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[1] Associated with Pacific-Australia plate convergence, the Lau Basin – Havre Trough is an active back-arc basin that has been opened since ~5.5 Ma by rifting and southward propagating oceanic spreading. Current back-arc opening rates decrease from 159 mm yr^{-1} in the northern Lau Basin to 15 mm y^{-1} in the southern Havre Trough. Major tectonic changes occur at the transition between Havre Trough rifting and full oceanic spreading of the Eastern Lau Spreading Center (ELSC), where the oblique-to-trench, westward subducting Louisville Seamount Chain (LSC) sweeps southwards along the Tonga trench. New swath bathymetry, seismic reflection data, and limited rock sampling in this area constrain a tectonic and kinematic back-arc model that incorporates the effects of LSC subduction. The ELSC, which extends southward to 24°55′S, forms a deep rift valley propagating southward through older, rifted arc basement. Present-day seismicity and fresh and fractured pillow lavas at 23°42′S are consistent with rift valley neovolcanism. Conversely, the northern Havre Trough has low seismicity and rifted volcanic basement ridges trending 25–45° oblique to the basin axis consistent with low levels of extensional tectonism and volcanism. This latter structural fabric is interpreted as an early stage of rifting that is now "locked" due to compression on the arc exerted by LSC subduction, while in the Lau Basin such effects have passed as the LSC swept along the Tonga Trench. It is proposed that the Lau-Havre back-arc opening is controlled by tectonic constraints exerted at the limits of the system by the LSC subduction, which determines the southward migration of the Tonga Arc pole of rotation and associated Lau Basin opening. A discrete three-stage back-arc opening evolution is proposed, comprising: (1) an initial phase of back-arc rifting along the whole length of the plate boundary, beginning at ~6–5 Ma; (2) a subsequent phase, mostly present in the southern part of the back-arc domain and still active in the Havre Trough, of transpression and transtension, starting at ~4 Ma in the north, as the LSC starts to subduct and sweeps southward along the Tonga trench; and (3) a renewed opening phase in the northern segment of the back-arc domain, with rifting and spreading, starting at ~3.5 Ma, as subduction of the LSC along the northern Tonga trench is progressively completed.

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1. Introduction

[2] Processes of oceanic accretion can show significant complexity in space and time, which is recorded in varying morpho-structural fabrics and spreading ridge instabilities. Within back-arc basins, where the lithosphere is young and weak, such complexity can occur with crustal rifting and oceanic spreading evolving rapidly through successive stages of plate accretion. Associated with the Tonga - Kermadec subduction system (SW Pacific), the Lau Basin - Havre Trough is a prime example of plate convergence with an evolving arc - back-arc system [*Karig*, 1970, 1971; *Packham and Falvey*, 1971]. The ~2700 km long system forms a contiguous, active back-arc basin that has opened since ~5.5 Ma at the present-day Pacific-Australia plate boundary, between the Tonga-Kermadec active arc and Lau-Colville remnant arc ridge (Figure 1). This back-arc records not only the first stages of rifting through to full spreading, but also the effect of oblique subduction and rapid southward sweeping of the Louisville Seamount Chain (LSC) atop the westward-subducting Pacific plate. The latter is an inactive highstanding seamount chain, that reaches up to ~3500 m elevation above abyssal seafloor where it subducts today at the junction between the Tonga and Kermadec trenches. The transition between mostly spreading in the Lau Basin, and rifting in the Havre Trough, hence, provides a key example in understanding the mechanisms and kinematics of back-arc opening where rates of basin widening vary longitudinally along the arc - back-arc system. Other arc - back-arc systems that record such complex evolution include the New-Hebrides - North-Fiji-Basin and Izu - Bonin - Mariana (IBM) systems.

[3] Within the Lau - Havre system both previous reconnaissance surveys and specific studies have focused on sectors north and south of the transition zone between spreading and rifting: e.g., the Valu Fa Ridge (southern Lau Basin) [*Foucher et al.*, 1988; *Lafoy*, 1989; *Ruellan et al.*, 1994], the central and northern parts of the Lau Basin [*Delteil et al.*, 2002; *Hawkins*, 1995; *Parson et al.*, 1990; *Parson and Wright*, 1996; *Taylor and Karner*, 1983; *Taylor et al.*, 1996], and the southernmost Havre Trough [*Caress*, 1991; *Gamble and Wright*, 1995; *Wright*, 1993]. Within the central and northern Lau Basin, magnetic anomalies [*Cherkis*, 1980; *Davagnier*, 1986; *Lawver et al.*, 1976; *Malahoff et al.*, 1982; *Sclater et al.*, 1972; *Weissel*, 1977; *Zellmer and Taylor*, 1999], heat flow, basement fabric, reduced sedimentary cover [*Katz*, 1976; *Larue et al.*, 1982] and recovery of MORB-basalts present convincing evidence of active spreading, although the precise configuration of spreading ridge segments has been equivocal [*Chase*, 1971; *Hawkins and Melchior*, 1985; *Hawkins*, 1974; *Sclater et al.*, 1972]. For the southernmost Lau Basin, ship track data for the transition zone between spreading and rifting are sparse, and do not allow various tectonic interpretations or kinematics models to be tested. In this

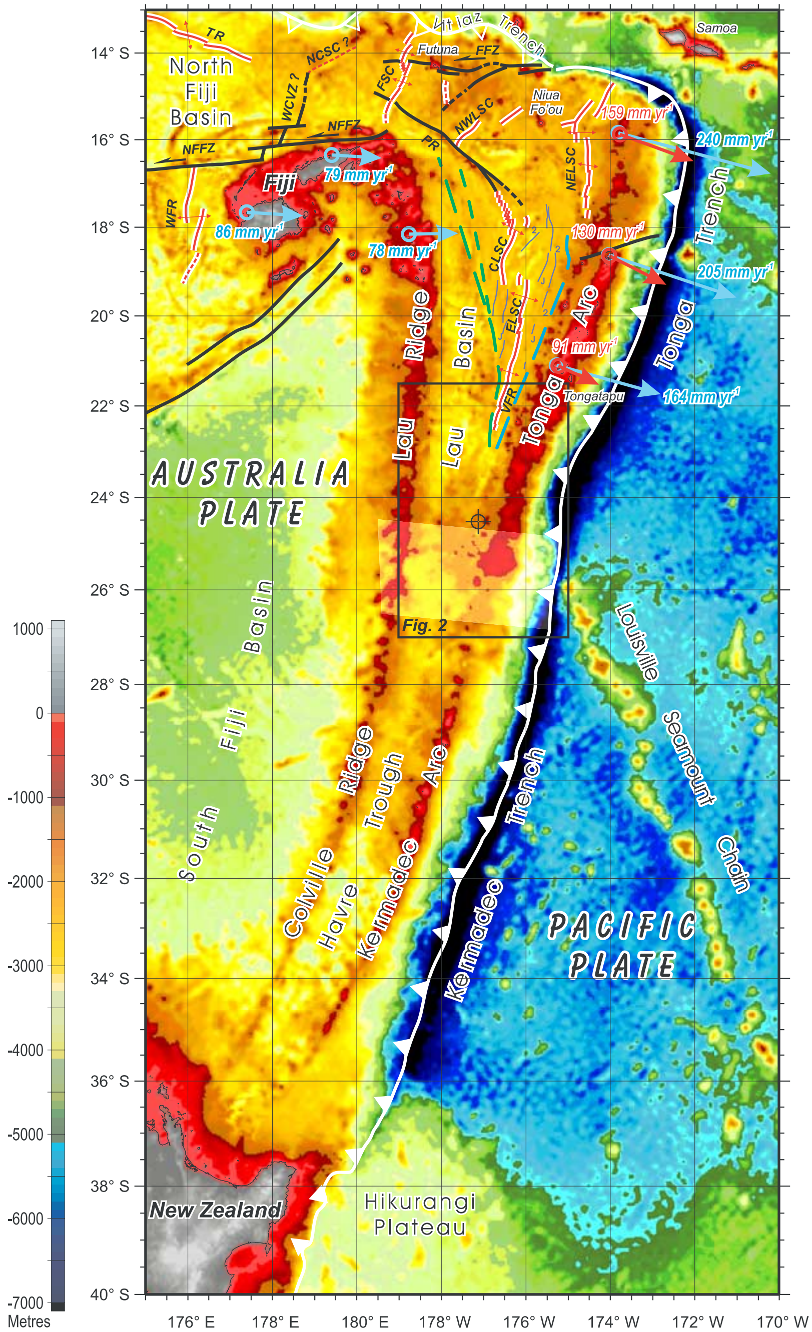

Figure 1. Geodynamic setting of Lau-Havre back-arc system along the Tonga-Kermadec plate boundary, in the Southwest Pacific, including recent published results [*Bevis et al.*, 1995; *Pelletier et al.*, 2001; *Zellmer and Taylor*, 2001], and location of the study area. Bathymetry is from predicted seafloor topography of *Smith and Sandwell* [1997]. Abbreviations are as follows: CLSC, Central Lau Spreading Center; ELSC, Eastern Lau Spreading Center; FFZ, Futuna Fracture Zone; FSC, Futuna Spreading Center; NCSC, North Cikobia Spreading Center; NELSC, Northeast Lau Spreading Center; NFFZ, Noth Fiji Fracture Zone; NWLSC, Northwest Lau Spreading Center; PR, Peggy Ridge; TR, Tripartite Ridge; VFR, Valu Fa Ridge; WCVZ, West Cikobia Volcanic Zone; WFR, West Fiji Rift.

paper, we present new multibeam bathymetry and single-channel seismic reflection data (acquired as part of the Japan - France New Starmer project) from this Lau - Havre transition zone to document: (1) the mechanical conditions and evolution of back-arc opening from nascent Havre Trough rifting to full, southward propagating oceanic spreading of the Valu Fa ridge (southernmost Eastern Lau Spreading Center), and (2) the influence of Pacific slab subduction (particularly the impingement of the LSC) on back-arc tectonism and volcanism.

2. Regional Setting and Characteristics of the Back-Arc Domain

[4] Westward subduction of the Pacific plate at the Tonga-Kermadec trench, ongoing since 30 to 40 Ma, had slightly varying oblique motion through to the present-day plate boundary, with Lau - Havre back-arc opening since ~5 Ma. With the present Australia/Pacific (AUS/PAC) rotation pole located near 62°S, 173°E [*DeMets et al.*, 1990; *Parson and Wright*, 1996], northward increasing rates of subduction and related back arc opening, should be essentially a function of conserving angular velocity with increasing distance from the rotation pole. From Nuvel 1, the Tonga-Kermadec segment of the Australia-Pacific plate boundary has an essentially constant AUS/PAC convergence azimuth of ~N90°E, while the convergence rate increases from 45 mm yr^{-1} at 39°S to 82 mm yr^{-1} at 17°S [*DeMets et al.*, 1990] which is consistent with GPS observations [*Bevis et al.*, 1995]. In detail though, plate convergence and back-arc opening have significant lateral variation. GPS observations show the Tonga Arc/Pacific Plate (TON/PAC) convergence rate varies from 164 ± 5 mm yr^{-1} at 21°S to 240 ± 11 mm yr^{-1} at 16°S [*Bevis et al.*, 1995]. Coeval back-arc opening, as relative Tonga-Kermadec Arc/Australia (TON/AUS) plate motion, likewise decreases southward from 45 mm yr^{-1} to 15 mm yr^{-1} in Havre Trough south of 24°S. To the north of 24°S, the rate increases significantly, being at least 100 mm yr^{-1} at 16–19°S and 90 mm yr^{-1} at 18°S from magnetic anomalies [*Parson and Wright*, 1996; *Taylor et al.*, 1996], or 91 ± 4 mm yr^{-1} at 21°S and 159 ± 10 mm yr^{-1} at 16°S from GPS observations [*Bevis et al.*, 1995]. Such subduction and back-arc opening rates are the fastest of any modern plate boundary in the world.

[5] Within much of the Lau Basin, tectonic structures accommodating such rates of back-arc opening and the magmatic evolution of the bounding arcs are relatively well known. Regional overviews are given by *Wiedicke and Collier* [1993], *Parson and Hawkins* [1994], *Hawkins* [1995], *Parson and Wright* [1996], and *Taylor* [1996]. The salient points for this study are (1) the remnant Lau Ridge is mainly an andesitic volcanic arc active between 14 to 6 Ma, with late volcanism persisting until 2.5 Ma, (2) opening of the Lau Basin and the Havre Trough first occurred by arc rifting of a pre-existing single proto-Tonga-Kermadec arc at about 5.5–6 Ma, (3) the western half of the adjacent Lau Basin comprises rifted arc crust with small, partly sedimented sub-basins and elongated basement blocks that have a range of petrogenetic affinities including MORB-like basalts, andesites, and rhyolites, (4) subsequent spreading located in the eastern half of the basin has occurred at the Eastern and Central Lau spreading centers (ELSC and CLSC, respectively), propagating southward at a speed of 110 mm yr^{-1} since ~5 Ma, with the Valu Fa Ridge forming the southernmost known segment of the ELSC extending to at least 22°50s, and (5) the Tonga Ridge to the east which comprises the western Tofua arc and the Tonga platform - the former being active since <1 Ma, while the latter has a core of middle Eocene to late Miocene volcanic arc-composition basement.

[6] For the Havre Trough, regional overviews are given by *Gamble and Wright* [1995], *Parson and Wright* [1996], and *Delteil et al.* [2002]. Likewise the salient points are: (1) The uplift by ~1000 m of arc and back-arc segments that face the LSC junction with the subduction zone, (2) the remnant Colville Ridge, which comprises andesites with an age of at least 5.4 Ma, (3) the back-arc domain where rifting is universally oblique to the bounding ridges and consisting of a heterogeneous fabric of rifted horsts and grabens, extrusive magmatism and partially sedimented rifts, (4) the significant differences that appear in back-arc morphology north and south of 32°S, where the

former is typically <2500 m water-depth while the latter is structurally complex with water-depths as great as 3000–3750 m, (5) the frontal Kermadec Ridge, to the east, that is capped by an active volcanic arc comprising basaltic-andesitic strato-volcanoes and silicic calderas; south of 32°S the arc is displaced 15–25 km west of the ridge, and (6) the ashore southward extension of the Havre Trough rifting into continental New Zealand as the Taupo Volcanic Zone.

3. Geological and Geophysical Data

[7] Marine geophysical data comprising multi-beam bathymetry, single-channel seismic reflection, and gravity and magnetic anomaly data were acquired during two legs of the RV *Yokosuka* in February–March 1997. Regional reconnaissance geophysical profiles plus three detailed survey boxes were acquired across the back-arc complex, from the Lau-Colville ridge to the Tonga-Kermadec arc ridge within the southernmost Lau Basin and northernmost Havre Trough (Figure 2). These reconnaissance profiles and survey boxes bracket the transition from back-arc rifting to oceanic spreading and were selected in particular to investigate the southward propagation of the active spreading Valu Fa ridge into a region of uplifted rifted arc crust.

[8] Multibeam bathymetry was acquired on all reconnaissance profiles and between 50–100% coverage within the three survey boxes. These data were acquired using a GPS-navigated Furuno HS10 multibeam system with a typical 5 km swath for an average water-depth of ~2500 m. The data were gridded at a 200 m mesh size. A total of 32 single-channel seismic reflection profiles were acquired using a 150 m GSJ type streamer and a 120 ci Bolt 1900C type airgun, with a shot interval of 8 s at an average ship speed of 10–11 knts. A set of closely spaced reflection profiles were acquired within the northernmost Havre Trough within an OBS survey area [*Nishizawa et al.*, 1999]. Magnetic anomaly data were acquired along all ship tracks using both a three component Tierra Technica SFG-1212 magnetometer and surface towed Kawasaki Geological Engineering STC10 proton precession magnetometer [*Fujiwara et al.*, 2001]. Gravity data were acquired using a LaCoste & Romberg S-63 gravimeter and tied to a gravity reference data point in Suva (Fiji). Twelve rock-dredging sites successfully collected samples from two E-W transects across the Lau Basin and Havre Trough (Figure 2) to test both along strike and transverse petrogenetic variations.

4. Morphotectonics of the Northern Havre Back-Arc Trough at 26°S

[9] The northernmost Havre Trough survey area covers the eastern 120 km of the total 150 km back-arc width, and lies immediately inboard of the junction of the LSC subducting into the Tonga Trench (Figure 2). The surveyed area (Figures 3 and 4) encompasses four main structural domains comprising a western sedimentary basin, northeast and southeast elevated domains consisting of ridges and fault-controlled elongated volcanoes, and a central transverse zone. The western basin, as revealed by swath bathymetry (Figure 3) seismic reflection profiles (Lines 8 and 9, Figure 5), and rock sampling (dredges 1 and 2), comprises a N10 trending elongated, 65 km wide, deep sedimentary sub-basin, within which occur a few relatively older and buried volcanoes (dredge 3). This sub-basin, immediately bounding the remnant Colville Ridge, has a flat seafloor <2400 m water depth, and is interpreted as recording nascent rifting of the Lau-Colville arc at about 6 Ma ago, prior to full back-arc opening.

[10] By contrast, the elevated northeast domain consists of numerous ridges and fault-controlled, elongated volcanoes, with two main structural trends (Figure 4) of N42 and N65, which are respectively 24° and 47° clockwise oblique to the regional N18 strike of the back-arc at this latitude. In addition, less common structures are identified as NS and N15-20 trending normal fault-scarps. Accordingly, seafloor topography is rugged, with the water-depth highly variable, ranging between 1100 m and 2300 m, but with no evidence of active tectonics. Rock-dredging in this domain, from a fault scarp (dredge 4), and the flank of a volcanic seamount (dredge 5), yielded

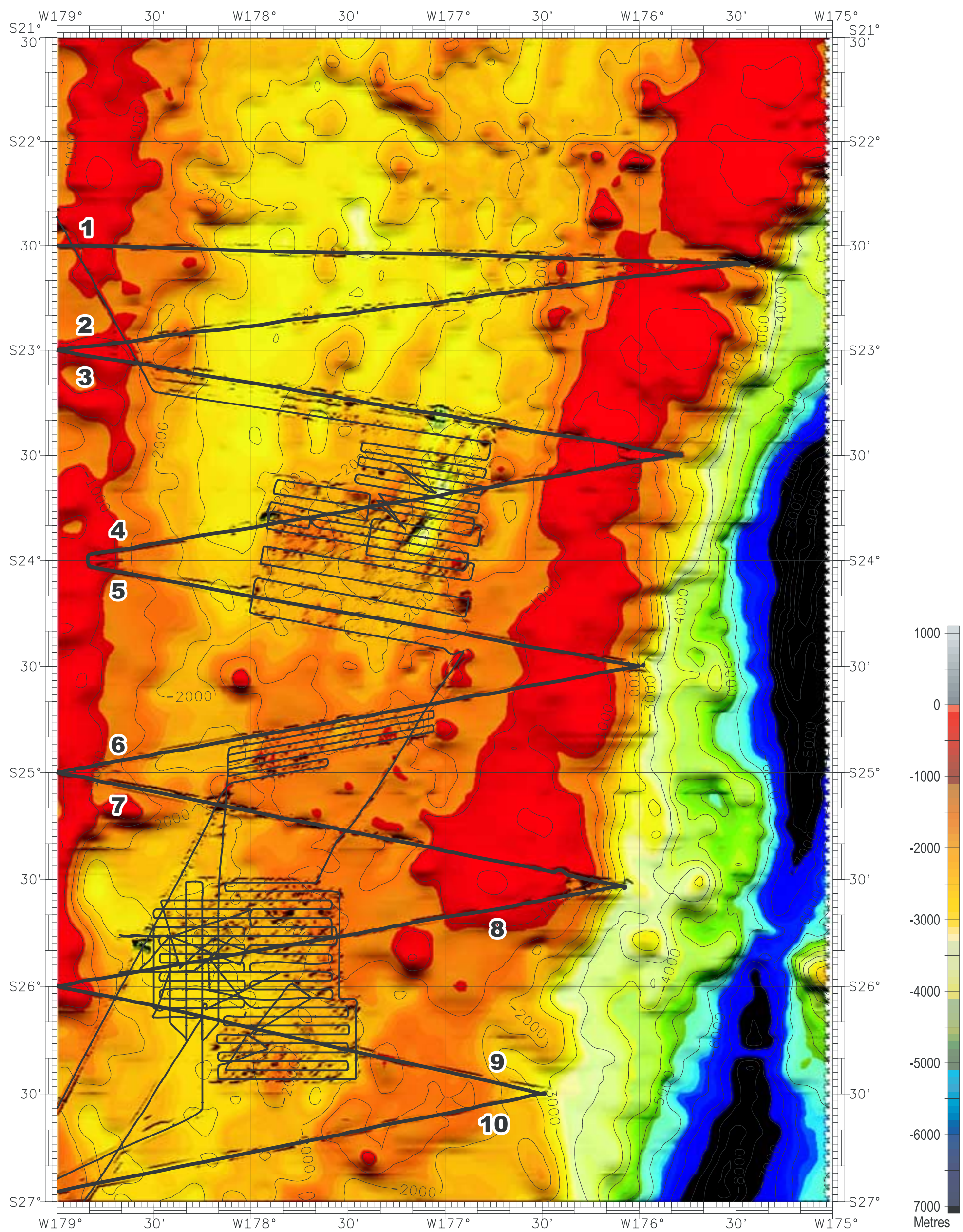

Figure 2. Location of the ship track lines during the two legs of the french-japanese New-Starmer Lauhavre97 cruise onboard R/V Yokosuka. The multibeam bathymetric survey and geophysical (e.g., gravity and magnetic) [*Fujiwara et al.*, 2001] measurements extend continuously over all ship tracks, with 50% to full bathymetric coverage on three detailed target areas, which are located in the northern Havre trough, the southern Lau basin, and the intermediate uplifted region. A set of 32 single-channel seismic reflection profiles was also acquired in the southern Lau Basin and the Havre Trough using a 150 m GSJ type streamer and a 120 ci Bolt 1900C type airgun, with a shot interval of 8 s, at an average ship speed of 10–11 knts. High density interval profiling survey was shot at the northern tip of the Havre Trough within the detailed OBS survey area [*Nishizawa et al.*, 1999].

variably weathered, fairly old volcanic rocks. The structural pattern of the elevated southeast domain is similar to the northeast, forming a pervasive basement fabric of tilt blocks, and rifted and elongated horsts and grabens. Tectonic fabric is mainly oriented N42, consistent with the northeast domain, and is likewise oblique to the N18 regional trough trend. These structures appear to

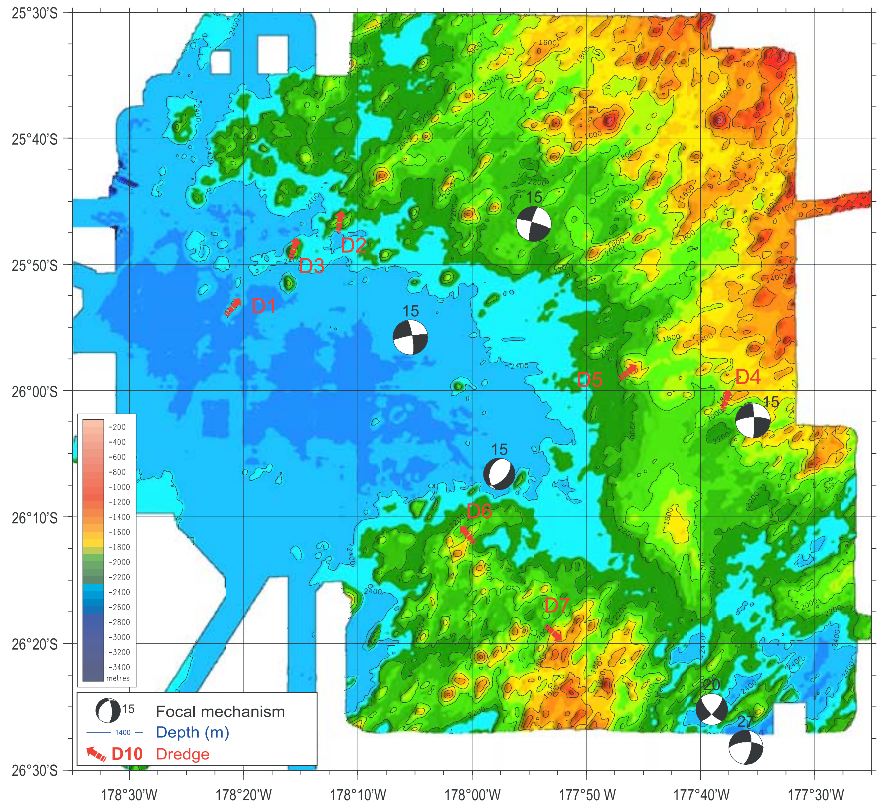

Figure 3. Bathymetry of the northernmost Havre Trough at latitude 26°S, with seismic focal mechanisms (CMT) and location of dredges (D#). The area faces the present-day Louisville Seamount Chain (LSC) subduction into the Tonga trench. The bathymetric data were acquired using the Furuno HS10 multinarrowbeam echo sounder (equipped with 45 beams) on board the japanese GPS positioned R/V *Yokosuka* (1997). With an average depth of ~2500 m, the swath coverage was ~5 km. The mesh size of the sampling grid, used to build the bathymetric Digital Elevation Model (DEM), was fixed to 200 m in order to fit accurately the original data set. The grid was filled by reading the data sequentially in chronological order. If a node already held data, newer values were substituted, in order to get the best DEM accuracy and preserve high frequency topographic signal. Data interpolation occurred only in data gaps; this avoided an unsuitable smoothing of the DEM and restricted fault scarp detection.

never offset the seafloor and hence are considered inactive, although indurated mudstones from rock-dredge sites 6 and 7 indicate that deeper sections of the sedimentary sequence have been faulted previously, with substantial throw, to the seafloor. In addition, old fault-controlled volcanic ridges and seamounts, especially between 177°50′W and 178°15′W, are partially mantled by younger recent sedimentary sequences.

[11] These two latter elevated basement domains are separated, and left-laterally offset by a 25 km wide transverse zone, that trends N120 ± 5°, being almost orthogonal to the tectonic fabrics of the bounding elevated domains. The transverse zone includes a sedimentary sub-basin merging with the main western sedimentary sub-basin. Seismic reflection data show fault-controlled ridges and volcanic seamounts of the northern elevated domain extend southward, beneath undeformed sediments of both the western sub-basin and the transverse zone. The ridges and seamounts either plunge gradually southwestward or are fault-down along subdued structures striking N120. Two-dimensional ray tracing derived from P wave speed modeling of the northern Havre Trough [*Nishizawa et al.*, 1999] shows crustal thinning from the western sedimentary sub-basin, in the SW (>9.4 km) to the northeastern elevated domain, in the NE (~8.7 km) beneath the transverse zone northern boundary. Hence, the transverse zone may represent the seafloor expression of a deep-crustal scale structure.

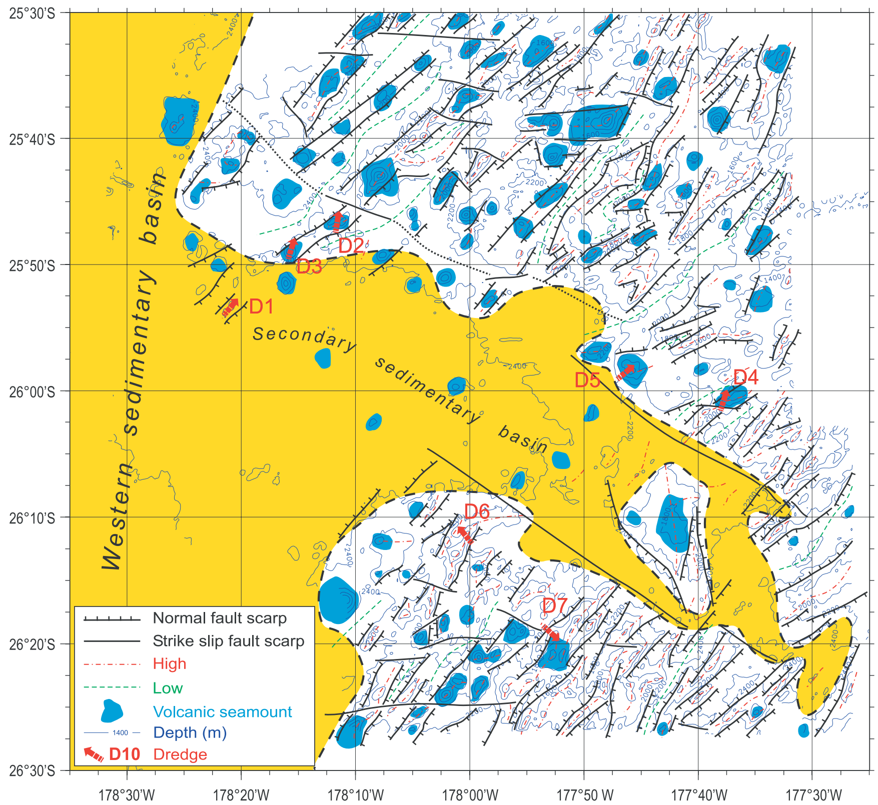

Figure 4. Structure and interpretation of the northernmost Havre Trough at latitude 26°S. A sedimentary sub-basin occupies the western third of the back-arc trough while two left-stepping elevated massifs constitute the eastern two others. The structural fabric of the massifs trends 42°, which is 29° to the trough axis, but does not relate to present-day active faulting. The secondary sedimentary transverse sub-basin that separates the massifs is characterized by very oblique, partly buried structures and underlain at depth by a crustal discontinuity [*Nishizawa et al.*, 1999], suggesting the occurrence of a transform fault.

[12] The Harvard Centroid Moment Tensor (CMT) catalogue shows occurrence of shallow seismicity in the Lau-Havre back-arc region. For the period 1977–1996, six teleseismic events were recorded in the northern Havre Trough and located in the vicinity of the northern and southern boundaries of the transverse zone (Figure 3). These events have focal mechanisms indicating NW-SE tensional axes with mostly strike-slip components, and reveal a rather low shallow seismicity in the area.

[13] Recovered rock samples from the elevated basement domains consist of mostly variably vesiculated, fairly altered, MORB-like basalts (L. Dosso, personal communication, 1999). Samples include pillow lavas (from sites 3 and 4) with moderately fresh, ~1 cm thick glass margins. This indicates volcanism that possibly occurred in relatively shallow (<2500 m) waters, is quite old and not presently active.

[14] Northern Havre Trough gravity anomalies, correlate well with the larger massive volcanic intrusives observed in the multibeam bathymetric and seismic reflection data, but display rather low, negative free air anomalies in comparison to the southern Lau Basin, where the presence of rifted arc crust [*Nishizawa et al.*, 1999] creates mass deficiency. A minimum free air anomaly corresponds with the toe of the Colville Ridge irrespective of the topographic low extending along the central basin, suggesting that the remnant arc is now almost in isostatic equilibrium after cessation of volcanic activity [*Matsumoto et al.*, 1997].

[15] The pervasive oblique N42 structures, as well as the N120 transverse zone, are consistent with previous regional extension directions of N120 to

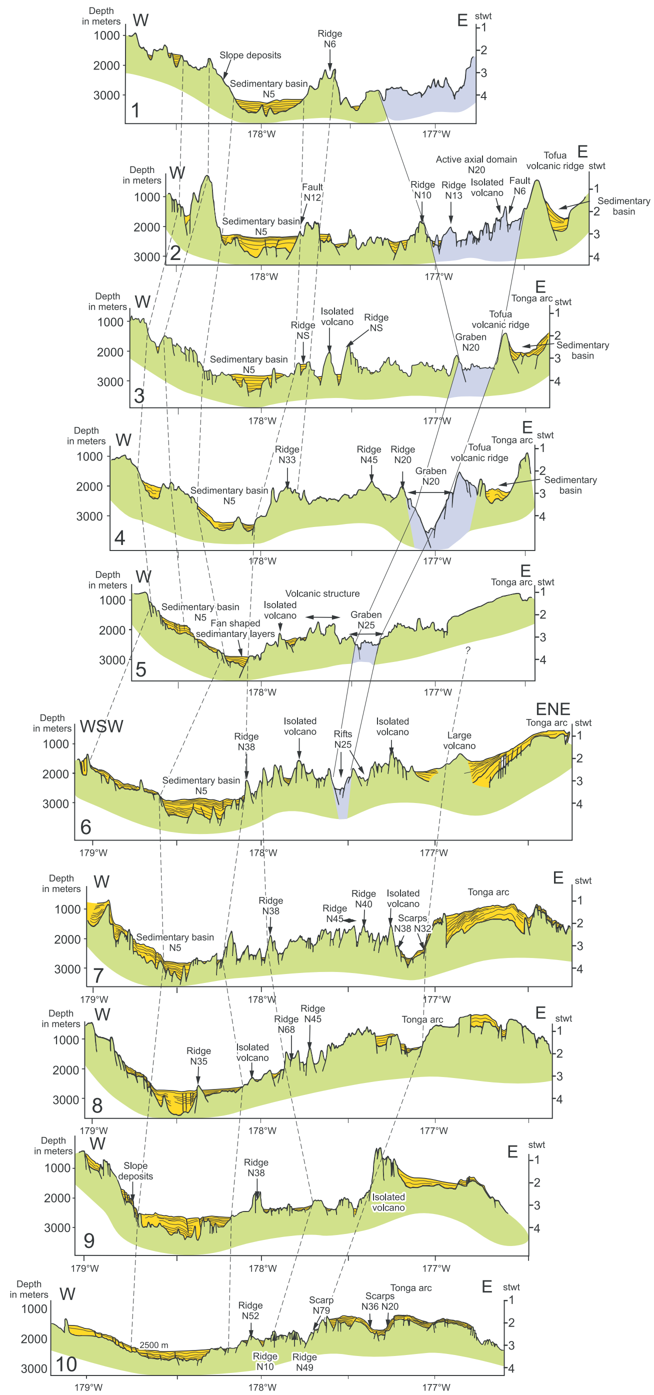

Figure 5. Interpreted seismic reflection profiles across the back-arc area (see location on Figure 2). Lines 1 to 5 cross the southern Lau Basin, lines 6 and 7 cross the transitional uplifted zone, and lines 8 to 10 cut trough the northern Havre Trough.

N150 for this sector of the back-arc [*Caress*, 1991; *Pelletier and Louat*, 1989]. However, we interpret these structures to be relatively old and presently inactive, as we do not observe any evidence of recent volcanism in the back-arc region. Indurated sediment outcrops gathered on tilted blocks of the NE and SE elevated domain are interpreted as corresponding to the high subsidence that is observed in the western sedimentary sub-basin, that occurred prior to oblique rifting. Early rift tectonism and magmatism were then succeeded by extensive, non-syntectonic sedimentation. All observations indicate that the northern 26°S sector of the Havre trough is presently tectonically and magmatically inactive.

5. Rifting and Spreading Propagation in Southern Lau Back-Arc Basin 23°–25°S

[16] This sector, extending over both the southern Lau Basin terminus and the immediate southward and elevated basement high (Figure 1 and 2), is located immediately north of the junction of the LSC with the Tonga trench. In detail, the survey covers the eastern 120 km of the 155 to 195 km width of the northward widening back-arc basin. Three main structural domains are identified; a western sedimentary sub-basin, a deep V shaped valley, and a central-southeastern elevated domain comprising ridges and fault-controlled volcanoes. The western sedimentary sub-basin is the projected extension of that observed at 26°S, and displays similar structural characteristics. Swath bathymetry (Figure 6) and seismic reflection (lines 1–7; Figure 5) reveal a N5 trending, elongated and deep sedimentary sub-basin, that includes buried volcanic/tectonic ridges, and several isolated, inactive volcanoes. Flat seafloor topography, 2200 to 2800 m deep, extends over a width of 65 km at 24°S which decreases southward to 50 km at 25°S. Structural fabrics are not observed suggesting minimal or no recent deformation, and we interpret this domain to have a similar history and tectonic evolution to that of the northern Havre Trough western sedimentary sub-basin, recording initial rifting of the Lau-Colville ridge, beginning at ~6 Ma.

[17] The deep V shaped rift, bounded by steep, high scarps (and here called the Southern Lau Rift, SLR), clearly imaged within both swath bathymetry (Figure 7) and seismic reflection (Line 4, Figure 5), is the predominant active tectonic element in the southernmost Lau back-arc region. Shallow seismicity, from the CMT catalogue, reveals 12 teleseismic events in this region within the period 1977–1996, consistent with being the locus of active tectonism. This is significantly different from what is observed in the northern Havre Trough. In particular, two shallow earthquake-swarms (August 1986 and March 1987), centered near 24°S, 177°07′W, and coinciding with the eastern flank of the rift, were extensional events with a slight strike-skip component. The rift axis generally trends N20 (Figures 7 and 8), consistent with Valu Fa Ridge trend to the north. However, up to N25 slight southward bending of the rift axis is observed, giving a slight curvature to the rift valley. Both flanks of the graben remain as high and steep scarps along strike, consisting of several fault-block terraces. In contrast, the axial rift valley shallows progressively (from a maximum depth of ~3250 m) from north to south, and becomes locally wider. Southward of 24°07′S, the rift is less pronounced, but its southern continuation is identified by focal mechanisms and numerous smaller, tectonic structures that indicate continued extensional tectonism. Near 23°35′S, the northern part of the rift valley splits northward into three narrower, but parallel and elongated grabens (Figure 7), with the two easternmost having slightly shallower water-depth. The two intervening sharp horst ridges and the axial graben are interpreted as a neovolcanic ridge emplaced within the wider rift valley. Dredged rock samples from the western side of the axial graben are pristine, and provide evidence for recent volcanism associated with extensional rifting. Rock samples from inside the graben (dredge 10) are mainly andesitic and/or dacitic in composition, and have variably undergone hydrothermal alteration, with many fragments of volcanic breccias displaying a propyllitic hydrothermal mineral assemblage of chlorite, clays and silica (C. de Ronde et al., manuscript in preparation, 2001). Rocks from the western margin of the rift (dredge 12) comprise mainly andesites and basalts with fresh glassy rinds. All samples within the graben indicate very recent magmatic and hydrothermal activity.

[18] Near 23°50′S–177°20′W (Figure 7), a further graben to the west is separated from the axial graben by a N25 trending horst ridge. This western graben is shallower (~2500 m water-depth), and is clearly bounded on each side by several fault terraces. Changes in trend of this graben, from N30 in the north to N20 in the south, produce a

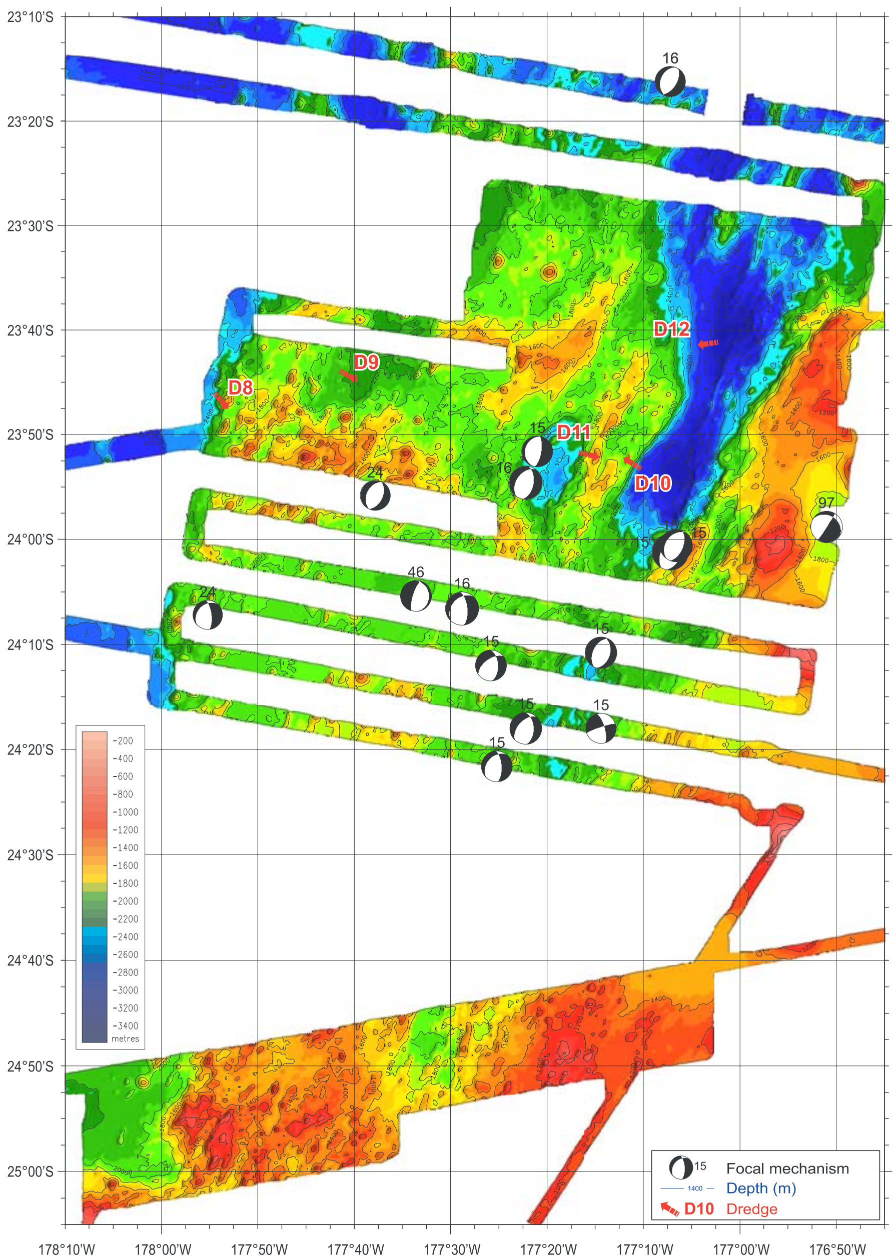

Figure 6. Bathymetry of the southernmost Lau Basin and transitional uplifted zone, with seismic focal mechanisms (CMT) and location of dredges (D#). The most prominent feature is the deep V shaped Southern Lau Rift (SLR), that sharply incises the seafloor at 177°W.

curved rift convex to the west. Such curvature is opposite to that of the main rift, indicating possible overlapping structures. Rock samples recovered from this western graben (dredge 11) appear to be altered and thus relatively older than those collected in the main rift. Two extensional focal mechanisms from the CMT database, located at the western faulted flank, indicate ongoing active tectonism. Free air anomalies associated with the southernmost shallower Lau Basin topography are relatively high and may correlate with spreading and possible upwelling, plume-like related magma supply [*Matsumoto et al.*, 1997].

[19] From these observations we interpret the SLR to be the active tectonic extension to the south of

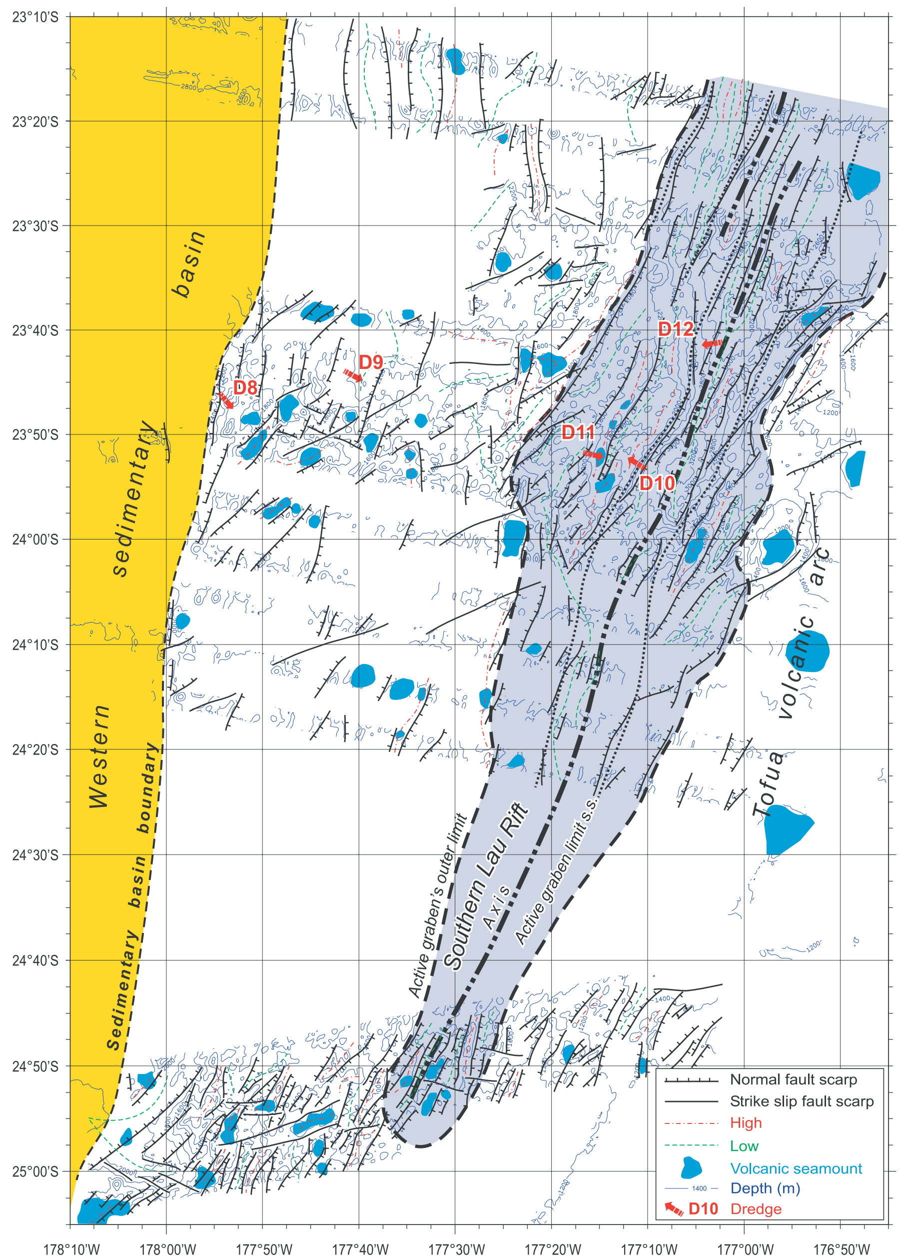

Figure 7. Structure and interpretation of the southernmost Lau Basin and transitional uplifted area. The sedimentary sub-basin lies in the western third of the back-arc basin. Active faults, trending parallel to the basin axis, and seismic activity concentrate in the eastern third of the basin, especially in the Southern Lau Rift (SLR), where fresh and fractured pillow lavas and hydrothermal deposits were recovered. Outside the SLR, the structural fabric trends 26 ± 2°, which is 13° oblique from the backarc basin axis, and suggests that two successive and differently oriented tectonics has occurred in eastern area.

the Valu Fa Ridge (ELSC). The central and south-eastern elevated domain, has a less organized structural fabric comprising either basement ridges and/or fault-controlled volcanoes. In the northern part of the domain, volcanic seamounts are observed and the structural fabric becomes chaotic, with trends ranging from N15 to N30 (Figure 7). In contrast, the western boundary of this domain with the sedimentary sub-basin is well defined by almost continuous steep west-facing fault scarps. Rock samples from these latter scarps (Dredge 8; Figure 7) mostly comprise old altered volcanic

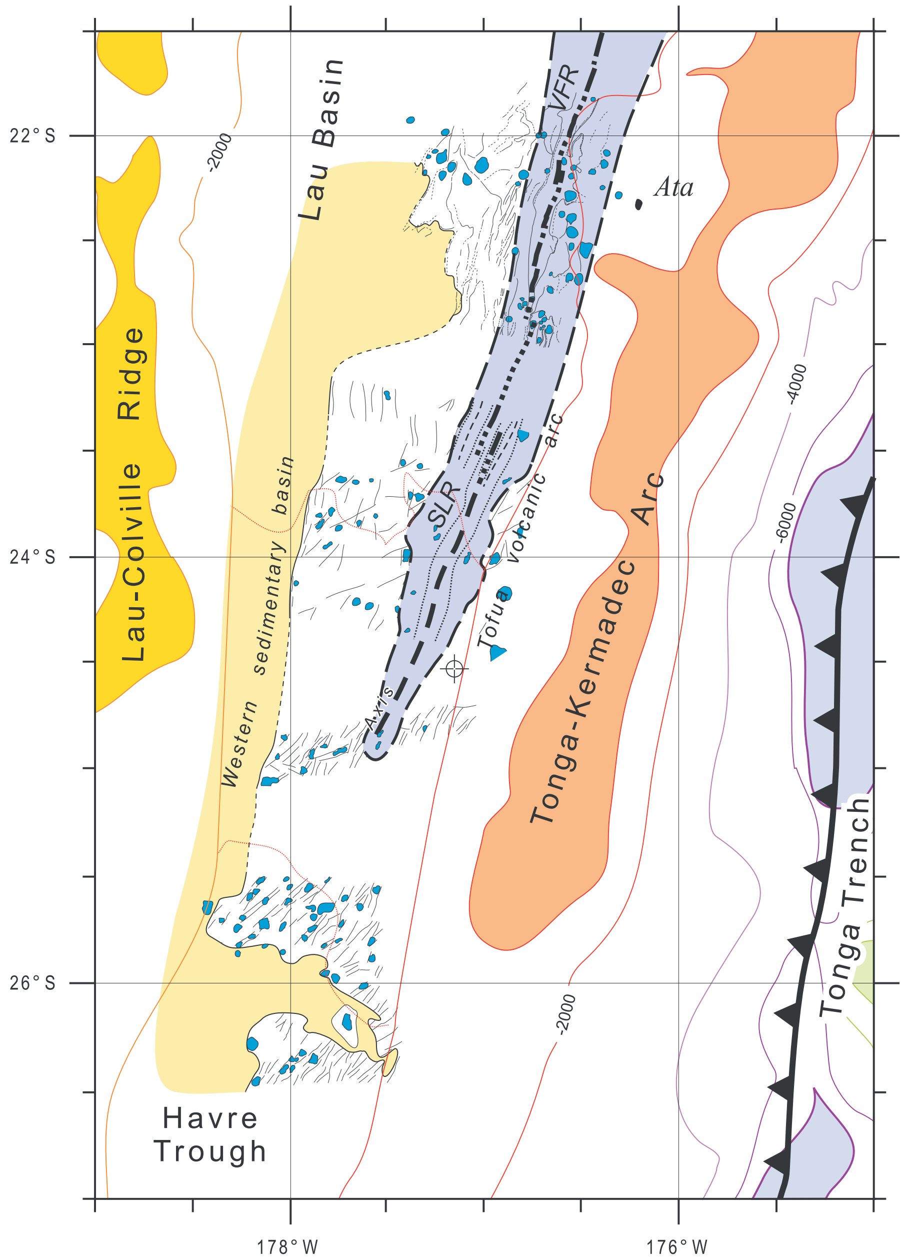

Figure 8. Regional structural sketch map of the back-arc transition between the Lau Basin and the Havre Trough. As it locates in the southward projected extension of the Valu Fa Ridge, and postdates obliquely rifted and uplifted arc basement, we interpret the Southern Lau Rift (SLR) as the structural prolongation of the Eastern Lau Spreading Center (ELSC). The southwards propagating tip of the latter is likely to extend presently to 23°40s, while the active extensional structures of the SLR are developing as far as 24°55′S. Conversely, the northern Havre Trough comprises ridges trending 25–45° oblique to the basin axis, from which volcanic rocks and indurated sediments, as well as low seismicity are consistent with minimal tectonic and volcanic activities there.

rocks and lithified sediments. At 24°S the seafloor comprises relatively flat topography with few N20 trending ridges, and volcanic seamounts that are partially buried by a thin sedimentary cover (Figure 5).

[20] At 24°50′S, the southern part of this domain, bounding the axial SLR both east and west, is characterized by a highstanding, poorly sedimented, rugged seafloor topography. The structural fabric is dominantly oriented N26 ± 2°, some 13°

obliquely clockwise to the regional back-arc basin axis. However, in the west the structural fabric is more complex with the superposition of N42° trending volcanic ridges and faults (29° oblique to basin axis) that plunge southwestward beneath the sediment fill of the western sedimentary basin. This very oblique trend, predating a part of sedimentation in the western sub-basin, is interpreted from the relationships between basement structures and sediment cover and cross-cutting basement fabrics, as an early, if not the earliest, Lau - Havre back-arc extension fabric. Similarly, oblique volcanic ridges prevail to the east but decrease in prominence westward as far as 177°25′W, whereas the principal N26° trending ridges and associated active faults conversely increase in the same direction. Where these fabrics intersect, N26° trending structures clearly and consistently cut and postdate N42° features, as inferred from N42° ridge-sediment relationships. Additional transverse structures trend 70° oblique to the orthogonal of the local dominant structural fabric.

6. Discussion

[21] Based on the bathymetric, seismic reflection, gravity and geologic data presented above for the Lau-Havre Basin transition zone, we propose a new kinematic model for back-arc rifting and spreading that incorporates the effects of the LSC subduction at the Tonga-Kermadec trench. A main result of our study is the overall asymmetry in back-arc structure (Figure 9). The western sub-basin, recording syntectonic sedimentation, is interpreted as the oldest back-arc domain and the locus of initial arc break-up. Subsequent rifting in the eastern domain is younger. Most recent active faulting and volcanism is localized within the southern Lau Basin, both in the intermediate uplifted domain, and eastern elevated sediment starved two thirds of the back-arc. In contrast, the northernmost Havre Trough has markedly less active tectonic structures.

[22] Active tectonics of the southernmost Lau Basin sector is dominated by the N20 trending Southern Lau Basin Rift (SLR) that cuts through the eastern back-arc domain between 23°15′S and 24°55′S. The SLR sited at the southward projected extension of the Valu Fa Ridge, postdating obliquely rifted and uplifted arc basement, is interpreted to be the structural prolongation of the Eastern Lau Spreading Center (ELSC). The southward propagating tip of the latter is likely to extend to 23°40′S, while the southern extremity of SLR reaches 24°55′S. Available seismic focal mechanisms, with the recovery of fresh glassy basalts and hydrothermal alteration crusts from within the rift, clearly indicate active extensional tectonism and associated magmatism, especially at the southern tip of the rift. The pronounced V shape of the rift indicates rapid southward propagation. The observation that active tectonism and magmatism cease south of 24°55′S but resume south of 27°S where it is characterized by en echelon oblique rifting [*Delteil et al.*, 2002] is significant. Between these latitudes there is no evidence of recent back-arc extension or volcanism. Accordingly, we interpret that in the northern Havre Trough the extensional tectonic regime is currently and temporarily locked as a consequence of compression exerted on the arc by the present-day subduction of the LSC in the Tonga-Kermadec trench at 26°S.

[23] The Havre Trough structural fabric is generally defined by two networks of structural trends [*Caress*, 1991; *Delteil et al.*, 2002]. These two structural orientations are interpreted here as recording successive stages of the back-arc development. The first trend is parallel with, and largely restricted to the back-arc trough margins, whereas the second, including subordinate orthogonal structures, is 24° to 47° clockwise oblique to the regional trough axis trend. The latter fabric is concentrated in the eastern two thirds of the basin. Oceanic spreading is not observed within the Havre Trough, but rather localized and active rift segments occur, particularly in the southern Havre Trough [*Delteil et al.*, 2002; *Parson and Wright*, 1996]. Our data confirm that the Havre Trough back-arc remains in a rifting stage, with the additional observation that such rifting has temporarily ceased within the northernmost sector. Hence, back-arc opening clearly appears to be presently locked in the area adjacent to the subduction point of the LSC.

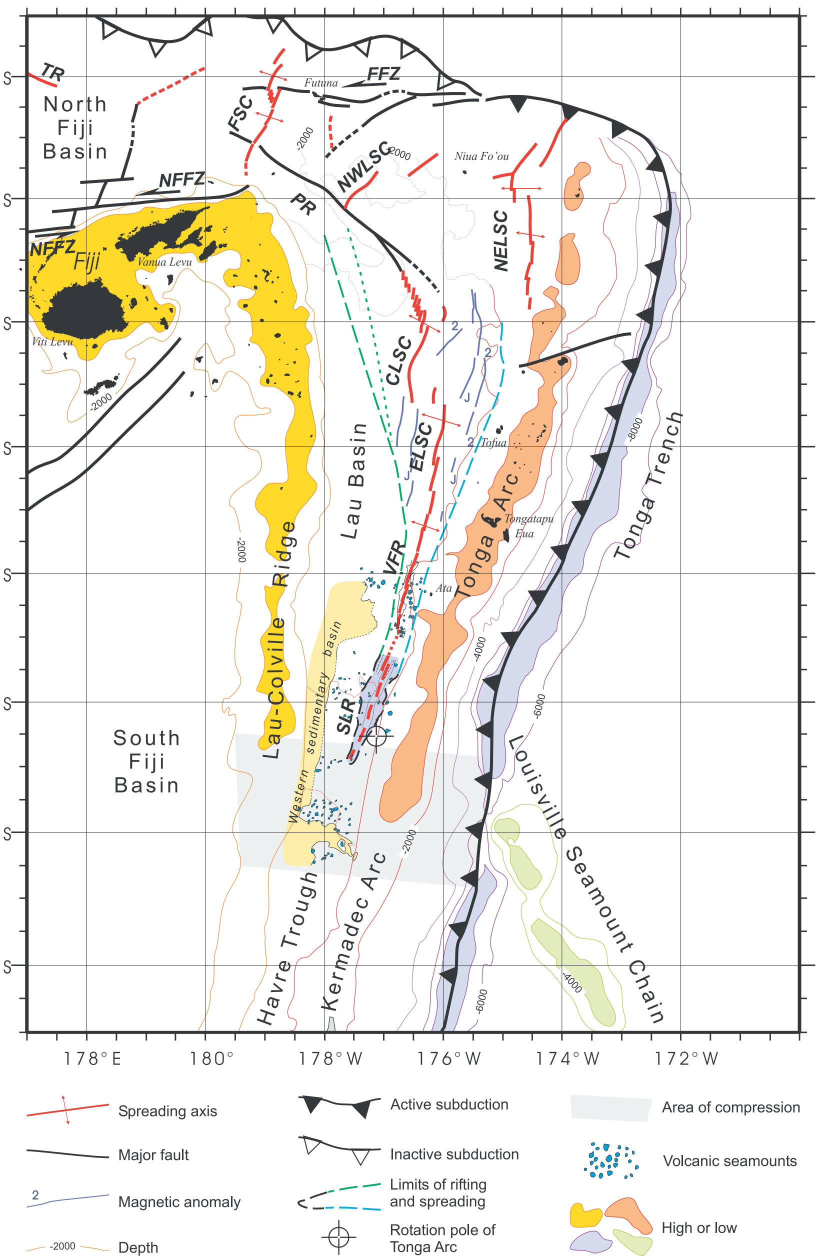

Figure 9. Updated synthetic structural map of the Lau back-arc basin and northern Havre Trough, including recent published work about central and northern Lau Basin [*Pelletier et al.*, 2001; *Zellmer and Taylor*, 2001] and our results. Abbreviations are as follows: CLSC, Central Lau Spreading Center; ELSC, Eastern Lau Spreading Center; FFZ, Futuna Fracture Zone; FSC, Futuna Spreading Center; NELSC, Northeast Lau Spreading Center; NFFZ, Noth Fiji Fracture Zone; NWLSC, Northwest Lau Spreading Center; PR, Peggy Ridge; SLR, Southern Lau Rift; TR, Tripartite Ridge; VFR, Valu Fa Ridge; WFR, West Fiji Rift.

[24] South of this point, the essentially constant width of the Havre Trough and parallelism of the remnant Colville and active Kermadec arc ridges strongly suggest that opening has occurred synchronously over the entire length of the Havre Trough. Accounting for alteration of oblique structural development in the Havre Trough, with concomitant northward increase in Pacific/Australian plate convergence obliquity, we interpret that during the stage of oblique back-arc opening this

mode of rifting extended to the southern Lau Basin.

6.1. The Effects of Louisville Seamount Chain Migration on Back-Arc Kinematics

[25] Previous models of Lau-Havre back-arc opening have generally proposed a relatively simple geometric southward propagation of rifting preceding similar southward propagation of spreading [*Parson and Wright*, 1996; *Taylor et al.*, 1996]. However, such simple southward propagation cannot easily account for significant longitudinal differences in structural basement fabrics and plate kinematics for the two sectors of the back-arc (e.g., Lau Basin and the Havre Trough) that bound the transition between rifting and spreading. Basement fabrics and tectonism from this transition zone reveal opening of the Lau-Havre back-arc to be more complex, which we interpret to reflect the geodynamic control of LSC subduction at the Tonga trench, and its consequent impingement of back-arc opening. The pronounced V shape of the Lau back-arc basin, the location and geometry of the oceanic spreading centers, magnetic anomalies, and inferred extent of oceanic crust are all consistent with southward-propagating oceanic spreading. Kinematic movement of the Tonga arc, relative to the Australian plate, corresponds to the Lau Basin opening rate. Instantaneous GPS measurements [*Bevis et al.*, 1995] consistent with recent magnetic anomaly spreading [*Zellmer and Taylor*, 1999; *Zellmer and Taylor*, 2001], show a sharp decrease of Tonga arc motion relative to the Austalian plate from north to south, that defines a present-day pole of opening at 24°35′S, 177°15′W. This pole location is near the tip of the propagating rift identified here, being west of the arc, and immediately north of the latitude of where the LSC is subducted.

[26] Given the kinematic constraints of varying oblique convergence, present-day PAC/AUS convergence rate remaining constant over the last few Ma period [*DeMets et al.*, 1990], back-arc opening rates [*Bevis et al.*, 1995], as well as geometrical constraints due to the rotating trend of the LSC and Tonga Arc, it is possible to calculate the rate of along-trench sweep of LSC subduction.

[27] With these parameters, the following points are derived:

[28] 1. Presently (Figure 10f), due to its NW-SE orientation (being both oblique to the plate convergence motion and 36° oblique to the trench) the calculated velocity of the current southward sweep of the LSC is ~128 mm yr^{-1}, which is of the same order of the ~100 mm yr^{-1} southward propagation of the ELSC in the Lau Basin [*Taylor et al.*, 1996].

[29] 2. The LSC extended northward and was likely connected with the Tuvalu seamount chain before it met the northernmost Tonga subduction trench; this is consistent with geochemical studies [*Turner and Hawkesworth*, 1997] that show LSC subduction signature in Tongan arc volcanism.

[30] 3. Accounting for the initial position of the Tonga Arc, prior to Lau Basin oceanic spreading, the trench/LSC angle has changed significantly over time, increasing from ~0° at the beginning of LSC subduction (Figures 10a and 10b), to the present-day 36° value (Figure 10f).

[31] 4. The along-trench southward migration of the LSC has occurred at a very high rate at the commencement of its subduction and progressively decreased with time (Table 1).

[32] 5. The ultra-fast Tonga-Pacific plate convergence only relates to Lau Basin opening that took place after the subduction of the LSC was completed.

[33] 6. Considering that the LSC has already swept the trench over a distance of ~880 km yields an estimated age of 4–5 Ma for the subduction initiation at the northernmost paleo-Tonga Trench. This age is comparable with the age commonly assigned to the opening of the whole back-arc domain.

[34] The good agreement between First the initiation of back-arc opening and succeeding entrance of the Tuvalu-Louisville Seamount Chain in the subduction trench, and Second the differing modes of back-arc opening occurring at the present-day junction point of the LSC at the trench, leads us to

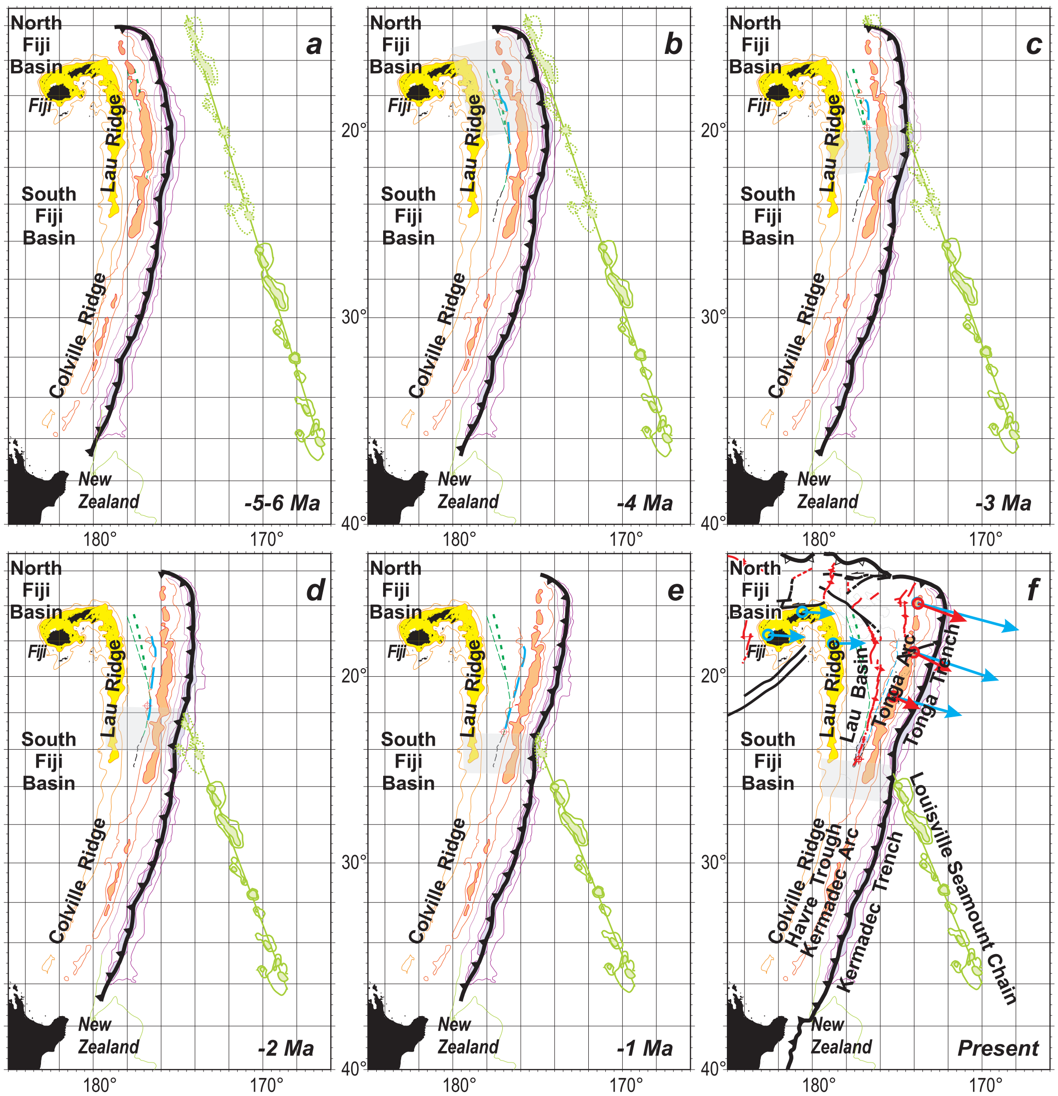

Figure 10. Kinematic evolution model of the Lau and Havre back-arc basin opening since 5–6 Ma (see comments in the text).

underline the effects of the seamount/ridge subduction on back-arc kinematics.

6.2. Three Stage Model for Kinematic Evolution of Lau-Havre Back-Arc System

[35] From these observations and interpretations of the effects of LSC subduction and the associated kinematic evolution of back-arc opening, we propose the following three-stage model.

[36] The first stage commences at ~6–5 Ma, by initial opening of the Lau Basin - Havre Trough (Figure 10a), before the LSC started subduction at the northernmost Tonga Trench. Such opening occurred by intra-arc rifting of the Lau-Colville-Tonga-Kermadec proto-arc, and succeeding back-arc rifting along the length of the arc. The longitudinal continuity of the early back-arc structures, comprising principally two opposing basin margin fault-systems and the western sedimentary sub-basin, suggest that early Lau Basin - Havre Trough opening occurred essentially simultaneously along the length of the proto-arc, from New Zealand to Tonga. Orientated parallel to the regional trend of the arc, these first tectonic structures mostly consist of high vertical offset faults that occur at the basin margins, indicating mainly dip-slip movement with possibly minor but southward increasing component of strike-slip. Extending over the length of

Table 1. Relationships Between the North to South Migration Rate of the Louisville Seamount Chain (LSC) Subduction and the Convergence Rate, According to the Ridge-Trench Angle[a]

Agr, Ma BP	Louisville Ridge Angle to Tonga Trench	Convergence Azimuth Angle to Tonga Trench	Calculated Migration Rate	Velocity of the Migration, mm a^{-1}
4	3			
3, 5	*16*	*90*	*3, 49*	*283*
3	25	84	2, 24	182
2	29	82	1, 93	156
1	31	81	1, 80	146
0	36	76	1, 58	128
Covered distance since the beginning of the subduction, km			878	
Pacific-Australia plate convergence average velocity (mm a^{-1}) an dazimuth (°) at Lau Basin latitudes			81	270

[a] Australia-Pacific plate convergence in the area is considered to be overall E-W. As the LSC-trench angle increase progressively, the calculated rate and the velocity of the migration both decrease.

the plate boundary, this stage represents a significant phase of Havre Trough opening, that imparts its present weakly curvilinear configuration. The associated pole of opening, at this time, would have been located south of the present Taupo Volcanic Zone, North Island, New Zealand.

[37] The second stage began at ~5–4 Ma, when LSC subduction started beneath the northernmost Tonga Arc (Figure 10b), and is presently the stage of opening still active in all the Havre Trough. When the rectilinear LSC, which we assume was morphologically continuous with the Tuvalu Seamount Chain, first encountered the northeastern tip of the Tonga Arc, it arrived almost parallel to the trench and its subduction started simultaneously over a length of ~380 km (Figure 10). As a consequence of the long length and highstanding topography of the LSC entering the subduction trench, and recognizing that present back-arc rifting has temporarily ceased in the northern Havre Trough in front of the present-day subduction of the ridge, we propose that back-arc rifting may have temporarily slowed. This slow rifting contributed to an ongoing stable width along both central and northern Lau Basin, while the LSC started to subduct Moreover, based on kinematic models [*Lallemand*, 1992; *Pelletier and Louat*, 1989], and the observed present-day structure of the Havre Trough [*Delteil et al.*, 2002] compared to the Lau Basin, such subduction of the LSC possibly caused significant heterogeneity in the tectonic style and location of back-arc opening.

[38] At this time the Tonga-Kermadec arc motion, relative to the Australia plate, was locked at either end, in the south by the oblique collision of the Hikurangi plateau [*Collot and Davy*, 1998], and in the north by the subduction of the LSC. Assuming that ~100 km of slab were subducted with the present-day plate dip, at a PAC/AUS convergence rate of 81 mm yr^{-1} in order to avoid the ridge tectonic effect, the duration of the latter can be estimated at ~1.2 Ma prior to renewal of opening in the northernmost Lau Basin. Nevertheless, the present-day near constant width of the Havre Trough suggests that the system retained significant longitudinal rigidity along its entire length whatever the local stress regime. Moreover, existing data do not reveal significant transverse fault structures indicative of longitudinal tectonic segmentation and weakness. Consequently, although LSC subduction was restricted to northern Tonga, back-arc opening may have ceased or significantly decreased along the full length of the Lau - Havre system.

[39] Basement fabrics record a second change over the length of the back-arc with the appearance of

oblique trans-extensional structures. These latter structures indicate a change in stress orientation, and the development of dextral-extensional tectonics within the back-arc coeval with the southward displacement of the active arc relative to the Australia plate [*Delteil et al.*, 2002]. Such motion possibly reflects both oblique Australia and Pacific plate convergence, and a dragging effect of the southwestward sweeping of LSC along the arc.

[40] The third stage started at ~3.5 Ma, when LSC subduction along the northern Tonga trench was complete, and the locking of back-arc rifting ceased in northern Lau Basin (Figure 10c). Diachronous back-arc rifting progressively resumed, followed by almost immediate oceanic spreading as recorded by ultra-fast opening (Figures 10c to 10f). Rifting, with successive spreading, then propagated southward at the rate of LSC sweeping along the trench during subduction. The position of the rotation pole of an increasing Tonga Arc length segment likewise migrated southward. Indeed, as this point of impinging LSC subduction migrated southward to its current position at 26°S, the northern part of the arc (Tonga segment) progressively unlocked, whereas the southern part (Kermadec segment) remains impeded. By inference, this model implies that Havre Trough opening rates proposed previously [*Parson and Wright*, 1996] are average rates due to the initial intraarc rifting identified here. A multistage opening, with initial active and pervasive rifting followed by a period of relative quiescence, requires fast initial opening, possibly comparable to those observed currently in the Lau Basin.

7. Conclusion

[41] The southern terminus of the Valu Fa spreading ridge system (southern Lau Basin) presently extends to 24°55′S, where it propagates southward into older and rifted back-arc crust. In contrast, present-day rifting has essentially ceased in the northern Havre Trough, in response to subduction of the LSC at its present position of 26°S in the trench. Southern Lau Basin – northern Havre Trough back-arc structural fabrics are consistent with back-arc opening being controlled by tectonic constraints associated with LSC subduction. Subduction of the LSC exerts compression on the arc and modifies the geometry of the back-arc structural fabrics and hence the kinematics of basin opening. As a result of LSC subduction, extension within the adjacent back-arc temporarily ceases and the back-arc is locked. Elevated topography of the arc and back-arc may also reflect uplift due to possible underplating of the LSC. Further, the north to south sweeping of the LSC along the Tonga Trench during subduction results successively in the reduction of rifting south of 26°S, rifting cessation at 26°S, uplift at 25°S, rifting recommencing north of 24°55′S, spreading tip propagation at 23°40s, and full spreading north of 23°S. Accordingly, since ~5–6 Ma, the tectonic and kinematic evolution of the northern Havre-Lau back-arc is controlled by the progressive southward sweep of the LSC during subduction and the associated southward correlative migration of the Tonga Arc rotation pole.

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