Recent tectonics around the island of Timor, eastern Indonesia

D. G. Masson
Institute of Oceanographic Sciences Deacon Laboratory, Brook Road, Wormley, Surrey GU8 5UB, UK

J. Milsom
Department of Geology, University College London, Gower Street, London WC1E 6BT, UK

A. J. Barber
Department of Geology, Royal Holloway and Bedford New College, University of London, Egham Hill, Egham, Surrey TW20 0EX, UK

N. Sikumbang and B. Dwiyanto
Marine Geological Institute, Bandung, Indonesia

Received 30 April 1990; revised 3 August 1990; accepted 10 September 1990

Eastern Indonesia is the site of active collision between the Banda Arc and the Australian continent. The zone of collision is a poorly understood area and, in particular, controversy exists regarding the sites and styles of Holocene deformation in the vicinity of the island of Timor. This paper describes evidence for late Holocene to historically active sea-floor and shallow subsurface tectonic activity in the area, mapped using the GLORIA sidescan sonar system and single-channel seismic reflection data. Our main conclusion is that the zone of plate contact and major compressional deformation, which lies along the Java Trench west of 119° 45′E, continues directly eastward into the Timor Trough. There is little evidence for recent upper plate shortening north of this major plate boundary in the vicinity of the islands of Savu and Timor. Changes in deformational style, from small-scale uniform deformation at the Java Trench to mud diapirism and broad thrust-bounded folds further east, partly disguise the continuity of the deformation zone. Lateral changes in the style of deformation appear to be controlled only by the thickness and facies of the subducting sedimentary section. Where thin, such as at the Java Trench, uniform small-scale folding results. Further east, in the Timor Trough, a thicker sedimentary sequence deforms into buckled thrust sheets. The location of a large mud diapir field in the Timor Trough south of Savu appears to correlate with a thick sequence of Early Cretaceous marine shale that underlies the Australian shelf. The same shale may be the source of mud diapirs on Timor, demonstrating that, within the convergence zone, sediment facies rather than precise tectonic setting is the principal control on the distribution of the diapirs. A zone of strike-slip, thrust, and possibly normal faults observed to the north of Timor, between the islands of Alor and Wetar, appears to have a complex origin. Some evidence suggests that it is part of a left-lateral offset which cuts across the entire arc, through Timor. However, the apparent south-easterly thrusting of the Banda Sea beneath Wetar, and the deep pull-apart basin developed south-east of Alor, seems also to indicate eastward translation of Wetar relative to the arc further west. This may be driven by deformation of the Banda Sea under north–south compression. We see no evidence for major thrusting north of Wetar, indicating that, at this longitude, little cross-arc compression is accommodated by shortening on its northern side.

Keywords: Timor, eastern Indonesia; collision zones; tectonic evidence

Introduction

Eastern Indonesia is widely recognised as the site of an active arc–continent collision between the Banda Arc and the Australian continental margin (*Figure 1*; e.g. Hamilton, 1979; von der Borch, 1979; Audley-Charles, 1986; Price and Audley-Charles, 1987; Karig *et al.*, 1987). Despite the importance of this example of collision processes, however, it is still a poorly understood area. For example, even in the best studied part of the collision zone, around the island of Timor, major disagreements persist regarding fundamental issues such as the location of the surface trace of the plate boundary and the provenance and emplacement mechanisms of major tectonic units on Timor. One school of workers believes that the surface trace of the northern edge of the Australian plate extends eastward from the Java Trench along the Timor Trough (*Figure 1*; Cardwell and Isacks, 1978; von der Borch, 1979; Hamilton, 1979; Breen *et al.*, 1986; Karig *et al.*, 1987). In this scenario, Timor is regarded as an 'outer arc high', composed of old accretionary wedge strata in the south and fragments of south-east Asian origin in the north; these two terrains were juxtaposed during the Banda Arc–Australia collision (Karig *et al.*, 1987). A

0264-8172/91/010035-15

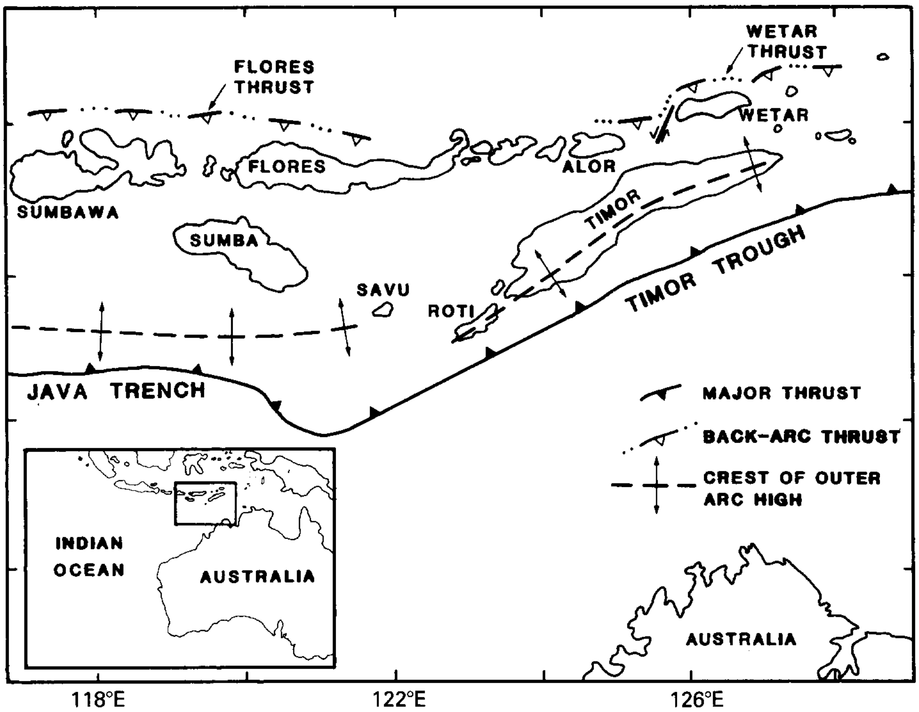

Figure 1 Map showing location of study area and the major tectonic features discussed in this paper

second school has suggested that the surface trace of the plate boundary lies north of Timor (Audley-Charles, 1986; Price and Audley-Charles, 1987). In this model, Timor is interpreted as the imbricated and uplifted edge of the Australian continent, partially buried beneath allochthonous thrust sheets derived from the north; the Timor Trough is then a foreland basin developed entirely within the Australian craton (Audley-Charles, 1986).

North of Timor, back-arc thrust faulting and offset of the volcanic arc are also a result of Australia–Banda Arc collision (*Figure 1*; Silver *et al.*, 1983; McCaffrey and Nabelek, 1984, 1987; Breen *et al.*, 1989). However, the importance, and in particular, the degree of evolution of the observed back-arc thrusting is also a matter of dispute. Silver *et al.* (1983), McCaffrey and Nabelek (1984, 1987) and McCaffrey (1988) suggest that it may represent the initial stages of polarity reversal of the arc, although as yet it accommodates only a small percentage of the total Australia–Banda Arc convergence. In contrast, the collision model of Audley-Charles (1986) requires that this polarity reversal is already completed, at least along the Wetar Thrust to the north of Timor.

The major aim of the study reported here was to use the GLORIA sidescan sonar system to look for evidence of recent sea-floor and shallow subsurface tectonics in an area which extended from the eastern

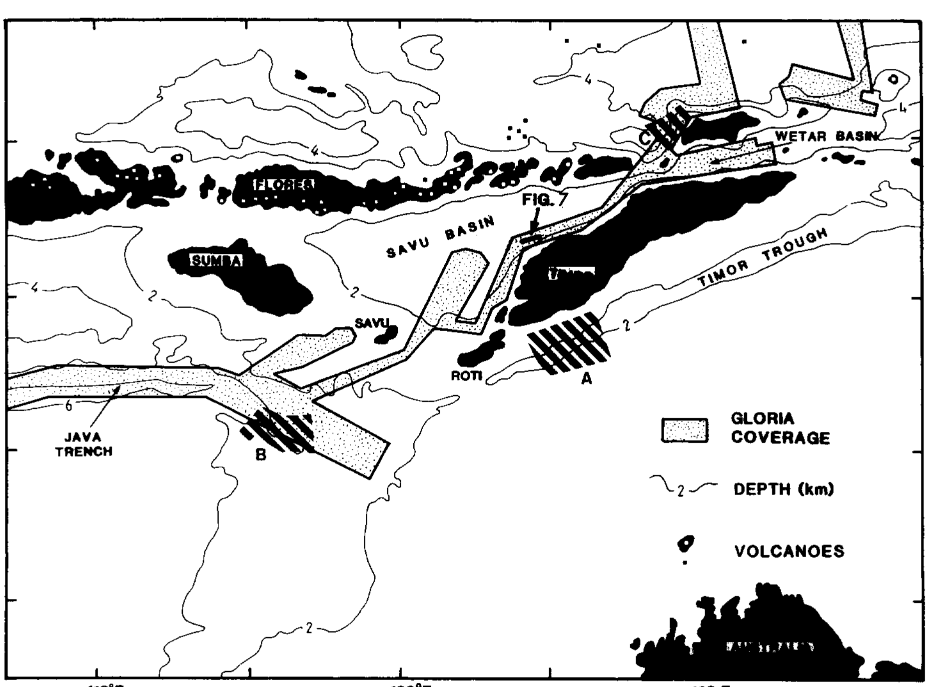

Figure 2 Simplified bathymetric map showing GLORIA coverage obtained during this study and published SEAMARC II data [A from Karig *et al.* (1987), B from Breen *et al.* (1986), C from Breen *et al.* (1989)]

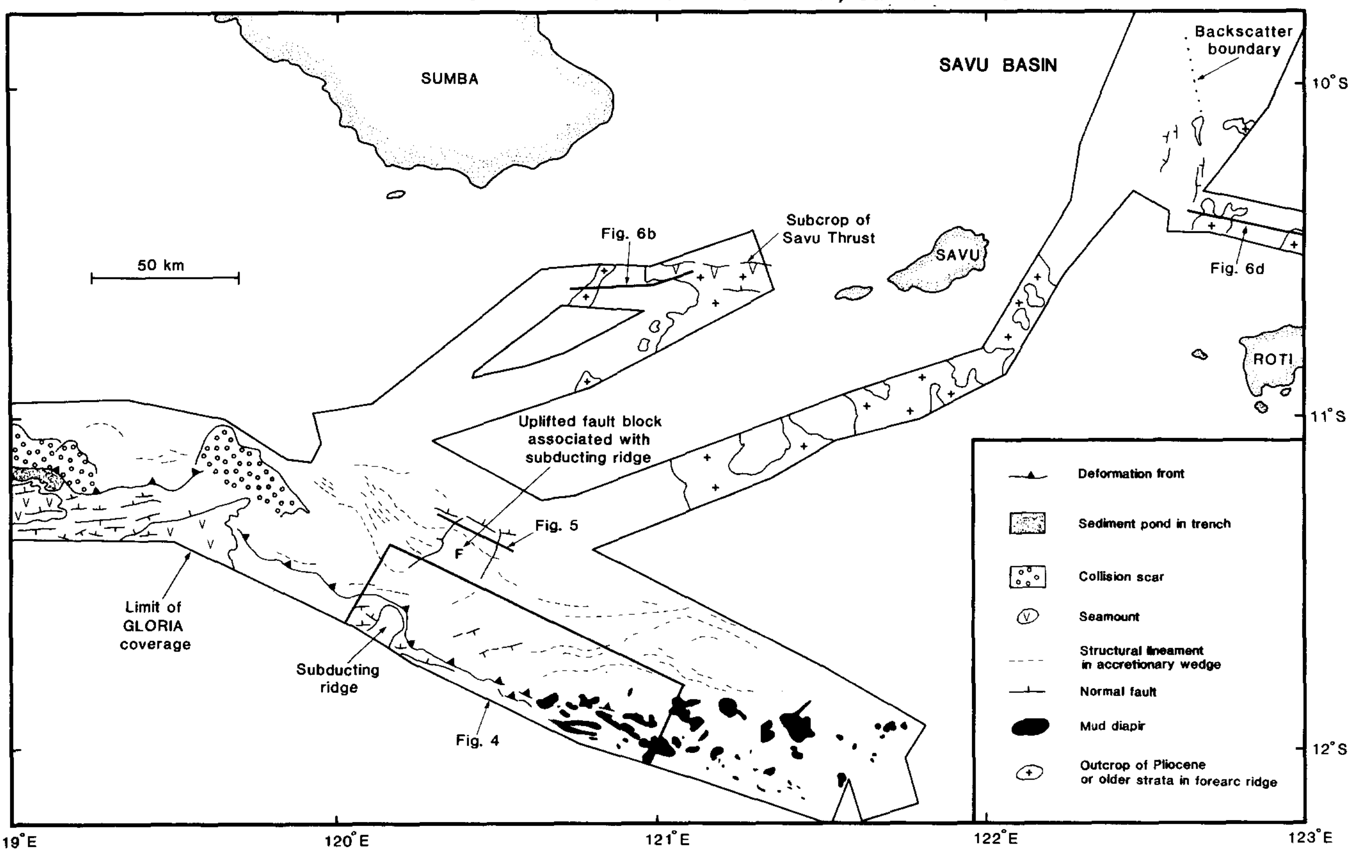

Figure 3 Interpretation of GLORIA data from the area south and west of Timor

end of the Java Trench to the volcanic arc in the vicinity of the Wetar Thrust (*Figure 2*). Such evidence (or its absence) would be used to test and possibly modify existing tectonic models of the collision zone. A basic assumption of the study is that if a significant proportion of the Australia–Banda Arc convergence (in total 7.5 cm y^{-1} in an approximate north–south direction) is transferred across the arc in the vicinity of western Timor, then some evidence of cross-arc faulting and linking compressional relays would be expected. The Savu Thrust (*Figure 3*) has been suggested as one element of such a system (Price and Audley-Charles, 1987, their *Figure 1*).

GLORIA system and survey

GLORIA is a long-range sidescan sonar operating at a frequency of 6.5 kHz. A maximum swath width of 45 km can be achieved in deep water. For detailed descriptions of the sidescan see Somers *et al.* (1978) and Somers and Searle (1984). Sonographs produced by GLORIA record acoustic energy back-scattered from the sea-bed. This may be influenced by both the large-scale topography of the sea-floor and by its texture or roughness (e.g. Somers and Searle, 1984). Corrections for slant-range distortion and for variations in ship's speed along track are applied to the raw data which are then displayed as plan-view photographic images.

The survey discussed here was carried out from R.R.S. *Charles Darwin* during February 1988. Ship's speed during the survey was 8 kts. An airgun seismic profiling system, 3.5 and 10 kHz high resolution profiling systems and a magnetometer were towed simultaneously with GLORIA. These profile data aid in the identification of sonar targets crossed by the ship.

Observations and interpretation

Eastern Java Trench and western Timor Trough

Previous studies. Two small areas in the western Timor Trough have previously been studied using SEAMARC II sidescan sonar (*Figure 2*; Breen *et al.*, 1986; Karig *et al.*, 1987). Between 123° 50′ and 124° 20′ E, Karig *et al.* (1987) mapped a series of large folds (up to 10 km wavelength) on the lower part of the slope south of Timor. Individual anticlines extend for up to 20 km alongslope, and most are thrust-bounded on their southern sides. Karig *et al.* (1987) interpreted the deformation in terms of discontinuous advance of the thrust front as new thrust slices are added from the subducting Australian continental margin. The thrust front is irregular because of the discontinuous nature of the thrust-bounded anticlines which mark it.

A contrasting style of deformation was observed by Breen *et al.* (1986) over most of the lower slope between 120° and 121° E. Here, large folds are absent, and deformation is believed to occur on a system of closely spaced seaward-verging folds and conjugate strike–slip faults. This uniformly advancing zone of shortening, distributed over the lower slope, gives rise to a laterally continuous deformation front. Breen *et al.* (1986) presented a hypothesis which explained the differences in structural style between the fold and thrust areas and those where more uniformly distributed deformation occurs. In their model, the length of the decollement developed ahead of the thrust front is the critical parameter — a long decollement gives rise to long, thin thrust sheets which buckle and deform by large-scale folding, while a short decollement produces short, thick thrust sheets which favour laterally uniform deformation.

Breen *et al.* (1986) also recognised a field of mud

diapirs within the Timor Trough at the eastern edge of their study area between 120°45′ and 121° E. These workers proposed a relatively simple relationship between the thrust front (defined as the 'farthest extent of surface thrusts'), the deformation front ('the farthest extent of the decollement propagating in front of the accretionary wedge'), and the distribution of mud diapirs. In their model, diapirs form due to elevated fluid pressures associated with the decollement propagating ahead of the thrust front; this accounts for their restricted occurrence in the region between the thrust and deformation fronts. The elongate nature of the diapirs mapped by Breen *et al.* (1986) also led to the suggestion that they may form along incipient thrusts propagating upward from the advancing decollement. However, these workers could offer no convincing explanation for the restriction of diapirs to the area east of 120° 45′ E. Theoretical calculations of fluid pressures showed only small (insignificant?) differences between east and west. They suggested variations in sediment type or thickness as a possible cause, but could offer no evidence because no sample information was available.

Mud diapirs and mud volcanoes are also developed extensively in Timor and the adjacent islands of the Outer Banda Arc (Tjokrosapoetro, 1978, Barber *et al.*, 1986, Barber and Brown, 1988). In central West Timor these are circumscribed plugs of clay derived from the Permo–Triassic sequence which can be correlated with the sequence drilled in the boreholes on the North-west Australian Shelf. A direct analogue to the diapirs seen in the sidescan sonar imagery to the south of Sumba occurs in the northern part of the Kolbano area, near Soe. Here, a 10 km wide, 80 km long linear belt of melange (Bobonaro Scaly Clay, Rosidi *et al.*, 1981) is composed largely of blocks of Lower Cretaceous radiolarian chert and Upper Cretaceous calcilutites in a matrix of Lower Cretaceous clays. This linear belt of melange is interpreted as a diapiric ridge generated by the overpressuring of clays in the distal Australian margin sequence as they were loaded by the southward advance of the accretionary complex. During the continued advance of the deformation front this ridge was incorporated into the accretionary complex and deformed and uplifted into the island of Timor.

New observations. West of 119° 45′ E, the Java Trench is a clearly defined bathymetric deep with a water depth exceeding 6 km (*Figure 2*). It seems reasonable to assume that this clearly defined trench corresponds to the area where Indian Ocean crust is being subducted beneath the Banda Arc, although the location of the north-western edge of the Australian continent is not precisely known. The GLORIA sonographs of this area image the trench axis, a narrow strip of oceanic crust to the south, and the lower part of the accretionary wedge to the north (*Figure 3*; Masson *et al.*, in press). The thrust front which marks the surface trace of the subduction zone is an irregular, easterly trending structure, clearly defined on the sonographs. Major indentations in the front, usually associated with areas of high back-scattering (interpreted as collision scars) on the accretionary wedge, are related to the subduction of sea-mounts (Masson *et al.*, in press). Two such structures occur near the eastern end of the trench, at 119° 05′ and 119° 45′ E (*Figure 3*). On sonographs of the accretionary wedge, individual folds are recognised only immediately adjacent to the thrust front, and rarely have wavelengths over 1 km. Landward of the thrust front, as deformation intensifies, the accretionary wedge acquires a typical high back-scattering, grainy appearance on the sonographs, with the grain aligned subparallel to the deformation front; individual structures cannot be differentiated using GLORIA data (Masson *et al.*, in press).

East of 119° 45′ E, the well defined trench disappears, although a trough marked by the 4000 m contour, and the thrust front associated with the trough's northern edge can be traced, in an ESE direction, at least as far as 120° 45′ E, and possibly as far as 121° E (*Figures 3* and *4*). Here, the identity of the thrust front is lost in a field of mud diapirs (*cf.* Breen *et al.*, 1986). The apparent abrupt change in the trend of the thrust front at 119° 45′ E is greatly exaggerated by the front's indentation by a sea-mount on the underthrusting plate at this point, and we do not believe that the trend change has major tectonic significance. The trend change and the associated southward bulge in the accretionary wedge (*Figure 1*) more probably mark only the eastward thickening of accreting sediment from the Australian continental margin, which in turn increases the rate of southward growth of the wedge. Eastward from 119° 45′ E, the thrust front follows a sinuous ESE trend until 120° 10′ E, where it is again indented by an upstanding basement block (*Figure 4*). However, in contrast to the sea-mounts further west, this indentor is an ENE trending, upstanding fault block of Australian continental crust, rising some 600–800 m above the surrounding sea-floor (Breen *et al.*, 1986). No collision scar is seen in the accretionary wedge landward of this indenting block, again a contrast with the area further west (Masson *et al.*, in press). Instead, we see an ESE trending uplifted ridge, probably fault bounded, in the accretionary wedge; this is 200–300 m high, about 15 km wide and extends some 40 km landward of the thrust front (*Figures 3* and *5*). No precise explanation of the differences in behaviour of the accretionary wedge in the two areas can be given. However, we would suggest that the much greater thickness of sediment on the underthrusting Australian continental margin, relative to the ocean plate further west, gives wide scope for the differences in behaviour of the resulting accretionary wedge.

East of 120° 10′ E, the thrust front again follows a sinuous ESE trend until 120° 45′ E, where the western end of a field of mud diapirs and ridges is encountered (*Figure 4*). Part of this diapir field has previously been mapped by Breen *et al.* (1986). However, with the advantage of the much greater areal coverage possible with the GLORIA system, several new observations concerning the diapir field can be made. Firstly, the diapir field is an important regional feature, extending at least 100 km east from 120° 40′ E (*Figure 3*). Secondly, the change in the style of deformation at 120° 40′ E first postulated by Breen *et al.* (1986) is even more dramatic than initially suggested (*Figures 3* and *4*). The well defined thrust front to the west, with its associated high back-scattering accretionary wedge, dies out abruptly, to be replaced eastward by the diapir field. No clearly defined laterally continuous thrust front can be recognised, on GLORIA or seismic reflection data, in the area of the diapir field; the high back-scattering lower part of the accretionary wedge is

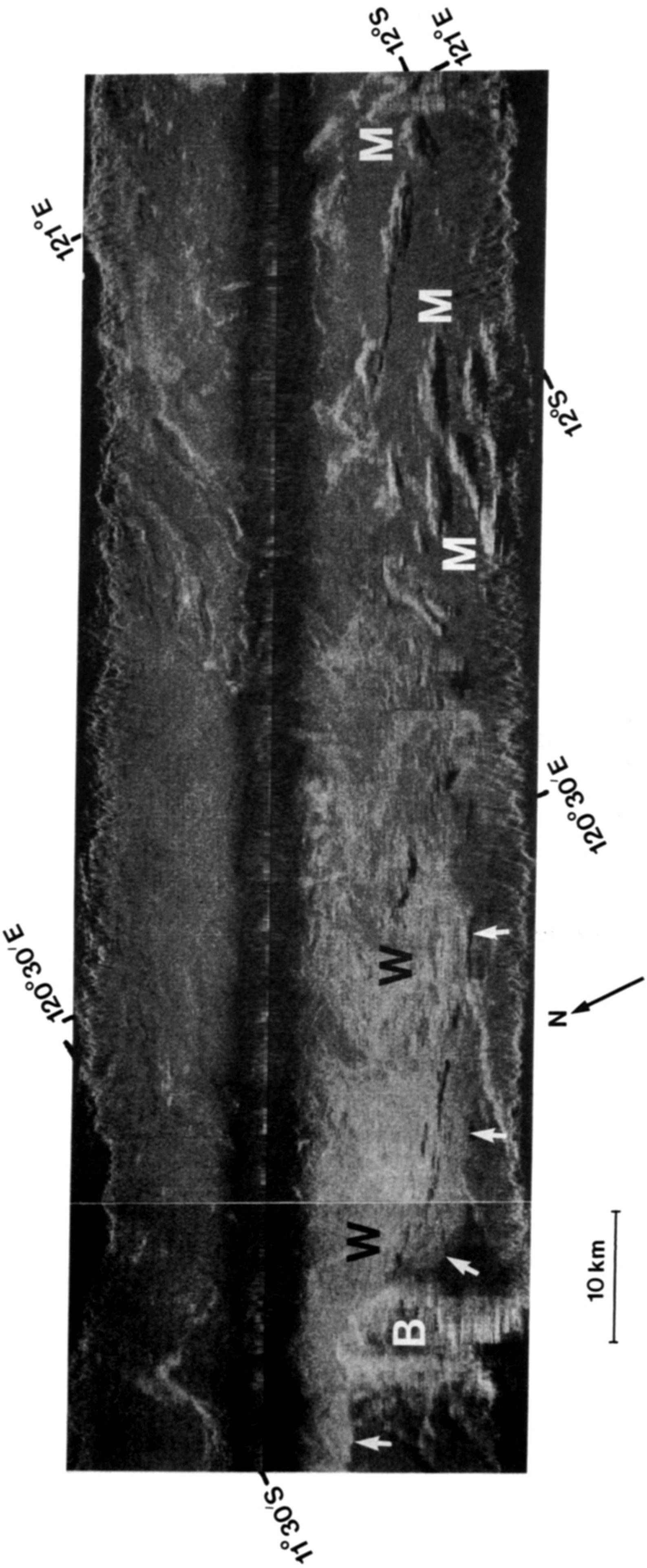

Figure 4 GLORIA sonograph from the western Timor Trough. At its western end, this shows an upstanding fault block (B) of the Australian continental margin indenting the accretionary wedge (W). At this point, the wedge is characterized by high back-scatter (light tones) and has a clearly defined deformation front (arrows). Further east, however, these characteristics disappear, and the expected position of the deformation front is occupied by a mud diapir province (M). Figure located on *Figure 3*

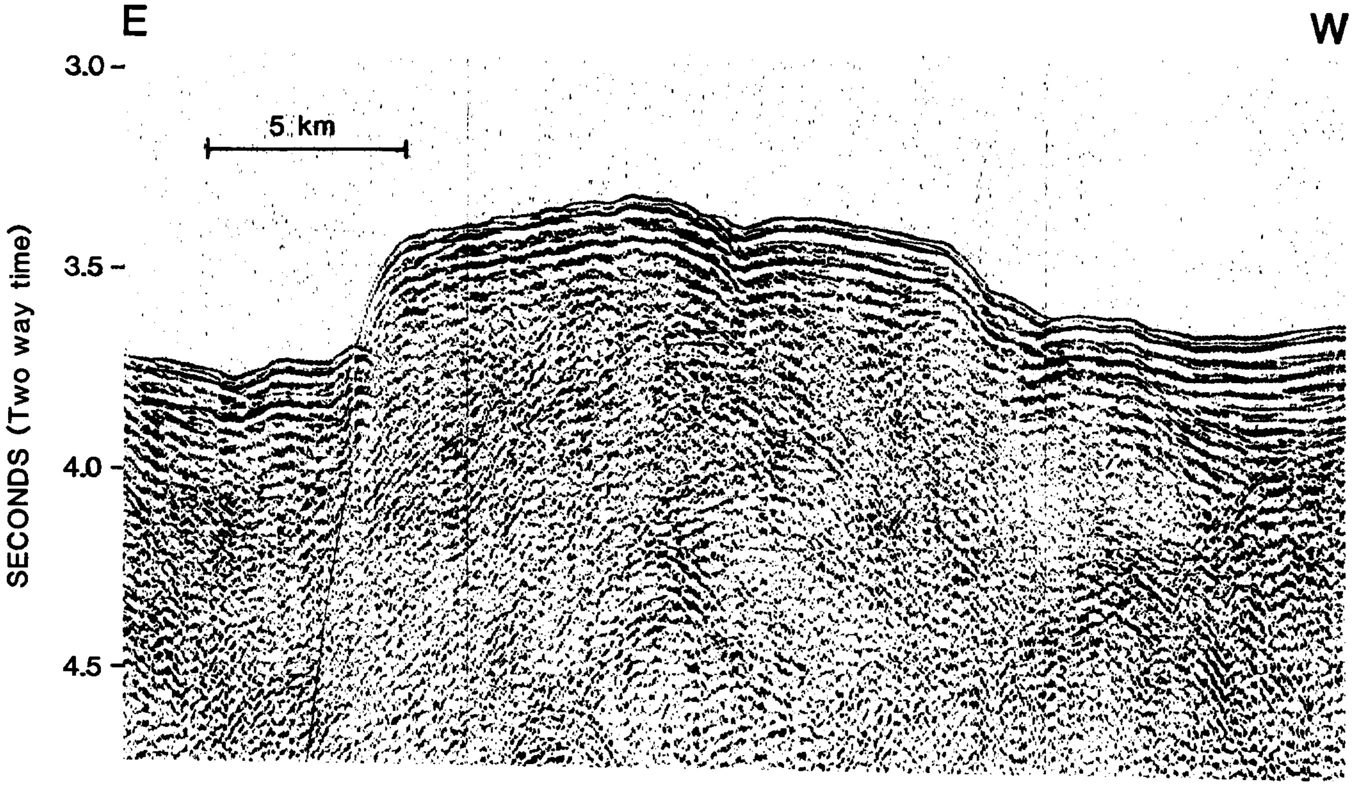

Figure 5 Seismic reflection profile across the fault-bounded ridge on the accretionary wedge which occurs landward of the subducting basement ridge shown in *Figure 4*. Profile located on *Figure 3*

also absent. Local thrusts may be associated with elongate diapirs, as recognised by Breen *et al.* (1986); indeed, the easternmost few kilometres of the thrust front mapped by these authors follows one such local thrust. Thirdly, the elongate nature of the diapirs at the western end of the field is not a regional characteristic of the diapir field. Further east, most of the diapirs have an irregular to sub-circular shape (*Figures 3* and *4*). Finally, the field of diapirs becomes wider eastward, with diapirs occurring both to the north and south of the bathymetric trough which, on a regional scale, defines the southern limit of deformation (*Figure 3*). The diapir field does not extend eastwards into the Timor Trough as far as the area covered by the SEAMARC II imagery described by Karig *et al.* (1987); only one possible diapir was observed in seismic reflection profiles in this area.

Away from the immediate vicinity of the thrust front, the accretionary wedge east of 119° 45′ E is characterized by only a few subtle lineations on the GLORIA data (*Figure 3*). Where these lineations cross the ship's track, they correlate with small fault scarps and the flanks of ridges and troughs, which collectively define the structural grain of the accretionary wedge. On the GLORIA data, this structural grain is parallel or sub-parallel to the thrust front along almost the entire length of the Java Trench and the western Timor Trough between 108° and 120° 45′ E (*Figure 3*; Masson *et al.*, in press). Between 119° 45′ and 120° 45′ E, most of the structures thus trend ESE, with only a few cross-cutting faults observed, such as those which define the uplifted fault block associated with the basement ridge subduction at 120° 10′ E. East of 120° 45′ E, however, the structural fabric bends round to an easterly or slightly north of east trend, paralleling the regional bathymetric contours (*Figure 3*). Easterly trends are also seen in SEAMARC II data collected farther east between 123° 50′ and 124° 20′ E (Karig *et al.*, 1987).

Discussion. (a) Relationship between the Java Trench and the Timor Trough In the interpretation of our new geophysical data from the eastern Java Trench, we have followed the well defined deformation front observed at the Java Trench (Masson *et al.*, in press), eastward into the Australia–Banda Arc collision zone. The main conclusion that must be drawn from our interpretation is that the major zone of deformation, which lies immediately landward of the trench west of 119° 45′ E, continues into the Timor Trough.

(b) Mud diapirs and deformation styles Three distinct styles of deformation have been documented along the eastern Java Trench and western Timor Trough. At the Java Trench, accretion of the thin (<400 m, e.g. Hamilton, 1979) sedimentary cover on the oceanic plate appears to result in small-scale folding and thrusting. This style of deformation occurs all along the eastern trench and into the western Timor Trough as far as 120° 45′ E, but it changes abruptly at this point (*Figure 4*). From here eastward, and extending to at least 121° 50′ E, the area of the apparent deformation is characterized by a field of mud diapirs. It is clear that mud diapirism is not superimposed on the same style of deformation as is seen further west, but that the entire style of deformation changes; as well as the abrupt appearance of diapirism, we also see the disappearance of the well defined thrust front and the high back-scattering accretionary wedge (*Figures 3* and *4*). Further east again, at about 124° E, yet another style of deformation is seen. Here, the thick (>5 km, Karig *et al.*, 1987) sediment pile deforms into broad folds, with wavelengths of up to 10 km,

which can be traced for up to 20 km along-slope (Karig *et al.*, 1987). Thrusts are developed along the outer flanks of the folds, giving rise to a discontinuous thrust front. Unfortunately, neither GLORIA nor SEAMARC data are available between 122° and 123° 50′ E, and the transition between the diapir province and the province of broad folds is not observed.

Factors which might control variations in deformation style have been discussed by Breen *et al.* (1986), and the most important are likely to be changes in the geometry of the convergence zone and changes in the facies and thickness of the deforming sediments. Considerable along-strike variation in the slope of the accretionary wedge does occur between the Java Trench in the west and the Timor Trough in the east. However, the changes in deformation style all occur within the western Timor Trough, along which such variation is small. According to Breen *et al.* (1986), the change in convergence zone geometry across the western margin of the mud diapir province is insignificant in terms of its effect on theoretical calculations of fluid pressures within the sediments, and is unlikely to be the factor controlling the location of the diapir province boundary. This leads us to the conclusion that changes in the sediments themselves must be the controlling factor.

Seismic profiles reveal that the daipirs rise from a seismically transparent unit of Early Cretaceous age which is widely distributed on the north-east Australian margin (Breen *et al.*, 1986). Drilling data from the adjacent Australian continental shelf indicate that this transparent unit consists of marine shale, which may reach 300 m in thickness (Exon *et al.*, 1982). In the area of the Timor Trough studied by Breen *et al.* (1986) and in this paper, this sequence is most clearly seen and is near its maximum thickness in the diapir field area, strongly suggesting that the occurrence of diapirs is restricted to the area where the shale is thickest. It is possible that the diapirs of southern Timor are sourced by the same Cretaceous shale unit. Continued active diapirism well to the north of the deformation front is suggested by the occurrence of 27 active mud volcano fields in the island of Timor (Barber *et al.*, 1986). Mud diapirs may be generated wherever suitable lithological units (i.e. impermeable shale units) are overpressured by thrusting.

Forearc Ridge around Savu, and the Savu Basin

Previous studies. The Savu Basin is a complex forearc basin to the west and north-west of Timor (*Figure 2*). An understanding of the tectonics of this basin and of the outer-arc high which forms its southern flank is essential to an overall understanding of the eastern Java Trench area (Silver *et al.*, 1983; Reed *et al.*, 1986; Karig *et al.*, 1987). Two depocentres are recognised in the Sava Basin; an older, mid-Miocene to Pliocene sub-basin in the south, and a younger, ?late Miocene to Holocene sub-basin in the north. Although the strata of the south Savu Basin depocentre have been weakly deformed and tilted toward the north, Karig *et al.* (1987) considered that current deformation in the Savu Basin is negligible, particularly when compared to the level of deformation occurring at the Timor Trough. However, they do note a possible right-lateral fault zone, recorded as a 'zone of stratal disruption' on seismic reflection profiles, which occurs between the islands of Savu and Roti.

Deformation along the southern boundary of the Savu Basin has occurred at the Savu Thrust, which displaces acoustically opaque material of the forearc ridge over the stratified fill of the Savu Basin (Silver *et al.*, 1983; Reed *et al.*, 1986, 1987; Karig *et al.*, 1987). However, there is some disagreement as to whether the Savu Thrust is an active or fossil feature. Reed *et al.* (1986) refer to the thrust as a 'developing' feature, and clearly believe it to be active. In contrast, Silver *et al.* (1983) and Karig *et al.* (1987) note that the thrust is, in places, overlain by several hundred metres of contourite sediment, which makes significant recent movement impossible. Locally, however, the thrust overides basin strata as young as Pliocene in age, indicating activity as late as the late Pliocene or early Quaternary (Karig *et al.*, 1987).

New observations (a) *The forearc ridge around Savu.* GLORIA data was collected over the forearc ridge both to the east and west of Savu (*Figure 2*). The main features of this area are irregular patches of high back-scatter which are particularly well developed towards the ridge crest. Airgun seismic and 3.5 kHz profiles show that these patches correspond to outcrop of acoustically opaque material at the sea-bed (*Figure 6*). Widespread erosion of the sea-floor by deep currents flowing from the Banda Sea to the Indian Ocean is recognised in the Savu area, where middle Miocene to late Pliocene consolidated sediment and possibly older strata are exposed (Reed *et al.*, 1986, 1987). We therefore interpret the high back-scatter as resulting from these rock outcrops, with the intervening low back-scatter areas corresponding to contourite deposits (*Figure 6*).

Immediately west of Savu, the northern edge of one of these high back-scattering patches lies close to the position of the Savu Thrust as mapped by Reed *et al.* (1986, 1987). However, our seismic profiles indicate that the thrust does not outcrop in this area, but that it is buried by several hundred metres of contourites, in agreement with the observations of Silver *et al.* (1983) and Karig *et al.* (1987). We note also that McCaffrey (1988) found 'no earthquakes on the Savu Thrust'. The boundary observed on the sonographs marks only the pinchout of the onlapping sediments, which overlie the Savu Thrust, onto the exposed acoustic basement of the Savu Ridge (*Figure 6*). East of Savu, we see no evidence of thrusting, in agreement with previous studies (Karig *et al.*, 1987).

(b) *The Savu Basin and the slope off north-west Timor.* Only subtle variations in back-scattering intensity are seen on GLORIA sonographs from the Savu Basin. Variations are probably due to changes in sea-floor sediment facies, as little correlation exists between features seen on the sonographs and small relief features seen on reflection profiles. The only exceptions to this observation are a composite northerly-trending lineament which extends from 10° 25′ S, 122° 40′ E to 9° 50′ S, 122° 39′ E and three minor scarps parallel to and just to the west of this lineament (*Figure 3*). This main structure is made up of a canyon in the south, an elongate basement ridge in its central part, and a subtle change in back-scatter in the north. It has the same trend as, and is almost coincident with, the eastern boundary of a 'zone of stratal disruption' mapped by Karig *et al.* (1987). These authors suggested

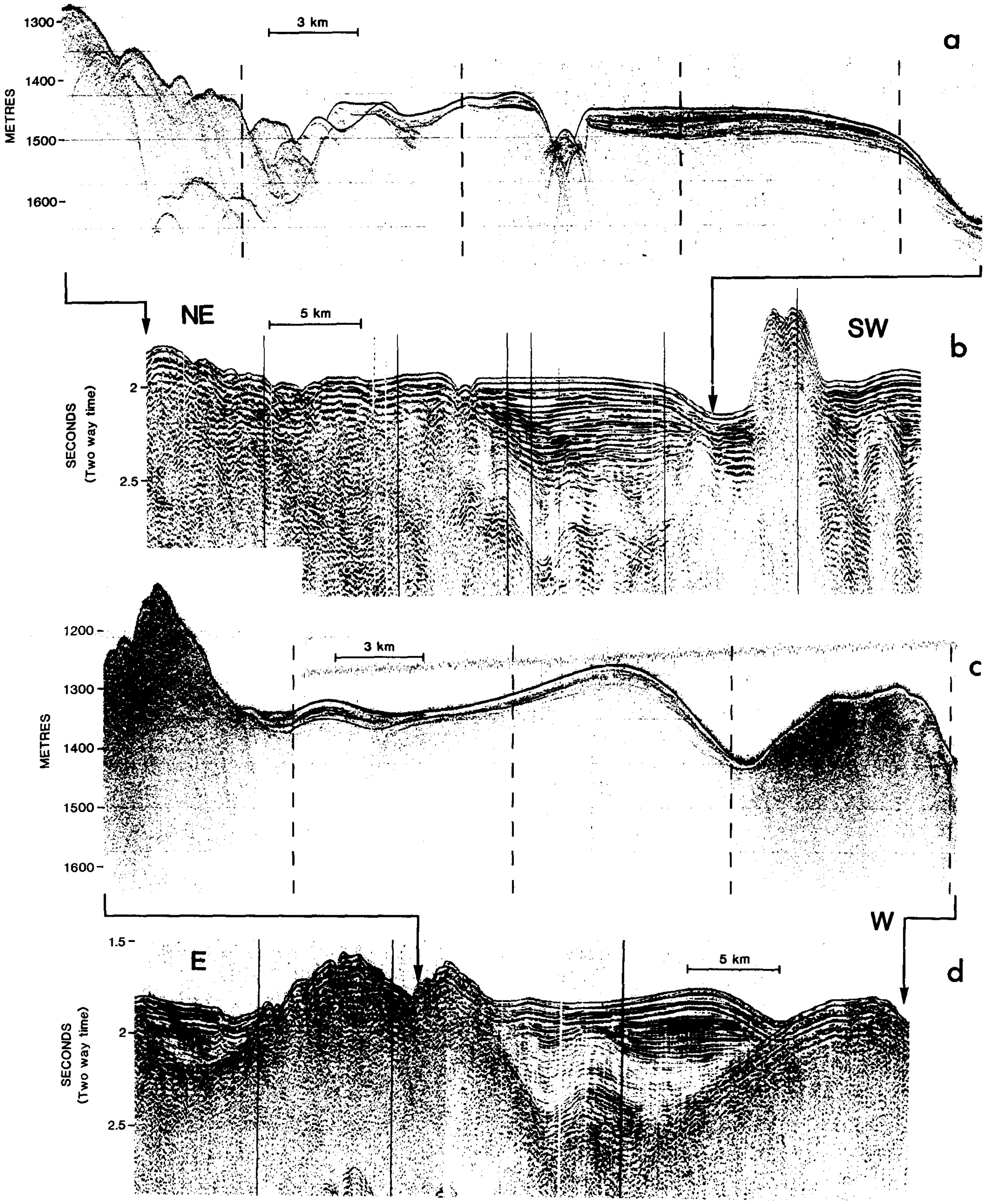

Figure 6 Airgun seismic reflection (b, d) and 3.5 kHz (a, c) profiles from the vicinity of Savu island showing areas of outcrop of consolidated sedimentary rocks interspersed with sediment drifts. The areas of rock outcrop, particularly well defined by their prolonged echo character on the 3.5 kHz record correspond to areas of high back-scatter on the GLORIA records. Profiles located on *Figure 3*

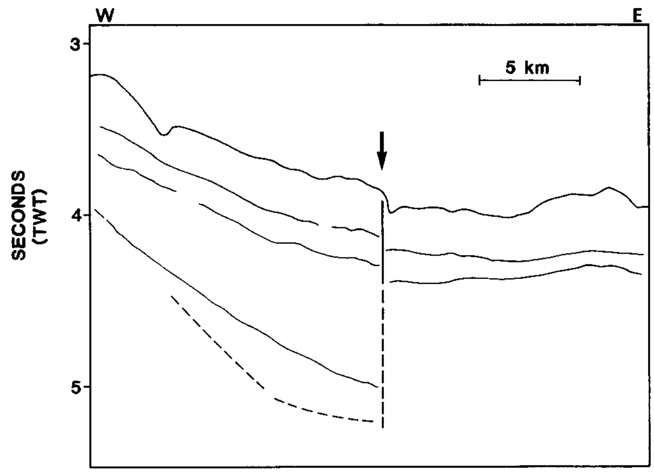

Figure 7 Line drawing of a single-channel seismic profile collected off north-west Timor showing a small normal fault with an offset which reaches the sea-floor. This fault scarp appears as a weak north-trending lineament on the corresponding GLORIA sonograph. Figure located on *Figure 2*

that this disruption zone could mark a (minor?) right-lateral strike-slip displacement, although they had no direct evidence to support this theory. However, the variability of the structure along strike would appear to be best explained in terms of a strike-slip feature.

Further to the north-east, the northern slope off Timor is dominated by erosion and canyon formation, with little evidence of recent tectonic activity. However, in two places there is evidence for northerly trending structures which parallel the possible strike-slip lineament seen in the Savu Basin. Firstly, north of the island of Roti, we see a north-trending canyon which cuts diagonally across the bathymetric contours, truncating tributary canyons which are perpendicular to the slope. This strongly suggests structural control. Secondly, north of Timor at 123° 40′ E, a north-trending scarp on the sonograph corresponds to a small normal fault seen on the seismic reflection profile collected along our cruise track (*Figure 7*). East of 123° 40′ E, many canyons also have a northerly trend, but as these are also perpendicular to the slope, the degree of structural control, if any, is unknown. No evidence of faulting, other than that at 123° 40′ E, is seen on the seismic profile along this part of the slope, but much of the profile shows little penetration, and cannot be taken as a reliable guide.

Discussion. In the region extending from east of Savu to western Timor, virtually no evidence was found for recent tectonic activity away from the immediate vicinity of the Timor Trough, with the possible exception of minor strike-slip faulting perpendicular to the deformation front. There seems little possibility that a significant proportion of the convergence is transferred to the north-east, through the Savu Basin, to be taken up north of Timor. In particular, we would agree that the Savu Thrust is a relict feature, as previously suggested by Silver *et al.* (1983) and Karig *et al.* (1987). This does not, of course, preclude the possibility that some convergence could be transferred along the coast of west Timor, or through the island itself as suggested by the mapping of onshore left-lateral faults (Charlton *et al.*, in press).

Volcanic arc offset between Alor and Wetar

Previous studies. The Banda Volcanic Arc is defined as the inner ring of islands surrounding the Banda Sea, all of which are of volcanic origin (e.g. Abbott and Chamalaun, 1981). Most of these islands have experienced historically active volcanism, although Wetar, Atauro and possibly Alor, within our area of interest, have apparently been inactive for about 3×10^6 years (Abbott and Chamalaun, 1981). Nevertheless, almost all authors refer to these islands as part of the volcanic arc, as they are entirely volcanic in origin and because this serves to distinguish them from the dominantly non-volcanic islands, such as Timor, of the Outer Banda Arc (e.g. Abbott and Chamalaun, 1981; Silver *et al.*, 1983; Breen *et al.*, 1989). The most striking feature of the volcanic island arc north of Timor is the northward displacement of Wetar and the islands to the east relative to Atauro, Alor and the islands to the west (*Figures 8* and *9*). Such an offset could be attributed to a north-trending left-lateral transcurrent fault running just off the west coast of Wetar and passing east of Atauro, and having a displacement of about 50 km [(*Figure 8(a)*]. However, such an explanation produces problems further south, most notably because there is no corresponding offset in the Timor coast due south of Atauro, and the gap between Timor and Eastern Alor is therefore anomalously small.

Breen *et al.* (1989) note that back-arc thrusts, which are features of the southern Banda Sea from Sumbawa to Wetar (Silver *et al.*, 1983) and which are associated with present day seismic activity (McCaffrey and Nabelek, 1984; McCaffrey, 1988) have an atypical NE–SW trend north-west of Wetar. They attribute this trend to a complex interplay between stike-slip faulting and back-thrusting of segments of both the volcanic and non-volcanic arcs. Of particular relevance is their recognition of left-lateral strike-slip faults west of Wetar. They solve the problem of close approach of Timor to Alor by postulating a thrust fault along a short length of the north Timor coast [(*Figure 8(b)*].

New observations (a) *The area between Alor and Wetar.* The GLORIA data collected in 1988 to the west of Wetar (*Figure 9*) confirm the existence of the series of north-east-trending thrusts which were previously mapped on the basis of the limited area of SEAMARC II data and several widely spaced seismic lines (Silver *et al.*, 1983; Breen *et al.*, 1989). Thrust structures typical of convergent margins are clearly imaged and the results from this area are, in fact, much more strongly suggestive of convergence than those from the 'normal' Wetar Thrust north of Wetar (Milsom *et al.*, in preparation). The GLORIA coverage south of the SEAMARC survey has allowed mapping of a suite of north-east to north-trending faults extending from the north coast of Timor at 125° 05′ E, around both sides of Atauro, to off the north-east tip of Wetar at about 125° 45′ E (*Figure 8*). In the north these faults merge to form the sidescan feature correlated by Breen *et al.* (1989) with a distinct sea-floor groove on seismic profiles (their *Figure 8*), and termed by them the Wetar-Atauro Fault. Clear evidence for left-lateral motion is seen in this area, with north-trending faults offsetting ridges in the convergence zone.

Further south, around Atauro, the faults trend

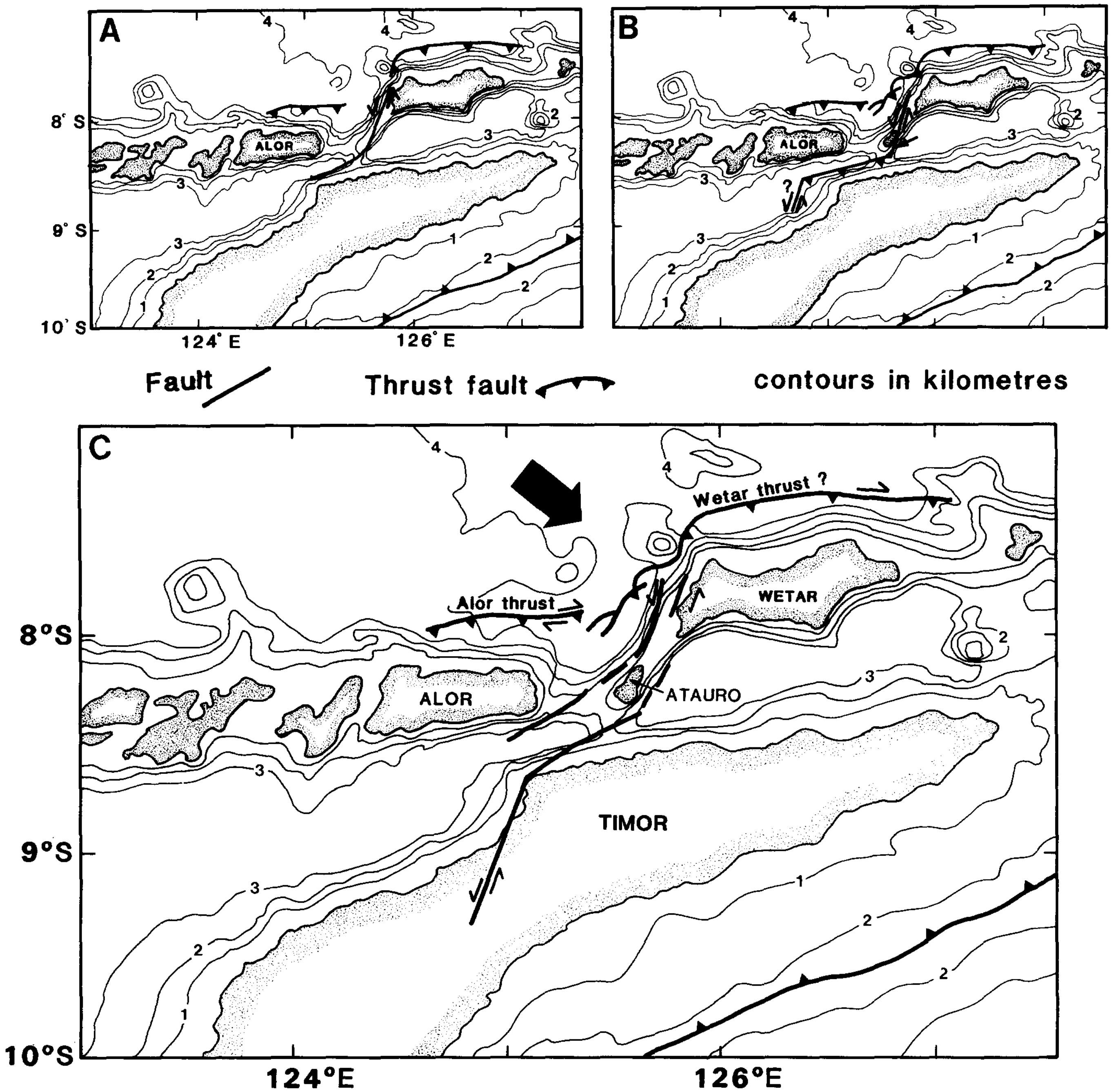

Figure 8(A) 'Minimum faulting' solution to the Alor–Wetar offset, with a single strike–slip fault offsetting the arc and the thrusts bounding it to the north. **(B)** Solution offered by Breen *et al.* (1989), with a short section of thrust along part of the north coast of Timor. **(C)** Solution based on GLORIA data, with eastward movement of Wetar under influence of Banda Sea deformation (schematically shown by arrow) giving rise to the deep basin in southern part of Alor–Wetar gap

NE–SW rather than north, commonly have no clear sea-floor expression or indication of vertical displacement, and may traverse obliquely across steep slopes. The very prominent fault trace illustrated in *Figure 10*, which crosses the strait between Timor and Atauro, marks the top of the slope off Timor but has traversed the slope and marks its base a few kilometres south of Atauro. It lies in approximately the location suggested for the Timor coastal thrust by Breen *et al.* (1989), but there is no indication of compression on the sidescan image. Instead, there is a strong suggestion that this fault, together with a parallel, although less well defined feature south-east of Alor, defines a pull-apart basin some 20 km wide and 5 km deep. Normal faulting is also indicated by two magnitude 5.6 and 5.8 earthquakes analysed by McCaffrey (1988).

A further observation that can be made on the basis of the sonar imagery is that although Atauro seems from its position to be a direct extension of the line of the volcanic arc through Alor, there is no evidence for volcanic activity between the two islands. This 50 km wide gap must be regarded as unusual when compared to the volcanic patterns to both east and west, and adds to the impression that the offset zone is not confined to a single transcurrent fault.

(b) *Wetar Basin.* The new data from the Wetar Basin show no evidence for recent compressional tectonic activity. The sonographs indicate an almost completely flat basin floor with only subtle back-scattering variations, interpreted as arising from changes in sediment facies. In particular, areas of high back-scatter appear to coincide with sediment slides seen on profiles (*Figure 11*). Seismic profiles show that the basin has the appearance of a large extensional

half-graben, with the deeper basin fill showing clear evidence of northward tilting, particularly towards the southern basin edge. The upper part of the basin fill consists of horizontally bedded strata disturbed only by the sediment slides noted above (*Figure 11*). Sonographs of the basin flanks show only sediment transport structures, such as canyons and slide scars, none of which show any obvious tectonic control.

Discussion (a) *GLORIA interpretation*. Our study, which covers a much larger area than that surveyed with SEAMARC by Breen *et al.* (1989), has led to an interpretation of the arc offset rather different from that previously offered. Firstly, the GLORIA data implies that convergence is greater west of Wetar than it is to the north. This suggests that the relative motion between Wetar and the Banda Sea has a west or north-west component, and is not simply north–south as implied by regional plate models. North-westerly convergence is also suggested by seismicity on the thrusts west of Wetar which indicate north-westerly (320–330°) thrust motion of Wetar relative to the Banda Sea (McCaffrey, 1988).

Secondly, rather than the single, north-north-east trending Wetar–Atauro Fault passing to the east of Atauro and terminating against a thrust parallel to the north coast of Timor (as interpreted by Breen *et al.*, 1989), we see a broad fault zone which passes on both sides of Atauro. The change in trend of this fault zone, from northerly off Wetar to north-easterly off Timor, eliminates the need for shortening along the north coast of Timor, for which there seems to be no evidence. However, the nature of the fault zone is not easy to understand, since a north-trending left-lateral fault, as apparently seen west of Wetar, cannot be associated with a north-easterly trending pull-apart basin, as apparently seen off Timor; in this situation north-easterly structures should be compressional rather than extensional. A possible explanation for this is that the fault seen off northern Timor is accommodating only strike-slip and vertical motion, and has no component of extension. This is not incompatible with the earthquake evidence, which indicates a very steeply (~80°) dipping fault plane (McCaffrey, 1988). Neither is it incompatible with the geological evidence, which indicates uplift of Timor in excess of 5 km relative to the basins to the north, since the mid-Pliocene (e.g. Price and Audley-Charles, 1987).

(b) *Arc segmentation between Alor and Wetar*. The observed left-lateral displacements on faults at the northern end of the Wetar–Alor gap suggests that the volcanic arc, formerly continuous between the two islands, has been offset by strike-slip faulting. It seems unlikely that the arc formed with an offset geometry, as there is no seismic evidence for any related disruption in the subducting slab, which would be required to create such an offset. However, at the southern end of the Wetar–Alor gap, near Timor, there is no evidence for faults with north or north-east trends anywhere west of 125° 00′ E, implying that any continuation of the fault zone causing the offset must run down the west of Timor or cut through this island itself. McCaffrey (1988) suggested that segmentation of the Banda Arc in this area is related to left-lateral strike-slip systems which cut across the entire arc, and one of the largest strike-slip faults identified by Charlton *et al.* (in press) runs from the south coast of Timor to the offset in the north coast south of eastern Alor. The apparent lack of

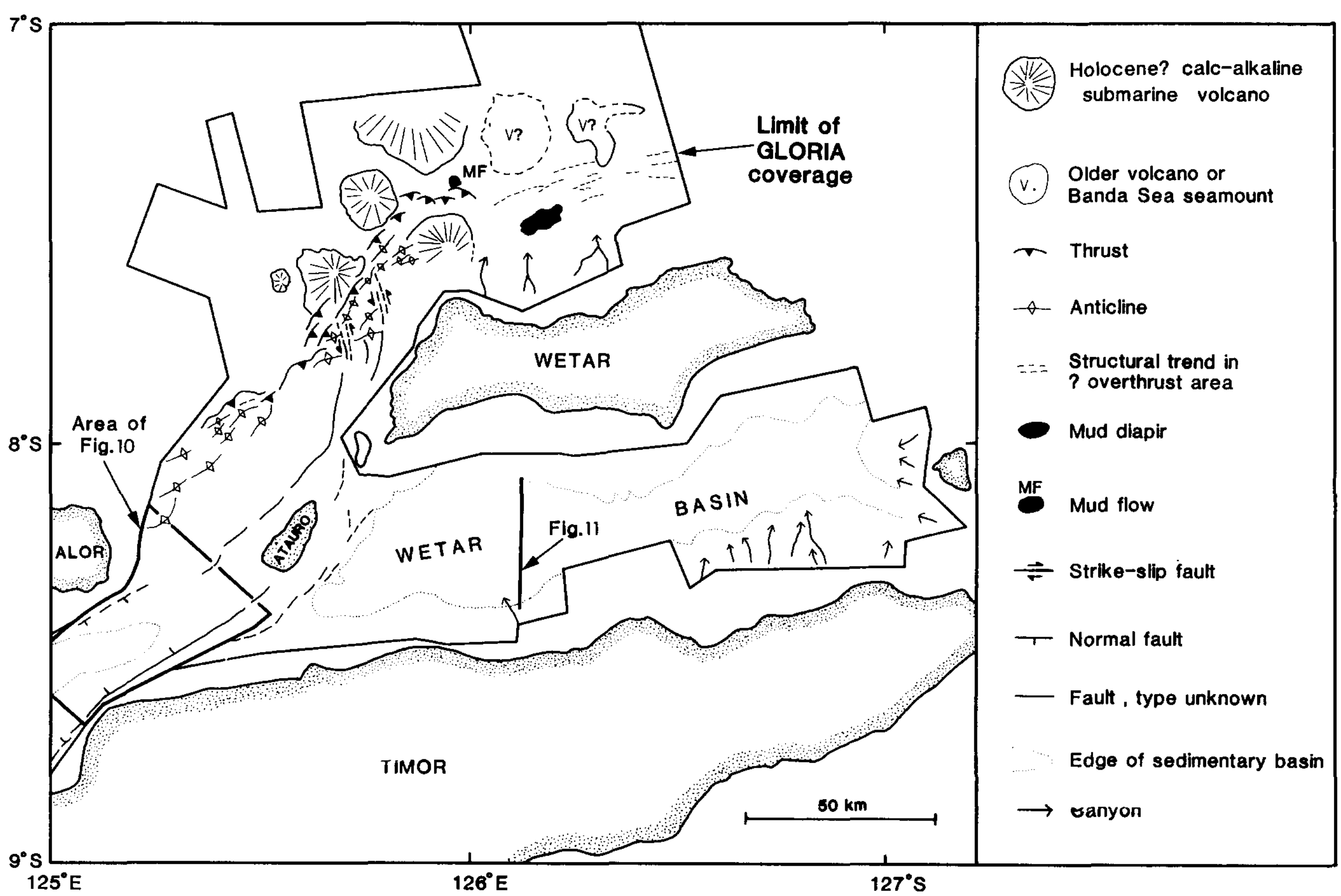

Figure 9 Interpretation of GLORIA data from the area of the arc offset between Alor and Wetar and from the Wetar Basin

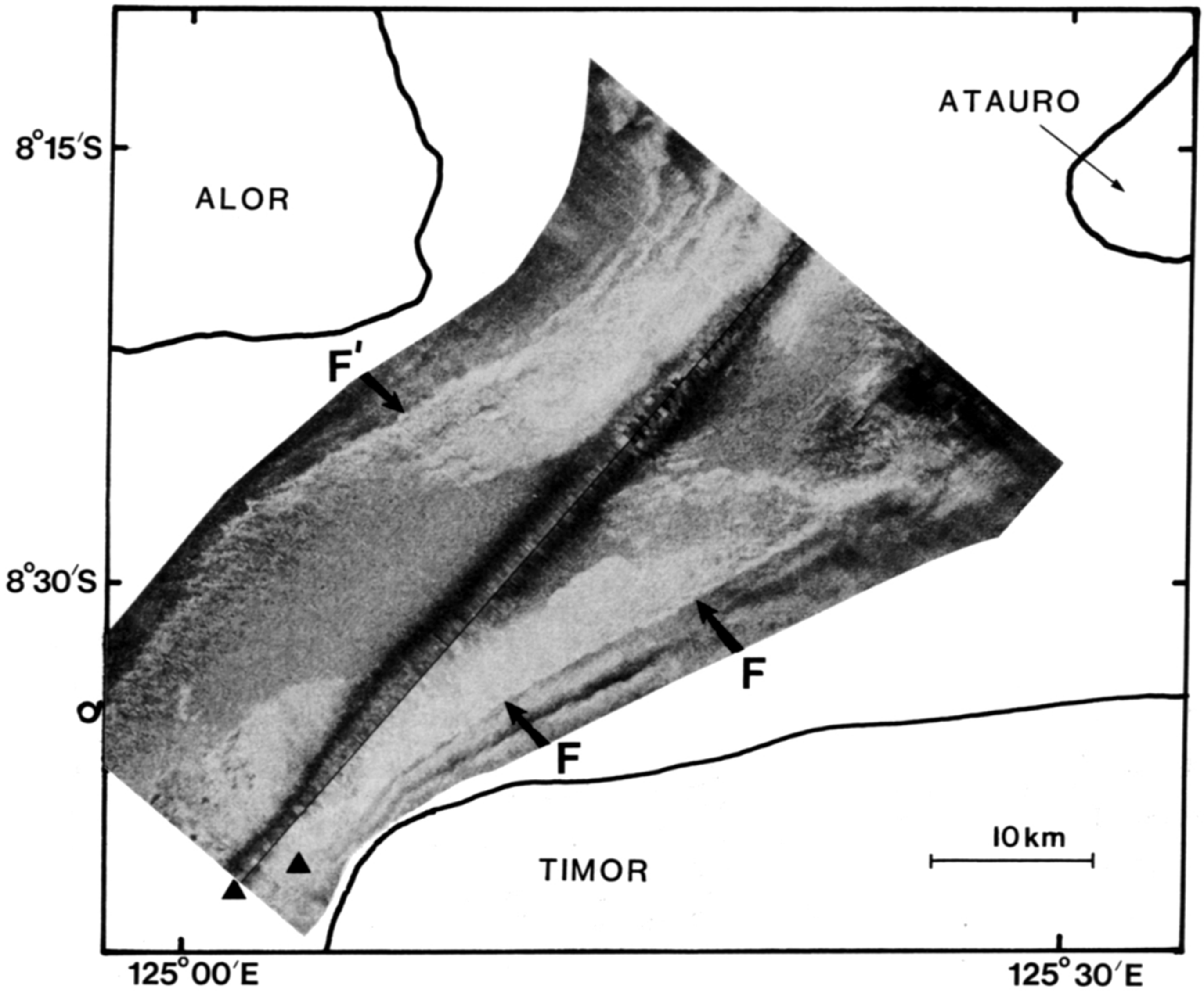

Figure 10 GLORIA sonograph covering the area between the north coast of Timor and the islands of Alor and Atauro. Areas of high back-scatter (light tones) correspond to steep basin slopes; low back-scatter areas are sediment-filled basins with little relief. Note the major fault (F) which extends from the continental shelf off northern Timor, crossing the slope in a north-easterly direction towards Atauro. Two large earthquakes (triangles), indicating normal faulting, have occurred near the southern end of this fault. A parallel fault (F') may occur on the other side of the basin, but it is less well imaged. The double image of part of the main fault trace on the GLORIA record appears to be an artifact related to the steep topography, which allows multiple sound paths with different travel times through the water column. Figure located on *Figure 9*

any zone of compression which might transfer motion between this fault and the Wetar–Atauro Fault of Breen *et al.* (1989) remains a problem, but a solution, outlined below, may exist which would also explain the anomalous width of the Wetar–Alor gap.

As already noted, the gap between Alor and Wetar–Atauro amounts to some 50 km and we suggest that this occurs because the Wetar block has been translated east as well as north. The fault-plane solutions presented by McCaffrey (1988) for the area north-west of Wetar imply that the Banda Sea floor is converging on Wetar from the north-west and this can only be the case if, as suggested in the same paper, the Banda Sea is deforming internally. The pressure exerted on Wetar from the west might be accommodated by eastward translation of the island as well as by underthrusting. Further south, the gap region is shielded from such pressure by Alor but could be dragged into extension by the movements of the Wetar block. The short-lived and now extinct volcanism on Atauro (Abbott and Chamalaun, 1981) could have accompanied one phase in this tearing process, another consequence of which could have been formation of the transtensional basin imaged by GLORIA. The pattern of faulting illustrated in *Figure 8C* seems to agree with all the observations made to date.

Conclusions

Distribution of deformation in the vicinity of Timor

The results of our GLORIA survey go some way to resolving the controversy concerning the accommodation of the present day convergence of the Indo-Australian and South-east Asian plates near Timor. The data now available indicates very clearly that little or no deformation is currently occurring on the Savu Ridge, in the Savu Basin, or in the Wetar Basin. When combined with existing data, our results also confirm that zones of faulting appear to cross the entire arc, through Timor, and that some shortening in the upper plate might be transferred from the Timor

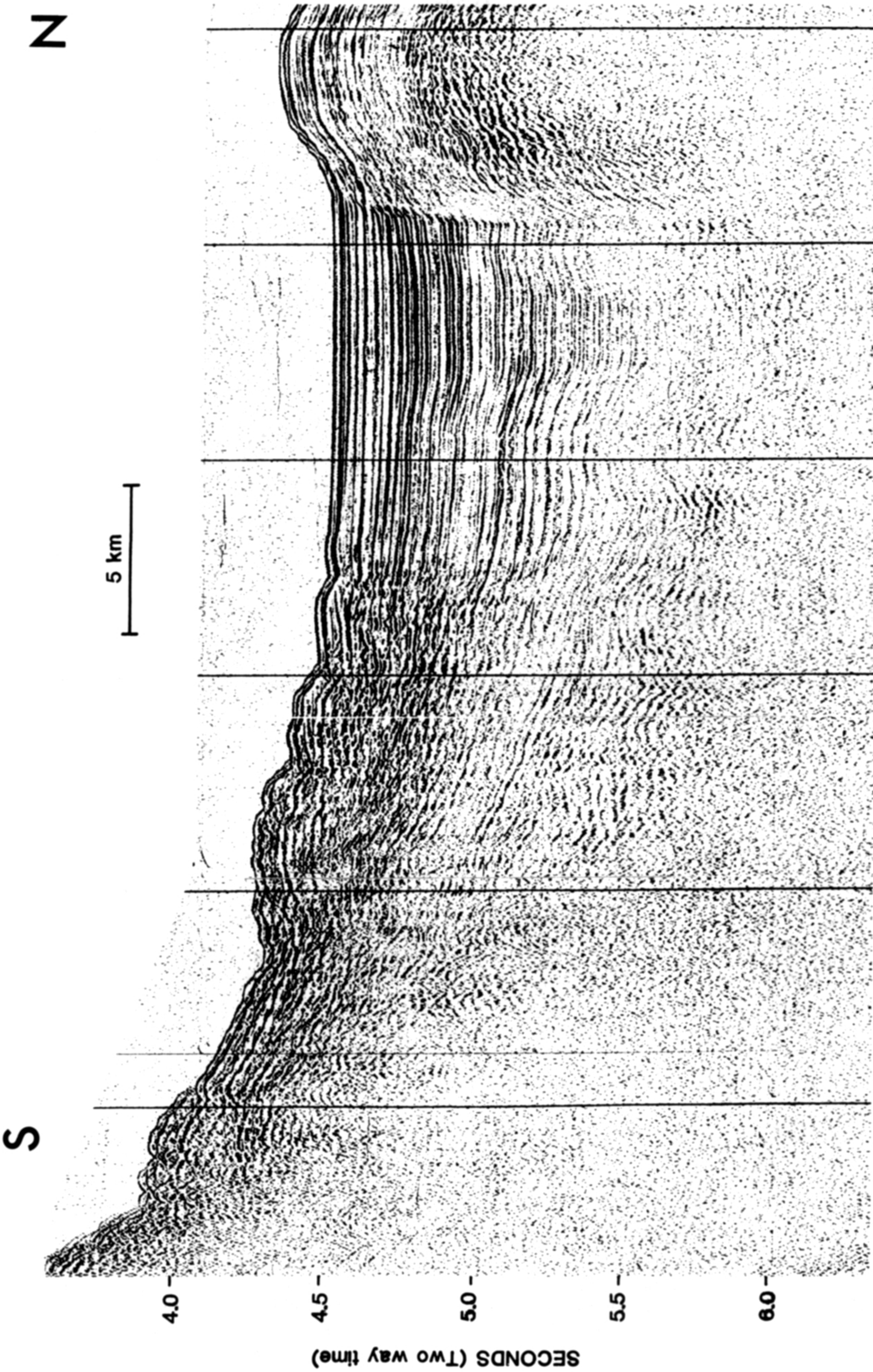

Figure 11 North–south seismic profile across the Wetar Basin interpreted as showing an extensional sedimentary basin. Limited stratal disruption seen on the southern side of the basin is confined to the upper part of the section and is due to a large slump. Deeper, basinward tilted strata in this area may be evidence for syn-depositional extension. Figure located on *Figure 9*

Trough to the back-arc region via such faults. However, neither our data nor that presented by McCaffrey (1988) implies much convergence on the Wetar thrust, and it seems unlikely that this thrust has done much more than accommodate the offset between Wetar and Alor. If this is correct, then the Timor Trough is the only significant convergence zone at a plate tectonic scale.

This conclusion appears to be in contradiction with that drawn from both seismicity and sedimentation history, which suggest a low convergence rate at the Timor Trough. Firstly, we note the calculations of McCaffrey (1988), based on strain released by major earthquakes, and his conclusion that only a fraction of the total plate convergence can be absorbed along the Timor Trough. However, continuing subduction at the Trough may be proceeding aseismically because of a high degree of lubrication by the water-rich sediments of the Australian margin. In this respect, it should be noted that the seismicity across the entire Banda Arc can account for only 20% of the convergent motion between Australia and the Arc (McCaffrey, 1988), strongly supporting the concept of aseismic convergence. Secondly, Johnson and Bowin (1981) and Charlton (1988) have suggested that sedimentation rate studies indicate a recent dramatic slowing of convergence at the Timor Trough. However, these studies take no account of the effects of possible episodic propagation of the deformation front, separated by periods of quiescence, within the trough sediment. In particular, Charlton has described the recent history of the trough near DSDP Site 262 as consisting of two periods of thrusting, dated at approximately 0.45 and 1.0 million years, separated by periods of tectonic inactivity at shallow depth. In this situation, the apparent slow-down of convergence over the last 0.45 million years could be only a temporary phenomenon. Charlton's conclusion that it shows regional slowing of convergence is not unequivocally supported by his data.

Styles of deformation at the Java Trench and Timor Trough

Three styles of deformation have now been reported along the Java Trench and Timor Trough collision zones. These range from small-scale folding along the eastern Java Trench, through a mud diapir province south of Savu, to broad thrust-bounded folds south of western Timor. The GLORIA survey has demonstrated that the mud diapir field identified by Breen *et al.* (1986) to the south of Savu is much more extensive than previously realised, extending at least 100 km eastwards from the eastern end of the Java Trench. The style of deformation appears to be controlled primarily by the thickness and facies of the subducting sediments. In particular, the occurrence of mud diapirs appears to correlate, both in the Timor Trough and onshore Timor, with the thickest development of a Lower Cretaceous shale unit.

The volcanic arc offset between Alor and Wetar

A complex pattern of thrust, strike-slip and ?normal faults have been mapped in the area between Alor and Wetar. Convergence at the Wetar Thrust appears to be on north-west–south-east lines rather than north–south as previously suggested. This, when combined with the pull-apart nature of the deep basin south-east of Alor, suggests eastward translation of Wetar relative to the arc further west. The driving force for such motion could be deformation of the Banda Sea under north–south compression, as suggested by McCaffrey (1988). However, this region is still poorly understood, and our present interpretation will undoubtedly be refined in the future, as additional data becomes available.

References

Abbott, M. J. and Chamalaun, F. H. (1981) Geochronology of some Banda Sea volanics. In: *The Geology and Tectonics of Eastern Indonesia* (Eds A. J. Barber and S. Wiryosujono) *Spec. Pub. Geol. Res. Dev. Centre, Bandung, Indonesia* **2**, 253–268

Audley-Charles, M. G. (1986) Timor-Tanimbar Trough: the foreland basin of the evolving Banda orogen *Spec. Pub. Int. Assoc. Sedimentol.* **8**, 91–102

Barber, A. J. and Brown, K. (1988) Mud diapirism: the origin of melanges in accretionary complexes *Geol. Today* **4**, 89–94

Barber, A. J., Tjokrosapoetro, T. and Charlton, T. R. (1986) Mud volcanoes, shale diapirs, wrench faults and melanges in accretionary complexes, eastern Indonesia *Bull. Am. Assoc. Pet. Geol.* **70**, 1729–1741

Breen, N. A., Silver, E. A. and Hussong, D. M. (1986) Structural styles of an accretionary wedge south of the island of Sumba, Indonesia, revealed by SEAMARC II sidescan sonar *Bull. Geol. Soc. Am.* **97**, 1250–1261

Breen, N. A., Silver, E. A. and Roof, S. (1989) The Wetar back arc thrust belt, eastern Indonesia: the effect of accretion against an irregularly shaped arc *Tectonics* **8**, 85–98

Cardwell, R. K. and Isacks, B. L. (1978) Geometry of the subducted lithosphere beneath the Banda Sea in eastern Indonesia from seismicity and fault plane solutions *J. Geophys. Res.* **83**, 2825–2838

Charlton, T. R. (1988) Tectonic erosion and accretion in steady state trenches *Tectonophysics* **149**, 233–243

Charlton, T. R., Barber, A. J. and de Smet, M. E. T. Banda Arc-Australia collision zone *J. Struct. Geol.* (in press)

Exon, N. F., von Rad, U. and Von Stackelberg, U. (1982) The geological development of the passive margins of the Exmouth Plateau off northwest Australia *Mar. Geol.* **47**, 131–152

Hamilton, W. (1979) Tectonics of the Indonesian region *US Geol. Surv. Prof. Paper 1078*, 345 pp

Johnston, C. R. and Bowin, C. O. (1981) Crustal relations resulting from the mid-Pliocene to Recent continent-island arc collision in the Timor region *BMR J. Aust. Geol. Geophys.* **6**, 223–243

Karig, D. E., Barber, A. J., Charlton, T. R. Klemperer, S. and Hussong, D. M. (1987) Nature and distribution of deformation across the Banda Arc-Australian collision zone at Timor *Bull. Geol. Soc. Am.* **98**, 18–32

Masson, D. G., Parson, L. M., Milsom, J., Nichols, G., Sikumbang, N., Dwiyanto, B. and Kallagher, H. Subduction of seamounts at the Java Trench — a view with long-range sidescan sonar *Tectonophysics* (in press)

McCaffrey, R. (1988) Active tectonics of the eastern Sunda and Banda Arcs *J. Geophys. Res.* **93**, 15163–15182

McCaffrey, R. and Nabelek, J. (1984) The geometry of back arc thrusting along the eastern Sunda Arc, Indonesia: constraints from earthquake and gravity data *J. Geophys. Res.* **89**, 6171–6179

McCaffrey, R. and Nabelek, J. (1987) Earthquakes, gravity, and the origin of the Bali Basin: an example of a nascent continental fold and thrust belt *J. Geophys. Res.* **92**, 441–460

Milsom, J., Masson, D. G., Nichols, G., Sikumbang, N. and Dwiyanto, B. Volcanic provinces and back-arc thrusts in the southern Banda Sea (in prep.)

Price, N. J. and Audley-Charles, M. G. (1987) Tectonic collision processes after plate rupture *Tectonophysics* **140**, 121–129

Reed, D. L., Silver, E. A., Prasetuyo, H. and Meyer, A. W. (1986) Deformation and sedimentation along a developing terrane suture; eastern Sunda forearc, Indonesia. *Geology* **14**, 1000–1003

Reed, D. L., Meyer, A. W., Silver, E. A. and Prasetuyo, H. (1987) Contourite sedimentation in an intraoceanic forearc system: eastern Sunda Arc, Indonesia *Mar. Geol.* **76**, 223–241

Rosidi, H. M. D., Suwitodirdjo, K. and Tjokosapoetro, S. (1981) *Geological map of the Kupang-Atambua Quadrangles, Timor* Bandung Geological Research Centre, Indonesia

Silver, E. A., Reed, D., McCaffrey, R. and Jowodiwiryo, Y. (1983) Back-arc thrusting in the eastern Sunda Arc, Indonesia: a consequence of arc-continent collision *J. Geophys. Res.* **88**, 7429–7448

Somers, M. L. and Searle, R. C. (1984) GLORIA sounds out the seabed *New Sci.* **104**, 12–15

Somers, M. L., Carson, R. M., Revie, J. A., Edge, R. H., Barrow, B. J. and Andrews, A. G. (1978) GLORIA II — An improved long range sidescan sonar. In: *Proceedings of Oceanology International 78, Technical Session J.*, BPS Exhibitions, London, pp 16–24

Tjokosapoetro, S. (1978) Holocene tectonics on Timor Island, Indonesia *Bull. Geol. Res. Develop. Centre, Indonesia* **4**, 48–63

von der Borch, C. C. (1979) Continental-island arc collision in the Banda Sea *Tectonophysics* **54**, 169–193