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Structure and structural development of the Havre Trough (SW Pacific)

J. Delteil,¹ E. Ruellan,² I. Wright,³ and T. Matsumoto⁴

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[1] Northeast of New Zealand the Pacific plate is obliquely subducted beneath the overriding Australian plate. Major differences appear in the oblique-convergence-driven structures that occur along the plate boundary. While strike-slip component of convergence is accommodated in the forearc domain to the south at the eastern North Island margin, we here substantiate that at least part of the strike-slip component is accommodated within the back arc Havre Trough to the north offshore New Zealand. New swath bathymetry and structural data collected in the Havre back arc domain show that the basin as a whole displays oblique to basin axis structures that allow considering the basin to be the loci of extensive tectonics associated with dextral displacement of the Kermadec Arc Block relative to the Australian plate. Therefore, where the two plates are oceanic, the oblique convergence between Pacific and Australian plates is partitioned at the subduction trench for its normal-to-trench component and at the rear of the Kermadec Arc Block for part or all of its along-strike component where it is intimately associated with extensional rifting within the back arc domain. The kinematic pattern of Australian-Pacific plate boundary northeast of New Zealand that straddles a limit between continental and oceanic lithosphere allows addressing the specificity of the structural development, the deformation distribution, and the assessment of movement components that occur in a back arc basin associated with oblique convergence.

INDEX TERMS: 0930 Exploration Geophysics: Oceanic structures; 3040 Marine Geology and Geophysics: Plate tectonics (8150, 8155, 8157, 8158); 3045 Marine Geology and Geophysics: Seafloor morphology and bottom photography; 8150 Evolution of the Earth: Plate boundary—general (3040); 9355 Information Related to Geographic Region: Pacific Ocean; *KEYWORDS:* SW Pacific, Back-arc dynamics, strain partitioning, Havre Trough, transtension

1. Introduction

[2] Lying at the leading edge of the Pacific-Australian convergent plate boundary where the Pacific plate is subducted westward beneath the Tonga-Kermadec arc, the Havre Trough is a site from which *Karig* [1970] first proposed the concept of back arc opening (or interarc basin). The Havre Trough and its northern extension into the Lau Basin form a 2700-km-long back arc basin that extends from 15°S, east of Fiji, to the Taupo Volcanic Zone within the central North Island, New Zealand, at 39.5°S (Figure 1). The boundary between the Havre Trough and Lau Basin segments of the back arc, presently located at 25°S, is marked by a significant change in the structure and style of back arc opening, which coincides with both the Louisville seamount chain impinging the subduction zone and a change in the orientation of the arc. Apart from the southernmost sector, the tectonic structure of

the actively widening Havre back arc has been, to date, poorly resolved, although the general oblique to basin axis structural fabric and the 32°S boundary that marks a significant change in back arc morphology and trench orientation have been recognized.

2. Havre Trough Back Arc

2.1. General Morphology and Tectonic Structure

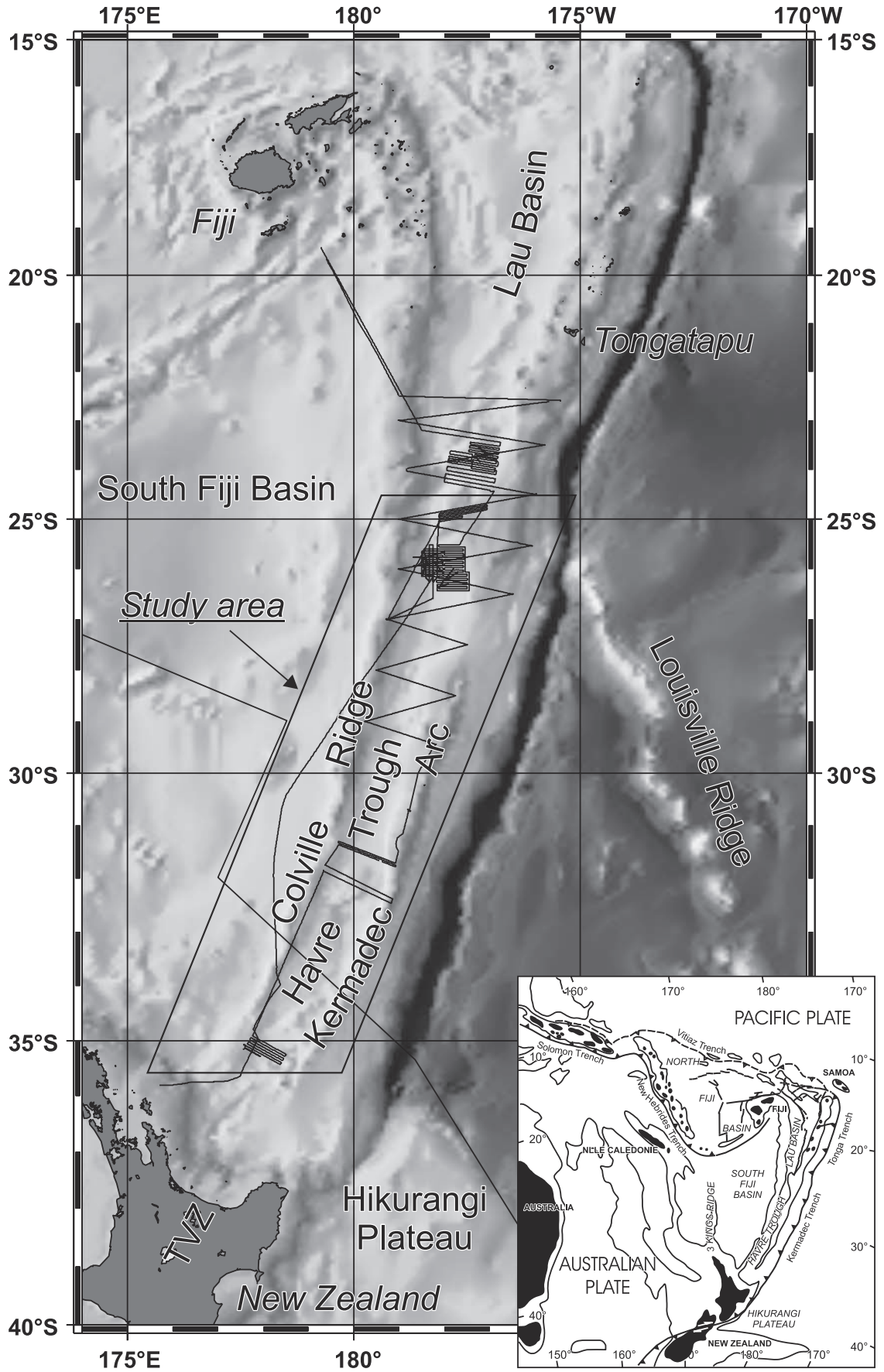
[3] The present study focuses on the sector of the Havre Trough back arc basin that extends from 35°20'S (north of New Zealand) to 24°40'S where the Louisville hot spot seamount chain impinges against the subduction zone. This segment of back arc, ~1270 km long, represents just under half of the 2700-km-long contiguous Lau-Havre-Taupo back arc basin system. Initially, oceanic ridge spreading was interpreted as the mechanism of basin widening as determined from anomalies derived from aeromagnetic surveys [*Malahoff et al.*, 1982]. Subsequent swath bathymetry and side-scan imagery surveys and rock dredging have found no evidence of oceanic spreading within the basin [*Caress*, 1991; *Parson and Wright*, 1996; *Wright et al.*, 1996; *Ballance et al.*, 1999]. The back arc basin, 179 ± 30 km wide, is interpreted as thinned rifted arc crust [*Parson and Wright*, 1996], which is bounded by the remnant arc of Colville Ridge and the active volcanic arc Kermadec Ridge, west and east, respectively. *Nishizawa et*

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al. [1999], using refraction derived P wave velocity structure, confirm the back arc, at least for the northern Havre Trough at 26°S, is composed of arc crust with a thickness of 9–10 km. Our data support these latter studies because no reliable magnetic anomalies or spreading fabric are observed from this study. Rather, the new swath bathymetry identifies a pervasive fabric of alternating horst-graben fault blocks and fault controlled extrusive volcanic ridges.

[4] *Caress* [1991] and *Wright* [1993] provided the first convincing evidence of oblique basement fabric within the Havre Trough, although *Karig* [1970] had originally inferred such a tectonic structure. Independently, shallow seismicity confirms the oblique basement fabric, from which *Pelletier and Louat* [1989] and *Pelletier et al.* [1998] proposed an oblique basin-opening model. Subsequent studies within the Havre back arc [e.g., *Parson and Wright*, 1996; *Wright*, 1997; *Ballance et al.*, 1999] have all further confirmed the clockwise deflection of basement structure relative to the regional basin strike.

[5] *Caress* [1991] and *Wright et al.* [1996] both observed that basement obliquity is defined by along basin axis left-stepping en echelon segmentation, with individual segment bounding zones being the loci of transverse volcanic ridges. These transverse ridges are interpreted as east–southeast migrating magmatic sources that form constructional ridges transverse to the basin axis as a consequence of back arc opening and eastward trench roll-back [*Wright et al.*, 1996]. Similarly, Havre Trough basement structure reveals an asymmetry with the western third of the back arc complex region (that nearest the remnant Colville arc) including a sediment filled subbasin [e.g., *Parson and Wright*, 1996; *Ballance et al.*, 1999], while farther east the remaining regions of the back arc are mostly composed of rugged, highstanding, and generally sediment starved volcanic basement. These differences in seafloor morphology and sediment thickness, asymmetry of shallow seismicity [*Pelletier and Louat*, 1989] and volcanism [*Wright*, 1994] are interpreted as evidence of recent tectonism and volcanism being predominantly distributed along the arcward part of the back arc complex, and coincident with the eastern basement morphology.

[6] The broad regional structure of the Havre back arc, and contiguous extensions, is marked by at least two significant changes along its length. The first, between the Lau Basin and Havre Trough, is the pronounced narrowing and higher elevation of the back arc complex (generally shoaling in mean depth from 2500 to 2000 m) [*Smith and Sandwell*, 1994] adjacent to the collision of the Louisville seamount chain with the Kermadec arc–trench [e.g., *Lonsdale*, 1986; *Ballance et al.*, 1989]. The second, originally observed by *Pelletier and Dupont* [1990], is the pronounced change in the morphology of the arc–back arc system at 32°S. Compared to typical water depths of 2000–2500 m for the northern Havre Trough, south of 32°S the back arc is composed of a rugged and complex rift and bounding horst topography that commonly deepens to 3000 m, and locally to 4000 m [*Charting Around New Zealand (Group)*

(CANZ), 1997; *Ramillien and Wright*, 2000]. Indeed, the southern Havre Trough forms the deepest known modern back arc basin. Deepening of the back arc further coincides with a significant narrowing in width of the bounding remnant Colville and active Kermadec arc margins [*Wright*, 1997] and reduction in sediment infilling [*Ballance et al.*, 1999], an apparent westward displacement of the active arc front [*Wright*, 1994], and changes in trench morphology [*Pelletier and Dupont*, 1990; *Ramillien and Wright*, 2000].

[7] In this paper, we present an extensive set of new swath bathymetry data from key sectors of the Havre Trough back arc from which we further substantiate significant longitudinal changes in tectonic structure and associated rift magmatism. These changes, particularly the longitudinal variations in structural orientation at 26°S and 32°S, are used to establish the kinematic development of the Tonga–Kermadec convergent plate boundary and the effect of anomalous reliefs impinging into the subduction trench and consequent partitioning of strain across the trench–arc–back arc system.

2.2. Data Acquisition

[8] Data for this present study were principally acquired during a 1997 R/V *Yokosuka* cruise [*Matsumoto et al.*, 1997; *Ruellan et al.*, 1998; *Delteil et al.*, 1999] to the Lau Basin–Havre Trough back arc system. The geophysical data include swath bathymetry mapping, single-channel seismic reflection profiling, three-axis component magnetometer observations, and an ocean bottom seismographic (OBS) refraction experiment. Results from the latter have been previously described by *Nishizawa et al.* [1999]. Data were acquired from widely spaced reconnaissance lines and detailed surveys of specific areas to document the underlying longitudinal and transverse changes in tectonic structure along the back arc complex.

[9] The swath bathymetric survey extends along zig-zag track lines and over three, 50% to full coverage, detailed target areas; the latter are located in the southernmost and northernmost segments of the Havre back arc trough. These data were acquired using the Furuno HS10 multinarrow-beam echo sounder (with 45 beams) on board the R/V *Yokosuka* [*Matsumoto et al.*, 1997]. With an average depth of ~2500 m the transverse coverage of the echo sounder was ~5 km. Ship navigation was based on Global Positioning System (GPS), and considering the lack of significant discrepancies in bathymetry at track crossings, navigation corrections were not necessary. Additional swath bathymetry is provided by one transit leg of the R/V *L'Atalante* [*Geli et al.*, 1997; *Davy et al.*, 1999]. In our study, the mesh size of the sampling grid, used to build the bathymetric digital elevation model (DEM) (Figure 1), was fixed to 200 m (with a square-mesh-size sampling zone centered on each node) in order to fit the original data set. The grid is filled by reading the data sequentially in chronological order. When a node that already has a data value is encountered, the newer value is substituted. In order to get the best DEM accuracy and to preserve high-frequency topographic signal,

Figure 1. (opposite) Location map of the Tonga–Kermadec subduction margin and associated arc–back arc system. Inset shows a location map of study area in the southwest Pacific. Bathymetry is from predicted seafloor topography of *Smith and Sandwell* [1994]. TVZ, Taupo Volcanic Zone.

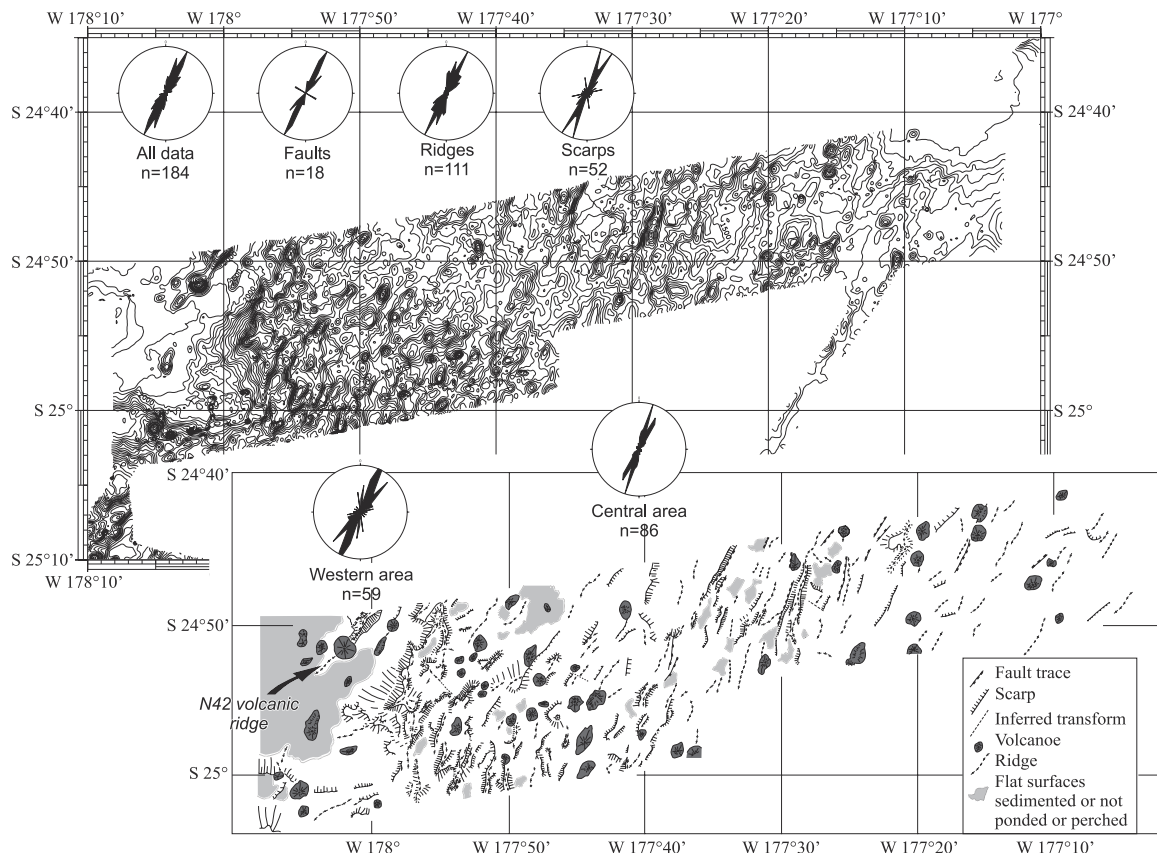


Figure 2. Bathymetry, structural trends, and interpretation of the northernmost Havre Trough at latitude 25°S. Plots below the rose diagrams indicate the number of measurements. Main structural grain trends $26 \pm 2^\circ$ (13° from the back arc basin axis). Rose diagrams reveal a cluster increase of structural data from west to east that suggests successive and variably oriented structures developed away from the western part of the basin. Active faults are more frequent in the eastern part of the basin where they are subparallel to the basin axis and occur in the projected southward extension of the Valu Fa spreading center.

data interpolation occurred only in data gaps; this avoided unnecessary smoothing of the DEM, which would significantly restrict fault scarp detection.

[10] A set of 27 single-channel seismic reflection profiles were acquired using a 150-m GSJ-type streamer and a 120-cubic inch Bolt 1900C-type air gun, with a shot interval of 8 s, at a 10–11 kt average ship speed. A high-density line interval profiling survey was also shot at the northern tip of the Havre Trough within the detailed survey of the OBS area (see above). The additional seismic survey from the transit leg of the R/V *L'Atalante* [Geli *et al.*, 1997] has been also included. Results for six survey areas, centered at 25°S, 26°S, 31°S, 32°S, 34°S, and 35°S are described here from north to south.

3. Havre Trough Survey Sectors

3.1. The 25°S Sector

[11] The northernmost survey area (Figure 2) is located immediately west–northwest of the junction of the Louisville hot spot chain into the Tonga subduction zone and south–southwest of the propagator tip of the Valu Fa spreading ridge [Wiedicke and Collier, 1993; Parson *et al.*, 1990; Delteil *et al.*, 1999; Ruellan *et al.*, 1998, 1999, 2000a,

2000b, also From rifting to active spreading in the Lau Basin–Havre Trough back arc system (SW Pacific)—Locking/unlocking induced by ridge subduction, submitted to *Geochemistry Geophysics Geosystems*, 2001, hereinafter referred to as Ruellan *et al.*, submitted manuscript, 2001]. Seven lines oriented N80° cover the central ~107 km of the total 250 km width of the back arc (between the bounding ridge crests) at this latitude. In the west, the surveyed area abuts the sediment-filled western subbasin and extends over much of the rugged, highstanding, and mostly sediment-free volcanic basement of the eastern portion of the back arc complex (Figure 2). The dominant seafloor morphostructural fabric is oriented $N26 \pm 2^\circ$, 13° oblique to the regional back arc axis. Although still observable, the deformation is less pronounced in the western part of the basin, with eastward increasing refinement of the structural grain orientation, as seen within rose diagrams (Figure 2), from west to east. This would indicate successively better developed and differently oriented basement faults and fault-controlled volcanic ridges. Volcanic ridges, although more frequent in the west, are less organized than faults, with the latter better developed east of 177°40'W. There they delimit a deep graben that is along the projected extension of the Valu Fa spreading ridge [Ruellan *et al.*, 1998, 1999, 2000a, 2000b;

Delteil et al., 1999]. The deep graben does not extend south of 24°55'S.

[12] The bathymetry and seismic data cannot reliably discriminate between scarps that are purely fault-related and those that are associated with volcanic edifices. Unambiguous scarps were mapped separately and form two distinct strike orientations (Figure 2) that probably partly image obliquely diverging slopes at axially plunging ridges.

[13] The pattern of crosscutting structures and the sediment distribution both provide insight into an initial assessment of Havre Trough back arc evolution. Although of restricted area, the westernmost part of the back arc reveals a very oblique (29°) to basin axis, N42° trending volcanic ridge that plunges southwestward and is buried by the sediment fill of the western subbasin. This very oblique trend predates sediment deposition and hence is an early structure of the back arc basin. Similarly obliquely oriented volcanic ridges occur to the west (Figure 2) but are less pervasive eastward and do not extend beyond 177°10'W. In contrast, the main N27° oriented ridges, together with associated active faults, are more dominant eastward. At intersections of these variably oriented structures (e.g., 24°50'S, 177°30'W; 24°46'S, 177°25'W) the N27° trend consistently cuts and postdates N42° structures, as interpreted from N42° ridge-sediment relationships. Although rare, transverse structures, inferred to be transform faults, are observed orthogonal to both the N42° and N27° oriented structures (Figure 2, e.g., at 24°53'50"S 177°55'50"W to the west and 24°48'50"S 177°27'50"W to the east).

3.2. The 26°S Sector

[14] The 26°S survey area is adjacent to the junction of the Louisville seamount chain with the Tonga-Kermadec subduction zone, covering some 110 km of the 215-km-wide basin. A substantial part of the western subbasin and two rugged and elevated basement massifs to the east are mapped (Figure 3). Both massifs have a pervasive structural fabric with a predominant N42° orientation, which is 29° clockwise oblique to the regional basin axis. The northwestern limits of the two massifs appear to have a sinistral offset; they are separated by a 37-km-wide transverse zone striking N120 ± 5° that is nearly orthogonal to the dominant massif structural grain. The transverse zone has more heterogeneous structural orientations than the adjacent massifs and is the loci of southeastward extended sediment deposition. Seismic profiles crossing the northwestern segment reveal volcanic ridges of the northern massif extending beneath the sediments of the western subbasin, progressively burying these ridges to the southwest. Although the boundary between the northern massif and western subbasin appears indistinct at the seafloor, a *P* wave velocity model derived from two-dimensional ray tracing reveals a moderate but sharp northward lessening in crustal thickness at this position [*Nishizawa et al.*, 1999].

[15] The dominant N42° strike alignment of volcanic ridges, within both the north and south massifs, although not associated with active seafloor-cutting faults, is likely to be fault controlled at depth. In detail, these volcanic ridges form either almost rectilinear single 9–17 km long ridges or a series of curved 3–5 km ridge segments that are often cut by subducted, transverse structures oriented N105 ± 5° (Figure 3). Curvature of the ridge segments at these transverse structures

universally indicates dextral displacement along the latter. The only structural similarity between the 25° and 26°S survey areas is the presence of the N42° trending basement structures that are associated with transverse structures. Although the N42° trend is more pervasive at 26°S, it is not active as it never offsets the seabed, consistent with a lack of seismicity between 1980 and 1990 within this part of the back arc region [*Ruellan et al.*, 1998, 1999; *Nishizawa et al.*, 1999].

3.3. The 31°S Sector

[16] The data comprise three adjacent bathymetry and seismic reflection lines acquired to obtain 100% swath coverage of a 12–13 km wide and 137-km-long survey area across the full width of the basin. The seismic reflection data allow accurate mapping of sediment isopachs, significant sediment depocenters, and buried faults (Figure 4). At the basin margins the bounding faults are parallel to the regional basin orientation of N19°. Sediment deposition is mostly restricted to both basin flanks, being more significant in the western subbasin, where sediment thickness, although highly variable, can be up to 0.7 s two-way travel time (TWTT) (~630 m). The underlying basement structure of the western subbasin includes southeast facing, parallel-to-basin-axis normal faults that control deposition of the oldest subbasin sedimentary sequences. Some of these N25 ± 10° faults are still active, as evidenced by seafloor displacements at the northwestern margin of the back arc bounding the remnant Colville arc. Similarly, although few in number, basin axis trending normal faults are identified at the southeastern margin of the back arc adjacent to the presently active Kermadec frontal ridge and arc. The presence of parallel-to-basin-axis faults is exclusive at the back arc margins. These basin-bounding faults should be considered together with the syntectonic control of the earliest intrabasin sedimentation. Although the faults may be reactivated, it is strongly suggested that they represent early tectonic structures associated with incipient back arc rifting.

[17] Apart from immediately adjacent to the lower Kermadec margin, the remaining eastern two thirds of the back arc complex is typically composed of a rugged, elevated massif some 1000–1500 m higher than the adjacent western subbasin. Like back arc sectors to the north, this elevated massif, where no sediment is evident, has a predominant N57°, oblique-to-basin-axis, basement fabric. A number of observations are noteworthy: (1) the basement fabric not only includes volcanic ridges and scarps but also active fault traces with seafloor displacement; (2) the obliquity of the basement fabric is ~38°, which is the highest observed value within the Havre Trough; and (3) a subordinate cluster of 120 ± 3° oriented structures (which are mostly fault traces) is observed, which intersect, offset, or terminate at the N57° fabric. The overall massif structural pattern is that of a 38° oblique-to-basin-axis set of scarps, normal faults, and fault-controlled volcanic ridges that were, and remain, coeval with transverse structures that are inferred to be transform faults.

3.4. The 32°S Sector

[18] Data here comprise two separate lines that lie at the northern extremity of the deepest mapped rift segment of the Havre Trough back arc (Figure 4). The mapped area includes a single-channel seismic reflection profile and rock

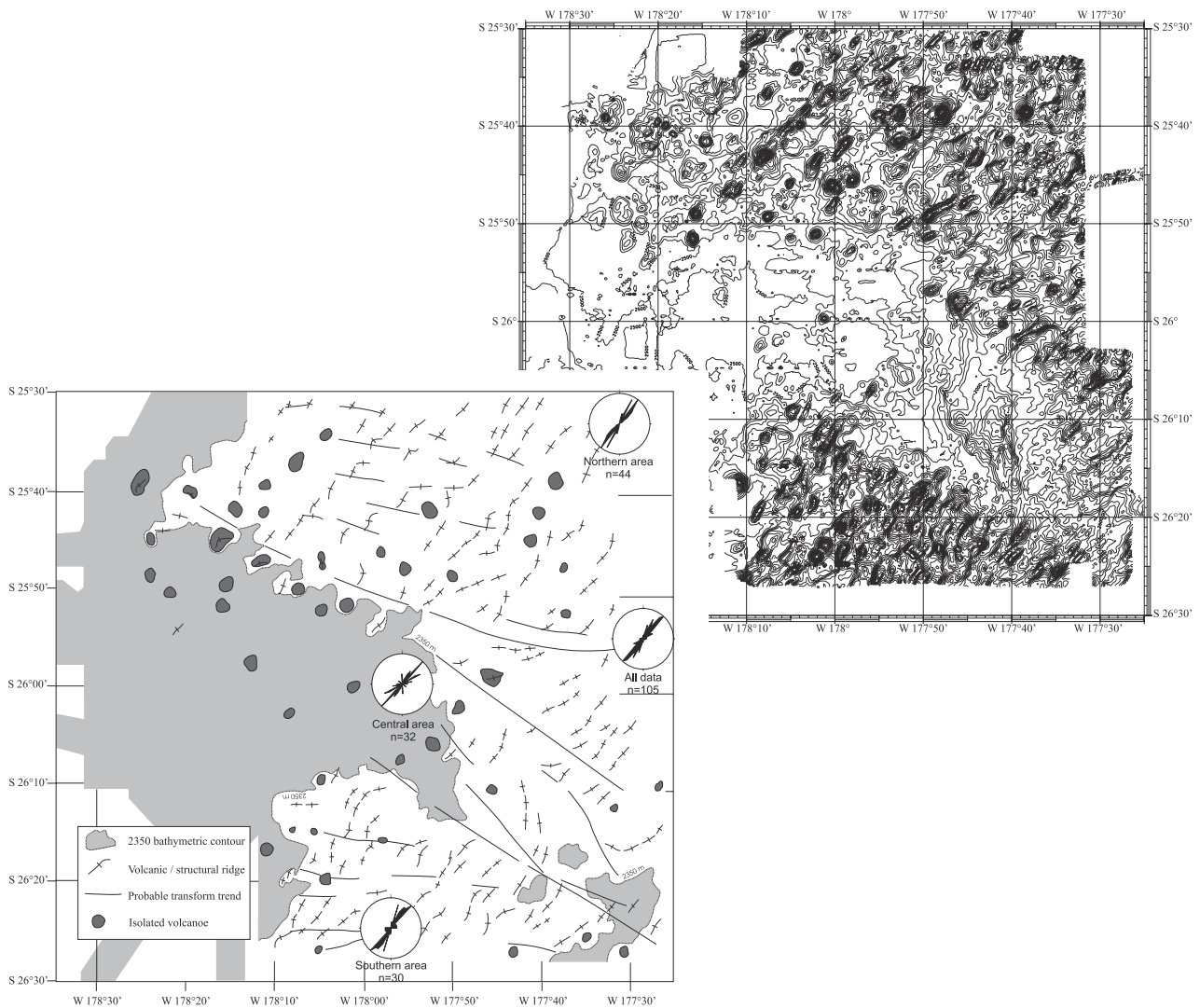


Figure 3. Bathymetry, structural trends, and interpretation of the Havre Trough at latitude 26°S. Plots below the rose diagrams indicate the numbers of measurements. This area faces the Tonga subduction zone–Louisville Ridge junction. The structural grain conspicuously occurs in two left-stepping elevated massifs. The structural grain trends 42° (29° to the back arc basin axis) but does not relate to active faulting. This fabric is characterized by a combination of curved ridges closely associated with discrete transverse trends that are indicative of dextral movement. The large transverse zone that separates the massifs is characterized by very oblique structures and is underlain at depth by a crustal discontinuity [Nishizawa *et al.*, 1999].

dredging described by Ballance *et al.* [1999], which agree with our interpretation of a significant change in back arc basin structure immediately north.

[19] This change is evidenced by a pronounced northward shallowing of the back arc complex between 31°40'S and 32°S with maximum water depths of 3000 and 3600 m for the two mapped areas, respectively. First recognized by Pelletier and Dupont [1990], this change at ~32°S is clearly identified within regional compilations of shipborne bathymetry [CANZ, 1997] and predicted seafloor topography [Ramillien and Wright, 2000]. A second change is the distribution of sediment that extends irregularly over the western half of the basin. Sediment is located within a series of narrow rift basins alternating with volcanic edifices. The rift basins are not aligned (Figure 4), and their structural pattern may indicate the existence of transverse structures like that

identified at 31°56'S, 179°28'E as shown by a 300-m-high scarp.

[20] Within the 32°S area the maximum sediment thickness does not exceed 0.4 s TWTT (~360 m), about half of that observed at 31°S. This marked decrease in sediment infilling, between 31°S and 32°S, suggests either that the deep “sediment-starved” southern sector forms a younger phase of rifting or that it developed at the expense of a previously thinned arc crust with a reduced flux of volcanoclastic sedimentation sourced from stratovolcanoes. The reduction of volcanic sedimentation may record transitory cessation of arc volcanism during the now southerly ongoing subduction of the Hikurangi Plateau.

[21] The structural fabric of this sector has a dominant trend of N37° that is 13° oblique to the regional basin axis, which is markedly less than the obliquity of 38° observed at

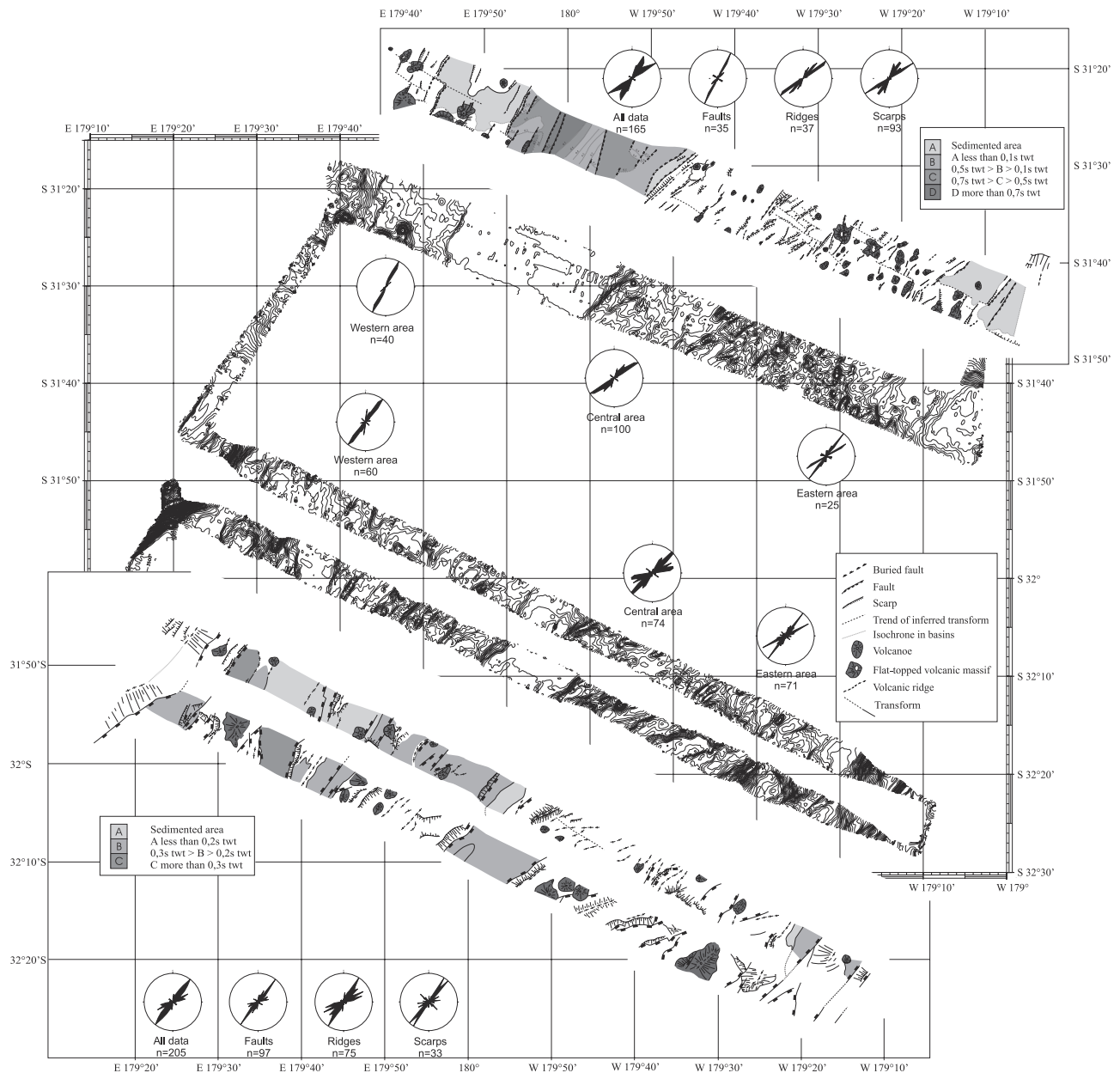


Figure 4. Bathymetry, structural trends, and interpretation of the Havre Trough at latitudes 31°S–32°S. Plots below the rose diagrams indicate the numbers of measurements. For 31°S, at the western subbasin, parallel to basin boundary faults (trending N19°) control deposition of the oldest sediments of the back arc domain. Some of these old faults have been reactivated and cut the sediment-free younger eastern basement. Together with very oblique (N46 ± 5°) faults and intruded volcanic ridge emplacement, this reactivation represents the more recent stage of the back arc domain activity. It is noticeable that the orthogonal trend, which may accommodate transform movement, occurs in relationship with the late very oblique normal faults and volcanic ridges. For 32°S, this deepest segment of the back arc basin is sediment starved compared to the northern areas. Only a little sediment was trapped in separate and elongated subbasins that are scattered over half of the back arc domain. The basin's most frequent fabric trends N37° markedly less oblique to the N24° trending back arc basin axis than in the previous 31°S area. Several orthogonal to fabric scarps bound deep subordinate grabens and strongly suggest transform structures.

31°S. The structural fabric also has a wider range of subordinate trends, especially within the central eastern part of the basin complex (Figure 4). As seen within other sectors of the Havre Trough, the more oblique structures

are characteristic of the central eastern parts of the back arc, developing in areas seemingly devoid of sediment. Active normal faults occur over the entire width of the basin, with a predominant trend of N37°. Intensive deformation thus

appears to have activated and reactivated faults, with a number of structural orientations spreading across the entire width of the back arc complex. Similarly, transverse morphostructures orthogonal to the dominant structural fabric are observed. Although not as frequent compared to the 31°S area, such transverse structures are identified from pronounced bathymetric features, inference of aligned volcanic ridge extremities, and mismatch of seafloor morphology between adjacent survey lines.

3.5. The 34°S Sector

[22] Data for this area comprise a single 18-km-wide, 126-km-long line of dual EM12 multibeam transit line of R/V *l'Atalante* [Geli *et al.*, 1997; Davy *et al.*, 1999] that images the entire back arc basin and bounding Colville and Kermadec Ridges (Figure 5). The inner flank of the remnant Colville arc consists of a series of fault blocks that downstep basinward, resulting in a succession of perched, flat surfaced, sedimented subbasins that progressively deepen from 2500, 3400, to 3600 m water depth. The opposing inner flank of the Kermadec ridge is obscured by a large arc stratovolcano, which itself appears dissected by normal faults. The intervening back arc basement fabric is N47°, which is 20° oblique to the regional basin axis, revealing a small southward increase in obliquity relative to the 32°S area.

[23] Sediment distribution within the back arc trough occurs in two domains. In the west, apart from perched subbasins associated with the Colville border fault blocks, the back arc is variably sediment-infilled within rifted subbasins. The latter are often bounded by conjugate normal faults. Within the western sector of the basin, faults are oriented $N40 \pm 5^\circ$, with another set oriented N66° and progressively developing southeastward.

[24] In contrast, except for proximal volcanoclastic sediments associated with the stratovolcano at 34°05'S, 179°35'E, the eastern half of the back arc complex is essentially devoid of sediment. Morphologic elements of this sector include flat horizontal surfaces within water depths >3000 m (and locally up to 3800 m) and a conspicuous 25-km-long volcanic ridge transverse to the basin that terminates southeastward at the stratovolcano. The deep, sediment-free seafloor areas are bounded by northeast trending scarps, some of which are clearly fault related. The flat surfaces abut southwestward against the transverse volcanic ridge as their bounding fault traces and scarps extend onto the lower ridge flank. Synchronicity of intensive structural development and construction of the transverse volcanic ridge can be demonstrated because although the ridge forms the southwest border of rifts and flanking fault terraces, faults associated with the latter partly dissect the lower flanks of the transverse ridge. Hence the overall structural pattern of this sector shows active extensional tectonism coeval with constructional volcanic-fed transform faults that are very similar to those proposed for other segments of the Havre Trough back arc [Wright *et al.*, 1996; Wright, 1997; Ballance *et al.*, 1999].

3.6. The 35°S Sector

[25] Data for this sector consist of only multibeam data, and hence the interpretation of basin sediment infilling and the tectonic evolution (Figure 6) are not constrained

by seismic reflection profile data. The swath data show that the back arc region is composed of two distinct areas adjacent to the remnant and active arcs, respectively. The northwest area, covering the boundary between the remnant Colville Ridge and back arc basin, is characterized by a series of small volcanoes and a basement fabric (consisting of basin-facing scarps and inferred faults) that is oriented N33°. The lower and easternmost of these faults form the slope-toe boundary to a 7.5-km-wide, flat western subbasin that is inferred to be sediment filled. The eastern margin of the western subbasin is underlined by two major rectilinear, northwest facing faults that show seafloor displacement. These latter features suggest that basin-buried normal faults are being reactivated and that recent tectonism is ongoing within back arc areas adjacent to the remnant arc. The N28° orientation of these inferred faults almost parallels the regional basin axis at this latitude.

[26] The southeast area is made of a series of alternating volcanic ridges and narrow rift basins that are consistently striking at N58° and have a very oblique (30°) orientation to the basin axis. Although sediment cover is probably thinner, this entire crustal block is very similar to structural domains observed within the 26°S sector, revealing transverse to basin structures oriented N°138. The transverse trends are typically weakly developed morphologic seafloor features that clearly cut and are cut by the main N58° structural fabric. The resulting basement pattern is one of ponded rift basins, of varying widths, which typically are not aligned, but retain the structural grain orientation. As shown by these fabric relationships, both N138° and N58° structures are considered tectonically synchronous, with the former interpreted as recording transform deformation. Although seldom observed, N30° trending structures that are parallel to the back arc basin axis do occur (e.g., 178°9'E, 35°12'S; Figure 6), but are interpreted to predate the dominant N58° structural orientation.

4. Interpretation

4.1. Structural Pattern

[27] Sectors of the Havre Trough mapped in this study, combined with other recent geophysical mapping, confirm that the entire back arc basin, including the deeper segment between 32° and 34°S, is made of faulted blocks of rifted arc crust intruded by volcanic massifs and ridges with no evidence of spreading ridge centers [Parson and Wright, 1996; Wright *et al.*, 1996; Ballance *et al.*, 1999; Nishizawa *et al.*, 1999]. Accordingly, the southern termination of the Valu Fa spreading system mapped at 23°40'S [Ruellan *et al.*, 1998, 1999, 2000a, 2000b, submitted manuscript, 2001] forms the southernmost ridge propagator within the Lau Basin and coincides with a marked increase in basin width (Figures 1 and 7). South of the Valu Fa spreading ridge propagator tip, active and pervasive rift tectonics with the same orientation extend south through thinned arc crust of the southernmost Lau Basin [Ruellan *et al.*, 1998, 1999, submitted manuscript, 2001]. Such extensional rifting, with the same orientation as Valu Fa spreading ridge, extends southwards to ~25°S, where a deep rift graben overprints all other back arc deformational structures (Figure 2).

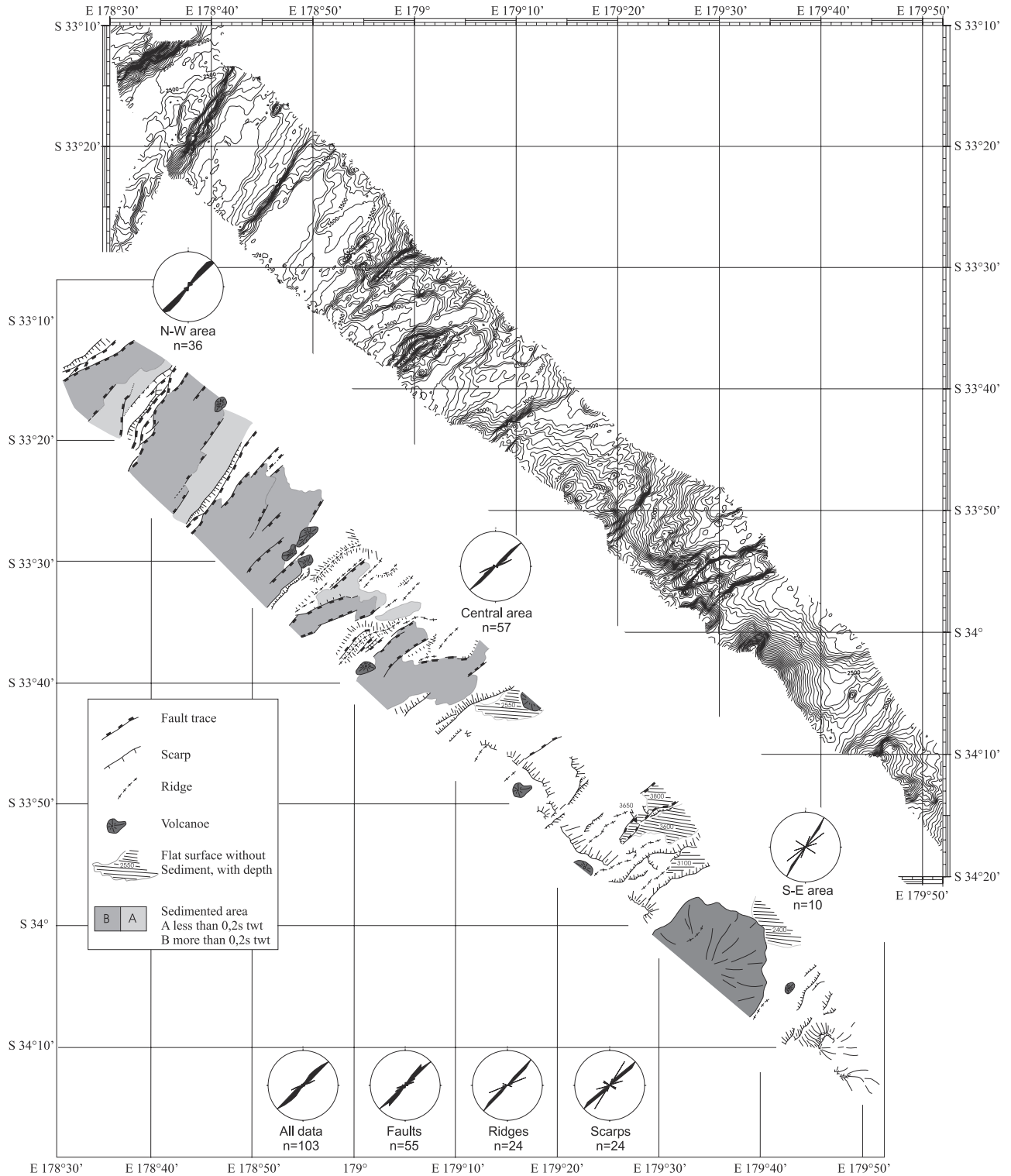


Figure 5. Bathymetry, structural trends, and interpretation of the Havre Trough at latitude 34°S. Plots below the rose diagrams indicate the numbers of measurements. This line from the R/V *L'Atalante* [Geli *et al.*, 1997] also shows that little sediment has been scattered over the whole western half of the basin, whereas the eastern half of the back arc domain is characterized by very deep grabens that abut southwestward against a highstanding transverse to basin volcanic ridge. This ridge terminates southeastward into a large sized stratovolcano. The main fabric, oriented N47°, is 20° clockwise to the back arc basin axis.

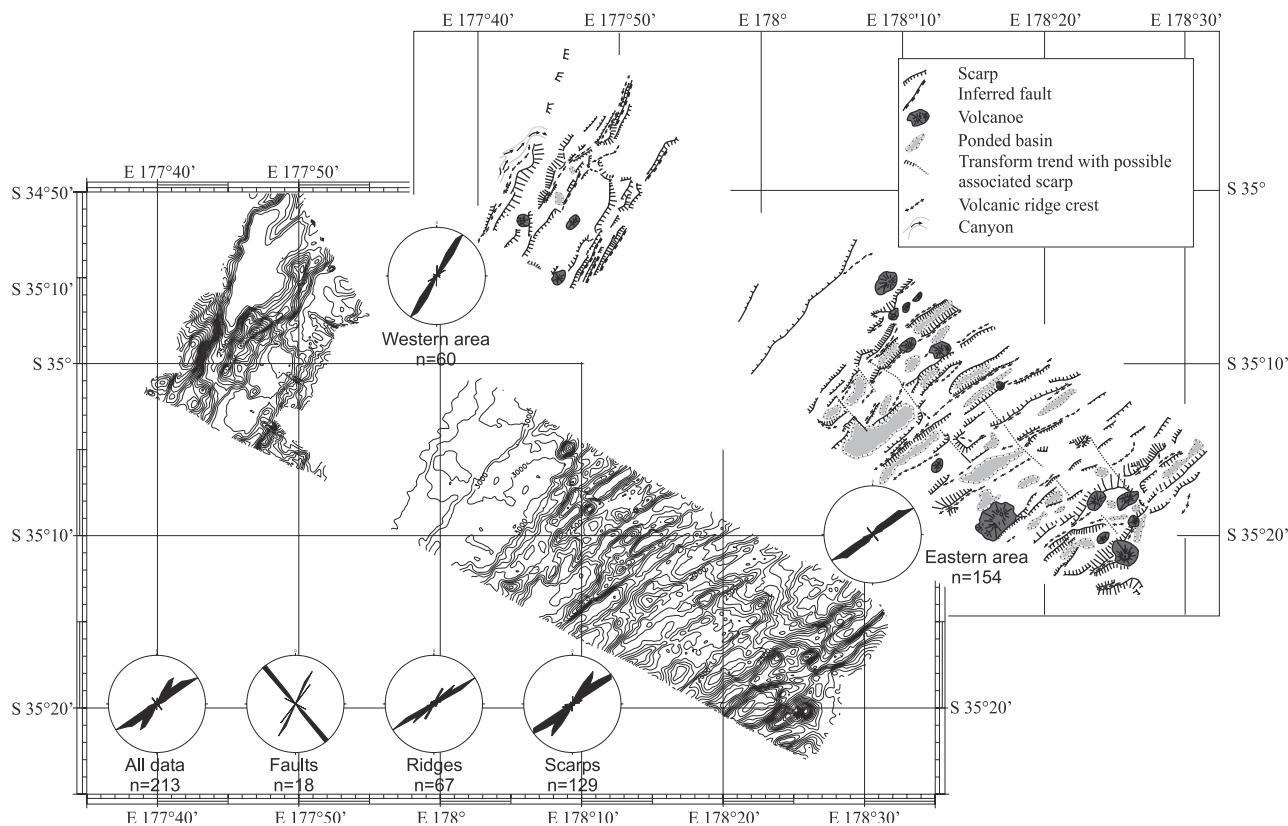


Figure 6. Bathymetry, structural trends and interpretation of the Havre Trough at latitude 35°S. Plots below the rose diagrams indicate the numbers of measurements. This southernmost area exhibits a deep flat topped western subbasin that likely receives sediment from the continent of North Island, New Zealand, to the south. The parallel to the back arc basin (N28° trending), west bounding faults have clearly been reactivated as they offset the sediment deposits. The eastern part of the domain is conspicuously made of regularly oblique (N47° trending) to main structural grain ascribed to fault scarps and fault-controlled volcanic ridges. These limit laterally narrow ponded basins that are axially bounded by numerous transform-like subordinate faults.

[28] Active faulting is observed throughout the length of the back arc except within the vicinity of 26°S, where there is no evidence of recent extensional deformation. At all other mapped sectors, including studies of *Parson and*

Wright [1996], *Wright* [1997], and *Ballance et al.* [1999], active faulting occurs on both bounding back arc border fault systems, and within the intraback arc complex, although the latter is more intense and pervasive to the east. Within the vicinity of 26°S, adjacent to the Louisville hot spot chain impinging the trench, all extensional structures are mantled with a sediment drape, and the transition between the sediment-infilled western subbasin and the volcanic floor of the central and eastern areas is gradual. This sector is not the locus of recent seismicity or extensional faulting [e.g., *Nishizawa et al.*, 1999] and has a slightly elevated topography relative to other sectors of the Havre Trough. The elevated seafloor relief and the absence of modern rifting are interpreted to be a consequence of the Louisville chain entering the subduction zone at this latitude and essentially “locking” back arc extension [*Ruellan et al.*, 1999; *Delteil et al.*, 1999].

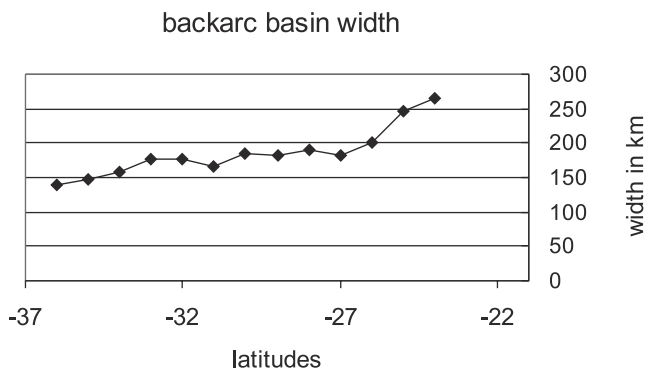


Figure 7. Havre Trough width plotted versus latitude. Three segments can be distinguished: the northern and southern segments are both characterized by northward increasing width. The median segment has almost constant width.

[29] Whether different sectors are undergoing recent extensional deformation or not, the back arc complex consistently displays an elevated and eastern volcanic massif, with little or no sediment, that gives the basin, as previously noted by other studies [e.g., *Caress*, 1991; *Wright et al.*, 1996; *Ballance et al.*, 1999], an asymmetric morphology extending all along the back arc domain.

A subsiding, sediment-filled subbasin, forming a counterpart to this asymmetry, extends across the western third of the back arc. This asymmetric structural pattern is best developed north of 31°S but is less apparent between 32° and 34°. Except for this latter sector, the western subbasin is characterized by syndepositional normal faults that reveal prolonged extensional deformation since the inception of back arc rifting. In contrast, the eastern, mostly sediment-starved, elevated massif forms the loci of pervasive fault-controlled volcanic edifices and ridges, where fault traces are deduced from volcanic ridge alignments and offsets of adjacent basement. At the base of the eastern bounding Kermadec border a narrow subbasin is occasionally observed, with a thin sediment infilling.

[30] The back arc sector between 32° and 34°, which is the deepest of the Havre Trough, is associated with significant narrowing of both west and east arc ridges compared to the north, suggesting that the entire back arc domain and bounding arc ridges probably contain super-thinned volcanic arc crust. At least part of the missing volume of arc crust could probably be found to the west in the Three Kings Ridge, as suggested by *Herzer et al.* [2000], the latter ridge being same length as the concerned back arc domain. An additional factor could be a local increase of tectonic erosion due to a now subducted northern extension of the Hikurangi Plateau and the subsequent subsidence of the back arc [*Collot and Davy, 1998*].

[31] Within the back arc basin the common eastern basement swell coincides with a zone of extensive volcanic intrusion and the active volcanic arc front [*Wright et al., 1996; Wright, 1997*]. This volcanic swell, remaining above the zone of subducted slab dehydration and mantle partial melting, progressively moves eastward with basin widening and trench roll-back. Such a pattern of volcanism is supported by the presence of cross-arc volcanic ridges at both the southernmost [*Wright et al., 1996; Wright, 1997*] and 33°50'S sectors (Figure 5) of the back arc. Those areas of the intrabasin basement fabric, sediment starved or covered with a thin sediment layer, have a mean trend that is oblique to the regional basin axis [*Caress, 1991*]. However, basement fabrics close to the basin axis orientation are observed in two different contexts. The first is where such trends are irregularly spaced across the back arc complex and are interpreted as being reactivated structures inherited from the earliest phases of back arc rifting. The second is a restricted zone of intensive rifting along the projected southward extension of the Valu Fa spreading ridge in the 25°S sector where such structures cut and postdate the oblique intrabasin tectonic fabric [*Ruellan et al., 1998, 1999, 2000a, 2000b, submitted manuscript, 2001; Delteil et al., 1999*]. The latter predominant fabric is commonly associated with a subordinate orthogonal structural grain that bounds or is interrupted by tilted fault blocks, horsts and rift grabens, and volcanic ridges. At 35°55'S, and farther south [*Wright et al., 1996; Wright, 1997*], this subordinate grain is also the locus of massive volcanic intrusion.

[32] Both the oblique fabric and the subordinate orthogonal grain support the contention of oblique extension, first proposed by *Caress* [1991], although it is now accepted that this is accomplished by arc crust rifting rather than oceanic spreading. If the predominant oblique fabric represents the orientation of recent Havre Trough extension, as proposed

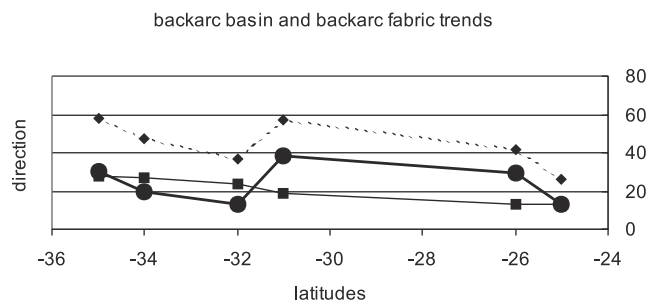


Figure 8. Trends of back arc basin, basin structural fabric, and resulting obliquity. Line with squares, the trend of the back arc basin axis; dotted line with diamonds, the break in the basin's fabric; and line with circles, the resulting obliquity between these.

here, the longitudinal distribution of obliquity along the basin will yield insight into the kinematics of the back arc basin opening. In fact, the variation of obliquity along the basin axis is characterized by two distinct gradients separated by the 32°S boundary (Figure 8). The northern gradient consists of three southward increasing values, with the northernmost sector at 25°S having low obliquity of 13° due to the basin parallel rifting structures associated with southward propagation of the Valu Fa spreading ridge. Obliquity increases southward to a maximum of 38° at 31°S. The second and southern gradient has increasing obliquity from 13° to 30° between 32°S and 35°S (Figure 8). If the southward increasing structural obliquity of the intrabasin fabric (and by inference the orientation of the back arc opening) is related to the similarly distributed obliquity of Australian and Pacific plate convergence, then the sharp change in back arc opening direction at 32°S presents a problem.

4.2. Tectonic Evolution and Basin Development

[33] The structural interpretation presented here implies a three-stage evolution of the Havre Trough back arc basin. The most recent stage of development is a basin-parallel deep rift that only occurs within the transition zone located between the northernmost Havre Trough and the southernmost Lau Basin, associated with intense extension prior to the onset of true oceanic spreading of the Valu Fa spreading ridge [*Ruellan et al., 1998, 1999, 2000a, 2000b, submitted manuscript, 2001*].

[34] In contrast, the two early stages of rifting are widespread, both across and along the length of the back arc, and consist of an oblique to basin axis extensional fault system that succeeds an older phase of parallel to basin faulting. This succession is shown by the older rift structures being infilled, some syntectonically, with the earliest phases of intrabasin sedimentation that in turn are crosscut by oblique structures. The latter structural relationship is not, however, exclusive, as early rift faults are locally reactivated during the second phase of extensional rifting.

[35] It is noteworthy that the direction of oblique Havre Trough opening (Figure 9) is markedly different from the Pacific/Australia plate convergence vector [*DeMets et al., 1990*], which implies that somewhere between the deforming Havre Trough and the obliquely subducting Pacific

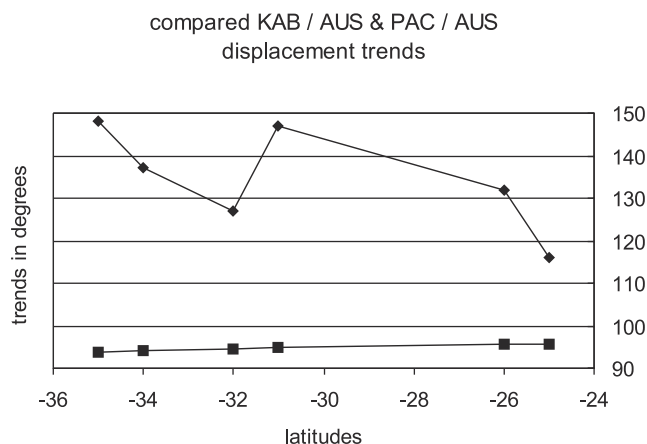


Figure 9. Compared movement directions of Kermadec Arc Block (KAB)/Australia (AUS) and Pacific (PAC)/Australia (AUS). The diagram compares the opening direction of the Havre Trough (line with diamonds) and the convergence direction of the Pacific Plate according to *DeMets et al.* [1990] (line with squares).

plate, displacement relative to the Australian plate is partitioned. Insight into where this partitioning occurs may be determined with reference to model experiments [e.g., *Tron and Brun*, 1991; *Richard*, 1991; *Richard et al.*, 1995; *Benes and Scott*, 1996]. The latter experiment assumes that no strike-slip movement is transferred from the Pacific/Australia oblique convergence to the back arc domain. This assumption appears to be contradicted by the presence of major strike-slip faults extending offshore from North Island, New Zealand, that bear vertical components of displacement as they extend into the offshore arc and back arc complex [*New Zealand Geological Survey*, 1972; *Wright*, 1992; *Davey et al.*, 1997]. Other experiments that involve wide box models that avoid edge effects and use gradual velocity distributions seem to correspond better to back arc basin rifting. In particular, experiments performed by *Richard* [1991] and *Richard et al.* [1995] show that oblique extensional slip on a basement fault results in a series of en echelon extensional segments in its overlying crustal sequence (Figure 10). The structural pattern of the Havre Trough, with normal-to-basin-axis extension followed by oblique extensional fabric, has many geometric similarities to the modeling undertaken by *Richard et al.* [1995]. Specifically, the observed segmentation of the deforming eastern swell of the basin into a series of left-stepping rifted segments characterized by right-lateral extensional tectonics is in good agreement with the modeling results. Nevertheless, these box models ultimately develop faults that individually accommodate oblique slip, which is probably not the case within the Havre Trough. Because oblique normal faults of the back arc are intimately associated with orthogonal transform-like faults, the former should accommodate little or no oblique slip. Thus the kinematics of the experimental models cannot be transposed directly to the Havre Trough. However, considering the above, the thinned arc crust and lithospheric mantle could be considered equivalent to the box model layers of sediment cover and basement, respectively.

[36] This interpretation implies that part, and possibly all, of the dextral component of the Pacific/Australia oblique convergence is accommodated at the rear of the Kermadec Arc Block within the Havre Trough back arc. We argue that this along-strike dextral component is closely associated with extensional tectonics as evidenced by the pervasive oblique structural pattern of the back arc domain. To assess the location of the along-strike-slip component, the rates of back arc opening orthogonal to basement fabric can be projected onto the regional basin orientation. Such values, reflect the southwestward displacement of the Kermadec Arc Block relative to the Australia plate and can be compared to those from relative motion of the Pacific/Australia plates. If the values are similar, it implies that the along-plate boundary Pacific/Australia slip component is accommodated entirely in the back arc domain. The Pacific/Australia motion is available from *DeMets et al.* [1990]; however, only two types of estimated rates of Havre Trough extension are available to constrain Kermadec Arc Block/Australia motion. The first, derived from geodetic strain across the onshore Taupo Volcanic Zone at the southernmost extent of the Havre Trough, gives a mean value of 17.5 mm yr^{-1} of widening orthogonal to the basin axis [*Wright*, 1993]. The second, estimated from T axes derived from focal mechanisms [*Pelletier and Louat*, 1989], provides values of 8 and 21 mm yr^{-1} , respectively, at 33° and 24°S , however, these may not be appropriate since only true slip vectors are comparable to strike-slip faults observed on the seafloor. The 17.5 mm yr^{-1} basin widening for the southernmost sector of the back arc requires some adjustment farther north to accommodate the increase in basin width. GPS work [*Bevis et al.*, 1995] has been performed across the Lau Basin to the north including the southernmost Lau Basin, but this work relates to processes, such as oceanic spreading, which are specific to the opening of the Lau Basin and not to that of the Havre Trough. Both the constant and weighted-along-strike rates due to oblique back arc opening are shown in Figure 11 and compared with the along-strike displacement component of Pacific/Australia convergence. As expected, the along-strike component of the Pacific/Australia convergence progressively increases southward, while the variable obliquity of the back arc basement fabric not surprisingly accounts for variable values of the Kermadec Arc Block/Australia along-strike component of motion. It is noteworthy that the displacements are the same order of magnitude, which implies that the buoyant Kermadec Arc Block is being carried in part southward along the plate boundary on top of the subducting plate. Such dragging is consistent with lithostatic stress acting at the base of thick arc crust onto the subduction surface and resulting in what has been termed “a suction effect” [*Shemenda*, 1993, 1994].

[37] A constant-along-basin length Kermadec Arc Block/Australia separation rate, not weighted to changes in basin width, divides relative displacements into two groups. From 32°S southward, the Kermadec Arc Block/Australia displacement rates account for only part of the along-strike Pacific/Australia motion that is accommodated in the back arc domain, implying a component of oblique subduction is still present beneath the Kermadec Arc Block (Figure 12b). However, to the north of 31°S , where the along-strike

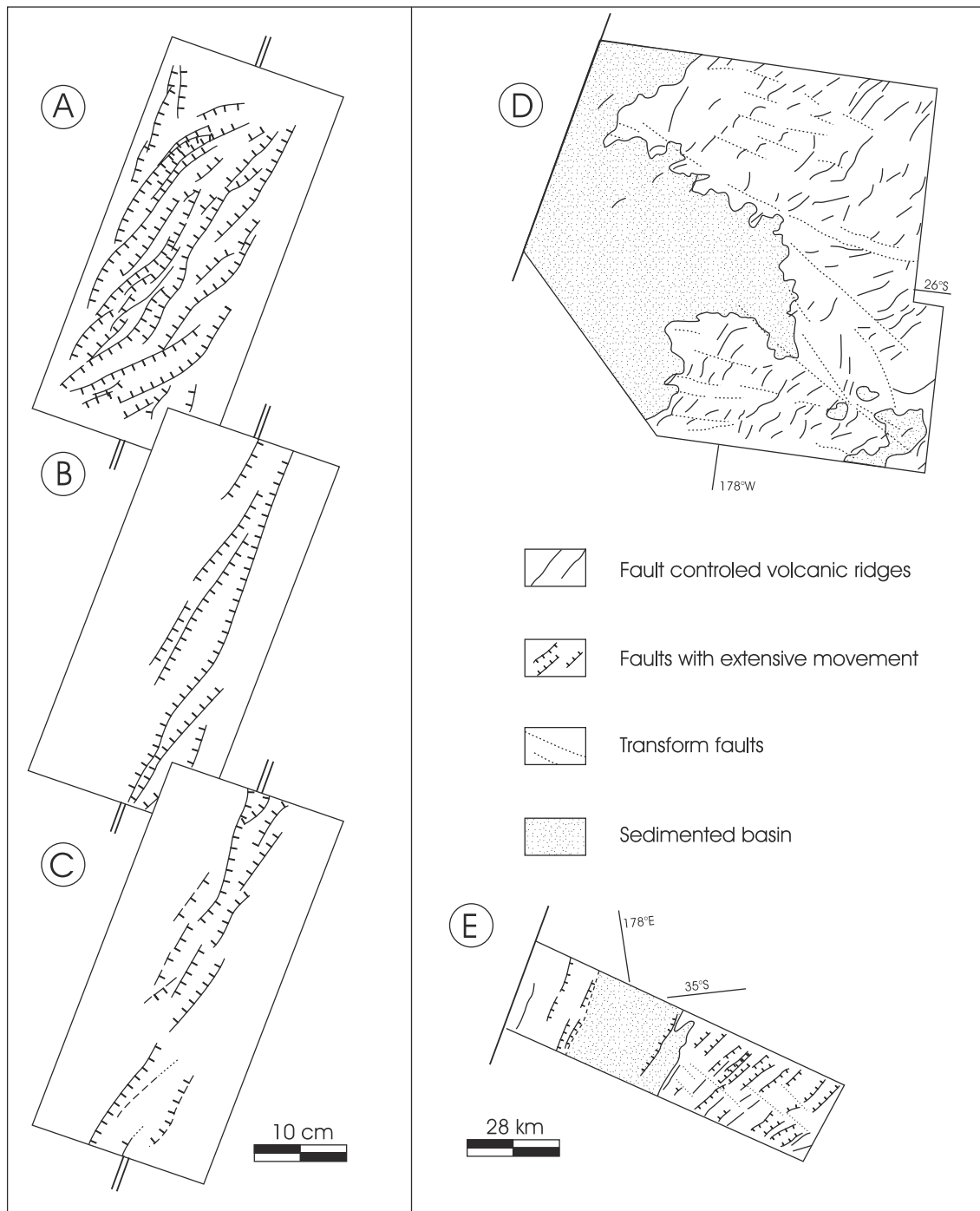


Figure 10. Comparison of Havre Trough and experimental models. (a–c) Plan views from published experimental models respectively from *Tron and Brun* [1991], *Richard* [1991], and *Richard et al.* [1995]. All models have been adjusted to the same scale and same extensional left-lateral movement. In Figure 10a (model A) the extensional component of movement is performed using a velocity discontinuity with no vertical offset at basement, whereas Figures 10b and 10c (models B and C) involve a 45° dipping (to the left) basement fault. It is clear that the braided pattern in model A does not fit well with observed back arc structure. Conversely model C exhibits clear left-stepping relays that are seen on the seafloor. (d and e) Two wider zones that were surveyed respectively at latitudes 26°S and 35°S. They have been brought to similar size as the models and oriented in order such that the back arc basin margin direction (heavy single line) is parallel to the basement discontinuity of the models (heavy double line). Several characteristics, such as oblique fabric and en échelon arrangement, are comparable. Others are distinctly different, such as the presence of transform faults or zones (that can be of crustal extent according to *Nishizawa et al.* [1999]) and also the fact that real deformation does not occur at a single basement fault but is distributed in a wide zone and associated with volcanic intrusion.

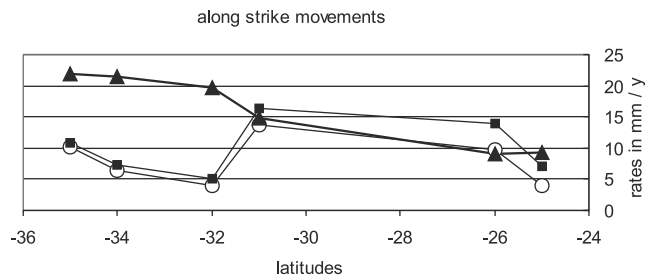


Figure 11. Comparison of along-strike rates of movements of Kermadec Arc Block (KAB)/Australia (AUS) and Pacific (PAC)/Australia (AUS). The diagram shows with reference to the Australian plate, along-strike component of the Pacific plate movement (line with solid triangles), with along-strike component of movement of the Kermadec Arc Block. Two attempts are proposed as to document the latter Kermadec Arc Block movement. A first series of values (line with open circles) was obtained based on a constant 17.5 mm yr^{-1} orthogonal to back arc axis opening rate. A second series (line with solid squares) refers to rates that have been weighted to the back arc width. For both cases the southern segment of the Kermadec Arc Block is shown to experience oblique underthrusting of the Pacific plate, and only part of along-strike displacement occurs in the back arc basin. Conversely, to the north, almost all along-strike movement is accommodated in the back arc domain, and mainly dip-slip subduction occurs under the Kermadec Arc Block. Moreover, the second series of values (solid squares) suggests that the Kermadec Arc Block migrates southward more rapidly than required by Pacific/Australia convergence. The rapid southward along trench sweeping of the Louisville hot spot chain is proposed to account for the increase of displacement rate (see text for more detailed explanations).

components of both Pacific/Australia and Kermadec Arc Block/Australia motions are equivalent, the partitioning is complete (Figure 12a). These results indicate that relative displacement within the Kermadec Arc Block itself should occur, with the northern segment of the arc moving faster southward than the southern segment. Along-strike arc displacement would occur between latitudes 32°S and 31°S and be of 10 mm yr^{-1} according to Figure 11. Assuming negligible kinematic change since Havre Trough inception at $\sim 5 \text{ Ma}$ [Wright, 1993], this internal deformation of the Kermadec arc would be of the order of 50 km longitudinal shortening. However, apart from a few earthquake focal mechanisms [Pelletier and Louat, 1989] and ridge crest offsets [Ballance et al., 1999], evidence for such deformation is not available since large areas of the system remain poorly mapped.

[38] Taking account of back arc width yields more reliable rates of displacement in the Havre Trough (Figure 11), providing two values (at 26°S and 31°S) that surprisingly slightly exceed the amount of along-strike component of displacement generated by the Pacific/Australia convergence. These results indicate additional deformation occurs within the northern Kermadec Arc Block itself, with the northernmost segment of the arc (at 26°S) moving 5 mm yr^{-1} faster southward than farther south (at 31°S).

Assuming the same kinematic steady state as above since $\sim 5 \text{ Ma}$, 25 km of extra intra-arc longitudinal shortening should be recorded within the northern Kermadec Arc. Seeking the cause of such high rates resulting in extra intra-arc deformation, it is noteworthy that the highest rate of along-strike displacement within the Kermadec Arc occurs at the facing point where the Louisville chain meets the subduction trench. Considering that north of this point (at 25°S), the Kermadec Arc Block/Australia along-strike motion decreases to a value lower than the comparable rate from Pacific/Australia motion leads to the possible relationship between rates of motion within the arc-back arc system and the subduction of the Louisville hot spot chain. The latter sweeps along the trench at a present-day rate of $\sim 128 \text{ mm yr}^{-1}$ [Ruellan et al., 1999, 2000a, 2000b, submitted manuscript, 2001], which is a very high rate with a low trench-ridge strike angle. It is proposed here that sweeping of the elevated and rugged Louisville hot spot chain southward along the subduction margin exerts longitudinal friction at the base of the volcanic arc with a consequent longitudinal component of movement. This movement is thought to be responsible for probable intra-arc longitudinal shortening specially at the southern limit (at 32°S) and within the northern Kermadec Arc.

5. Conclusion

[39] Oblique opening of the Havre back arc basin reveals part or all right-lateral component of movement of the Australian-Pacific oblique convergent plate boundary is taken up within the back arc domain. Such a process, which is consistent with model experiments of extensional rifting with small margin parallel components, is supported by major thinning and weakening of the arc-back arc lithosphere. Along basin axis investigations show that left-lateral en echelon rifted segments produce a heterogeneous along-axis dextral displacement of the Kermadec Arc Block relative to the Australian plate. These variations in displacement coincide with two main changes in basin width and bathymetry. One occurs at 25°S and corresponds to the incipient oceanic spreading of the Valu Fa spreading ridge (southernmost Lau Basin) and related similarly trending rifting. Another, located at 32°S , is associated with increasing southward deepening of the Havre back arc and narrowing of the bounding arc ridges. At the latter latitude the probable super-thinned arc crust that underlies the back arc domain is here proposed to be explained by separation of the Three Kings Ridge to the west prior to Havre Trough opening and possibly also by tectonic erosion from the southward sweeping Hikurangi Plateau.

[40] When compared to the dextral component of the Pacific to Australia plates displacement, the calculated rates obtained from the structural analysis of the back arc domain suggest that from latitude 32°S southward, only part ($5\text{--}10 \text{ mm yr}^{-1}$) of the dextral displacement is accommodated in close association with extensional tectonics in the back arc domain, the remainder being taken up at the subduction surface (Figure 12b). North of latitude 32°S the convergence between Pacific and Australia plates is entirely partitioned with the dextral right-lateral component being totally accommodated in the back arc domain (Figure 12a).

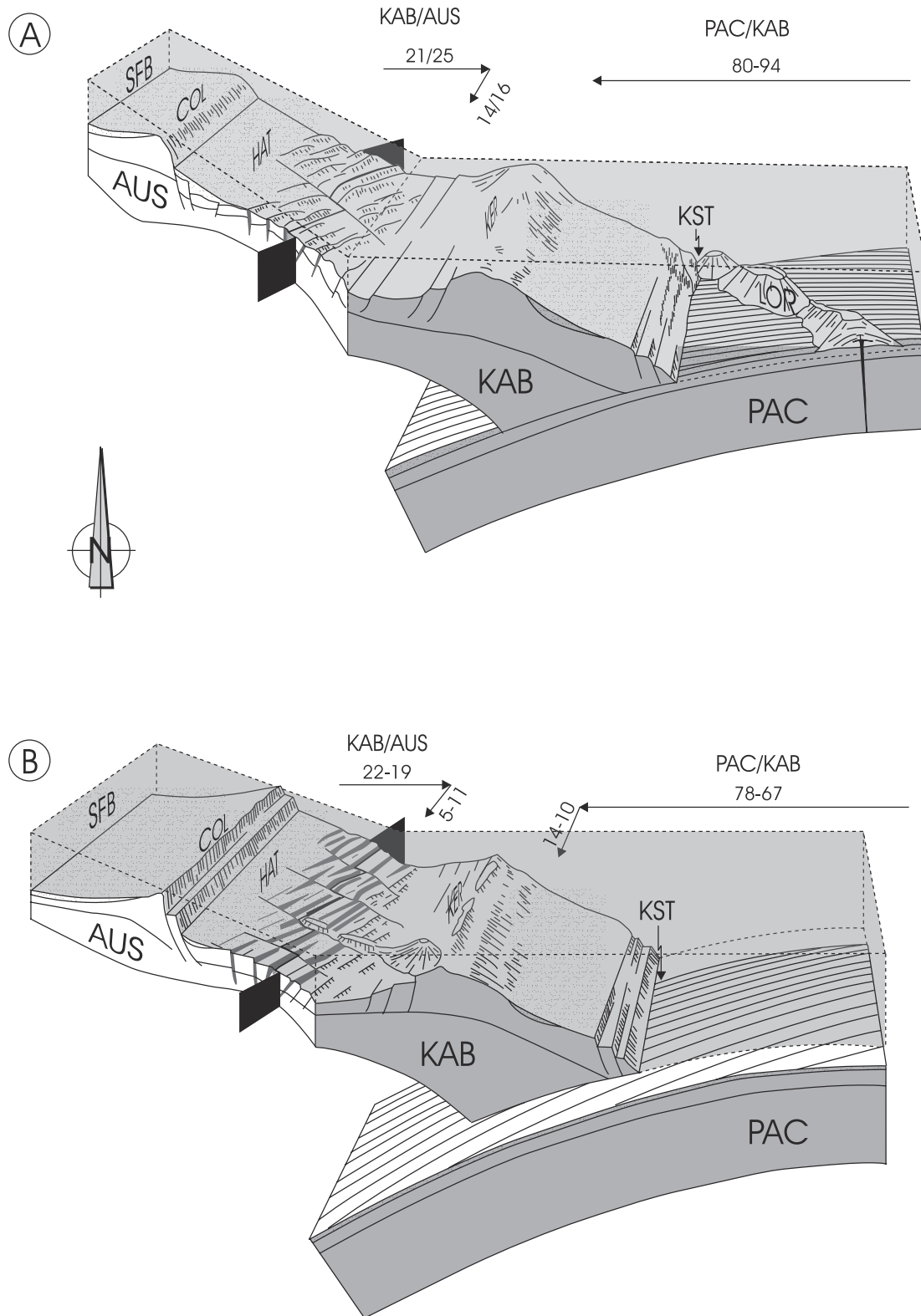


Figure 12. Three-dimensional block diagrams of the Havre Trough tectono-kinematical context. (a) Structures that occur in the region extending from latitude 26°S to 31°S. (b) Structures that occur in the region extending from latitude 32°S to 35°S. AUS, Australian plate; KAB, Kermadec Arc Block; PAC, Pacific plate; SFB, South Fiji Basin; COL, Colville Ridge; HAT, Havre Trough; KST, Kermadec Subduction Trench; LOC, Louisville chain. Dashed lines show the ocean surface, and frontal and along-strike displacement vectors are given in millimeters per year (for each of two values that correspond to the northern and southern areas, respectively, of each region). Approximate Pacific/Kermadec Arc Block direction of displacement is indicated on top of the Pacific plate.

As a consequence, the northern Kermadec Arc moves faster southward than its southern segment; this would impart intra-arc deformation to appear just north of 32°S. Furthermore, the northern Kermadec Arc segment appears to undergo more lateral displacement than required by the Pacific-Australia convergence. We propose that the rapid southward sweep of the Louisville Ridge along the trench accounts for partial transfer of additional movement at the northern tip of the Kermadec Arc and be responsible for extra intra-arc longitudinal shortening.

[41] The scenario of back arc development proposed here is supported, in part, by model experiments that involve basement normal oblique slip major fault reactivation and resulting en echelon fault patterns across the overlying cover sediments [Richard, 1991]. These experiments provide strong evidence that in tectonic-erosion-associated intraoceanic obliquely convergent plate boundaries, the lateral component of convergence may flip into the actively opening back arc and even within the arc. Such accommodation of partitioning depends on a favorable rheology with the heated and softened lithosphere of active arc and back arc domains. Furthermore, the Havre Trough back arc basin shows that along-strike heterogeneities in the distribution of the lateral component of convergence also depend on either inherited episodes of crust thinning (south of 32°S) or incipency of oceanic spreading (north of 25°S).

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