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Structure of an active arc-continent collision area: the Aleutian–Kamchatka junction

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Abstract

The plate boundary between the North American and Pacific plates along the westernmost portion of the Aleutian arc is formed by several active, dextral strike-slip fracture zones. Fracturing is expressed by fault escarpments visible in reflection seismic profiles, and narrow zones of high seismicity. The seismicity changes from the Aleutian arc, where shallow earthquakes occur, to intermediate to deep earthquakes in the Kamchatka–Aleutian junction area and to the south. In the vicinity of this junction, the distribution of earthquakes follows the traces of major Aleutian fracture zones down to a depth of 100 km. South of the Kronotsky Peninsula, the distribution of earthquakes changes and is similar to other subduction zones. The fracture zones cut the western Aleutian arc into individual blocks, which move along strike-slip faults to the west and collide with Kamchatka. Related transtension and transpression has led to the development of pull-apart basins and block tilting. The fracture zones splay into numerous strike-slip faults to the west, where they meet the Kamchatka margin. The main faults of the Aleutian fault system can be traced on the Kamchatka Mys Peninsula, where deformed Pleistocene sediments, high uplift rates, recent thrust faulting, and changes in the drainage system provide evidence for neotectonic activity. The fault pattern onshore and offshore in the junction area supports an indentation tectonic model of the collision of Aleutian arc slivers with Kamchatka.

Keywords: Aleutian arc; fracture zone; Kamchatka; neotectonic; plate boundary; seismicity

1. Introduction

The Kuril–Kamchatka and Aleutian Trenches meet in the area of the Kamchatka Mys Peninsula at nearly right angles (Fig. 1). The Pacific plate is subducting along the Kuril–Kamchatka Trench. North of the Aleutian–Kamchatka junction, no subduction has occurred recently along the continental margin. Along the eastern part of the Aleutian arc, the Pacific plate is being subducted obliquely at the Aleutian Trench; in the western part, the Pacific plate is moving past the Komandorsky Islands and the Bering Sea, which is part of the North American plate. Therefore, the westernmost part of the Aleutian Trench is not

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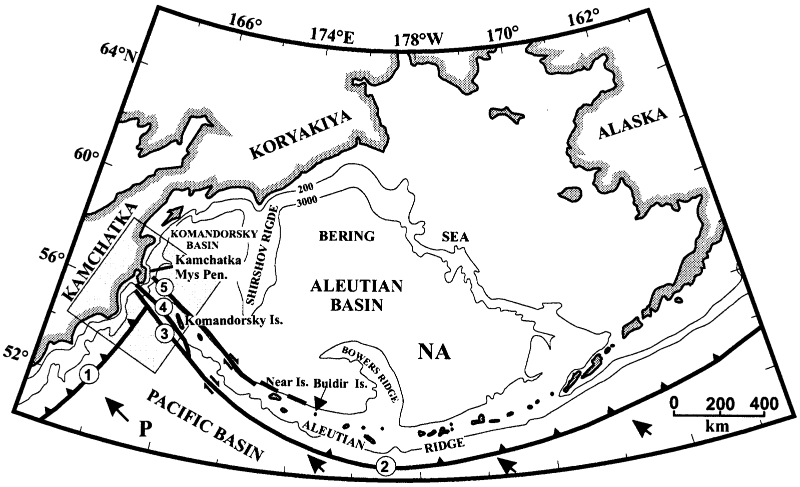


Fig. 1. Map of the Aleutian–Bering region and location of the study area (rectangle). Lines with barbs indicate subduction zones: (1) Kamchatka Trench and (2) Aleutian Trench; lines with sense of displacement mark fracture zones (FZs): (3) Steller, (4) Pikezh and (5) Bering FZs. Single arrows show relative direction of convergence of the Pacific (P) and North American (NA) plates. Bathymetric contours are in meters.

a subduction zone, but a transform fault (McKenzie and Parker, 1967). The Aleutian arc is moving along this transform fault and colliding with Kamchatka (Watson and Fujita, 1985; Zonenshain et al., 1990a,b; Geist and Scholl, 1994; Geist et al., 1994).

In this paper we review data from several marine geophysical surveys carried out during the last two decades in the Aleutian–Kamchatka junction area, mainly by the Institute of Volcanology, Far East Branch of the Russian Academy of Sciences. Most of this data has only been published in Russian literature (Seliverstov, 1983, 1987, 1998; Seliverstov et al., 1986., 1988, 1995; Baranov et al., 1991). Single-channel reflection seismic surveys now cover a dense grid within the Aleutian–Kamchatka junction area, and detailed echo-sounding provides bathymetry. These data show that the westernmost Aleutian arc has a complicated structure and consists of a number of fracture zones represented by dextral strike-slip faults. Single-channel seismic and bathymetric surveys provide evidence for the continuation of the strike-slip faults on the Kamchatka shelf. It is assumed that some of them continue onto the Kamchatka Mys Peninsula (Seliverstov, 1987).

Neotectonic investigations have been carried out to study the onshore continuation of fracture zones and to understand how the Aleutian arc has affected the present structural pattern on the Kamchatka Mys Peninsula, and how it has influenced accretion/collision processes in this region (Baranov et al., 1998; Gaedicke et al., 1998). We focus our investigations on the youngest stratigraphic unit (Olkhovsk Formation) in outcrops along the coast of the Kamchatka Mys Peninsula.

In this paper we present and discuss structural maps of the junction area compiled from published Russian data obtained during marine expeditions carried out by the Institute of Volcanology (Petropavlovsk–Kamchatksy) (Seliverstov, 1983, 1987, 1998; Seliverstov et al., 1986, 1988, 1995) and recent results from studies of the neotectonics of the Kamchatka Mys Peninsula. We compare this data with seismological observations and focal mechanism studies (Fedotov et al., 1987; Zobin et al., 1988; Zobin, 1990; Geist and Scholl, 1994). Using this data, we have constructed a geodynamic model for arc–continent collision in the Aleutian–Kamchatka junction area. This geodynamic model is compared with similar tectonic settings in arc–arc collision zones.

2. Offshore structure of the Komandorsky fracture zone system

Structures in the westernmost Aleutian arc include several fracture zones (Fig. 2), from the Alpha fracture zone in the Komandorsky Basin in the north to the Naturalist fracture zone, south of Bering Island. We refer to this part of the Aleutian island arc as the Komandorsky fracture zone system. The Bering fracture zone, which separates the Aleutian Ridge from the Komandorsky Basin, stretches more than 700 km from the Kamchatka continental slope along the Komandorsky Islands up to Near Islands (Figs. 1 and 2). Except for the Alpha fracture zone (Fig. 3a and b) in the north, all of the fracture zones show significant shallow to intermediate seismicity. Thus, recent motion occurs at the boundary between the Pacific and

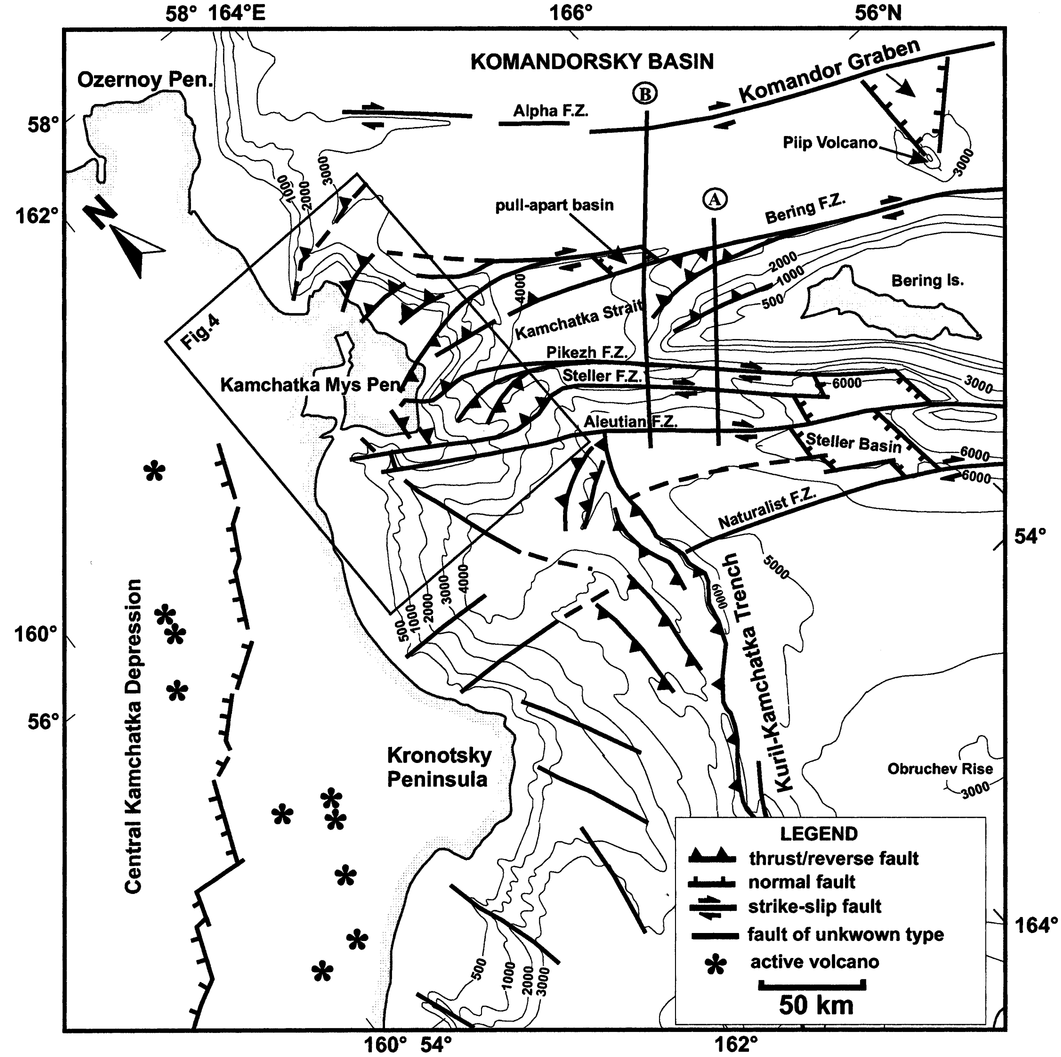


Fig. 2. The main tectonic features of the Kamchatka–Aleutian junction area modified from Seliverstov (1983), Seliverstov et al. (1988) and Baranov et al. (1991). The eastern side of the Central Kamchatka depression is bounded by normal faults. Contour interval is 1000 m. Lines A and B indicate the locations of profiles shown in Fig. 3; the rectangle marks the location of the area shown in Fig. 4.

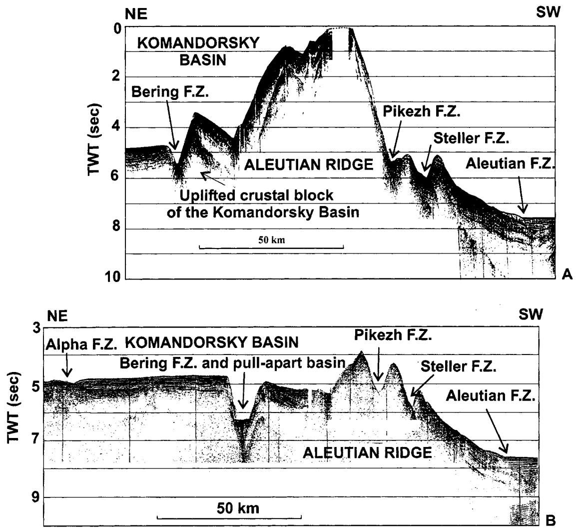


Fig. 3. Two single-channel seismic profiles (A and B) showing major fracture zones and structure of the Komandorsky fracture zone system. For location, see Fig. 2.

North American plates in a zone about 150 km wide between the Naturalist and Bering fracture zones.

2.1. Komandorsky segment of the Aleutian island arc

Focal mechanisms (Cormier, 1975; Newberry et al., 1986) and structural studies (Seliverstov, 1983; Seliverstov et al., 1988; Baranov et al., 1991) provide evidence for a general dextral strike-slip displacement on fracture zones along the westernmost Aleutian arc. Nevertheless, the en-echelon pattern and bending of the strike-slip faults resulted in transtensional and transpressional horst-and-graben features (e.g. the Komandor graben and the Steller Basin). Compressional structures are most obvious along the Bering fracture zone near the northern continental rise of Bering Island, where right-lateral displacement is accompanied by a system of east–west-trending reverse faults.

The northern slope off Bering Island is fragmented into rigid, tilted blocks separated by fracture zones. The Bering fracture zone appears on reflection seismic profiles as a V-shaped trough about 500 m deeper than the Komandorsky Basin (Fig. 3a and b). Two units can be distinguished in the reflection seismic records: (1) an upper, stratified sedimentary unit similar to the sedimentary cover of the Komandorsky Basin and (2) a lower, acoustically transparent sequence. Both units, which trend east–west, are tilted to the southwest toward the island arc and are uplifted about 1500 m above the Komandorsky Basin floor in the north. Seliverstov (1987) inferred that at least the lower part of the slope is composed of blocks of Komandorsky Basin crust. Andesites dredged on this slope and yielding an absolute K–Ar age of 8.8 ± 0.4 Ma (Scholl et al., 1976) may represent basement rocks of the southern Komandorsky Basin overthrust onto the Aleutian Ridge. Similar magnesian andesites of Upper Miocene (?) age were dredged from the submarine Piip volcano (Fig. 2) (Volynetz et al., 1992). We interpret these uplifted and tilted blocks to be transpressional features related to the southward bend in the Bering fracture zone, which has a dextral sense of motion. Further to the west, a branch of the Bering fracture zone is offset to the north. As a consequence, a small pull-apart basin appears in a transtensional regime (Figs. 2 and 3b).

The system of fracture zones south of the Komandorsky Islands becomes increasingly complicated from east to west. The Steller Basin is bounded by the Pikezh and Naruralist fracture zones. It is cut into sub-basins by the Aleutian fracture zone (Fig. 2). The rhomb-shaped basin is several hundred meters deeper than the surrounding seafloor. Here, the Aleutian Trench reaches its maximum depth of 6800 m. To the east, the basin is marked by north-northwest–south-southeast normal faults, which were recorded during deep dives with the MIR submersible (Galkin, personal communication) The geometry of the basin, its location between major fracture zones, and the existence of bordering normal faults are evidence for a pull-apart origin in a dextral, transtensional setting.

The seafloor between the Pikezh and Steller fracture zones is characterized by highs and troughs (Figs. 2 and 3a and b). These highs form en-echelon ridges along the southern slope of Aleutian Ridge. The ridge related to the Steller fracture zone extends from the western side of the

Steller pull-apart basin up to the Kamchatka Mys Peninsula continental rise. No significant compressional deformation is observed on seismic profiles crossing this segment of the trench (Fig. 3a and b). In general, reflectors in the sedimentary cover of the Pacific plate may be traced across the Aleutian Trench into the Aleutian Ridge outer slope. Nevertheless, Seliverstov (1987) suggests that, close to Kamchatka, blocks of oceanic crust from the Pacific plate may overthrust the Aleutian Ridge from the south as a result of displacement along the Pikezh and Steller fracture zones.

The Naturalist fracture zone is located on the Pacific plate and consists of two parts. The northeastern branch can be traced along the western side of the Steller Basin and the outer slope of the Aleutian Trench, where deformation of sedimentary cover and seismic activity are observed. The southeastern branch corresponds to a linear basement high that can be traced from the Steller Basin up to the Kuril–Kamchatka Trench axis. In contrast to the general dextral sense of motion along the Komandorsky fracture zone system, left-lateral displacement of the trench axis is observed in this segment of the fracture zone (Fig. 2). The Naturalist fracture zone is being subducted under Kamchatka, causing fracturing of the overriding plate. The upper part of the Kamchatka continental slope in the continuation of the Naturalist fracture zone is cut by canyons corresponding to east–west faults. These faults can be traced to the middle part of the slope and fore-arc basins. The lower part of the continental slope off Kamchatka is composed of deformed sediments typical of accretionary wedges with ridges parallel to the trench axis and separated by thrusts faults (Seliverstov, 1987).

2.2. Kamchatka Mys Peninsula slope and shelf

A grid of single-channel seismic reflection and echo-sounding profiles covers the area off Kamchatka Mys Peninsula (Seliverstov, 1998) and provides the data base to construct detailed bathymetric and tectonic maps of the area (Fig. 4). Seismic profiles C-4 and C-5 run parallel to the coast east of Kamchatka Mys Peninsula (Figs. 4 and 5a and b). A deep canyon in the northern part represents a fault that splays off the Bering fracture zone. In its upper part, the submarine canyon is some 2 km wide and about 650 m deep (water depth 950 m). Folded strata between 56°35′N and 56°15′N in the offshore profiles C-4 and 5 (Fig. 5a and b) indicate a compressional deformation event of unclear age. Similar folds are observed in Paleogene sediments exposed in coastal outcrops. Offshore, the folds are truncated by an erosion surface on the continental shelf. Some sections of the folded sequence are uplifted along steep faults. This caused the development of half-graben basins in which an onlapping sequence may be trapped (see around 56°30′N profile C-4). Recent fault activity is indicated by the lack of sedimentation south of the fault step near 56°35′N in profile C-4 (Fig. 5). Since the east–west-striking faults are splays off the dextral Bering fracture zone (Fig. 4), we suggest that they are reverse faults. Results of an onshore geological survey support this idea (see Section 3.3).

The Pikezh fracture zone continues to the west into the Pikezh Canyon, which is one of the largest canyons cutting the slope of the Kamchatka Mys Peninsula (Fig. 4). The canyon is traceable from 4000 m water depth in the Kamchatka Strait to the shelf of Kamchatka Mys Peninsula.

The Steller and Aleutian fracture zones form the boundary of the Kamchatka Mys Peninsula and its shelf to the south. The bathymetry of this part south of the Pikezh Canyon exhibits a complicated pattern of canyons and ridges caused by a number of closely spaced splay faults between the major fracture zones (Fig. 4). The prevailing northwest–southeast orientation of structural elements beneath the slope corresponds to the general orientation of the Steller and Aleutian fracture zones. An east–west-trending ridge (Fig. 4) on the slope of the peninsula (the top of this high is at 55°47′N, 162°50′E) corresponds to a left-hand bend in the northern section of the Steller fracture zone and apparently represents a compressional structure (Fig. 4). Canyons northwest of this high correspond to faults related to the Pikezh fracture zone. Both the Steller and Aleutian fracture zones cross the north-northwest–south-southeast Kamchatsky Canyon, which apparently follows a large fault, but the kinematics of this fault and its

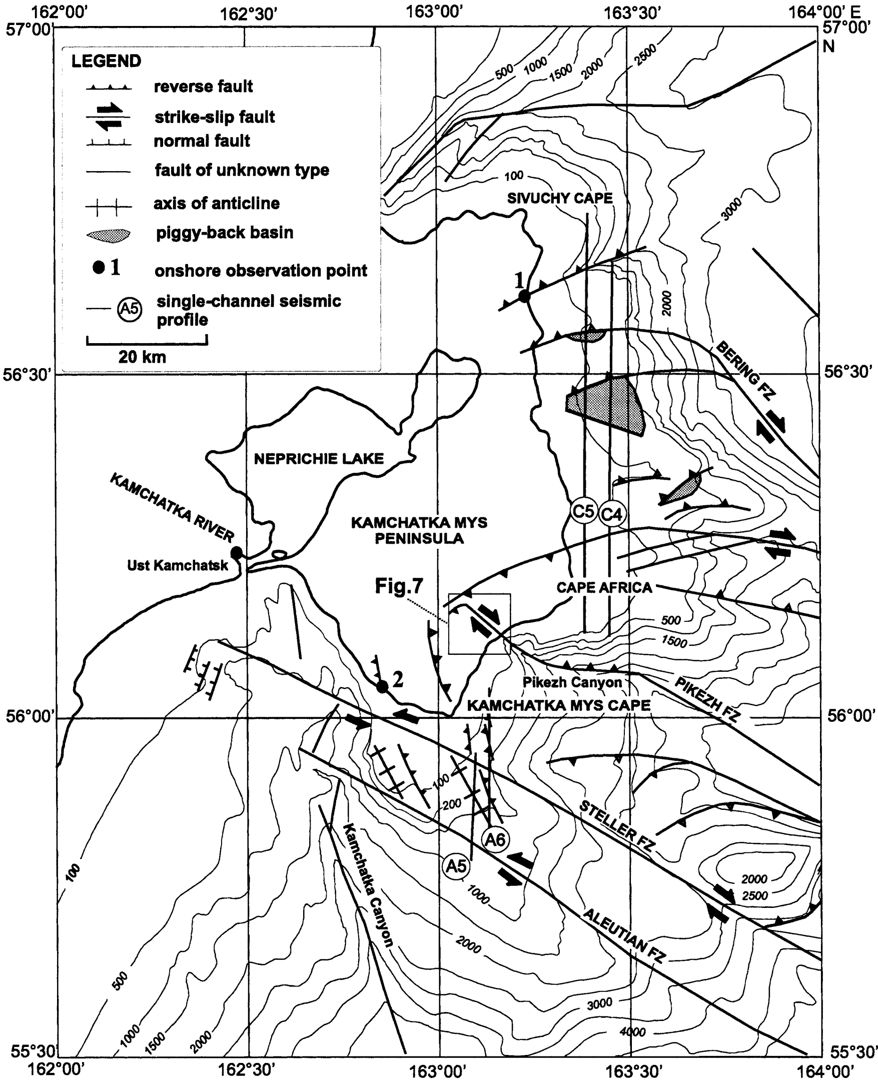


Fig. 4. Bathymetry (meters) and main tectonic features off Kamchatka Mys Peninsula. The rectangle shows the location of the area in Fig. 7.

relationship with the main fracture zones are still unknown.

Profiles A-5 and A-6 run north–south off the southern tip of the peninsula (Fig. 4). An upright, northwest-trending fold is unconformably overlain by subhorizontal coarse-grained sediments (Fig. 6a and b). Samples from the slope area have Late Pliocene to Early Quaternary age (Seliverstov, 1998), suggesting that folding took place in the Late Quaternary. Recent deformation is also indicated by the presence of steep faults in the northern part of profile A-6. The occurrence of steps in the seafloor indicates that fault movement is occurring faster than erosion and sedimentation.

The northwest–southeast Steller fracture zone has been traced up to the shelf area, south of the Kamchatka estuary. It terminates in the west at a trough-like, northwest-trending canyon. Paleontological data on dredge samples show that this structure is of very recent (Holocene) origin.

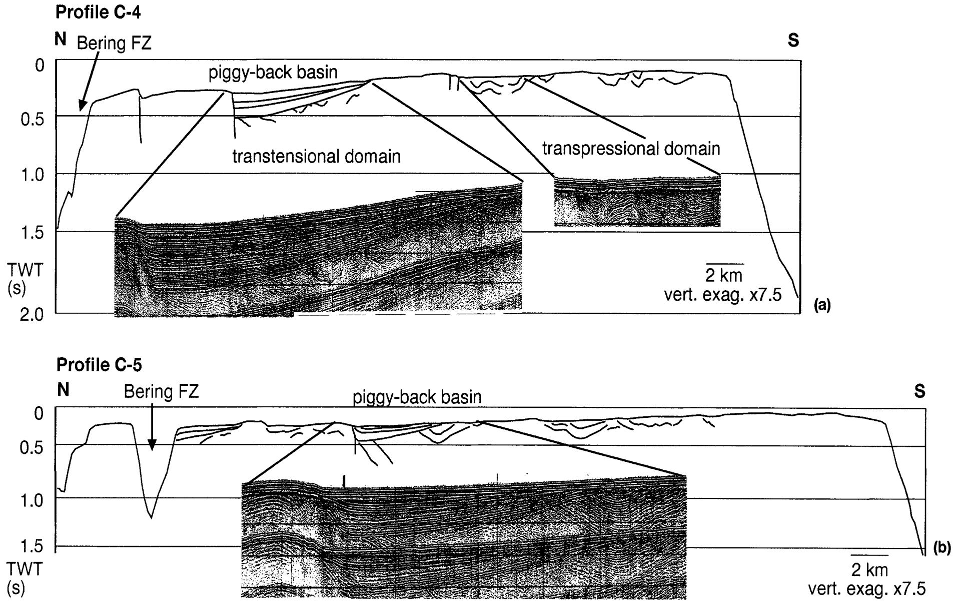


Fig. 5. (a), (b) Single-channel seismic profiles C-4 and C-5 showing splay structure at the western end of the Bering fracture zone. For location, see Fig. 4.

Differences in the lithology of dredged rocks north and south of the fracture zone are evidence for a lateral shift along it. Detailed bathymetric and seismic investigations carried out in this area showed that the sides of the canyon are formed by normal faults perpendicular to the Steller fracture zone (Seliverstov, 1998). Left-lateral movement is inferred from the bends in the Kamchatka Canyon observed in the areas where it is crossed by the Steller and Aleutian fracture zones.

3. Onshore neotectonics of the Kamchatka Mys Peninsula

We examined different areas on the Kamchatka Mys Peninsula for neotectonic activity. Recent deformation is verified by thrusting in alluvial sediment, the involvement of Recent to Upper Pliocene deposits in the deformation, and changes in the drainage pattern of small rivers. The offshore fracture zones of the Aleutians continue onshore and are traceable in aerial photographs.

3.1. Pikezh deformation zone

The Pikezh fracture zone appears as a deep submarine canyon on the shelf and continental slope, and continues onshore into the Pikezh deformation zone (Fig. 4), which was identified in earlier investigations (Khotin, 1976). Cretaceous acid lavas and tuffs of the Smagin unit and mafic and ultramafic rocks of the Kamchatka Mys ophiolite complex crop out in the southern part of the Kamchatka Mys Peninsula. In contrast, clastic sediments of the Cretaceous Pikezh unit crop out north of the Pikezh fracture zone (Khotin, 1976; Shapiro, 1976; Zinkevich et al., 1985; Tsukanov, 1991). In the central and western part of the peninsula, Late Pliocene to Early Quaternary coarse-grained, semi-consolidated marine sediments of the Olkhovsk Formation unconformably overlie the older formations (Basilyan and Bylinskaya, 1997).

We have investigated the Pikezh deformation zone in detail (Gaedicke et al., 1998). It covers an area of about 100 km^2, juxtaposes the Smagin and Pikezh units, and forms a complexly deformed,

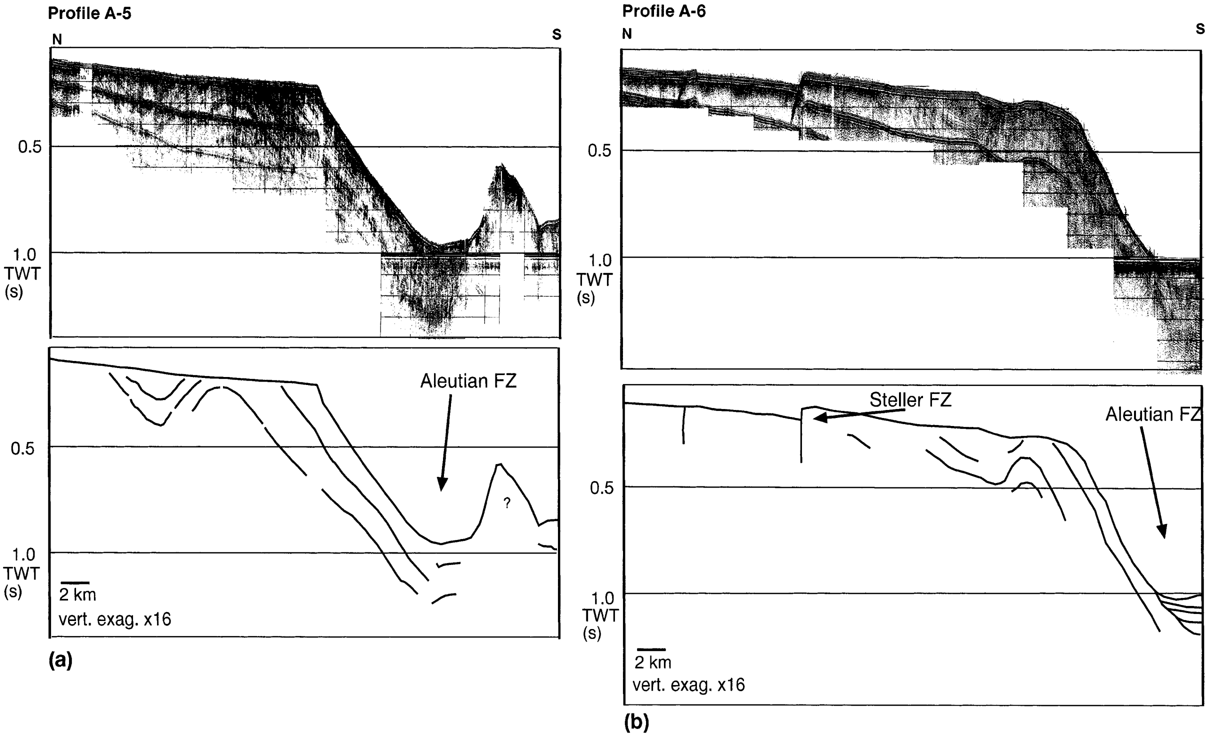


Fig. 6. (a), (b) Single-channel seismic profiles A-5 and A-6 showing splay structure at the western end of the Steller and Aleutian fracture zones. For location, see Fig. 4.

mélange-like unit. Single splays off the main fault zone may be more than 10 m wide. Two types of recent fracture are observed: northwest–southeast, right-lateral strike-slip faults and east-northeast to north-northwest reverse faults. On the east coast of the Kamchatka Mys Peninsula, the Pikezh deformation zone is more than 5 km wide (Fig. 7). The zone continues for 8–10 km to the northwest, ending north of the Perevalnaya River. The zone consists of elongated blocks and slices of the Smagin, Pikezh and Olkhovsk rocks, and the ultramafics, gabbros and basalts of the southern Kamchatka ophiolite complex in a matrix of strongly weathered reddish to greenish jasper and mudstone. The components are elongated in a northwest–southeast direction. This mixture of weak and strong rocks in a clay matrix points to a mélange of tectonic origin. Tectonic contacts between blocks and lenses with the surrounding matrix are generally very sharp, although the sense of shear on these contacts is not preserved.

High-resolution aerial photographs show a major Holocene strike-slip fault on the southeastern side of the Perevalnaya River extending northwest from the coast (320°) for about 8 km (Fig. 7). In the field, the fault is marked by a steep gully that cuts the rivers draining toward the Perevalnaya River (Fig. 8a). This fault offsets the Nepropuskovy stream dextrally about 250 m. Since the Nepropuskovy stream cuts alluvial terraces of Early to Middle-Pleistocene age, the rate of displacement can be estimated as 2.5 mm/year. Alluvial deposits exposed on a displaced section of the Nepropuskovy stream are cut by faults striking 50–80° and dipping 85–88°. These are probably faults splaying off the main fault. Locally, the offset stream flows in a ravine exceeds 40 m in depth (Fig. 7b, profile B–B′).

In the area of the upper tributaries of the Perevalnaya River, the trend of the main fault (Figs. 7 and 8a) changes from northwest–southeast to northeast–southwest. Here, the fault is

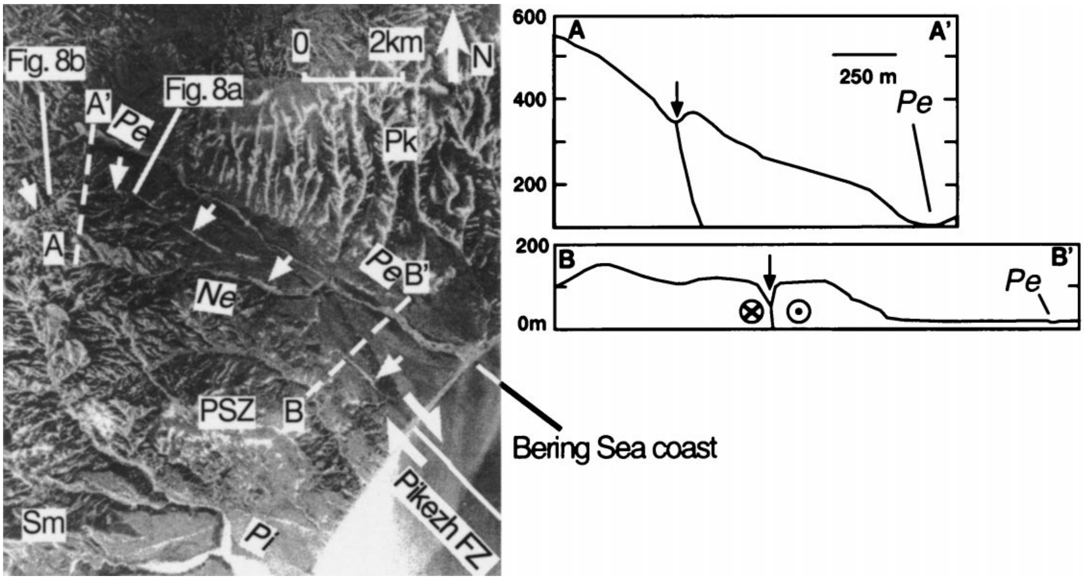


Fig. 7. Aerial photograph of the Pikezh fracture zone (PFZ) and two cross-sections of a recent fault. The active dextral strike-slip fault is visible as a straight line in the photo or as a c. 50 m deep ravine on cross-section B–B′ (indicated by arrows). It continues to the northwest, where it terminates as a thrust fault that forms an NE–SW-trending closed valley, cross-section A–A′. This strike-slip fault is the continuation of the offshore fracture zone corresponding to Pikezh Canyon (see Fig. 4). Locations from where the photos in Fig. 8 were taken are shown. Sm = Smagin unit, Pk = Pikezh unit, PZS = Pikezh shear zone, N*e* = Nepropusknoi stream, P*e* = Perevalnaya River, P*i* = Pikezh River.

expressed at the surface as a closed gully up to 50 m wide at an elevation of 300 m above sea level. The long axis of this gully is perpendicular to the slope of the mountain (Fig. 7b, profile A–A′), and it has already considerably modified the drainage system on the south side of the mountain (height 700 m). Streams draining the mountain are truncated by the fault scarp, form small lakes at the scarp, change direction, and flow parallel to the scarp (Fig. 8b) until a new valley is cut. Smaller streams that initially flowed straight downhill have lower sections still showing alluvial deposits, but are now dry because the upper section of the river has been diverted by the scarp. The hanging wall of the fault has been uplifted by about 12 m. Some undulating sections of this gully are dry and contain no alluvial deposits, thus indicating the non-erosional origin of the gully.

3.2. Northern Kamchatka Mys Peninsula

Lower Eocene sandstone is exposed on the north coast of Kamchatka Mys Peninsula. A submarine canyon that follows a splay off the Bering fracture zone continues on land as a broad, west-southwest–east-northeast valley (observation point 1; Fig. 4), which widens into Lake Nerpichie to the southwest. The valley is bounded by neotectonic scarps several hundred meters high. Major reverse faults crop out along the north shore (Fig. 9a). They are subparallel and dip north-northwest (315–335°) at 65°. Thrusting along these faults is inferred from the uplift of the hanging wall block, and by well-developed drag folds in the footwall. North and south of this valley, the rocks of the Lower Eocene formation form a low-angle monocline (5° dip in a direction of 25°).

3.3. Southwestern Kamchatka Mys Peninsula

The lower part of the Olkhovsk Formation (Late Pliocene to Early Quaternary) crops out in cliffs along the southwest coast of Kamchatka Mys Peninsula (Figs. 4 and 9b). The lower section is composed of conglomerates and gravel grading upward to sandstone and silty sandstone. Several

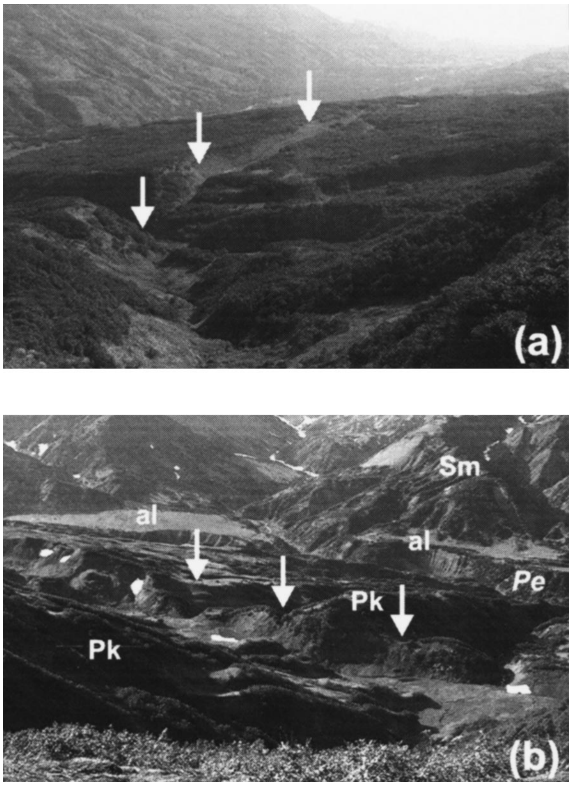


Fig. 8. (a) View to the southeast of the onshore continuation of the Pikezh fracture zone. Arrows point to a strike-slip fault, which appears as a V-shaped valley that cuts across the valleys of small streams. It shifts the Nepropusknoi valley to the right. (b) View to the northwest showing an active thrust fault. The thrust has blocked the drainage systems of small streams, which now deposit their sediment in ponds at the base of the fault scarp. Arrows mark abandoned valleys belonging to the former drainage system that have been uplifted by the fault. al = alluvial deposits, *Pe* = Perevalnaya River valley, Sm = Smagin unit, Pk = Pikezh unit. See Fig. 7 for location.

reverse faults dipping 55°W and cutting the Olkhovsk Formation crop out in the cliff at observation point 2 (Fig. 9b). The sense of displacement on the faults is indicated by: (1) thrusting of conglomerates of the lower section of the formation onto finer grained upper parts, and (2) drag folding of the footwall rocks in the vicinity of fault planes. Moreover, the sandstones in the footwall dip to the east, whereas elsewhere they have a westward dip.

A fault can be distinctly seen in aerial photographs and satellite images north of Cape Africa (Fig. 4). It bounds a ridge to the northwest that is topped by an eroded surface at an elevation of about 700 m. This surface is interpreted as a Late Pleistocene marine terrace (Melekestsev and Erlikh, 1974). Age determinations on the displaced alluvial terraces indicate that the fault is Holocene and has a right-lateral offset with a rate of about 2 mm/year (Kozhurin, 1985).

To the south of the Pikezh deformation zone, at observation point 2, the recent reverse faults strike north-northwest–south-southeast. Since these appear to splay off the Steller fracture zone, we suggest that left-lateral displacement has taken place in this area. This is in agreement with the sense of displacement determined on the basis of the orientation of fold axis and faults in marine seismic data for the continental shelf south of the Kamchatka Mys Peninsula (Fig. 4). Many thrusts, whose orientations vary from north–south to northwest–southeast have been mapped in the southwestern part of Kamchatsky Mys Peninsula (Khotin, 1976, Zinkevich et al., 1985). Khotin (1976) suggests that deformation started in the mid-Eocene. We believe that thrusting may still be continuing, especially in the case of the fault extending north from Cape Kamchatka Mys (Fig. 4), where Upper Cretaceous rocks overlie Pliocene–Quaternary deposits.

4. Seismicity

The area is characterized by high seismicity (Fedotov et al., 1987; Zobin et al., 1988; Geist and Scholl, 1994) (Figs. 10 and 11), although no deep to intermediate earthquakes occur along the westernmost Aleutian arc, pointing to the transform origin of the Aleutian arc. Some features of the seismicity along the northern Kuril–Kamchatka arc are different from the seismicity pattern typical of subduction zones. Earthquake foci related to the subduction of the Pacific plate under the Kamchatka Peninsula in the junction area form a fan-shaped pattern.

4.1. Shallow seismicity

Most shallow earthquakes in subduction zones are related to the main thrust, and their epicenters

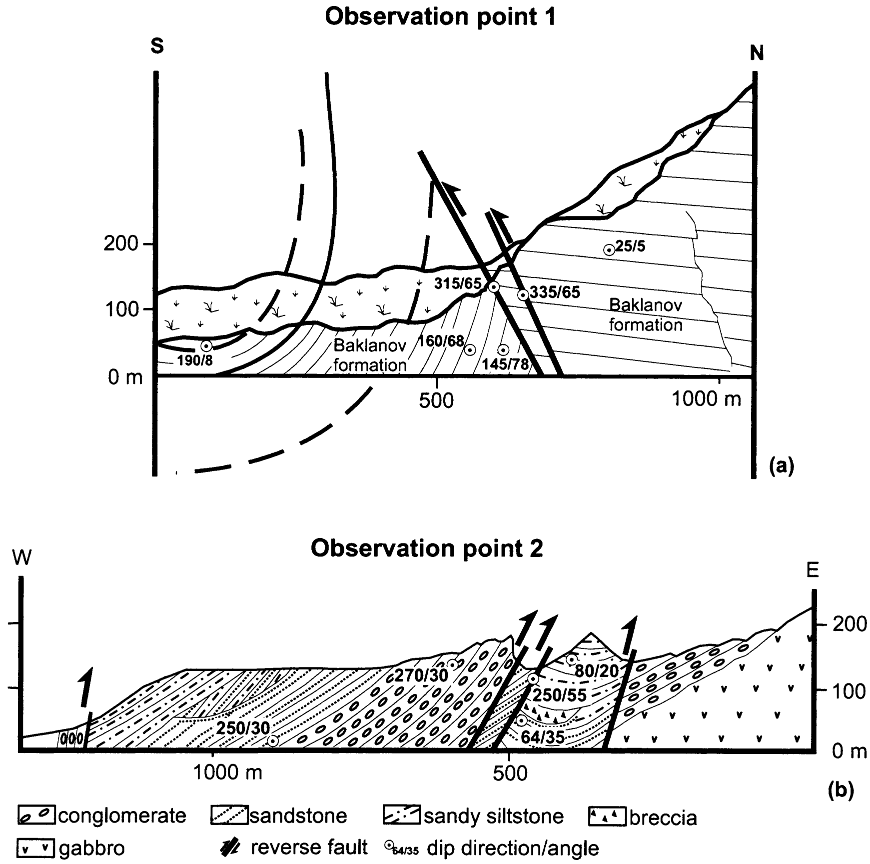


Fig. 9. (a) Sketch of coastal outcrop at point 1 in Fig. 4. (b) Cross-section of the Olkhovsk Formation at point 2 in Fig. 4 [from Basilyan and Bylinskaya (1997)].

are located along the continental slope. South of the Kronotsky Peninsula, this typical pattern of shallow earthquakes parallel to the trench was recorded by the regional network of seismic stations along the Kamchatka subduction zone during 1977 (Fig. 10). A seismic belt with an earthquake distribution typical of subduction zones extends from the southern tip of Kamchatka as far as the Kronotsky Peninsula. Further to the north, the distribution of earthquakes changes: in this area, the epicenters of earthquakes spread over the whole continental slope and beneath the eastern part of Kamchatka, and continue northwards up to the Aleutian Trench.

Several bands of earthquake epicenters are observed in the junction area, if strong events with a magnitude of 5 or more are observed over a period of 30 years (Fig. 11). These bands trend northwest–southeast and east–west. The more distinct band runs from the southern end of Kamchatka Bay and to Bering Island. It can be traced as far as the Central Kamchatka depression, approaching it in the region where the chain of active volcanoes is offset to the west (Fedotov et al., 1985). This band is characterized by focal mechanism solutions with strike-slip motion (Zobin and Simbireva, 1977; Zobin, 1990; Geist and Scholl, 1994). We infer that it is related to displacement along the Naturalist fracture zone, which is being subducted under Kamchatka.

The western branches of the Bering, Steller, and Aleutian fracture zones (Fig. 2) are also active, and correspond to seismic zones east and south of the Kamchatka Mys Peninsula (Fig. 11). Focal

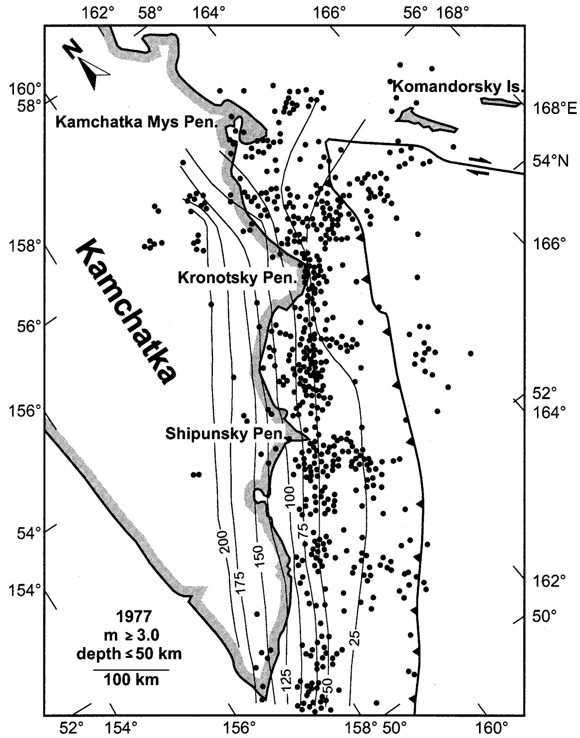


Fig. 10. Shallow seismicity ($h \leq 50$ km) of the Kamchatka subduction zone recorded by the local seismometer network in 1977. Contour lines indicate depth (kilometers) of the Benioff zone [according to Fedotov et al. (1985)]. The line with barbs indicates a trench; the line with arrows marks a strike-slip fault.

mechanism solutions of earthquakes beneath the Kamchatka Mys Peninsula and offshore exhibit combinations of strike-slip displacement and compression perpendicular or oblique to the Kamchatka Mys Peninsula. This zone is interpreted as the area of recent collision of the Aleutian arc with Kamchatka (Geist and Scholl, 1994). Reverse faults and minor folds related to major strike-slip faults are prominent features in this area, both onshore and offshore (Figs. 2 and 4).

Further to the east, inside the western segment of Aleutian arc, earthquake epicenters are observed in two zones, north and south of Bering Island. The main extensional feature south of the Bering Island is the Steller Basin as part of the Aleutian Trench. Normal faulting is inferred from focal mechanisms (Fig. 11). North of Bering Island, earthquakes cluster near the base of the continental slope, and do not occur often with a magnitude of more than 4.5, i.e. less than those off the Kamchatka Mys Peninsula (Zobin et al., 1988). The seismicity is relatively constant only near the Kamchatka Mys Peninsula, where the Aleutian and Kuril–Kamchatka seismic zones meet and the strongest earthquakes are recorded.

4.2. Strong earthquakes and seismic potential of junction area

The Kamchatka region is characterized by very high seismicity and a well-defined Benioff zone beneath eastern Kamchatka. During the 20th century, seven events with a magnitude $M_w \geq 7.7$ have occurred with epicenters beneath the continental slope of Kamchatka (Fedotov et al., 1987; Vikulin, 1997). According to their aftershock distributions, all rupture zones of the strong earthquakes south of the Kronotsky Peninsula extend beneath the continental slope (Fig. 12) exhibiting a well-defined Benioff zone related to the subduction of the Pacific Plate under eastern Kamchatka.

The fault related to the strong earthquake recorded on 15 December 1971 ($M = 7.8$) in the junction area extends northwest along the Aleutian arc (Zobin et al., 1988). Macroseismic data analysis of two other strong earthquakes with magnitudes $M_w \geq 7.7$ in the junction area (1 Jan. 1917 and 2 Feb. 1923) also show rupture zones trending northwest–southeast and east–west (Vikulin, 1986). The 1917 event occurred near the western end of the Aleutian trench and may, like the 1971 earthquake, be connected with displacements along the Pikezh, Steller and Aleutian fracture zones. The rupture zone of the 1923 earthquake was apparently associated with displacement along continuation of the Naturalist fracture zone beneath the continental slope of the Kamchatka Peninsula.

North of the junction area, only one strong earthquake has been recorded, on 22 November 1969 (Fig. 12) with a rupture zone on the continental slope off Kamchatka, east of the Ozernoy Peninsula. In view of the northeast–southwest trend of the fault zone perpendicular to the strike of the Alpha fracture zone, it is inferred that this event was not associated with the Komandorsky fracture zone system, but

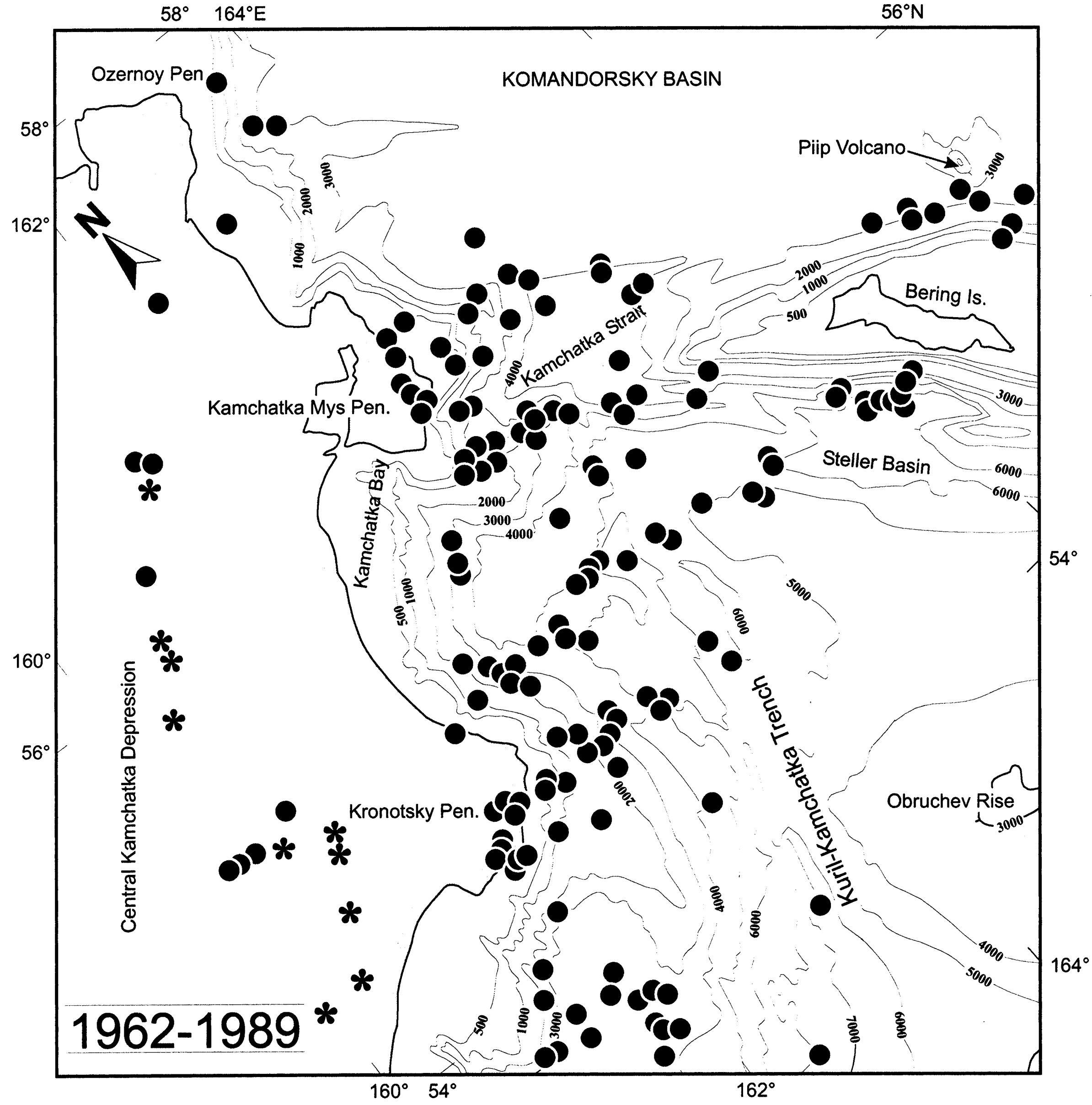


Fig. 11. Shallow seismicity ($h \leq 50$ km) in the Kamchatka–Aleutian junction area. Epicenters are from the Kamchatka regional catalog (1962–1989, $m_b \geq = 5$).

may be related to another plate boundary separating the northern Kamchatka Peninsula from the Komandorsky Basin (Savostin et al., 1983).

Only two earthquakes with $M_w = 7.1$ occurred north of Komandorsky Islands in the 20th century (Fig. 12). These two earthquakes, together with lower-magnitude earthquakes, suggest that the Bering fracture zone has a lower seismic potential than the Pikezh and Steller fracture zones and, consequently, that the main displacement between North American and Pacific plates occurs along the fracture zones south of the Aleutian arc.

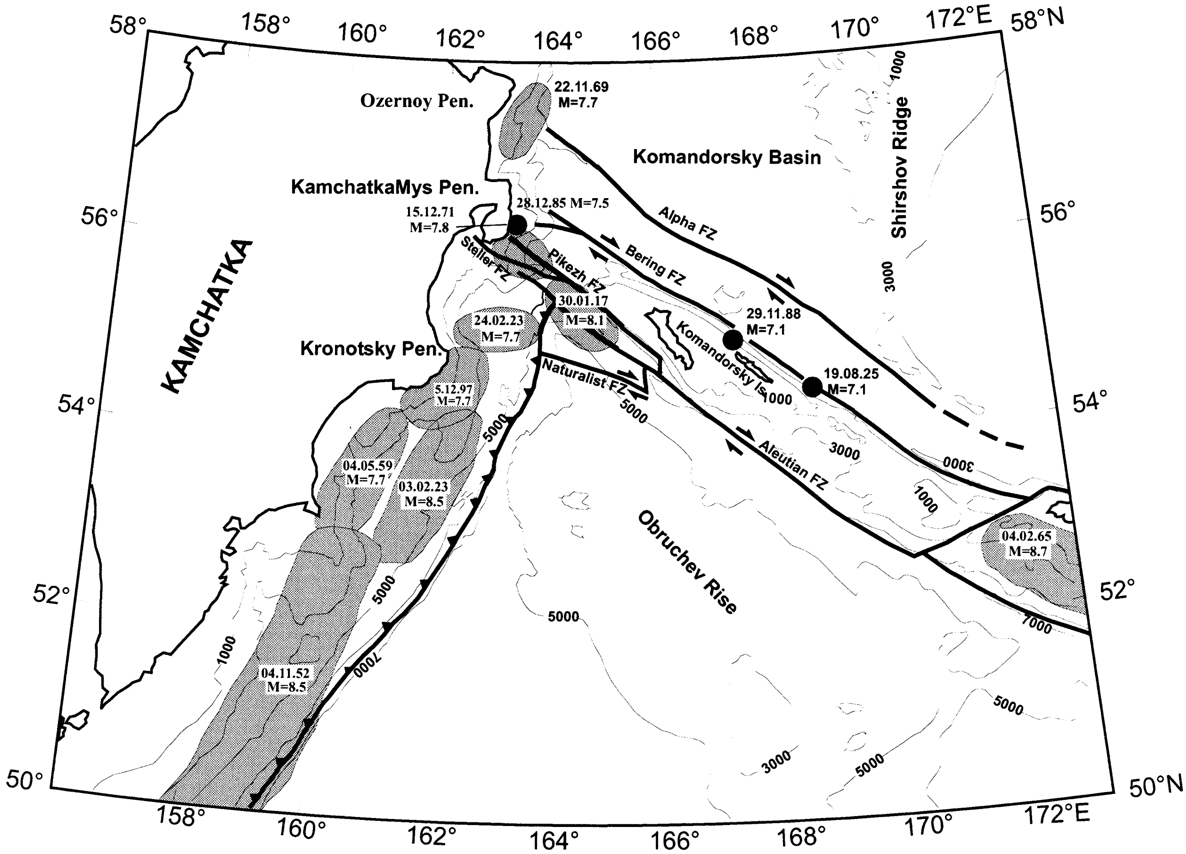


Fig. 12. Rupture zones of the major earthquakes in the Kamchatka–Aleutian junction area [according to Vikulin (1997)]. Earthquakes with a magnitude of $M_w > 7$ are shown.

4.3. Segmentation of the downgoing Pacific plate in the junction area

The Benioff zone beneath Kamchatka has been investigated in detail by Fedotov et al. (1985, 1987). This seismic zone extends about 700 km northeastwards from the southern tip of the Kamchatka Peninsula. In this area, the Pacific plate descends at an angle of about 50° to the northwest. North of the Kronotsky Peninsula, this angle decreases to 35°. Thus, the seismic zone in the Aleutian–Kamchatka junction area is wider and more fragmented than in the southern part of the Kamchatka continental margin.

Earthquake centers connected with the subduction of the Pacific plate under Kamchatka Peninsula in the junction area form a fan-shaped pattern. The trend of shallow (0–50 km) earthquake foci bends to the east, and the trend of the deep (51–200 km) foci bends sharply to the north (30° anticlockwise) (Fedotov et al., 1985). The northward bend of the focal zone may be a result of buckling of the downgoing Pacific plate at the arc junction (Geist and Scholl, 1994). On the other hand, these features may be caused by individual fractures in the Komandorsky fracture zone system.

The eastward bend in the hypocenter trend in the depth interval 0–50 km is observed in clusters of earthquake epicenters extending towards the Aleutian arc (Figs. 10 and 11). These clusters are related to deformation along the Komandorsky fracture zone system. Analysis of earthquake density (Fedotov et al., 1985, 1987) for the 51–100 km,

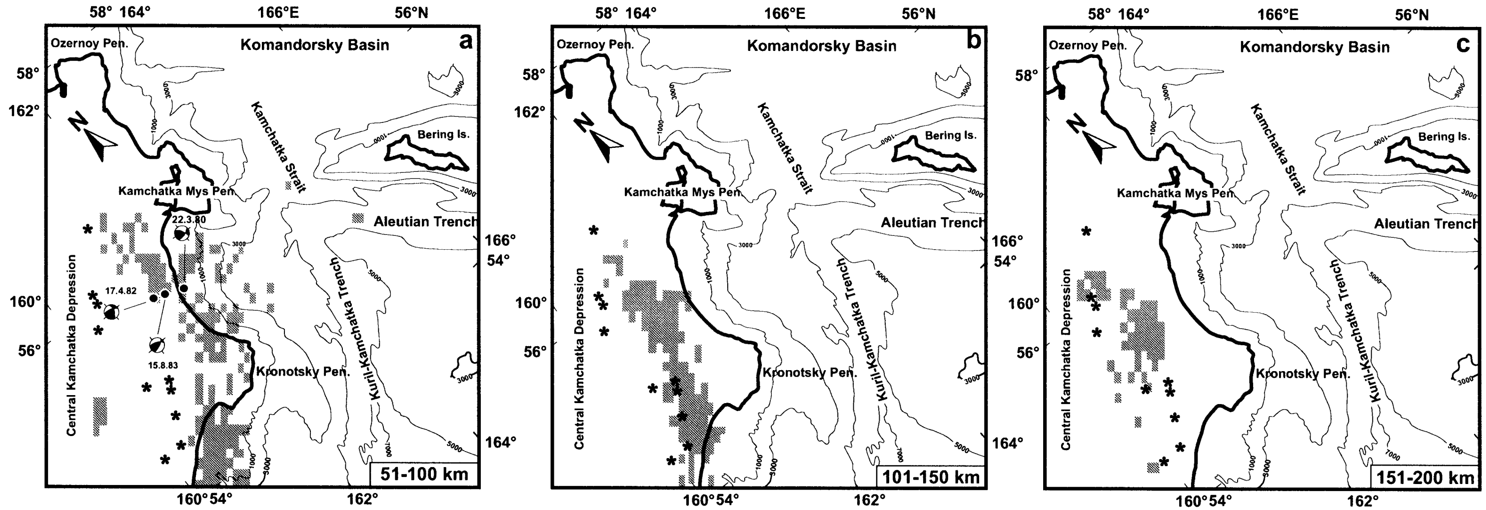


Fig. 13. Density of earthquakes at different depth intervals. (a) 51–100 km, (b) 101–150 km, (c) 151–200 km [according to Fedotov et al. (1985)]. Density was determined as the number of events with a magnitude $m_b = 3.2$ in a 6.25×10.5 km^2 area between 1962 and 1982. Gray: two to nine events per 6.25×10.5 km^2 area. Dots indicate a series of strong intermediate earthquakes that occurred from 1980 to 1983. Asterisks mark active volcanoes. Focal mechanisms are shown.

101–150 km and 151–200 km depth intervals documents the fragmentation of the crust in the junction area (Fig. 13). In this area, the westward shift in seismic activity is best exhibited in the 151–200 km depth interval (Fig. 13c). Earthquake occurrence in the intermediate interval (51–100 km) is diffuse north of the Kronotsky Peninsula. Therefore, faults separate a number of slices dipping beneath Kamchatka. The high earthquake density in the 51–100 km interval also extends westward under the continental slope (Fig. 12). South of the Kronotsky Peninsula, the high seismicity belt in the depth interval 51–100 km narrows beneath the continental slope (Fedotov et al., 1987). In contrast, the intermediate earthquakes under the inner trench slope in the junction area may be connected with a longitudinally segmented subducting slab. The segment boundaries probably form extensions to the major Komandorsky fracture zones.

For the northern part of the Kamchatka Trench, south of the junction area, the fragmentation of the downgoing slab is evident, firstly, in a general westward displacement of the seismic zone, best expressed within the depth interval of 51–100 km and, secondly, by three parallel bands of earthquake hypocenters within the 0–50 km depth interval (Fig. 11) extending from the Steller pull-apart basin to the northern part of the Kronotsky Peninsula. The hypocenters of earthquakes are located in the oceanic lithosphere.

A series of three strong earthquakes at intermediate depth (60–100 km) in the early 1980s (Zobin, 1982; Zobin et al., 1988) supports the theory of slab segmentation (Fig. 13a). The first earthquake, magnitude $M_w = 5.7$, was on 22 March 1980; the second, magnitude $M_w = 5.6$, on 17 April 1982; and the third, magnitude $M_w = 6.2$, on 15 August 1983. Focal mechanisms of the 1980 and 1982 events displayed a strike-slip sense of displacement and the 1983 event was compressional. The large magnitude of the 1983 event points to an intraplate origin (Zobin et al., 1988).

5. Geodynamic implications

5.1. Timing of collision and deformation

There are several models of the tectonic evolution of Eastern Kamchatka, but all models come to the conclusion that accretion and collision are the most important processes in the evolution of western Kamchatka (Watson and Fujita, 1985; Tsukanov, 1991; Bazhenov et al., 1992; Zinkevich et al., 1993; Geist and Scholl, 1994; Bakhteev et al., 1997; Pechersky et al., 1997). The most controversial aspects are the timing of collision and the paleoposition of exotic terranes.

A change in the direction of motion of the Pacific plate relative to the North American plate in the mid-Eocene (43 Ma) led to a reorganization of plate structures in the northwest Pacific and the development of a strike-slip regime along the western Aleutian arc (Engebretson et al., 1987; Scholl et al., 1987). Northwestward motion of the Aleutian island arc may have started after the mid-Eocene.

Paleomagnetic data show that, in the Eocene, the Kamchatka Mys terrane was located more than 2000 km south of its present-day position, and that it was accreted to Kamchatka 15 Ma ago (Bazhenov et al., 1992; Pechersky et al., 1997; Levashova et al., 2000). According to this model, an oceanic basin that belonged to the Kronotsky arc until Middle Miocene was located between the Kamchatka margin and Kamchatka Mys terrane. Provenance data, paleocurrent directions, and structural data suggest that the Kamchatsky Mys terrane was accreted to Kamchatka in Middle or Late Eocene (Tsukanov, 1991; Zinkevich et al., 1993; Alexeiev et al., 1997). This may have involved multiple deformation and collision, since the ophiolite complex of the Kamchatka Mys terrane was deformed several times (Zinkevich et al., 1985; Bakhteev et al., 1993).

The Tyushevka basin embraces the northwestern part of the Kronotsky Peninsula and extends northeast for 300 km along the collision suture zone between both the Kamchatka Mys and Kronotsky terranes and mainland Kamchatka. Predominantly sandstone and siltstone accumulated in this basin in a deep marine slope environment during the late Eocene to mid-Miocene. Provenance analysis and sedimentary structure studies were carried out in the northeastern and central parts of the Tyushevka basin (west of the Kamchatka Mys and Kronotsky Peninsulas). The provenance of the Tyushevka sandstones is in the western and northwestern parts of Kamchatka (Alexeiev et al., 1999). Structural investigations carried out by the authors show that the upper part (Miocene) of the Tyhuschvaka basin sediment west of the Kamchatka Mys Peninsula has undergone no significant deformation. The upper Eocene to Middle Miocene Tyushevka basin is interpreted to represent a foredeep or foreland basin formed by lithosphere flexure. This implies that no back-arc or oceanic basins have been present between the Kamchatka Mys and Kronotsky terranes and mainland Kamchatka since the Late Eocene and, therefore, that collision of the terranes with Kamchatka occurred before that time. If collision had taken place after that time, sediment derived from Kamchatka would have been trapped in a back-arc or intra-oceanic basin between Kamchatka and the terranes.

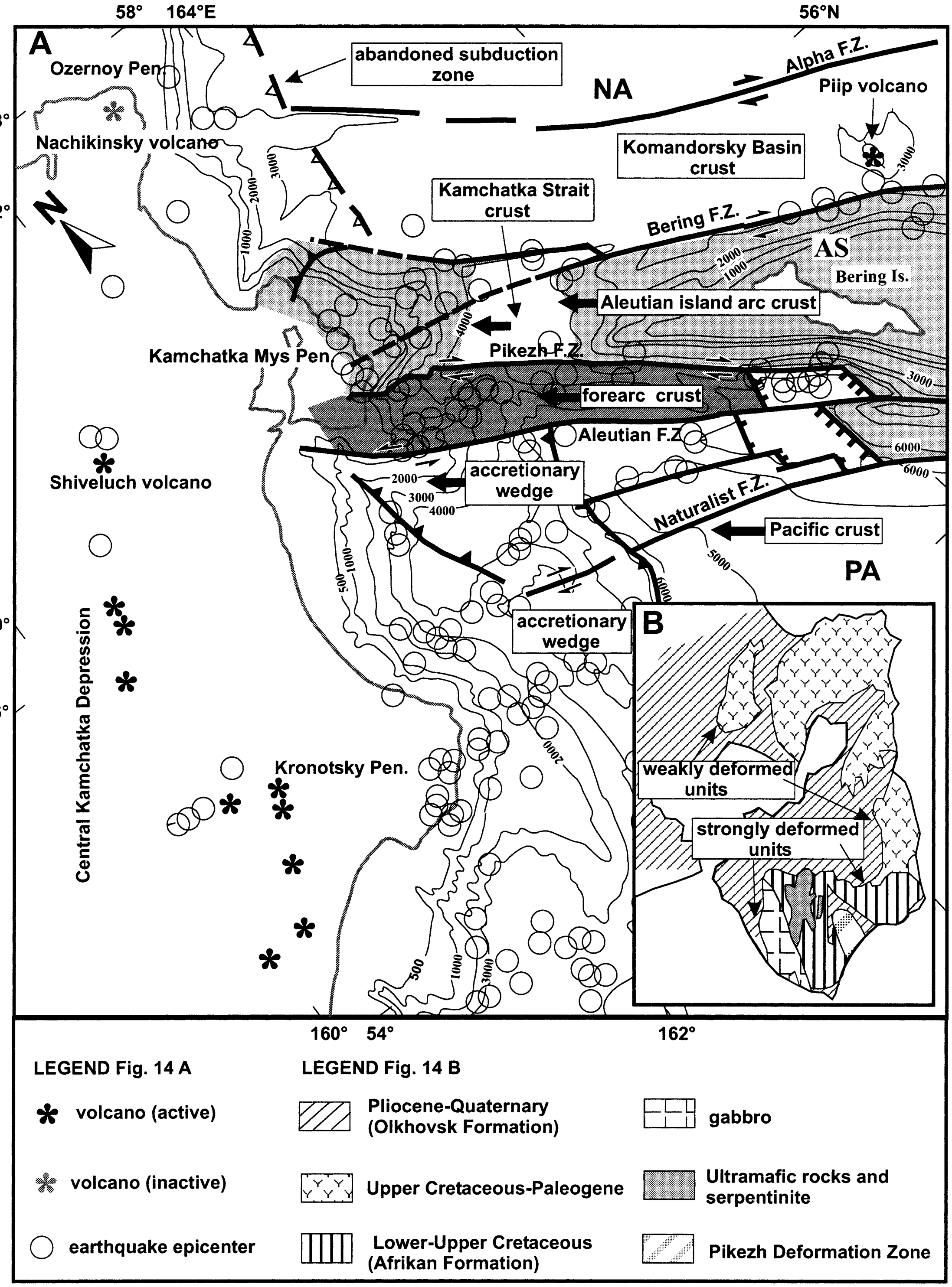
The youngest phase of collision must have started in the Late Pleistocene, when marine sediments of the Olkhovsk Formation (Upper Pliocene to Lower Quaternary) became rapidly uplifted on the Kamchatka Mys Peninsula. Analysis of mollusk and foraminifer assemblages (Basilyan and Bylinskaya, 1997) verify that 1.5 Ma ago a shelf and continental slope ranging in depth from 60 to 500 m existed at the site of the Kamchatka Mys Peninsula. The maximum uplift for the Olkhovsk Formation is estimated to have been 1500 to 2000 m (Basilyan and Bylinskaya, 1997). The rate of uplift of the southeastern part of the Kamchatka Mys Peninsula is 1.0 to 1.3 mm/year decreasing to the west to zero in the Nerpichie Lake area north of Ust Kamchatsk. Similar rates of uplift have been obtained for the marine terraces of Kamchatka Mys Peninsula, now at an elevation of up to 700 m (Melekestsev and Erlikh, 1974). Involvement of Upper Pliocene to Lower Quaternary sediments of the Olkhovsk Formation in mélange formation give further evident for neotectonic activity. We believe this tectonic activity is caused by the collision and underplating of fragments of the Aleutian island arc.

The location of the subduction zone along the eastern Kamchatka Peninsula is well documented from the distribution of earthquakes and volcanism. The zone of high seismicity can be traced along the east coast of Kamchatka up to the junction with the Aleutian island arc. Both the seismicity and the volcanism are related to the present-day subduction of the Pacific plate. Shiveluch, the northernmost active volcano on Kamchatka (Fig. 14a), is at the latitude of Kamchatka Mys Peninsula, whereas Holocene volcanism extends further to the north, i.e. the Nachikinsky volcano on the Ozernoy Peninsula (Fig. 14a). Data on the distribution of island arc volcanism indicate that the subduction zone existed along the entire western boundary of the Komandorsky Basin until the early Quaternary (Stavsky et al., 1988), when subduction ceased in this area due to the collision of the Aleutian arc with Kamchatka in the region of Kamchatka Mys Peninsula. We believe that the collision of the Aleutian arc with Kamchatka caused a reorganization of plate boundaries in this area and the cessation of subduction north of its present position.

5.2. Recent geodynamics

Evidence for a dextral sense of movement along the Bering, Pikezh and Aleutian fracture zones is given above. However, the Aleutian fracture zone west of its junction with the axis of the Kuril–Kamchatka trench appears, from the trends of compressional structures oblique to it, to be sinistral. Both dextral and sinistral strike-slip faults are present in the northern and southern parts of the Kamchatka junction. An indentation model with collision of Aleutian island arc slivers suggested by Geist and Scholl (1994) fits these observations. Kusunoki and Kimura (1998) show that a similar kind of extrusion is taking place in the Hokkaido–Kuril junction area and suggest that it may be a common tectonic feature even in the case of small-scale collision at an arc–arc junction.

The Naturalist fracture zone segments the crust of the Pacific plate and extends under the accretionary wedge of the Kamchatka margin. Segments up to 200 km thick are observed, and appear as a shift in earthquake frequency (Fig. 13c). We suggest that parts of the accretionary wedge and the Kamchatka Trench axis itself are moving northwest relative to an almost stationary accretionary wedge south of the Naturalist fracture zone


A
58°
164°E
56°N
Ozernoy Pen.
Nachikinsky volcano
abandoned subduction zone
NA
Alpha F.Z.
Piip volcano
Komandorsky Basin crust
Kamchatka Strait crust
Bering F.Z.
AS
Bering Is.
Aleutian island arc crust
Kamchatka Mys Pen.
Pikezh F.Z.
forearc crust
Aleutian F.Z.
Shiveluch volcano
accretionary wedge
Naturalist F.Z.
Pacific crust
PA
54°
162°
160°
56°
Central Kamchatka Depression
Kronotsky Pen.
B
weakly deformed units
strongly deformed units
164°
160°
54°
162°
LEGEND Fig. 14 A
volcano (active)
volcano (inactive)
earthquake epicenter
LEGEND Fig. 14 B
Pliocene-Quaternary (Olkhovsk Formation)
Upper Cretaceous-Paleogene
Lower-Upper Cretaceous (Afrikan Formation)
gabbro
Ultramafic rocks and serpentinite
Pikezh Deformation Zone

(Fig. 14a). In this case, the sense of motion on the western branch of the Aleutian fracture zone north of the Naturalist fracture zone should be sinistral, and the Kamchatka Canyon marks a reverse fault.

The tectonic complexity of the Aleutian island arc increases to the west (Figs. 1, 2 and 4). For example, its westernmost Komandorsky segment is characterized by the splaying of the major fracture zones into several branches and the formation of transpressional and transtensional structures. Transtentional structures, like the Steller Basin, are common features in the eastern, trailing parts of the Komandorsky fracture zone system. The transpressional structures appear on the leading edges in the west, starting at the shelf and continental slope of Kamchatka Mys Peninsula.

The rate of displacement of the onshore section of the Pikezh fracture zone is 2.5 mm/year in the Late Pleistocene (see Section 3). Similar rates are estimated for the onshore continuation of the dextral strike-slip Bering fracture zone (Kozhurin, 1985). This fault offsets the contour lines of uplifted marine terraces (age 6000 ± 50 years) by 12 m, yielding a rate of displacement of 2 mm/year in the Holocene. Bakhteev et al. (1992) determined displacement rates of 10–20 mm/year for the dextral continuation of the Pikezh fracture zone. This fault offsets Late Pleistocene–Holocene terraces by 100–200 m. Such a high displacement rate does not agree with the model of Geist and Scholl (1994), who estimated, using the thin viscous sheet theory, an average convergence rate across the Kamchatka Mys collision zone of 3 mm/year. This estimate was mainly constrained by the inferred change in crustal thickness beneath the collision zone over the last 5 Ma.

The Komandorsky fracture zone system, which comprises, from north to south, the Alpha, Bering, Pikezh, Aleutian and Naturalist fracture zones, is in fact the Pacific–North American plate boundary, at which the rate of convergence is 7.9 cm/year (DeMets et al., 1990). The movement is not confined to any single master fault. Cormier (1975) suggested that plate motion in the western segment of the Aleutian island arc is spread over the width of the Aleutian Ridge. The existence of several fracture zones is evidence that plate motion is distributed between them. Geological observations suggest that during the Holocene the rate of strike-slip movement along the onshore continuation of the Pikezh fracture zone may have changed from 2 to 20 mm/year. The seismic potential of any single fracture zone increases from north to south over the Komandorsky fracture zone system. Therefore, we suggest that the displacement rate also increases from north to south. It follows that the southern crustal blocks are moving faster northwestwards than the northern blocks (Fig. 14a). Similarly, the central part of the southern Kamchatka Mys Peninsula are more deformed than the northern parts (Fig. 14b).

5.3. Crustal structure and collision

Typical of the Aleutian arc is a block structure made up of rhomb-shaped blocks of varying size (Geist et al., 1988). These blocks or slivers consist of island-arc crust and are separated by down-faulted segments of thinned island arc crust or oceanic crust. The Bering Island and Kamchatka continental slopes are separated by the Kamchatka Strait, which is more than 4000 m deep. We suggest that the collision of the Aleutian island arc with Kamchatka is a discontinuous process depending on which types of crust are actually colliding. In consequence, the plate boundaries must become reorganized after each collision event. The Holocene cessation of volcanism north of the junction area and a cluster of earthquake hypocenters at depths of up to 100 km beneath the Kamchatka Strait (Fedotov et al., 1985) may have been caused by Holocene reorganization of the plate boundaries due to an onset collision.

The Bering fracture zone separates the southern part of the Komandorsky Basin from the Aleutian ridge, which consists of island arc rocks. Magnetic

Fig. 14. (a) Tectonic indentation model for the Kamchatka–Aleutian junction area. Length of the bold arrows indicates the relative motion of slivers (different shades of gray) of the Aleutian arc with respect to Kamchatka. NA = North American Plate; AS = Aleutian island arc slivers; PA = Pacific Plate. (b) Formations of the Kamchatka Mys Peninsula. The degree of deformation is indicated.

anomalies indicate that the crust of the southern part of the Komandorsky Basin is of oceanic origin and was formed between 10 and 20 Ma ago (Valyashko et al., 1993). Up to the Late Quaternary, the southern part of the Komandorsky Basin moved northwestwards and was subducted under northern Kamchatka, and, after cessation of subduction, it became part to the North American plate.

Between the Bering and Pikezh fracture zones, the Aleutian Ridge consists of crust of different origins (Fig. 14a). Paleogene–Neogene volcanic, volcaniclastic and sedimentary rocks of island-arc affinity crop out on the Komandorsky Islands (Ivaschenko et al., 1984; Tsvetkov, 1991). Sandstone and siltstone similar to sedimentary rocks on Bering Island were found during dives of the MIR submersible on the north side of the Steller Basin in water depths of 3000–6000 m (Galkin, personal communication), suggesting that island-arc crust exists under this part of the Aleutian Ridge. The Komandorsky Basin crust is partially thrust over Aleutian Ridge crust along the Bering fracture zone.

The Kamchatka Mys Peninsula, north of the Pikezh fracture zone, is the northwestern part of this Aleutian island arc sliver. It consists of Cretaceous to Paleogene pyroclastic and clastic sequences (Fig. 14a and b) (Borsunova et al., 1969; Khotin, 1976; Shapiro, 1976). These formations were formed on the trench slope of a volcanic. Some authors (i.e. Markov et al., 1969) compare this formation with volcanogenic units of Bering Island and suggest that geological structures of the Aleutian arc continue on the Kamchatka Mys Peninsula.

The Pikezh and Aleutian fracture zones cut and offset slivers of the Aleutian arc with different rocks of fore-arc origin. Seliverstov (1987) suggests that some blocks of oceanic crust have separated from the Pacific plate and have been thrust onto the Aleutian Ridge from the south during their displacement along strike-slip faults, and, therefore, they may be incorporated into fore-arc units. The Kamchatka Mys Peninsula, south of the Pikezh fracture zone, is located on the northwestern continuation of this Aleutian fore-arc section. In southwestern Kamchatka Mys Peninsula (Fig. 14b), volcaniclastic rocks and chert of Lower to Upper Cretaceous age, gabbro, ultramafic, and serpentine mélanges are exposed (Khotin, 1976; Zinkevich et al., 1985; Tsukanov, 1991). This ophiolite complex is derived from an oceanic rise with shallow volcaniclastic sediment overlain by clastic sediment (Vysotsky, 1989; Fedorchuk, 1989). Peive and Kazimirov (1986) suggest that this complex represents the basement of the Aleutian arc.

5.4. Comparison with other arc–arc junction areas

An overview of arc–arc junction areas for the Circum-Pacific region has been presented by Kimura (1996). Collision is typical of most arc–arc junctions. They may be subdivided into two types. Firstly, slivers of the fore arc move, due to oblique subduction, towards the junction area, colliding with the adjacent island arc (Fitch, 1972). The Kuril–Japan island-arc junction is a typical example of this case, where the fore arc of the Kuril arc has been moving southwest, colliding with Hokkaido, since the Late Miocene. Dextral and sinistral strike-slip faults are present in both the northern and southern halves of the arc–arc junction as a result of collision of the fore arc of the Kuril arc and the subsequent extrusion of the Japan arc (Kusunoki and Kimura, 1998).

In the second case, two active island arcs move towards each other, colliding as whole units. The Izu–Bonin island arc has been colliding with the Honshu mainland in central Japan since the Middle Miocene (Kimura, 1996). The collision is related to the opening of the Japan Sea and the cessation of spreading in the Shikoku Basin (Taira et al., 1989). Volcanic and volcaniclastic rocks of the Izu–Bonin arc are being thrust southwards over Honshu due to extrusion of the Izu–Bonin arc. The Izu collision zone is related to a syntaxis structure to the north of the peninsula (Taira et al., 1992). The deformation is propagating to the south, while the Izu–Bonin arc is being subducted beneath Honshu.

The Kamchatka–Aleutian junction is different from the examples mentioned above. The junction is comparable to the Izu–Bonin/Honshu junction because both island arcs are moving as one unit.

In contrast to the Izu–Bonin arc, however, no subduction occurs along the western portion of the Aleutian arc.

Kimura (1996) suggests that most arc–arc junctions in the Circum-Pacific region represent different stages of collision. For example, the Hokkaido junction is a mature collision zone, where the lower crust has been exposed as a result of collision, whereas Kamchatka is at a rather juvenile stage. In contrast, the Kamchatka junction has a long history of deformation south of the Pikezh fracture zone, where highly deformed ophiolite complexes are present (Fig. 14b). This ophiolite complex can be considered to be lower crust–upper mantle uplifted to the surface during collision.

6. Conclusions

The Aleutian island arc is moving northwest toward the Kamchatka Mys Peninsula. The collision was initiated after the direction of plate motion changed in the Middle Eocene. We suggest that the last collision episodes started recently. The Kamchatka Mys Peninsula forms the buttress in this colliding system, and underplating and docking of the Aleutian Islands onto Kamchatka forces the reorganization of the westernmost island arc. This leads to its fragmentation into several blocks bounded by strike-slip faults. The fracture zones continue onshore. Development of the strike-slip faults, especially the predominance of sinistral strike-slip faults west of the junction of the trench axes, must be explained by extrusion as a result of collision of the Aleutian arc. Strike-slip faults splay into thrust faults with associated folds beneath the Kamchatka Mys slope and shelf.

The Aleutian Ridge consists mainly of island arc volcanoes and volcaniclastic sediments. Locally, however, blocks of Komandorsky Basin crust and Pacific oceanic crust are displaced along strike-slip faults and are tectonically juxtaposed against the arc. Individual islands on the ridge are separated from each other by deep water underlain by oceanic crust or thinned island arc crust, e.g. in the Kamchatka Strait between the Kamchatka Mys Peninsula and Bering Island. The irregularity of the Aleutian island arc causes irregularities in the rheologic behavior of individual parts and thus irregularities in the collision process. Accretion or subduction may occur, depending on the buoyancy of the material actually colliding with Kamchatka. Consequently, the type of tectonic activity at the junction area is determined by the type of Aleutian island arc crust impinging on Kamchatka.

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