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Tectonic interpretation of aftershock relocations in Eastern Papua New Guinea using teleseismic data and the Arrival Pattern method

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SUMMARY

The Arrival Pattern method and teleseismic data have been used to relocate aftershocks following three major (M_w >= 7.8) interplate earthquakes that occurred in eastern Papua New Guinea in November 2000. The first event was a M_w=8.0 strike-slip earthquake that ruptured the Weitin Fault over a length of ∼100 km. No aftershocks were located in the upper 15 km, suggesting that the accumulated strain was fully released in this event. The two subsequent M_W=7.8 thrust events occurred on the New Britain Trench. Wadati-Benioff zones dipping ∼20° define the locations of the thrust events at 152°E and 153°E on fault planes with strikes of 75° and 65°, respectively. The plot of aftershocks defines a complex seismic zone beneath New Ireland where events have occurred in the over-riding Pacific and South Bismarck Plates above the deeper zone of subduction of the Solomon Sea Plate. These events cluster in a broad zone to the northeast of the Weitin Fault rather than defining a linear feature that might have been expected following a near-vertical major strike-slip event.

Key words: Weitin Fault – aftershocks – Arrival Pattern method – Papua New Guinea – seismology.

1 INTRODUCTION

Papua New Guinea is one of the most tectonically complex and seismically active regions in the world. Trapped between the convergence of the Pacific and Australian Plates, it provides examples of almost every possible type of interplate tectonic boundary. The South Bismarck-Solomon Sea-Pacific Plate triple junction is a complex tectonic area that accommodates left-lateral strike slip motion between the South Bismarck and Pacific Plates (Taylor, 1979; Tregoning et al., 1998, 1999) and subduction of the Solomon Sea Plate on the New Britain and San Cristobal Trenches (Figure 1a). In addition, the subduction trench undergoes a 70° change in azimuth near the triple junction and the interaction of faults and trenches in this region is not known. For example, do the faults found in New Ireland join up with the subduction plate boundaries? Has the sharp change in azimuth of the subducting slab produced a tear (or tears) in the subducting slab?

Based on recent GPS results, relative motion between the South Bismarck and Pacific Plates is predicted to be ∼130 mm/yr left-lateral slip with ∼17 mm/yr convergence (Tregoning et al., 1999). Mapped faults in southern New Ireland include the Weitin Fault (Hamilton, 1979) - a strike-slip fault beneath the Weitin and Kamdaru river valleys - and the Sapom Fault that was thought to be part of the transform boundary (Johnson, 1979), although Mori (1989) suggested that aftershocks of the 1985 southern New Ireland earthquake showed that it was a thrust fault dipping 40° to 50° to the northeast. Passing beneath the surficial interaction of the South Bismarck and Pacific Plates lies the subducted Solomon Sea Plate, clearly imaged in seismic tomography (Hall & Spakman, 2002; Tregoning and Gorbatov, 2004) and with a well-defined Wadati-Benioff zone of seismicity extending down to 400 km (e.g. Denham, 1969; Pascal, 1979)

Accurate earthquake locations could potentially reveal some of the tectonic features of the Papua New Guinea region, although the epicentres in available global seismicity catalogues are not accurate enough to provide sufficient resolution. For this reason, we used the Arrival Pattern method (Nicholson et al., 2002) and multiple phases, not routinely used in solutions of other catalogues, to improve the accuracy of aftershocks following three major earthquakes in November 2000.

The interpretation of aftershocks to investigate the dynamics of seismic events is a technique that has been used to great advantage. In particular, aftershocks can provide information that leads to the identification of fault rupture planes, thereby permitting the focal mechanisms of events to be determined (e.g. Stein & Lisowski, 1983; Hauksson & Jones, 1991; Beroza & Zoback, 1993). Most studies of aftershocks rely principally upon seismic data recorded on local networks, usually installed immediately after a major seismic event. However, when no local seismic network data have been collected, aftershocks can only be relocated using teleseismic data recorded by global networks. Despite the high frequency of large earthquakes in Papua New Guinea (4 to 20 events of M_w >6 each year since 1976), there are rarely rapid deployments of local seismic networks to record aftershock patterns. In fact, the only known studies that used seismic data from temporary deployments of seismometers were studies of the Rabaul volcanic zone (e.g. Mori & McKee, 1987; Finlayson et al., 2003) (not a post-seismic response), a study of aftershocks following the 1985 New Ireland earthquake (Mori, 1989), a microseismic study of the Lae Seismic Zone (Kulig et al., 1993) (not a post-seismic response), and a study of aftershocks of the 1998 Sissano earthquake (Hurukawa et al., 2003).

2 NOVEMBER 2000 EARTHQUAKE SEQUENCE

On 16 November, 2000, a M_w=8.0 earthquake occurred in eastern Papua New Guinea near the boundary between the South Bismarck and Pacific Plates (Figure 1). This earthquake (hereinafter called Event 1) was followed ∼4 hours later by a M_w=7.8 thrust earthquake (Event 2) on the New Britain Trench to the south of New Ireland, the inter-plate subduction zone between the South Bismarck/Pacific and Solomon Sea Plates. Thirty one hours later another M_w=7.8 thrust event occurred (Event 3), again on the New Britain Trench but ∼100 km further west. Aftershocks and subsequent earthquakes continued for several months, with 1400 events of magnitude > 3 occurring in the next 6 months. Surficial ruptures (in the form of offset vehicule tracks) were found along the mapped strike of the Weitin Fault (Finlayson et al., 2003; Itikarai & Tregoning, 2004).

Seismic instruments at the Rabaul Volcano Observatory saturated on each of the three main events (I. Itikarai, pers. comm.); the only other seismometers in Papua New Guinea that recorded the events were located at least 400 km away and are included in the teleseismic observation data set. No local seismic network was subsequently installed in southern New Ireland to record the pattern of aftershocks; therefore, the only seismic data that are available to locate the earthquakes are global teleseismic data and phase arrivals recorded by RVO seismometers that captured the smaller events. While the local data may assist in estimating event locations, the data are not publically available and the events occurred outside the geographical coverage of the local array. Furthermore, the array sits above a low-velocity caldera which may introduce systematic errors in locations. In this study we make use of only global teleseismic data to locate the aftershocks.

3 TELESEISMIC DATA AND EVENT LOCATIONS

Algorithms used to relocate aftershocks are commonly written for the cases where data from local seismic networks are available [e.g. HYPODD (Waldhauser & Ellsworth, 2000)] and are unsuitable for hypocentre locations using teleseismic data recorded at distant stations. An exception is the Joint Hypocenter Determination (JHD) method (Dewey, 1971, 1983) in which one event is designated a 'master' event and the locations of other events are calculated relative to this master event. This technique has been used successfully in studies of large earthquakes [e.g. the 2000 Wharton Basin earthquake (Robinson et al., 2001), the 1996 Biak earthquake (Henry & Das, 2002), the 1998 Antarctic Plate earthquake (Henry et al., 2000)]. The limitation of using a master event is that errors in its location will map directly into the values of all events calculated relative to it.

The tectonic interpretations that can be made using event locations by the Harvard Central Moment Teonsor (CMT) (e.g. Diewonski & Woodhouse, 1983), International Seismological Centre (ISC, 2001) and National Earthquake Information Center (NEIC) catalogues are limited in Papua New Guinea by the fact that the depths of the events are often fixed when tradeoffs with origin time cannot be resolved (Aki & Richards, 1980). The NEIC locations show horizontally striated patterns (that do not match any likely tectonic regime) with little depth-dependent structure (Figure 2a). The hypocentres of the ISC catalogue (Figure 2b) show some depth resolution but there are no clear tectonic features highlighted by the aftershock patterns. There are insufficient earthquakes in the Harvard CMT catalogue (magnitudes >5) to identify any tectonic features.

The NEIC fast moment tensor solution for Event 1 (shown in Figure 1b) shows that the rupture initiated to the northeast of Rabaul. If one extends the fault rupture from the epicentre using the azimuth of the fault plane from the original NEIC focal mechanism (strike=134°, dip=87°, rake=26°) then the rupture passes between the Weitin and Sapom Faults. A subsequent NEIC focal mechanism solution (shown in blue in Figure 1b) is that of a normal fault (strike=126°, dip=82°, rake=79°) and does not match the local tectonic setting.

There is no consensus on the nature of the mapped faults in Southern New Ireland. Mori (1989) concluded from an aftershock sequence in 1985 that the Sapom Fault was a thrust fault that accommodated convergence between the South Bismarck and Pacific Plates. From relocations of Event 1 and earthquakes before and after 16 November 2000, Rham & Das (2003) concluded that the Sapom Fault had ruptured with pure left-lateral strike slip on a vertical fault plane. Clearly, accurate 'absolute' event locations could provide valuable evidence to aid in the identification of the locations of the active faults in the region.

Two types of database information are used in the following sections: arrival times of seismic waves and hypocentre locations. For clarity, below we refer to assemblages of arrival time observations as "observation catalogues" and suites of hypocentre coordinates as "event catalogues", with the particular catalogue referred to by name. The catalogues used include the Harvard CMT event catalogue (e.g. Diewonski & Woodhouse, 1983), the ISC observation and event catalogues (ISC, 2001), the NEIC observation and event catalogues (accessible through the web site at http://neic.usgs.gov/neis/tours/neic_bulletins.html) and the EHB observation and event catalogues (Engdahl et al., 1998) - where the EHB observations are the same as the ISC observations but the hypocentres have been estimated in a process that included additional phases.

4 ARRIVAL PATTERN METHOD

With the recently developed Arrival Pattern method (Nicholson et al., 2002) one compares phase arrival times of a new event with those of previous events whose positions are assumed to be known (see below) and, by interpolation of a misfit function based on these comparisons, estimates the location of the new event. Effectively, travel times predicted by an Earth model are replaced by an ensemble of observation times from previous events (although it is recognised that the locations of the previous events have been estimated using travel times predicted by an Earth model; therefore the Arrival Pattern method is not completely "free" of an Earth model). The closer a new event lies to a previous event, the smaller will be the differences in the phase arrival times at any particular station for the same phases; hence the misfit function will be smaller near that event. The solutions are dependent upon the accuracy of the event locations in the database, although the random errors in the estimates of new locations are smaller by a factor of two than those associated with the hypocentres contained in the database of previous events. That is, the median new location error is about 50% of the median database error (Nicholson et al., 2002). Therefore, one can estimate locations of new events with greater accuracy than the accuracies of the events contained in the catalogue. One limitation of the Arrival Pattern method is that it interpolates (and cannot extrapolate) the misfit function at the previous events; therefore, the new event must be contained within the geographical region covered by previous events with matching phases.

It is difficult to assess statistically the uncertainties of the estimated event locations using the AP method because of the complex nature of random and systematic errors affecting seismic observations. Nicholson et al. (2002) addressed this issue to some extent by using Monte Carlo procedures (ibid) for many events in many different regions, and concluded that the likely 95% confidence ellipse lay approximately at the 2 second contour around the event (about 10 km). It is not feasible to perform Monte Carlo simulations for every one of the 1400 aftershocks that occurred; therefore, we assume that the conclusions of Nicholson et al. (2002) are valid here as well. Another means of assessing the accuracy of the solutions is by looking at the resolution of tectonic structures evidenced by the aftershock locations. While such an assessment can only be subjective, the results shown below demonstrate clearly that the event locations from the AP analysis reveal more structure than do other location sets. No clustering algorithms have been employed to generate the suite of event locations; rather, each individual aftershock epicentre and depth has been estimated independently.

We used arrival times from the NEIC catalogue and locations of previous events from the EHB catalogue to relocate the events after 16 November 2000. An event that has observations in common with many catalogue events and is surrounded geographically by the catalogue events is more likely to be located accurately than one that lies on the edge of the catalogue events or, even worse, lies outside the catalogue events. Furthermore, one can have greater confidence in a solution if there is a clear decrease in the misfit function at each of the catalogue events as one moves towards the solution location. That is, if there is a clear 'bullseye' pattern of the misfit function.

Below, we describe modifications that we implemented in the original algorithm of Nicholson et al. (2002).

4.1 Phase Selection

Both the Engdahl catalogue of observations and the NEIC observations of aftershocks are heavily dominated by P-wave arrival times, with only ~10% of observations being for other phases. It is well known that the use of the arrival times of some of the additional phases (e.g. pP) significantly improve the accuracy of depth estimates; therefore, we chose to relocate only events that contained at least one additional phase observation recorded by at least one station in addition to the P-wave arrival times. We used additional phase observations of type S, Pn, Sn, pP, PcP, PKPbc, PKPab and weighted the observations as described by Nicholson et al. (2004, Table 1).

Figure 3 shows the locations of aftershocks using various selections of arrival phases, starting with only P-phases. Very few pP arrivals were recorded at the teleseismic stations; therefore, fewer events were located using only pP and P-wave arrivals (Figure 3b). The inclusion of S-wave arrivals (Figure 3c) highlights clearly a zone of seismicity dipping to the north at ~20°. Also, there appears to be another zone of seismicity further north and above the Wadati-Benioff zone. This is discussed further in Section 6.

The inclusion of yet more phases does not alter significantly the resulting pattern of seismicity (compare Figure 2c computed with 7 additional phases with Figure 3d where only 4 additional phases were used). In general, P-wave observations form 53% of the total with Pn (16%) and S (10%) being the most prevalent other phases.

4.2 Detecting pP Observation Outliers

It is critical that the phase arrivals used in the AP solutions are accurate and that there are no misidentification errors. Any such errors propagate directly into the calculated misfit function and will affect the accuracy of the new event location. There are many pP phase arrivals in both the EHB and the NEIC observation catalogues that are inconsistent with the EHB hypocentre solutions and other pP phase observations. We concluded that some of the pP arrival times were in error and devised simple filters to remove outlier observations. It is beyond the scope of this paper to investigate the causes of these errors.

Given the arrival times of both the P-wave and the pP phase at a particular teleseismic station and the distance from the station to the event, it is possible to calculate the depth of the event by interpolating predicted arrival delays based on some Earth model (we used AK135). We calculate the depth derived from this calculation, $Depth_{pP-P}$, for each station where the pP arrival time was recorded, thereby producing multiple, independent estimates of the depth of events. It was quite common for depths for a single event calculated in this manner to differ significantly from station to station, with the depth differing by up to 50 km from the quoted hypocentre depth in the catalogue (Figure 4). We found that when the depth estimates of $Depth_{pP-P}$ from all stations had a standard deviation of less than 5 km, the depth estimates from each station were within 10 km of the hypocentre depth, indicating consistency between observations and the final location estimate.

We imposed a set of criteria on the observations to eliminate the erroneous pP arrival times in observations of both new and catalogue events. We used only pP arrival times when at least two seismic stations recorded this secondary phase and the $Depth_{pP-P}$ estimate for each individual station was within 10 km of the hypocentre depth. The pP observations that met these criteria were considered the most 'reliable' observations and were subsequently used in the relocations.

4.3 Selection of Catalogue Events

The selection of the catalogue events can be made according to several criteria. For example, one could make a selection based on geographical proximity or on magnitude, starting with either highest or lowest magnitude events. Our results were generated using up to 400 catalogue events, with the selection based on magnitude starting with the largest events (in fact, selecting the catalogue events with/without a criterion on the magnitude of the events made little difference to the resulting solutions). We relocated only new events with at least 10 matching catalogue events within 400 km of the a priori location (the NEIC estimated location).

4.4 Quality of Arrival Pattern Solution

Finally, we viewed the solution of each of the relocated events and assessed the pattern of the misfit at the catalogue events. Recall that all events are treated separately with no cluster algorithms employed and no bias towards clustering of events on anticipated tectonic structures. Only new events with a well-defined misfit pattern showing a clear local minimum were considered as being 'reliable' relocated events (e.g. Figure 5a). Events with sparse observations and no clear 'bullseye' pattern were considered unreliable and were rejected (e.g. Figure 5b). This is a subjective process; however, given that each event was assessed independently and accepted or rejected without any consideration of its actual location, this approach seems reasonable for removing poorly located events without biasing the result. 1006 of the 1400 events passed this assessment criterion and are shown in Figure 2c. Only these events and their corresponding solutions from other event catalogues were used when comparing solutions and to interpret the tectonic setting.

The locations estimated with the AP approach and only P-wave observations (Figure 3a) show a tighter clustering of epicentres than either the NEIC (Figure 2a) or ISC events (Figure 2b). Figure 6a shows a histogram of changes in locations (epicentre and depth) between the P-wave only locations and the ISC locations (we didn't compute the comparison for the NEIC solutions because there are so few events with estimated depths). The locations of around 75% of events were changed by more than 10 km in both depth and epicentre. This may be indicative of the location errors of events in this region in the ISC (and other similar) catalogues derived from only P-wave arrival times, although this can only be verified by performing similar comparisons with datasets from either different time periods or nearby areas.

The use of the additional 7 additional phases further refined the AP locations and the histogram of changes is shown in Figure 6b. About 40% of epicentres and only ~20% of depths were changed significantly between Arrival Pattern solutions using only P-wave and P-wave plus additional phases, with the remainder shifting by less than our expected uncertainty of event location (~10 km, 2σ). We consider the solutions derived using additional phases to be our 'best' estimates of the epicentres and depths of the aftershocks and it is these locations (Figure 2c) that we use in the tectonic interpretations below.

The total set of relocated events (including events not shown here within the Solomon Sea Plate and along the San Cristobal Trench) can be viewed interactively in three-dimensions over the internet (see http://rses.anu.edu.au/geodynamics/gps/NI_eq/png_ap.html).

5 GPS OBSERVATIONS

A regional GPS network had been observed on a sporadic basis since 1998 to monitor deformation across the boundary between the Pacific and South Bismarck Plates (Tregoning et al., 2000). Re-observations of some of these sites commenced on 18 November, 2000. Only four GPS sites, all located near Rabaul on the nearby volcanoes, were recording during the three major earthquakes and for the first two day afterwards. The GPS data were analysed using the GAMIT/GLOBK software (King & Bock, 2002; Herring, 2002) utilising data from local and global tracking stations. We calculated site displacements of two sites on the southern coast of New Ireland (shown in Figure 1b) from the difference in ITRF2000 coordinates from the last measurement before Event 1 (August 2000) and the first occupation after Event 3 (December 2000). The reobservations were made after the three major events and after several days of post-seismic relaxation had occurred; hence the displacements are the sum of three co-seismic offsets and possibly three post-seismic relaxation effects. Because of the magnitudes of the displacements (up to 5 m), a careful analysis of the geodetic data is not necessary for estimating the first-order surface deformations caused by the earthquakes and, for simplicity, we ignore any possible second-order post-seismic creep.

Our preliminary results show that Event 1 occurred on the Weitin Fault (rather than the Sapom Fault) with relative left-lateral shear of up to 8 m occurring between two GPS sites separated by < 13 km (Figure 1b). The site northeast of the Weitin Fault uplifted ~18 cm, while the site to the southwest subsided ~26 cm. An analysis and interpretation of the GPS dataset is currently being prepared, including the separation of the effects of the three major earthquakes and numerical values of the co- and post-seismic deformations. Here we present only two critical displacement vectors to demonstrate that Event 1 ruptured the Weitin Fault and not the Sapom Fault.

6 DISCUSSION

The Arrival Pattern algorithm does not force any clustering on the hypocentre estimates yet the events are more clustered than the same events in other catalogues. In this particular tectonic setting, it is reasonable to expect that the events would have occurred on (or very close to) the plate boundary interfaces. We interpret the enhanced clustering of the events as indicating that our estimates of hypocentre locations are more accurate.

A significant number (~85%) of the aftershocks occurred on the New Britain Trench and define a clear Wadati-Benioff zone associated with the subducting Solomon Sea Plate slab. Most of the events for which there are CMT focal mechanisms lie in this zone and are thrust-type events, consistent with interplate subduction earthquakes. Coulomb stress failure calculations show that the southward displacement of the over-riding South Bismarck Plate caused by Event 1 increased the shear stress on the nearby subduction zone, initiating the subsequent thrust events (Park & Mori, 2003). Aftershocks occurred to a depth of 230 km.

The dip angle of the subducting Solomon Sea Plate slab has been characterised previously to be ~20° to a depth of 60 km, beyond which it steepens to 70°-75° (Cooper & Taylor, 1987). The aftershocks near 152°E support this earlier conclusion; however, further east it is possible that the dip of the slab becomes shallower as it approaches the 70° change in azimuth of the trench (Figure 7) (given the complex nature of the geometry of these tectonic features, it is extremely difficult to portray in two-dimensional figures. A rotating, 3-dimensional image of the aftershock locations can be viewed at http://rses.anu.edu.au/geodynamics/gps/NI_eq/Nov00.html). The deeper earthquakes near 153°E may have occurred on either the northwest- or northeast-dipping segments of the slab which may account for the apparent 'smearing' of the events over a broad zone (Figure 7a) rather than defining a sharp, linear descending slab as seen further west (Figure 7b).

One result of our relocation of events was that, while some events located on the subducting slab are shallow, no events are found in the top 20 km of the lithosphere along the Weitin Fault. Indeed, nearly all the events geographically located in southern New Ireland appear to be related to the subduction process or to have occurred above the subduction interface but at depths greater than 20 km. The majority of the aftershocks in New Ireland that are located above the subduction zone do not lie beneath the Sapom Fault but are clustered to the east of the Weitin Fault; however, they do not define a linear zone of seismicity as might be expected following a near-vertical strike-slip event (Figure 8, see also a rotating figure at http://rses.anu.edu.au/geodynamics/gps/NI_eq/weit.html).

The shallow rupture of the Weitin Fault may have reactivated many smaller faults and older subduction-related fractures (Mori, 1989) in the upper plates. Aftershocks following the M_w=8.0 event do not provide clear information about the locations of the major features and cannot be used to confirm definitively whether the Weitin Fault or Sapom Fault ruptured. However, GPS co-seismic displacements (Figure 1b) and observed surface offsets (Finlayson et al., 2003; Itikarai & Tregoning, 2004) do provide conclusive evidence that the strike-slip event occurred on the Weitin Fault.

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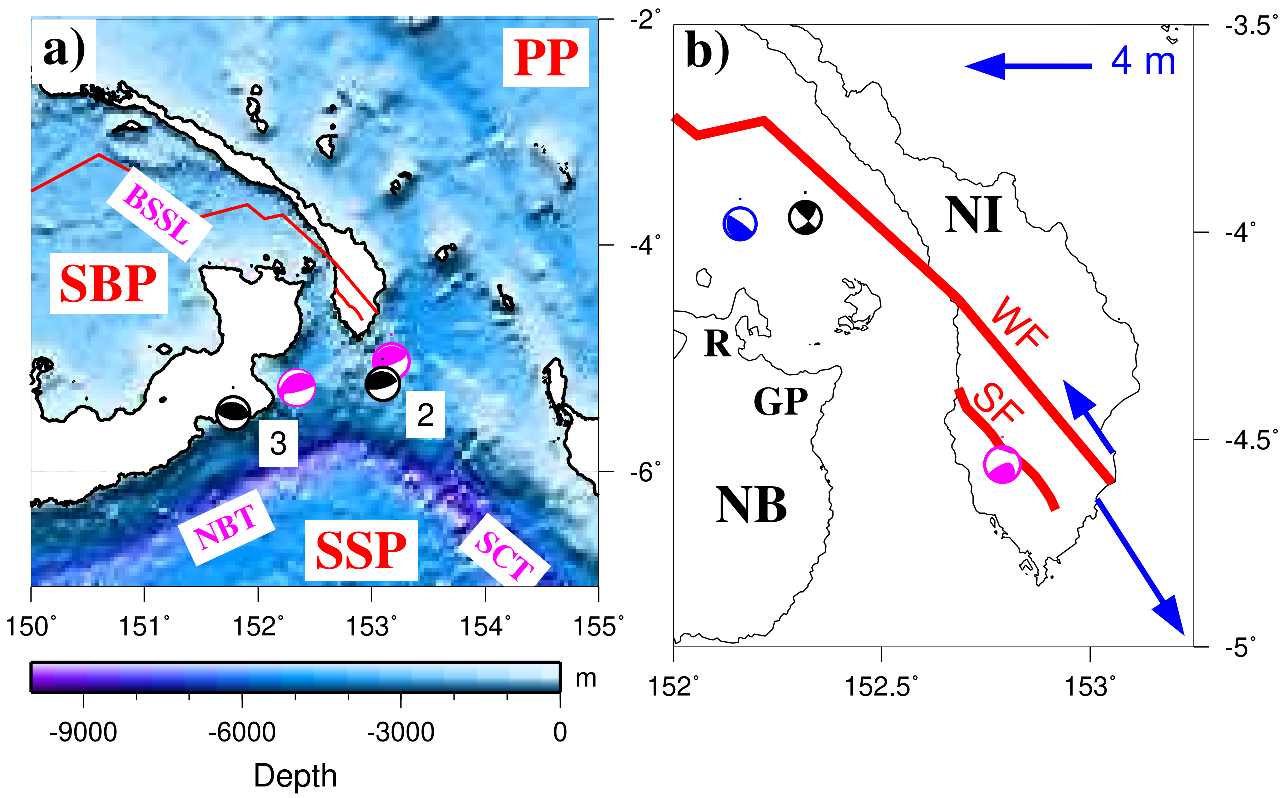

Figure 1. a) Map of eastern Papua New Guinea showing the bathymetry and tectonic boundaries. Focal mechanisms of NEIC (black) and Harvard CMT (pink) are shown for the M_w=7.8 thrust events that occurred on November 16 (labelled "2") and November 17 (labelled "3"), 2000. b) Focal mechanisms for the M_w=8.0 left-lateral event of November 16, 2000. GPS co-seismic displacements measured at the two monitoring sites closest to the Weitin Fault are plotted as arrows. Note that the observed co-seismic displacement includes the possible displacements caused by the two major thrust events as well as the left-lateral rupture of the Weitin Fault. The revised NEIC focal mechanism is plotted in blue. BSSL: Bismarck Sea Seismic Lineation; GP: Gazelle Peninsula; NB: New Britain NBT: New Britain Trench; NI: New Ireland; PP: Pacific Plate; R: Rabaul; SBP: South Bismarck Plate; SCT: San Cristobal Trench; SF: Sapom Fault; SSP: Solomon Sea Plate; WF: Weitin Fault.

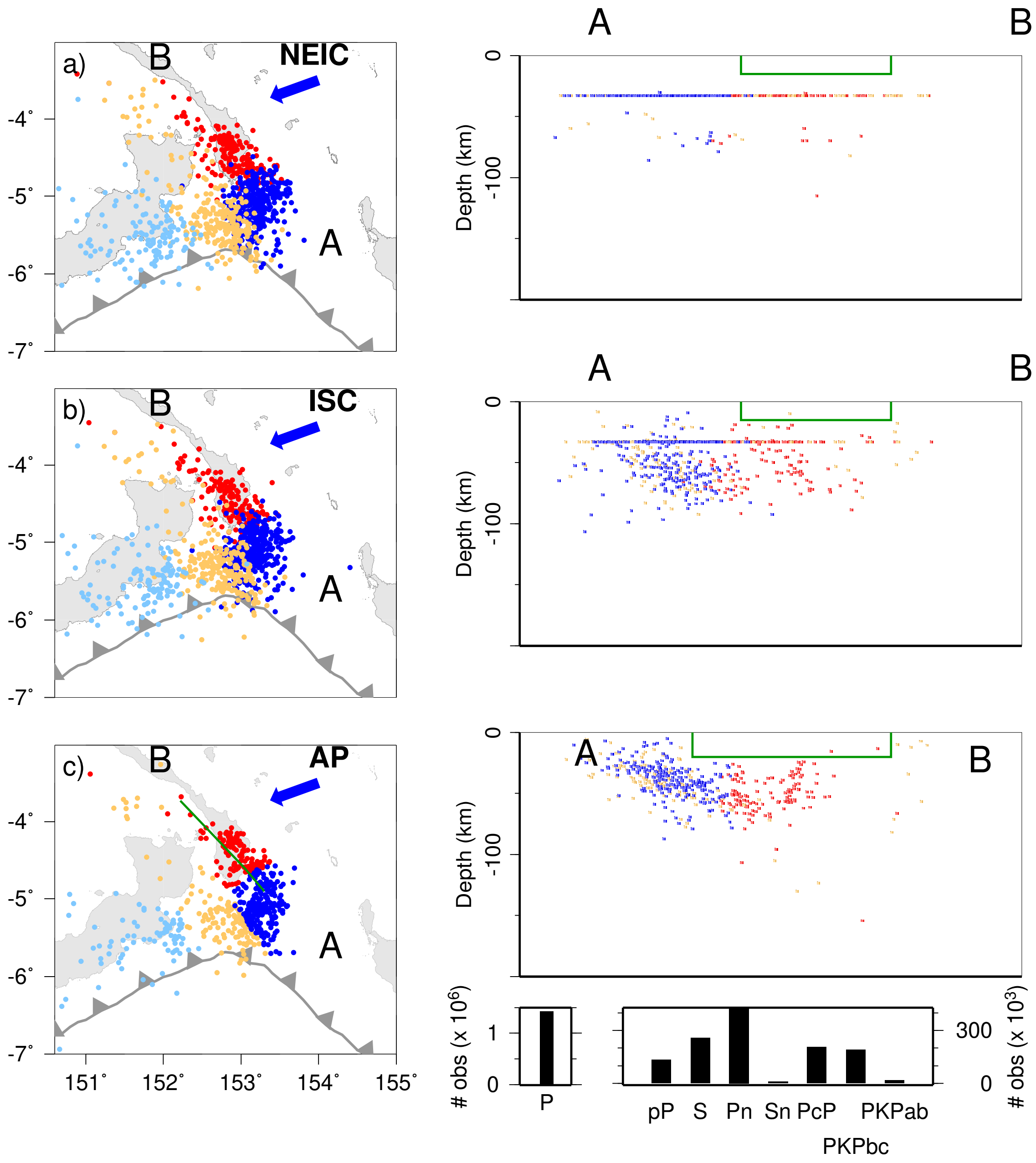

Figure 2. Epicentres of earthquakes from 16 November 2000 to 31 May 2001 from (a) NEIC, (b) ISC catalogues and (c) estimates using the Arrival Pattern (AP) method (P-wave plus 7 additional phases). Only the events deemed 'well resolved' in the AP method have been plotted, and only the locations of the corresponding events from the other two sources. Colour coding of events correspond to differing geographical regions, with arbitrary boundaries of colour-coded zones shown for the AP events: events near the Weitin Fault (red), events near the New Britain Trench (mustard), events near both features (blue) and events further west associated with the second thrust event (light blue). Cross-sections show events projected onto plane A-B when viewed in the direction of the arrow. The total number of phase observations used in the AP solutions are shown. Events shown contain observations of at least one (but not necessarily all) of the additional phases listed. The location of the Weitin Fault is plotted indicitively in green as a rectangle to a depth of 20 km. No vertical exaggeration.

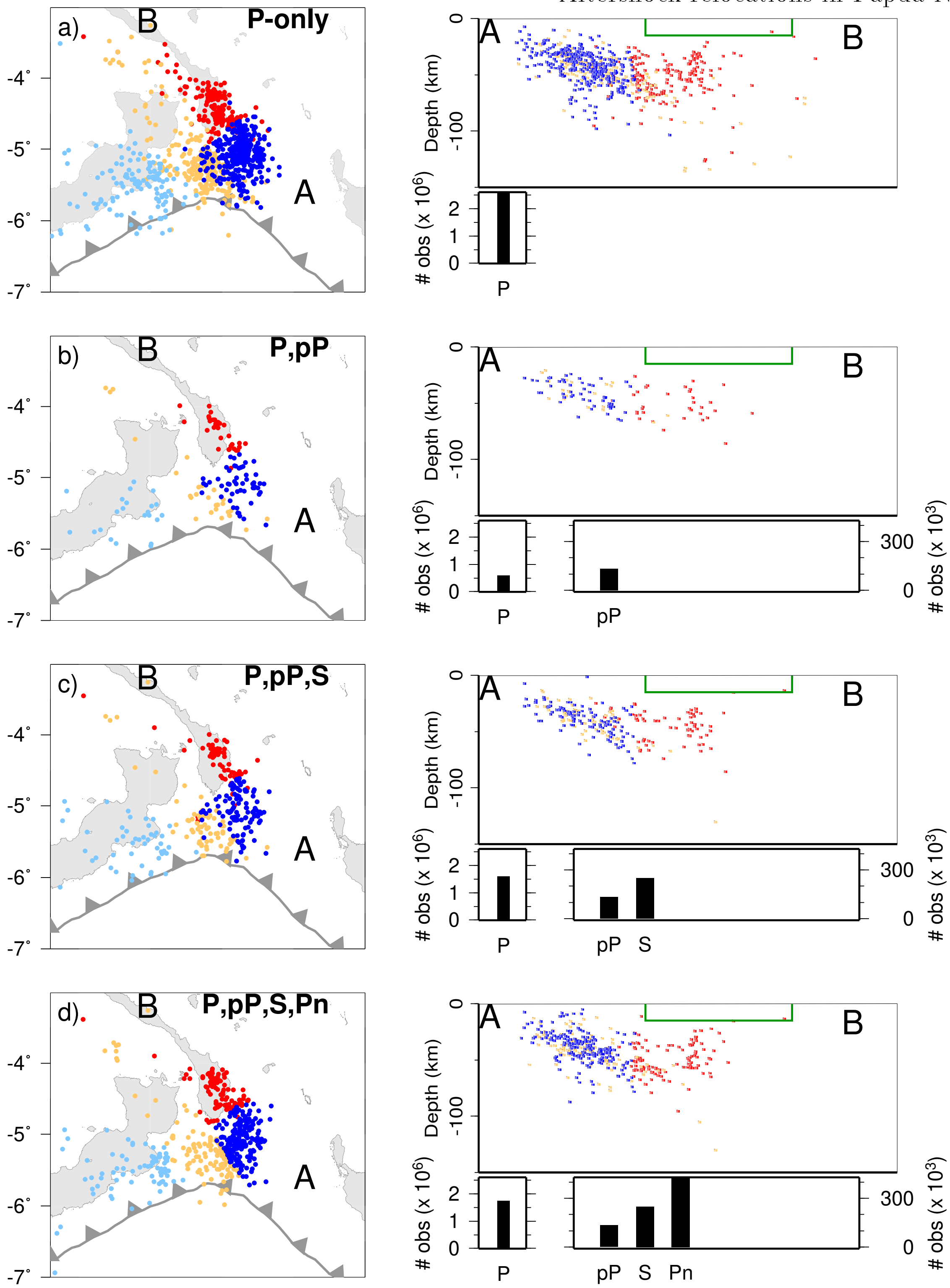

Figure 3. Epicentres and cross-sections using different combinations of additional phases. (a) P-wave only. (b) P and pP. (a) P, pP and S. (a) P, pP, S and Pn. Colour-coding is the same as for Figure 2. No vertical exaggeration.

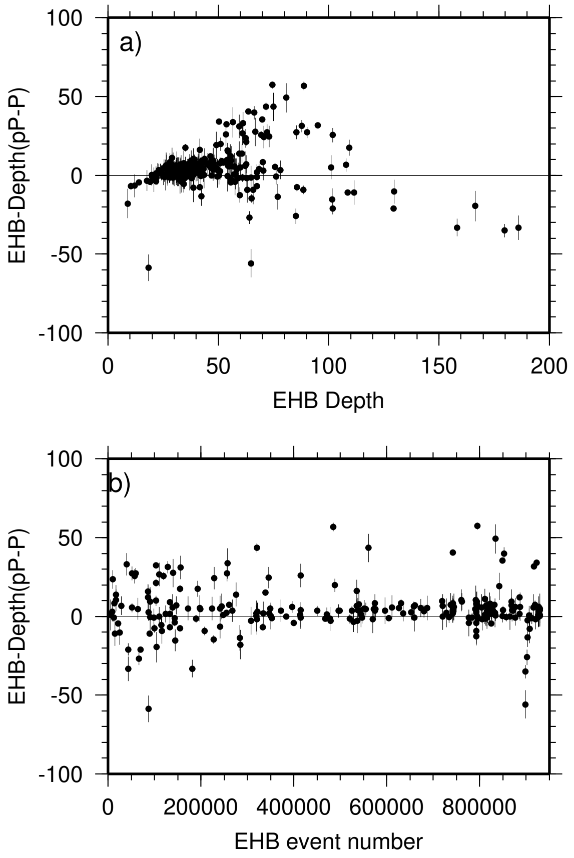

Figure 4. Differences in the EHB catalogue depths of events and those calculated from pP-P arrival times a) as a function of depth ; b) as a function of time. Event #1 occurred in 1964 while the last event in the catalogue occurred on 31 August, 1999. 2σ uncertainties are plotted on the difference estimates as calculated from the scatter of the $Depth_{pP-P}$ values.

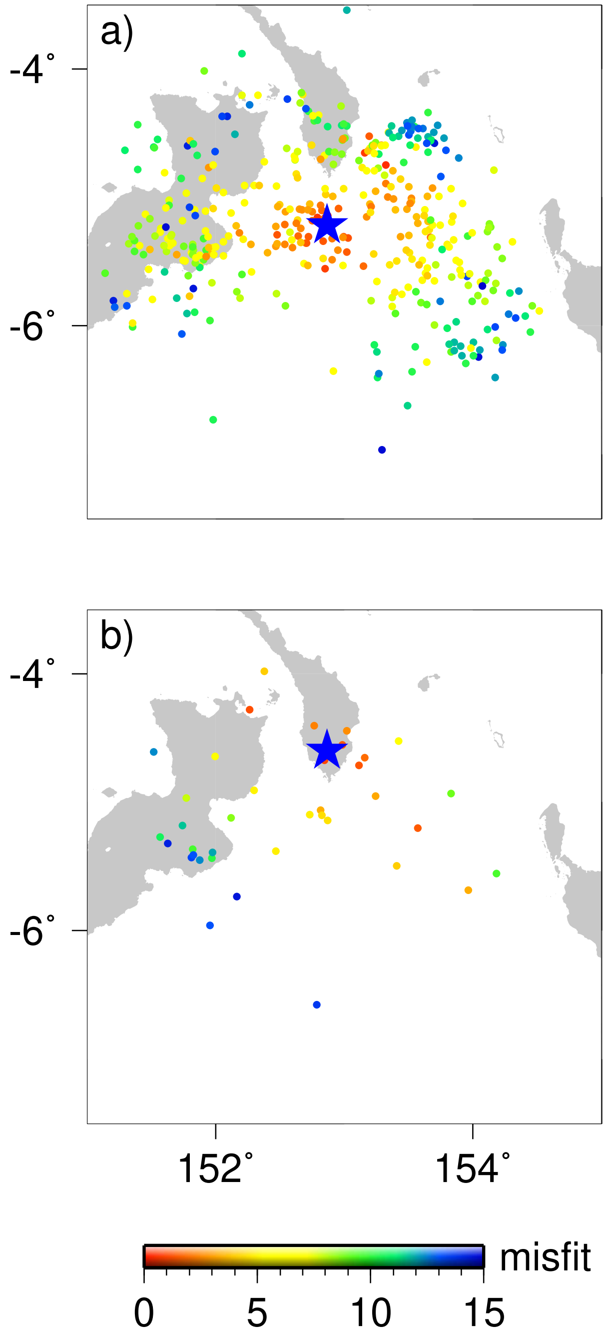

Figure 5. Examples of Arrival Pattern estimates of hypocentres: a) well determined. b) poorly determined. EHB catalogue earthquakes used in the solution are colour-coded by their misfit values from high (blue) through to low values (red). The AP hypocentre estimate is indicated by a star.

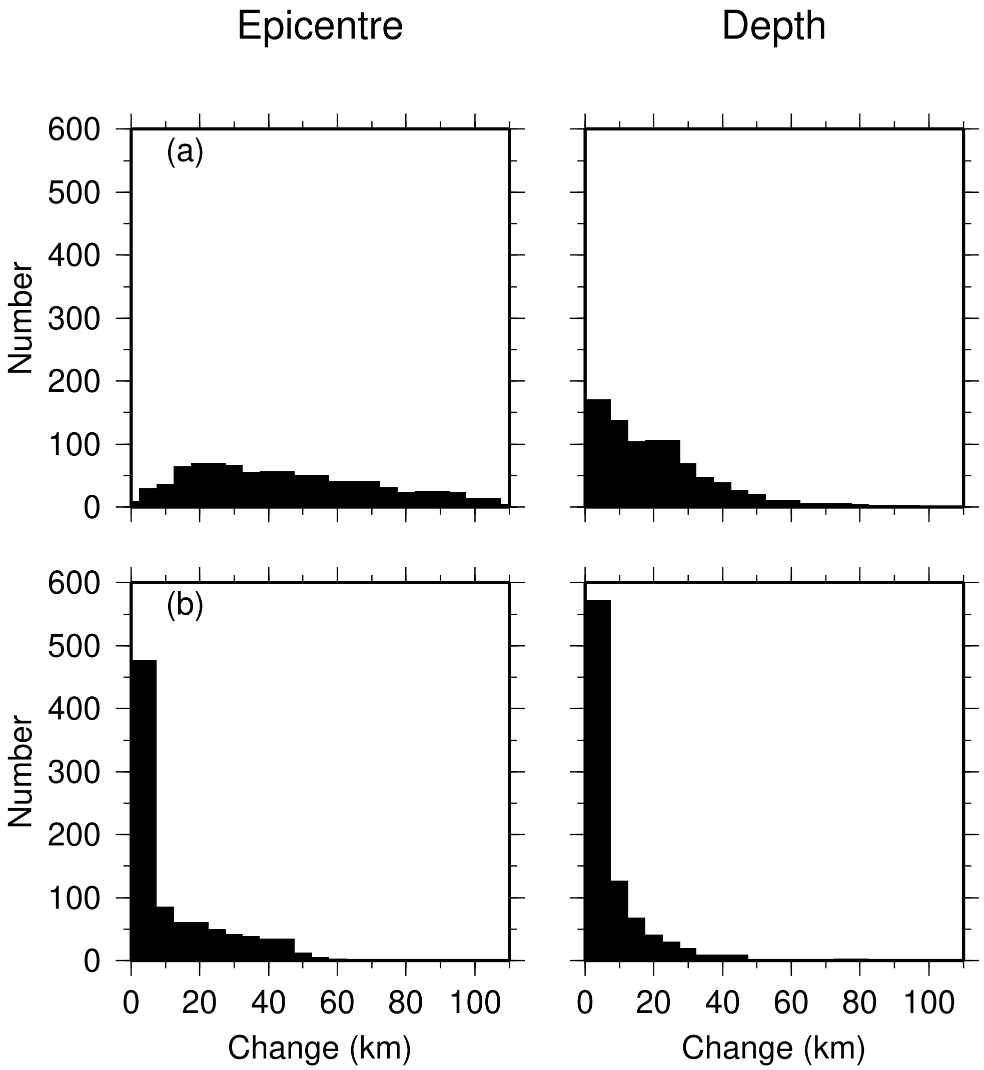

Figure 6. Histograms showing the changes in event locations: a) between ISC and AP (P-wave only) solutions; b) between AP solutions using P-wave only and P-wave plus 7 additional phases

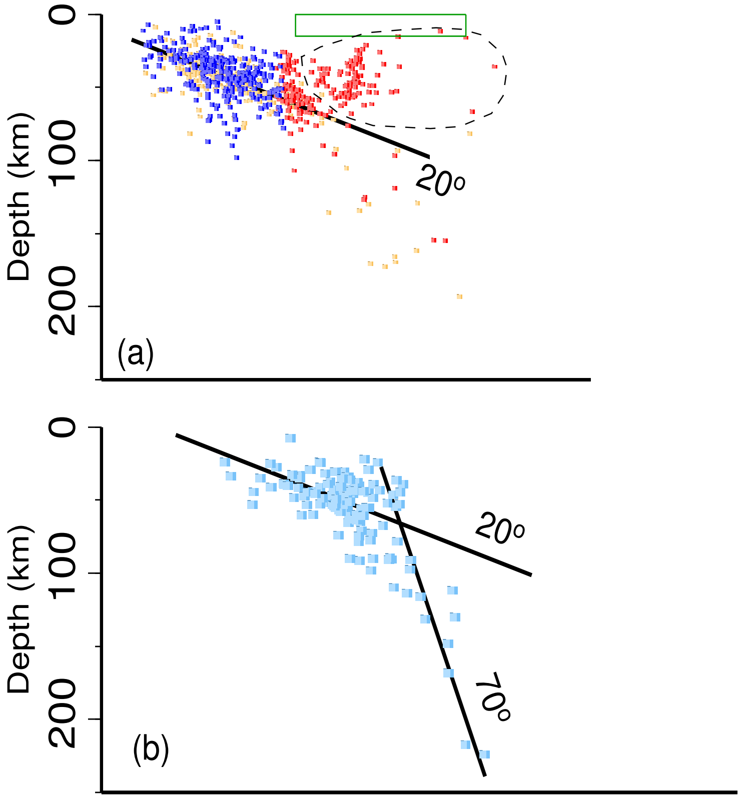

Figure 7. Cross-section of aftershocks most likely associated with the major subduction earthquakes of: (a) Event 2 projected onto a vertical plane of azimuth 345°. (b) Event 3 projected onto a vertical plane of azimuth 335°. Dip angles of the subducted slab as proposed by Cooper & Taylor (1987) are plotted for comparison and match well the aftershock pattern. Events located inside the dotted region in (a) lie above the subduction zone. Colour-coding of events is the same as in Figure 2.

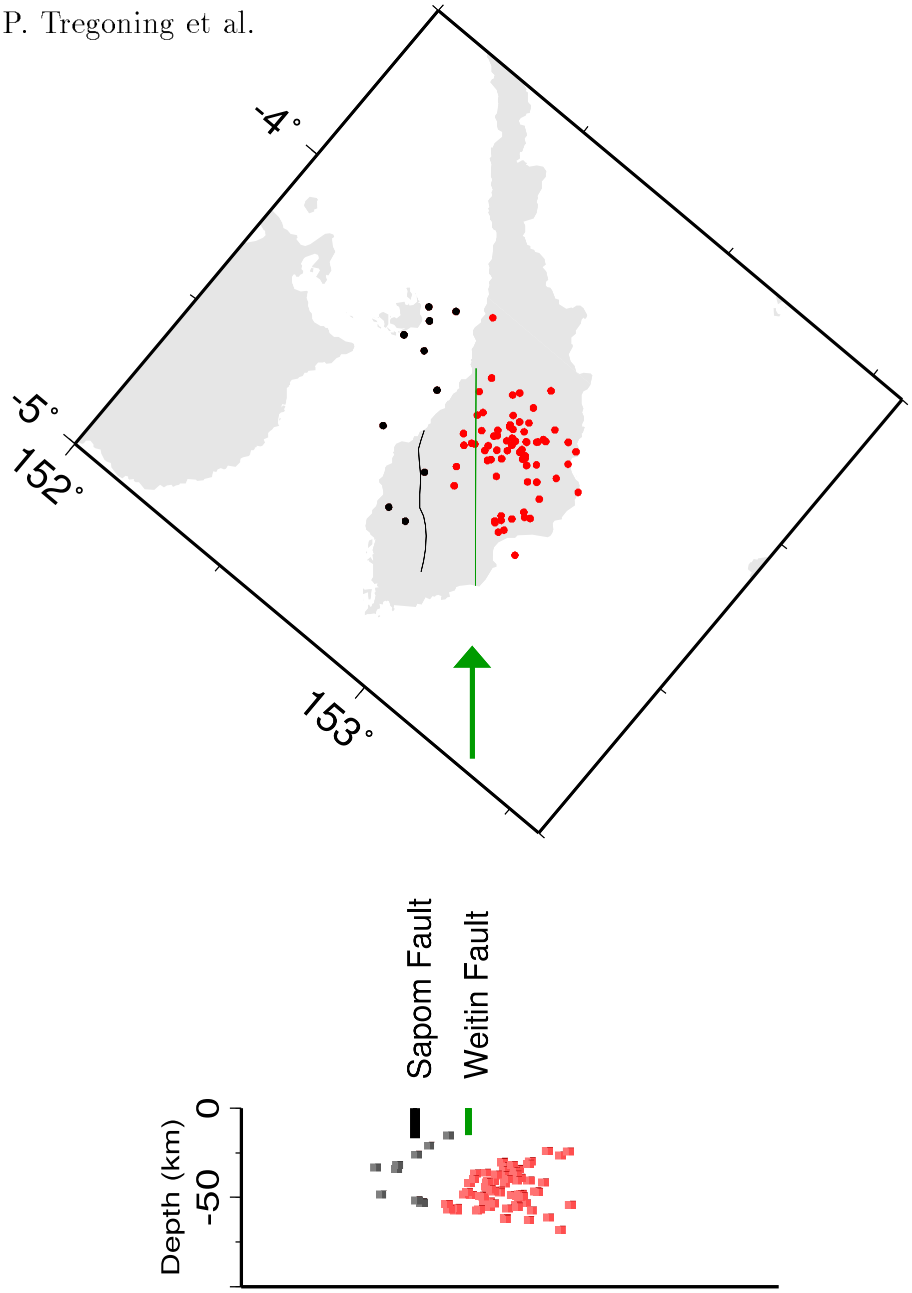

Figure 8. Events near New Ireland that occurred above the subduction zone (ie within the dotted region in Figure 7a), plotted in plan view and in cross-section looking in the direction of the arrow (NW along the strike of the Weitin Fault).