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Magnetic Lineations in Marginal Basins of the Western Pacific [and Discussion]

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Magnetic lineations in marginal basins of the western Pacific†

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[Pullouts 1 and 2]

This paper separates the small oceanic basins around the western perimeter of the Pacific Ocean into marginal basins that have formed through back-arc extension and those that apparently have not, and reviews our knowledge of magnetic lineation patterns observed in possible and probable back-arc basins. Magnetic lineations in these basins resemble lineations commonly associated with the world's mid-oceanic spreading systems, indicating that similar processes of crustal accretion occur in both tectonic environments. In some back-arc basins of the southwestern Pacific, magnetic lineation and other evidence suggest that back-arc basins can evolve through the interaction and growth of 'multi-plate' systems. Because of the small time and space characteristics of back-arc basins compared with the world's major oceanic spreading systems, tectonic conditions favourable for the generation of back-arc basins are either relaxed rapidly or easily interrupted. Models proposed to account for back-arc basin development include (*a*) 'local' models, where back-arc extension is mechanically driven by the downgoing slab, and (*b*) global plate kinematics models, where conditions favourable for back-arc extension are governed by the motion of the overriding plate relative to the trench axis.

1. Introduction

Crustal extension behind island arc-trench systems is an apparent paradox in plate tectonics because convergent plate boundaries are widely viewed as natural expressions of regional compression. A close association of small oceanic basins with active or relict island arc–trench systems is observed most notably around the western boundary of the Pacific Ocean (figure 1, pullouts 1 and 2). Collectively, these oceanic basins are known as the marginal basins of the western Pacific (Karig 1971; Packham & Falvey 1971). Seismic refraction measurements, and the petrochemistry of igneous rocks recovered from numerous Deep Sea Drilling Project (D.S.D.P.) holes and ocean floor dredges, indicate that almost all of these basins are underlain by crust which is similar to that underlying the major ocean basins of the world. Moreover, magnetic lineation patterns observed in many marginal basins of the western Pacific (figure 1) resemble magnetic lineation patterns associated with spreading systems in the major ocean basins of the world, implying that similar processes of crustal accretion occur at the world's mid-oceanic ridge systems and in marginal basins.

The first step in this paper is to classify marginal basins according to whether their evolution can be understood as resulting from tensional failure in the 'overriding' plate at an oceanic subduction zone (table 1). 'Back-arc' basins are marginal basins formed when an island arc rifts apart and new oceanic material is accreted between the diverging 'active' and 'remnant' island arc fragments. This concept of back-arc ('inter-arc' or 'inner-arc') spreading was formulated by Karig (1970, 1971). Since the existence of a convergent plate boundary is a

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necessary condition in this model for the formation of a back-arc basin, the seafloor of the back-arc basin postdates the age of initiation of the associated subduction zone. 'Not back-arc' basins show no obvious tectonic relation to zones of plate convergence and thus cannot be considered 'back-arc' as defined above. For example, the Aleutian Basin, which geographically appears in a back-arc setting, is believed to be older than the adjacent Aleutian island arc–trench system (Cooper *et al.* 1976). The Aleutian Basin is an example of pre-existing oceanic crust 'trapped' in the rear of the island arc when an island arc–trench system developed in oceanic lithosphere (Uyeda & Miyashiro 1974; Cooper *et al.* 1976).

TABLE 1. MARGINAL BASINS OF THE WESTERN PACIFIC

(See text for explanation of underlining.)

(*a*) *back-arc basins* (1) probable	(*a*) *back-arc basins* (2) possible	(*b*) *not back-arc*
†Okinawa Trough (? Plio.–)	†Andaman Basin (m. Mio.–)	Woodlark Basin (m. Plio–)
†Mariana Trough (l. Mio.–)	Sulu Basin (? Olig.)	South China Basin (Olig.–e. Mio.)
Bismarck Basin (m. Plio.–)	Celebes Basin (Eocene)	Coral Sea Basin (Palaeocene)
†Fiji Plateau (l. Mio.–)	†West Philippine Basin (Eocene)	Solomon Sea Basin (?)
†Lau Basin (l. Mio.–)	Banda Basin (?)	Tasman Basin (l. Cret.–Palaeocene)
Havre Trough (? Plio.–)	Caroline Basins (Olig.)	Aleutian Basin (l. Jur.–e. Cret.)
†Japan Sea Basin (? Olig.–e. Mio.?)	†South Fiji Basin (Olig.)	
†Parece-Vela Basin (Olig.–e. Mio.)	New Hebrides Basin (l. Pal.–l. Eocene)	
†Shikoku Basin (m. Olig.–e. Mio.)	Kamchatka Basin (? Olig.)	
Okhotsk Basin (?)		

† Discussed in this paper.

Table 1 shows that while some marginal basins of the western Pacific fall fairly clearly into 'probably back-arc' and 'not back-arc' categories, several basins listed as 'possibly back-arc' defy simple classification. All but one of the possibly back-arc basins are no longer tectonically active and it is thus difficult to obtain clear evidence linking generation of these basins with zones of plate convergence. Many of these basins have been partly subducted since their formation (e.g. West Philippine and Celebes basins in figure 1*a*, and New Hebrides and South Fiji basins in figure 1*b*), complicating even further the recognition of any possible tectonic relation between crustal extension in these basins and plate convergence.

The purposes of this review are to (*a*) provide an overview of magnetic lineation patterns in several probable and possible back-arc basins (table 1), (*b*) compare crustal accretion processes (inferred from magnetic lineations) in back-arc environments and at mid-ocean ridges, (*c*) examine whether the rules of plate tectonics apply to the opening of back-arc basins, and (*d*) discuss mechanisms that have been proposed for the generation of back-arc basins.

2. MAGNETIC LINEATION PATTERNS

(*a*) *General*

Several factors determine the overall quality of magnetic lineation patterns developed in the world's oceans. By separating these into factors affecting signal amplitude and factors affecting noise amplitude, we can view the quality of magnetic lineations in terms of a signal : noise ratio.

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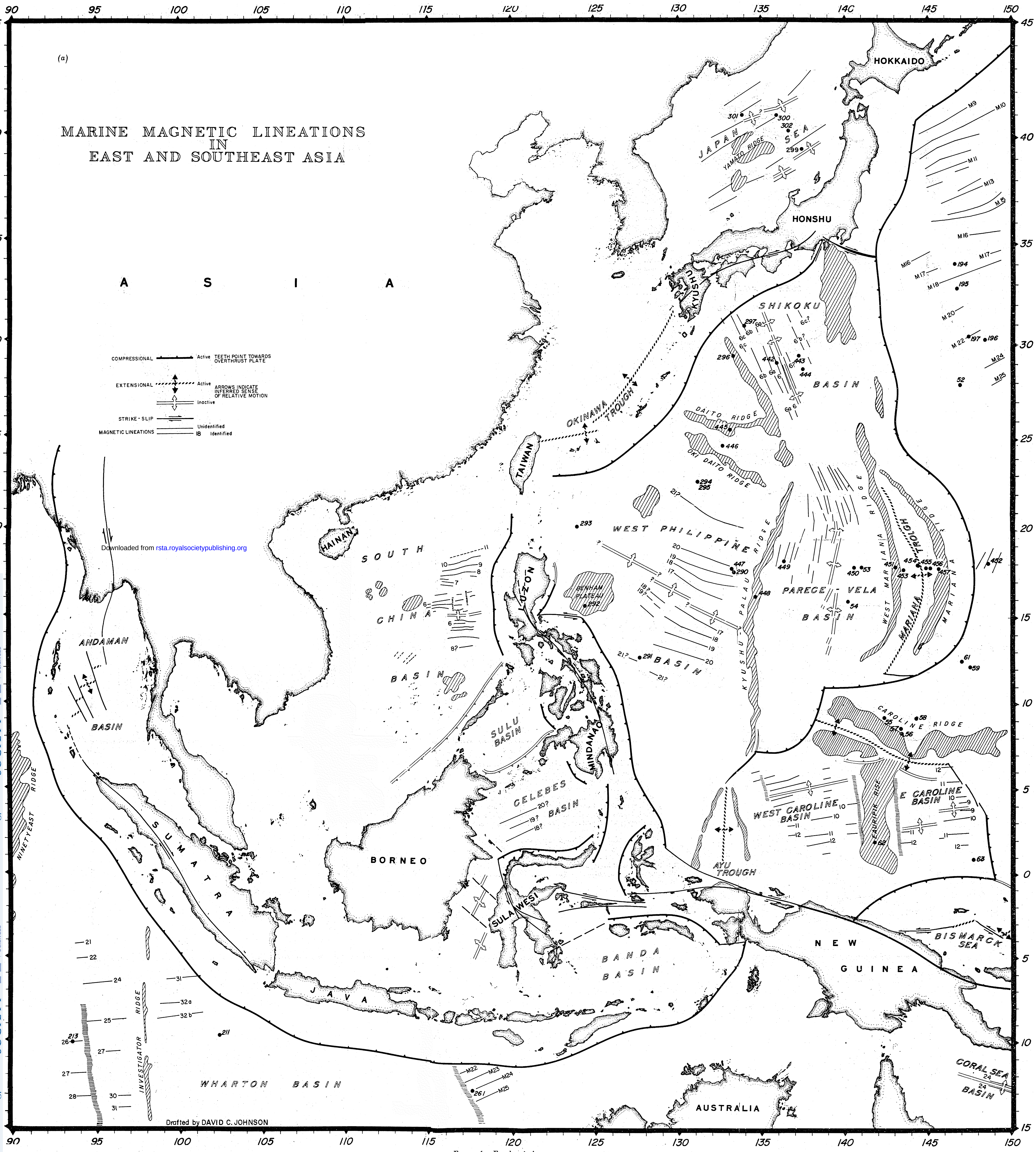

FIGURE 1a. For description see over.

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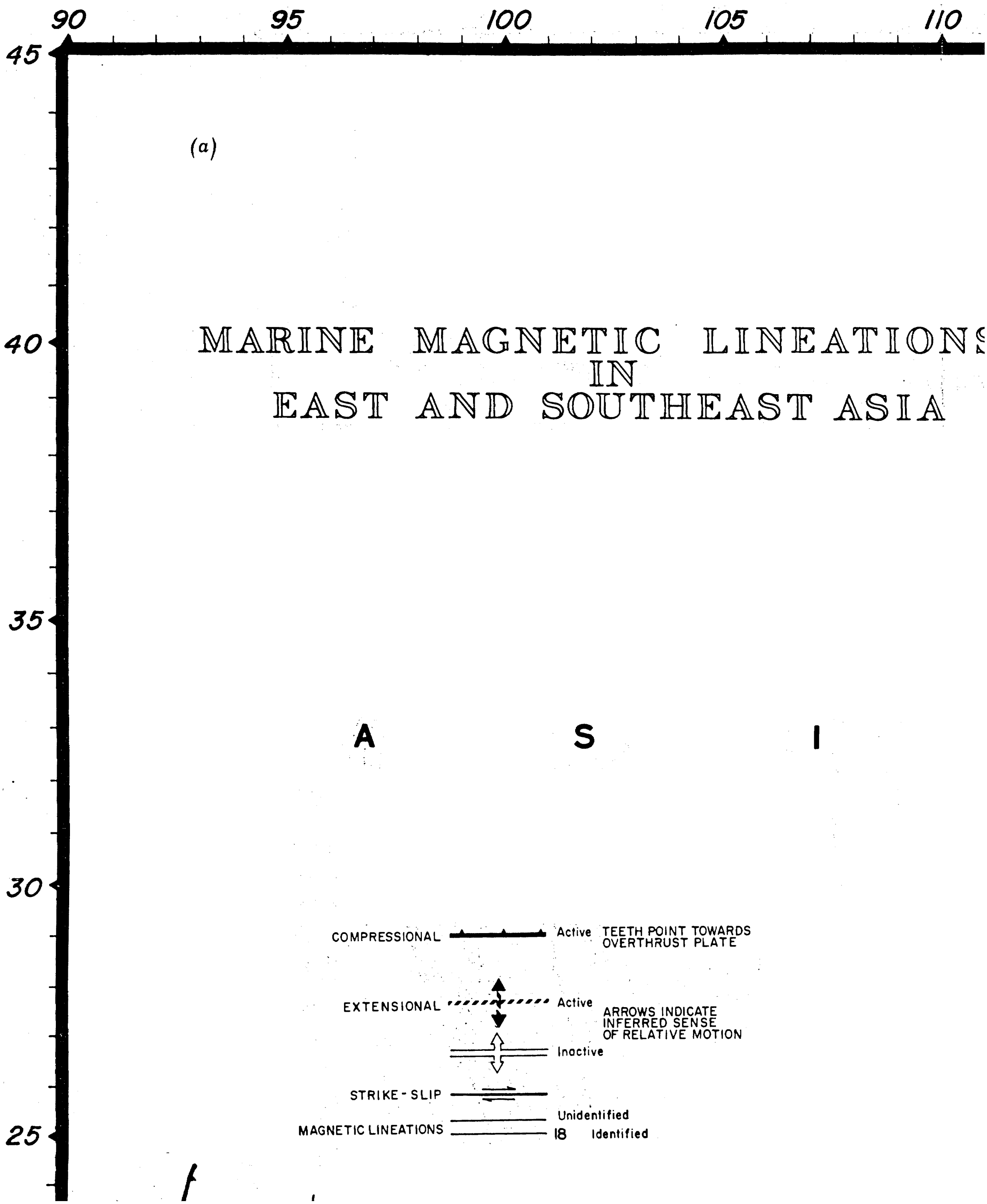
90
95
100
105
110
45
40
35
30
25
(a)
MARINE MAGNETIC LINEATIONS IN EAST AND SOUTHEAST ASIA
A S I
COMPRESSIONAL
Active
TEETH POINT TOWARDS OVERTHRUST PLATE
EXTENSIONAL
Active
ARROWS INDICATE INFERRED SENSE OF RELATIVE MOTION
Inactive
STRIKE-SLIP
MAGNETIC LINEATIONS
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18 Identified


110
115
120
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A
KYUSHU
OKINAWA
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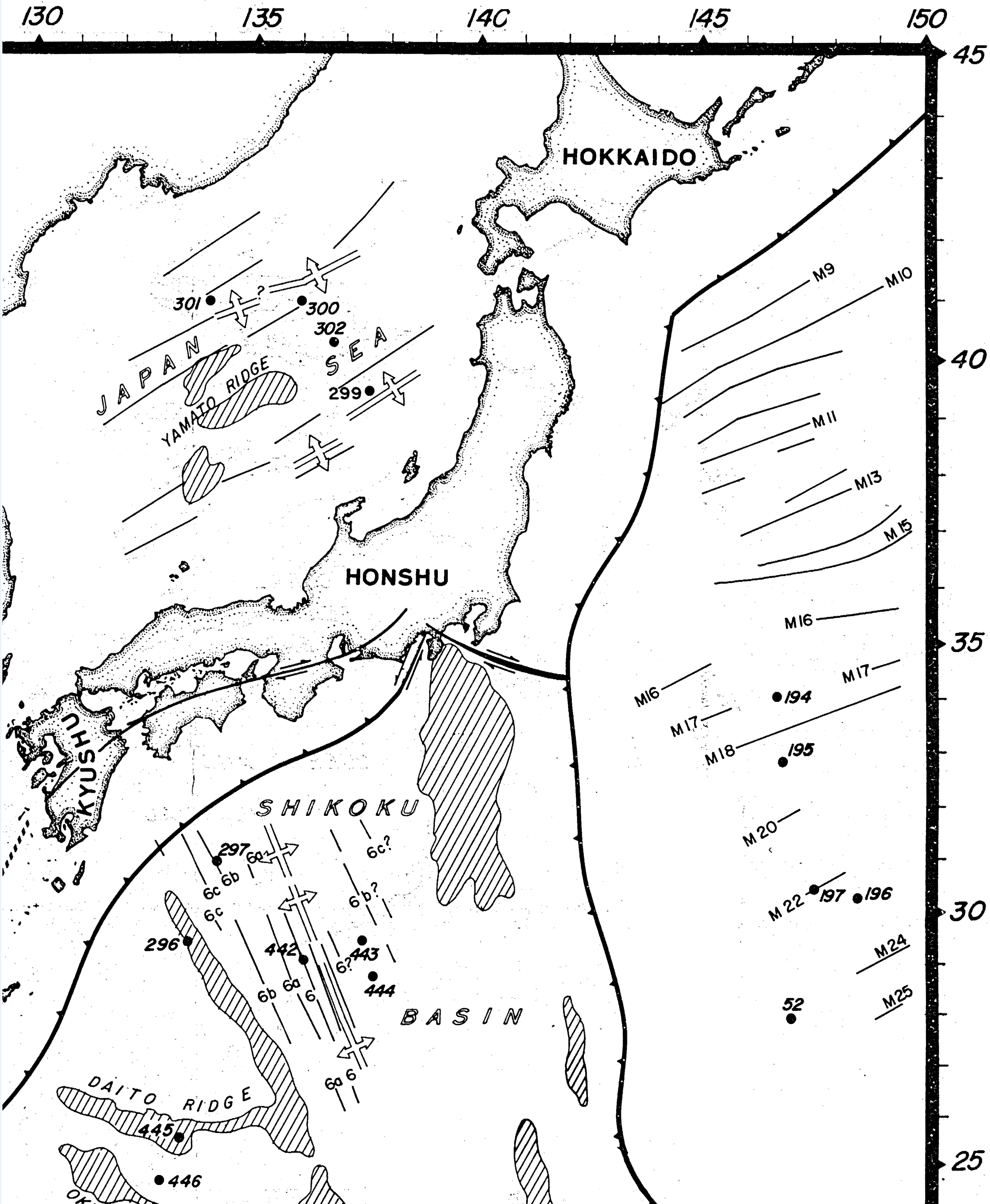
130
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HOKKAIDO
HONSHU
KYUSHU
JAPAN SEA
YAMATO RIDGE
SHIKOKU BASIN
DAITO RIDGE
OKI
301
300
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297
296
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445
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196
197
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M10
M11
M13
M15
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M25
6
6a
6b
6c
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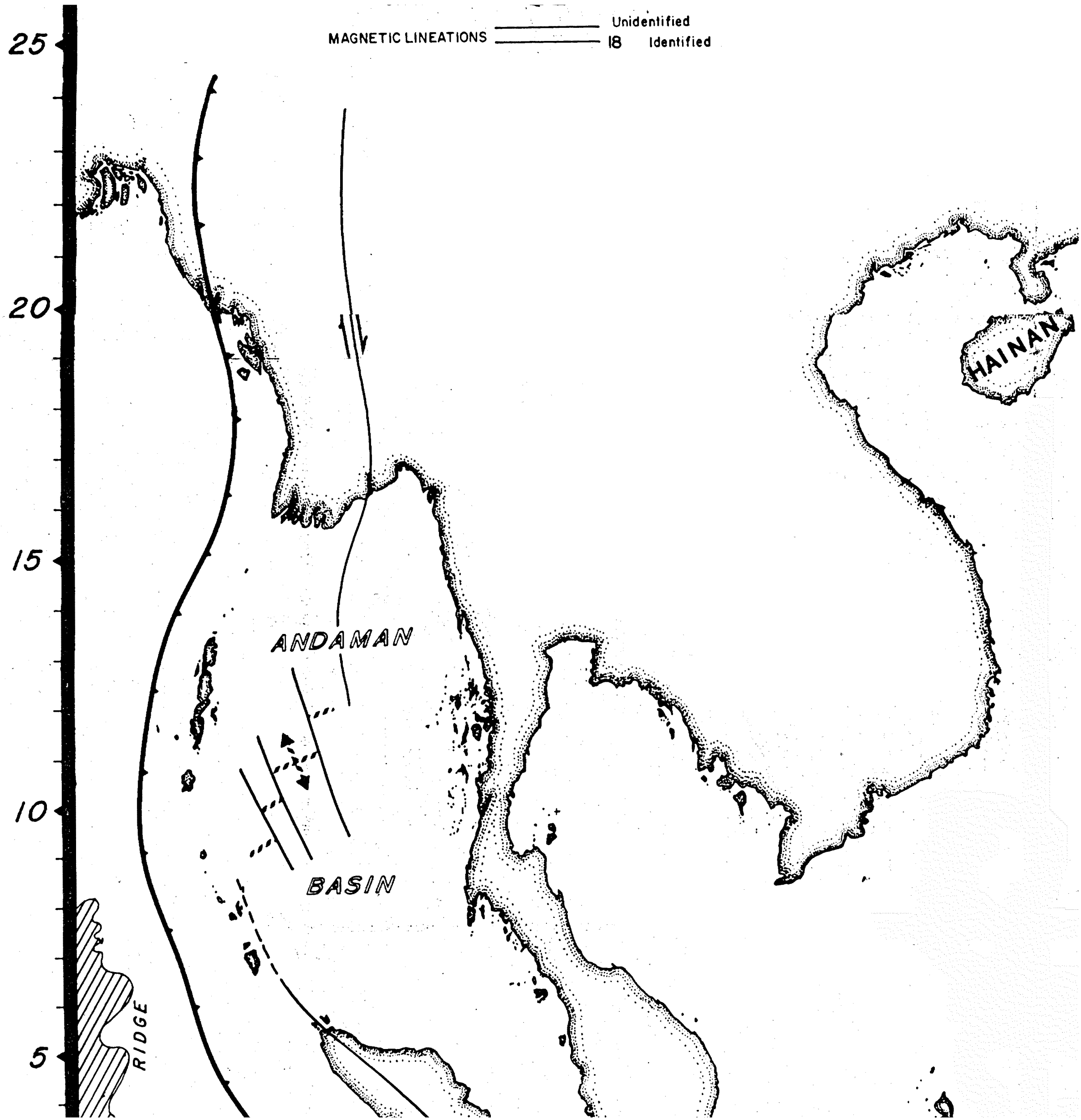
6b?
6?



MAGNETIC LINEATIONS
Unidentified
18 Identified
25
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5
ANDAMAN
BASIN
HAINAN
RIDGE


TAIWAN
HAINAN
SOUTH CHINA BASIN
WEST PHIL
BASI
LUZON
BENHAM PLATEAU
292
293
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SULU BASIN
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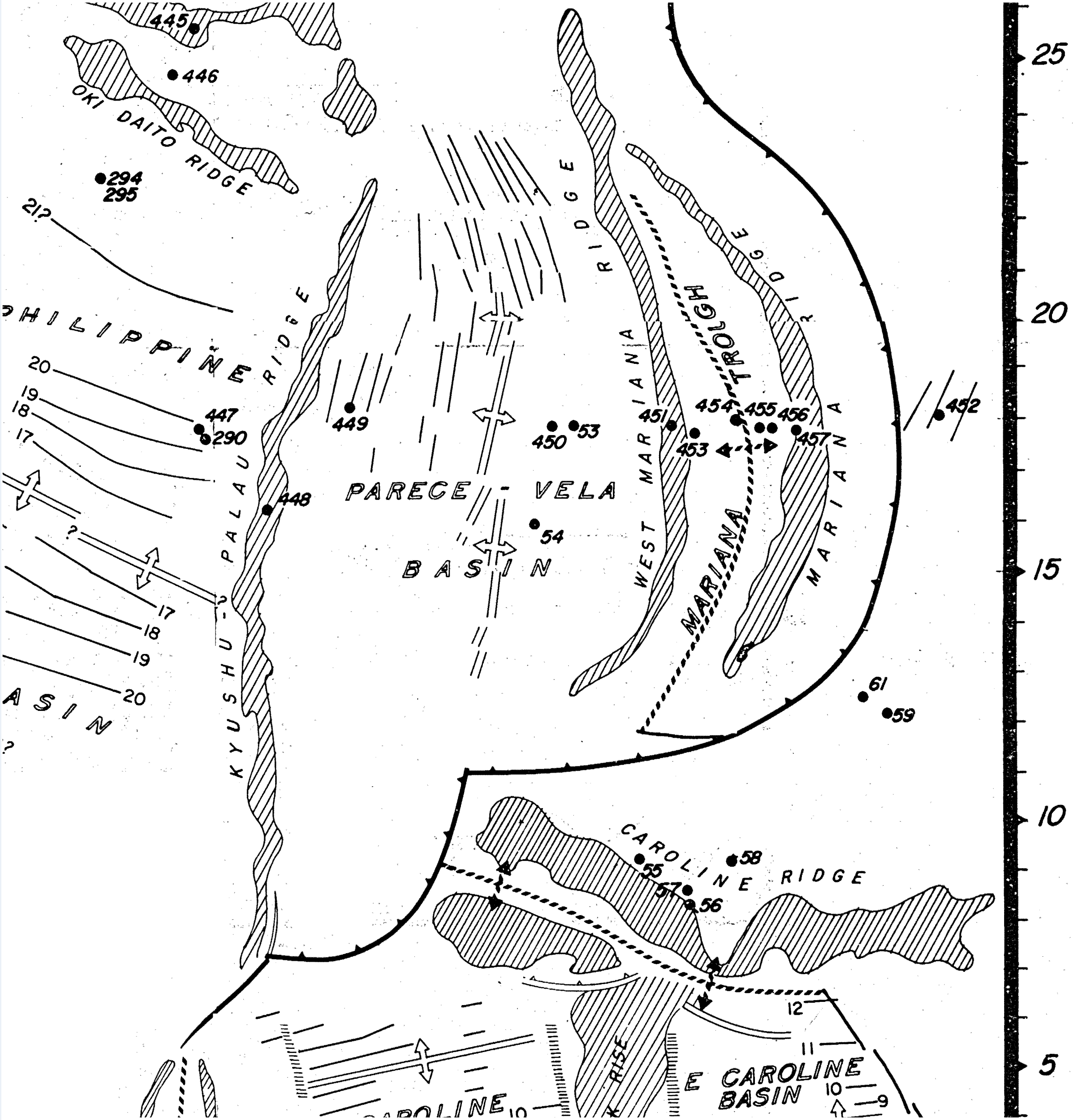

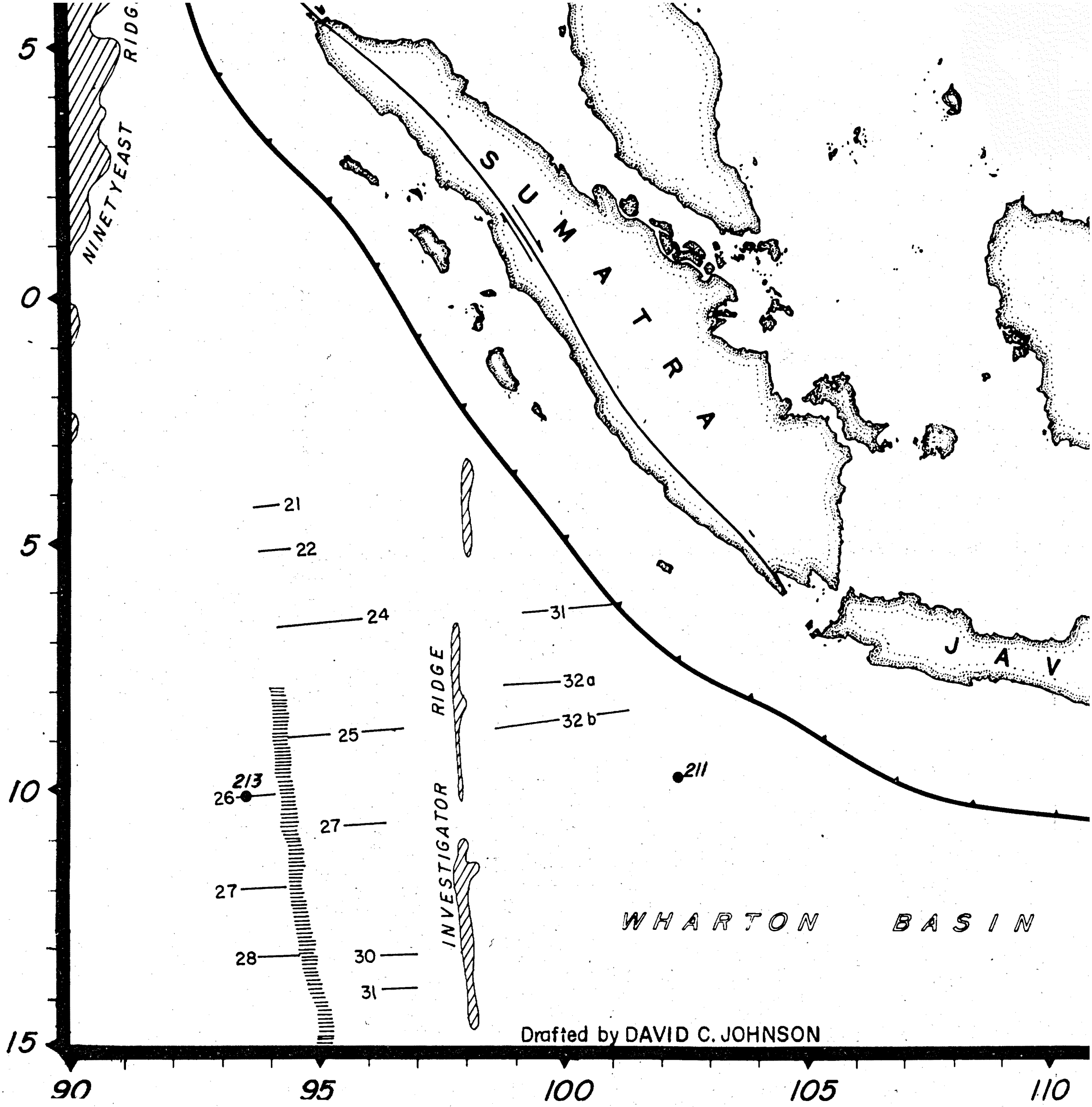
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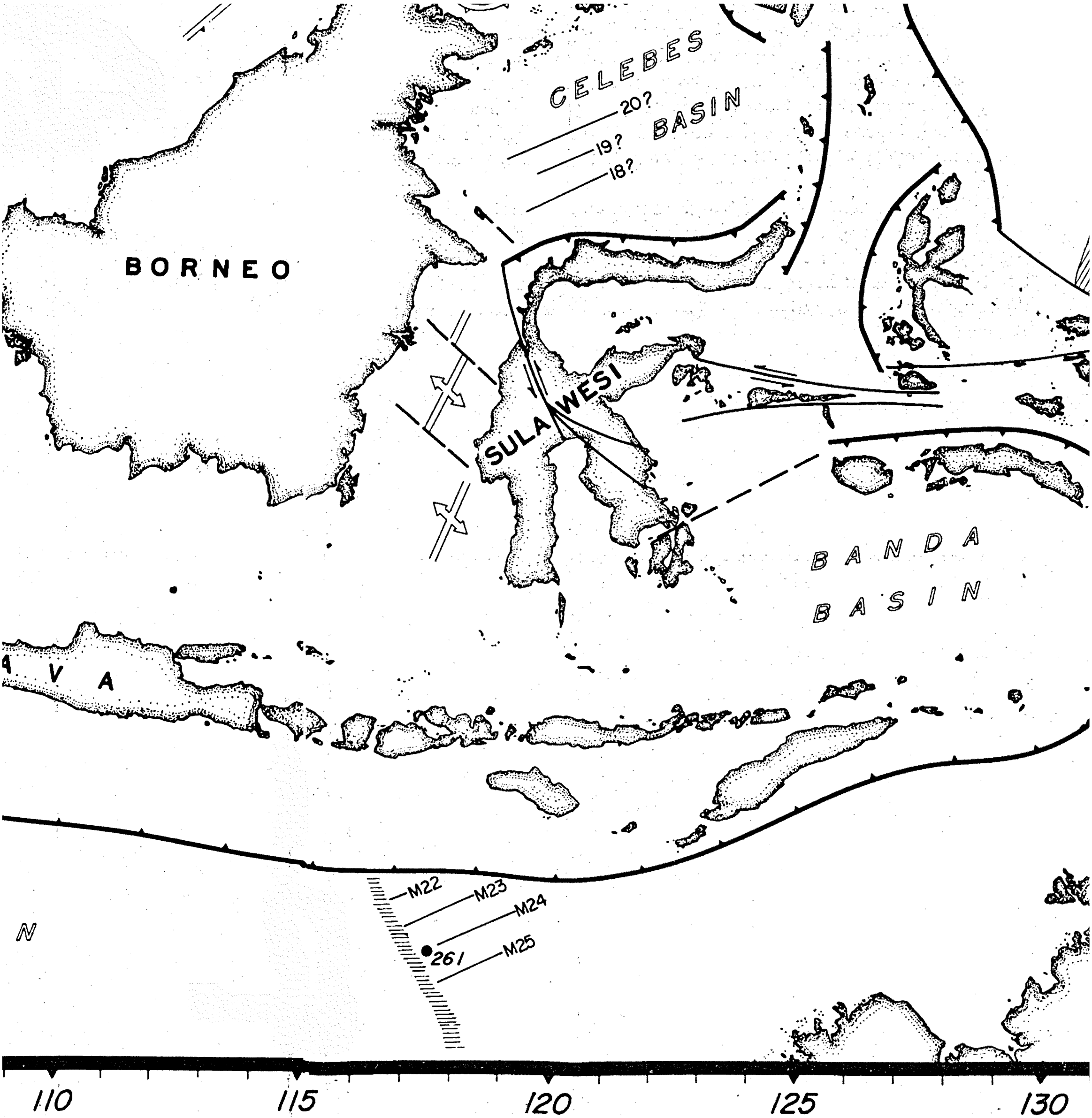
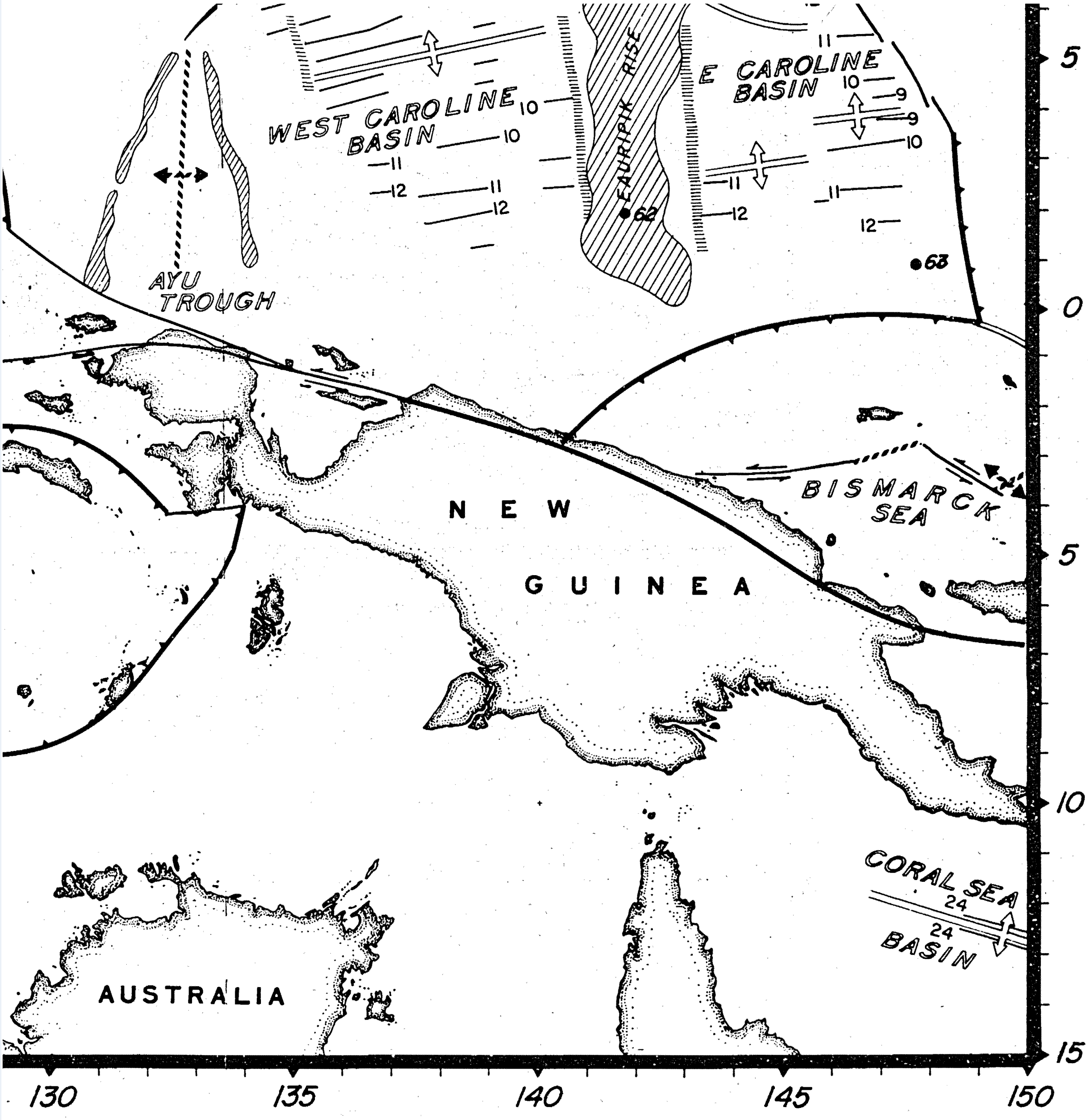


Figure 1*a*. For description see over.


WEST CAROLINE BASIN
E CAROLINE BASIN
EAURIPIK RISE
AYU TROUGH
NEW GUINEA
BISMARCK SEA
CORAL SEA BASIN
AUSTRALIA
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5
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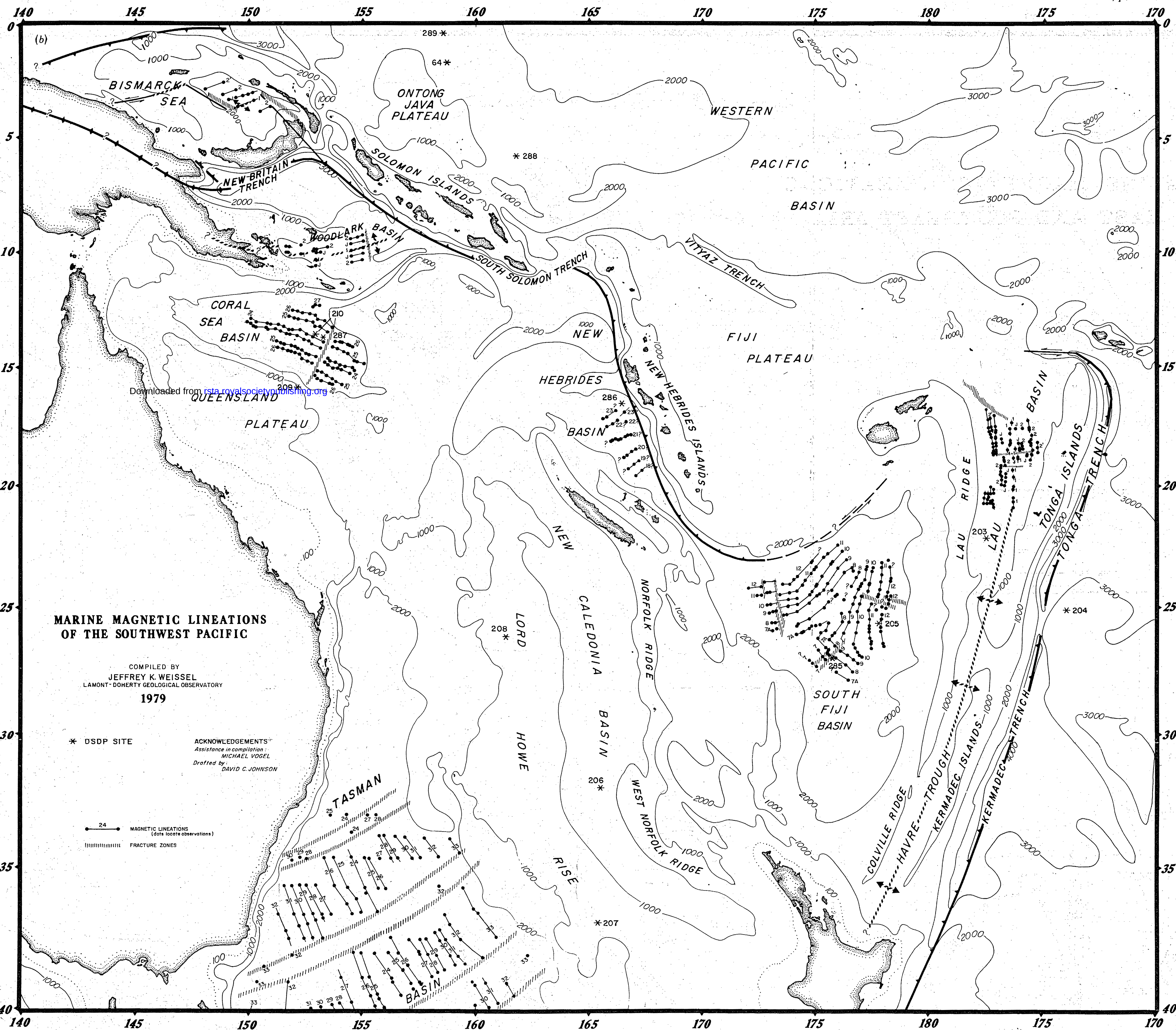

Figure 1. Magnetic lineations in marginal basins of the Western Pacific: (a) east and southeast Asia (after Hayes & Taylor 1978); (b) the southwestern Pacific.

Sources. (a) Mariana Trough, Karig *et al.* (1978); Parece-Vela Basin, Mrozowski & Hayes (1979); Shikoku Basin, Watts & Weissel (1975) and Kobayashi & Nakada (1979); West Philippine Basin, Louden (1976), Watts *et al.* (1977*a*) and Shih (1980); Japan Sea Basin, Isezaki (1975); Okinawa Trough, Herman *et al.* (1979); Andaman Basin, Curray *et al.* (1979, 1980); South China Basin, Taylor & Hayes (1980) and Ben-Avraham & Uyeda (1973); Celebes Basin, Weissel (1980); Caroline Basins, Bracey (1975) and Weissel & Anderson (1978); Wharton Basin, Sclater & Fisher (1974) and Larson (1975); northwestern Pacific, Hilde *et al.* (1976).

(b) Tasman Basin, Hayes & Ringis (1973) and Weissel & Hayes (1977); Coral Sea Basin, Weissel & Watts (1979); New Hebrides Basin, Weissel *et al.* (1980*a*); South Fiji Basin, Weissel & Watts (1975), Watts *et al.* (1977*b*), Malahoff *et al.* (1980) and Davey (1980); Fiji Plateau, Chase (1971) and Malahoff *et al.* (1980); Lau Basin, Sclater *et al.* (1972), Lawver *et al.* (1976) and Weissel (1977); Havre Trough, Malahoff *et al.* (1980); Woodlark Basin, Luyendyk *et al.* (1973) and Weissel *et al.* (1980*b*); Bismarck Basin, Connelly (1976) and Taylor (1979).

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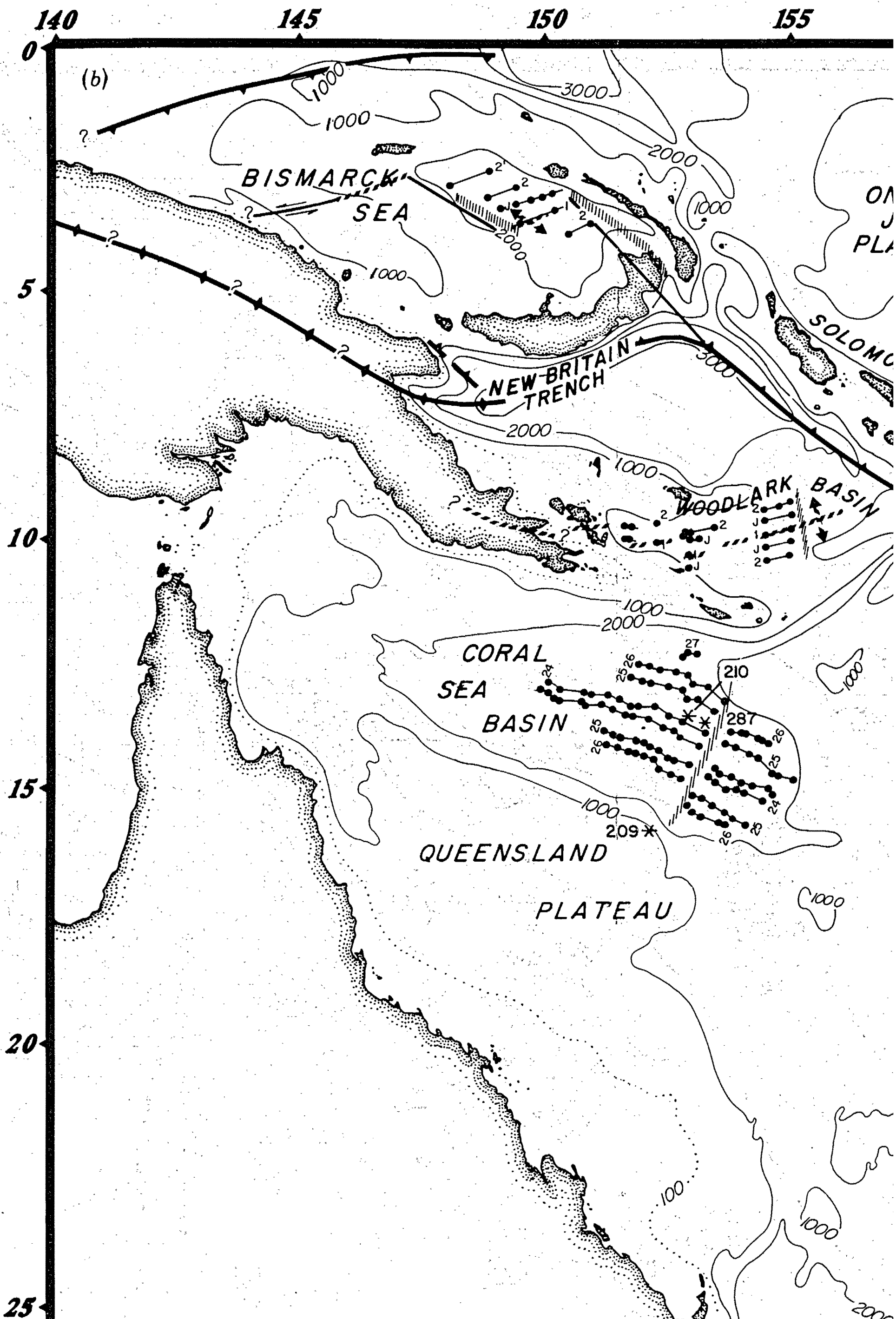

MARINE MAGNETIC LINEATIONS OF THE SOUTHWEST PACIFIC

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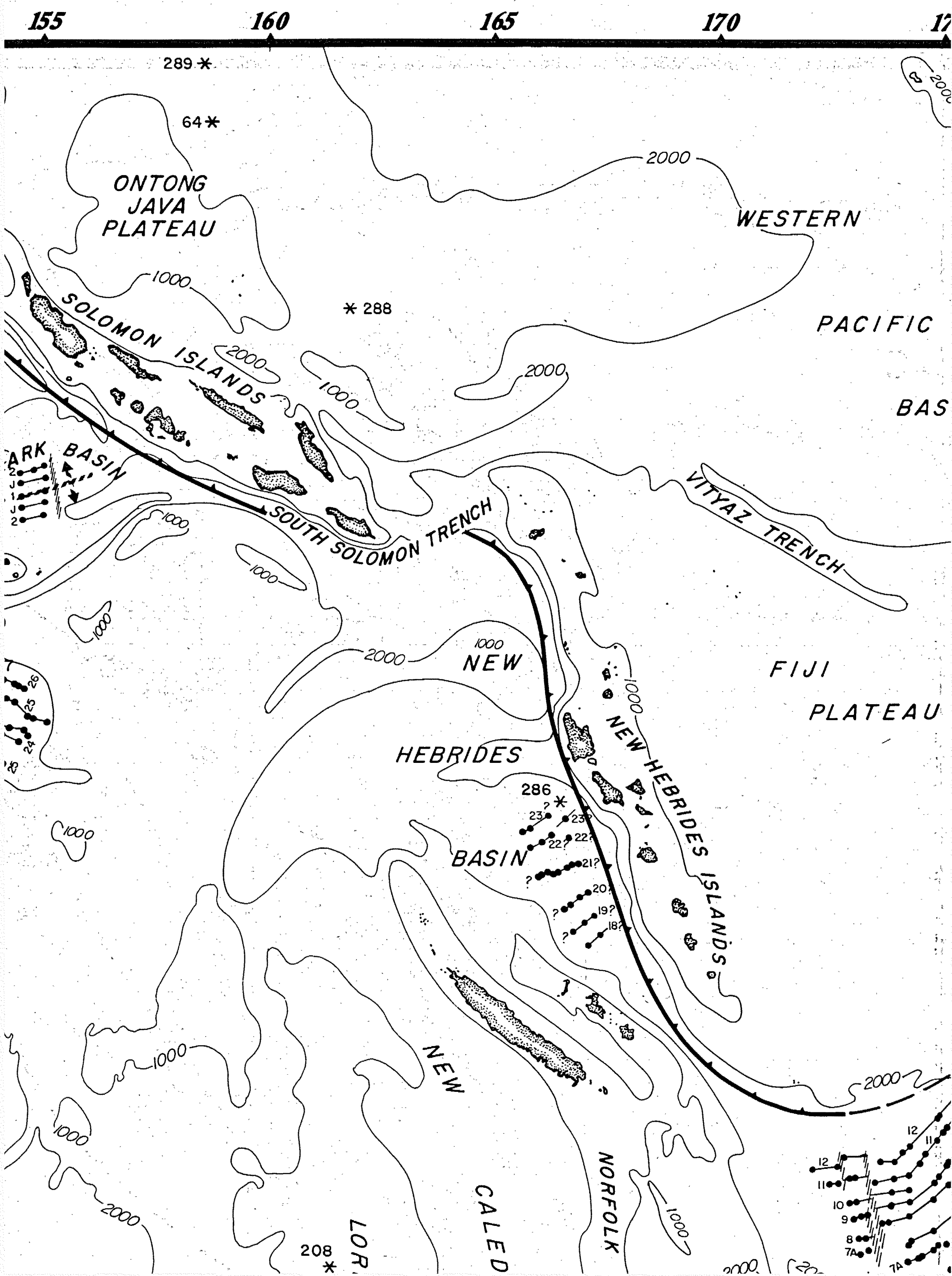

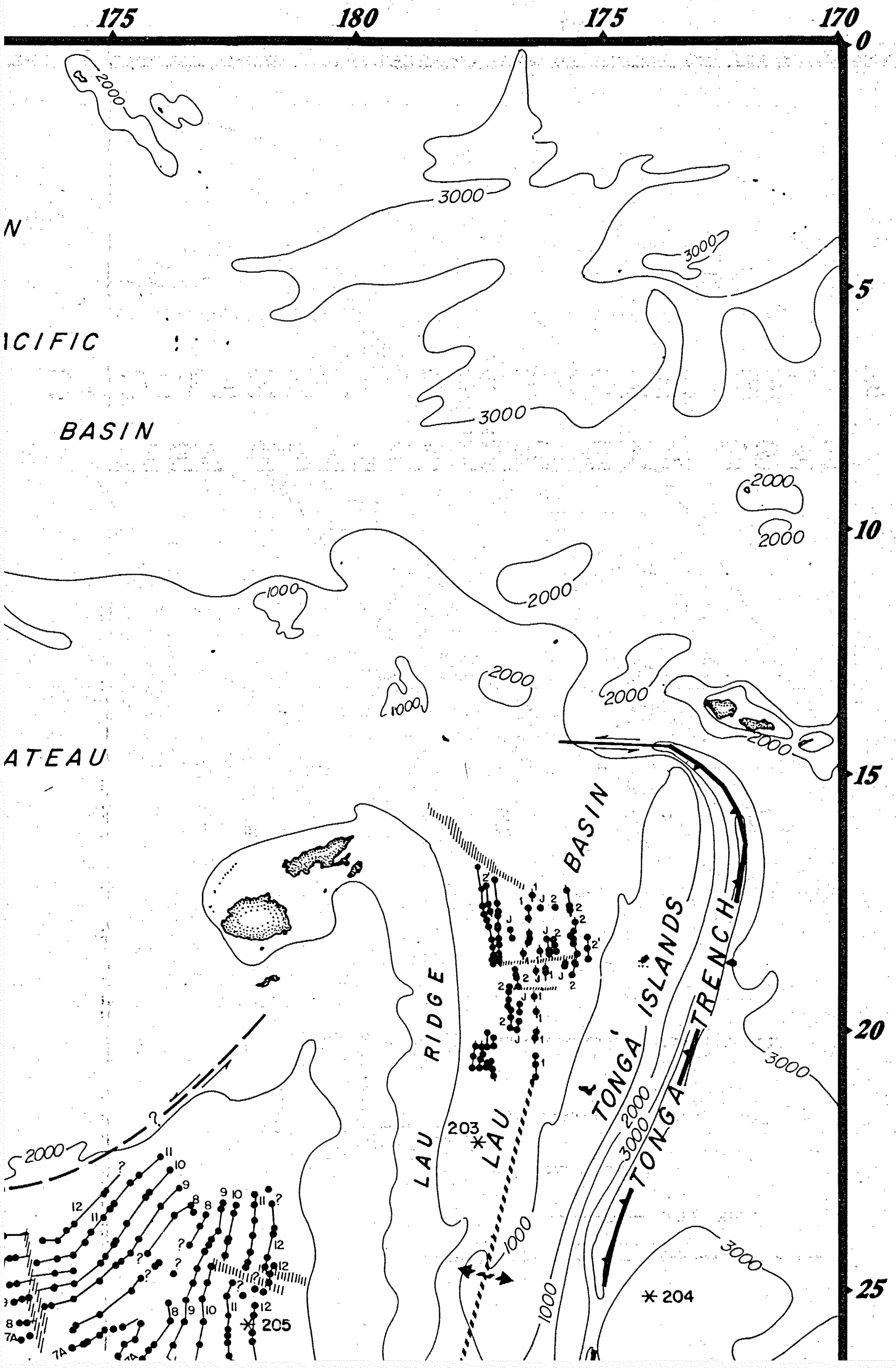

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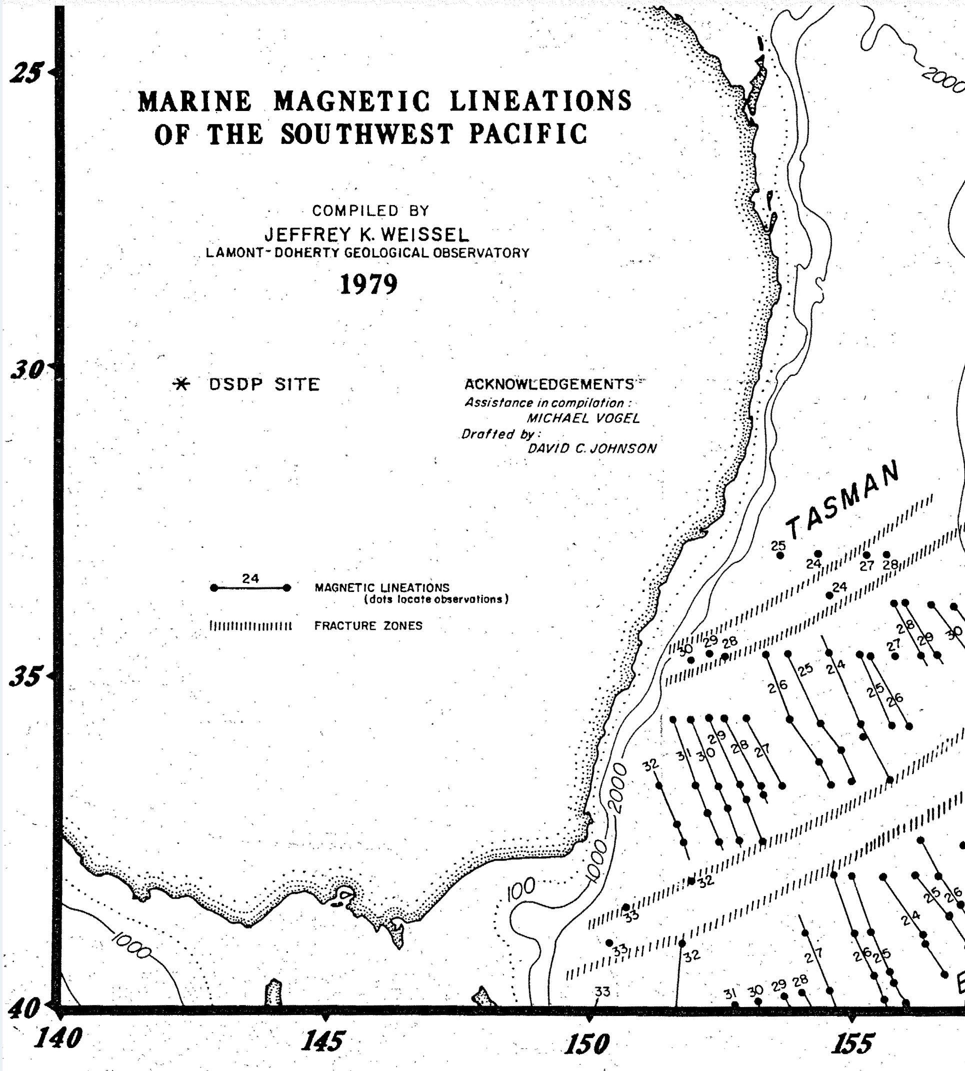

FIGURE 1. Mag
Taylor 197
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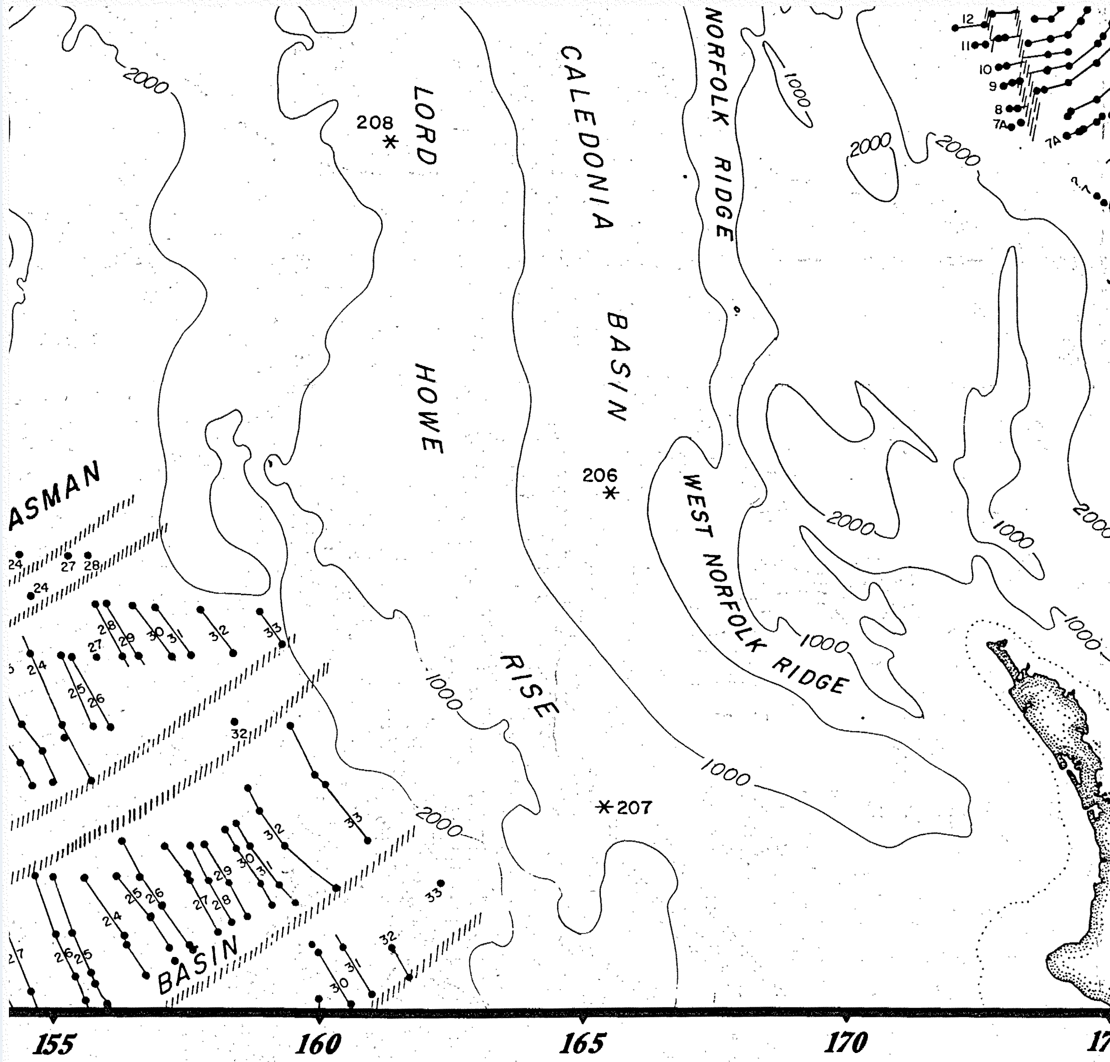

FIGURE 1. Magnetic lineations in marginal basins of the Western Pacific: (*a*) east and southeast Asia (after Hay
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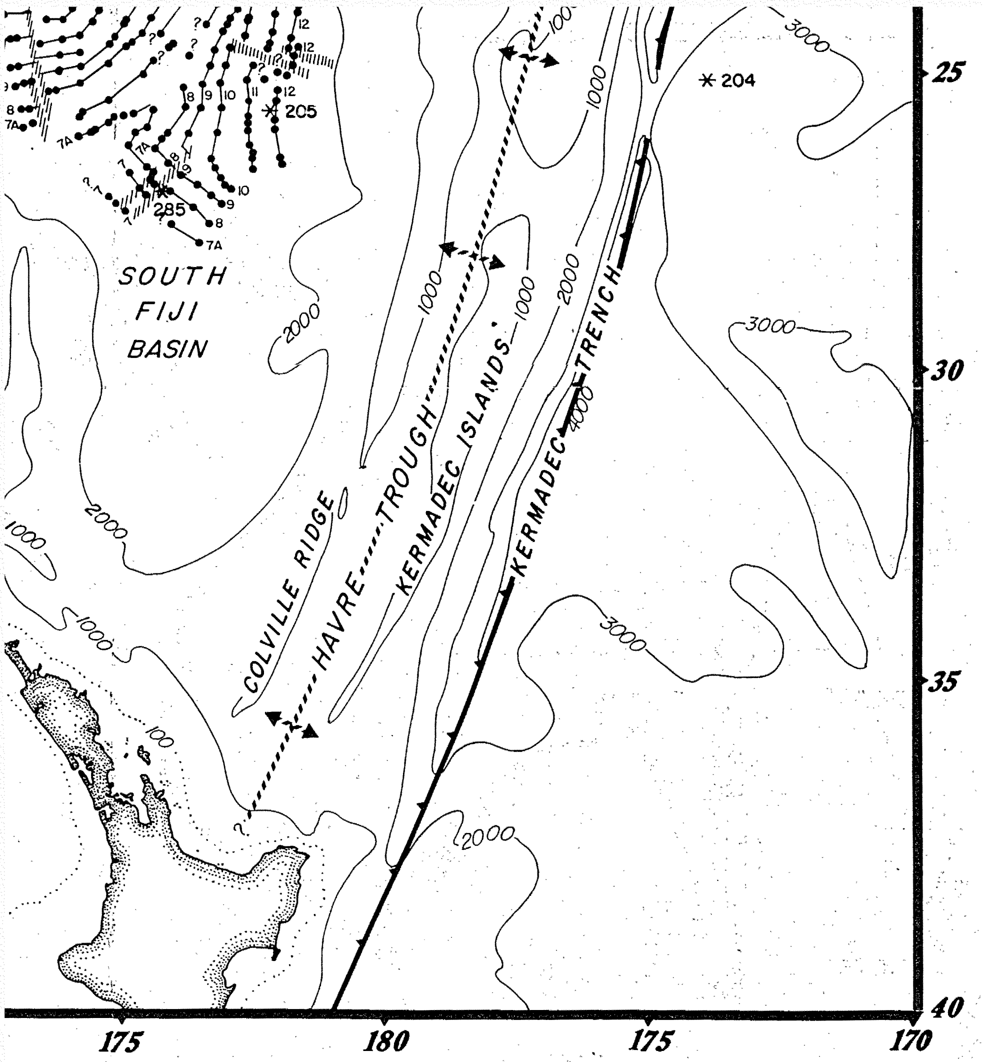
(*b*) Tasman Basin, Hayes & Ringis (1973) and Weissel & Hayes (1977); Coral Sea Basin, Weissel & W (1979); New Hebrides Basin, Weissel *et al.* (1980*a*); South Fiji Basin, Weissel & Watts (1975), Watts *e* (1977*b*), Malahoff *et al.* (1980) and Davey (1980); Fiji Plateau, Chase (1971) and Malahoff *et al.* (19 Lau Basin, Sclater *et al.* (1972), Lawver *et al.* (1976) and Weissel (1977); Havre Trough, Malahoff *et al.* (19 Woodlark Basin, Luyendyk *et al.* (1973) and Weissel *et al.* (1980*b*); Bismarck Basin, Connelly (1976) Taylor (1979).



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nelly (1976) and

Factors determining signal strength include the palaeogeographic attitude of the spreading system relative to the palaeomagnetic field when the crust was formed, its present geographic attitude relative to the present geomagnetic field, and the strength of the remanent magnetization in the oceanic crust. To these might be added such tectonic factors as spreading rates, since geomagnetic field reversals appear to be recorded with high fidelity at rapid spreading rates. Examples of noise factors are extraneous magnetic effects due to rugged basement topography, fracture zone topography and seamounts, plus complicating tectonic factors such as spreading centre 'jumps', all of which can separately or collectively degrade the magnetic lineation 'signal'.

In table 1, the quality of seafloor spreading magnetic anomalies in each basin is given a qualitative assessment indicated by the type of underlining. Basins with good magnetic signatures have solid underlining, basins with poor signatures dotted underlining, and basins with no known lineations are not underlined. Basins with variable magnetic signature have combinations of underlining.

(*b*) *Basins in east and southeast Asian seas*

In discussing magnetic lineation patterns in probable and possible back-arc basins located in figure 1*a*, basins on the Philippine plate will be considered first, followed by basins on the Eurasian plate.

(i) *Mariana Trough*

Along with the Lau Basin (see figure 1*b*), the Mariana Trough was considered by Karig (1970, 1971) to represent a typical back-arc basin that is tectonically active. Relatively shallow crustal depths, lack of sediment cover and high but variable heat flow (Karig 1971; Anderson 1975; Karig *et al.* 1978; Bibee *et al.* 1980) collectively indicate that the Mariana Trough is a young basin. Results of D.S.D.P. holes in the Mariana Trough (figure 1*a*) indicate that crustal accretion probably started in late Miocene time (Hussong *et al.* 1978). The existence of lineated magnetic anomalies in this back-arc basin is questionable (Karig *et al.* 1978; Bibee *et al.* 1980). Among the reasons for the lack of well developed magnetic lineations are that (*a*) the basin is opening in an E–W direction very near the magnetic equator and (*b*) magnetic 'noise' produced by the shallow rugged basement morphology may seriously obscure the expected small amplitude magnetic anomalies.

(ii) *Parece-Vela Basin*

This basin (figure 1*a*) is thought to represent a mid-Tertiary episode of back-arc extension that preceded the modern episode in the Mariana Trough, which lies immediately to the east (Karig 1971). D.S.D.P. results are consistent with a late Oligocene to early Miocene age for the crust in this basin (Kroenke & Scott 1978). In a detailed study of magnetic anomaly data, Mrozowski & Hayes (1979) found that magnetic anomaly amplitudes are extremely small (*ca.* 150 nT) and that magnetic lineations are poorly developed, particularly in the southern part of the basin (figure 1*a*). The reasons cited above for a similar lack of magnetic lineations in the Mariana Trough probably apply to this basin as well. However, in the northern part of the basin (further from the magnetic equator), Mrozowski & Hayes (1979) found a N–S striking lineation pattern over the western flank of the Parece-Vela back-arc spreading system (figure 2). In figure 3, magnetic anomaly profiles from this area of the basin are compared with model profiles based on the Oligocene to Early Miocene part of the geomagnetic reversal time scale (La Brecque *et al.* 1977). On the basis of these magnetic anomaly correlations, Mrozowski & Hayes (1979) concluded that the Parece-Vela Basin was generated between mid-Oligocene and early Miocene time in response to the separation of an active island arc on the east (the West Mariana Ridge; figure 1*a*) from a remnant arc on the west (the Palau–Kyushu Ridge).

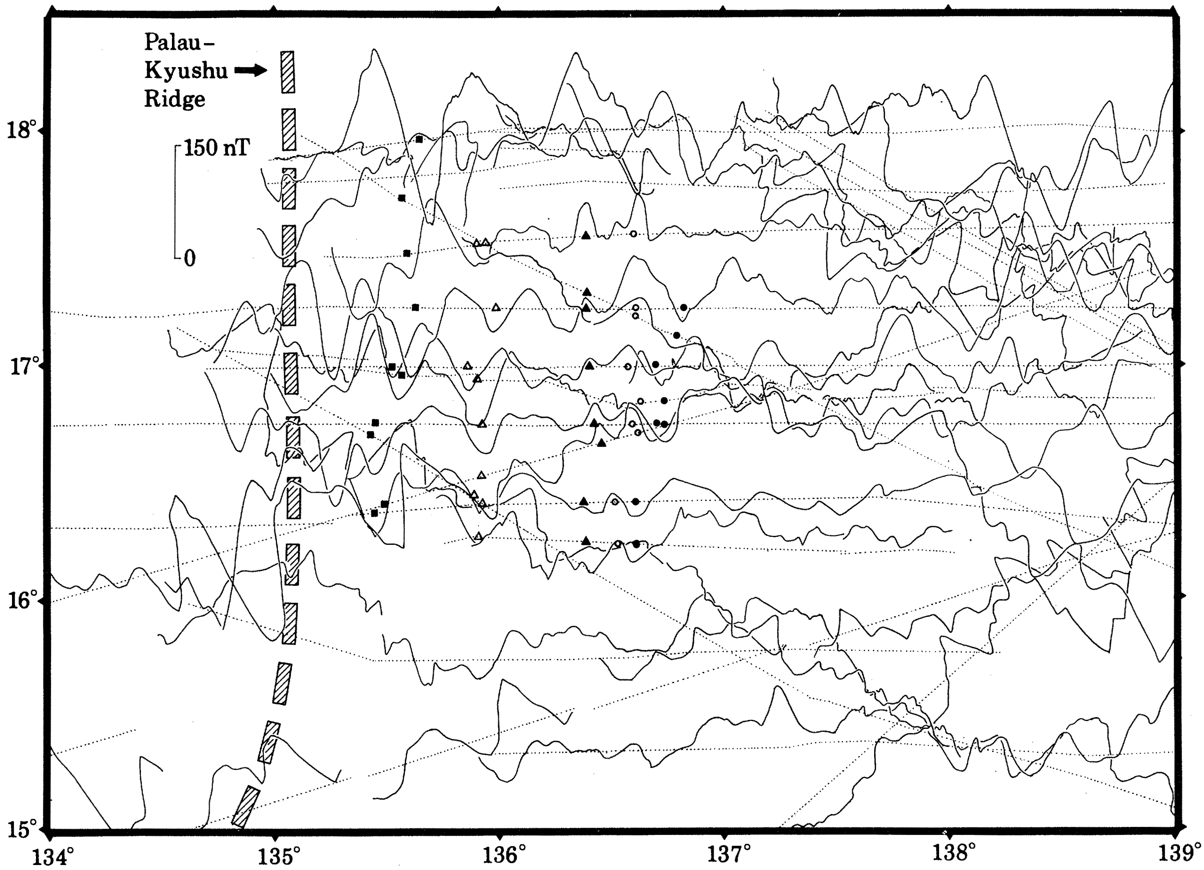

FIGURE 2. Magnetic anomalies along track in the northwestern part of the Parece-Vela Basin (figure 1*a*). The small symbols are used to trace anomalies from track to track (Mrozowski & Hayes 1979).

(iii) *Shikoku Basin*

The Shikoku Basin (figure 1*a*) is widely believed to be a northward tectonic continuation of the Parece-Vela Basin, since D.S.D.P. results give essentially comparable ages for the crust of these two basins (Karig *et al.* 1975; Klein *et al.* 1978; Kroenke & Scott 1978). Situated further north of the magnetic equator than the Parece-Vela Basin, the Shikoku Basin is associated with a much clearer magnetic lineation pattern (figure 1*a*) (Tomoda *et al.* 1975; Isezaki 1975 Kobayashi & Nakada 1979). Magnetic data from the Shikoku Basin have been variously interpreted in the past but most workers now believe that the basin opened between the late Oligocene (slightly later than the Parece-Vela) and the early Miocene (Watts & Weissel 1975; Kobayashi & Nakada 1979). A feature of both the Shikoku and Parece-Vela basins is that the magnetic lineations on the eastern (active arc) flank of the back-arc spreading system are degraded relative to the lineations on the western (or remnant arc) flank (Watts & Weissel

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1975; Mrozowski & Hayes 1979). For the Shikoku Basin, this feature is explained by proposing that after its formation, the eastern flank has suffered deformation due to the collision between the Iwo-Jima Ridge (the active arc) and southern Honshu (Watts & Weissel 1975). A representative magnetic anomaly and seismic reflexion profile across the western flank of the Shikoku back-arc spreading system is shown in figure 4 (Watts *et al.* 1977*a*).

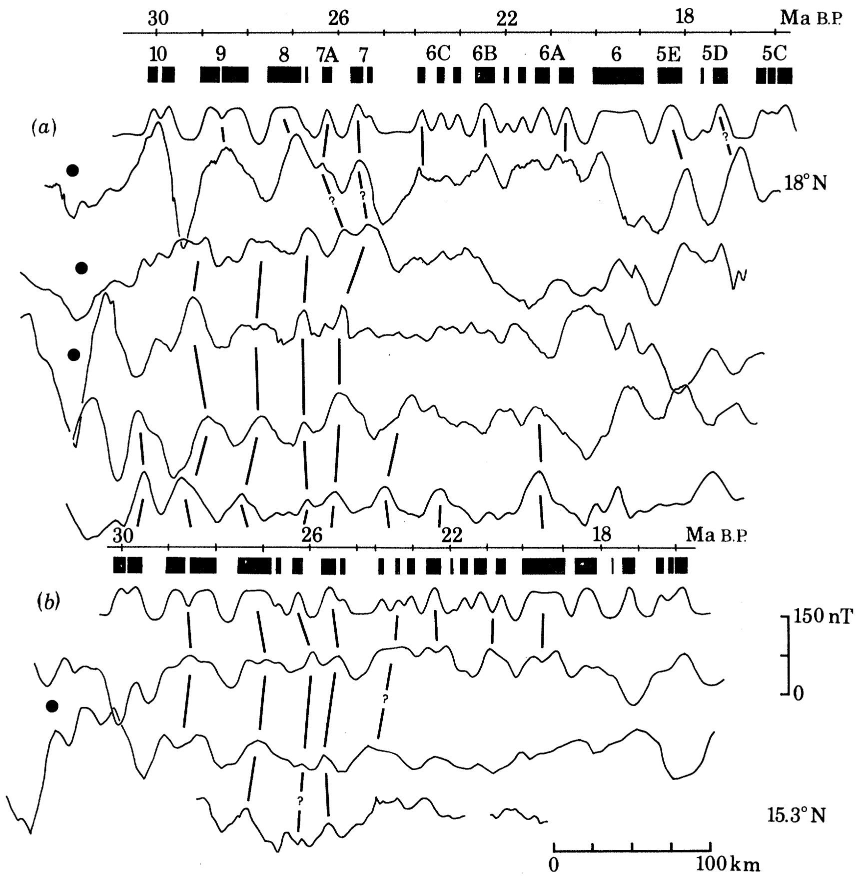

FIGURE 3. East–west projected magnetic profiles from the western province of the Parece-Vela Basin and magnetic block models with computed anomalies. Model profiles (*a*) and (*b*) differ only in half-spreading rates. Half-rates for model (*a*) are 2.9 cm/a for crust older than 25 Ma, 2.0 cm/a for crust between 24 and 25 Ma, and 2.9 cm/a for crust younger than 24 Ma. Half-rates for model (*b*) are 3.0 cm/a for crust older than 25 Ma, 1.0 cm/a for crust between 24 and 25 Ma and 2.4 cm/a for crust younger than 24 Ma. These slight rate changes were used to improve the model fit and may or may not be physically meaningful. Filled circles indicate the position of the Palau–Kyushu Ridge (from Mrozowski & Hayes 1979).

As stated above (see § 1), one of the purposes of this paper is to examine the apparent similarities between crustal accretion processes in back-arc and in normal mid-oceanic ridge settings. The shapes of lineated magnetic anomalies contain information concerning the horizontal distribution of magnetization in the oceanic crust. If we assume that the magnetization is confined to a layer of constant thickness and that accretion of crustal material at a spreading centre occurs with a scatter described by a normal distribution of standard deviation σ, then the horizontal distribution of magnetization in the crust can be treated mathematically as a convolution of the crustal accretion process with the history of reversals of the geomagnetic field (Blakely & Cox 1972; Schouten & McCamy 1972; Atwater & Mudie 1973). Blakely & Cox

(1972) have shown that crustal accretion processes for moderate to fast spreading systems in the Pacific Ocean could be described by standard deviations between 1 and 3 km. This approach is taken in modelling the magnetic lineations from the Shikoku Basin (figure 5), where the distribution of geomagnetic reversals shown at the bottom is convolved with Gaussian filters of standard deviations ranging from 0 to 5 km. Comparison of these models with the observed

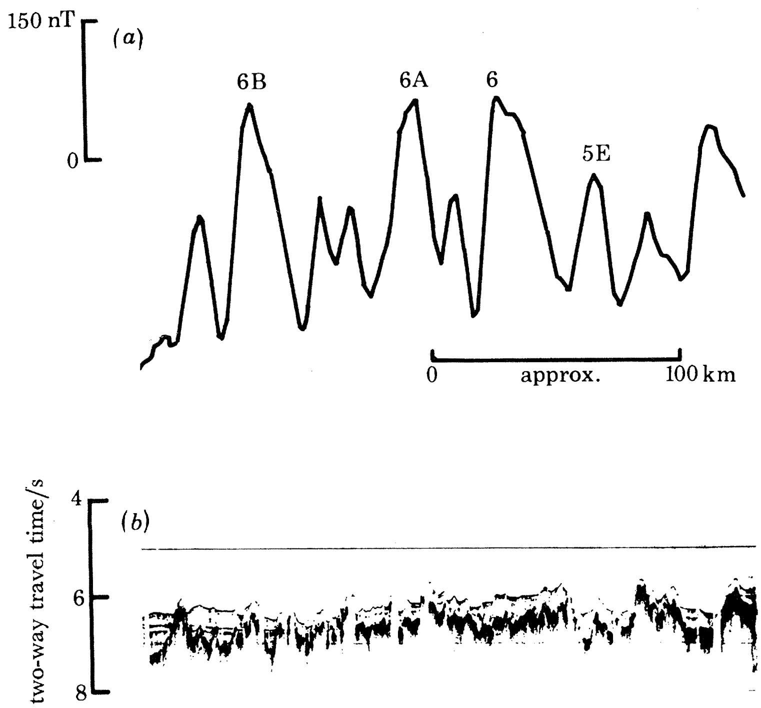

FIGURE 4. Magnetic anomaly (*a*) and seismic reflexion profile (*b*) across the western part of the Shikoku Basin. The identification of the magnetic anomalies is from Watts & Weissel (1975).

profile suggests that crustal accretion processes in the Shikoku Basin are confined to a region characterized by a relatively small width of 2–3 km (Watts *et al.* 1977*a*). Therefore, the shape characteristics of magnetic anomalies observed on this particular profile over the western flank of the Shikoku Basin (figure 4) suggest that similar crustal accretion processes occur in back-arc and in mid-oceanic ridge settings. Similar analyses of magnetic anomaly profiles from other back-arc basins must be made before this preliminary conclusion can be accepted with confidence.

(iv) *West Philippine Basin*

The West Philippine Basin occupies the western half of the Philippine Sea (figure 1*a*) and according to D.S.D.P. evidence (Karig *et al.* 1975; Kroenke & Scott 1978; Ozima *et al.* 1977) the basin is underlain by Eocene to possibly Oligocene oceanic crust. A magnetic lineation pattern is readily discernible in the West Philippine Basin (Louden 1976; Watts *et al.* 1977*a*; Shih 1980) and most workers agree that an extinct spreading centre (called the Central Basin Fault) is preserved in the basin (figure 1*a*).

In figure 6, magnetic anomaly profiles from the West Philippine Basin are compared with the preferred magnetic block model due to Watts *et al.* (1977*a*). Note that the observed profiles have been phase-shifted into approximately symmetric anomaly shapes to facilitate comparison with the model profile. The shapes of corresponding anomalies either side of the Central Basin Fault (C.B.F.) are quite dissimilar, requiring substantial differences in the amounts of phase-shifting required to achieve symmetric shapes (Watts *et al.* 1977*a*).

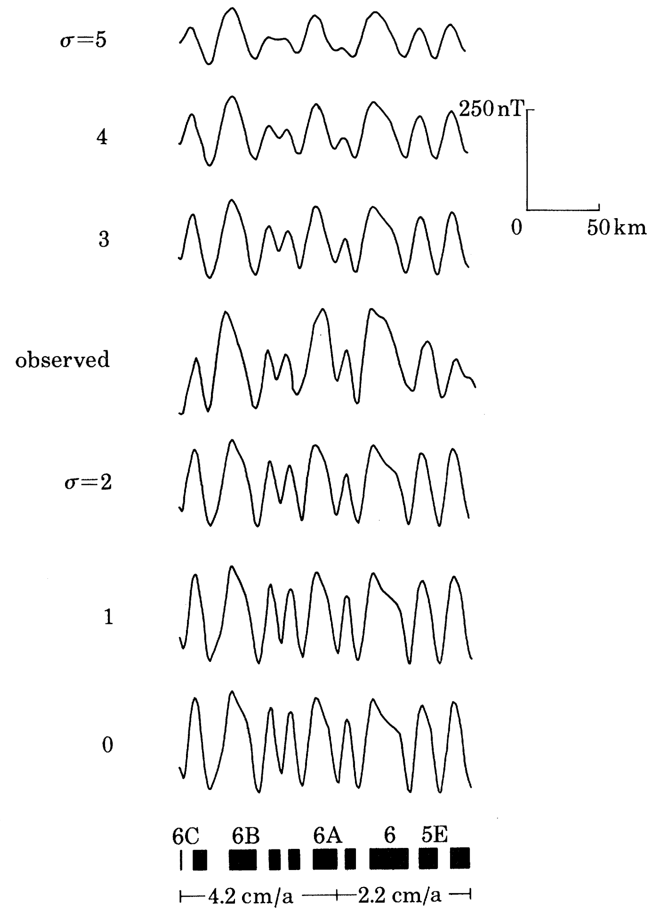

FIGURE 5. Comparison of the magnetic anomaly profile (in figure 4) from the western part of the Shikoku marginal basin to computed profiles based on the geomagnetic timescale. The computed profiles were generated for a model in which the binary function representing the standard magnetic models was convolved with a Gaussian distribution function with σ = 0, 1, 2, 3, 4 and 5 km. The effect on the computed profiles of increasing σ is to attenuate the amplitudes of higher frequencies (short events) in the profiles. The most satisfactory fit to the observed profile is for $\sigma = 2$ to $\sigma = 3$ (from Watts *et al.* 1977*a*).

Note that anomalies in the group 18–20 correlate well with the model profile, indicating that spreading ceased about 39 Ma ago (late Eocene). Apparently, spreading rates in the basin were initially much faster than the half-rates of 4.4 cm/a inferred from the anomaly sequence 18–20 because the broader anomalies further from the C.B.F. are poorly matched by the constant spreading rate model (figure 6). It is difficult to determine whether the West Philippine Basin formed in a back-arc setting because the basin is not clearly bounded by ancient island arc fragments. Although the Oki Daito Ridge on the north (figure 1*a*) may represent part of an old island arc system (Mizumo *et al.* 1979; Klein *et al.* 1978), south of the C.B.F. there is apparently no feature that could represent the rifted counterpart of the Oki Daito Ridge.

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(v) *Japan Sea Basin*

Magnetic anomaly data from the Sea of Japan, although abundant, have proved difficult to correlate with the geomagnetic reversal timescale (Isezaki & Uyeda 1973; Isezaki 1975; Kobayashi & Isezaki 1976). Moreover, D.S.D.P. sites in the Sea of Japan do not provide good constraints on the age of the underlying crust. All sites failed to reach igneous basement and were terminated after penetrating the mid-Miocene or younger section (Karig *et al.* 1975) of the

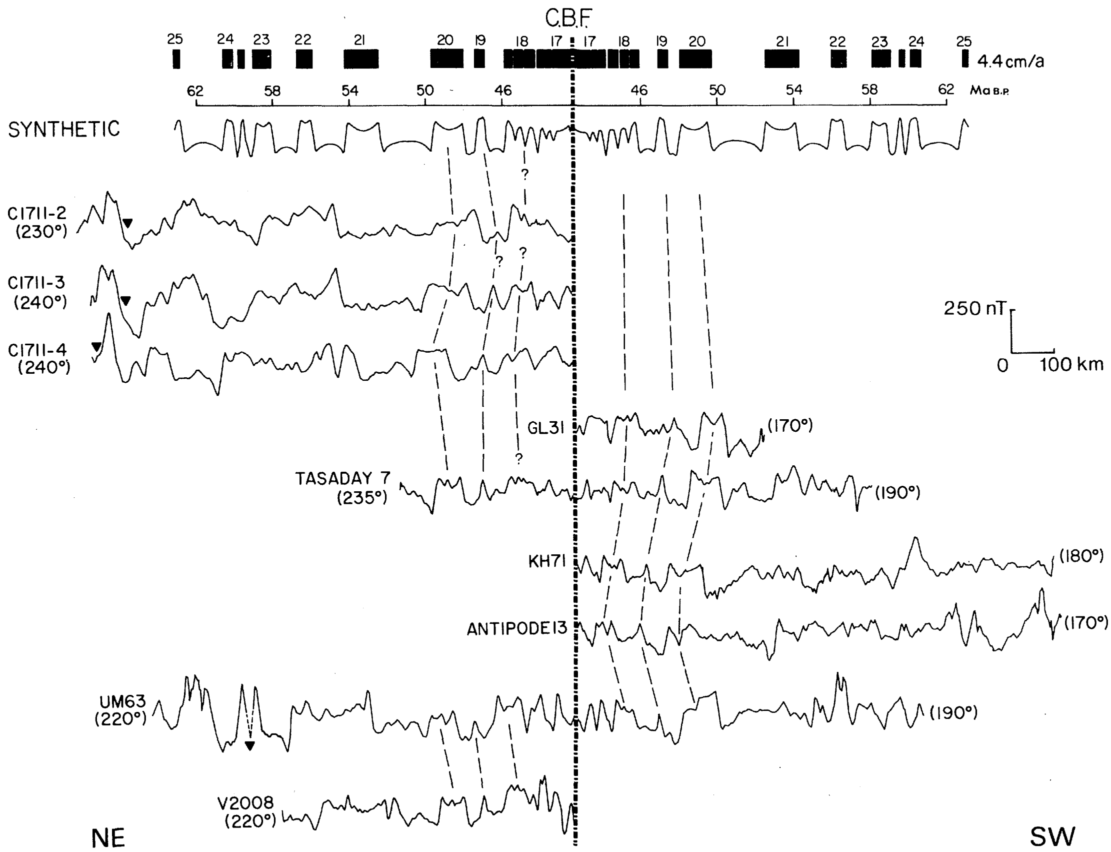

Figure 6. Comparison of de-skewed magnetic anomaly profiles across the Central Basin Fault (C.B.F.) to a computed profile based on the standard magnetic block model for the early Tertiary part of the geomagnetic reversal timescale. The computed models assume a depth to upper surface of the two-dimensional blocks of 6.0 km, a layer thickness of 0.5 km, uniform magnetization contrast of 5 A m^{-1} cm^{-3} and $\theta = 0$. The numbers in parentheses (from Watts *et al.* 1977*a*) indicate the values of θ (multiplied by -1) required to phase-shift anomalies to symmetry.

rather thick sediment cover of the Japan Sea (Ludwig *et al.* 1975). However, by applying cross correlation techniques to observed magnetic anomaly profiles, Isezaki (1975) defined likely centres of approximate symmetry in the basin (figure 1*a*). The Oligocene to early Miocene age assigned to the Japan Sea Basin in table 1 is inferred from other geophysical data, such as basement depths (Ludwig *et al.* 1975) and heat flow (Watanabe *et al.* 1977), and should be considered tentative.

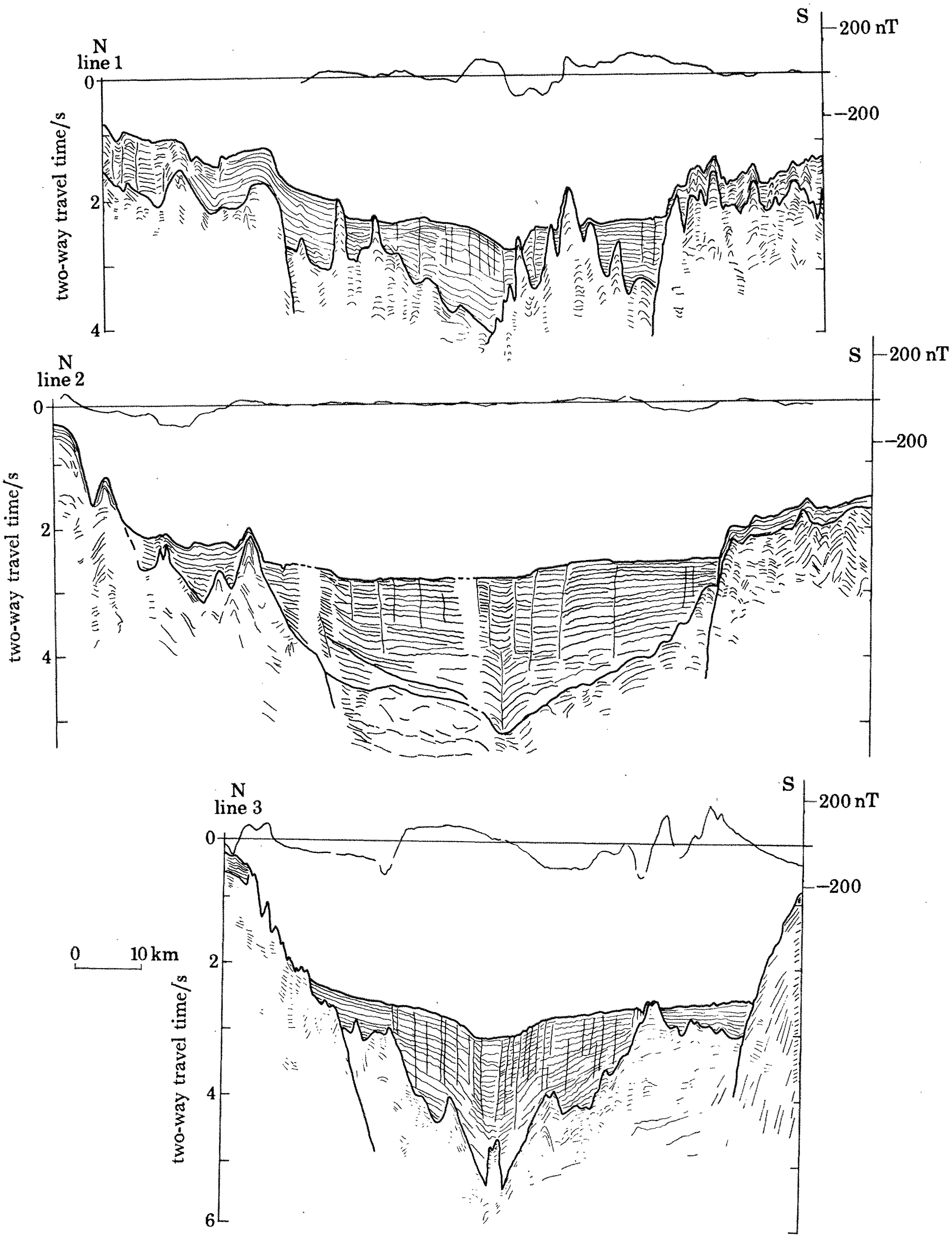

FIGURE 7. Line drawings from original seismic reflexion records for three profiles across the southwest part of the Okinawa Trough (by R. N. Anderson). Associated magnetic anomaly profiles are shown above each line drawing.

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(vi) *Okinawa Trough*

This narrow back-arc basin, which is believed to be the product of post-Miocene rifting of the Ryukyu island arc from the Asian mainland (Karig 1971; Wageman *et al.* 1970; Herman *et al.* 1979), is located northeast of Taiwan (figure 1*a*). A thick sedimentary section primarily of terrigenous origin is present in the deeper parts of the Okinawa Trough. Widespread normal faulting observed in seismic sections suggests that the Okinawa Trough is currently undergoing extension (figure 7). Such a tectonic régime is also suggested by shallow focus earthquake activity and scattered large heat-flows within the trough (Herman *et al.* 1979). The seismic profiles shown in figure 7 (see Herman *et al.* (1979) for additional profiles) show that in some areas faulting pervades the entire width of the trough (line 2), whereas a clear central graben marked by concentrated normal faulting is present most notably in the southwest part of the trough (line 3). For the most part, magnetic anomaly amplitudes are subdued (figure 7). It is not obvious that seafloor spreading (in the strict sense) has begun in the Okinawa Trough, which may therefore still be in a 'rifting' stage. The composition of the basement that underlies the trough is not well known. However, highly vesicular basalt was dredged from one of several basement 'pinnacles' that protrude into or through the central graben of the trough, and diorites were recovered from a prominent ridge, believed to be a stranded piece of island arc (Herman *et al.* 1979; R. N. Anderson, personal communication, 1980).

(vii) *Andaman Basin*

Although this basin is geographically in a back-arc setting (figure 1*a*), there is question as to whether subduction or shear is the tectonic régime that governs the opening of the Andaman Basin. A marked axial graben is observed in the thick sedimentary section of the Andaman Basin (figure 8) (Curray *et al.* 1979). Curray *et al.* interpreted magnetic anomalies in the basin as the sequence from anomaly 1 over the rift to anomaly 5 near the Andaman Islands to the northwest, and suggested that seafloor spreading at short spreading segments (trending about ENE–WSW) offset by large transform faults has occurred since mid-Miocene time.

Since convergence between the Indian plate and the Andaman island arc is highly oblique, Curray *et al.* (1979) proposed that the opening of this marginal basin may be similar to the opening of the Gulf of California, which is primarily governed by dextral shear between the Pacific (Baja California) and North American (Mexico) plates. In the Andaman Basin, if some degree of coupling occurs between a small plate containing the Andaman island arc and the major Indian plate, stresses induced in the adjacent part of the Eurasian plate by such coupling could be relieved by dextral slip along the Sumatran fault system and along a strike-slip zone through Burma, and by the observed NNW–SSE extension in the Andaman Basin (Curray *et al.* 1979; Lawver & Hawkins 1978). The possibility of this tectonic régime (see figure 1*a*) was recognized by Curray *et al.* who gave the name Burma plate to the small plate containing the Andaman island arc, and the name China plate to the southwestern part of the Eurasian plate.

(*c*) *Basins of the southwestern Pacific*

The small oceanic basins of the southwestern Pacific are located adjacent to the zone of mainly convergent interaction between the major Pacific and Indo-Australian plates (figure 1*b*). The important feature of magnetic lineation patterns in basins such as the South Fiji

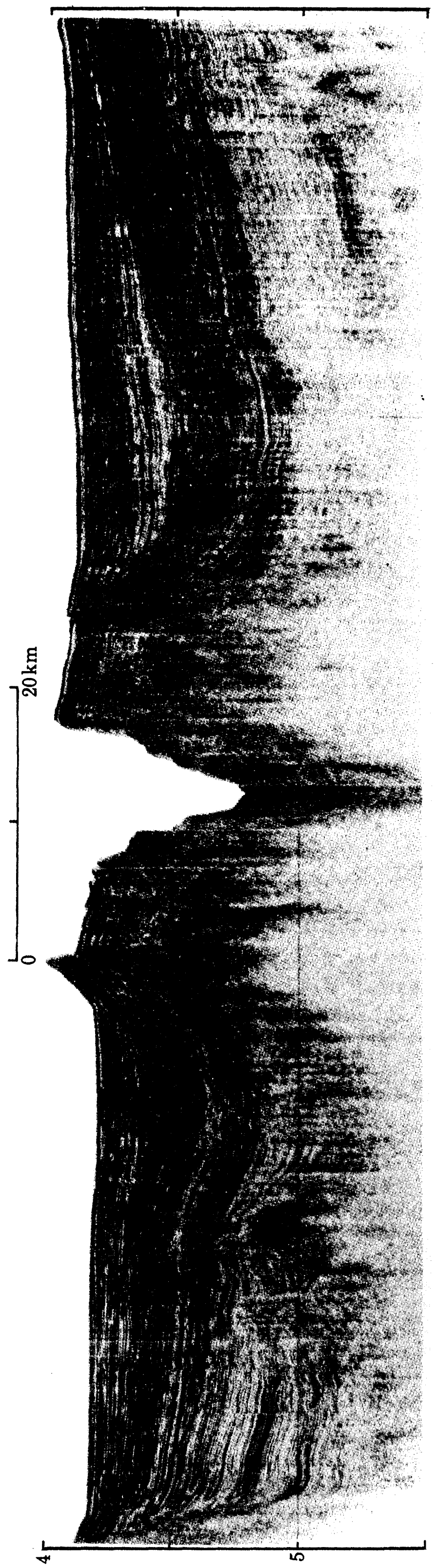

FIGURE 8. Single-channel seismic reflexion profile across a segment of axial rift in the Andaman Basin. Vertical exaggerations: water, ×24; sediments, ×*ca.* 18. Note the older buried, upturned and rifted sections of sediment (from Curray *et al.* 1979).

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Basin (and possibly also the Lau Basin and Fiji Plateau) is that they reveal that back-arc basins can evolve through the growth of more than just two 'plates'.

(i) *Fiji Plateau*

Of major interest is the evolution of the Fiji Plateau, where the distribution of shallow earthquakes indicates the interaction of a number of small plates (figure 9). The strike-slip focal mechanism (Johnson & Molnar 1972) for an event within a prominent E–W band of earthquakes across the plateau (figure 9), can be interpreted as showing approximately E–W

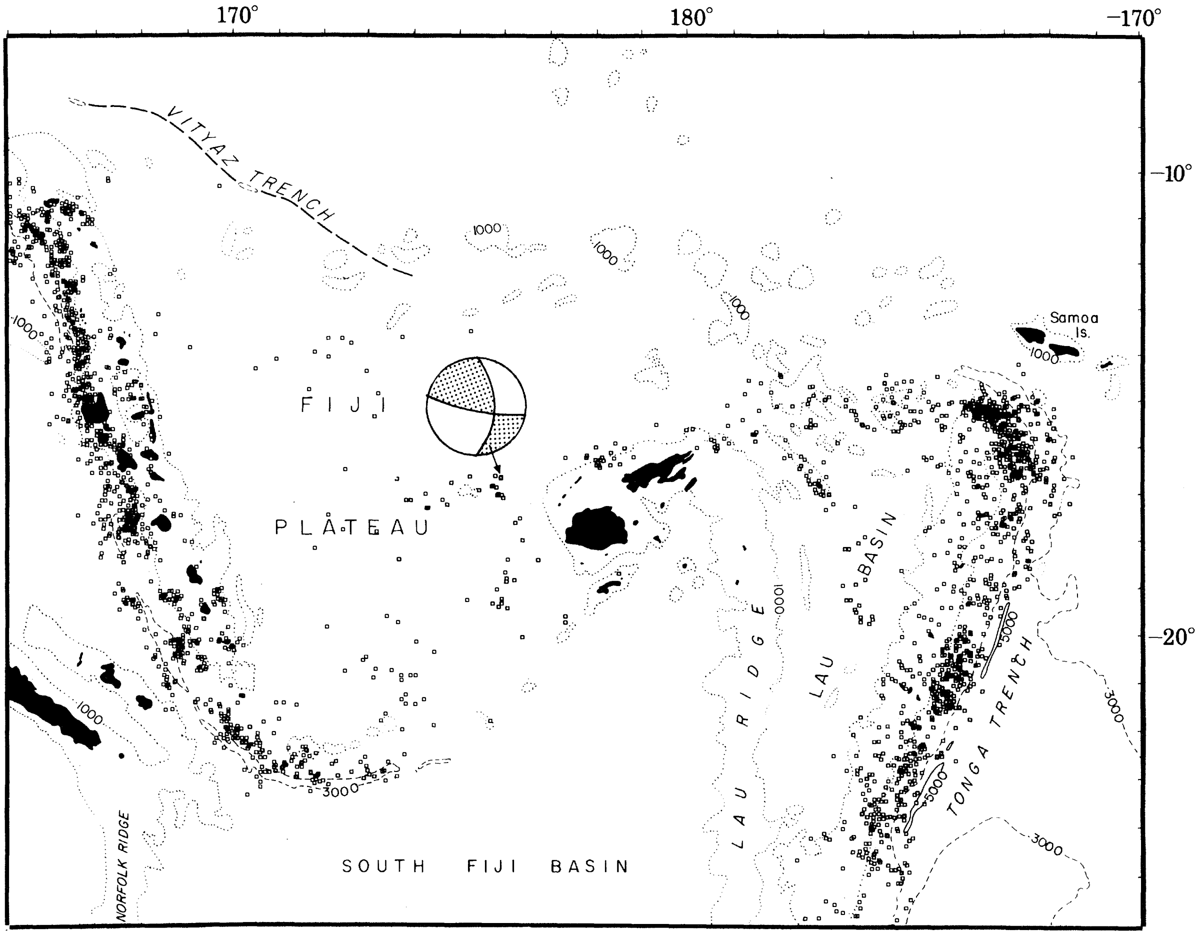

FIGURE 9. Shallow earthquakes (depth no greater than 75 km) in the area of the Fiji Plateau and Lau Basin from W.W.S.S.N./N.O.A.A. sources. Strike-slip focal mechanism from the Fiji Plateau is from Johnson & Molnar (1972).

sinistral slip along a transform fault 'plate' boundary. The N–S bands of seismicity could thus be interpreted as indicative of spreading segments. This is essentially the view of Chase (1971), who proposed that the Fiji Plateau has grown since middle Miocene time by the formation of new oceanic crust at several mainly N–S spreading centres. The relatively shallow depths of oceanic crust, small amount of sediment cover, and large but scattered heat flows (Halunen & Von Herzen 1973) also attest to the fairly small age of the Fiji Plateau. More recently, Malahoff *et al.* (1980) have collected a large quantity of low-level aeromagnetics data over the Fiji

Plateau. Their interpretation of the aeromagnetics data modifies to some degree the configuration of 'plate' boundaries originally proposed by Chase (1971). However, most workers agree that the Fiji Plateau can be viewed as a back-arc basin formed by the rotation of the New Hebrides island arc–trench system away from an original position parallel to the trace of the Vityaz Trench (figure 9) since mid-Miocene time (see, for example, Falvey 1975).

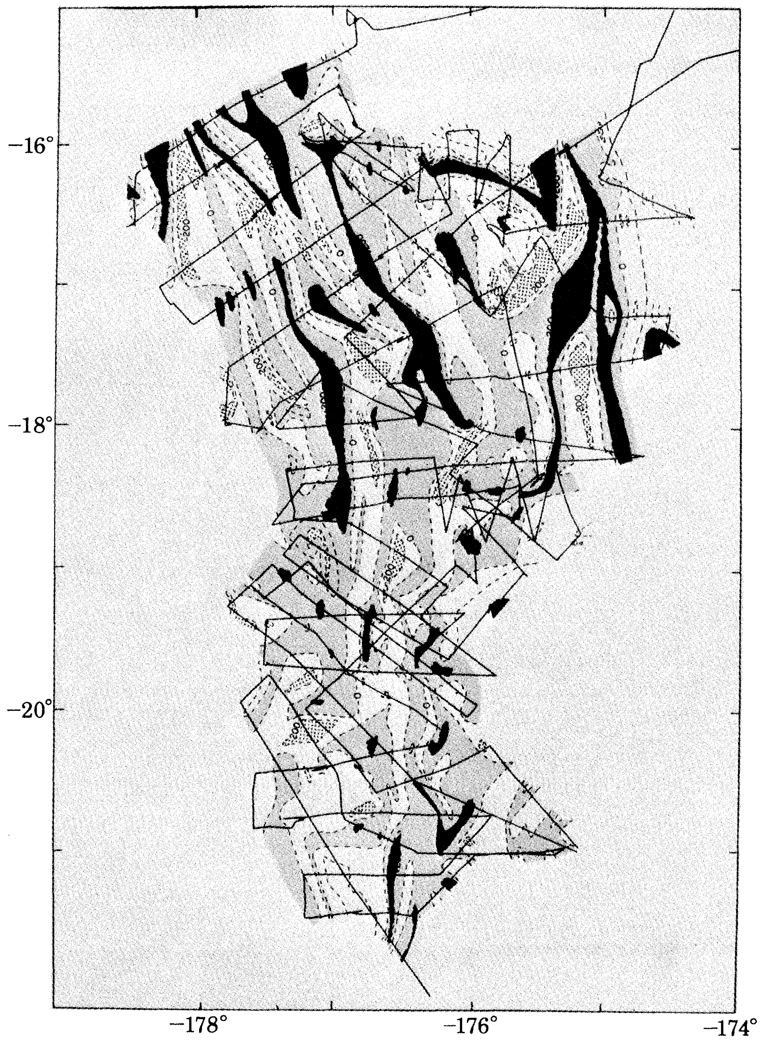

Figure 10. Contoured magnetic anomalies in the Lau Basin from data obtained by vessels of Scripps Institution of Oceanography. Contour interval is 200 nT, with over +200 nT being black areas, 0–200 nT dark grey areas, −200–0 nT light grey areas, and less than −200 nT stippled areas (from Lawver & Hawkins 1978).

(ii) *Lau Basin*

The distribution of shallow earthquakes shown in figure 9 reveals probable plate boundary activity in the northern part of the Lau Basin. An E–W band of epicentres centred along 15° S probably reflects left-lateral motion of the Pacific plate along the northern boundary of the Lau Basin. The interpretation of magnetic anomalies in the Lau Basin has been a matter of some conjecture. While most workers agree that a predominantly N–S magnetic lineation fabric exists in the basin (figure 10), specific correlation of magnetic lineations with the geomagnetic reversal timescale is a matter of debate (Sclater *et al.* 1972; Lawver *et al.* 1976; Weissel 1977;

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Lawver & Hawkins 1978). Although Hawkins (1974, 1976) has shown that basalts flooring the Lau Basin are closely similar to basalts erupted at mid-oceanic ridges, Lawver *et al.* (1976) proposed that well defined magnetic lineations symmetric about a spreading centre were lacking in this basin. They proposed instead that crustal accretion in the Lau Basin occurs simultaneously at a number of spreading ridges and seamounts, which could account for the apparently diffuse character of the magnetic lineations (Lawver & Hawkins 1978). On the

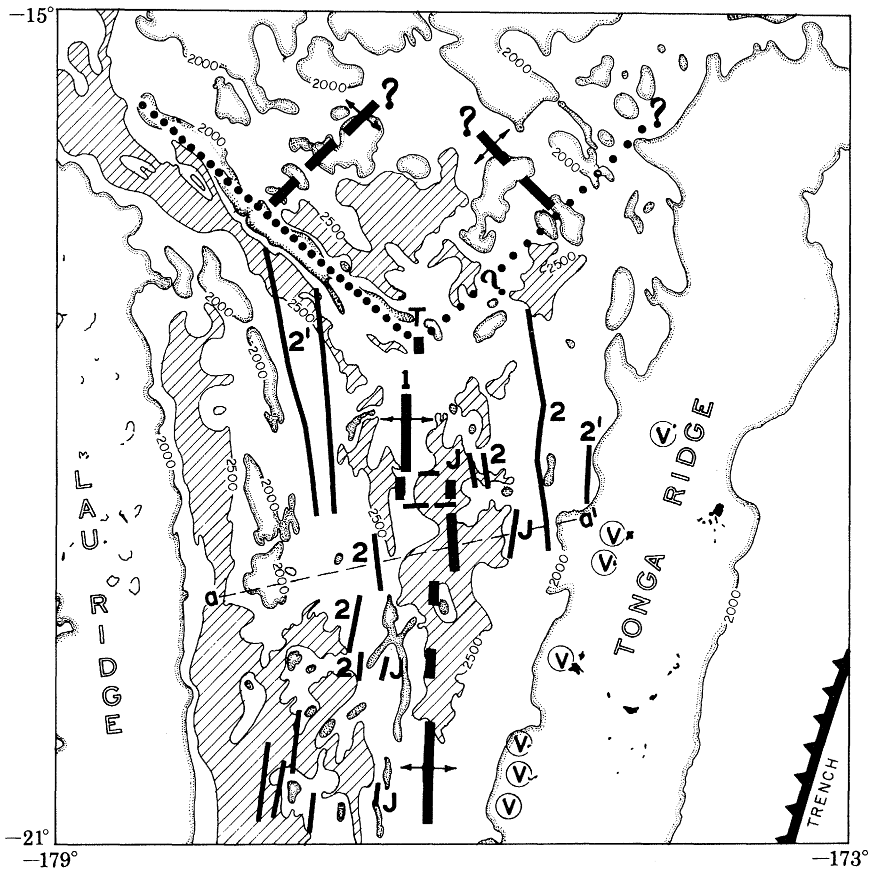

FIGURE 11. Tectonic elements of the Lau Basin (from Weissel 1977). Active extensional plate boundaries are the broad solid lines, trench axis is the saw-tooth line, and proposed strike-slip plate boundaries are heavy dotted lines. Magnetic lineations are the thinner solid lines. Bathymetric contours are adapted from Hawkins (1974). the V symbols on the Tonga Ridge represent active island arc volcanoes. T denotes the location of the inferred r.f.f. triple junction.

other hand, Weissel (1977) suggested that although the spreading history is complicated by spreading centre jumps, a recognizable sequence of approximately N–S magnetic lineations dating from the Present to about 3.5 Ma B.P. is present in the basin south of the Peggy Ridge (figures 11 and 12). The apparent truncation of the approximately N–S magnetic lineations against the Peggy Ridge, a recognized strike-slip feature (Karig 1970; Chase 1971; Selena Billington, personal communcation), led Weissel to propose that the Lau Basin has evolved by the growth of small plates, three of which meet at a ridge–transform fault–transform fault (r.f.f.) triple junction (figure 11).

Clearly, Lawver *et al.* (1976) and Lawver & Hawkins (1978) view back-arc extension in the Lau Basin as disorganized and diffuse in contrast to the more organized plate-like evolution proposed by Weissel (1977). These two models for back-arc extension are illustrated in figure 13. Perhaps these models should be regarded as end-members of a continuum of modes of back-arc extension, the type of extension process in a given back-arc basin being governed by its total tectonic setting. The implications of these two extreme modes of back-arc extension for the

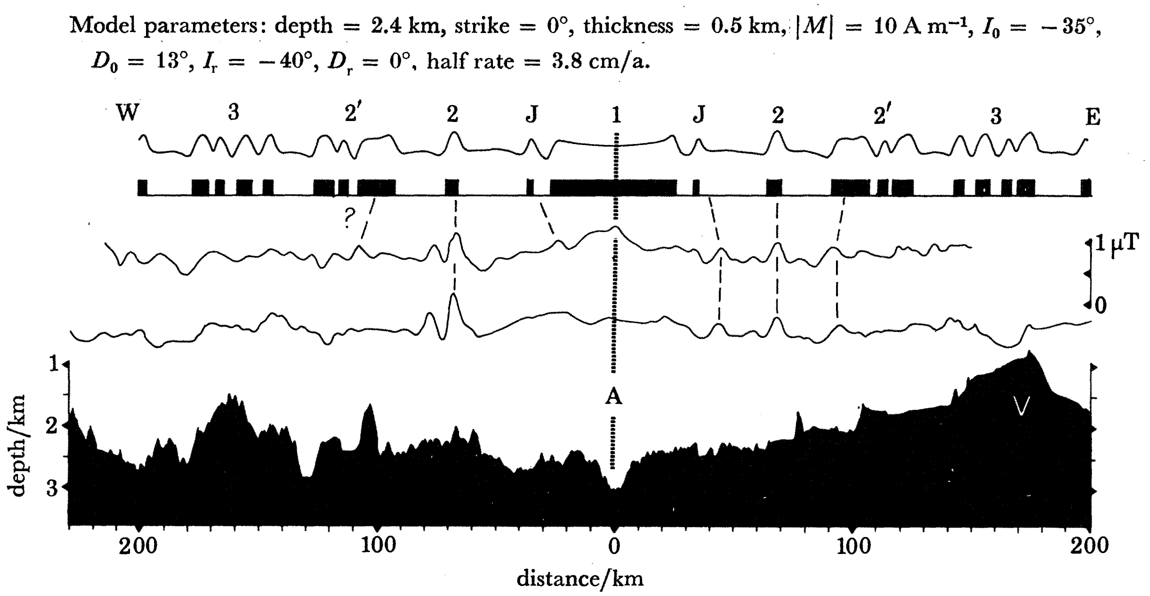

FIGURE 12. Comparison between two adjacent magnetic anomaly profiles from the Lau Basin (along azimuth aa′ in figure 11) and a synthetic profile calculated from the geomagnetic reversal timescale. In the model parameters the '0' and 'r' subscripts denote the ambient and remanent geomagnetic fields respectively. The morphology shown at the bottom is associated with the lower magnetic anomaly profile. A refers to the axial rift and V to the volcanic axis on the Tonga island arc (from Weissel 1977).

development of magnetic lineation patterns in back-arc basins are important. For the disorganized extension model (figure 13*a*), magnetic lineations should be diffuse and difficult to correlate with the geomagnetic reversal timescale (Lawver & Hawkins 1978). For the more organized ridge–transform form of extension (figure 13*b*), magnetic lineations should be relatively easy to map and correlate with the geomagnetic timescale, given favourable conditions for the generation of a strong magnetic 'signal' (see § 1).

(iii) *South Fiji Basin*

Strong evidence for the evolution of a marginal basin through the growth of at least three plates is seen in the magnetic lineation pattern preserved in the South Fiji Basin (figure 1*b*). However, it cannot be conclusively shown that the South Fiji Basin qualifies as a back-arc basin as defined in § 1 (table 1). Weissel & Watts (1975) and Watts *et al.* (1977*b*) proposed that a three-plate system meeting at a ridge–ridge–ridge (r.r.r.) triple junction generated most of the oceanic crust observed in the northern part of the basin during Oligocene time. In figure 14, representative magnetic anomaly profiles from the northern part of the South Fiji Basin indicate that spreading began at the three-plate system before anomaly 12 (33 Ma B.P.) and crustal accretion ceased completely by about anomaly 7 time (25 Ma B.P.). The crustal ages inferred from the

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observed magnetic lineations are consistent with ages obtained from two D.S.D.P. sites in the northern part of the South Fiji Basin (Burns *et al.* 1973; Andrews *et al.* 1975). Only one of the three Oligocene spreading centres is easily recognized today in the northeastern part of the basin. It is preserved as a NE–SW trending rough basement ridge (the Bounty Ridge) with magnetic lineations symmetric about it. An interesting feature of the magnetic pattern in the

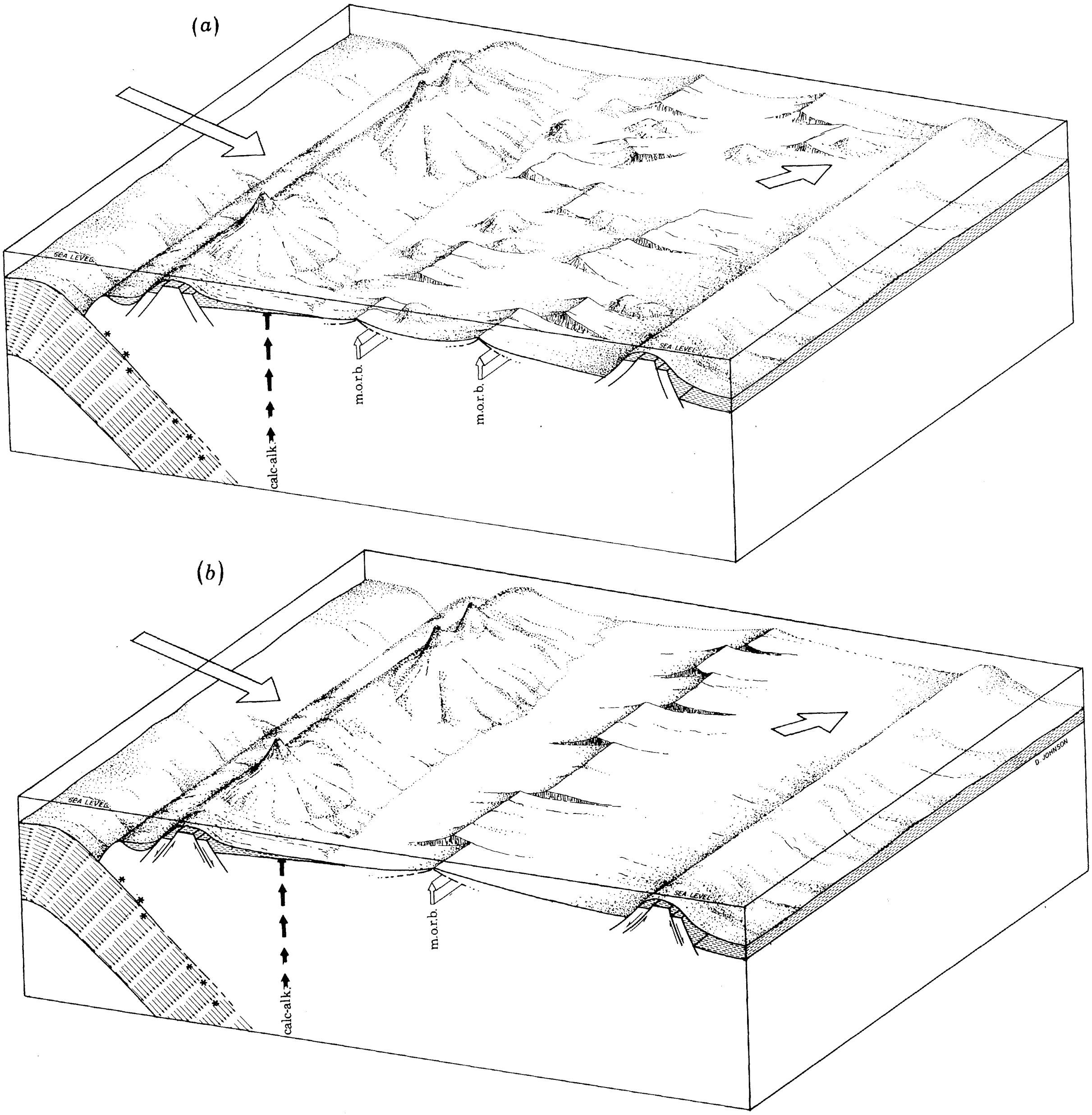

FIGURE 13. Schematic block diagrams for (*a*) disorganized and (*b*) organized back-arc extension (not to scale). The active (or frontal) arc is on the left and the remanent arc is on the right. In (*a*), the back-arc basin has numerous seamounts and short spreading segments with various orientations. In (*b*), back-arc spreading is organized into distinct ridge and transform segments. The broad oblique arrows denote the absolute velocities of the incoming and subducting plate on the left, and the overriding (or remnant arc) plate on the right. For convenience, the absolute velocity of the trench axis and the frontal arc plate is taken to be zero. These drawings were inspired by those of Lawver & Hawkins (1978). M.o.r.b., mid-ocean ridge basalts.

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basin is that oceanic crust and associated magnetic lineations from the southwestern plate of the three plate system appear to be almost entirely missing (figures 1*b* and 14). Watts *et al.* (1977*b*) and Davey (1980) ascribed this missing crust to subduction of the southwestern plate to the south beneath the Three Kings Rise, a prominent volcanic ridge that extends northwards from New Zealand along longitude 173° E.

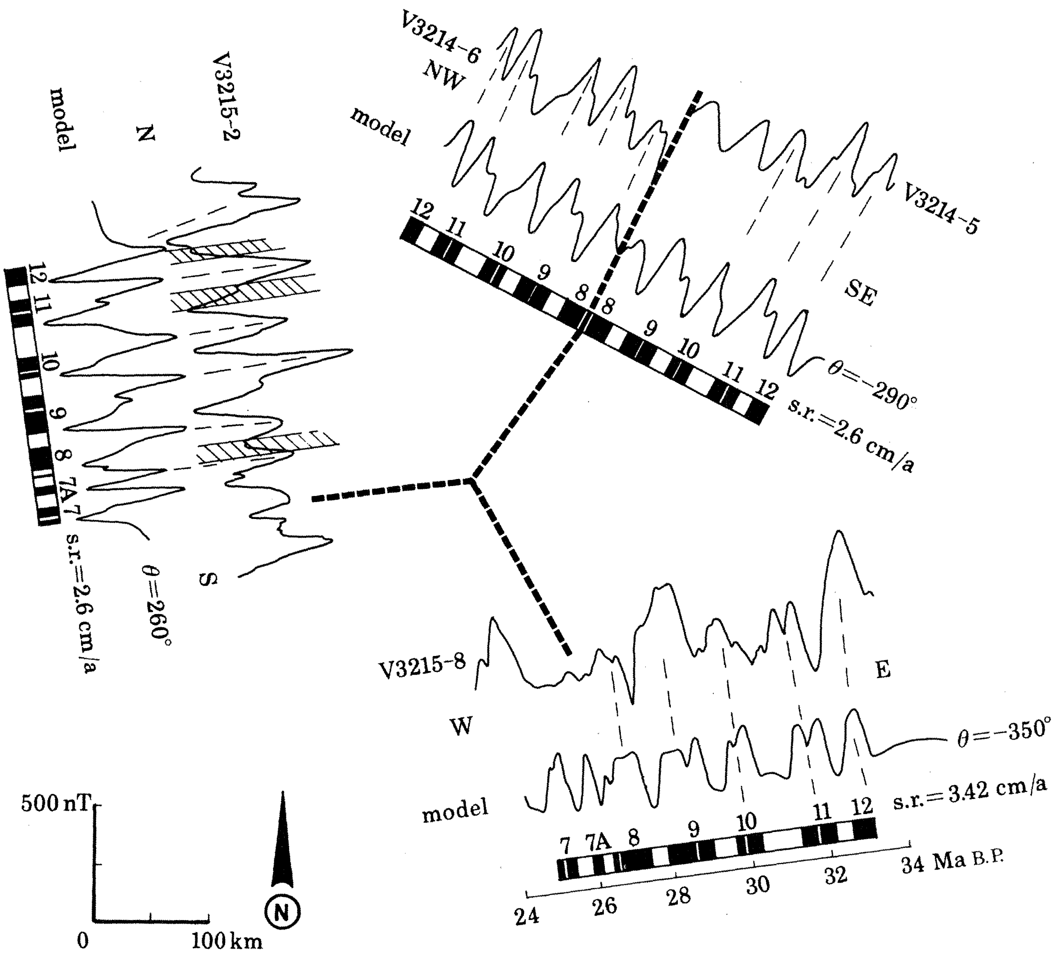

FIGURE 14. Schematic representation of magnetic lineations associated with the Oligocene three-plate spreading system in the northern part of the South Fiji Basin (Watts *et al.* 1977*b*; Davey 1980). Note that the southwestern plate of the system is now missing and believed to be subducted.

(iv) *Bismarck Basin*

The Bismarck Basin appears to be the product of back-arc extension behind the New Britain island arc–trench system (figure 1*b*) (Taylor 1979). The Bismarck Basin is divided morphologically into two sub-basins, the larger and deeper Manus Basin in the east (floored by oceanic crust) and the New Guinea Basin in the west, separated by a NW–SE trending volcanic ridge, the Willaumez–Manus Rise (Johnson *et al.* 1979). Magnetic lineations have been mapped in the Manus Basin and correlated with anomalies 1–2′ of the geomagnetic reversal timescale (figures 15, 16) (Taylor 1979). Comparison of the lineation trends with slip directions inferred from earthquake focal mechanisms (figure 15) reveals that spreading is oblique in the Manus Basin. It is likely that the NE and SW margins of this basin have formed through strike-lip motion.

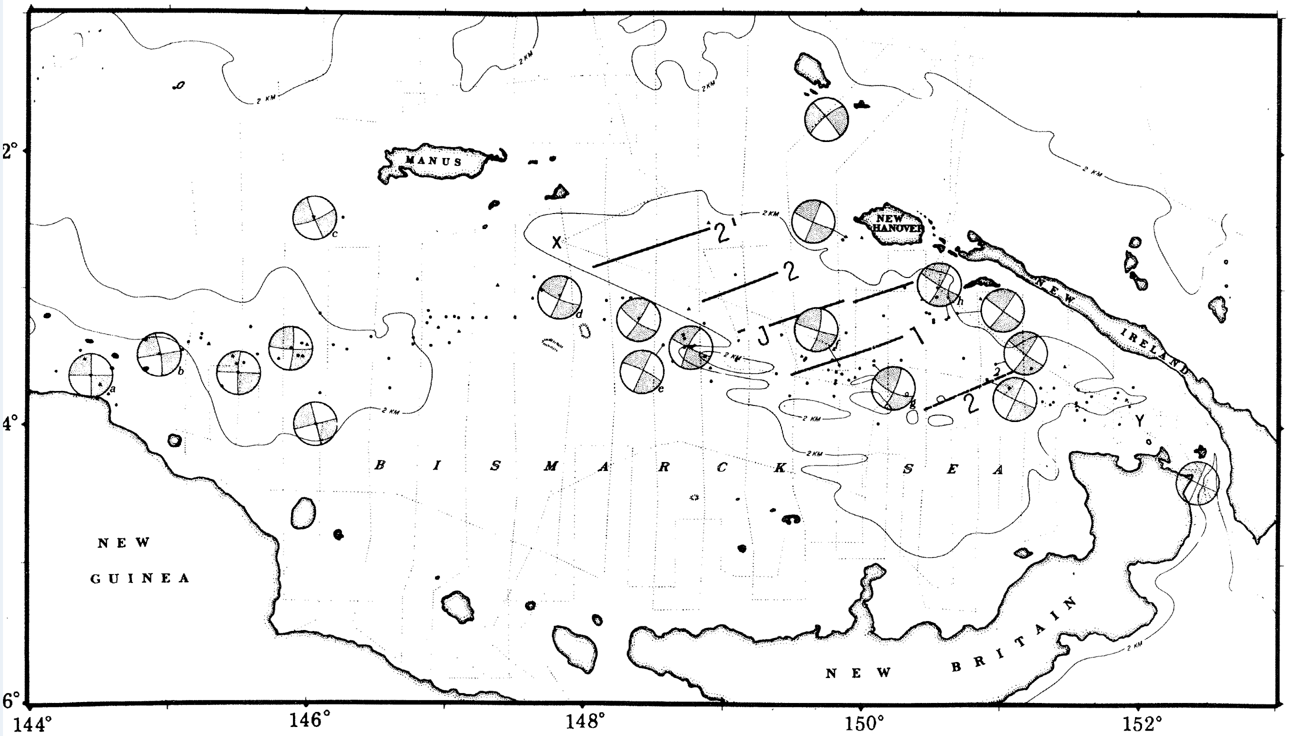

FIGURE 15. Ship tracks (dotted), focal mechanisms (compressional quadrants shaded), and magnetic lineations in the Bismarck Sea. Earthquakes (small dots and triangles) in the region 2°–4° S, 144°–152° E define the plate boundary (from Taylor 1979).

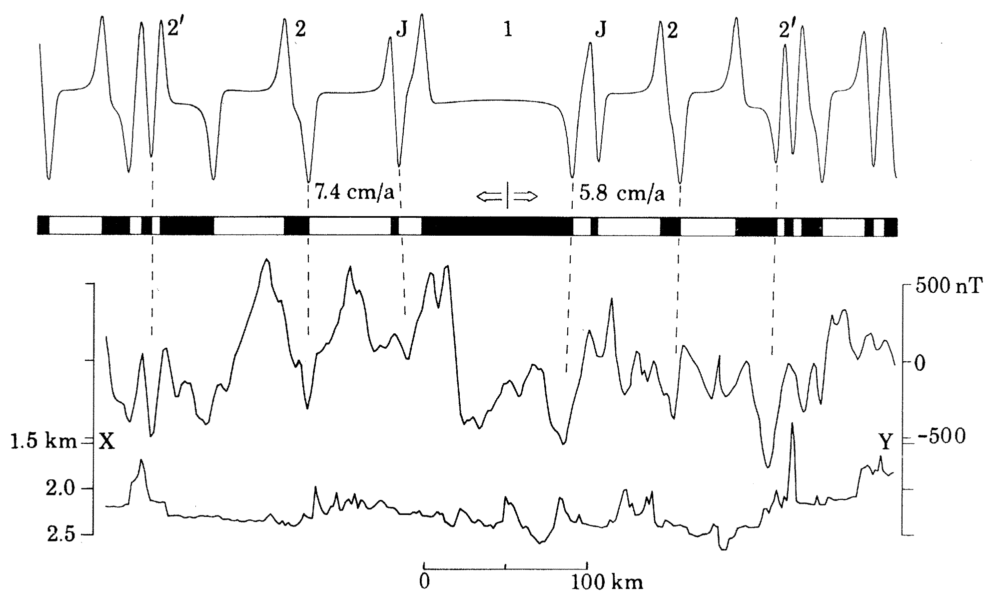

FIGURE 16. Comparison of projected magnetic anomaly profile (track XY, figure 15) to a computed profile with an assumed depth to the upper surface of the block model of 2.4 km, a layer thickness of 0.5 km, and a uniform magnetization contrast of 4 A/m. The computed profile was generated from a model in which the binary function representing a standard magnetic model was convolved with a Gaussian distribution function of $\sigma = 2$ km (see Watts *et al.* 1977*a*). The vertical exaggeration of the bathymetric profile is 56:1 (Taylor 1979).

Earthquake activity west of the Manus Basin suggests that E–W sinistral shear occurs along the western portion of the plate boundary in the Bismarck Sea. Taylor (1979) suggested that a small component of extension accompanying strike-slip motion has generated oceanic crust in the New Guinea Basin. The Bismarck Basin is interesting because the observed magnetic lineation and earthquake focal mechanism solutions (figure 15) combine to yield a pole of relative motion that places the opening of the basin in a plate tectonics framework (Taylor 1979). From the slight azimuthal differences between inferred transform faults bounding the spreading segment in the Manus Basin (figure 15), Taylor (1979) determined a pole at 18.5° S, 141° E for the mid-Pliocene to Present opening of the Bismarck Sea, and an angular opening rate of 4°/Ma was obtained from the observed spreading rates in the Manus Basin (figure 16). Taylor's analysis of marine magnetics and earthquake focal mechanism data from the Bismarck Sea is one of the more convincing applications of plate tectonics techniques to the opening of a back-arc basin. An earlier determination of the opening of the Mariana Trough in terms of a single finite rotation (Le Pichon *et al.* 1975) was governed largely by the geometry of the margins of the trough. However, Karig *et al.* (1978) criticized the finite rotation model of Le Pichon *et al.* on the grounds that it is not consistent with the trends of small-scale morphological features observed within the Mariana Trough.

The foregoing examination of magnetic anomaly and other geophysical observations in possible and probable back-arc basins of the western Pacific is not exhaustive; further information is available on each basin in table 1 through the original papers referred to in figure 1. The basins examined above were selected because they span the range from basins still in a rifting stage, through actively opening basins, to basins that have been tectonically inactive for a considerable length of time. Highlighted by this survey are variations from basin to basin in how well the tectonic processes responsible for crustal generation have been recorded in observed magnetic lineation patterns. It remains in this review to consider the various models that have been proposed to account for crustal extension behind island arc–trench systems.

3. Models for the generation of back-arc basins

Models for formation of back-arc basins fall into two broad categories: slab-driven models and global plate motion models.

(*a*) *Slab-driven models*

The subducted (downgoing) slab perturbs and modifies the overlying asthenospheric material in two likely ways.

(i) The descending slab encounters frictional resistance, which heats the overlying asthenosphere, eventually producing a 'diapir' of partial melt (Oxburgh & Turcotte 1971; Karig 1971). The buoyant 'diapir' rises and induces tensional failure in the lithosphere behind the island arc–trench system, eventually leading to production of new oceanic material (a back-arc basin) behind the associated island arc (see Karig 1971).

(ii) The descending slab induces by viscous drag convective flow in the wedge of asthenosphere above it (McKenzie 1969; Sleep & Toksöz 1971; Andrews & Sleep 1974; Toksöz & Bird 1977). The induced convection heats, and produces tensional failure in, the overriding plate of the subduction system. Partial melting occurs in the material which rises by convection, providing a source of new lithosphere for a back-arc basin. Numerical model studies show that at observed rates of subduction, convection in the asthenospheric wedge becomes well established within a few megayears of the initiation of subduction, and that heating, rifting and generation of a back-arc basin in the overriding plate can take place within 20–40 Ma after subduction starts (Toksöz & Bird 1977).

In the above slab-driven models, the driving mechanism is provided by the descending slab, so that the kinematics of subduction determines the vigour with which back-arc extension becomes established. Once started, it is not clear why back-arc extension does not proceed indefinitely, because a cessation or drastic interruption of subduction is required in the model to stop the process. The slab-driven models can be regarded as 'local' in the sense that the characteristics of plate convergence in the immediate vicinity govern the evolution of back-arc extension.

(b) *Global plate motion models*

This category of models assumes that back-arc extension is governed by the global budget of plate motions and that the local magnitude and direction of plate convergence are inconsequential.

When viewed in a reference frame that minimizes asthenospheric motions (Chase 1978*a*; Minster & Jordan 1978), overriding (remnant arc) plates where back-arc extension is occurring show mostly a component of motion *away* from their associated trench axes (Chase 1978*b*; Molnar & Atwater 1978; Uyeda & Kanamori 1979; Wu 1978; Dewey 1980). However, trench axes (loci of subduction) may themselves move in this reference frame but apparently only in a *seaward* direction. Reduction in size of the Pacific Ocean by seaward migration of trenches since Mesozoic time was proposed by Elsasser (1971) to conserve global surface area because the Atlantic and Indian Oceans have grown over the same time interval. Molnar & Atwater (1978) suggested that the negative buoyancy of old oceanic lithosphere would enhance such seaward trench migration. They proposed that the magnitude of the gravitational instability of oceanic lithosphere increases with age so that trenches subducting Mesozoic oceanic lithosphere (around the western Pacific) should move seaward more easily than trenches where relatively young lithosphere is subducted (eastern Pacific). The velocity of seaward migration of the trench axis has been termed the 'roll-back' velocity by Dewey (1980). Chase (1978*b*) and Dewey (1980) believe that because of a trench 'suction' force (Forsyth & Uyeda 1975), the frontal arc plate (containing the trench inner wall and fore-arc region to the volcanic axis) is also pulled seaward at the 'roll-back' velocity.

The work of Chase (1978*b*), Molnar & Atwater (1978), Uyeda & Kanamori (1979), Wu, (1978) and Dewey (1980) may be summarized thus: back-arc extension can occur when the resultant of the velocities of the overriding plate and the trench 'roll-back' has a component directed *away* from the trench. Presumably, when this condition is met, tensional failure in the overriding plate occurs along the volcanic axis and back-arc spreading will take place with a spreading direction governed by the direction of the resultant velocity vector (see Dewey (1980) for a discussion of all kinematic possibilities). Rarely will the strike of magnetic lineations in the back-arc basin coincide with the strike of either the trench axis or the volcanic axis (Dewey 1980). In the global plate motion models, accretion in a back-arc setting occurs passively just as accretion at mid-oceanic ridges is thought to occur. The global plate kinematics model is appealing because a glance at a world map of absolute plate motions (e.g. Chase 1978*a*; Minster & Jordan 1978) shows that important back-arc basins (like the Mariana Trough, Lau

Basin and East Scotia Basin) are opening in accordance with predictions. Reorganization of plate motions on a global scale provides a way to start or stop episodes of back-arc extension (Jurdy 1979).

4. Summary

Marginal basins of the western Pacific can be classified according to the likelihood of their formation in a 'back-arc' (or 'inter-arc') setting as defined by Karig (1971). An examination of magnetic anomaly data from several possible or probable back-arc basins (table 1) leads to the following conclusions.

1. Magnetic lineations that are correlatable with the geomagnetic reversal timescale are found repeated about active or extinct spreading centres in back-arc basins. There are exceptions: the Mariana Trough and the southern Parece-Vela Basin, which are in close proximity to the geomagnetic equator, the Okinawa Trough, which may still be in a rifting stage, and the Japan Sea Basin (for reasons yet unknown).

2. Magnetic lineations on the frontal arc plate of the back-arc spreading systems in the Parece-Vela, Shikoku, Lau and Bismarck basins are of poorer quality than lineations on the remnant flank (overriding plate). Further, in these basins and the Mariana Trough the accreting plate boundary is offset towards the volcanic axis of the frontal arc. Magnetic anomaly evidence from the Scotia Sea (Barker 1972; Barker & Hill, this symposium) shows a similar situation there. Note that island arc volcanism can and does occur on the frontal arc flank once it has formed. The frontal arc flank of back-arc spreading systems may also be more prone to intraplate deformation and seamount volcanism since it is closer to the descending slab and volcanic axis of the subduction zone and may therefore be 'hotter' and weaker than the remnant arc flank.

3. The shapes of magnetic anomalies indicate that the width of the zone of crustal accretion in back-arc basins is similar to the width determined for the world's mid-oceanic ridge systems.

4. Magnetic lineation patterns in the South Fiji and Lau basins and the distribution of shallow earthquakes in the Lau Basin and Fiji Plateau indicate that these basins have grown as a result of the evolution of more than two plates. Although on a smaller scale, plate boundary geometries in these three basins resemble configurations of three-plate systems observed in the major ocean basins.

5. The duration of back-arc extension (*ca.* 10 Ma) is short compared with the histories of major oceanic spreading systems (*ca.* 100 Ma). This implies that tectonic conditions favourable for the generation of back-arc basins are either relaxed relatively quickly or are easily interrupted (such as by buoyant material arriving at the trench).

6. The Bismarck Basin remains a plausible example of a back-arc basin whose opening appears to follow rules of plate tectonics. The relative motion between the active arc and the remnant arc is reasonably well constrained by earthquake focal mechanisms and by opening rates inferred from magnetic lineations (Taylor 1979).

This survey of magnetic anomalies in back-arc basins suggests that similar processes of crustal accretion operate in the back-arc environment and at the world's mid-oceanic spreading systems; but the time and space scales of back-arc basins appear systematically smaller.

Two categories of models proposed to account for back-arc extension have been discussed in this paper.

(*a*) Models in which back-arc extension is caused or induced by the descending lithosphere of the subduction system may be considered 'local' systems because the kinematics of the slab provides the energy that ultimately produces back-arc extension.

(*b*) In global plate motion models, conditions for back-arc extension depend only on whether the resultant of the absolute velocities of the overriding plate and the trench 'roll-back' (in a 'mantle' reference frame) has a component directed away from the trench axis.

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Discussion

H. G. Reading (*Department of Geology and Mineralogy, University of Oxford, U.K.*). How is a 'back-arc basin' defined and how is it distinguished from a 'not back-arc marginal basin'? Is the definition purely geographical, i.e. a basin on the concave side of an active volcanic arc? Or is it genetic, i.e. a basin that occurs above a present or inferred past subduction zone? It is peculiar that the general ages of the 'certain back-arc basins' are younger than the 'uncertain back-arc basins' which, in turn, are younger than the 'not back-arc basins'. This suggests that the 'certainty' of a basin depends more on the ease with which a subduction zone can be recognized than on any real change of type. Assuming that the definition is genetic, does there have to be a causal connection between subduction and spreading, and which is supposed to have caused which?

With regard to the orientation of the magnetic lineations, in some cases it may be the result of the direction of motion of an associated strike-slip fault zone. This is certainly so for the Andaman Sea where the magnetic lineations trend approximately NE–SW and appear to be the direct result of movement on the N–S trending dextral fault zone that links the Burma fault with the Sumatra fault system; the resulting basins are pull-aparts whose location and shape are governed by the strike-slip motion, rather than by the N–S trending island arc and subduction zone. In the Gulf of California, similarly, NE–SW trending magnetic lineations appear to result from the N–S trending dextral San Andreas fault. Dr Weissel comments on the apparently anomalous E–W trending magnetic lineations in the Philippine Sea. Is it just coincidence that they are adjacent to the sinistral NW–SE trending Philippine fault? Or are they both the response to a regional sinistral strike-slip motion in that part of the western Pacific?

J. K. Weissel. A 'back-arc' basin is formed through extension behind an already established island arc–trench system; that is, an existing convergent plate boundary is necessary (but not sufficient) for the formation of a back-arc basin. Where the tectonic relation implied by this definition cannot be demonstrated, a marginal basin should be considered 'not back-arc'. Thus, the classification of marginal basins according to 'back-arc' and 'not back-arc' in table 1 is a genetic one. There are two relevant points regarding marginal basins that are 'not back-arc': (1) the Woodlark Basin is young and currently active, and (2) a purely geographic or morphological classification of marginal basins would have the Aleutian Basin as a 'back-arc' basin even though it almost certainly pre-dates the Aleutian arc. It is generally true that basins placed in the 'possible back-arc' category are older than those in the 'probable back-arc' category, and this is probably because the activity in the basin and at its associated subduction zone has ended, precluding a positive link between the trench and back-arc basin. Often portions of the marginal basin in question have been subducted at other more recently active trench systems (e.g. South Fiji Basin, New Hebrides Basin, West Philippine Basin).

I agree that the opening of the Andaman Basin is somewhat analogous to the opening of the Gulf of California, and it is not clear whether the Andaman Basin should be considered a back-arc basin at all. I think that it is a coincidence that the WNW–ESE trending Eocene lineations in the West Philippine Basin are adjacent to the NNW–SSE Philippine fault zone, which currently shows a component of sinistral strike-slip motion (see focal mechanisms associated with the Philippine fault zone (Hayes & Taylor 1978)). However, it must be remembered that when the West Philippine Basin formed (before 40 Ma ago), it was 20–30° farther south, and that since its formation it has rotated clockwise by 50–60° (see, for example, Louden 1977). Some of the crust of the West Philippine Basin has been subducted at the Philippine Trench since the Eocene. Although the history of movement along the fault zone is poorly known (see, for example, Rutland 1968), I believe that the Philippine fault zone accommodates some of the recent oblique convergence between the Philippine and Eurasian plates.

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L. Stegena (*Department of Cartography, Lorand Eötvös University, Budapest, Hungary*). On the basis of magnetic lineations, Jurdy (1979) suggested that the western Pacific marginal basins are derived from the motion of the Pacific plate relative to Eurasia, which was directed to the west (80–59 Ma), to the north (59–36 Ma) and again to the west (36–0 Ma). However, it seems to me that magnetic lineations in marginal basins exhibit a complicated pattern and their formation can not simply be explained in terms of relative motion of the Eurasian and Pacific plates. What does Dr Weissel think about it?

J. K. Weissel. Before evaluating Jurdy's (1979) model, the assumptions inherent in the model and her basic conclusions should be repeated. She assumes that because back-arc basins form at convergent plate boundaries, formation of these basins is tied to relative motion of the plates across the convergent zone. The conclusions are that (*a*) the timing and directions of opening of back-arc basins of the western Pacific are related to changes in motion of the Pacific plate relative to the fixed Eurasian plate, and (*b*) this correlation supports slab-driven models for the generation of back-arc basins. Her work emphasizes the connection between episodes of back-arc extension and major reorganizations of plate motions. I have reservations about the way that she uses magnetic lineation information to support her model. First, some of the basins that she cites are not back-arc (e.g. South China Basin, Coral Sea Basin). Secondly, the movement of the Philippine plate was not considered, and we know (see my response to Dr Reading) that spreading in the Philippine Basin occurred along an azimuth very different from that observed today for magnetic lineations in that basin. Thirdly, I see evidence that suggests that east and west Antarctica were one plate by 45–50 Ma ago (Weissel *et al.* 1977) as opposed to the 36 Ma age used in Jurdy's model.

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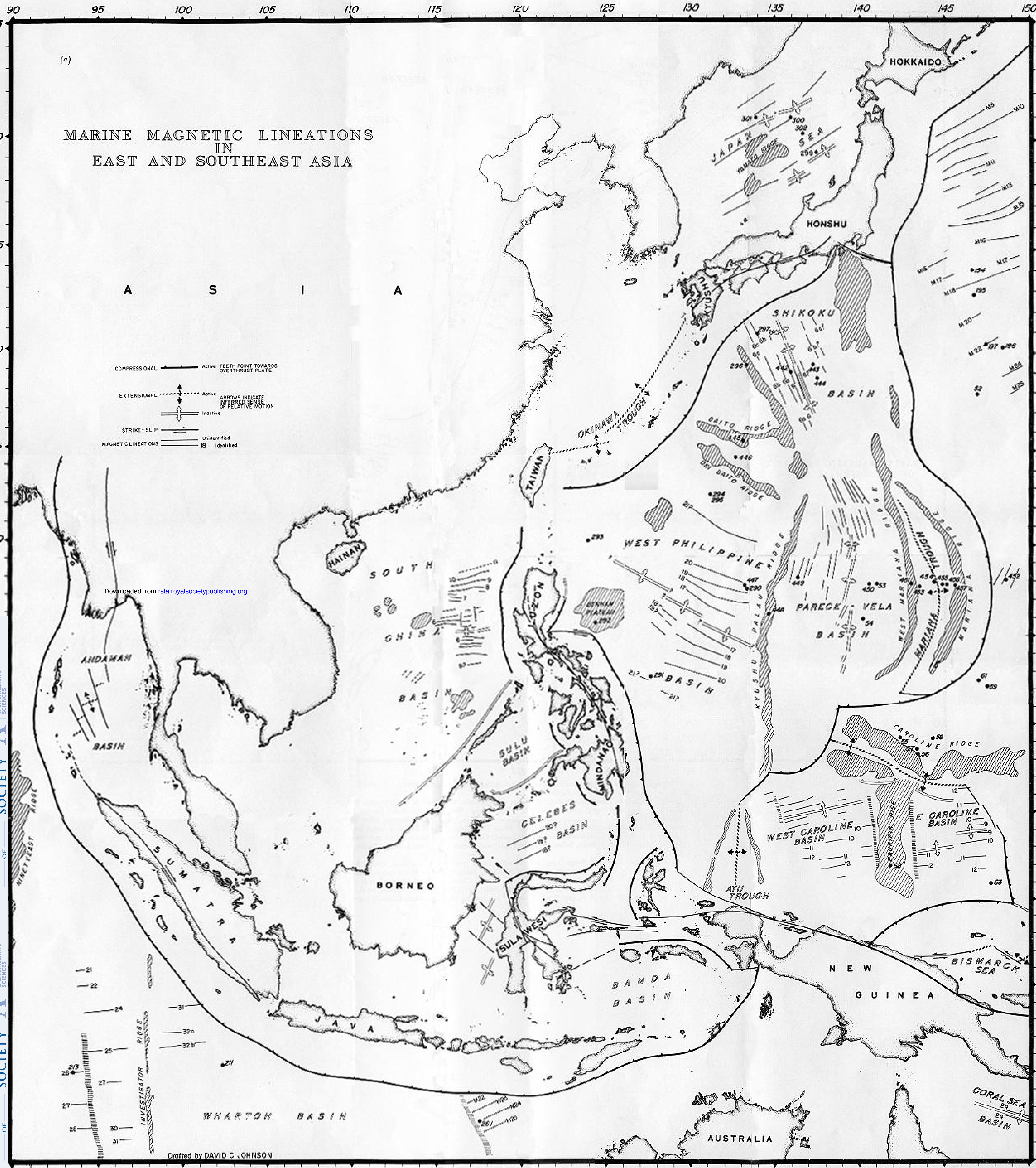

FIGURE 1a. For description see over.

(Facing p. 224)

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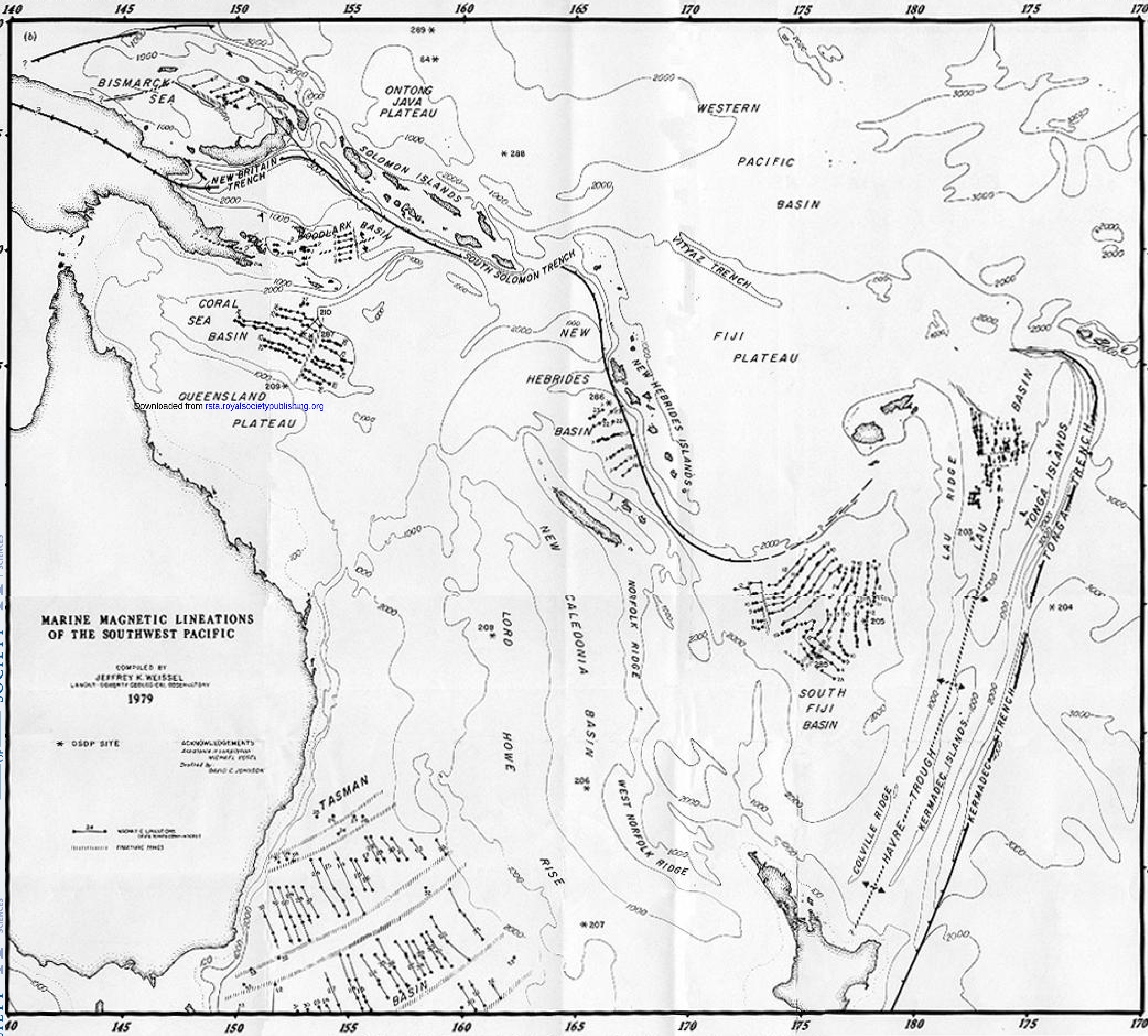

Figure 1. Magnetic lineations in marginal basins of the Western Pacific: (*a*) east and southeast Asia (after Hayes & Taylor 1978); (*b*) the southwestern Pacific.

Sources. (*a*) Mariana Trough, Karig *et al.* (1978); Parece-Vela Basin, Mrozowski & Hayes (1979); Shikoku Basin, Watts & Weissel (1975) and Kobayashi & Nakada (1979); West Philippine Basin, Louden (1976), Watts *et al.* (1977*a*) and Shih (1980); Japan Sea Basin, Isezaki (1975); Okinawa Trough, Herman *et al.* (1979); Andaman Basin, Curray *et al.* (1979, 1980); South China Basin, Taylor & Hayes (1980) and Ben-Avraham & Uyeda (1973); Celebes Basin, Weissel (1980); Caroline Basins, Bracey (1975) and Weissel & Anderson (1978); Wharton Basin, Sclater & Fisher (1974) and Larson (1975); northwestern Pacific, Hilde *et al.* (1976).

(*b*) Tasman Basin, Hayes & Ringis (1973) and Weissel & Hayes (1977); Coral Sea Basin, Weissel & Watts (1979); New Hebrides Basin, Weissel *et al.* (1980*a*); South Fiji Basin, Weissel & Watts (1975), Watts *et al.* (1977*b*), Malahoff *et al.* (1980) and Davey (1980); Fiji Plateau, Chase (1971) and Malahoff *et al.* (1980); Lau Basin, Sclater *et al.* (1972), Lawver *et al.* (1976) and Weissel (1977); Havre Trough, Malahoff *et al.* (1980); Woodlark Basin, Luyendyk *et al.* (1973) and Weissel *et al.* (1980*b*); Bismarck Basin, Connelly (1976) and Taylor (1979).

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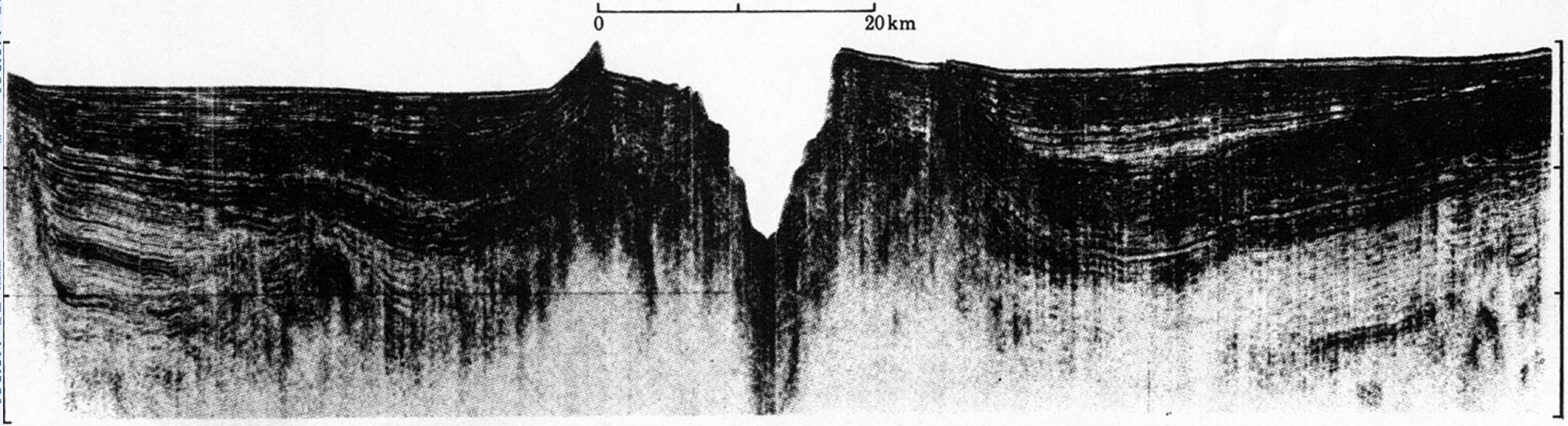

FIGURE 8. Single-channel seismic reflexion profile across a segment of axial rift in the Andaman Basin. Vertical exaggerations: water, ×24; sediments, ×*ca*. 18. Note the older buried, upturned and rifted sections of sediment (from Curray *et al*. 1979).

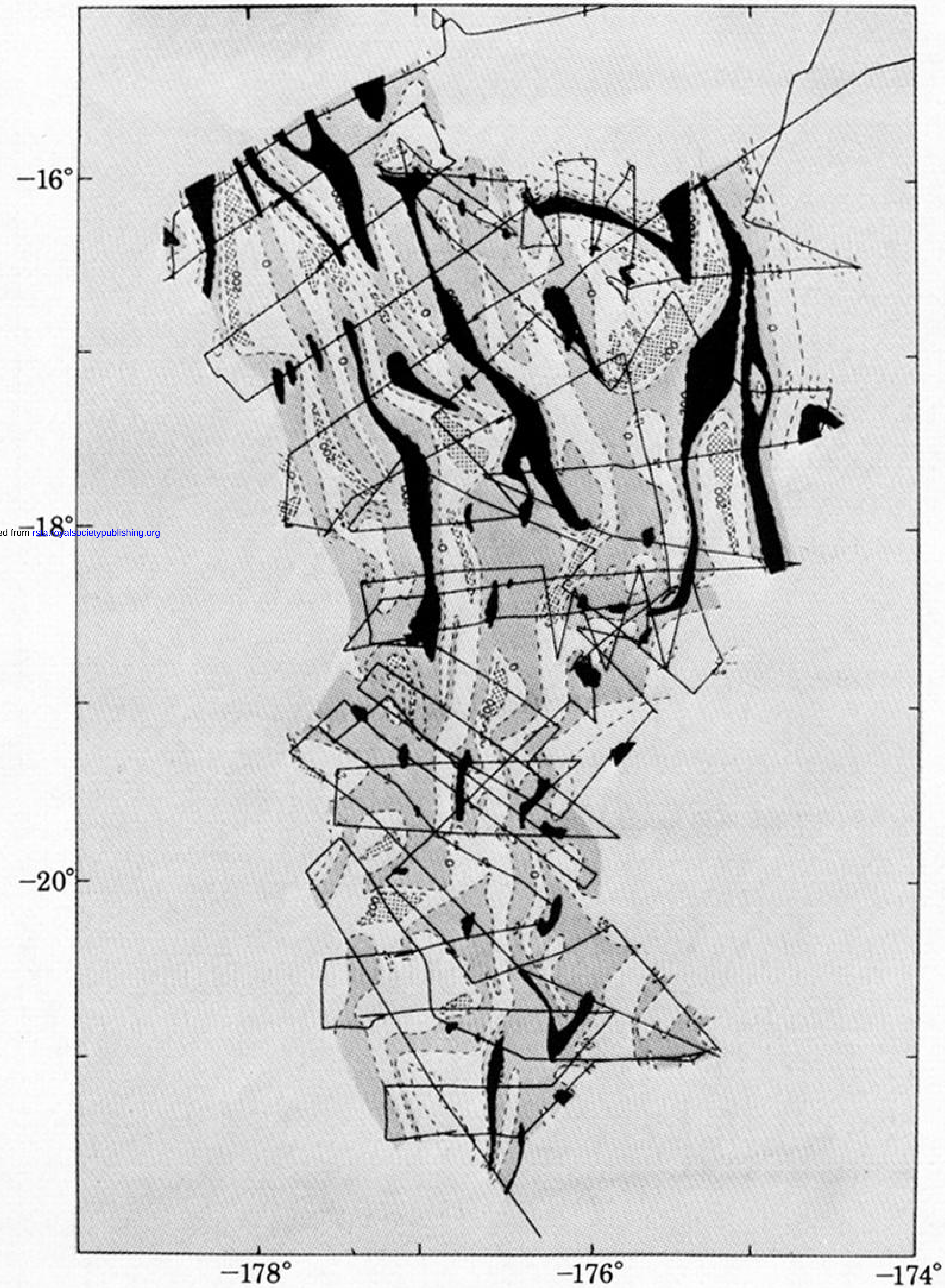

FIGURE 10. Contoured magnetic anomalies in the Lau Basin from data obtained by vessels of Scripps Institution of Oceanography. Contour interval is 200 nT, with over +200 nT being black areas, 0–200 nT dark grey areas, −200–0 nT light grey areas, and less than −200 nT stippled areas (from Lawver & Hawkins 1978).

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