, for another the first motions are invariably small and lastly some of the surface waves recorded in PNG are many times larger than the body waves. We know from a study of isoseismal maps of past earthquakes (Ripper and others, 1993 and 1996) and a study of the quality factor Q in SE Australia (Wilkie and Gibson, 1995) that the ground motion attenuation is much higher in PNG, the felt area being much smaller than for a similar sized earthquake in Australia. For example, the felt area of the magnitude 7.5 mainshock on 26 February is similar to the felt area of the Newcastle NSW earthquake of 28 December 1989, its magnitude being just 5.5. This is an important factor in assessing relative or absolute earthquake hazard and risk.

Focal depth is an important parameter for modeling structural response either with a time-history analysis or a design spectra so appropriate strong motion records are essential. Focal depth is the parameter with the highest uncertainty in locations using whole Earth models used by international seismological agencies USGS or ISC.

The recording of the near-field ground shaking at 6 stations from one major M7.5 earthquake is important but not sufficient for the Papua New Guinea Building Code e.g. Wyatt, (1964). A modern network of strong motion recorders should be deployed throughout PNG as recommended in a paper by Ghasemi in this conference.

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