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Possible strain partitioning structure between the Kumano fore-arc basin and the slope of the Nankai Trough accretionary prism

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[1] A 12 km wide, 56 km long, three-dimensional (3-D) seismic volume acquired over the Nankai Trough offshore the Kii Peninsula, Japan, images the accretionary prism, fore-arc basin, and subducting Philippine Sea Plate. We have analyzed an unusual, trench-parallel depression (a “notch”) along the seaward edge of the fore-arc Kumano Basin, just landward of the megasplay fault system. This bathymetric feature varies along strike, from a single, steep-walled, ~3.5 km wide notch in the northeast to a broader, ~5 km wide zone with several shallower linear depressions in the southwest. Below the notch we found both vertical faults and faults which dip toward the central axis of the depression. Dipping faults appear to have normal offset, consistent with the extension required to form a bathymetric low. Some of these dipping faults may join the central vertical fault(s) at depth, creating apparent flower structures. Offset on the vertical faults is difficult to determine, but the along-strike geometry of these faults makes predominantly normal or thrust motion unlikely. We conclude, therefore, that the notch feature is the bathymetric expression of a transtensional fault system. By considering only the along-strike variability of the megasplay fault, we could not explain a transform feature at the scale of the notch. Strike-slip faulting at the seaward edge of fore-arc basins is also observed in Sumatra and is there attributed to strain partitioning due to oblique convergence. The wedge and décollement strength variations which control the location of the fore-arc basins may therefore play a role in the position where an along-strike component of strain is localized. While the obliquity of convergence in the Nankai Trough is comparatively small (~15°), we believe it generated the Kumano Basin Edge Fault Zone, which has implications for interpreting local measured stress orientations and suggests potential locations for strain-partitioning-related deformation in other subduction zones.

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Theme: Mechanics, Deformation, and Hydrologic Processes at Subduction Complexes,
With Emphasis on the Nankai Trough Seismogenic Zone Experiment
(NanTroSEIZE) Drilling Transect
Guest Editors: D. Saffer, P. Henry, and H. Tobin

1. Introduction

[2] Subduction zones are some of the most geologically hazardous areas of the world. The largest earthquakes (Chile 1960, Alaska 1964, Sumatra 2004) and many of the deadliest tsunamis (Sumatra 2004, Java 1883, Japan 1707) on record are subduction related [e.g., *Dunbar*, 2008; *Satake and Atwater*, 2007]. The societal impact of such events makes an understanding of the stresses, strains and structures involved imperative.

[3] In subduction zones characterized by convergence that is oblique to the plate boundary, partitioning of strain between a generally convergent subduction complex and a trench-parallel transform fault or set of faults is often observed [*Fitch*, 1972]. This partitioning results in a system of faults, often located near the volcanic arc, which can produce significant strike-slip earthquakes. Examples include the Sumatra fault [*Fitch*, 1972; *Jarrard*, 1986] and the Median Tectonic Line in southern Japan [*Nishimura and Hashimoto*, 2006; *Tabai et al.*, 2002]. The northeastern Caribbean exhibits varying degrees of strain partitioning as the subduction zone curves to the northwest [*Manaker et al.*, 2008]. Obliquity of convergence is at a maximum near Hispaniola and Puerto Rico, where onshore faults accommodate margin parallel motion. Additionally, the Aleutian, Chilean and Peruvian margins exhibit onshore strike-slip faulting consistent with the obliquity of convergence [*Jarrard*, 1986]. Cascadia also has a number of both onshore and offshore strike-slip faults, but many of these lie within the subducting plate [*Goldfinger et al.*, 1997] and may or may not be a direct result of strain partitioning. From Japan and Sumatra to Hispaniola and Chile, geohazards of oblique subduction zones therefore include both dip-slip megathrust events with potential, associated tsunami generation and strike-slip "fore-arc sliver" earthquakes.

[4] Most studies of strain partitioning focus on strike-slip faults near or beneath the volcanic arc, but some margin-parallel motion may occur offshore as well. The West Andaman and Mentawi Fault systems offshore northern and central Sumatra are thought accommodate a significant amount of dextral transform motion [*Malod and Kemal*, 1996; *Samuel and Harbury*, 1996]. Strike-slip faults extend offshore from Hispaniola and many of the observed transform faults along the Cascadia margin are in the submarine fore arc. Perhaps strike-slip faults caused by strain partitioning in oblique subduction zones can nucleate offshore, in the fore arc, as well as along the volcanic arc.

[5] In this study, we focus on the Nankai Trough subduction zone, probably the most studied subduction zone in the world [e.g., *Bangs et al.*, 2004; *Gulick et al.*, 2004; *Kinoshita et al.*, 2009; *Mikada et al.*, 2005; *Moore et al.*, 2007; *Park et al.*, 2002; *Taira et al.*, 1992]. Along this margin, the convergence vector between the Philippine Sea Plate and the Eurasian Plate is ~15° from perpendicular to the trench [*Seno et al.*, 1993], but despite this minimal obliquity evidence of strain partitioning is still apparent. Japan's Median Tectonic Line is located along the center of the volcanic arc and exhibits right-lateral motion, consistent with the margin parallel component of strain [*Tabai et al.*, 2002], while a subduction megathrust (in combination with the associated megasplay fault) accommodates margin perpendicular strain along the plate boundary [*Moore et al.*, 2007; *Nishimura and Hashimoto*, 2006; *Park et al.*, 2002]. Historically, earthquakes on both the strike-slip faults (e.g., Kobe 1995) and the subduction megathrust (1944 and 1946 M~8.0 tsunamigenic events) have caused significant damage [*Dunbar*, 2008].

[6] In an effort to further understand the mechanics and spatial distribution of strain in the Nankai Trough, we have utilized a three-dimensional, multichannel seismic reflection volume acquired

over the Nankai Trough accretionary prism, which images a trench-parallel, linear depression (a "notch") along the edge of the fore-arc basin [*Moore et al.*, 2009]. If this notch is a structural feature, its strike may make it a candidate for strain partitioning. Our study concentrates on this notch feature in an effort to determine the degree to which strain partitioning may be involved in its formation and the implications for localization of strike-slip faults adjacent to fore-arc basins in oblique subduction settings. We also discuss the implications of a structure between the fore-arc Kumano Basin and the fore-arc slope for studies of the local stress field.

2. Nankai Trough Tectonic Setting

[7] In the Nankai Trough, the Philippine Sea Plate is subducting beneath the Eurasian Plate at ~4 cm/yr [*Seno et al.*, 1993] with a convergence vector ~15° from perpendicular. Convergence obliquity varies with local changes in the strike of the trench, which are fairly common. To the northeast, where the Izu-Bonin arc enters the subduction zone, the trench axis deflects to the north and a complex system of thrusts and dextral strike-slip faults have been observed [*Huchon et al.*, 1998; *Tokuyama et al.*, 1999]. To the southwest, the trench axis bends gradually toward the south, decreasing the obliquity of convergence offshore Kyushu.

[8] Seismic surveys imaging the portion of the margin off the Kii Peninsula show a strong set of reflections branching upward from the main megathrust ~50 km landward of the trench, which is interpreted as a splay of this fault [*Moore et al.*, 2007; *Park et al.*, 2002]. Along with several other less reflective thrust splays, this megasplay cross-cuts older faults interpreted to be part of the imbricate thrusting sequence and is therefore an out-of-sequence thrust (OOST). Inversion of tsunami waveforms caused by the 1944 M~8.1 Tonankai seismic event, which ruptured the megathrust beneath the fore-arc Kumano Basin, indicates that slip could have occurred on the megasplay fault instead of the plate boundary during this event [*Baba et al.*, 2006]. Seismic slip on a splay fault (steeper than the décollement) could have implications for the magnitude of tsunami generation in seismic events [*Moore et al.*, 2007].

[9] Above this imaged megasplay fault system, bathymetric measurements off the Kii Peninsula in the Nankai Trough show a trench-parallel, linear bathymetric low (a "notch") on the seaward edge of the fore-arc Kumano Basin. This notch varies in relief and width but extends along strike nearly 100 km (Figure 1). This location places the notch feature in the hanging wall of the uppermost mapped fault of the megasplay fault system, just landward of the surface expression of this uppermost fault and almost directly on the slope break.

3. Data

[10] The Nankai accretionary prism, the fore-arc Kumano Basin and the subducting Philippine Sea Plate are imaged in a 12 km wide, 56 km long, three-dimensional (3-D) seismic reflection volume acquired offshore the southeastern Kii Peninsula, Japan [*Moore et al.*, 2009]. These data were acquired using a commercial seismic vessel towing two air gun source arrays (totaling 3090 cu in) and four 4.5 km long hydrophone streamers. The recorded sonic wavefield data were processed using a 3-D prestack time migration, and later a prestack depth migration was performed which more clearly imaged details of faults and small-scale structures [*Uraki et al.*, 2009].

[11] The vertical resolution of the resultant data set is 5–7 m at the seafloor, 10–20 m at depths near 1400 m (~580 ms) and ranges down to ~100 m near the oceanic crust [*Moore et al.*, 2009]. The well-imaged area beneath the observed notch feature is relatively shallow, corresponding to vertical resolutions between 5 and 20 m. We utilize both the time and depth sections in this study, as some features are more distinct in each.

[12] This data volume is an integral part of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE), the goal of which is to investigate subduction fault mechanics and seismogenesis [*Ashi et al.*, 2007; *Kinoshita et al.*, 2007]. This integrated imaging, drilling, and monitoring initiative will utilize multiple platforms and expeditions to combine in situ measurements, sampling and long-term monitoring of several faults within the Nankai Trough subduction complex. *Moore et al.* [2007] have mapped the megasplay fault system using these same data, as well as a number of 2-D seismic lines. Our study utilizes both the 3-D seismic data below the notch area and interpretations of megasplay fault geometry performed pre-

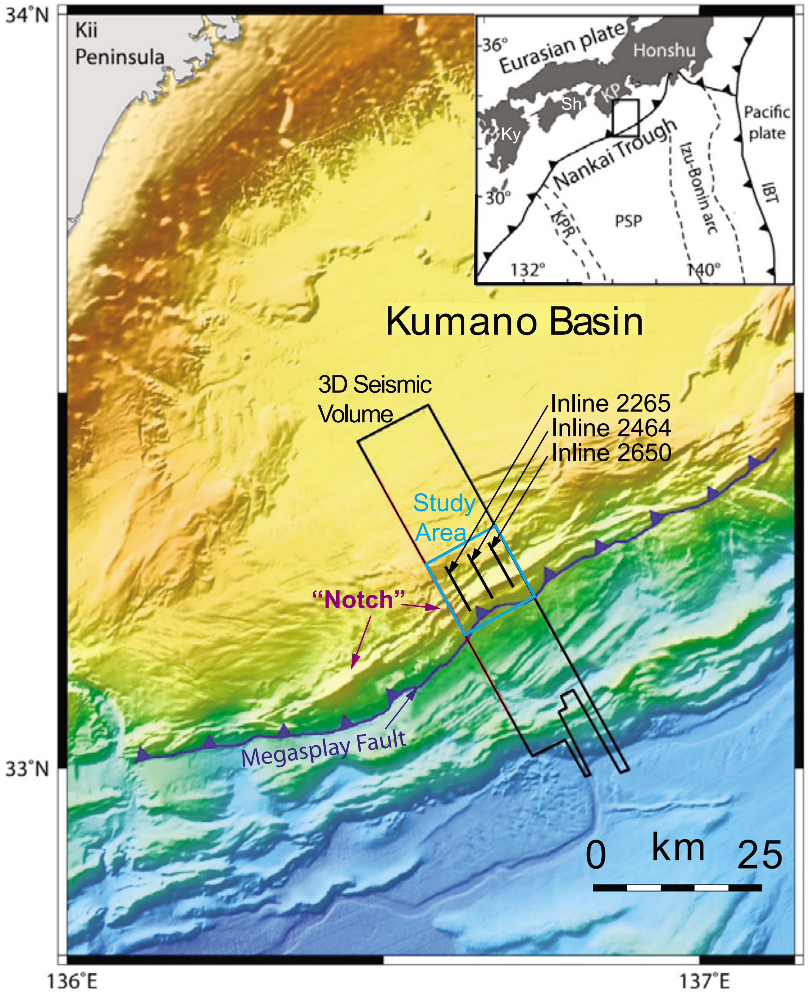

Figure 1. Bathymetry of the Nankai Trough, showing the location of the 3-D seismic survey and previously interpreted faults. The notch feature discussed in this paper crosses near the center of the 3-D survey area, striking NE–SW. The portion of the feature imaged by the 3-D seismic data set is 750 m deep and 3 km across in the northeast and splits to the southwest into several parallel ~250 m deep depressions across a zone of deformation approximately 5 km wide. The deepest part of this feature (~1.2 km deep) is found northeast of the study area. The convergence direction between the Philippine Sea Plate and the Eurasian plate is shown at the bottom right [*Seno et al.*, 1993]. Inset shows the regional setting of the Nankai Trough. PSP, Philippine Sea Plate; KPR, Kyushu-Palau Ridge; IBT, Izu-Bonin Trench; KP, Kii Peninsula; Sh, Shikoku Island; Ky, Kyushu Island. (Modified from *Moore et al.* [2007].)

viously [*Bangs et al.*, 2009; *Moore et al.*, 2007; *Pangborn*, 2007].

4. Methods

[13] In this study we performed interpretations of the 3-D seismic data in the vicinity of the notch. Our interpretation of these faults included both mapping and classification components. For the mapping portion, we interpreted the laterally extensive faults below the notch (Figures 2 and 3), as well as the edges of the sediment packages found in the southwest portion of the study area. Given the complexity of the structure, the mapping study was only possible due to the horizontal (along strike) resolution of the 3-D data. Faults often could only be conclusively differentiated from noise or artifacts by considering continuity and similarity of seismic character across multiple inlines.

[14] Our classification focused on determining whether the mapped features are transform, normal or thrust faults. Bases for classification included direction and amount of seafloor offset, dip angle and variations in dip angle, relationship(s) to other features and continuity of characteristics. We sug-

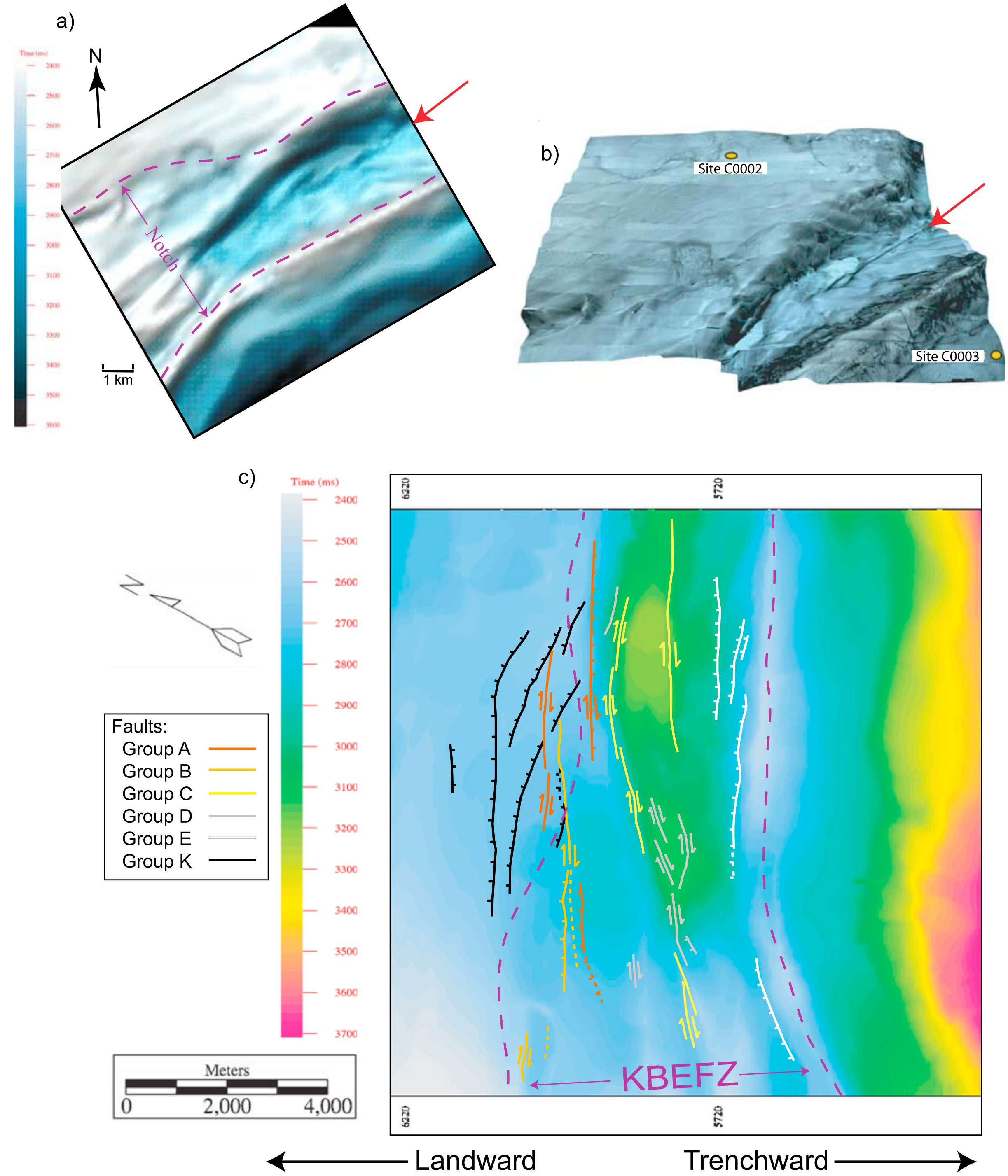

Figure 2. (a) Bathymetric map generated from the seafloor reflection picked in the 3-D seismic data. The notch is deep and narrow to the northeast and shallower and wider to the southwest. Note the linear feature in the right-hand (NE) portion of the depression (arrow). This feature, more evident in the side-scan sonar image in Figure 2b, corresponds to the central fault mapped below the northeastern notch (see Figure 3). (b) Side-scan sonar image draped over bathymetry, collected by deep tow side-scan sonar Wadatsumi over the fore-arc Kumano Basin and fore-arc slope [*Ashi et al.*, 2007]. Yellow dots indicate proposed NanTroSEIZE sites which have now been drilled (IODP sites C0002 and C0003). (c) Bathymetric map showing mapped fault locations. Faults which appear to be transform in nature are shown with an offset direction based on convergence direction. Based on the correspondence between faults and bathymetric features, we introduce the idea that the notch is the surface expression of a Kumano Basin Edge Fault Zone (KBEFZ).

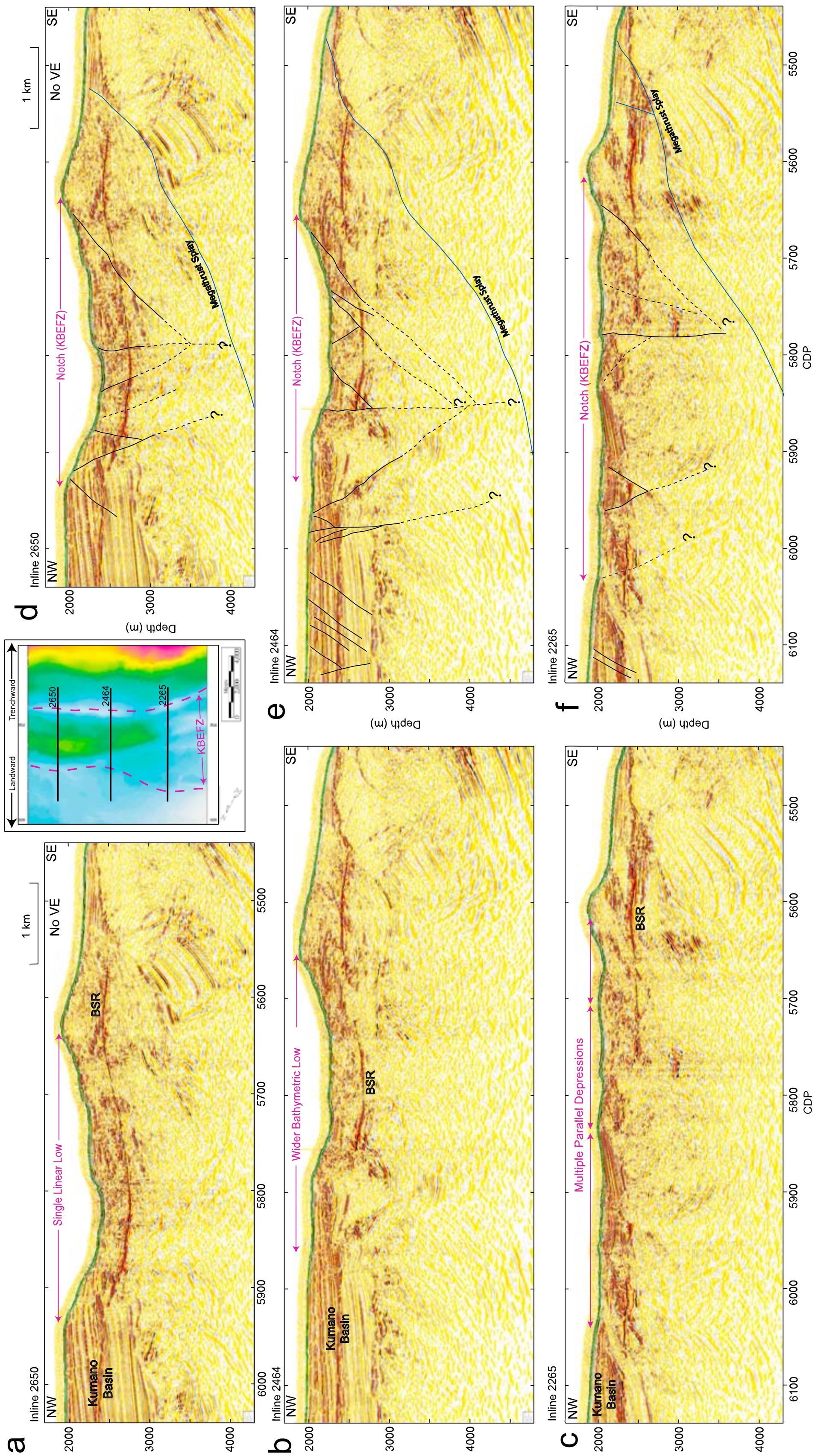
a
b
c
d
e
f
Inline 2650
Inline 2464
Inline 2265
NW
SE
1 km
No VE
Depth (m)
2000
3000
4000
CDP
6100
6000
5900
5800
5700
5600
5500
Kumano Basin
BSR
Single Linear Low
Wider Bathymetric Low
Multiple Parallel Depressions
Notch (KBEFZ)
Megathrust Splay
?
Landward
Trenchward
2650
2464
2265
KBEFZ

Figure 3

gest that faults which display a lack of continuity or highly variable characteristics such as reflectivity and dip angle are unlikely to play a major role in the deformational history of the notch. We consider continuous along strike faults with consistent characteristics for their regional significance.

[15] Examination of the data shows a lack of continuous or uniquely identifiable sedimentary packages within the notch (Figure 3), which made determination of fault offset difficult. Dipping faults (between 40 and 70°) that reach the seafloor show normal offset with the downthrown side most often oriented toward the center of the notch. Therefore we make the assumption based on degree of dip, this offset and the existence of a significant bathymetric low (0.75 deep in our study area to 1.2 km deep moving northeast along strike) that these dipping faults are primarily extensional. In contrast, features that are primarily vertical (dipping 85 to 90°) or exhibit changes in vergence along strike, we interpret to be dominantly translational. Faults that dip toward an apparently transform feature may be elements of a flower structure.

[16] We find no conclusive evidence of reverse offsets on mapped dipping faults. Without coherent reflectors to correlate across the faults, we rely mostly on seafloor offset and fault dip for our classification of fault motion. The faults with the clearest surface traces are generally vertical or exhibit changes in vergence along strike, precluding a purely reverse sense of motion. However, a component of compression or extension on primarily translational faults is possible.

5. Observations

[17] Within the seismic reflection volume, the shape of the notch varies along strike, from a single, steep-walled, ~3 km wide and ~0.75 km deep depression in the northeast to a broader, ~5 km wide zone with several shallower linear bathymetric lows in the southwest (Figure 2). A linear, trench-parallel depression of this magnitude between the slope of the accretionary wedge and the fore-arc basin is seemingly unique. The Bottom Simulating Reflector (BSR) is strong throughout most of the study area but has distinct gaps beneath steep seafloor slope breaks, such as the landward (northwestern) edge of the notch. Interpretation below 2000 m subseafloor is hampered by poor imaging due to the trough-like topography, strong BSR and likely associated gas deposits, and structural complexities from extensive deformation and fracturing. The splay fault geometry in this poorly imaged zone is inferred from the updip and downdip mapping [*Bangs et al.*, 2009; *Moore et al.*, 2007].

[18] Faults within the Kumano Basin (Table 1 and Figure 2, group K) generally strike in two directions, ~90° and ~60° east of north, with a few faults bending from one orientation to the other (S. P. S. Gulick et al., Uplift history of the outer Kumano forearc basin: Implications for splay fault development, submitted to *Geology*, 2009). These faults typically dip 55–60° to the northwest in the portion of the basin nearest the notch. A couple of faults with the more northerly orientation dip to the southeast at an angle near 80°, steeper than their northwest dipping counterparts. To the southeast, near the bathymetric notch discussed in this paper, we find two faults (group A) striking at 60–65° east of north, which dip southeast at a similar angle of 75–80°. Group A faults appear similar in dip and normal offset to the southeast dipping Kumano Basin faults, but offset amount varies along strike or is unclear due to disruption of sediments.

[19] Several packages of sediments within the southwestern notch resemble basin sediments in apparent brightness and seismic contrast. Between

Figure 3. (a–c) Cross sections (in depth) of the notch and (d–f) corresponding interpretations. Sections are displayed with no vertical exaggeration. The notch feature is a linear bathymetric low along the edge of the fore-arc Kumano Basin and in the hanging wall of the uppermost branch of the megasplay fault system [*Moore et al.*, 2007]. A bottom-simulating reflector (BSR) is evident in most of the study area. Figures 3a and 3d show northeast inline (2650): The notch is narrow (~3 km wide and ~0.75 km deep) with basin sediments truncated by faults bounding the bathymetric low. Faults are mostly steep and occasionally vertical or sinuous, indicating a possible strike-slip nature. The vertical fault at center corresponds to a linear feature in the bathymetry (Figure 2). Figures 3b and 3e show central inline (2464): The coherent basin sediments begin stepping to the northwest. Steep faulting along the edge of the basin is more laterally continuous than that in the center of the notch. The megathrust splay is deeper here than in the northeast. Figures 3c and 3f show southwest inline (2265), characterized by distinct blocks of sediment where the basin boundary continues to retreat northwest. These sediment blocks may be remnants of basin packages disrupted by faulting. The bathymetric low is wider than that in the northeast and encompasses several shallow depressions. The geometry of the megathrust splay is similar to that in the central part of the study area, placing it deeper than in the northeast.

Table 1. Mapped Faults Classified by Dip and Apparent Offset Where Possible[a]

Group	Fault	Strike	Dip	Fault Type	Description
A	A1	66	−78 to −81	SS/N	Consistent strike and dip with evidence for transform motion.
	A2	64	−81	SS/N	
	A3	62	−76	SS/N	
	A4	40 to 58	83	SS/N	
B	B1	60	−68 to 90	SS/N	Variation in dip along strike, bound basin or coherent sediment packages.
	B2	62	63	SS/N	
	B3	68	90	SS	
	B4	66	variable	SS	
C	C1	63	−67 to 90	SS	Near vertical. Some switch vergence along strike.
	C2a	70	~80	SS	
	C2b	58	86	SS	
	C2c	48	80 to 90	SS	
	C3	41	90	SS	
	C4	52	~90	SS	
D	D1	42	~90	SS	Shorter faults with fewer clear indications of offset direction. Most bend in both strike and dip.
	D2	39	variable	SS/N	
	D3	44 to 72	variable	?	
	D4	38 to 55	67 to 90	SS/N	
	D5	34	−56	N?	
	D6	63	80	SS	
	D7a	63	variable	?	
	D7b	63	~90	SS	
E	E1	61	~50	N	Normal faults beneath seaward slope, dip NW.
	E2	70	58	N	
	E3a	65	43	N	
	E3b	65	43	N	
	E4	40	49	N	
	E5	76	46	N	
K	K1a	62	66	N	Normal faults within the Kumano Basin. Only K6 dips SE.
	K1b	75	54	N	
	K2a	88	55	N	
	K2b	68	52	N	
	K3	85	53	N	
	K4	85	57	N	
	K5a	91	58	N	
	K5b	61	59	N	
	K6	61	−79	N	

[a] SS, strike slip; N, normal; SS/N, transtensional.

these packages the sediments appear disrupted, with no parallel layering and few continuous reflectors. Along the northwest edge of the notch feature, several faults bound the edge of the basin sediments as well as these sediment packages. These faults (group B) exhibit more changes in dip along strike than the faults of group A, as well as some vertical sections. The consistent difference in apparent sediment coherence across group B faults could indicate out-of-plane motion along these faults.

[20] Within the depression itself, we have mapped several faults (group C) which are generally vertical and sometimes sinuous in depth. Group C faults, while all similar in dip, vary in strike from 42 to 70° east of north. The best example of this group is fault C1, which is also visible in the side scan sonar and seafloor bathymetry maps (Figure 2). This fault strikes at 60° and is near vertical, but rolls over along strike, dipping to the northwest on the northeastern end and the southeast on the southwestern end. Such geometric variation on an active fault can only occur when the sense of motion is translational.

[21] Faults which are difficult to categorize make up group D, which are all beneath the bathymetric depression, mostly toward the center. Several of these faults have variable dips (60–90°) and several bend 30 to 40° in strike direction. Within the group, strikes vary from 35 to 110° east of north. Change

in dip associated with a change in strike indicates a compound fault type. The nature of the surrounding faults and the associated seafloor low makes transtension more likely than transpression.

[22] The seaward side of the bathymetric depression is smoother and more consistent than the landward side in both strike and dip. Beneath this slope and in many places defining this slope are a number of normal faults (group E). These faults dip between 43 and 57° to the northwest, shallower than the dips of the normal faults within the Kumano Basin. Horizontal and subhorizontal reflectors indicate more coherent sediment packages beneath this slope than beneath the central notch or the landward slope. However, these packages are not distinctive enough to determine explicit offset amounts across any of the group E faults.

6. Interpretations

[23] From our detailed interpretation of the shallow notch area, we find a number of faults with varying dips and lateral extents. These faults are distinct from the suite of normal faults found in the Kumano Basin sediments to the northwest (Gulick et al., submitted manuscript, 2009); most faults below the notch dip more steeply and are notably more variable along strike than the extensional faults which formed in the basin. Fault strikes associated with the depression are consistently more northerly than those of the basin faults. This area is therefore considered to be a distinct zone of faulting along the edge of the fore-arc basin, which we refer to as the Kumano Basin Edge Fault Zone (KBEFZ [*Moore et al.*, 2009]).

[24] Faults below the central axis at the bottom of the bathymetric notch are near vertical and sometimes sinuous or upwardly splayed when viewed in cross section (Figure 3). Therefore these faults probably have a significant translational component of motion. Off-axis faults often dip toward the central axis, but some of these faults show no definitive indication of the sense of slip.

[25] The northeast portion of the study area (Figures 3a and 3d), where the KBEFZ is narrow and basin sediments are truncated by faults bounding the bathymetric low, exhibits the clearest structure. These faults are mostly steep (dipping greater than 60°) and dip toward a vertical fault at the center of the depression, indicating possible strike-slip deformation. The vertical fault at the center of this possible flower structure, corresponds to a linear feature noted in side scan sonar data (Figure 2b) [*Ashi et al.*, 2007] and visible in the bathymetry (Figures 2a and 2c), reinforcing the interpretation of strike-slip deformation. The two outermost splays of this possible flower structure correspond to the sloped walls of the notch.

[26] The central and southwest portions of the study area exhibit more complexities, as the bathymetric low broadens and splits into several parallel depressions (Figures 3c and 3f). Shallow, vertical faults are still evident, but are less continuous and not as linear along strike. Shallow packages of sediments, similar in seismic reflection character to those of the adjacent Kumano Basin, are found to the northwest, between several of these faults.

7. Discussion

[27] Several origins are feasible for a shelf edge bathymetric low like the notch, including submarine channel incision, surface expression of underlying splay fault geometry, and partitioned margin-parallel strain. Each of these processes would lead to different bathymetric signatures and patterns of subsurface deformation, potentially including gravitational normal faults, fault bend folds and translational faulting. Submarine channel incision is unlikely as an independent cause because of the notch feature's rough bathymetry, size of the depression, and lack of channel fill through most of our data set. The correspondence of bathymetric features to subsurface faults instead indicates a structural control. We believe the observed bathymetric notch is most likely the surface expression of KBEFZ. What then controls the formation of the KBEFZ and how important is this fault zone in the mechanics of the system as a whole?

[28] We consider first the possibility that the KBEFZ is simply a system of gravitationally driven faults due to bathymetry. In deepwater anticlines, swarms of normal faults on the scale of 100s of meters have been observed and attributed to gravitational collapse on the flanks of bathymetric highs created by the anticlines [*Morley*, 2007]. However, this mechanism would require the creation of a significant bathymetric low on the edge of the Kumano Basin through some means independent of the normal faulting. We find no evidence of coherent anticlinal folding in the sediments beneath either side of the notch. Nor is there evidence of uplift along the entire edge of the basin independent of the splay fault which daylights farther

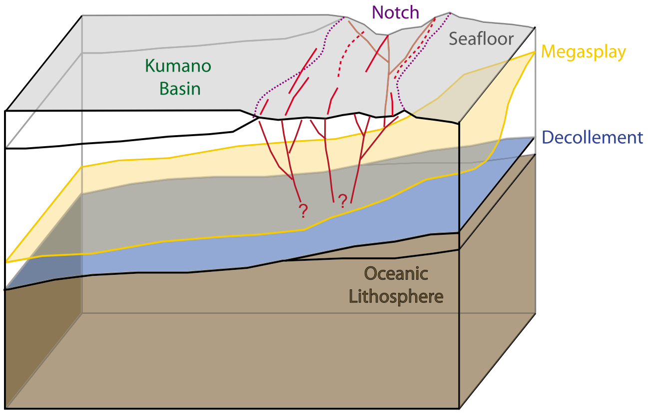

Figure 4. Block diagram of KBEFZ ("notch") and surroundings. Note the corkscrew geometry of the megasplay fault, which twists up to the northeast within the 3-D seismic data set.

seaward. Movement along the splay fault would cause uplift in the entire area, not a narrow ridge and trough. A stronger case can be made for the normal faults that we have mapped being the structural cause of the notch feature rather than a result of it. Also, the mechanism of gravitational normal faulting cannot explain the occurrence of vertical faults at the center of the bathymetric low. These faults are instead consistent with transform motion across our entire study area.

7.1. Effect of Underlying Splay Fault

[29] The angle of the megasplay fault varies both along strike and downdip. *Pangborn* [2007] has mapped the uppermost fault segment within the splay fault system beneath our study area. Both this splay and the ones beneath it [*Moore et al.*, 2007] exhibit a corkscrew geometry, twisting down to the southwest as they diverge from one another (Figure 4). Thrusting along this spiraling fault during coseismic or interseismic shortening would cause greater uplift to the northeast and relatively less to the southwest, skewing the hanging wall(s) of the fault(s). The faults of the megasplay system all converge to a relatively flat décollement at depth [*Pangborn*, 2007], and therefore significant differential motion along strike should be limited to the seaward portion of the splays themselves. This geometry could create a left or right lateral sense of motion somewhere in the overriding sediments. Normal faulting and deformation as well as slumping oblique to the trench-axis direction are possible.

[30] Fault bend folding associated with changes in underlying fault dip with depth could cause a trench-parallel depression, but would not account for the steepness of the sidewalls without much sharper bends in the underlying splay fault. Along-strike variations in the fault bends (such as the "lateral ramp" observed by *Moore et al.* [2007]) could cause local strike-slip features on a scale similar to the wavelength of the variations. However, this wavelength is only about 8 km within the region imaged by the 3-D seismic data set, while the bathymetric notch extends laterally over 100 km at a consistent strike near 235°. We therefore conclude that the linear depression is too extensive to have been caused by variations in the geometry of the underlying splay fault.

[31] While another cause must be found for the notch as a whole, the changes in splay fault geometry on a ~10 km scale may explain similar wavelength variations in the geometry of the notch or complexities in the KBEFZ. The depression extends over 100 km with a consistent strike, but its depth and width are somewhat variable. The portion of the feature imaged by the 3-D seismic data set is 750 m deep and 3 km across in the northeast and splits to the southwest into several parallel ~250 m deep depressions across a zone of deformation approximately 5 km wide. The steepening of the splay fault to the northeast of the imaged section may contribute to the narrowing and deepening of the depression as the fault bend flexes the overlying sediments. Proof or disproof of this contribution is hampered by the lack of deformation rate information available in the seismic data and the disruption of the sedimentary sequences, which makes offset distances impossible to measure.

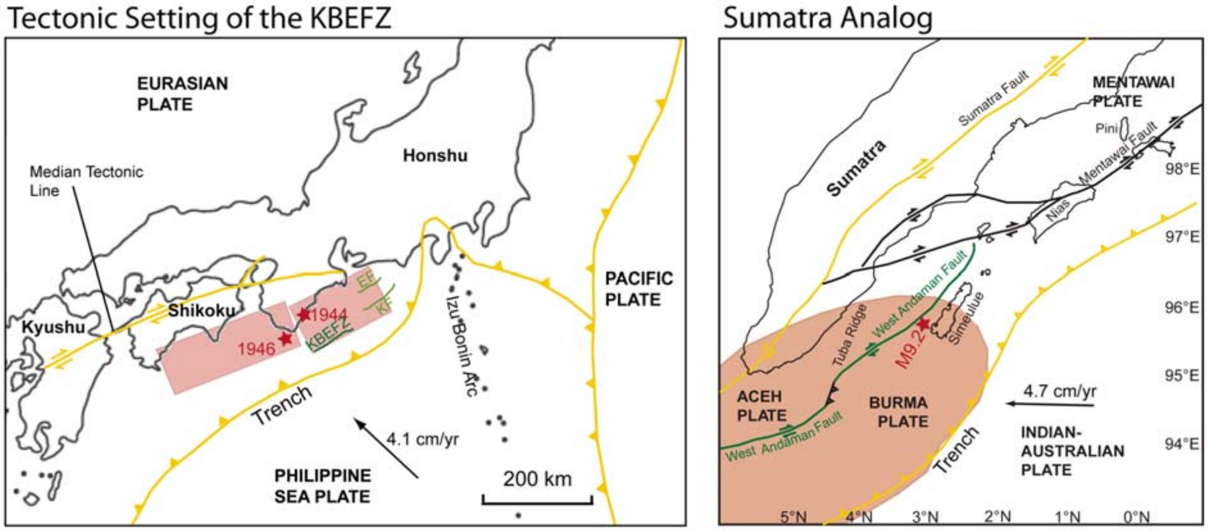

Figure 5. Tectonic setting comparison between Nankai and Sumatra. Major earthquake epicenters and approximate rupture areas are in red. In Sumatra (diagram modified from *Mosher et al.* [2008]), strike-slip faults are found within the volcanic arc (the Sumatra Fault) and along the seaward edge of the fore-arc basins (West Andaman and Mentawi faults). Oblique convergence along the margin is partitioned between these strike-slip faults and the megathrust. In Japan, the Median Tectonic Line (MTL) is a strike-slip fault within the volcanic arc, and the KBEFZ is a strike-slip fault along the seaward edge of the fore-arc basin. The Enshu and Kodaiba faults (EF and KF, respectively) are the main strike-slip faults to the northeast associated with subduction of the Izu-Bonin ridge. Oblique strain is known to be partitioned between the MTL and the megasplay fault system. Could the KBEFZ be further evidence of partitioned strain localizing in the fore arc?

7.2. Strain Partitioning

[32] The oblique convergence direction, the existence of a major strike-slip fault beneath the arc and the orientation of the KBEFZ parallel to the trench all support the hypothesis of strain partitioning. The location of this potentially structural feature along the seaward edge of the fore-arc basin is reminiscent of the locations of the Andaman and Mentawi faults (Figure 5), although the distance from the trench is only ~30 km instead of 100–200 km as in the case of the strike-slip faults off Sumatra [*Mosher et al.*, 2008]. The Sumatra subduction zone is the type example of strain partitioning in an obliquely convergent setting [*Fitch*, 1972]. Near the island of Sumatra, a convergence vector that ranges between 60 and 87° from perpendicular is accommodated by normal convergence on the megathrust of ~45 mm/yr and right lateral strike-slip along the Sumatra fault of 11–48 mm/yr [*McCaffrey et al.*, 2000; *Subarya et al.*, 2006]. Significant motion along the trench-parallel, strike-slip Sumatra fault and earthquake slip vectors perpendicular to the trench on the main subduction thrust, are both necessary to accommodate the oblique convergence of the Indian and Eurasian plates. The original model by *Fitch* [1972] called for complete partitioning of trench-parallel and trench-perpendicular strain into separate discrete faults. Subsequent studies along other margins [*McCaffrey*, 1993] suggest that a different partitioned strain regime is possible, in which trench-parallel motion is accommodated by distributed deformation within the fore arc instead of by a single strike-slip fault.

[33] Other major, margin-parallel fault systems are apparent within the Sumatra margin, namely the offshore Andaman and Mentawi systems [*Malod and Kemal*, 1996; *Samuel and Harbury*, 1996]. These faults occur closer to the deformation front, just seaward of a series of fore-arc basins, but are still landward of most subduction-related compressional features that produce seafloor topography [*Henstock et al.*, 2006]. Recent high-resolution seismic reflection data found near-vertical and undulating fault strands on the seaward edge of the Aceh basin, believed to be strands of the West Andaman fault system [*Mosher et al.*, 2008]. This observation combined with the geometry of Tuba Ridge, believed to be a pop-up structure, suggest that the West Andaman fault is a right-lateral strike-slip fault with a restraining bend at Tuba Ridge. While the nature of the Mentawi fault system farther south is debated [*Diament et al.*, 1992; *Malod and Kemal*, 1996], high-resolution seismic

data over that area might also suggest strike-slip motion. The existence of both onshore and offshore strike-slip faults implies a more complex system of strain partitioning, where trench-parallel motion can be accommodated in multiple localities within the fore arc. Distribution of trench-parallel deformation between several faults both within the fore arc and near the arc itself would suggest a regime between the two theoretical end-members of purely localized and entirely diffuse strain partitioning.

[34] Considering the convergence vector in Nankai, the trench-parallel component of motion should be right-lateral. Motion along the Median Tectonic Line is known to be right lateral [*Nishimura and Hashimoto*, 2006], consistent with partitioning of the strain caused by the obliquity of convergence (Figure 5). If the KBEFZ is also a right-lateral transform system, it must accommodate some portion of the trench-parallel motion on the margin.

[35] The disruption of sediments in the KBEFZ makes direct observation of offset along most of the faults impossible. Instead we must look to the overall geometry of the feature, which makes a slight bend within the bounds of the data volume. To the southwest, the mapped faults and the axis of the bathymetric low strike ~10° more northerly then those observed in the northeastern portion of the seismic data set. Northeast of the study area, the notch feature broadens and a single axis is difficult to trace. Right-lateral motion parallel to the southern portion of the KBEFZ would make this bend to the east a releasing bend, explaining our observed increase in extension and prevalence of normal faulting to the northeast.

7.3. Implications

[36] The existence of partitioned strain in the Nankai margin is not an altogether unique idea. The collision of the Izu Bonin arc with the subduction zone in the Tokai area results in a complex system of both thrust and strike-slip faults throughout the area [*Huchon et al.*, 1998]. Convergence is distributed seaward as well as landward of the trough, implying overall deformation of the down going Philippine Sea Plate. The shear complexity of this region makes it difficult to differentiate strain due to strain partitioning from strain caused by the effects of arc collision. Faults with potential translational components found in eastern Nankai generally die out around 33° 30′. The KBEFZ to the southwest, in contrast, provides an example of a single translational fault complex along a more laterally consistent portion of the trench without the added intricacy of faulting associated with an arc collision.

[37] The potential strain partitioning we observe along the edge of the fore-arc Kumano Basin, is on a much smaller scale than the strain partitioning observed on the Sumatran margin with its greater obliquity. The observed notch feature exhibits greater symmetry in bathymetric relief than the surface expression of the Andaman and/or Mentawi faults. Laterally, the KBEFZ does not extend as far as the Andaman or Mentawi fault systems, implying a smaller-scale instance of strain partitioning than previously observed. Southwest of our study area the trench bends immediately to the west and then gradually to the south as it passes Shikoku and Kyushu. A number of studies [*Bangs et al.*, 2006; *Gulick et al.*, 2004] off these islands, including one 3-D seismic survey off the Muroto Peninsula on the same scale as our data, show no indication of strike-slip features. We believe the change in trench strike along this portion of the margin has decreased the obliquity to the point such structures are not required.

[38] We suggest location of the KBEFZ in the hanging wall of the megathrust splay system in Nankai also likely precludes this strike-slip fault from extending to depths similar to those suggested for the Andaman and Mentawi faults [*Malod and Kemal*, 1996; *Mosher et al.*, 2008]. The interaction of the megasplay and the KBEFZ is not well imaged in our data due to problems with resolution at depth below the notch bathymetric feature. If the strike-slip fault(s) cut the megasplay, we could cast doubt on the role of the megasplay in recent seismogenic events. However, given the low magnitude of obliquity, overall translational motion expressed on the KBEFZ and Median Tectonic Line should be dramatically less than the associated compressional motion expressed on the megathrust and megasplay fault. Between this consideration and the scale of the megasplay, which extends to the décollement at depth and covers more of the margin along strike than the KBEFZ, we find it likely that the megasplay accommodates more total motion than the KBEFZ. Therefore our mapped faults probable either sole into or are cut by the megasplay at depth.

[39] The mechanics of strain partitioning in subduction settings are not fully understood. Localization of different components of strain may be the result of variations in coupling between the dipping oceanic slab and the upper plate lithosphere [*Jarrard*, 1986; *Malod and Kemal*, 1996; *Manaker*

et al., 2008]. Alternatively, variations in material properties within the accretionary prism have been suggested to constrain the updip extent of a seismogenic zone [*Fuller et al.*, 2006; *Wang and Hu*, 2006]. This edge of the seismogenic zone is frequently located at the seaward limit of the fore-arc basins [*Song and Simons*, 2003; *Wells et al.*, 2003], where the rheology of the accretionary wedge transitions to weaker materials. Such a change in rheology could cause shear strain to localize on the edge of relatively strong zones, implying a preferential location of strain partitioning structures along the seaward edge of fore-arc basins. Margin-parallel, strike-slip faults along volcanic arcs are similarly thought to form due to the area's relative crustal weakness, which is caused by thermal softening from the underlying mantle wedge [*Fitch*, 1972].

[40] With a portion of the megathrust or décollement locked, trench-parallel forces may be released on vertical transform faults in particularly weak zones at stress levels below those required to rupture the décollement [*Jarrard*, 1986]. With weaker faults accommodating the trench-parallel shear component of strain, the seismogenic portion of the décollement has only the convergent strain to accommodate. This mechanical idea implies that every seismogenic subduction zone with oblique convergence should exhibit some degree of strain partitioning. Thus, an understanding of the particular distribution of partitioned strain is important to the understanding of subduction zone dynamics and our results show a likely candidate for one localization of this strain is along the seaward edge of fore-arc basins.

[41] IODP Expedition 314 conducted logging-while-drilling operations along a transect within the 3-D seismic data set as part of the NanTroSEIZE project [*Kinoshita et al.*, 2007]. Ongoing analysis of observed fractures and borehole breakouts by members of the science party has constrained the state of stress, which varies markedly on either side of the notch. A distinct change in stress orientation has been noted across the KBEFZ, from the trenchward side which exhibits a maximum principle stress orientation perpendicular to the trench, to the landward side which exhibits a maximum principle stress orientation subparallel to the trench [*Kinoshita et al.*, 2009]. Such a change in stress orientation over only a few kilometers is consistent with crossing a significant fault system. As they are combined with stress states estimated from ongoing core analysis, these changes in stress orientation will become important to models of prism and basin formation. The presence and geometry of the KBEFZ should be considered as a significant constraint in attempts to model the change in stress state between the basin and the prism slope. In particular, the out-of-plane motion indicated by translational movement along the KBEFZ calls for three-dimensional modeling when attempting to explain the change in stress state between drilling sites.

8. Conclusions

[42] The geometry of faulting within the KBEFZ implies a dominantly strike-slip deformation regime. Based on an apparent releasing bend, we believe the sense of motion to be right lateral, which is consistent with the direction of obliquity of motion on the margin as a whole and implies that the KBEFZ is accommodating one component of the total strain. Localization of partitioned margin-parallel strain is therefore observed in two places within the Nankai margin: the KBEFZ and the Median Tectonic Line.

[43] The evidence for strain partitioning seaward of the fore-arc basin in the Kii Peninsula region of Japan as well as previously reported case of Sumatra implies that localization of strike-slip deformation within the fore arc is likely to occur in other oblique margins as well. Extreme obliquity, as observed in Sumatra, is apparently not required to create multiple localities of localized, margin-parallel strain. In addition, transform faults that accommodate the margin-parallel component of strain may not require a zone of notable weakness (such as that below the arc) to form. Instead, zones of significant contrast in strength or deformation style within the wedge or along the décollement may allow trench-parallel strain to localize. Whether the fore-arc basin is stabilized by wedge strength or décollement properties, it does not deform as extensively internally as the imbricate thrust faulted zones present in outer parts of accretionary prisms. Therefore the strain that could be accommodated diffusely within the span of the basin will instead be localized adjacent to it. Systems created by partitioned strain in convergent margins are thus more complicated than the early models of *Fitch* [1972] and *Jarrard* [1986], with the possibility of several transform faults and shear zones within a single margin that collectively accommodate the margin-parallel component of partitioned strain.

[44] In addition, the existence of a strike-slip feature along the edge of the fore-arc basin is important for understanding and contextualizing ongoing work in the Nankai subduction zone. The observed stress states in the NanTroSEIZE boreholes give an idea of how the stress field may vary along dip in a convergent margin. Modeling these changes in stress could lead to a better understanding of the changes in rheology and fault frictional properties along dip within both the Nankai region and subduction zones in general. However, attempts to explain the observed stress field changes between the Kumano Basin and the fore-arc slope should take into account the presence of the Kumano Basin Edge Fault Zone.

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