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 (AP) 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 2000 November. The first event was an $M_w = 8.0$ 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 overriding 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: aftershocks, arrival pattern method, Papua New Guinea, seismology, Weitin fault.

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 (Fig. 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$^{-1}$ left-lateral slip with ~17 mm yr$^{-1}$ convergence (Tregoning et al. 1999). Mapped faults in southern New Ireland include the Weitin fault (Hamilton 1979), which is a strike-slip fault beneath the Weitin and Kamdaru river valleys, and the Sapom fault, which 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 & 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 (AP) 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 2000 November.

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

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2000 November Earthquake Sequence

On 2000 November 16, an $M_w = 8.0$ earthquake occurred in eastern Papua New Guinea near the boundary between the South Bismarck and Pacific plates (Fig. 1). This earthquake (hereinafter called event 1) was followed ~4 h later by an $M_w = 7.8$ thrust earthquake (event 2) on the New Britain trench to the south of New Ireland, the interplate subduction zone between the South Bismarck/Pacific and Solomon Sea plates. 31 h 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 month. Surficial ruptures (in the form of offset vehicle tracks) were found along the mapped strike of the Weitin fault (Finlayson et al. 2003; Itikarai & Tregoning 2003).

Seismic instruments at the Rabaul Volcano Observatory (RVO) saturated on each of the three main events (Itikarai, 2000, private communication); the only other seismometers in Papua New Guinea were used seismic data from temporary deployments of seismometers 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 hypocentre 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 Tensor (CMT; e.g. Dziewonski & Woodhouse 1983), International Seismological Centre (ISC; 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 trade-offs 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 (Fig. 2a). The hypocentres of the ISC catalogue (Fig. 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 Fig. 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 Fig. 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 2000 November 16, Rham & Das (2003) concluded that the Sapom fault had ruptured with pure left-lateral strike-slip on a vertical fault. 

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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. Dziewonski & 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 AP 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, estimate the location of the new event. Effectively, traveltime predicted by an Earth model are replaced by an ensemble of observation times from previous events (although it is recognized that the locations of the previous events have been estimated using traveltimes predicted by an Earth model; therefore, the AP 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 2 than those associated with the hypocentres contained in the database of previous events. That is, the median new location error is approximately 50 per cent 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 AP 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 per cent confidence ellipse lay approximately at the 2-s contour around the event (approximately 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 2000 November 16. 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 bull’s-eye 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 per cent 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 and PKPab and weighted the observations as described by (Nicholson et al. 2004 table 1).

Fig. 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 (Fig. 3b). The inclusion of S-wave arrivals (Fig. 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 Fig. 2c computed with seven additional phases with Fig. 3d where only four additional phases were used). In general, P-wave observations form 53 per cent of the total with Pn (16 per cent) and S (10 per cent) 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, DepthpP, 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...
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Figure 3. Epicentres and cross-sections using different combinations of additional phases: (a) P-wave only; (b) P and pP; (c) P, pP and S; (d) P, pP, S and Pn. Colour-coding is the same as for Fig. 2. No vertical exaggeration.

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 (Fig. 4). We found that when the depth estimates of $\text{Depth}_{pP-P}$ 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 $\text{Depth}_{pP-P}$ 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 the 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 AP 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. Fig. 5a). Events with sparse observations and no clear bull’s-eye pattern were considered unreliable and were rejected (e.g. Fig. 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 Fig. 2(c). 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 (Fig. 3a) show a tighter clustering of epicentres than either the NEIC (Fig. 2a) or ISC events (Fig. 2b). Fig. 6(a) shows a histogram of changes in locations (epicentre and depth) between the P-wave–only locations and the ISC locations (we did not compute the comparison for the NEIC solutions because there are so few events with estimated depths). The locations of around 75 per cent 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 data sets from either different time periods or nearby areas.

The use of the additional seven phases further refined the AP locations and the histogram of changes is shown in Fig. 6(b). Approximately 40 per cent of epicentres and only ∼20 per cent of depths were changed significantly between AP 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 (Fig. 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://rnes.anu.edu.au/geodynamics/gps/N1_eq/png_ap.html).

![Epicentre and Depth Histograms](image)

**Figure 6.** Histograms showing the changes in event locations: (a) between International Seismological Centre (ISC) and arrival pattern (AP; P-wave only) solutions; (b) between AP solutions using P-wave only and P-wave plus seven additional phases.

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 2000 November 18. Only four GPS sites, all located near Rabaul on the nearby volcanoes, were recording during the three major earthquakes and for the first 2 d afterwards. The GPS data were analysed using the GAMIT/GLOBK software (Herring 2002; King & Bock 2002) utilizing data from local and global tracking stations. We calculated site displacements of two sites on the southern coast of New Ireland (shown in Fig. 1b) from the difference in coordinates from the last measurement before event 1 (2000 August) and the first occupation after event 3 (2000 December). The re-observations 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 coseismic 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 (Fig. 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 data set is currently being prepared, including the separation of the effects of the three major earthquakes and numerical values of the coseismic 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 AP 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 per cent) 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
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 (Fig. 8, see also a rotating figure at http://rses.anu.edu.au/geodynamics/gps/Nl_eq/weitin.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 coseismic displacements (Fig. 1b) and observed surface offsets (Finlayson et al. 2003; Itikarai & Tregoning 2003) do provide conclusive evidence that the strike-slip event occurred on the Weitin fault.

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