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Asymmetric deformation in the backarc region of the Kuril arc, northwest Pacific: New insights from analogue modeling

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[1] The Eocene to middle/late Miocene tectonic evolution of the Kuril arc and backarc region has been simulated with analogue experiments. The experiments simulate asymmetric deformation in the overriding plate due to anticlockwise rollback of the subducting Pacific plate. The results show the formation of a N-S to NE-SW-oriented dextral shear zone near the far edge of the retreating boundary analogous to the Sakhalin-Hokkaido dextral shear zone. Contemporaneously, normal faults and grabens form, striking parallel to the retreating boundary near the far edge but striking more oblique near the hinge point and away from the retreating boundary. This is similar to extensional structures observed in the Kuril Basin and the Sea of Okhotsk. Furthermore, the model shows that the amount of extension progressively decreases away from the retreating boundary. This appears to have also happened in the Kuril-Okhotsk region, as evidenced by crustal thickness variation in the region. Finally, the model results show that extension is increasingly accommodated by the region close to the retreating boundary with progressive deformation. This can account for the Eocene-early Miocene extension in the Sea of Okhotsk followed by Miocene spreading in the Kuril Basin. *INDEX TERMS:* 8122 Tectonophysics: Dynamics, gravity and tectonics; 8109 Tectonophysics: Continental tectonics—extensional (0905); 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8107 Tectonophysics: Continental neotectonics; *KEYWORDS:* Kuril arc, Sea of Okhotsk, backarc basin, subduction, rollback, analogue. **Citation:** Schellart, W. P., M. W. Jessell, and G. S. Lister, Asymmetric deformation in the backarc region of the Kuril arc, northwest Pacific: New insights from analogue modeling, *Tectonics*, *22*(5), 1047, doi:10.1029/2002TC001473, 2003.

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1. Introduction

[2] Backarc basins are enigmatic features on Earth that develop in an overall convergent tectonic framework. Most backarc basins develop by extension, which seems rather contradictory with respect to the overall tectonic setting in which they develop. Examples are numerous in the western Pacific and Mediterranean region and can be found in intra-oceanic subduction settings and along active continental subduction margins. The formation of such backarc basins is often explained by the retreat of the hinge line of the subducting lithosphere (rollback) and collapse and extension of the overriding plate toward the retreating hinge line [*Elsasser*, 1971; *Molnar and Atwater*, 1978; *Garfunkel et al.*, 1986; *Royden*, 1993; *Lonergan and White*, 1997; *Wortel and Spakman*, 2000; *Faccenna et al.*, 2001a]. The physical concept behind the rollback mechanism is explained in terms of negative buoyancy of the subducting slab. The subducting oceanic lithosphere is denser than the asthenosphere because it is colder. Therefore the slab is pulled down by a negative buoyancy force, which results in sinking of the lithosphere, not only in a direction parallel to the slab dip but also perpendicular to it [*Elsasser*, 1971; *Molnar and Atwater*, 1978; *Lonergan and White*, 1997]. The physical validity of this concept has been verified in numerous physical and numerical experiments [*Kincaid and Olson*, 1987; *Christensen*, 1996; *Faccenna et al.*, 1996, 1999; *Becker et al.*, 1999; *Faccenna et al.*, 2001b]. If slab rollback either is a driving agent of backarc extension [*Elsasser*, 1971; *Molnar and Atwater*, 1978; *Le Pichon*, 1982; *Lonergan and White*, 1997] or is passively being pushed back [e.g., *Hatzfeld et al.*, 1997] remains a debate, but most geoscientists seem to favor the former view [*Taylor*, 1995]. Also, experimental insights into this matter indicate that the negative buoyancy of the slab plays a more significant role in rollback than the buoyancy force resulting from potential energy contrast between the overriding plate and the subducting plate in

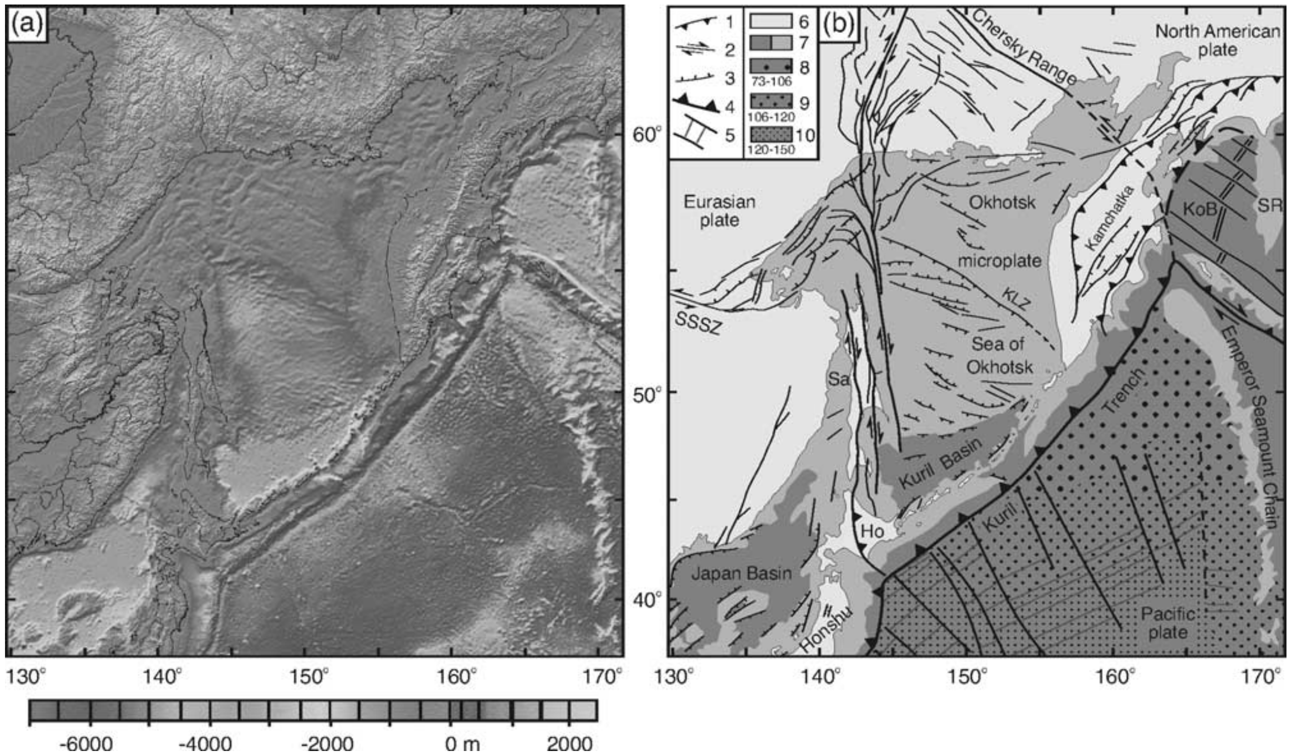

Figure 1. (a) Topographic map of the Kuril Basin, the Sea of Okhotsk, and surrounding areas [from *Smith and Sandwell*, 1997]. (b) Regional tectonic setting of Figure 1a (compiled after *Hilde et al.* [1977], *Gnibidenko and Khvedchuk* [1982], *Jolivet* [1987], *Hochstaedter et al.* [1994], *Worrall et al.* [1996], *Jolivet et al.* [1999], and *Konstantinovskaia* [2001]). For the Pacific plate, three different regions are indicated with different ages (in Ma) (from *Hilde et al.* [1977]). Ho, Hokkaido; KLZ, Kashevarov linear zone; KoB, Komandorsky Basin; Sa, Sakhalin; SR, Shirshov Ridge; SSSZ, Stanovoy sinistral shear zone; 1, reverse/thrust fault; 2, strike-slip fault; 3, normal fault; 4, subduction zone; 5 magnetic anomalies (thin lines) and transform faults (thick lines); 6, land; 7, sea, with basin/ocean floor (left) and continental shelf/morphological high on basin/ocean floor (right); 8–10, oceanic crust of the Pacific plate with age in Ma. See color version of this figure at back of this issue.

ocean-continent subduction (e.g., Hellenic arc, Ryukyu arc, Kuril arc) [*Faccenna et al.*, 1996]. In an ocean-ocean setting, this buoyancy force would be even smaller (e.g., Mariana arc, Tonga arc, New Hebrides arc), pointing to a more prominent role of the negative buoyancy of the slab compared to the excess potential energy of the overriding plate with respect to the subducting plate.

[3] In this paper we discuss the Kuril arc-backarc region (Figure 1), located in the northwest Pacific, and in particular focus on the extensive deformation the region has experienced from the Eocene to the middle/late Miocene. Two popular models that exist for the structural development of the Kuril region are the extrusion tectonics model, where backarc deformation is the result of collision between India and Eurasia [*Worrall et al.*, 1996], and the rollback model, resulting in collapse of the overriding plate toward the retreating hinge line and extension in the backarc region [*Maeda*, 1990]. It has also been suggested that both extrusion tectonics and rollback acted together to result in the deformation observed in the region [*Jolivet et al.*, 1990, 1994, 1999; *Fournier et al.*, 1994]. From these two models it was suggested that the extrusion model is best in explaining the large-scale strike-slip structures observed on the islands of Sakhalin and Hokkaido, while the rollback model is best in explaining the opening up of the Kuril backarc Basin. However, timing of transtensional dextral shearing along the Sakhalin-Hokkaido dextral shear zone exactly coincides with backarc extension in the Sea of Okhotsk [*Worrall et al.*, 1996], which would suggest that the dextral shear zone is also a direct consequence of rollback and not related to extrusion tectonics.

[4] In this work we will present a simple tectonic model, which can explain the primary characteristic features of the region and support this model with results from analogue experiments. In the experiments, deformation of the overriding plate has been modeled during asymmetric anticlockwise hinge line retreat of the subducting lithosphere. Such anticlockwise retreat can be implied to have occurred from paleomagnetic rotation along the Kuril arc and the asymmetric structures observed in the backarc region. These asymmetric structures include the wedge-shaped geometry of the Kuril Basin, the Sakhalin-Hokkaido dextral shear zone bounding the west of the backarc region, and the extensional structures in the Sea of Okhotsk striking at high

angle to the arc. The first-order structural and geometrical patterns in the model are similar to the characteristic features of the Kuril arc-backarc region, supporting the validity of the conceptual tectonic model. The paper is concluded with an evolutionary model of the Kuril arc-backarc region for the past 65 Myr, which has been inspired by the results of the analogue experiments.

2. Geological Setting

[5] The Kuril arc is located at the convergent plate boundary between the overriding Okhotsk microplate in the northwest and the subducting Pacific plate in the southeast (Figure 1). The Okhotsk microplate is further outlined by diffuse intracontinental plate boundaries with the Eurasian plate to the west and the American plate to the northeast. These boundaries are defined by the Sakhalin-Hokkaido dextral shear zone and the Chersky Range sinistral shear zone, respectively [*Savostin et al.*, 1983; *Parfenov et al.*, 1988; *Riegel et al.*, 1993; *Seno et al.*, 1996]. The manifestation of the present tectonic setting, however, was accomplished quite recently (<3 Ma [*Cook et al.*, 1986; *Imaev et al.*, 1990]) and has been preceded by a history of Paleocene to Eocene accretion events and subsequent back-arc deformation. This included the collision and accretion of the Okhotsk block and several arc terranes to the N-S-trending Sikhote-Alin and ENE-WSW trending Okhotsk-Chukotsk-Koryak paleomargins. At present, the accreted arc terranes are exposed on the Kamchatka peninsula and the Southern Siberian margin toward the east. Most of the Okhotsk block is underlying the Sea of Okhotsk and is composed of thinned continental crust [*Gnibidenko and Khvedchuk*, 1982; *Savostin et al.*, 1983; *Gnibidenko et al.*, 1995]. Small parts of the crust are exposed along the east coast of Sakhalin Island [*Rozhdestvenskiy*, 1982; *Fournier et al.*, 1994], the west coast of Kamchatka [*Parfenov et al.*, 1979; *Parfenov and Natal'in*, 1986], and at several sub-aqueous outcrops in the Sea of Okhotsk [*Gnibidenko and Khvedchuk*, 1982]. The crust is of Paleozoic to Mesozoic age and has undergone Mesozoic metamorphism [*Fournier et al.*, 1994; *Gnibidenko et al.*, 1995].

[6] The Okhotsk block has been extended during the Eocene to early Miocene [*Gnibidenko and Khvedchuk*, 1982; *Worrall et al.*, 1996]. The thickness of its crust is up to 25 km beneath the basement rises and 15–20 km beneath the troughs [*Savostin et al.*, 1983]. Most of this extension is located beneath the Central Sea of Okhotsk, which is separated from the less extended Northern Sea of Okhotsk by the Kashevarov linear zone. This zone trends approximately NW-SE and has been interpreted as a south-west dipping normal fault zone [*Jolivet*, 1987]. The southern part of the Sea of Okhotsk is underlain by the wedge-shaped Kuril backarc Basin. This basin has an average depth of ~3300 m [*Maeda*, 1990] and is underlain by oceanic crust [*Gnibidenko and Khvedchuk*, 1982; *Gnibidenko and Svarichevsky*, 1984; *Savostin et al.*, 1983; *Gnibidenko et al.*, 1995] covered by some 3000–4000 m of undeformed sediments [*Gnibidenko and Svarichevsky*, 1984]. Initially, it has been suggested that the Kuril Basin formed during the late Oligocene to early Miocene [*Kimura and Tamaki*, 1986a], based on heat flow, basement depth and sediment thickness. Later, *Maeda* [1990] suggested that the Kuril Basin formed in the middle Miocene between ~17 and 15 Ma, based on the southward migration of the northern terminus of subduction related arc magmatism on the islands of Sakhalin and Hokkaido. Such a fast opening would explain the rather uniform package of tectonically undisturbed sediments overlying the oceanic crust [*Gnibidenko et al.*, 1995]. This would suggest a very high but still realistic opening rate of the basin. With a maximum basin width of ~300 km and a time span of 2 Myr, this results in a maximum opening rate of ~15 cm yr^{-1}. For comparison, the maximum present-day GPS-determined opening rate of the Lau backarc Basin (in its northernmost part) is 16 cm yr^{-1} [*Bevis et al.*, 1995]. Following similar arguments as *Maeda* [1990] but referring to a larger data set, it has been suggested that the basin has opened up from the early Miocene to late Miocene (~23–9 Ma) [*Takeuchi et al.*, 1999, and references therein]. Also, *Ikeda et al.* [2000] suggested that the Kuril Basin continued opening until 7–9 Ma, based on similar aged basaltic rocks from northeast Hokkaido, which have a backarc basin rift-related affinity and have been related to the opening of the Kuril Basin. In any case it is most likely that the Kuril Basin opened up in the Miocene and therefore postdates the extension in the Sea of Okhotsk. The northern and southern margins of the basin are rifted margins with normal faults dipping toward the depression [*Gnibidenko and Svarichevsky*, 1984; *Jolivet*, 1987]. From south along the Kuril arc to north on the Siberian mainland the strike of the normal fault structures in the backarc region gradually changes from approximately southwest to approximately northeast [*Gnibidenko and Khvedchuk*, 1982; *Worrall et al.*, 1996].

[7] The Kuril volcanic arc lies south of the Kuril Basin and is underlain by continental crust [*Gnibidenko and Khvedchuk*, 1982; *Gnibidenko et al.*, 1995]. The basement is at least of Late Cretaceous age, as indicated by the oldest volcanogenic sediments [*Gnibidenko and Khvedchuk*, 1982]. Paleomagnetic data has indicated that the Nemuro Island region, located at the eastern end of Hokkaido in the western part of the Kuril arc, rotated anticlockwise some 29.4° ± 10.4° after the early Eocene [*Tanaka and Uchimura*, 1989].

[8] The Kuril Basin and the Sea of Okhotsk are bounded to the west by a regional system of approximately N-S-trending dextral strike-slip faults (the Sakhalin-Hokkaido dextral shear zone) [*Rozhdestvenskiy*, 1982; *Fournier et al.*, 1994]. These faults formed in the Eocene and are still active [*Worrall et al.*, 1996]. Typical structures associated with the major strike-slip faults in the shear zone are NW-striking thrusts, steep reverse faults, and en echelon folds, as well as a small amount of NE-striking normal faults and grabens filled with Paleogene-Neogene sediments [*Rozhdestvenskiy*, 1982]. All these associated structures point to a dextral sense of shear [*Rozhdestvenskiy*, 1982; *Fournier et al.*, 1994; *Worrall et al.*, 1996]. The shear zone has been described by *Fournier et al.* [1994] as a 2000 km long crustal-scale structure. However, estimates of dextral offset

along the fault zone are in the order of at least 400 km [*Jolivet and Tamaki*, 1992], implying that the structure is most likely of lithospheric scale. Faults belonging to this system are exposed on the islands of Sakhalin and Hokkaido [*Rozhdestvenskiy*, 1982; *Jolivet and Huchon*, 1989; *Jolivet et al.*, 1992; *Fournier et al.*, 1994] and have also been interpreted to continue farther northward to the Siberian mainland. To the south, splays of the shear zone continue west of Honshu bordering the Japan Basin. The shear zone reactivated Late Cretaceous-Paleocene shortening structures of the Sakhalin-Hokkaido accretionary complex, which formed due to collision of the Okhotsk block with the Eurasian active margin [*Rozhdestvensky*, 1986; *Jolivet and Huchon*, 1989; *Fournier et al.*, 1994; *Gnibidenko et al.*, 1995; *Worrall et al.*, 1996]. The dextral shear zone was mainly transtensional from the Eocene to early Miocene and transpressional from the late Miocene to Present [*Worrall et al.*, 1996].

[9] The Kuril arc exhibits two cusps. The northern cusp shows a spatial relationship with the Emperor Seamount Chain located on the subducting Pacific plate [*Vogt*, 1973]. The southern cusp seems to have no relationship with any topographic feature on the subducting plate. However, the southern cusp seems to be linked to the N-S-striking Sakhalin-Hokkaido dextral shear zone located on the overriding plate, where the western part of the shear zone probably extends to the cusp [*Worrall et al.*, 1996].

3. Analogue Models

[10] The scaling theory for analogue modeling of geological and tectonic processes was first described by *Hubbert* [1937] and was later discussed by *Horsfield* [1977], *Davy and Cobbold* [1991], and *Cobbold and Jackson* [1992]. In mechanical modeling, surface forces (stresses) should be properly scaled when compared to body forces (gravity). This implies that when the experiments are executed in a normal field of gravity, stresses should be scaled down as the product of density and length scales down [*Horsfield*, 1977; *Davy and Cobbold*, 1991]. In the experiments described here a scale factor of $\sim 2.5 \times 10^{-7}$ (1 cm in experiment corresponds to ~40 km in nature) and a density factor of ~0.5 have been applied. Thus stresses should be scaled down by $\sim 1.25 \times 10^{-7}$. Both brittle and viscous rheologies were used to simulate the natural behavior of rocks. For brittle rocks, cohesion and friction coefficient are the most important parameters, as described by Coulomb's fracture criterion [*Coulomb*, 1776; *Handin*, 1969]. Since cohesion has the dimensions of Pascal (Pa), it should be scaled down in a similar fashion as stresses [*Davy and Cobbold*, 1991; *Cobbold and Jackson*, 1992]. The friction coefficient is dimensionless and should therefore have similar values in both model and nature. Finally, for viscous material, viscosity should scale down as the product of stresses and timescales down [*Davy and Cobbold*, 1991]. The experiments described here are executed in the normal field of gravity and the materials used in the experiments have been chosen as such, that they have been properly scaled to model the deformation of natural rocks.

[11] The model that has been used consists of a three-layered system situated in a box (Figure 2). On one side of the box a rotational sidewall is situated, which can rotate outward in an anticlockwise fashion (Figure 2a), simulating the progressive anticlockwise retreat of the hinge line of the subducting Pacific plate with respect to the overriding plate (Figure 2c). The Eocene position of the trench as plotted in Figure 2c has been estimated from the amount of spreading (maximum of 300 km in the western Kuril Basin) and extension (500–700 km in the western Sea of Okhotsk) in the backarc region, based on the crustal thickness map of *Gnibidenko et al.* [1995] and assuming a 40 km thick preextensional crust. The rotating sidewall model is based on the conceptual tectonic model of *Elsasser* [1971] to explain backarc extension. In this conceptual model the overriding plate is only extending and spreading when the subducting plate allows it to extend and spread toward the retreating hinge line. The most important aspects of the retreating hinge line are that it results in deviatoric tension along the boundary and that the retreating hinge line does not separate from the overriding plate (since in nature the overriding plate never separates from the subducting plate along the trench). From an intuitive point of view, separation between a hinge line and overriding plate would seem less likely for a dipping hinge (nature) than for a vertical hinge (analogue model), since the overriding plate would partially rest on top of the hinge in the former case. However, in our model with the vertical hinge, no separation occurred, so there was no need to make the dip of the hinge more realistic, which would unnecessarily complicate the construction of the model.

[12] In the analogue model the uppermost two layers represent the overriding lithosphere. The lowermost layer represents the asthenosphere and gives the overlying lithosphere isostatic support. The uppermost brittle layer is made of fine-grained glass microspheres simulating the brittle upper lithosphere in nature, which show a Mohr-Coulomb-type behavior and are properly scaled to model brittle behavior of rocks [*Schellart*, 2000]. The high-viscosity middle layer is made of silicone putty (mixed with a dense filler) with a viscosity of $\sim 2.0 \times 10^4$ Pa s, simulating the viscous lower lithosphere in nature. The low viscosity lower layer is made of glucose syrup with a viscosity of ~100 Pa s. Some physical properties of the individual experiments discussed in the text are given in Table 1, and an overview of the scaling of the physical parameters is given in Table 2.

[13] The three-layered rheological stratification of the model (Figure 2b) has been adopted previously in arc-backarc-related analogue experiments [e.g., *Hatzfeld et al.*, 1997; *Gautier et al.*, 1999; *Martinod et al.*, 2000]. The locus of extension in the Kuril Basin and the Sea of Okhotsk was most likely located on lithosphere previously thickened due to the collision of the Okhotsk block with the Sikhote-Alin and Okhotsk-Chukotsk paleomargins of Eurasia in the early Tertiary [e.g., *Gnibidenko and Khvedchuk*, 1982; *Savostin*, 1983; *Zonenshain et al.*, 1990; *Gnibidenko et al.*, 1995]. Therefore a two-layer representation of a continental lithosphere would be most realistic, since thermal relaxation

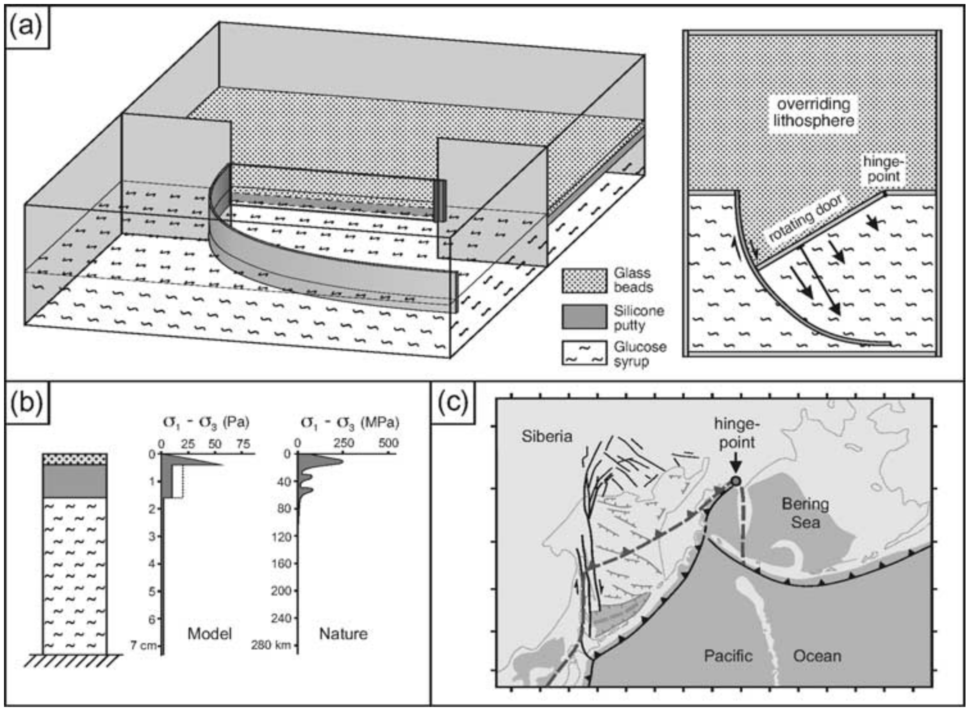

Figure 2. (a) Three-dimensional view (left) and top view (right) of experimental apparatus to investigate asymmetric backarc deformation of a two-layered brittle/ductile plate, simulating the overriding lithosphere (Okhotsk block), during opening of a door, simulating the asymmetric hinge line retreat of the subducting lithosphere (Pacific plate). The model lithosphere is underlain by glucose syrup, simulating the asthenosphere, which gives the lithosphere isostatic support. (b) Strength profiles (for extension) for experiment 2 and natural prototype at the onset of deformation. Strength for silicone layer has been calculated for a strain rate of 10^{-3} s^{-1} (dashed line) and 5×10^{-4} s^{-1} (solid line). It should be noted that strain rate is highly variable in space and time in experiment due to asymmetry of applied boundary condition and will be smaller than 10^{-3} s^{-1} in most places. (c) Tectonic map of the Kuril region at the end of slab retreat (middle or late Miocene), superposed on which is the approximate location of the Kuril subduction zone (thick shaded dashed line) at the start of slab retreat (Eocene). This illustrates the amount ($\sim$30°) and orientation (anticlockwise) of asymmetric retreat as well as the approximate location of the hinge point.

would have diminished the strength of the upper mantle of the Okhotsk block, especially if the thermal relaxation time was sufficiently long. In this case the strength of the lithosphere would reside almost entirely in the crust (Figure 2b). From Table 2 it can be concluded that the experiments are properly scaled with respect to integrated strength and buoyancy force of the overriding lithosphere, since the buoyancy force to integrated strength ratio in model and nature is comparable.

[14] In the following experiments, 1 hour corresponds to $\sim$10 Myr in nature. With such a timescale factor, a viscosity of $\sim$100 Pa s (glucose syrup) and $\sim 2.0 \times 10^4$ Pa s (silicone mix) in the model are equivalent to a viscosity of $\sim 7.0 \times 10^{19}$ Pa s and $\sim 1.4 \times 10^{22}$ Pa s in nature, respectively. The first number is a reasonable approximation for the asthenosphere viscosity ($\sim 10^{19}$–10^{20} Pa s [*Artyushkov*, 1983]) or the sublithospheric mantle viscosity ($\sim 10^{20}$–10^{21} Pa s [*Ranalli*, 1995]). Furthermore, the viscosity contrast between

Table 1. Experimental Properties

Experiment	Material	Rheology	Layer Thickness, cm	Opening Rate, deg h^{-1}	Density $\times 10^3$ kg m^{-3}
2	microspheres	brittle	0.4	12	1.22
	silicone	viscous (high)	1.2		1.22
	glucose	viscous (low)	5.5		1.42
3	microspheres	brittle	0.6	12	1.22
	silicone	viscous (high)	1.2		1.22
	glucose	viscous (low)	5.5		1.42
6	microspheres	brittle	0.5	12	1.22
	silicone	viscous (high)	1.2		1.22
	glucose	viscous (low)	5.5		1.42

Table 2. Scaling of Parameters for Nature and Reference Experiment 2

Physical Parameter	Units	Nature	Experiment
Gravitational acceleration	m s^{-2}	9.8	9.8
Lithosphere thickness (overriding plate)	m	$\sim 6.4 \times 10^4$	0.016
Upper lithosphere brittle thickness	m	$\sim 1.6 \times 10^4$	0.004
Lower lithosphere viscous thickness	m	$\sim 4.8 \times 10^4$	0.012
Lower lithosphere viscosity	Pa · s	$\sim 1.4 \times 10^{22}$	2.0×10^4
Lithosphere average density	kg m^{-3}	$\sim$2960	1220
Asthenosphere density	kg m^{-3}	$\sim$3300	1420
Asthenosphere viscosity	Pa · s	$\sim 7 \times 10^{19}$	100
Overriding plate integrated strength (BS + VS)[a]	N m^{-1}	$\sim 4.4 \times 10^{12}$	0.24
Buoyancy force overriding plate	N m^{-1}	$\sim 3.6 \times 10^{12}$[b]	0.21
BF/(BS + VS)		$\sim$0.82	0.88
Characteristic time	s	3.15×10^{14} (10 Myr)	3600 (1 hour)
Angular velocity retreating slab/opening door	deg s^{-1}	$\sim 3.2 \times 10^{-14}$ (1° Myr^{-1})	$\sim 3.3 \times 10^{-3}$ (12° h^{-1})

[a]Calculated from diagrams in Figure 2b. BS, brittle strength; VS, viscous strength; BF, buoyancy force.
[b]Calculated with a crustal thickness and density of 40 km and 2750 kg m^{-3}, respectively, and with a mantle density of 3300 kg m^{-3}.

the silicone mix and glucose syrup has a factor of ∼200, which falls in the natural range for the lithosphere and sublithospheric mantle (∼100–500 [*Faccenna et al.*, 2001a]). The progressive opening of the sidewall is driven by a step motor. The angular velocity of gate opening has been scaled as such that the 30–40 Myr it took for the slab to rotate 30° ± 10° corresponds to 3 hours in the model to rotate ∼35°. A passive grid (line spacing of 3 cm) and marker spheres have been laid on top of the brittle layer to monitor deformation. The progressive development of the model has been recorded by a camera from above, under oblique lightning of the top surface of the experiment to enhance the visibility of faults.

4. Results

[15] Below follows the description of the results of experiment 2. Deformation begins close to the rotating boundary at the western side (Figure 3a), slowly migrating toward the east and north (Figure 3b). The earliest defor-

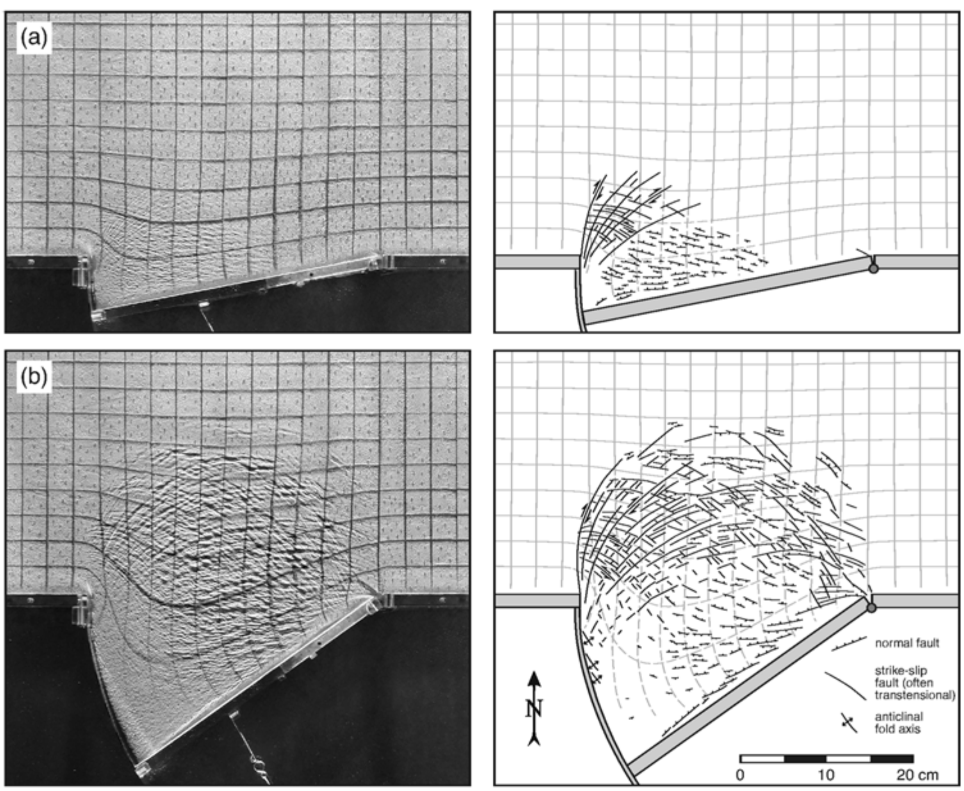

Figure 3. Model results (left) and schematic interpretation (right) of experiment 2 (4 mm brittle layer and 12 mm viscous layer) with (a) after 1 hour (11°) and (b) after 3 hours (35°).

mation is associated with the formation of normal faults forming graben-like structures striking approximately parallel to the rotating boundary. New grabens that develop toward the east and northeast develop at more oblique angles to the rotating boundary, striking approximately WNW-ESE. Simultaneously, a number of closely spaced (spacing $\approx$ 2–4 mm) subparallel N-S to NE-SW-trending dextral strike-slip faults develop at the western corner of the gate. These strike-slip faults propagate toward the north and northeast and are accompanied by conjugate sinistral strike-slip faults, which are generally less continuous and develop at an angle of 60°–70° to the strike of the dextral faults. Each of the dextral strike-slip faults displays a small amount of dextral offset and in total the shear zone displays a large amount of dextral shearing, as can be observed from the displacement of the passive grid. During progressive deformation, these strike-slip faults progressively show a more transtensional type of strike-slip behavior. In a later stage a relatively undeformed ~2 cm wide ridge develops along the entire length of the rotating boundary (i.e., the arc). This ridge increases in width from west to east (Figure 3b). To the north of this ridge a diffuse zone of extension has developed, which starts to accommodate most extension. In this region, normal faults strike NW-SE in the west and north and strike E-W to NE-SW in the center and along the retreating boundary. To the north of the gate a diffuse zone of conjugate transtensional strike-slip faults forms, where the dextral shears near the western side of the gate are best developed. In an advanced stage of deformation, dextral shearing of the spreading sheet along the curved boundary results in the formation of NW-SE-striking en echelon right-stepping folds. Also, individual grabens form in the northernmost part of the deformation front in a late stage of deformation. At places of such graben formation, the silicone layer has been thinned and has risen considerably due to the isostatic support of the brittle-ductile layer by the underlying glucose syrup. This rise was observed at the end of each experiment during dismantling of the model lithosphere after removal of the brittle top layer. This isostatic support was also evident from small amounts of rift shoulder uplift (<1 mm) for well-defined individual rift segments that developed in the north. The fault escarpments of such rift segments had an estimated dip of roughly ~60°–80°. Interestingly, several strike-slip fault zones located close to the hinge point, which were later reactivated as normal fault zones, had fault escarpments with a dip estimated at ~30°–50°. This could be explained as follows: In a layer of poured or sprinkled granular material, the material has a small cohesion [*Krantz*, 1991; *Schellart*, 2000]. When this layer is faulted, then the material in the fault zone looses its cohesion [*Krantz*, 1991]. Thus if a normal fault forms at the former sight of a strike-slip fault zone, then the material in the footwall immediately adjacent to the normal fault plane will already have lost most of its cohesion and will therefore not be able to support a steep normal fault escarpment. If a normal fault forms in previously unfaulted granular material, then the material in the footwall immediately adjacent to the normal fault plane will still have most of its cohesion and will therefore be able to support a steep normal fault escarpment.

[16] The spreading pattern of experiment 2 has been plotted in Figure 4 for 12° increments of rotation. It can be observed that the spreading velocity increases from the hinge point toward the west, while the spreading velocity decreases from the retreating door toward the north. The spreading vectors close to the retreating boundary show a strong asymmetry, which decreases toward the north. The diagram in Figure 4f shows that the length of the spreading vectors immediately north of the retreating boundary slightly decreases in magnitude during progressive opening, while the length of spreading vectors more to the north decreases considerably. This implies that the region close to the retreating boundary increasingly absorbs extension. This behavior can also be observed in Figure 5, where the incremental length increase (Δx) for several N-S-trending grid-line segments has been plotted for an incremental rotation of 6°. In Figure 5a, segments have been plotted, which are located at some distance from the retreating boundary. In Figure 5b, segments have been plotted, which are located close to the retreating boundary. From the diagram in Figure 5b it can be concluded that Δx increases for segments g–j during progressive rotation. However, a decrease is observed for segments d–f in Figure 5a, while segments a–c remain approximately constant. Thus it can be concluded that the region close to the far end of the rotating boundary accommodates increasingly more of the total extension with progressive rotation at the expense of regions located farther to the north. This behavior can be explained from the velocity field in the early stage of the experiment (Figure 4a), from which a decrease in strain rate from south to north can be deduced. Overriding plate extension due to continued retreat of the boundary will preferentially be absorbed by the region with the lowest integrated strength, i.e., the zone which has experienced maximum extensional strain. This zone is located close to the retreating boundary.

[17] The deformed surface grid and the amount of total horizontal extension of experiment 2 are illustrated in Figure 6 after 30° of rotation. In general, the amount of extension decreases from the retreating boundary toward the north. The greatest amount of extension is found close to the western end of the retreating boundary. It can also be observed that the E-W asymmetry in extension close to the retreating boundary decreases toward the north (as observed in Figures 4 and 5). Small amounts of shortening can be observed north of the corners of the gate.

[18] Different experiments with different ratios of brittle to viscous strength (BS/VS) indicate that with increasing BS/VS ratio the deformation becomes more localized with fewer faults accommodating more deformation. Thus the fault density decreases with increasing BS/VS ratio. This can be observed when the results of experiment 2 in Figure 3b (BS/VS $\approx$ 0.12 N m^{-1}/0.12 N m^{-1}) are compared with experiment 6 in Figure 7a (BS/VS $\approx$ 0.18 N m^{-1}/0.12 N m^{-1}) and experiment 3 in Figure 7b (BS/VS $\approx$ 0.25 N m^{-1}/0.12 N m^{-1}). Here BS has been

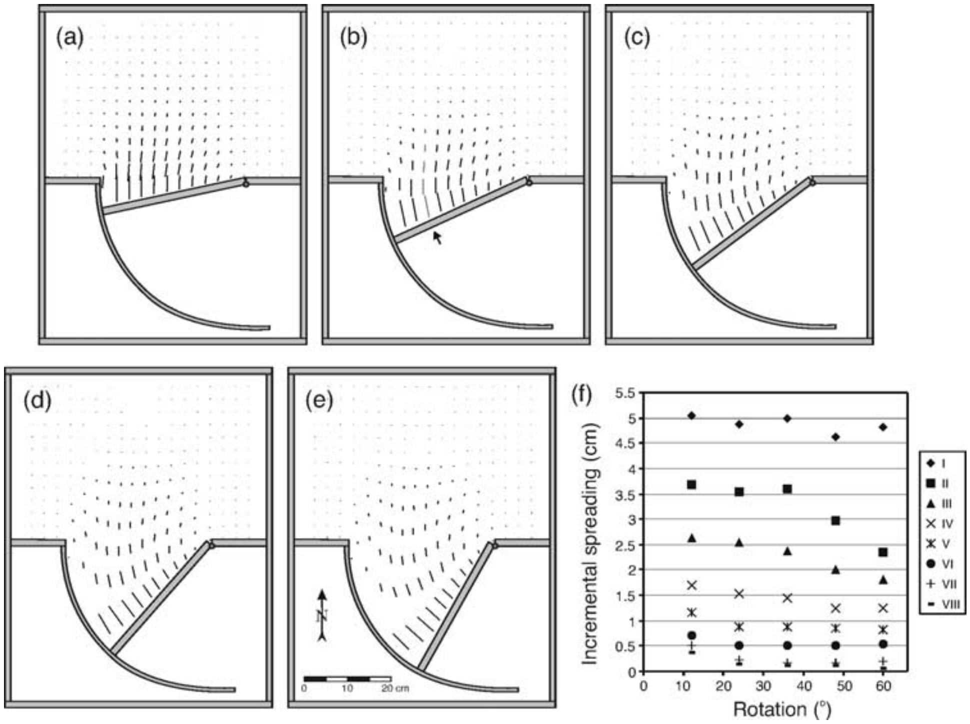

Figure 4. (a–e) Displacement fields of experiment 2 between progressive stages of deformation. The increment of rotation used to determine the displacement vectors is 12°. (f) Diagram showing the amount of spreading for every 12° increment of rotation for eight successive spreading vectors located at grid intersection points of an initially N-S-oriented grid line (see arrow in Figure 4b). Here I is the vector of the southernmost intersection point and VIII is the vector of the eighth intersection point (counting from south to north).

calculated with data from *Schellart* [2000] and VS has been calculated for a strain rate of 5×10^{-4}. Also, with increasing BS/VS ratio the structures in the interior of the box display a higher degree of asymmetry, where normal fault structures are better developed at the expense of strike-slip structures. For relatively high BS/VS ratios, deformation near the far end corner is absorbed by strike-slip faulting, and deformation near the hinge point corner is mainly absorbed by normal faulting. In contrast, a diffuse zone of conjugate (transtensional) strike-slip faults develops for relatively low BS/VS ratios.

5. Discussion

5.1. Asymmetric Slab Rollback and Backarc Opening

[19] We have presented a model to explain the structural and tectonic patterns in and around the Sea of Okhotsk and

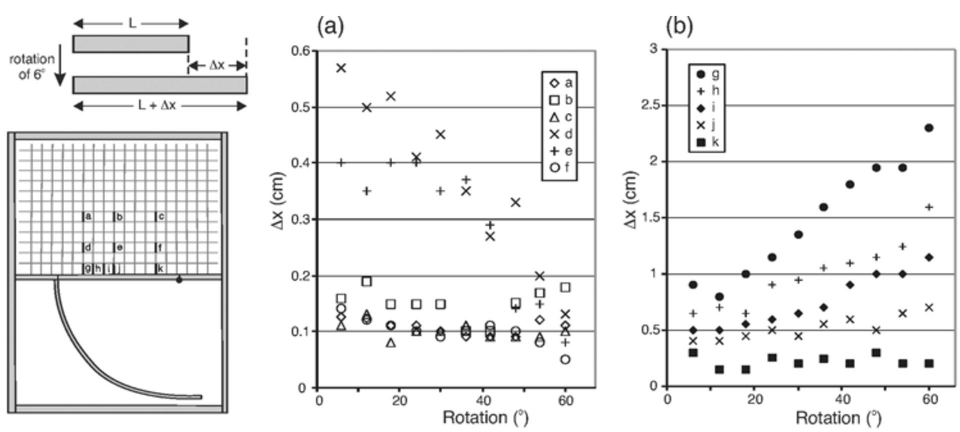

Figure 5. Diagram illustrating increase in line length (Δx) in experiment 2 for every incremental increase in rotation of 6° for different segments of N-S-oriented grid lines. Note the difference in scale for Δx in Figures 5a and 5b.

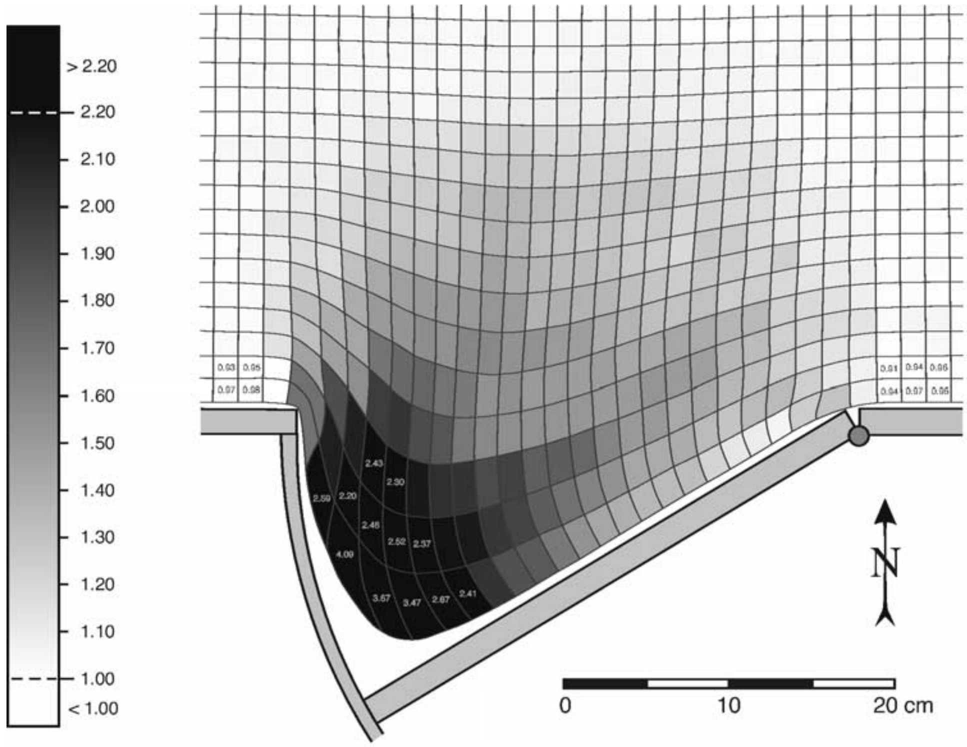

Figure 6. Deformed surface grid of experiment 2 after 30° of rotation. Different shaded scales indicate different factors of total horizontal surface stretch S ($S = A_F/A_O$, where A_F is final surface area and A_O is initial surface area).

the Kuril Basin and to test the hypothesis that rollback is responsible for the deformation observed in the area. In this model, asymmetric anticlockwise rollback of the hinge line of the subducting plate is responsible for the wedge-shaped opening of the Kuril Basin, asymmetric extension in the Sea of Okhotsk, transtensional shearing along the Sakhalin-Hokkaido dextral shear zone and anticlockwise rotation of the arc. Rollback of the hinge line of the subducting lithosphere results in extension in the overriding lithosphere (i.e., backarc extension), since the overriding lithosphere is not strong enough to sustain a potentially vacant region along the subduction boundary [*Elsasser*, 1971; *Lonergan and White*, 1997]. Therefore the overriding plate collapses, extends, and passively follows the retreating slab. This scenario has been simulated with the analogue experiments with extension in the overriding plate during collapse toward the retreating door. This collapse is facilitated by the potential energy difference between the overriding plate and subducting plate, which will force the overriding plate to spread toward the retreating boundary.

[20] Hinge line migration most likely results from the negative buoyancy of the subducting lithosphere compared to the asthenosphere, resulting in sinking of the slab [*Elsasser*, 1971; *Molnar and Atwater*, 1978; *Lonergan and White*, 1997]. The asymmetric opening and extension in the Kuril Basin and the Sea of Okhotsk implies an increase in hinge retreat velocity along the Kuril Trench during backarc deformation in the Eocene to middle/late Miocene. Similar conceptual models have been proposed for the formation of the North Fiji backarc Basin bordering the New Hebrides arc [*Schellart et al.*, 2002] and the Lau backarc Basin bordering the Tonga arc [*Bevis et al.*, 1995]. Both basins have a wedge-shaped geometry, and paleomagnetic data support the idea of rotation of the arc. The amount and orientation of rotation [e.g., *Musgrave and Firth*, 1999; *Sager et al.*, 1994] is in both cases comparable to the amount one would expect with respect to the wedge-shaped geometry of the basin (~40–50° for the North Fiji Basin and ~20° for the Lau Basin). In addition, GPS data for these arcs show the increase in backarc opening velocity from hinge point toward the end [*Taylor et al.*, 1995; *Bevis et al.*, 1995], supporting the concept of wedge-shaped opening for the basins.

[21] The asymmetric slab retreat along the Kuril arc could be related to the increase in age (i.e., density) of the Pacific plate toward the south [*Hilde et al.*, 1977; *Clague and Dalrymple*, 1987] (Figure 1b). However, the age polarity of the subducting Pacific plate along the Kuril Trench might have been different during backarc extension in the Eocene-middle/late Miocene. If the age of the plate did indeed increase toward the southwest, this could result in a faster retreat velocity of the hinge line in the southwest compared to the northeast. In this model the Emperor Seamount Chain, a buoyant ridge located on the Pacific plate, could have defined the hinge point at the northeastern cusp, although its location with respect to the trench is uncertain during extension of the Sea of Okhotsk and opening of the Kuril Basin (see also section 5.4). Deformation in the western part of the overriding plate would be accommodated by the N-S-trending Sakhalin-Hokkaido dextral shear zone, as also shown in the analogue models. Shear zones with a similar

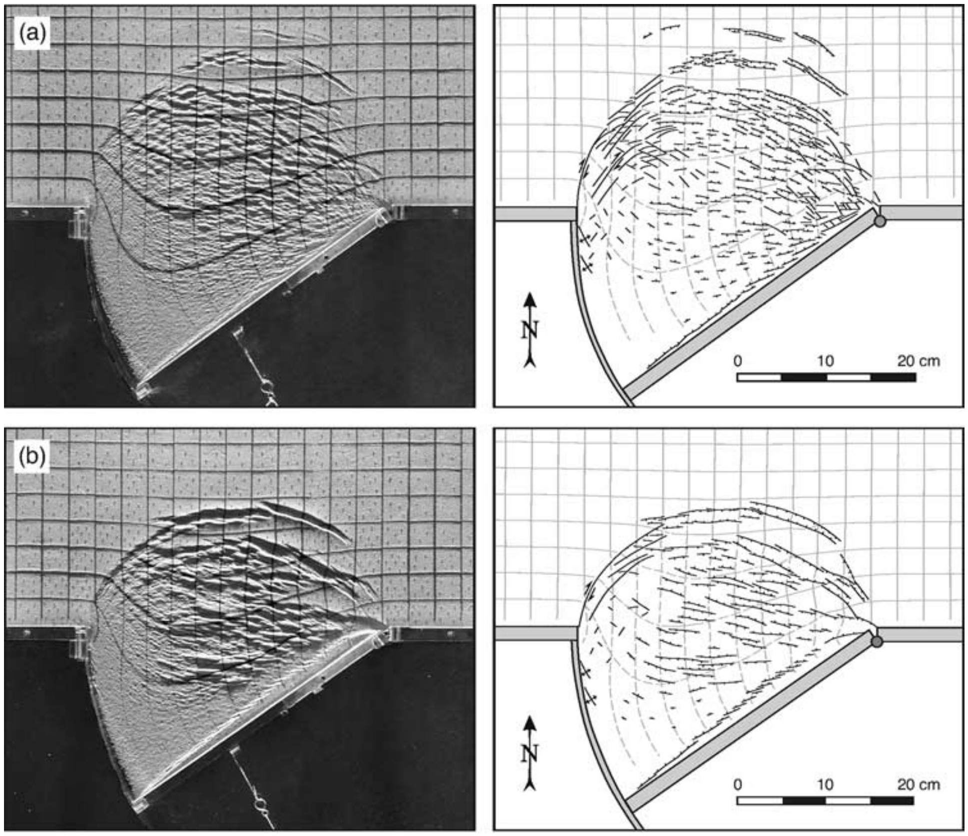

Figure 7. Model results (left) and schematic interpretation (right) of (a) experiment 6 (5 mm brittle layer and 12 mm viscous layer) after 2 hours and 42 min (36°) and (b) experiment 3 (6 mm brittle layer and 12 mm viscous layer) after 2 hours and 54 min (35°).

tectonic significance are the Hunter fracture zone for the New Hebrides arc and the Western Samoa fracture zone for the Tonga arc. Asymmetric slab retreat around a hinge point located in the northeast would necessitate the formation of a (sub)vertical tear in the slab along the SW side of the arc (compare with tear at northern extremity of the Tonga arc [*Millen and Hamburger*, 1998]). Such a tear would allow lateral asthenosphere flow around the slab edge from underneath the slab toward the mantle wedge and would further facilitate asymmetric rollback.

5.2. Comparison Between Analogue Model and Nature

[22] Out of seven experiments executed with a varying BS/VS ratio (ranging from ~0.6–25) and buoyancy force (BF = 0.03–0.27 N m^{-1}), experiment 2 (BS/VS ≈ 1, BF ≈ 0.21 N m^{-1}) gave the results most similar to the structures observed in the Kuril backarc region, with relatively diffuse and widespread deformation in the backarc region and the formation of a N-S to NE-SW-striking transtensional dextral shear zone. This experiment had a relatively low BS/VS ratio and high BF number, corresponding to lithosphere with a relatively thick crust and warm geotherm. This probably corresponds to the rheological scenario for the Okhotsk block after it collided with the Eurasian margin in the early Tertiary [e.g.,*Gnibidenko and Khvedchuk*, 1982; *Savostin*, 1983; *Zonenshain et al.*, 1990; *Gnibidenko et al.*, 1995], where collision resulted in shortening and thickening of the crust, which itself led to an increased geothermal gradient. The buoyancy force to integrated strength ratio (BF/(BS + VS)) in the Kuril region prior to collision has been estimated to be similar to the BF/(BS + VS) ratio for experiment 2 (see Table 2).

[23] Several similarities between the most characteristic structures for both model and nature can be recognized. One of them is the wedge-shaped geometry of the Kuril Basin, which widens toward the southwest and is located close to the retreating hinge line of the subducting Pacific plate. In the model most extension is also observed close to the retreating door with maximum extension close to the far end of the retreating boundary (up to 300% (experiment 2), 325% (experiment 3) and 360% (experiment 6) after 30° rotation). Such extension would probably be sufficient to generate backarc spreading in nature, since the continental crust just north of the Kuril Basin has experienced ~100–233% extension (with a present crustal thickness of 15–20 km [*Gnibidenko et al.*, 1995] and assuming a preextension thickness of ~40–50 km). A difference between model and nature is that the Kuril Basin formed by spreading, while the zone of maximum extension in the model formed by extension, but this is simply explained by the limitation of the model, which is a mechanical model and not a

thermomechanical model. Furthermore, the basin is bordered on the Pacific side by a thin strip of continental lithosphere (i.e., the Kuril arc) [*Gnibidenko and Khvedchuk*, 1982; *Gnibidenko et al.*, 1995; *Kimura and Tamaki*, 1986a], which is considered to be at least Late Cretaceous in age [*Gnibidenko and Khvedchuk*, 1982; *Kimura*, 1986]. This strip was separated from the overriding plate during opening of the Kuril Basin [*Maeda*, 1990]. In the experiment, such a strip of relatively undeformed lithosphere developed along the retreating boundary as well (Figures 3 and 7).

[24] Another analogy between model and nature is the orientation of normal faults bordering the Kuril Basin and in the Sea of Okhotsk. The normal faults are oriented parallel to the arc (striking NE-SW) close to the southwestern end of the retreating boundary and become progressively oblique to the arc (striking E-W to NW-SE) toward the hinge point (NE) and away from the boundary (N-NW). Extension is preferentially oriented toward the SW corner due to the relative fast retreat of this corner with respect to the hinge point. In the model, pure strike-slip faults mainly formed near the far end of the retreating boundary in an early stage of deformation striking N-S to NE-SW and had a dextral sense of shear, similar to the northernmost part of the Sakhalin-Hokkaido dextral shear zone (northernmost part of Sakhalin until well into the Siberian mainland). This part of the shear zone shows a fanning pattern of dextral strike-slip faults changing strike from approximately N-S in the west to approximately NE-SW in the east. Soon after formation of these strike-slip faults in the model, the faults became more transtensional dextral strike-slip faults. This has also been reported for the Sakhalin-Hokkaido dextral shear zone, which was transtensional from Eocene to early Miocene, a period which coincides with the timing of normal faulting in the Sea of Okhotsk [*Worrall et al.*, 1996]. The southern part of the Sakhalin-Hokkaido dextral shear zone reflects a plate boundary remnant of the Late Cretaceous to Paleocene Sakhalin-Hokkaido accretionary complex (Figure 2c) [*Rozhdestvensky*, 1986; *Jolivet and Huchon*, 1989; *Fournier et al.*, 1994; *Gnibidenko et al.*, 1995; *Worrall et al.*, 1996] along which the western most part of the retreating slab migrated. Along this part of the shear zone numerous NW-striking en echelon folds and thrust have been reported [*Rozhdestvenskiy*, 1982; *Fournier et al.*, 1994; *Worrall et al.*, 1996], similar to the NW-striking right-stepping en echelon folds which developed along the curved boundary in the analogue model (Figure 3b).

[25] Both model and nature show that most extension is concentrated close to the arc (e.g., Kuril Basin, which is ~3300 m deep and underlain by oceanic crust) and decreases toward the north. North of the Kuril Basin the extended Central Sea of Okhotsk is 1000–2000 m deep [*Maeda*, 1990], reflecting a relatively thin continental lithosphere [*Gnibidenko et al.*, 1995]. Farther to the north lies the slightly extended Northern Sea of Okhotsk, which is 0–1000 m deep [*Maeda*, 1990]. In the northernmost part, subarial Southern Siberia attests to only marginal or no lithospheric extension. We stress that the N-S-oriented strain gradient is best explained by a tensional boundary condition located south of the Kuril arc and would therefore be related to the subduction zone along the Kuril arc. Furthermore, spreading is greatest in the southwest of the Kuril Basin and extension in the Sea of Okhotsk is greatest just east of the Sakhalin-Hokkaido dextral shear zone and decreases further to the east. This is also observed in the model and indicates that retreat along the subduction zone must have been asymmetrical and anticlockwise. This anticlockwise retreat is supported by paleomagnetic data from Nemuro Island (located along the Kuril arc just east of Hokkaido), which indicate that the region has rotated 29.4° ± 10.4° anticlockwise after the early Eocene [*Tanaka and Uchimura*, 1989], suggesting a similar amount of rotation for the entire Kuril arc. Finally, the model results show that extension is increasingly accommodated by the region close to the retreating boundary with progressive deformation (e.g., Figures 4 and 5). This can account for the late stage (Miocene) opening of the Kuril Basin located close to the retreating boundary [*Maeda*, 1990; *Takeuchi et al.*, 1999; *Ikeda et al.*, 2000], which was preceded by a prolonged period of extension in the Sea of Okhotsk from the Eocene-early Miocene [*Worrall et al.*, 1996].

5.3. Comparison With Other Tectonic Models

[26] The structures of the Kuril arc, the Kuril backarc Basin, and the Sea of Okhotsk have been explained by a number of other conceptual tectonic models, which will be discussed in this section. One model explains the backarc region by oceanic lithosphere entrapment [*Kimura*, 1994]. This model can be rejected, since the Sea of Okhotsk is underlain by thinned continental crust and not by oceanic crust [*Gnibidenko and Khvedchuk*, 1982; *Savostin et al.*, 1983; *Gnibidenko et al.*, 1995].

[27] Another conceptual tectonic model explains the structures in the region by northward retreat of the backarc microplate [*Savostin et al.*, 1983]. This model can be disregarded because there is no indication that extensive Eocene to middle/late Miocene extension is being absorbed by comparable amounts of shortening north of the backarc plate. Furthermore, there is no obvious driving mechanism present to drive such a backarc microplate toward the north and at the same time create extension at its trailing southern end. A third point is that during the Eocene to middle/late Miocene, there was no such thing as a “rigid” backarc plate, since the entire region underwent extensive diffuse deformation.

[28] *Kimura and Tamaki* [1986b] have suggested that the structures in the region have resulted from the India-Eurasia collision, which led to northward retreat and clockwise rotation of the backarc microplate due to dextral shear along the Sakhalin-Hokkaido dextral shear zone, resulting in opening of the Kuril Basin contemporaneous with shortening in Kamchatka. This model also does not explain the lack of extensive Eocene to middle/late Miocene shortening north of the backarc plate, as well as the observed widespread Eocene to early Miocene extension in the Sea of Okhotsk region. Furthermore, paleomagnetic data indicates that (at least part of) the Kuril arc has rotated some 30° anticlockwise after the early Eocene [*Tanaka and Uchimura*,

1989], contrary to what the model of *Kimura and Tamaki* [1986b] would predict (e.g., no rotation of the Kuril arc but clockwise rotation of the Okhotsk region). Finally, the shortening structures observed in the Kamchatka region resulted from the accretion of several arc terranes to the overriding plate [*Bakhteev et al.*, 1997; *Konstantinovskaia*, 2001] and not from rotation of the supposed backarc microplate as suggested by *Kimura and Tamaki* [1986b].

[29] The extrusion model has first been proposed by *Molnar and Tapponier* [1975] to explain the extensive intracontinental deformation of East and northeast Asia as resulting from the India-Eurasia collision. This model was supported by analogue results of plane-strain experiments [*Tapponier et al.*, 1982], which showed the sequential eastward extrusion of blocks along NE-SW-oriented sinistral shear zones. This model was later refined by *Davy and Cobbold* [1988], who scaled their analogue experiments for gravity to incorporate buoyancy forces. In these more realistic experiments the importance of N-S-trending dextral shear zones as conjugates to the NE-SW-trending sinistral shear zones was discovered. This led L. Jolivet and coworkers to suggest that approximately N-S-oriented dextral shear zones along the East Asian margin (such as the Sakhalin-Hokkaido dextral shear zone) resulted from extrusion tectonics while backarc basin formation resulted from slab rollback along the East Asian active margin [e.g., *Jolivet et al.*, 1990, 1994, 1999; *Fournier et al.*, 1994; *Worrall et al.*, 1996]. In addition, *Jolivet et al.* [1990, 1994] stated that without internal deformation of Asia due to collision with India, marginal basins along the East Asian margin would have opened in a symmetrical way. However, examples of asymmetric backarc basins in the southwest Pacific (North Fiji Basin and Lau Basin) confirm that backarc basins can open up asymmetrically purely resulting from subduction related processes [*Bevis et al.*, 1995; *Schellart et al.*, 2002]. Also, analogue modeling results of extrusion tectonics have shown that the approximately NE-oriented sinistral shear zones (compare with Stanovoy sinistral shear zone) are the major shear zones which accommodate relatively large amounts of shearing, while the conjugate approximately N-S-oriented dextral shear zones are subsidiary (compare with Sakhalin-Hokkaido dextral shear zone) with relatively small amounts of offset [*Davy and Cobbold*, 1988; *Jolivet et al.*, 1990, 1994]. In northeast Asia, however, the opposite is observed. The amount of shearing along the Stanovoy shear zone can be estimated by estimating the amount of extension along the Baikal rift, which is (in the extrusion model) a releasing bend along the sinistral shear zone. Extension along the rift (and thus sinistral shearing) has been estimated at $\sim$7 km based on structural mapping [*San'kov et al.*, 2000] and <20 km based on crustal gravity modeling [*Zorin and Cordell*, 1991]. In stark contrast, dextral shearing along the Sakhalin-Hokkaido dextral shear zone has been estimated to be at least 400 km [*Jolivet and Tamaki*, 1992], based on the amount of opening of the Japan Sea. We suggest, however, that the maximum amount of dextral shearing is even much higher (800–1000 km), based on the amount of extension in the western Sea of Okhotsk (500–700 km) and spreading in western Kuril Basin (300 km). Thus it can be concluded that the N-S-oriented Sakhalin-Hokakido dextral shear zone did not result from the India-Eurasia collision. To finalize, timing could be invoked as an argument to support the connection between India-Eurasia collision (started in the Eocene [*Searle et al.*, 1987]) and backarc deformation in the Sea of Okhotsk (started in the Eocene). However, backarc deformation in the Sea of Okhotsk region ended in the early Miocene [*Gnibidenko and Khvedchuk*, 1982; *Worrall et al.*, 1996] and was subsequently followed by Miocene backarc spreading in the Kuril Basin [*Maeda*, 1990; *Takeuchi et al.*, 1999; *Ikeda et al.*, 2000], while the India-Eurasia collision is active up to the Present. This timing of backarc activity in the Kuril region closely coincides with the time of slow convergence between the Eurasian and Pacific plates (Paleocene-middle Miocene) and faster convergence during the Cretaceous and late Miocene-Present [*Northrup et al.*, 1995]. Therefore it would seem more logical to connect the backarc deformation with Pacific slab behavior along the Kuril Trench.

[30] As it is likely that the Okhotsk region was thickened due to collision with the Eurasian margin [e.g., *Gnibidenko and Khvedchuk*, 1982; *Savostin*, 1983; *Zonenshain et al.*, 1990; *Gnibidenko et al.*, 1995], one could invoke another mechanism for extension in the backarc region, which is gravitational or extensional collapse [e.g., *Dewey*, 1988]. For instance, this scenario has been proposed for the formation of the Betic/Rif arc and Alboran backarc region [*Platt and Vissers*, 1989] and the Hellenic arc and Aegean backarc region [*Hatzfeld et al.*, 1997; *Gautier et al.*, 1999], with collapse of an over-thickened orogenic wedge advancing over the subducting plate. For the Okhotsk region, however, not much is known about the extent of thickening of the region due to the Paleocene collision. It could be that southward collapse of the thickened region played some role in extension of the region, but a prerequisite for this collapse to occur is southwestward retreat of the slab. Analogue and numerical modeling, and analytical insights into the role of collapse versus slab retreat, indicate that slab retreat is the main driving agent of backarc extension [*Le Pichon*, 1982; *Faccenna et al.*, 1996; *Meijer and Wortel*, 1997]. It could be that collapse played some role in the early stage of backarc deformation, but this role would have diminished with time due to thinning of the region and decrease in excess potential energy of the region. Finally, one would expect collapse to result in extension perpendicular to the arc in alignment with the steepest potential energy gradient, while the extension in the backarc region is highly asymmetrical and therefore not easily explained by collapse of a thickened lithosphere.

5.4. Evolutionary Model

[31] Below we describe an evolutionary model proposed for the Kuril arc-backarc region and surrounding regions, based on the model results and published geological and geophysical data. A conceptual scenario for the evolution since $\sim$65 Ma is presented in Figure 8. Although our

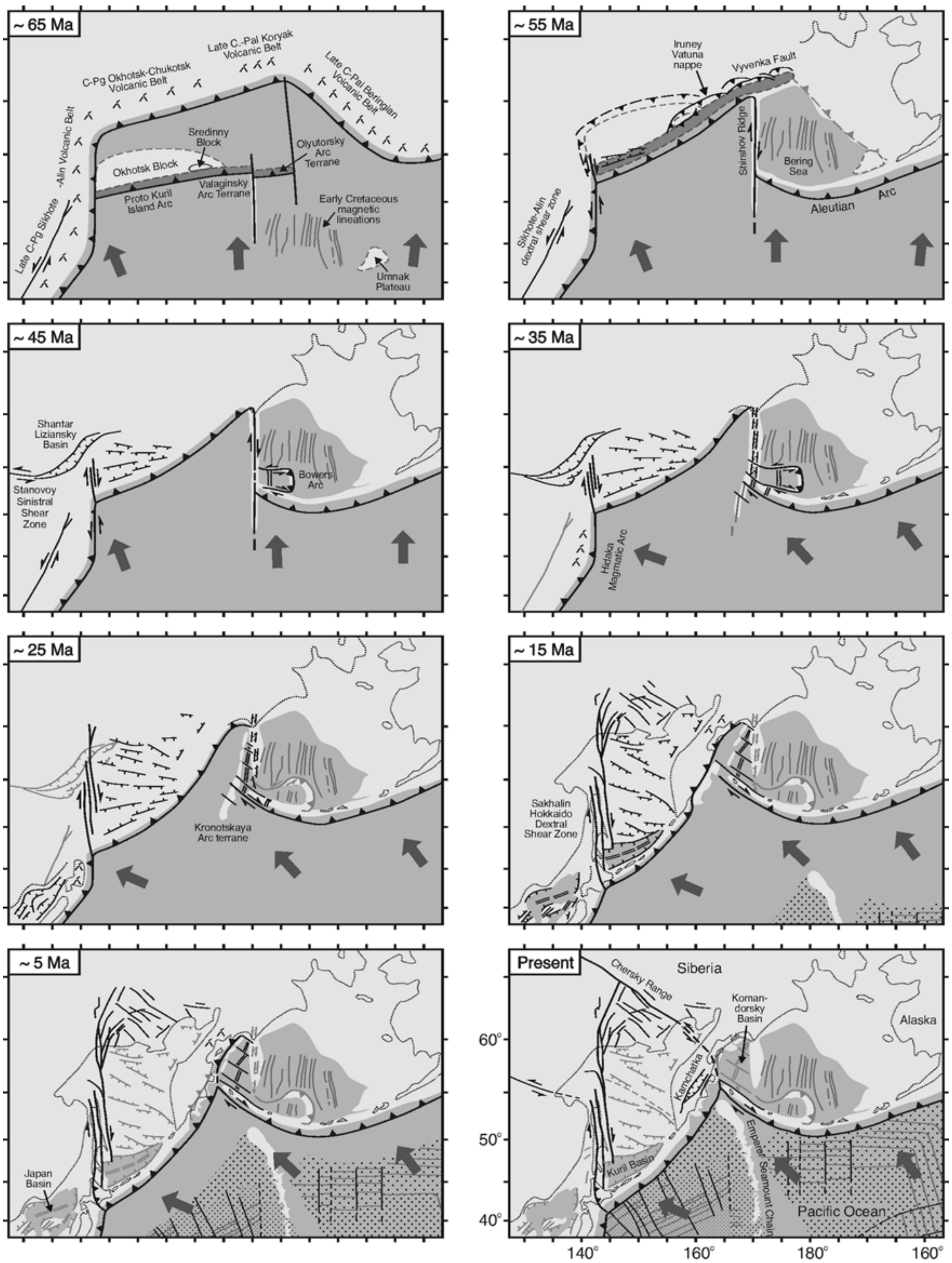

Figure 8. Conceptual scenario for the evolution of the Kuril arc-backarc region and surrounding for the past ∼65 Myr. For explanation of the diagrams see text. For explanation of symbols see Figure 1. The stippled patterns in the last three diagrams indicate the age of the subducting Pacific lithosphere, which is 120–150 Ma (fine pattern), 106–120 Ma (medium pattern), 73–106 Ma (coarse pattern), and 40–73 Ma (very coarse pattern).

analogue model has not been intended to explain the structures that have formed in the region for the last few Myr, the final diagram of Figure 8 at ~0 Ma has been included to offer a complete evolutionary scenario from ~65 Ma to Present.

[32] Approximately 65 Ma: Oceanic lithosphere was subducted northward [*Gordon and Jurdy*, 1986], accompanied by Late Cretaceous to Paleogene volcanism along the paleomargins of Sikhote Alin and Okhotsk-Chukotsk [*Worrall et al.*, 1996] and Late Cretaceous to Paleocene volcanism along the Koryak and Beringian shelf [*Cooper et al.*, 1987a, 1987b].

[33] Approximately 55 Ma: During the Paleocene the Okhotsk block was accreted to the Eurasian continent [*Gnibidenko and Khvedchuk*, 1982; *Zonenshain et al.*, 1990; *Worrall et al.*, 1996], followed by the accretion of the Valaginsky arc terrane during the latest Paleocene-early Eocene [*Konstantinovskaia*, 2001] and the accretion of the Olyutorsky terrane in the early Eocene [*Worrall*, 1991; *Fedorchuk and Izvekov*, 1992]. After accretion of the Okhotsk block to Eastern Siberia, continued convergence was accommodated by a subduction zone located south of the Okhotsk block, i.e., the proto-Kuril Trench. We propose that the proto-Kuril Trench started to retreat southward asymmetrically somewhere in the Eocene akin to what is shown in the analogue models (Figures 3 and 7), with deformation starting close to the retreating boundary and migration of the deformation front toward the north. Such retreat would lead to backarc extension in the overriding plate and would explain the Eocene to (early) Miocene extension in the Okhotsk region with sedimentary deposition into fault-bound grabens [*Gnibidenko and Khvedchuk*, 1982; *Worrall et al.*, 1996]. Contemporaneously, the Sakhalin-Hokkaido dextral shear zone formed to the west of the basin due to asymmetric retreat. Accretion of the Olyutorsky terrane and Umnak Plateau to the Koryak-Beringian margin stopped subduction along this active margin and resulted in a southward step back of the subduction zone [e.g., *Karig*, 1974]. This resulted in the formation of the eastern part of the Aleutian arc with voluminous magmatism between 55 and 37 Ma [*Scholl et al.*, 1970; *Marlow et al.*, 1973; *Hein and McLean*, 1980] and led to entrapment of Early Cretaceous oceanic lithosphere in the Bering Sea [*Cooper et al.*, 1976, 1992; *Ben-Avraham et al.*, 1981]. The Shirshov Ridge functioned as a transform ridge with a component of convergence in its early stages possibly reactivating an older structure, since dredge samples from the ridge show both Late Cretaceous to Paleogene oceanic-type rocks [*Bogdanov et al.*, 1983; *Tzukanov et al.*, 1984] and late Eocene to Oligocene island arc type rocks [*Cooper et al.*, 1987a, 1987b; *Bogdanov*, 1988].

[34] Approximately 45 Ma: Retreat along the Kuril arc continued accompanied by backarc extension and dextral shearing. The deformation front slowly migrated northward and eastward, akin to what is shown in the analogue model results. Somewhere during early Tertiary times, the Shantar-Liziansky Basin formed west of the Siberia-Okhotsk block collision due to shearing along the Stanovoy sinistral shear zone and was filled with Eocene to Oligocene sediments [*Worrall et al.*, 1996]. Initiation of formation of the Bowers arc occurred accompanied by backarc spreading [*Scholl et al.*, 1975; *Cooper et al.*, 1987a, 1987b, 1992].

[35] Approximately 35 Ma: Retreat along the Kuril arc and the Bowers arc continued. At ~43–42 Ma a change in Pacific plate movement took place from approximately northward to approximately west-northwestward [*Dalrymple et al.*, 1977; *Engebretson et al.*, 1985; *Gordon and Jurdy*, 1986]. This change would have triggered WNW-ESE oriented extension in the Shirshov Ridge, which changed from a transform plate boundary to a transtensional plate boundary. Extension in the Shirshov Ridge has been reported to have started in Oligocene times and continued into the Miocene [*Baranov et al.*, 1991; *Cooper et al.*, 1992]. The change also caused expansion and growth of the Aleutian arc toward the northwest, resulting in the formation of a transform boundary [*Cooper et al.*, 1992; *Yogodzinski et al.*, 1993]. The extension of the Shirshov Ridge culminated in formation of and spreading in the Komandorsky Basin. On the basis of heat flow data, *Baranov et al.* [1991] suggested that spreading in the basin began at ~30–25 Ma. Finally, *Maeda* [1990] suggested that the change in convergence direction resulted in formation of the Hidaka magmatic arc from ~43 to 17 Ma due to a change from subduction at an acute angle to nearly perpendicular subduction.

[36] Approximately 25 Ma: Extension in the Shantar Liziansky Basin ceased in the late Oligocene or early Miocene [*Worrall et al.*, 1996], while continued retreat of the Kuril arc caused the backarc deformation front to migrate northward. This resulted in overprinting of the Sakhalin-Hokkaido dextral shear zone and E-W and NW-SE-trending normal faults on top of the older structures of the Shantar Liziansky Basin [e.g.,*Worrall et al.*, 1996]. In the Bering Sea region, arc migration of the Bowers arc stopped [*Cooper et al.*, 1992]. Toward the southwest of the Kuril arc, rollback along the Japan arc resulted in the formation of the Japan Basin in the late Oligocene (~30 Ma) [*Tamaki et al.*, 1992; *Jolivet et al.*, 1999].

[37] Approximately 15 Ma: Opening and subsequent spreading in the Kuril Basin occurred from ~17 to 15 Ma [*Maeda*, 1990] or from ~23 to 8 Ma [*Takeuchi et al.*, 1999; *Ikeda et al.*, 2000]. Prior to and during opening of this basin, the Kronotskaya arc terrane (of Coniacian-Eocene age) collided with the Kamchatka peninsula and finally got accreted in the late Miocene [*Bakhteev et al.*, 1997; *Konstantinovskaia*, 2001]. Active subduction continued along the northeast part of the Kamchatka Peninsula around 15 Ma, as indicated by subduction related volcanism in Northeast Kamchatka [*Hochstaedter et al.*, 1994].

[38] Approximately 5 Ma: The Kuril Basin stopped opening at 15 Ma [*Maeda*, 1990] or ~8 Ma [*Takeuchi et al.*, 1999; *Ikeda et al.*, 2000]. This would imply that the Pacific slab stopped retreating during this time. The reason for such a halt in rollback is not immediately evident, since the Pacific slab continued to subduct along the Kuril trench. It could be related to accretion of the Kronotskaya arc terrane to the Kamchatka peninsula in the late Miocene. It could also be that interaction of the slab tip with the upper-lower mantle transition zone retarded or even halted slab retreat, therefore

stopping backarc extension. A similar scenario has been proposed by *Faccenna et al.* [2001a, 2001b] for the Calabrian arc-backarc system in the central Mediterranean and has been supported by analogue experiments. Spreading in the Komandorsky basin continued with subduction along northern Kamchatka, while the Japan Sea stopped opening at ~10 Ma [*Jolivet et al.*, 1999].

[39] Present: Active intraarc extension is observed on the Kamchatka Peninsula, which might indicate that the Pacific slab is starting to retreat again. Spreading in the Komandorsky Basin has stopped and the only active volcanism occurs in the southernmost part of the basin [*Yogodzinski et al.*, 1994]. Subduction and related spreading might have continued until ~1.3 Ma, which is the age of the youngest volcanic rocks in northeastern Kamchatka [*Honthaas et al.*, 1995]. Subduction might have stopped due to the approach of buoyant fragments at the trench, which originated from the Shirshov Ridge but were split from it due to opening up of the Komandorsky Basin [*Yogodzinski et al.*, 1993].

[40] At present, the Okhotsk microplate can be distinguished from the Eurasian plate to the west and the North American plate to the east and is moving toward the southeast with respect to the Eurasian plate. It is bounded to the west by the Sakhalin-Hokkaido dextral shear zone and in the northeast by the Chersky range sinistral shear zone [*Parfenov et al.*, 1988; *Riegel et al.*, 1993; *Seno et al.*, 1996]. The intracontinental plate boundaries are rather diffuse, however, and have been determined from a sparse amount focal mechanism data [*Parfenov et al.*, 1988; *Riegel et al.*, 1993; *Seno et al.*, 1996].

[41] From the reconstruction presented in Figure 8 it can be concluded that the evolution of the Kuril-Aleutian cusp is complex and that its position changed through time. The cusp seems to have developed independently from the Emperor Seamount Chain, and the spatial correlation between the cusp and the chain seems to be a coincidence rather then of tectonic significance, as was suggested by *Vogt* [1973]. In addition, no signs of collision between the chain and the Kuril arc have been reported, possibly because the chain does not extend further to the northwest and therefore is now only starting to approach the trench. This idea is supported by the rapid decrease in topography of the chain at the northwestern extremity of the chain to ~3000 m below sea level. Also, the chain approaches the Kuril Trench ~150 km south of the junction, again questioning the relevance of this chain with regards to the formation of the Kuril-Aleutian cusp.

6. Conclusions

[42] We have presented the results of analogue experiments to simulate the structural and tectonic evolution of the Kuril arc and backarc region. The results demonstrate that the first order structures in the region can be explained by asymmetric anticlockwise rollback of the Pacific slab and collapse of the overriding plate toward the retreating hinge line. Similar models of asymmetric rollback and wedge-shaped backarc opening have been proposed for the Tonga arc and New Hebrides arc in the southwest Pacific [*Sager et al.*, 1994; *Bevis et al.*, 1995; *Musgrave and Firth*, 1999; *Schellart et al.*, 2002], indicating that asymmetric slab retreat might be a fundamental type of slab behavior. The analogue results show the progressive development of a N-S to NE-SW-oriented dextral shear zone (compare with Sakhalin-Hokkaido dextral shear zone) near the far edge of the retreating boundary (compare with Kuril-Japan cusp), striking oblique to perpendicular to the boundary. Contemporaneously, normal faults and grabens form, striking parallel to the retreating boundary near the far edge but more oblique toward the hinge point and toward the north. Similar structures are observed in the Kuril Basin and the Sea of Okhotsk, which developed contemporaneously with the Sakhalin-Hokkaido dextral shear zone. Furthermore, the model shows that the amount of extension progressively decreases away from the retreating boundary. Most likely, this has also happened in the Kuril-Okhotsk region, where the crustal thickness increases from south to north [*Gnibidenko et al.*, 1995], probably reflecting the amount of thinning of previously relatively thick continental crust. Such a N-S-oriented strain gradient implies that the Kuril-Okhotsk region formed due to tensional stresses along the Kuril Trench. We conclude that the Sakhalin-Hokkaido dextral shear zone and extensional structures observed in the Kuril-Okhotsk region are not necessarily the far field effect of the India-Eurasia collision (e.g., extrusion model). Rather, they are better explained as to have resulted from anticlockwise retreat of the subducting Pacific slab and collapse of the overriding plate toward the retreating hinge line.

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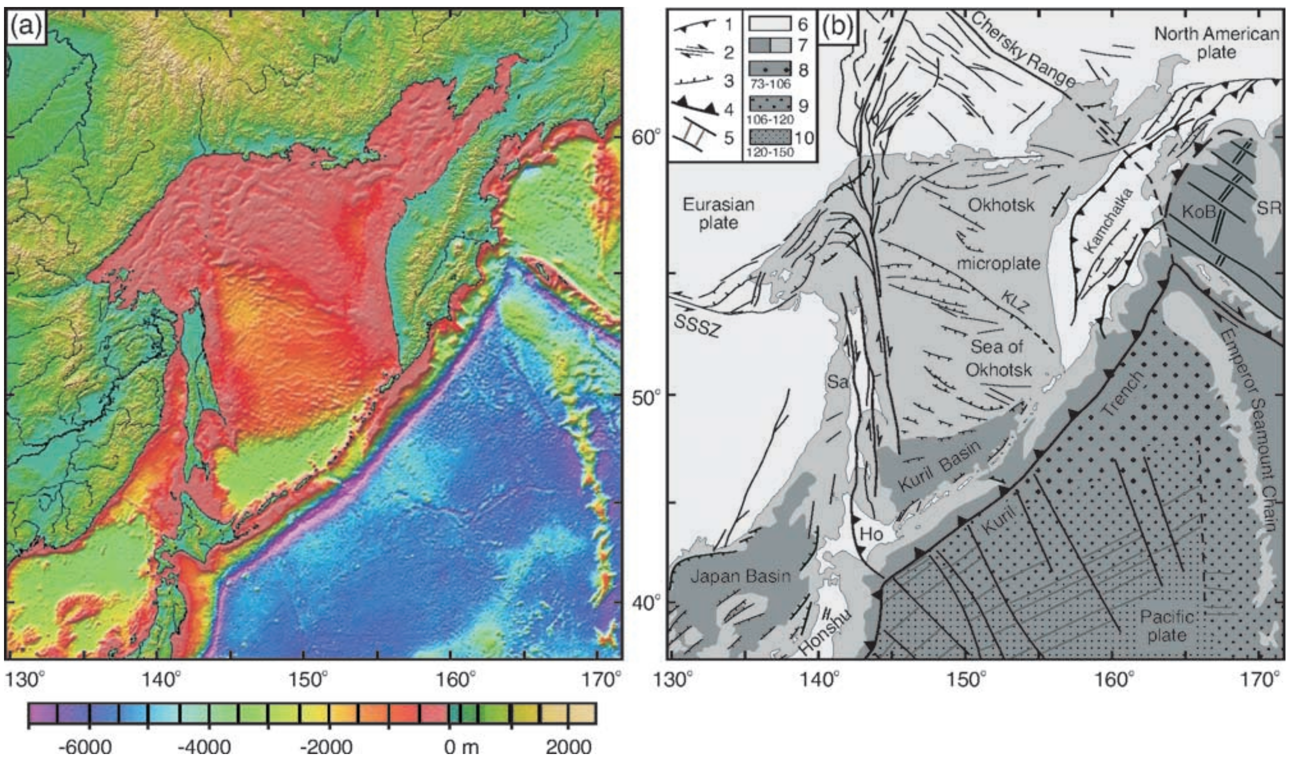

Figure 1. (a) Topographic map of the Kuril Basin, the Sea of Okhotsk, and surrounding areas [from *Smith and Sandwell*, 1997]. (b) Regional tectonic setting of Figure 1a (compiled after *Hilde et al.* [1977], *Gnibidenko and Khvedchuk* [1982], *Jolivet* [1987], *Hochstaedter et al.* [1994], *Worrall et al.* [1996], *Jolivet et al.* [1999], and *Konstantinovskaia* [2001]). For the Pacific plate, three different regions are indicated with different ages (in Ma) (from *Hilde et al.* [1977]). Ho, Hokkaido; KLZ, Kashevarov linear zone; KoB, Komandorsky Basin; Sa, Sakhalin; SR, Shirshov Ridge; SSSZ, Stanovoy sinistral shear zone; 1, reverse/thrust fault; 2, strike-slip fault; 3, normal fault; 4, subduction zone; 5 magnetic anomalies (thin lines) and transform faults (thick lines); 6, land; 7, sea, with basin/ocean floor (left) and continental shelf/ morphological high on basin/ocean floor (right); 8–10, oceanic crust of the Pacific plate with age in Ma.