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Anisotropy and Flow in Pacific Subduction Zone Back-arcs

KAREN M. FISCHER,[1] MATTHEW J. FOUCH,[1] DOUGLAS A. WIENS,[2] and MARGARET S. BOETTCHER[1]

Abstract—We have obtained constraints on the strength and orientation of anisotropy in the mantle beneath the Tonga, southern Kuril, Japan, and Izu-Bonin subduction zones using shear-wave splitting in *S* phases from local earthquakes and in teleseismic core phases such as *SKS*. The observed splitting in all four subduction zones is consistent with a model in which the lower transition zone (520–660 km) and lower mantle are isotropic, and in which significant anisotropy occurs in the back-arc upper mantle. The upper transition zone (410–520 km) beneath the southern Kurils appears to contain weak anisotropy. The observed fast directions indicate that the geometry of back-arc strain in the upper mantle varies systematically across the western Pacific rim. Beneath Izu-Bonin and Tonga, fast directions are aligned with the azimuth of subducting Pacific plate motion and are parallel or sub-parallel to overriding plate extension. However, fast directions beneath the Japan Sea, western Honshu, and Sakhalin Island are highly oblique to subducting plate motion and parallel to present or past overriding plate shearing. Models of back-arc mantle flow that are driven by viscous coupling to local plate motions can reproduce the splitting observed in Tonga and Izu-Bonin, but further three-dimensional flow modeling is required to ascertain whether viscous plate coupling can explain the splitting observed in the southern Kurils and Japan. The fast directions in the southern Kurils and Japan may require strain in the back-arc mantle that is driven by regional or global patterns of mantle flow.

Key words: Anisotropy, mantle flow, subduction zones, shear-wave splitting.

Introduction

The presence of seismic anisotropy within subduction zones has been documented by numerous studies (e.g., ANDO *et al.*, 1983; FUKAO, 1984; BOWMAN and ANDO, 1987; SHIH *et al.*, 1991; YU and PARK, 1994; FISCHER and YANG, 1994; RUSSO and SILVER, 1994; YANG *et al.*, 1995; KANESHIMA and SILVER, 1995). However, recent shear-wave splitting measurements have added new constraints on the strength and geometry of anisotropy within the back-arc mantle regions of several Pacific subduction zones: Tonga, the southern Kurils, Japan, and Izu-Bonin (FISCHER and WIENS, 1996; FOUCH and FISCHER, 1996). Shear-wave splitting

[1] Department of Geological Sciences, Brown University, Providence, Rhode Island, 02912, U.S.A. E-mail: karen@emma.geo.brown.edu, Fax: 401-863-2058, Tel.: 401-863-1360.
[2] Department of Earth and Planetary Sciences, Washington University, St. Louis, Missouri, 63130, U.S.A.

parameters (fast directions and splitting times) were obtained for *S* phases from local earthquakes and *SKS*, *SKKS*, and *PKS* phases from teleseismic events recorded at subduction zone stations. These splitting measurements yielded two primary results: a striking variation in fast direction orientation between different back-arc regions, and patterns of splitting time with source location that constrain the distribution of anisotropy with depth in the mantle. The strength of anisotropy as a function of depth was extensively modeled in FISCHER and WIENS (1996) and FOUCH and FISCHER (1996), and in this paper we only briefly summarize these results. Rather, this paper focuses on the geometry of back-arc flow implied by the observed splitting and explores the resulting implications for coupling of the subducting slab and overriding plate to the back-arc asthenosphere.

Observed Shear-wave Splitting

In the Tonga subduction zone, shear-wave splitting parameters were obtained for *S* and *SKS* phases recorded at three stations of the southwest Pacific PASSCAL experiment (WIENS *et al.*, 1995) and an IRIS/Global Seismic Network station (Fig. 1). Data in the Izu-Bonin, Japan, and southern Kuril subduction zones were collected from the Japanese POSEIDON network, IRIS/Global Seismic Network stations, and one GEOSCOPE station (Fig. 2). Analysis was restricted to paths with free surface incidence angles of 35° or less to avoid contamination of particle motions by converted phases and phase shifts from crustal discontinuities and the free surface. In Tonga, event depths range from 380 km to 660 km. The number of splitting measurements displayed in Figure 1 is about 50% larger than the FISCHER and WIENS (1996) data set, although the splitting parameter patterns are virtually identical. Among the northwest Pacific splitting measurements of FOUCH and FISCHER (1996), event depths range from 50 km to 600 km. However, to keep Figure 2 both compact and readable, we display shear-wave splitting parameters only for events deeper than 200 km.

We parameterized shear-phase splitting by finding the fast direction, ϕ, and splitting time, δt, which most completely describe ellipticity in the shear phase particle motions. Splitting values were determined by computing the covariance matrix for the horizontal seismogram components rotated to azimuths of ϕ and $\phi + \pi/2$ and time-shifted by δt, over a grid of ϕ and δt values. Splitting parameters for a given phase were defined as those values of ϕ and δt which minimized the smaller of the two covariance matrix eigenvalues. Error bars for individual splitting parameters correspond to the 95% F-test confidence regions for $\varphi_2/\varphi_{2\,\min}$, where φ_2 is the smaller of the two covariance matrix eigenvalues at any point on the ϕ and δt grid and $\varphi_{2\,\min}$ is the minimum value of φ_2 that corresponds to the best-fitting ϕ and δt.

Shear-wave splitting fast directions in these subduction zones display a fairly simple pattern. For earthquakes in Tonga and in Izu-Bonin, *S* and *SKS* fast directions are roughly parallel to absolute Pacific plate motion. For earthquakes in western Honshu and the Japan Sea, *S* and *SKS* fast directions are roughly parallel to the strike of the trench, and for earthquakes in the southern Kurils, fast directions are N–S to NNE–SSW (Figs. 1 and 2). The distribution of local *S* phase splitting times from Tonga and Izu-Bonin also differs from that in Japan and the southern Kurils (Fig. 3). In Tonga and Izu-Bonin, local *S* splitting times are fairly uniform with source depth, particularly at 95% confidence, whereas in Japan and the southern Kurils, local *S* splitting times manifest a significant increase with source depth. In the two regions where consistent estimates of splitting in *SKS* and other teleseismic core phases were obtained (Tonga and the southern Kurils), the teleseismic splitting times overlap with the *S* splitting times from the deepest local events.

The Distribution of Anisotropy with Depth

The observed splitting time patterns qualitatively suggest that anisotropy is confined to the upper mantle in Tonga and Izu-Bonin, and that no evidence exists in any region for splitting due to lower mantle anisotropy. However, in order to fully account for differences in path length and angle between individual phases, shear-wave splitting parameters were modeled using a method that predicts shear-wave splitting on individual phase paths and determines the strength, orientation and depth extent of anisotropy that best fits the complete data set of observed splitting times and fast directions (FISCHER and WIENS, 1996; FOUCH and FISCHER, 1996). For example, the distribution of paths in the Tonga back-arc is shown in Figure 4.

Modeling results indicate that contributions to observed shear-wave splitting from the lower mantle are not required in any of these subduction zones and are ruled out beneath the southern Kurils and Tonga. This result is most plausibly explained by an absence of significant anisotropy widely distributed within the lower mantle. Assuming that the strength and orientation of anisotropy are roughly uniform throughout the back-arc mantle, anisotropy is ruled out beneath 400 km in Izu-Bonin and beneath 435 km in Tonga. In contrast, the increase of observed splitting times over transition zone source depths in the southern Kurils (Fig. 3b) requires anisotropy on the order of 0.5% to depths of at least 500 km. However, the strength of transition zone anisotropy could be weaker if the strength of anisotropy was allowed to vary with depth. Data from all the subduction zones are consistent with a model in which the lower transition zone (520–660 km) and lower mantle are largely isotropic, and the upper transition zone (410–520 km) contains weak anisotropy (possibly due to preferred orientation of β spinel) in some regions but not others. Significant anisotropy in the back-arc upper mantle is ubiquitously required.

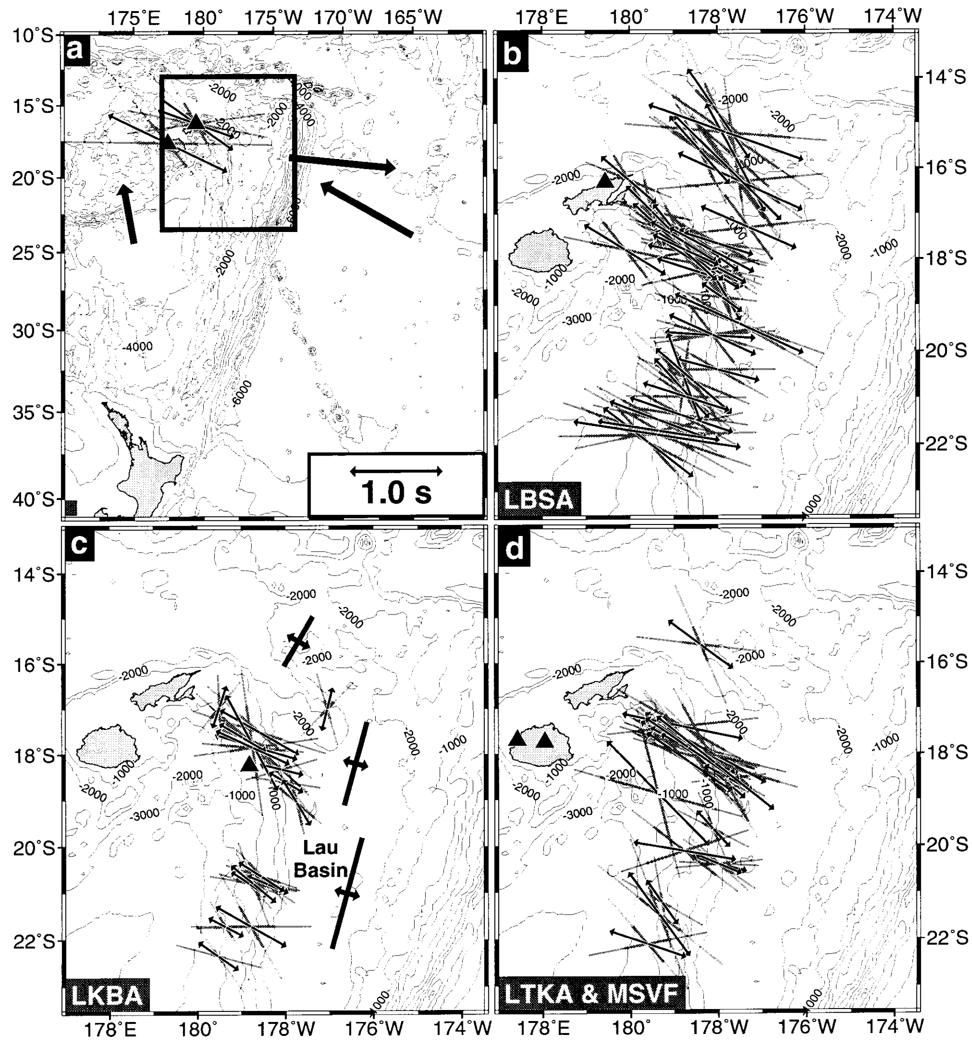

Figure 1

Shear-wave splitting in the Tonga subduction zone observed at 3 stations of the southwest Pacific PASSCAL experiment (LBSA, LKBA, and LTKA) and one IRIS/GSN permanent station (MSVF) (triangles). a) *SKS* splitting parameters at LBSA and LTKA, plotted at the stations. Bold arrows denote the direction and relative rates of absolute Pacific plate motion (PPM), absolute Australian plate motion, and absolute Tonga arc motion (Gripp and Gordon, 1990; Bevis *et al.*, 1995). Box outlines area magnified in b–d. b–d) Local *S* splitting measurements plotted at the earthquake source. The location and orientation of active back-arc spreading are indicated by the thicker arrows in (c). Splitting parameters are shown as vectors parallel to ϕ (fast direction) with lengths scaled to δt (splitting time); corresponding 95% confidence limits are represented by thick and thin line segments. A 1 s reference vector is shown at bottom right, and bathymetry is contoured in 1000 m intervals. Fast directions for paths in Tonga are roughly parallel to PPM.

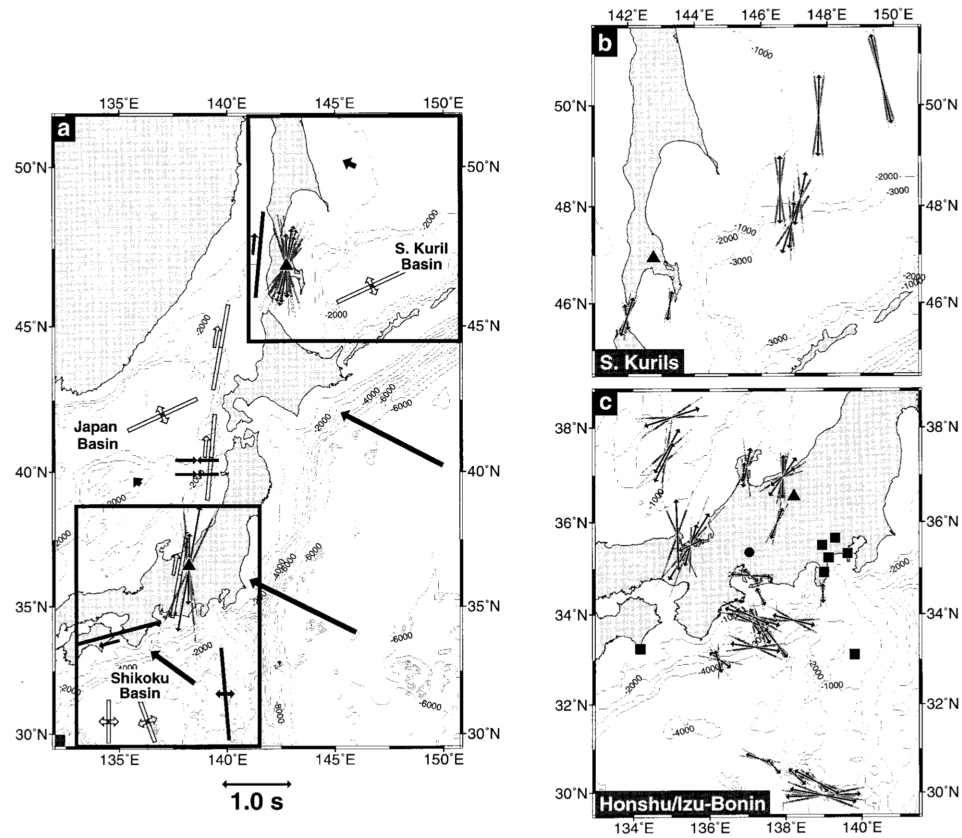

Figure 2

Shear-wave splitting observed in Japan and the southern Kurils at IRIS/GSN stations YSS (Sakhalin Island) and MAJO (Honshu) (triangles), GEOSCOPE station INU (solid circle), and 8 POSEIDON network stations on Honshu and in the Izu-Bonin arc, HKY, TKO, SGN, YCU, JIZ, HCH, MRM, and OGS (squares, OGS out of box). (To make this condensed figure clearer, we have omitted a few of the splitting measurements and stations shown in Fouch and Fischer (1996).) a) *SKS* splitting parameters at MAJO and YSS, plotted at the stations. Bold arrows denote the direction and relative rates of absolute Pacific plate motion (PPM), and the absolute motions of the Philippine, Eurasian and North American plates (Gripp and Gordon, 1990). Smaller solid arrows indicate present-day rifting, shearing, and compression. Smaller outlined arrows indicate past and now inactive back-arc spreading and shearing. Boxes outline areas magnified in b–c. b–c) Local *S* splitting measurements plotted at the earthquake source. Splitting parameters are shown as vectors parallel to ϕ (fast direction) with lengths scaled to δt (splitting time); corresponding 95% confidence limits are represented by thick and thin line segments. A 1 s reference vector is shown at bottom right, and bathymetry is contoured in 1000 m intervals. Fast directions for paths in Izu-Bonin are roughly parallel to PPM, but beneath the Japan Sea, western Honshu region and Sakhalin Island, fast directions are N–S to NNE–SSW.

Implications for the Geometry and Dynamics of Back-arc Flow

The observed fast directions indicate that the geometry of back-arc strain varies systematically across the western Pacific rim. Beneath Izu-Bonin and Tonga, fast directions are roughly parallel to the azimuth of Pacific plate motion, whereas beneath the Japan Sea, western Honshu region, and Sakhalin Island, fast directions are either roughly parallel to the trench (Japan) or are aligned within 35° of trench (Sakhalin Island) (Figs. 1 and 2, Table 1). The northwest Pacific fast directions are corroborated by local *S*-phase splitting measurements on similar paths in a recent study by SANDVOL and NI (1997). Reviews of earlier splitting studies in the northwest Pacific and Tonga are provided in FOUCH and FISCHER (1996) and FISCHER and WIENS (1996).

Assuming that anisotropy is produced by lattice preferred orientation (LPO) of mantle minerals, olivine should dominate the geometry of anisotropy within a peridotite upper mantle (WENK *et al.*, 1991; RIBE, 1992). The *a* axis (fast symmetry axis) of olivine aligns roughly parallel to the direction of maximum finite strain (e.g., KARATO, 1987; NICOLAS and CHRISTENSEN, 1987) or is controlled by the flow direction (ZHANG and KARATO, 1995). Therefore, the fast directions in Tonga and Izu-Bonin may be easily explained by shearing and extension in back-arc mantle entrained by the subducting slab. However, the observed fast directions in Japan and Sakhalin Island indicate the presence of significant strain that is not coupled to subducting plate motion. We have examined the possibility that the apparent fast direction patterns are due to sampling bias, i.e., that the

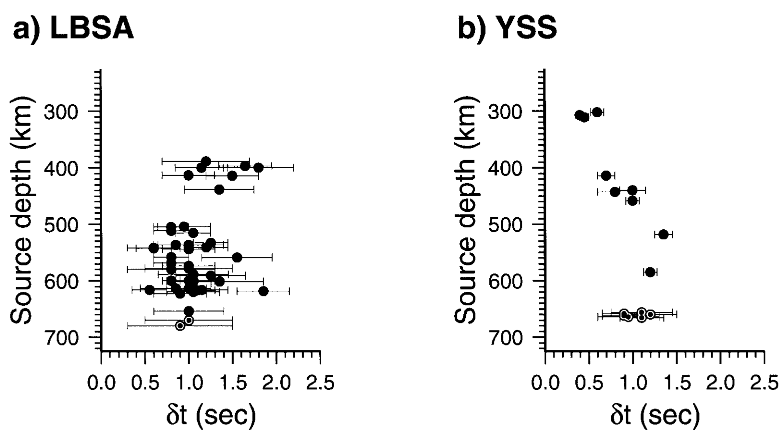

Figure 3
Observed splitting times for local *S* phases (solid circles) and their 95% confidence limits shown as a function of earthquake source depth. Splitting times for *SKS* phases (bullseyes) are plotted near 670 km depth for comparative purposes. a) Splitting times for station LBSA in the Tonga back-arc are roughly uniform with source depth, particularly at 95% confidence. b) Splitting times for station YSS on Sakhalin Island in the southern Kuril back-arc show a significant increase with source depth.

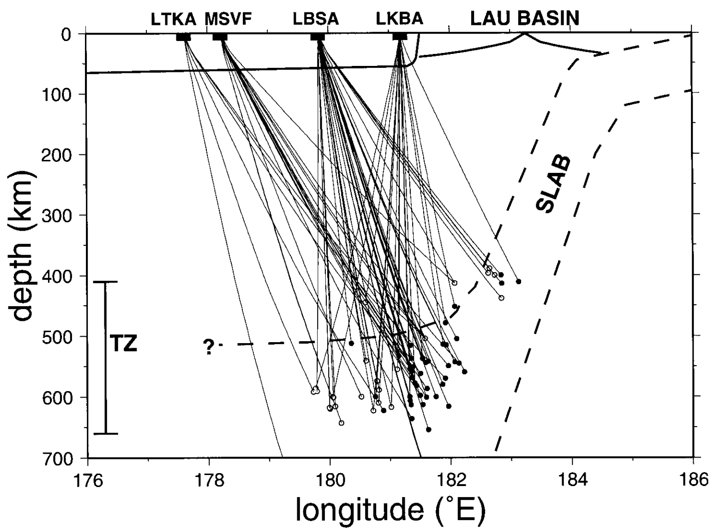

Figure 4
S and *SKS* raypaths through the Tonga slab and back-arc. Bold dashed contours show the approximate outline of the high velocity subducting lithosphere from recent inversions for *P*-wave velocity (VAN DER HILST, 1995; ZHAO *et al.*, 1995). Bold solid contours show the probable shape of the overriding plate. The profile passes through station LKBA at an azimuth of 80°. Solid dots show events located within 2° of the profile; open dots are from more distant arc segments where slab shape may differ from the given outline. Raypaths are relative to the IASP91 radial velocity model.

back-arc strain patterns in the four subduction zones are similar but the *S* paths in Tonga and Izu-Bonin sample a different region of the back-arc than those in Japan and the southern Kurils. However, although *S* paths from local earthquakes in Izu-Bonin in general lie closer to the strike of the subducting slab than local *S* paths in the other subduction zones, no systematic difference in path distribution can explain the observed fast direction patterns.

What factors control the apparent differences in back-arc strain patterns between Tonga and Izu-Bonin and Japan and the southern Kurils? An examination of absolute plate motions indicates little difference in the properties of the subducting plate between these subduction zones, but demonstrates fundamental variations in the rate of overriding plate motion and in the style and geometry of back-arc tectonism. The subducting Pacific plate enters the trench in all four subduction zones with roughly the same azimuth and rate of absolute plate motion (GRIPP and GORDON, 1990) (Table 1). However, the total rates of overriding plate motion (V_{up}, Table 1) and the components of overriding plate motion normal to the trench are much larger in Tonga and Izu-Bonin than in Japan and the southern Kurils (Figs. 1 and 2). In terms of back-arc tectonism, Tonga and Izu-Bonin are strongly extensional environments, while the southern Kuril and Japan back-arcs are dominated by a combination of N–S shearing and E–W compression (Table 1).

Table 1

Shear-wave splitting, plate motions, and back-arc tectonism

Region	ϕ average	PPM azimuth[a]	PPM rate[a] (cm/y)	V_{up} (cm/y)	Dominant mode of overriding plate deformation	Rate of overriding plate deformation	Minimum overriding plate age
Tonga	~300°	~300°	10.5	Australian: 5.0[a] Tonga arc: >10[b]	extension at 280°–300°[b,c]	10–16 cm/y[b,c]	present[c]
Izu-Bonin	~290°	~293°	10.7	Philippine: 5.0[a]	extension at 255°–20°[d]	?	Shikoku Basin: 15 Ma[d] Sumisu Rift: present[d]
Japan	~20°	~294°	10.5	Eurasian: 0.9[a]	compression at ~90° after shear at ~0°[e]	1–2 cm/y or less[e]	18 Ma[f]
S. Kurils	~10°	~299°	9.8	N. American: 1.3[a]	shear at ~0°[e]	1–2 cm/y[e]	~20 Ma[e,g]

[a] Gripp and Gordon (1990).
[b] Bevis *et al.* (1995).
[c] Weissel (1977), Hamburger and Isacks (1988), Hawkins (1995).
[d] Haston and Fuller (1991), Taylor *et al.* (1991), Kobayashi *et al.* (1995), Clift (1995).
[e] Fournier *et al.* (1994, 1995), Jolivet *et al.* (1994, 1995).
[f] Tamaki (1995).
[g] Gnibidenko *et al.* (1995).

In Tonga, earthquake source mechanisms (HAMBURGER and ISACKS, 1988) and back-arc spreading in the Lau Basin (active since 6 Ma) (WEISSEL, 1977; HAWKINS, 1995) indicate extension at an azimuth that is roughly normal to the trench and parallel to the observed fast directions (Fig. 1). In Izu-Bonin, back-arc spreading occurred in the Shikoku Basin from 29 to 15 Ma and has continued in the Sumisu Rift from 2 Ma to the present (TAYLOR *et al.*, 1991; CLIFT, 1995; KOBAYASHI *et al.*, 1995). The initial orientation of back-arc spreading in the Shikoku Basin was roughly ENE–WSW, but later spreading had an azimuth closer to E (KOBAYASHI *et al.*, 1995) (Fig. 2). The orientation of normal faults in the Sumisu Rift (TAYLOR *et al.*, 1991) and source mechanisms from the Harvard Centroid Moment Tensor Catalog for Sumisu Rift earthquakes are consistent with extension at a roughly E–W azimuth that is normal to the trench and lies within 30° of most observed fast directions. In the southern Kuril and Japan back-arcs, paleomagnetic data suggest that the overriding plates deformed along a roughly N–S dextral shear system during the Miocene. This shear zone appears to have remained active in the southern Kurils through the present, but has been replaced by E–W compression to the west of Honshu (Fig. 2, Table 1) (FOURNIER *et al.*, 1994, 1995; JOLIVET *et al.*, 1994, 1995). The N–S shearing is roughly parallel to the observed fast directions in both the southern Kurils and Japan. In contrast to the active rifting in the Tonga and Izu-Bonin back-arcs, spreading in the Japan Sea and southern Kuril basins was due to pull-apart tectonism and ended prior to 18 Ma (TAMAKI, 1995; GNIBIDENKO *et al.*, 1995). Finally, the Izu-Bonin and Tonga trenches have undergone much greater seaward trench migration over the last 25 Ma than have the trenches in Japan and the southern Kurils (HASTON and FULLER, 1991; VAN DER HILST and SENO, 1993; FOURNIER *et al.*, 1994; VAN DER HILST, 1995). We are therefore left with an intriguing picture in which fast directions in Tonga and Izu-Bonin are parallel to subducting plate motion and parallel or subparallel to overriding plate deformation, but fast directions in the southern Kurils and Japan are highly oblique to subducting plate motion and parallel to present or past overriding plate shearing.

How might these differences in back-arc tectonics influence the back-arc strain patterns responsible for the apparent anisotropy? One possibility worth considering is that overriding plate anisotropy with the geometry of recent overriding plate deformation makes a large contribution to the observed splitting and is particularly dominant in Japan and the southern Kurils where the overriding plate is thicker due to the absence of recent back-arc spreading. (Even though the N–S shear system no longer appears to be active in the Japan Sea (FOURNIER *et al.*, 1994, 1995; JOLIVET *et al.*, 1994, 1995), the recent E–W compression could produce E–W olivine *b* axes and N–S fast directions.) However, while lithospheric anisotropy may have some influence on the observed fast directions, it is insufficient to completely explain their variation. The observed increase of splitting times with source depth from 200–600 km in the southern Kurils (Fig. 3b) and Japan indicates that anisotropy with a N–S to NNE–SSW fast direction must persist deep into the asthenosphere. In addition, the portions of the overriding plate sampled in Tonga and Izu-Bonin largely lie outside the Lau Basin and the Sumisu Rift where the youngest and thinnest lithosphere occurs (Fig. 4), so the differences in sampled lithospheric thickness between subduction zones may not be significant.

Two types of models might explain the apparent differences in deep back-arc mantle strain geometry between Tonga/Izu-Bonin and the southern Kurils/Japan: large-scale flow and local viscous plate coupling. In the first type of model, regional to global patterns in mantle buoyancy and flow dictate back-arc strain patterns, and overriding plate deformation either passively reflects or is decoupled from these deeper processes. For instance, larger-scale flow patterns could drive predominantly N–S flow along the Kuril and Japan back-arcs, producing the N–S to NNE–SSW fast directions. In Tonga and Izu-Bonin, larger-scale flow might either be negligible, allowing viscous coupling to surface plate motions to dominate, or have an azimuth roughly in the direction of absolute Pacific plate motion.

In the second type of model, viscous coupling to local plate motion dominates back-arc flow. For instance, McKenzie (1979) and Ribe (1989) show that a subducting slab entrains surrounding mantle material, aligning olivine *a* axes with the slab-mantle interface and driving circulation throughout the back-arc wedge. This type of model works well in Izu-Bonin where Pacific plate motion. Philippine plate motion, and the probable orientation of recent back-arc extension are all either parallel or subparallel to the observed fast directions (Fig. 2, Table 1) (Stine *et al.*, 1996). It is also easily applicable to Tonga where Pacific plate motion and back-arc extension are parallel to the observed fast directions and have much higher rates than the more northerly motion of the Australian plate (Fig. 1, Table 1) (Hall *et al.*, 1997). However, the viscous plate coupling model is less obviously consistent with the N–S to NNE–SSW fast directions in the southern Kurils and Japan. Although the roughly N–S geometry of shearing in the overriding plate near Sakhalin Island (Fig. 2) aligns with the trend of the fast directions observed in the southern Kurils, its rate is much less than the rate of subducting plate motion. Moreover, tectonic reconstructions suggest that similar $\sim$N–S shearing in Honshu and the Sea of Japan ended at 12–15 Ma (Jolivet *et al.*, 1995). The ability of viscous plate coupling to explain fast directions observed in the southern Kurils and Japan is now under investigation using three-dimensional mantle flow calculations (Hall *et al.*, 1997).

The viability of the viscous plate coupling model in the southern Kurils and Japan could be enhanced if the subducting slab was partially decoupled from back-arc mantle flow, allowing overriding plate motions to dominate shallow back-arc strain. Two-dimensional flow calculations indicate that the presence of a thin low viscosity layer at the slab-mantle interface can reduce entrainment of the surrounding mantle by the slab, but would not prevent viscous plate coupling from modeling the shear-wave splitting in Tonga and Izu-Bonin (Stine *et al.*, 1996).

Because the viscosity of olivine dramatically decreases with increasing water content (CHOPRA and PATERSON, 1984; HIRTH and KOHLSTEDT, 1996), de-watering of slab minerals and hydration of the adjacent mantle (DAVIES and STEVENSON, 1992; PEACOCK, 1996), could produce such a low viscosity zone, at least to depths of roughly 200 km. Subducted sediments could also contribute to low viscosities at the slab surface, perhaps to even greater depths (PLANK and LANGMUIR, 1993). Finally, more complex viscosity structures, including viscosity variations due to partial melting widely distributed within the back-arc mantle (DAVIES and STEVENSON, 1992; PEACOCK, 1996), would also affect the distribution of back-arc strain and should be investigated.

In summary, shear-wave splitting observed in the Tonga, Izu-Bonin, Japan and southern Kuril subduction zones requires significant anisotropy in the upper mantle beneath their back-arcs. Fast directions in Tonga and Izu-Bonin are parallel to the azimuth of subducting Pacific plate velocity and are easily modeled by mantle strain coupled to local plate motion. In contrast, fast directions in the southern Kurils and Japan are highly oblique to the azimuth of subducting Pacific plate velocity. Future three-dimensional back-arc flow modeling will address whether these fast directions can be explained by viscous plate coupling, or whether they require strain in the back-arc mantle that is driven by larger-scale mantle flow.

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