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Geophysical contributions to the COASTPLAN project, Lae area, Papua New Guinea, 1998

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Abstract: The Lae Coastal Hazards study is one of three pilot projects currently sponsored by CCOP as part of the overall COASTPLAN programme. The aim of the study is to assess the vulnerability of the coastal region at the head of the Huon Gulf, and particularly the Lae urban area, to natural disaster. Detailed investigations of possible risk made in early 1998 by the COASTPLAN team were supported by a gravity survey designed to clarify the factors controlling uplift and subsidence in this tectonically active region. The total of 93 new gravity stations established in the Leron-Lae-Finschafen area confirmed the presence of a major foreland basin gravity low in the northern Markham Valley and the probability of an extension of the Papuan Ultramafic Belt beneath the Huon Peninsula. Correlations between gravity patterns and local and regional seismicity suggest that some potential long term and short term sources of geological hazards may have been overlooked.

GEOGRAPHICAL SETTING

Lae, the second largest town in Papua New Guinea and the principal centre of communications, lies at the eastern end of the Markham valley, a little to the north of the point at which the Markham River flows into the Huon Gulf (Fig. 1). The town is both the terminus of the Highlands Highway and an important harbour, and is the main centre for transhipment of goods going to and from the highlands. It may in the future become important as the terminal for pipelines from Highlands gas fields. The small airstrip adjacent to the town is now used only by helicopters, while scheduled air services, including light aircraft services run by commercial companies and the Mission Aviation Fellowship, use the airstrip at Nadzab, some 30 km inland along the Highway.

The Lae urban area is centred on a small area of raised ground, an outlier of the Atzera Range, overlooking the mouth of the Markham River. Maximum heights in the Atzera Range amount to only a few hundred metres (from a base virtually at sea level), but it is itself merely a spur of the Finisterre Range, in which mountain peaks which reach in places to more than 4,000 m were extensively glaciated during the Quaternary. The eastern end of the Finisterres, to the north and east of Lae, form the Huon Peninsula, which is separated from eastern Papua by the Huon Gulf. West of Lae, however, the Finisterres are separated from the main mountain masses of central New Guinea by the Ramu-Markham river valley, a depression of variable width within which the main east-west watershed occurs at an elevation of only a few hundred metres.

Within the Markham valley, the land surface slopes gently southwards from the Finisterre mountain front to the Markham River, which flows close to the southern margin of the depression. The slope is formed by alluvial fans sourced from the rapidly rising mountain ranges. Sediments transported across these fans by rivers draining the Finisterres are then carried east by the Markham River and are deposited either immediately offshore in the Markham delta or in deeper water via the Markham Canyon (von der Borch, 1972; Davies *et al.*, 1987). The deltaic pile is prone to collapse and turbidity currents derived from its steep eastern face have been observed to travel large distances at high speeds down the axis of the New Britain Trench (Krause *et al.*, 1970).

THE FINISTERRE COLLISION ZONE

Northern New Guinea was first recognised as a site of arc-continent collision in the very early days of plate tectonics (Dewey and Bird, 1970; Jaques and Robinson, 1977) and has therefore been studied intensively over a period of some thirty years.

Additional interest was generated by the publication of a classic paper by Chappell (1974) documenting rapid uplift of reef corals which form impressive terraces in the northeastern part of the Huon Peninsula. The collided arc was first mapped in detail by the Australian Bureau of Mineral Resources (BMR, now AGSO) and the Geological Survey of Papua New Guinea (Jaques and Robinson, 1977), and initial sedimentological studies of the syn- and post-collisional sediments were carried out at the Australian National University in Canberra (Crook, 1989; Liu and Crook, 1993). More recently, much work has been done by the University of California at Santa Cruz (UCSC) (Abbott *et al.*, 1994; Abbott *et al.*, 1997). The history of offshore studies has been rather similar, with early work by the BMR (von der Borch, 1972) being refined and extended by cruises from the University of Hawaii (Davies *et al.*, 1987) and UCSC (Silver *et al.*, 1991; Abbott *et al.*, 1994; Galewsky and Silver, 1997). The geological and marine geophysical work has been supplemented by gravity surveys (Pettifer, 1974; Abers and McCaffrey, 1994) and by studies of teleseismic patterns (Abers and McCaffrey, 1994) and local microearthquakes (Kulig *et al.*, 1993).

One of the most controversial aspects of the area concerns the location of, and nature of, the terrane suture. It has long been assumed (Dow,

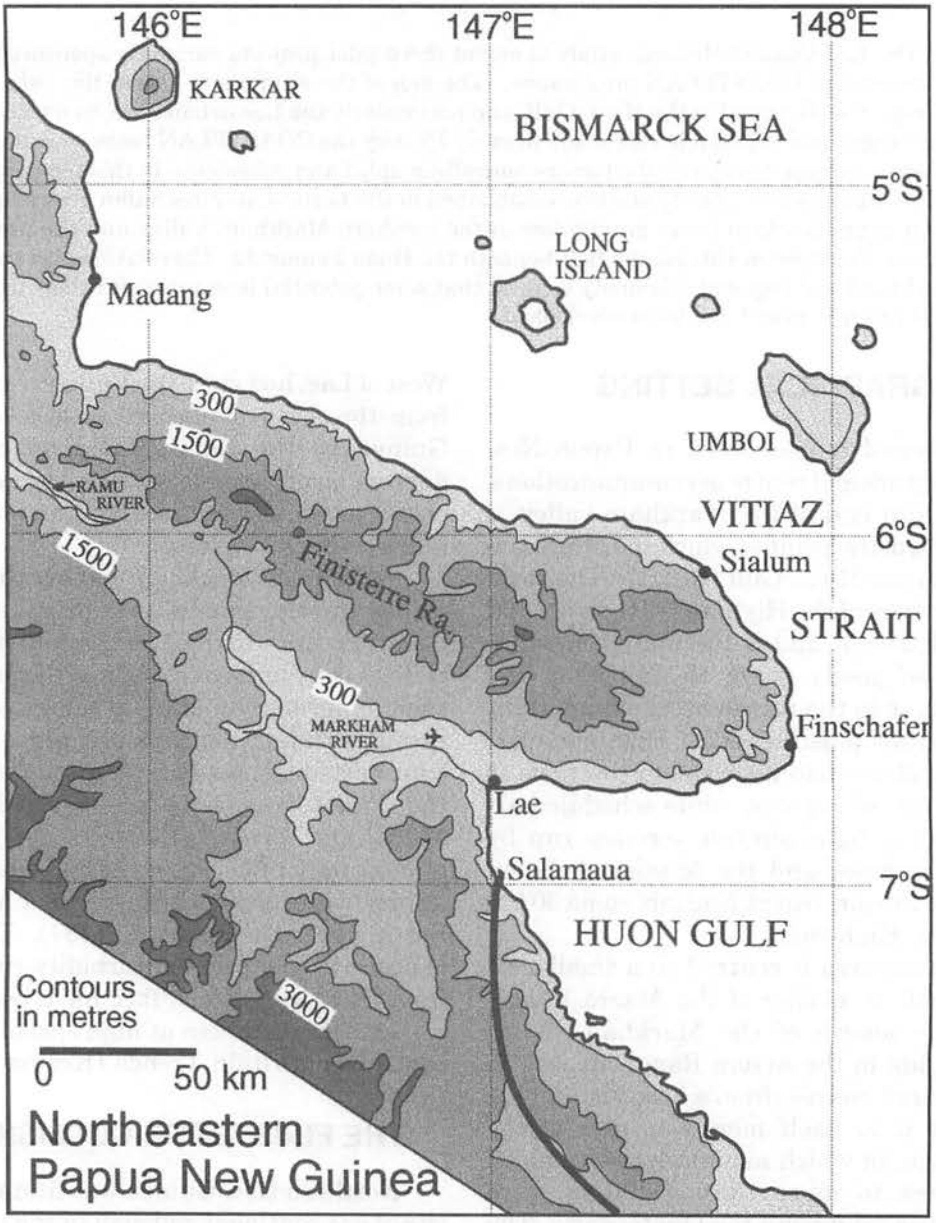

Figure 1. Northeastern Papua New Guinea. The thick curved line cutting through the mountainous region south of the Huon Gulf indicates the location of the Owen Stanley Fault which separates the Owen Stanley Metamorphics (to the west) from the Papuan Ultramafic Belt (to the east).

1977) that, since the basement rocks to the north and south are markedly different, a major fault must underlie the Ramu-Markham valley. However, no such fault has ever been either mapped on the ground or imaged by seismic reflection surveys, and the seismological evidence is ambiguous. Abers and McCaffrey (1994) noted that earthquakes at depths of about 30 km beneath the northern part of the Huon peninsula could be assigned to a Ramu-Markham Fault dipping north at about 20° but that earthquakes occurring farther south at only slightly shallower depths could be associated with a fault which reached the surface in the valley only if it had an almost vertical dip. This would be compatible with the largely transcurrent Ramu-Markham Fault suggested by Hamilton (1979) and Cullen and Pigott (1989) but this interpretation has been rejected by Abers and McCaffrey (1994) and most other recent workers. Relocated deeper earthquakes (Abers and Roecker, 1991) define a Wadati-Benioff Zone which dips steeply north at depth but which flattens sharply at about 100 km and has no obvious link with the surface. If the fault plane represented by this zone does outcrop, it must do so well to the south of the Markham Valley.

The situation has been further complicated by the proposal (Milsom, 1981) that the Finisterre Ranges have moved forward, relative to both the Adelbert Range to the west and New Britain to the east, as a nappe sliding on a near-horizontal thrust which may currently dip north at only one or two degrees. If this is the case, then the original terrane boundary has been overidden and its surface trace now lies beneath the Finisterre Ranges and not beneath the Ramu-Markham depression. Gravity data, which can provide information on the deep structure beneath the Finisterres, have an important role to play in evaluating this hypothesis.

GRAVITY SURVEY

In February 1998, a gravity survey was mounted in the Huon Peninsula-Markham Valley region in association with the COASTPLAN programme. Combining the gravity survey with a part of the regional geological study allowed efficient use of vehicles and support facilities. However, since the relevance of gravity data to geological hazard studies tends to be indirect, no funds were sought from the COASTPLAN budget and the programme was funded by the University of London Consortium for Geological Research in Southeast Asia. Although the primary aim of the gravity work was to investigate a possible large positive anomaly on the Huon Peninsula, it was also hoped that the results would contribute to a better understanding of the subsurface structure of the Lae urban area.

The Earth's gravity field provides not merely a convenient, if ambiguous, means of studying subsurface structures but is also in its own right a (perhaps the) major tectonic driving force. Where gravity fields are high, there are mass excesses which give the region in question a tendency to subside. Where they are low, there are mass deficits and the region will rise unless prevented from doing so. Throughout the Markham-Lae-Finschafen region, Bouguer gravity is negative (when referred to stable continental crust at sea level as a standard) and uplift is therefore favoured. The very considerable variations observed within this overall pattern allow regions to be identified where uplift tendencies will be most strongly concentrated.

Background to the 1998 survey

The first gravity readings in the Huon-Finisterre region were taken in conjunction with the triangulation survey of the then Territory of Papua New Guinea, and many of the widely scattered stations were located at the tops of mountain peaks and were subject to very large and uncertain terrain effects. This project (St John, 1967) did, however, result in the production of the first gravity maps to cover the whole of Papua New Guinea. An intriguing feature of the data set was a single reading in the south-central part of the Huon Peninsula which suggested the presence of a positive Bouguer gravity anomaly of more than 100 mGal amplitude. This was particularly interesting since very large anomalies are also associated with the Papuan Ultramafic Belt (PUB), one of the world's largest ophiolite belts, which reaches the coast on the south side of the Huon Gulf (Milsom, 1973). The suggested Huon gravity high lay exactly where an extension of the PUB would be expected, could this feature be simply extrapolated along strike across the Huon Gulf. Such extrapolation would, however, be inadmissable were the Ramu Markham Fault either a major strike-slip fault (in which case any northward continuation of the PUB should have suffered considerable lateral offset) or a terrane boundary subcropping the Markham Valley and Huon Gulf (in which case there should be no relationship between the rock units on either side of the Gulf).

Following the pioneering regional work of St John (1967), a significant contribution to the gravity coverage was made by Pettifer (1974) in a survey mounted in an attempt to map thickness variations in the unconsolidated sediments of the Markham valley. A major gravity low was defined which occupied most of the valley, but Bouguer values were found to be still decreasing at the mountain front. This pattern is typical of the forelands of many thrust mountain ranges, where the topographic masses are supported by downbending of an elastic lithosphere rather than by a point-for-point isostatic balance. In such an environment there could have been little hope of achieving the original aim of the survey, which was to determine the thickness of the valley fill. Some part of the gravity low in the mountain area can be attributed to the unknown but probably large thicknesses of the Pleistocene Leron Formation beneath the overthrust but several kilometres of crustal thickening are also indicated. The combined results of these and later surveys were used by Abers and McCaffrey (1994) to investigate lithospheric strength in the region but their modelling was hampered by the still patchy distribution of gravity stations and, in particular, by the lack of control on the gravity field to the east and northeast of Lae. The single point high on the Huon Peninsula was specifically ignored because of the lack of supporting data.

The 1998 gravity survey

The primary academic objective of the 1998 gravity survey was to determine whether the Huon gravity high actually existed and, if so, whether it could be reasonably interpreted as due to a northern extension of the PUB. It was fortunate, since work in the interior of the peninsula would have been both logistically extremely difficult and have required very large terrain corrections with correspondingly large uncertainties, that the crucial test could be made merely by traversing along the coast from Lae to Finschafen, with only a very small number of inland stations. Although the main aim of the survey was to complete this traverse, it was also hoped that the gaps in the existing coverage of the Markham valley could be reduced and that more detail could be obtained in the vicinity of Lae itself, where it would be most relevant to the COASTPLAN studies. All three objectives were largely achieved, using road transport and, for the coastal work, fibreglass speedboats powered by large outboard motors. An additional bonus, made possible by the strong support provided by the District Office in Finschafen and the excellence of the road along the east coast from Finschafen to Sialum, was the extension of the coastal traverse to the northeast corner of the Huon Peninsula.

A total of 93 new stations were established, their positions being determined using a hand-held GPS receiver. Elevations of coastal stations were determined by direct reference to sea level and inland stations were levelled barometrically, using a single base technique. Thanks to the relative stability of tropical air masses, this method generally provides estimates accurate to better than 3 m, equivalent to about 0.5 mGal error in Bouguer anomaly (Milsom, 1971). Additional uncertainties exist in elevations in the Markham valley, which for stations in the Leron area were based on a spot height value taken from the 1:100,000 map and for stations near Nadzab used the assumption that the 1998 Nadzab base was at the same height as the Abers and McCaffrey (1994) gravity station. The additional errors in the elevations for these stations are probably no greater, and may be less, than those introduced in converting heights above actual sea level to heights above mean sea level. Because the very large gravity variations require the use, even in detailed maps, of contour intervals of 10 mGal or more, these errors are not important.

The locations of the actual observation points are shown in Figure 2, the Bouguer gravity map produced by combining the results of the 1998 and earlier onshore surveys. With very few exceptions, readings are confined to the coastal regions and the Markham Valley. The extent of the gravity low in the south central Finisterres is thus undefined, as are the links (or lack of them) between the gravity highs in the north and south of the Huon Peninsula. The most that can be said of these features is that they certainly exist. As already noted, the obstacles to obtaining data in the Finisterre Ranges, and to making terrain corrections to an acceptable degree of accuracy, are formidable.

One bizarre result of the 1998 survey can also be noted. Although the existence of a gravity high in the south-central part of the Huon Peninsula was verified, the peak values observed were considerably less than the Bouguer value estimated by St John (1967) for the station which originally prompted the survey. Checks of the original data listings showed that this station, at trig point AA041, had been allocated an elevation of 500 m rather than the true elevation of 186 m Possibly the 500 m was a nominal value inserted in the early stages of processing before the results of the triangulation survey became available, and its subsequent correction had been overlooked. Whatever the reason, it has to be admitted that the Bouguer gravity value which provided the main impetus for the 1998 gravity survey was actually in error.

Huon gravity high

The gravity high in the central south coast of the Huon Peninsula can be attributed to the continuation of the PUB from eastern Papua across the Huon Gulf and beneath the Finisterre overthrust. This implies that the Owen Stanley Fault, which has an almost N-S strike where it reaches the coast (Fig. 1), continues on this strike across the Huon Gulf. This has implications for the COASTPLAN study since it provides an explanation for the N-S orientation of the short section of coast near Lae and for the very steep slopes immediately offshore. Galewsky *et al.* (1996) cited the presence of drowned carbonate platforms to the east of this region as evidence of rapid subsidence. The estimated rates, of almost 6 mm/yr, are an order of magnitude greater than those found in most foreland basins and it seems reasonable to suppose that the sea floor is being depressed by the large mass of the ophiolite as well as by normal foreland loading. Onshore, the PUB produces gravity effects amounting to between 100 and 200 mGal, testifying to a very large total excess mass. It seems that the rough but fluctuating balance between coastal progradation and delta fan collapse near Lae is being maintained by deep controls on the offshore slope and may be relatively stable over geologically significant periods.

In the light of the gravity results, it also becomes less surprising that coastal retreat, attested in conversations with local villagers, is a continuing problem along the Huon coast despite the large sediment input to the area and the high uplift rates documented by Chappell (1974) in other parts of the Huon Peninsula. There is clearly an interplay of forces favouring subsidence and forces favouring uplift, and the central part of the south coast region, in particular, must have some tendency to subside under the weight of the ophiolite. Until further information is available, it would be unwise to assume that the high uplift rates determined for the north-eastern Huon Peninsula or estimated by Crook (1989) in the Lae region are typical of the whole of the region. If they are not, then the faults which accommodate differential vertical movements may themselves be sources of geological risk.

Integration of the 1998 results with earlier work, and particularly with the results quoted by Abers and McCaffrey (1994), has also provided insights into the subsurface structure of the region around Lae itself. The coverage is irregular and still far from comprehensive, but would have provided some indications of a gravity low between the Atzera Range and the main Finisterre Block had this existed. It does not (see Fig. 5a), and consequently, although the density contrast between the Leron Formation 'basement', which forms the Atzera Range, and more recent deposits would not be expected to be very large, it seems reasonable to conclude that the alluvial fill in the valley of the Buso River, which separates the two regions of higher ground, is only a few tens of metres thick.

SEISMICITY

The major geological hazards in the Lae area are linked to its location within a wide region of intense seismic activity. Future earthquakes could obviously cause direct destruction of town buildings, but might also trigger large scale slumping from

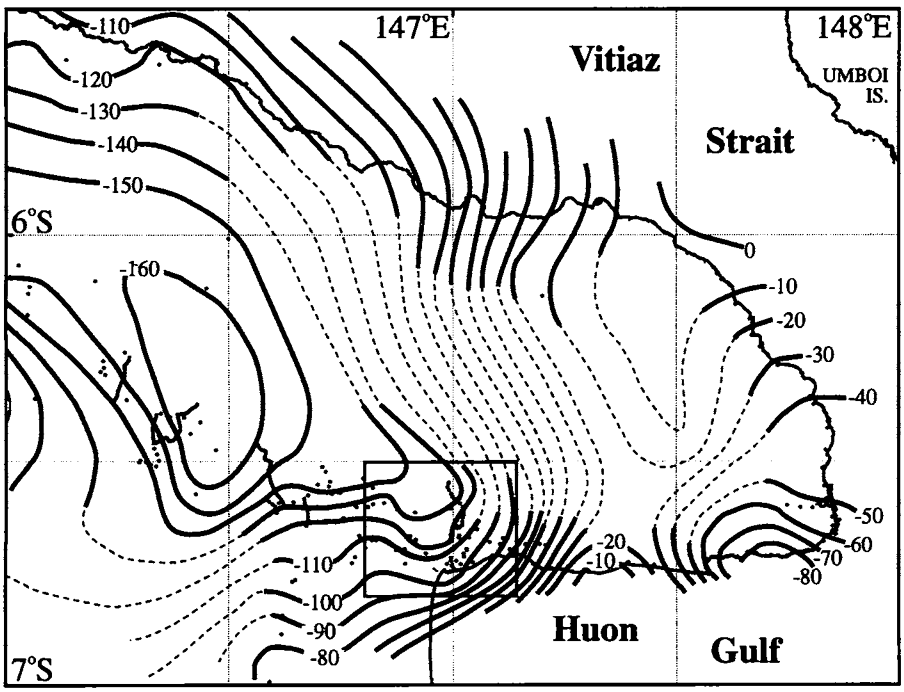

Figure 2. Preliminary Bouguer gravity map of the Huon Peninsula and adjacent regions. Contour interval 10 mGal. Dashed contour lines are used in areas of inadequate control.

the face of the Markham offshore fan and could lead to destructive tsunamis affecting the port area. Furthermore, earthquakes have a major effect on river flow. Landslides can be triggered in the mountain regions, damming rivers and impounding large volumes of water, and further earthquakes can destabilise these dams leading to catastrophic floods. An understanding of earthquake distribution in both space and time is therefore fundamental to any hazard assessment. Fortunately, there have been recent studies of both regional and local seismicity.

Regional seismicity

The seismicity of Papua New Guinea was first mapped in three dimensions in regional studies which covered the whole of the southwestern Pacific (Johnson and Molnar, 1972). The work was based on the then newly available ISC catalogues, which continued to be employed for many years, despite the use of global approximations of crustal and upper mantle velocity structure which led to considereable errors in hypocentre locations in areas of strong velocity contrasts. These errors were dramatically reduced in the New Guinea region by Abers and Roecker (1991) who used tomographic techniques to obtain better velocity control. This work showed the north coast Wadati-Benioff Zone (WBZ) to be much narrower and better defined at depth than had previously been thought (Fig. 3). Perhaps equally significant was the reappraisal of the evidence for a south-dipping WBZ beneath the New Guinea Highlands and western Papuan Peninsula. Although some deep earthquakes do occur in this region, the relocated hypocentres do not support the interpretation of Cooper and Taylor (1987), which was based on ISC locations, of a south-dipping limb to the WBZ.

The relocated epicentres also emphasise differences between the seismic patterns beneath the Finisterre collision zone and beneath the as yet uncollided portion of the arc. The WBZ beneath New Britain (Fig 3b) dips steeply from a region on the surface which can be identified with the physical trace of subduction in the New Britain Trench. In the Finisterre-Huon region, however, the deep seismic zone, which has a steep to vertical dip below 150 km, dips northwards at roughly 45° between 90 and 150 km and at about 90 km flattens to form a horizontal feature above which no WBZ can be defined (Fig. 3a). No conclusive explanation has been offered for this pattern but it does seem that the original terrane suture may now be deeply buried and that very complex deformation is taking

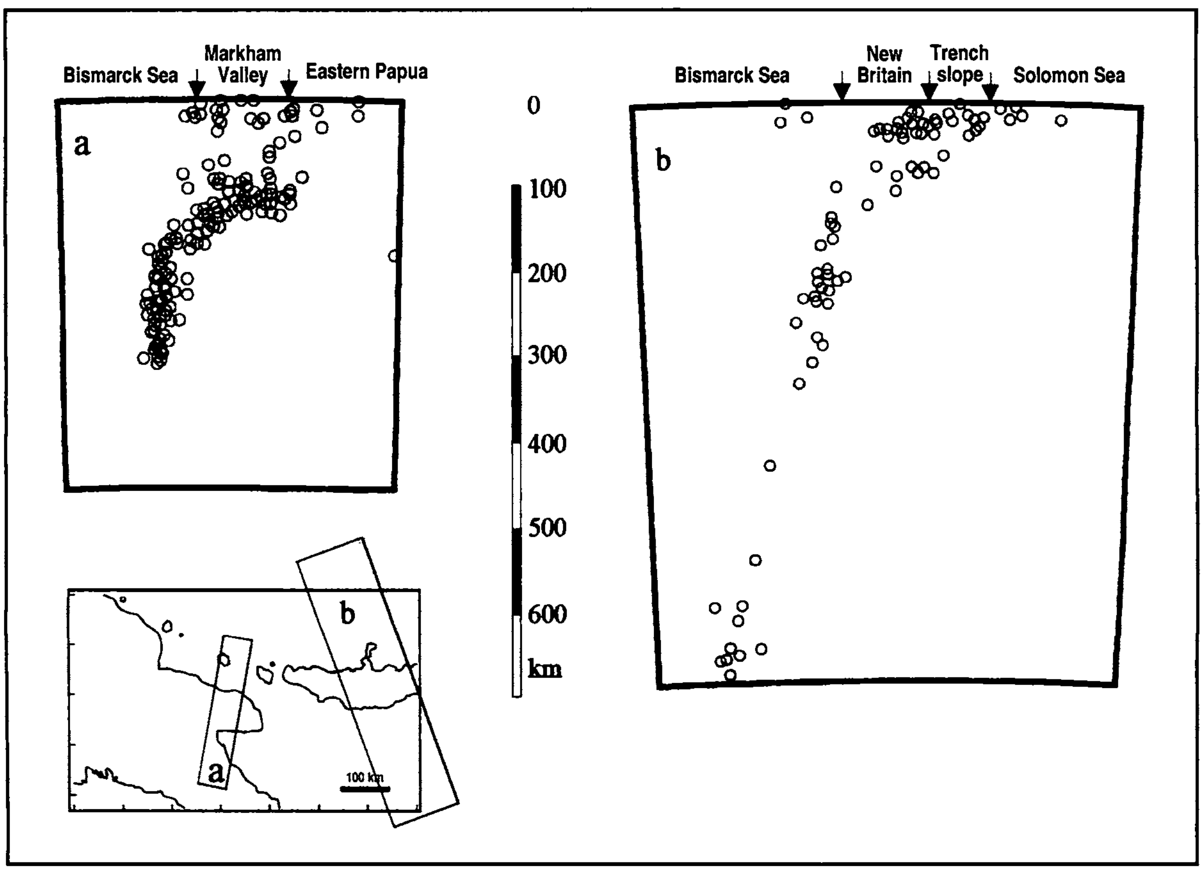

Figure 3. Wadati-Benioff Zones in northeastern Papua New Guinea after Abers and Roecker (1991), (a) beneath the Finisterre Range (b) beneath New Britain. Map shows locations of transects.

place nearer the surface.

Following on from the work of Abers and Roecker (1991), focal mechanism solutions for 21 teleseismically located shocks were published by Abers and McCaffrey (1994). The majority of these solutions indicated thrusting (Fig. 4), but important groupings of strike-slip solutions were identified near Madang (which suffered a particularly damaging earthquake in 1970) and in the Vitiaz Strait, where there was a magnitude 7.4 shock, with a lesser foreshock and several aftershocks, in 1987. Earthquakes in these two areas, which are the most seismically active in the entire region (both as regards the frequency of events and their magnitudes), are not likely to cause significant direct destruction in the Lae area but damage might be caused there by tsunamis generated in the Vitiaz Strait.

Local seismicity

In 1988 a local seismograph network was established in the Lae area and was operated for a period of six weeks, during which time a number of shallow (generally 10–20 km depth) microearthquakes were recorded (Kulig *et al.*, 1993). Although there was some degree of scatter, the majority of shocks occurred in an ENE-WSW oriented zone passing across the SE end of the Atzera Range, a few kilometres north of Lae (Fig. 5). First motion studies pointed to dip-slip, N-side downwards movement in this zone, which runs at a high angle to the supposed direction of the Ramu-Markham Fault. This pattern of seismicity was unexpected, being related to no known or interpreted features, except possibly a slight change in geological strike close to the end of the Atzera Range. The indicated sense of movement is also anomalous, in that the Atzera Range is a prominent feature on the northern side of the zone, which the focal mechanism studies suggest is the downthrown side, and disappears on the southern, upthrown side. It is also difficult to relate the seismicity to any processes likely to be taking place at the terrane suture and Kulig *et al.* (1993) offered two quite different interpretations, with the shocks located in, respectively, either the upper or the lower plate.

Although the reasons for the existence of the Lae seismic zone are obscure, there is an interesting spatial correlation between it and a sharp local flexure in the Bouguer gravity contours which defines a residual low (Fig. 5a). This is, in fact, the only piece of information which seems consistent with downthrow to the north, since locally lower gravity would be expected over the downthrown block, but this does not make understanding either the gravity or the seismic pattern any easier. It is also true that the earthquake sample is a very biased one, relating only to a very short period of time and to a very local network of stations which would preferentially detect and locate shocks in the immediate vicinity of Lae. From the point of view of risk assessment, it is perhaps less important at this stage to understand the root causes of the seismicity than to simply recognise the proven history of shallow crustal movements close to Lae. As Kulig *et al.* (1993) point out, the fact that more than a dozen low intensity events were recorded in a mere six weeks of observation suggests a potential for much larger shocks which could cause considerable damage.

CONCLUSIONS

Considerable risk exists in the Lae urban area both of damaging earthquakes and of serious longer term subsidence. Gravity and seismological studies have pointed to a complex subsurface structure which is quite different from the structural pattern observed at the surface. It is clear that major developments in and around Lae should conform to the highest standards of earthquake engineering, and should take advantage of high ground where the consequences of subsidence, and the risks of flooding following the collapse of landslip dams in the Finisterres, would be minimised. Better quantification of the risk might be provided by extended microearthquake monitoring covering a wider area than in the studies completed to date.

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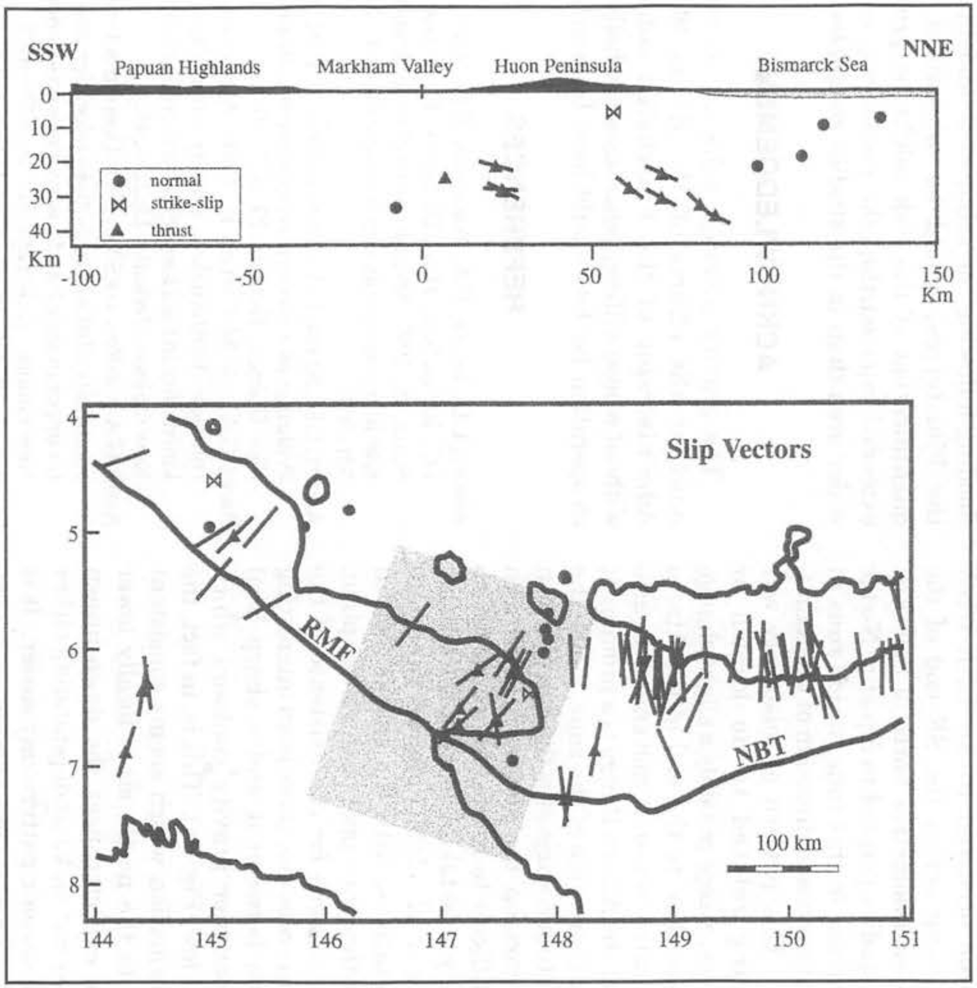

Figure 4. Seismicity of northeastern Papua New Guinea, after Abers and McCaffrey (1994), showing earthquake types and orientation of slip vectors. The cross-section shows only those earthquakes falling within the area shaded on the map.

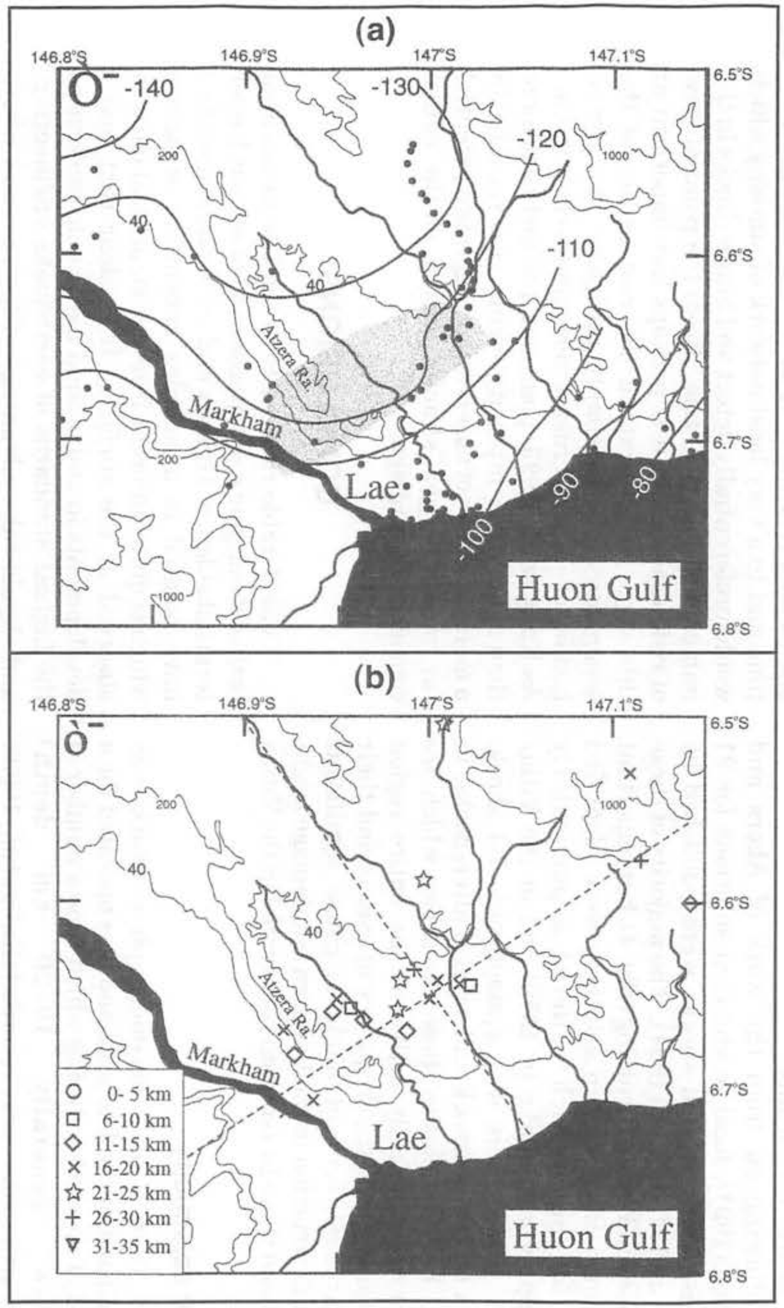

Figure 5. Lae local area (a) Bouguer gravity (b) microseismicity, after Kulig *et al.* (1993). The shaded area in (a) indicates the location of the 'Lae Seismic Zone'. Symbols in (b) indicate focal depths and dotted lines indicate the inferred dip and strike of the zone.

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