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ORIGINAL PAPER

Dmitriy V. Alexeiev · Christoph Gaedicke
Nikolay V. Tsukanov · Ralf Freitag

Collision of the Kronotskiy arc at the NE Eurasia margin and structural evolution of the Kamchatka–Aleutian junction

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Abstract Structural evolution of the Kamchatka–Aleutian junction area in late Mesozoic and Tertiary was generally controlled by (1) the processes of subduction in Kronotskiy and Proto-Kamchatka subduction zones and (2) collision of the Kronotskiy arc against NE Eurasia margin. Two structural zones of the pre-Pliocene age and six structural assemblages are recognized in studied region. 1: Eastern ranges zone comprises SE-vergent thrust folded belt, which evolved in accretionary and collisional setting. Two structural assemblages (ER1 and ER2), developed there, document shortening in the NW–SE direction and in the N–S direction, respectively. 2: Eastern Peninsulas zone generally corresponds to Kronotskiy arc terrane. Four structural assemblages are recognized in this zone. They characterize (1) *precollisional* deformations in the accretionary wedge (EP1) and in the fore-arc basin and volcanic belt (EP2), and (2) *syn-collisional* deformation of the entire Kronotskiy terrane in plunging folds (EP3) and deformations in the foreland basin (EP4). Analysis of paleomagnetic declinations versus present day structural strike in the Kronotskiy arc terrane shows that originally the arc was trending from west to east. Relative position of the accretionary wedge, fore-arc basin and volcanic belt, as well as northward dipping thrusts in accretionary wedge indicate, that a northward dipping subduction zone was located south of the arc. The accretionary wedge developed from the Late Cretaceous through the Eocene, and it implies that the subduction zone maintained its direction and position during this time. It implies that Kronotskiy arc was neither a part of the Pacific nor Kula plates and was located on an individual smaller plate, which included the arc and Vetlovka back-arc basin. Motion of the Kronotskiy arc towards Eurasia was connected only with NW-directed subduction at Kamchatka margin since Middle Eocene (42–44 Ma). Emplacement of the Kronotskiy arc at the Kamchatka margin occurred between Late Eocene and Early Miocene. This is based on the age of syn-collisional plunging folds in Kronotskiy terrane, and provenance data for the Upper Eocene to Middle Miocene Tyushevka basin, which indicate in situ evolution of the basin with respect to Kamchatka. Collision was controlled by the common motion of the Kronotskiy arc with Pacific plate towards the northwest, and by the motion of the Eurasian margin towards the south. The latter motion was responsible for the southward deflection of the western part of the Kronotskiy arc (EP3 structures), and for oblique transpressional structures in the collisional belt (ER2 structures).

D. V. Alexeiev · N. V. Tsukanov
P. P. Shirshov Institute of Oceanology, Moscow, Russia

C. Gaedicke
Federal Institute for Geosciences and Natural Resources,
Hannover, Germany

R. Freitag (✉)
Friedrich-Schiller University Jena, Institute of Earth Sciences,
Jena, Germany
E-mail: Ralf.Freitag@uni-jena.de
Fax: +49-3641-948622

Introduction

Since the Jurassic through the Cenozoic the northeastern Eurasian margin widened due to accretion of various allochthonous terranes (Watson and Fujita 1985; Parfenov et al. 1993; Nokleberg et al. 1994; Sokolov and Byalobzhebskii 1996). Kamchatka peninsula, which comprises a peripheral part of this giant collage, incorporates two oceanic island arc terranes—Achaivayam-Valaginskiy (AV) and Kronotskiy, which welded with Eurasia in Tertiary time (Fig. 1). Kronotskiy arc terrane, the easternmost one, is accreted to the continent only partially. The eastern segment of the terrane continues in the western part of the Aleutian arc. Collision of the AV arc has been studied during past years in quite detail, whilst the processes of the

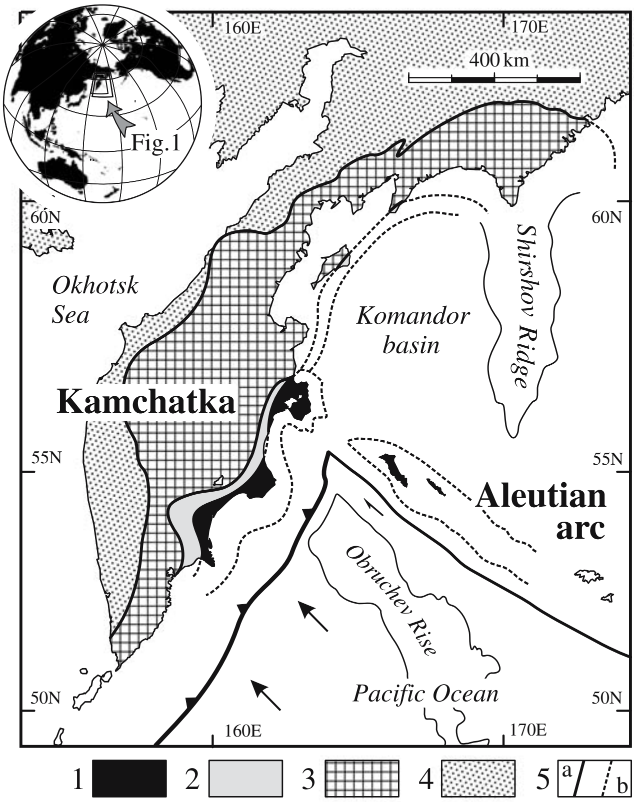


Fig. 1 Principal basement terranes of the Kamchatka peninsula and west Aleutian arc. *1* Kronotskiy arc terrane, *2* Vetlovskiy terrane, *3* Achaivayam-Valaginskiy arc terrane, *4* Mesozoic terranes of the NE Eurasia margin, *5* terrane boundaries. *a* certain, and *b* inferred

collision of the Kronotskiy arc remain far from clear. Mechanism of convergence and character of relative plate motions, history of deformation, kinematics of precollisional and syn-collisional structures, and the age of the Kronotskiy arc collision are the subjects of recent discussions. The collisional history of this arc affects the understanding of plate tectonic evolution of the entire northwest Pacific region during the Late Mesozoic and Cenozoic.

We present structural and sedimentological data, which were obtained for the Cretaceous and Tertiary rocks in the Kumroch Range, on the Kronotskiy Peninsula and Cape Kamchatka. Structural analysis focused on (1) the recognition of structural complexes due to different structural episodes, (2) dating deformational events, and (3) reconstruction of the stress field through time. Sedimentological criteria were used for more precise definition of the paleogeodynamic setting and paleotectonic zones through time. Synthesis of obtained data allows to reconstruct tectonic and deformation history of the Kamchatka–Aleutian junction area during the late Mesozoic and Tertiary, and to shed some light on the processes, which led to accretion of the Kronotskiy arc to the Eurasian margin.

Regional tectonic setting

Pre-Pliocene structures of the eastern Kamchatka peninsula are comprised of three Upper Mesozoic and Lower Cenozoic allochthonous terranes: Achaivayam-Valaginskiy, Vetlovskiy, and Kronotskiy, and two Upper Tertiary sedimentary basins: Central Kamchatka and Tyushevka basin (Figs. 1, 2).

Achaivayam-Valaginskiy (AV) terrane occupies major part of Kamchatka and continues north in the Olyutorskiy region (Fig. 1). It comprises an ensimatic volcanic arc overlaid by siliciclastic turbidites. Volcanic formations range in age from Campanian to Early Paleocene and consist of tholeiitic and calc-alkaline basalts, andesites, tuffs and agglomerate tuffs, intercalated by deep marine tuff-sedimentary and cherty deposits (Fig. 3). Petrochemical analysis points to their primitive intra-oceanic island arc origin (Zinkevich et al. 1993; Shapiro 1995; Konstantinovskaia 2000).

Late Maastrichtian to Early Eocene siliciclastic turbidites (Fig. 3) exhibits proximal and moderately distal facies (Zinkevich et al. 1993; Shapiro 1995; Shapiro et al. 1992; Soloviev et al. 2006). Individual cycles vary from 0.1 to 1.0 m in thickness and typically demonstrate A, A–B, and A–B–C Bouma sequences. Turbidite sandstones are volcanic greywackes and quartz–feldspar greywackes. Relatively higher contents of quartz and feldspar grains imply sedimentary input from the Eurasian mainland (Shapiro et al. 1987, 1992). Paleocurrent directions determined by turbidite flute casts and cross bedding indicate sediment transport from the northwest and re-deposition along the base of the slope in northeast direction (Alexeiev et al. 1998; Fig. 2, site 1).

Paleomagnetic data imply that the AV arc was located up to 2,500 km south of Kamchatka in the Late Cretaceous (Kovalenko 1992; Levachova et al. 1998). Northward migration and subsequent collision with Eurasia occurred during the latest Paleocene to Middle Eocene (Shapiro 1995; Brandon et al. 1999; Soloviev et al. 1998, 2002; Shapiro and Soloviev 1999; Konstantinovskaia 2000; 2001).

Vetlovskiy terrane extends from the Shipunskiy peninsula to Karaginskiy island (Fig. 1) and consists of intensively sheared deep marine sedimentary and volcanic rocks, which accumulated initially in the Vetlovskiy back-arc basin (Tsukanov 1991; Zinkevich and Tsukanov 1992, 1993; Zinkevich et al. 1993). Along its northwestern flank the terrane is built up by proximal turbidites and sandstones (Stanislavskaya formation) ranging in age from the Paleocene to Bartonian (Tsukanov et al. 1991; Soloviev et al. 2006). In the southeast it is comprised of deep marine fine-grained siliceous tuff sandstones and tuff siltstones, brown and green cherts, argillaceous cherts and jaspers, distal siliciclastic turbidites, red argillites, basalts, and thin-laminated limestones (Fig. 3). Turbidites are characterized by very small thickness of individual cycles

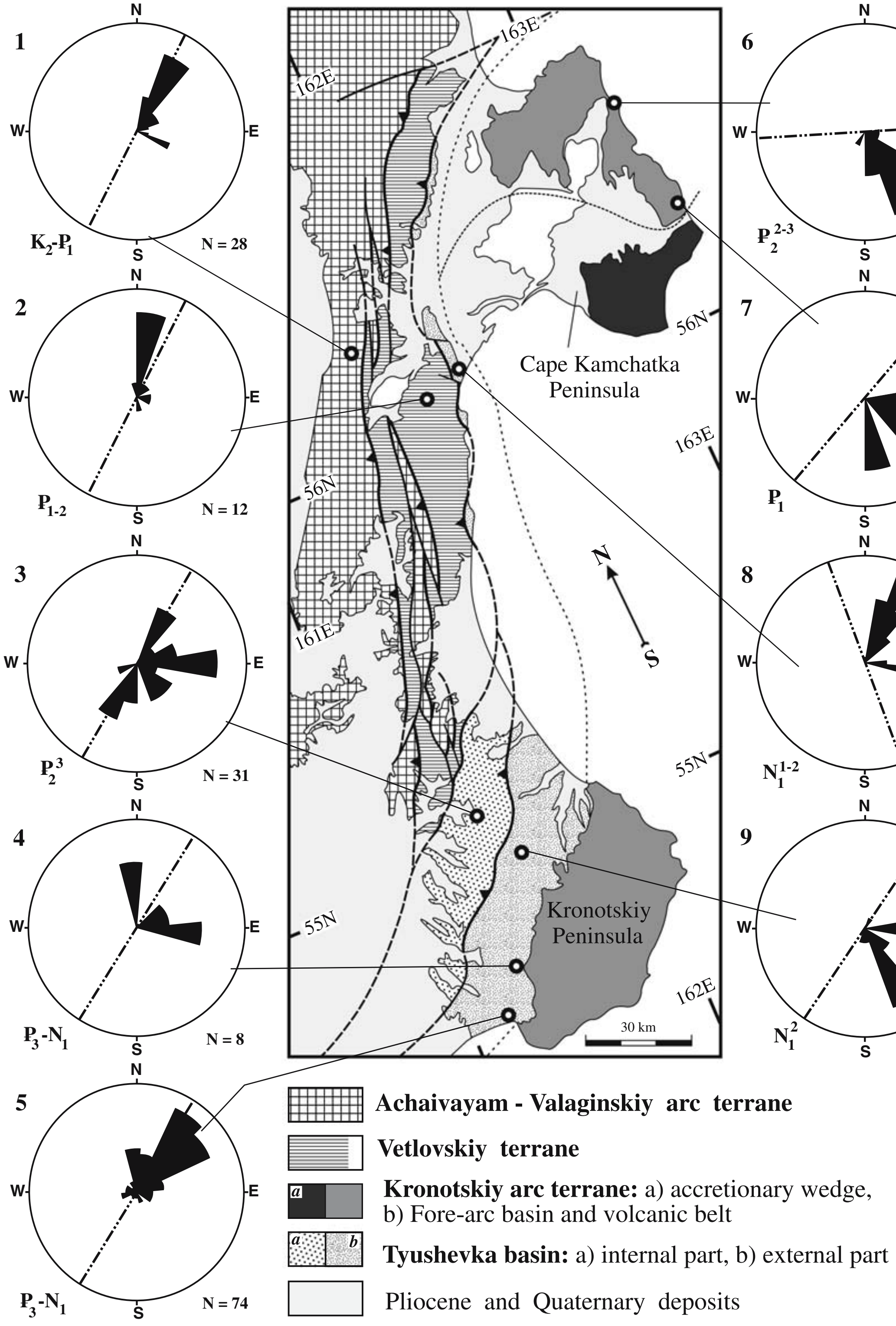


Fig. 2 Tectonic setting of the Eastern Kamchatka and sediment transport directions in the Tertiary formations

(several centimeters) and incomplete C–D and D Bouma sequences accounting for extremely distal depositional settings with respect to provenance areas. Cross-bedding structures in turbidites document the principal direction of sediment transport as toward the north, which is presumably slope-parallel direction (Fig. 2, site 2) (Alexeiev et al. 1998). Deeper marine deposits in Vetlovskiy terrane vary in age from Paleocene to Early

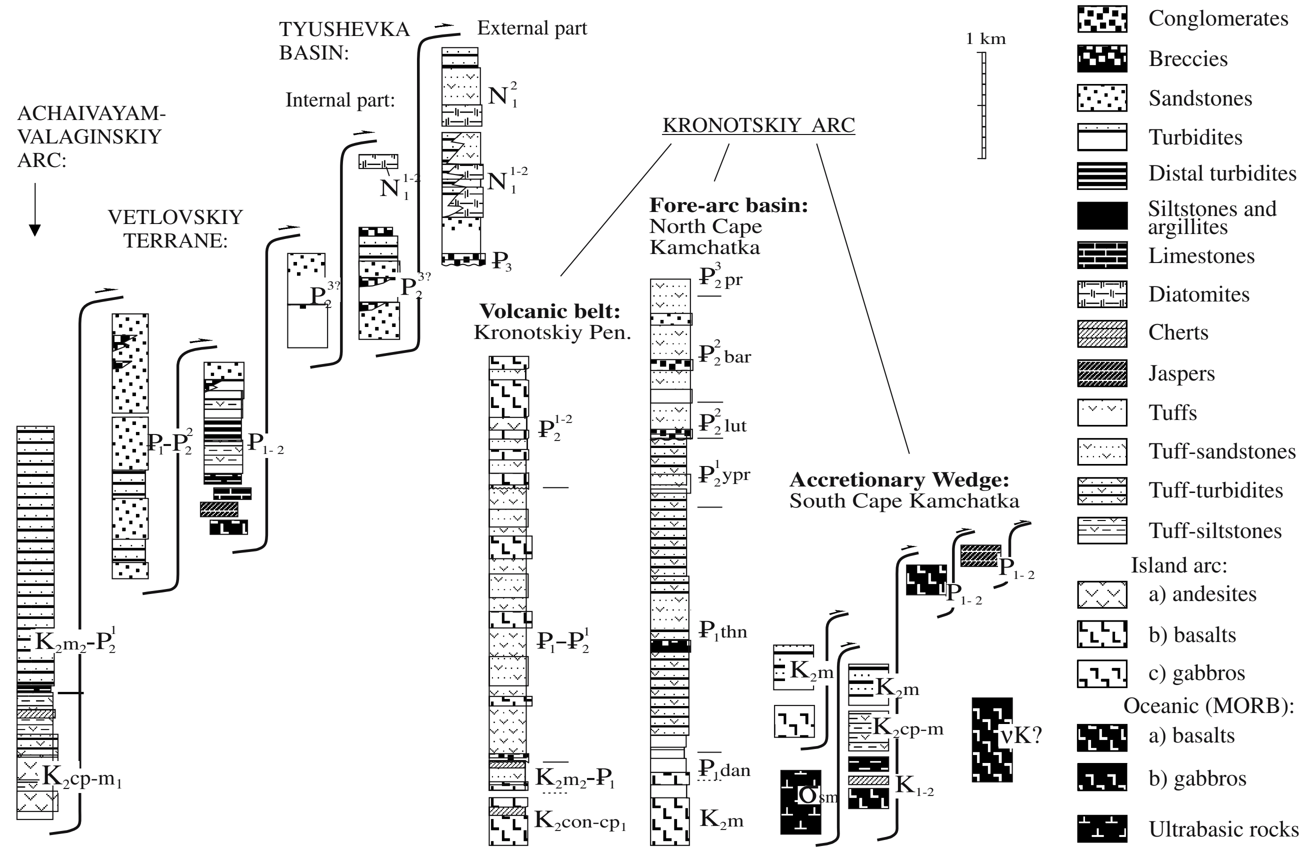


Fig. 3 Basic stratigraphy of the Eastern Kamchatka

Eocene within Eastern Kamchatka (Tsukanov et al. 1991; Zinkevich et al. 1993; Bakhteiev et al. 1994) and they go up-section up to the Late Eocene and Oligocene on the Karaginskiy island (Chekhovich et al. 1989). MORB-type basalts found in the Vetlovskiy terrane allocate oceanic crust for parts of the Vetlovskiy basin during the Paleocene and Eocene (Tsukanov and Fedorchuk 1989; Fedorchuk et al. 1990). Thrust faulted complex in the Vetlovskiy terrane is interpreted to form in a fore-arc accretionary wedge setting. Within the Eastern Kamchatka the wedge evolved into a collisional suture during collision of the Kronotskiy arc (see below) (Zinkevich and Tsukanov 1992, 1993), whilst in the Karaginskiy area further north an accretionary wedge setting remained till the late Tertiary (Chekhovich et al. 1989).

Kronotskiy terrane is aligned SW–NE along the eastern shore of Kamchatka, then changes strike to ESE on Cape Kamchatka and continues on the Komandor islands (Bazhenov et al. 1992) (Fig. 1). The terrane comprises an oceanic volcanic arc, which evolved from mid-Cretaceous through the Late Eocene, and it preserves fragments of the paleo accretionary wedge, fore-arc basin, and arc volcanic belt.

The *accretionary wedge* of the Kronotskiy arc crops out in the south of the Cape Kamchatka (Shapiro et al. 1997) and comprises a south and southwest-vergent thrust sheet package. It consists of oceanic sediments and volcanic rocks ranging in age from Early Cretaceous to Early Eocene, gabbros, peridotites, and tectonic mélanges (Figs. 3, 4). Aptian, Albian, and Cenomanian rocks are red, brown and gray siltstones, argillites and cherts, ribbon jaspers, basalts, and thin-laminated limestones. Upper Cretaceous is comprised of tuff-siliceous rocks and siliciclastic turbidites. Paleocene and Lower Eocene assemblages are presented by red jaspers, argillites, and pillow basalts (Khotin 1976; Fedorchuk 1989; Vysotskiy 1989; Bogdanov et al. 1991; Fedorchuk et al. 1991; Zinkevich et al. 1993). Both Lower Cretaceous and Paleogene basalts are oceanic tholeiites (Fedorchuk 1989; Skolotnev et al. 2001).

MORB-type gabbros form lowermost thrust sheets in the south of the wedge, and Boninite-type gabbros are developed in small blocks in the north (Skolotnev et al. 2001). According to geochemical and mineralogical data, peridotites composing major thrust sheets in the central part of the wedge (Fig. 4) were formed in the upper mantle supra-subductional setting (Kramer et al. 2001; Skolotnev et al. 2001, 2003).

Intensive magnetic anomaly connected with ultramafic slabs on the Cape Kamchatka continues up to 200 km south within Kamchatka bay (Fig. 6). Numerical modeling shows that in the latter area the anomaly is related to several bodies at a depth of 2–4 km, dipping west (Seliverstov 1998). These bodies can be interpreted as thrust sheets of ultramafic rocks in buried accretionary wedge, as they have the same signatures in the magnetic field, and the wedge can be expected to continue in subsurface within Kamchatka bay.

Fore-arc basin is preserved in the north of the Cape Kamchatka and in the south of the Komandor islands (Rostovtseva 1993; Shapiro et al. 1997). In first area the sediments range from the Late Maastrichtian to Late Eocene in age, and exceed 4 km of total thickness (Figs. 3, 4). Maastrichtian rocks are basalts and tuffs of an island arc affinity (Khubunaya 1987; Fedorchuk 1989). Lower Paleocene consists of deeper marine cherts, tuff-siliceous rocks, and argillites. Upper Paleocene and Lower Eocene are comprised of tuff-sandstone turbidites and debris-flow breccies intercalated by in situ siltstones, tuff siltstones, and argillites. These slope deposits change laterally northward into the shallow marine sandstones and tuff-sandstone facies. Middle and Upper Eocene rests with an erosional unconformity upon the Lower Eocene and consist of shallow marine sandstones, tuff sandstones, and fluvial conglomerates (Borzunova et al. 1967; Beniyamovsky et al. 1992; Shapiro et al. 1997; Shcherbinina 1997; Boyarinova et al. 1999).

Major contents of volcanic glass in tuff sandstones and occurrence of unaltered volcanic rocks in debris-flow clasts indicate active volcanic provenance. According to geological indications the volcanic belt is located to the north and northeast of the basin (Rostovtseva 1993; Shapiro et al. 1997). Such reconstruction agrees with our data on paleocurrent directions both in the Upper Paleocene and Middle Eocene deposits, which indicate sediment transport from the north and northeast (Fig. 2, sites 6 and 7).

Volcanic arc formations crop out on Shipunskiy and Kronotskiy peninsulas, in the north of the Cape Kamchatka and north of the Komandor islands (Khubunaya 1987; Tsvetkov 1991; Shapiro et al. 1997). Dredge samples in Kronotskiy and Kamchatka bays account for the extension of the volcanic belt offshore on the shelf of Kamchatka (Seliverstov 1998; Fig. 6).

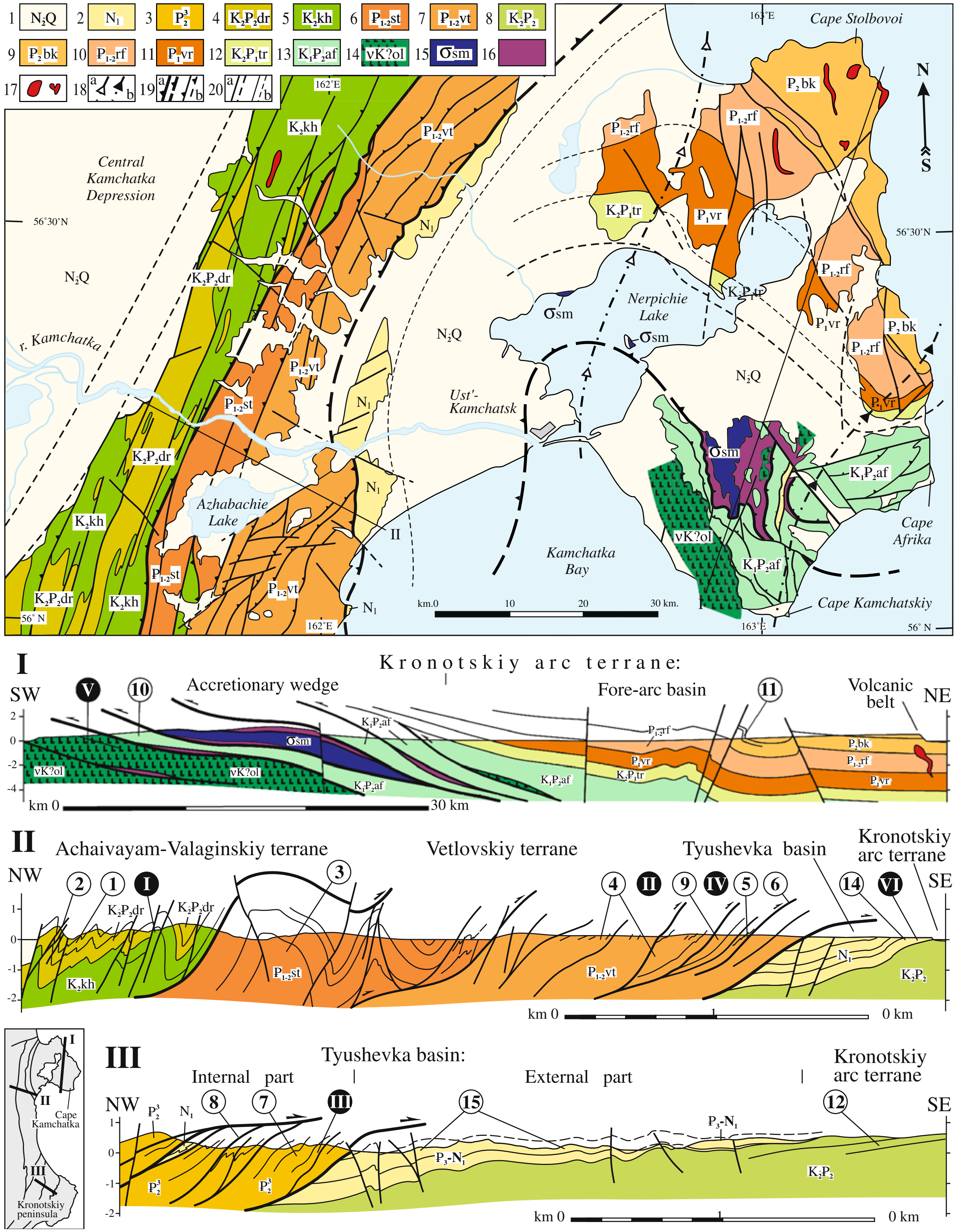
On Kronotskiy peninsula, volcanic rocks range from Late Cretaceous to Middle Eocene in age (Fig. 3). Upper Cretaceous rocks are comprised of basalts, hyaloclastites, and tuff sandstones and tuff siltstones. They are unconformably overlain by tuffs, tuff-sedimentary rocks, and basalts of the Paleocene age, which change up-section into the Lower and Middle Eocene basalts and andesites with minor number of tuff sandstone and tuff-siltstone strata (Raznitsyn et al. 1985; Shcherbinina 1997; Levashova et al. 2000b). Paleocene and Eocene basalts, andesites, and tuffs are also widespread on the Shipunskiy peninsula (Tsukanov et al. 1991). In the north Cape Kamchatka, the arc volcanic rocks are found in the Upper Maastrichtian and in the Middle to Upper Eocene (Khubunaya 1987; Boyarinova et al. 1999; Skolotnev et al. 2001); on the Komandor islands they developed in the Middle and Upper Eocene (Tsvetkov 1991).

Eastern part of the Kronotskiy terrane (Komandor islands) is separated from the continent by deeper marine Kamchatka strait, about 80 km in width, which is floored most likely by an oceanic crust (Seliverstov 1998; Gaedicke et al. 2000). This break is too large to be explained in terms of arc-parallel extension due to oblique convergence of the oceanic plate against the arc (Lallemant and Oldow 2000). Most probably it is formed due to Miocene spreading in Komandor basin, as it is supported by the similarities in the relief, average sediment thickness, and average depth of the Kamchatka strait and Komandor basin (Seliverstov 1998).

Upper Tertiary basins occupy major territory in the east Kamchatka. *Central Kamchatka* depression (Figs. 2, 4) is comprised of shallow marine and non-marine siliciclastics, tuff-siliciclastic and diatomic deposits which range from the Late Eocene to Quaternary in age. Tertiary sediments with a total thickness of over 5 km accumulated there in a fore-arc setting with respect to coeval volcanic belt in the Median ridge northwest of the basin (Shapiro et al. 1987; Zinkevich et al. 1993).

Tyushevka basin represents narrow asymmetric depression 5–40 km wide and over 350 km long, which trends NE–SW along the boundary between Kronotskiy terrane and Kamchatka mainland (Figs. 2, 6). In the SE, the basin rests on the Kronotskiy terrane. In the NW it borders on AV and Vetlovskiy terranes along SE-directed thrusts. Depositional contacts with older terranes in the NW on the basin were reported within isolated block in Valaginskiy ridge (Zinkevich and Tsukanov 1993; Bakhteiev et al. 1994; Konstantinovskaia 2000), but it is not clear whether this block comprises a part of the Tyushevka basin sensu stricto.

Tyushevka basin is comprised of shallow marine sandstones, conglomerate sandstones and siltstones, which change up-section into the diatomites, tuff-diatomites, and/or siliciclastic turbidites (Fig. 3). The rocks range in age from Early Oligocene and Early Miocene to Middle Miocene (Shapiro 1976; Markevich 1978; Bakhteiev et al. 1997; Stupin et al. 1998). Fluvial conglomerates (Tundrovskaya formation) and proximal siliciclastic turbidites are also developed in the Upper Eocene in the NW of the basin in Chazhma ridge (Figs. 2, 3) (Shapiro 1976; Bakhteiev et al. 1997). In some works this part of the basin was related to Vetlovskiy terrane (Konstantinovskaia 2000) and interpreted to form in deeper marine accretionary wedge setting. We believe, that fluvial conglomerates are incompatible with such environment, and they should not be related to Vetlovskiy terrane as such facies are not developed anywhere else. On the other hand, the diatomites and tuff-diatomites of the Miocene age in Chazhma ridge are identical to their counterparts in the rest of the Tyushevka basin, and it allows to relate Chazhma block to the basin as well (Shapiro 1976; Markevich 1978). Total sediment thickness in


1 N2Q
2 N1
3 P2 3
4 K2P2dr
5 K2kh
6 P1-2st
7 P1-2vt
8 K2P2
9 P2bk
10 P1-2rf
11 P1vr
12 K2P1tr
13 K1P2af
14 νK?ol
15 σsm
16
17
18 a b
19 a b
20 a b
Central Kamchatka Depression
56°30'N
162°E
163°E
Cape Stolbovoi
N
S
r. Kamchatka
Azhabachie Lake
Nerpichie Lake
Ust'-Kamchatsk
Kamchatka Bay
Cape Afrika
Cape Kamchatskiy
56° N
km.0 10 20 30 km.
II
I
Kronotskiy arc terrane:
Accretionary wedge
Fore-arc basin
Volcanic belt
SW
NE
V
10
11
km 0
30 km
Achaivayam-Valaginskiy terrane
Vetlovskiy terrane
Tyushevka basin
Kronotskiy arc terrane
NW
SE
2 1 I
3
4 II 9 IV 5 6
14 VI
km 0
0 km
III
Tyushevka basin:
Internal part
External part
Kronotskiy arc terrane
8 7 III
15
12
P3-N1
Cape Kamchatka
Kronotskiy peninsula

◀

Fig. 4 Geological map of Kamchatka–Aleutian junction, Ust'-Kamchatsk area (modified after Markovskiy et al. 1989; Boyarinova et al. 1999), and geological cross-sections. *1* Pliocene and Quaternary; *2* and *3* Tyushevka basin: *2* Lower and Middle Miocene (N_1) and Oligocene to Middle Miocene (Pg_3-N_1), *3* Upper Eocene (on cross-section); *4* and *5* *Achaivayam-Valaginskiy arc terrane*: *4* Maastrichtian to Lower Eocene, Drozdovskaya formation, *5* Campanian and Maastrichtian, Khapitskaya formation; *6* and *7* *Vetlovskiy terrane*: *6* Paleocene to Middle Eocene, Stanislavskaya formation, *7* Paleocene to Middle Eocene, Vetlovskaya formation; from *8* to *16* Kronotskiy arc terrane: *8* Upper Cretaceous to Eocene undifferentiated (on cross-sections), *9–12 Fore-arc basin*: *9* Middle and Upper Eocene, Baklanovskaya formation, *10* Paleocene and Lower Eocene, Rifovskaya formation, *11* Paleocene, Vereschaginskaya formation, *12* Maastrichtian and Paleocene, Tarkhovskaya formation; *13–16 accretionary wedge*: *13* Lower Cretaceous to Eocene, Africa complex, *14* Cretaceous? gabbro, Olenegorskiy complex, *15* Ultramafic rocks, Soldatskaya mount complex, *16* Serpentinite and terrigenous melanges; *17* subvolcanic bodies (Oligocene); *18* plunging fold axes: *a* anticline, *b* syncline. *Arrow* shows plunge direction; *19* thrust faults major (*a*) and minor (*b*), traced and inferred in subsurface; *20* high angle faults (*a*) and stratigraphic contacts (*b*) traced and inferred in subsurface. *Arabic and Roman numerals* on cross-sections correspond to structural and paleostress diagrams, respectively, in Figs. 7 and 9

Tyushevka basin ranges from 0.5–1 km in the SE to 3–4 km in the NW (Fig. 4) (Shapiro 1976; Markevich 1978).

There are two alternative points of view on origin of the Tyushevka basin (Fig. 5). One is that the basin formed "in situ" with respect to Kamchatka (Shapiro 1976; Markevich 1978; Tsukanov 1991; Zinkevich et al. 1993). Another is that the basin evolved on inactive Kronotskiy arc at the distances of up to 1,500 km from Kamchatka and was accreted to continent in the Late Miocene (Kononov 1989; Bakhteiev et al. 1997; Levashova et al. 2000a, b). The latter is based mainly on paleomagnetic evidences. These two models predict that completely different depositional systems would develop in the basin. The first model suggests that the principal provenance would be located within orogenic uplifts NW of the basin (Fig. 5a). The second model assumes that rather no sediment would be able to be transported across wide deeper marine area between the Kronotskiy terrane and Kamchatka and deposited into the Tyushevka basin from the NW (Fig. 5b). Provenance analysis of Tyushevka sandstones therefore allows to check the validity of both tectonic models by sedimentological criteria.

Detrital modes of the Tyushevka sandstones indicate a moderately evolved continental or microcontinental volcanic arc provenance (Marsaglia et al. 1999). The sandstones commonly contain grains derived from acid igneous and metamorphic rocks, which occur in central Kamchatka and are unknown in Kronotskiy terrane (Morozov and Rostovtseva 1996; Bakhteiev et al. 1997; Marsaglia et al. 1999). Abundant detrital coal fragments in Tyushevka deposits indicate wide provenance area with a well-developed vegetation and broad river system which assumes continental setting (Markevich 1978). Turbidite flute casts, cross-bedding structures, and drag folds in soft-sediment slumps document principal sediment transport from the west and northwest both in the Upper Eocene, Lower and Middle Miocene deposits (Fig. 2, sites 3, 8, 9) (Alexeiev et al. 1999; Marsaglia et al. 1999). Detritus derived from Kronotskiy terrane is found in the lowermost horizons of the Tyushevka sequences and it plays only a minor role in the basin fill (Marsaglia et al. 1999).

These indications point at Kamchatka mainland as principal provenance and argue in favor of "in situ" evolution of the basin with respect to Kamchatka. Such interpretation is also supported by the Miocene rocks in Tyushevka and Central Kamchatka depression are presented by similar facies and it suggests that the two basins were depositionally linked (Tsukanov 1991; Zinkevich et al. 1993). Higher contents of tuff material in Tyushevka sediments (Markevich 1978; Bakhteiev et al. 1997) suggest that the basin evolved relatively close to the Miocene Central Kamchatka volcanic belt as well (Markevich 1978).

As it was noted first by Shapiro (1976) principal tectonic features of the Tyushevka basin are similar to that of foreland basins (fore-deeps). The basin is located in front of the collisional thrust folded belt, it follows the shape of the thrust front and at a major extend it is overridden by orogenic thrust wedge (Fig. 6). The basin is asymmetric in a cross-section, as sedimentary layers thicken towards orogenic belt and pinch out towards the foreland, and the basin propagated into the foreland with time (Shapiro 1976; Markevich 1978). Since these features are indicative for foreland basins, which form due to lithosphere flexure (Allen and Allen 1993) this mechanism can be assumed to play certain role in a Tyushevka basin subsidence.

Structural complexes and deformation history

Based on distinct structural patterns and deformational histories the Eastern Kamchatka divides into two structural zones. (1) *Eastern Ranges zone* is a NE trending and SE vergent thrust folded belt, which evolved in accretionary and collisional setting along the Tertiary Kamchatka margin, and (2) *Eastern Peninsulas zone*, which generally corresponds to Kronotskiy terrane and Tyushevka basin (Fig. 6).

Eastern Ranges (ER) zone embraces southeastern part of the Achaivayam-Valaginskiy terrane, entire Vetlovskiy terrane, and northwestern parts of the Tyushevka basin. Two structural assemblages are recognized there: (1) the structures due to NW–SE directed compression (ER1) and (2) the structures, which document shortening in north–south direction (ER2).

ER1 structures are dominating in the Eastern Ranges (Shapiro 1976; Shapiro et al. 1987; Zinkevich et al. 1984, 1985, 1993; Tsukanov and Zinkevich 1987). They are characterized by a stable strike NE 25–30°, which

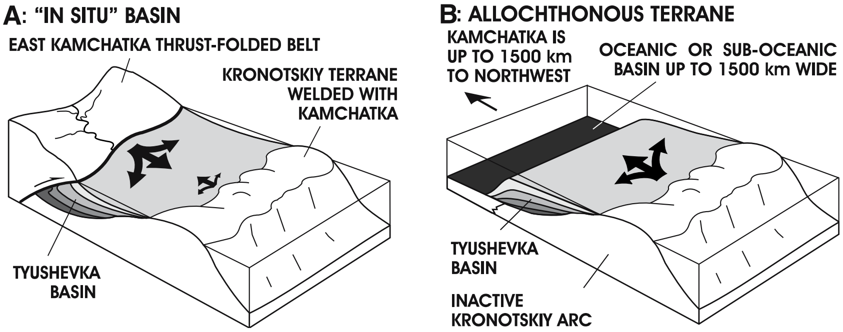


Fig. 5 Alternative depositional models of the Upper Eocene to Middle Miocene Tyushevka basin. *Arrows* show predicted directions of the sediment transport

implies principal shortening direction with an azimuth of SE 115–120°. In the *AV terrane* the ER1 structures are presented by linear folds, relatively few reverse faults and thrusts. The folds are closed to tight, ranging from 0.5 to 2 km wide and 5 to 20 km long (Fig. 4). Fold hinges are sub-horizontal, axial plains dip NW with the angles of 60–80° (Fig. 7-1). Stratification typically is well preserved, axial plain cleavage is poorly developed; boudinage and mullion structures are rare. The folds are accompanied by NW dipping reverse faults, minor thrusts (Fig. 7-2) and diagonal strike-slip faults. The AV terrane is thrusted southeast over the Vetlovskiy terrane along the Vetlovskiy thrust with an amplitude exceeding 10 km (Fig. 4) (Shapiro et al. 1987; Tsukanov 1991).

In the *Vetlovskiy terrane* ER1 structures are dominated by SE-directed thrusts (Tsukanov 1991). Thrust faults dip NW with the angles ranging from 40° to 70° (Fig. 7-4, 7-6), thickness of individual sheets vary from 300 to 1,500 m. Fold structures are rather few: in the NW they are presented by larger, upright or inclined box-shaped and closed structures 0.5–3 km wide (Fig. 4); in the SE only small tight and closed folds, ranging from 1 to 50 m in size develop locally. Fold axial planes are sub-vertical or dip NW with the angles of 70–85° (Fig. 7-3, 7-5).

Intensive boudinage, penetrative cleavage, and tectonic mélanges are characteristic of the Vetlovskiy terrane structures (Tsukanov 1991). Boudinage develops without connection with fold structures; it commonly pre-dates fold deformations and apparently formed due to thrust faulting. Rate of the layer-parallel extension in boudinaged strata ranges from 20 to 50%. Tectonic mélange zones develop along major thrusts and change in thickness from 2–3 to 50–100 m. Southwest of the Azhabachie lake a large mélange zone up to 1 km width and 100 km length marks presumably one of the main displacement zones in Vetlovskiy terrane (Tsukanov 1991; Zinkevich and Tsukanov 1993; Slyadnev 2000). Melanges consist of flattened cobbles and blocks ranging in size from tens of centimeters to first tens of meters, which are distributed in sheared argillaceous matrix. The blocks are comprised of jaspers, cherts, cherty siltstones, and thin-laminated limestones, derived from neighboring strata, and "exotic" rocks such as MORB-type basalts and diabases (Tsukanov 1991).

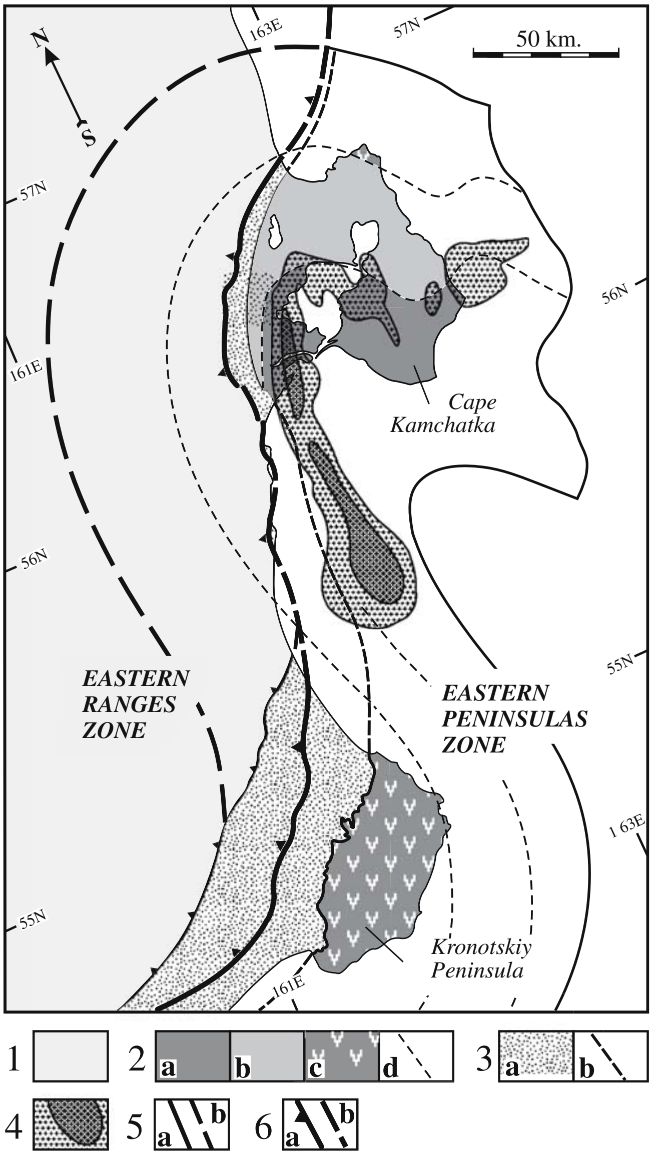


Fig. 6 Structural zoning of the Eastern Kamchatka: *1* Achaivayam-Valaginskiy and Vetlovskiy terranes, *2* Kronotskiy arc terrane: accretionary wedge (*a*), fore-arc basin (*b*), volcanic belt (*c*), and their boundaries inferred in subsurface (*d*); *3* Tyushevka basin (*a*), and its boundaries inferred in subsurface (*b*); *4* magnetic anomalies related to ophiolites in the accretionary wedge of the Kronotskiy arc; *5* contours of the Kronotskiy arc terrane: offshore (*a*) and inferred beneath the collisional thrust folded belt (*b*); *6* boundary of the Eastern Ranges Zone and Eastern Peninsulas Zone

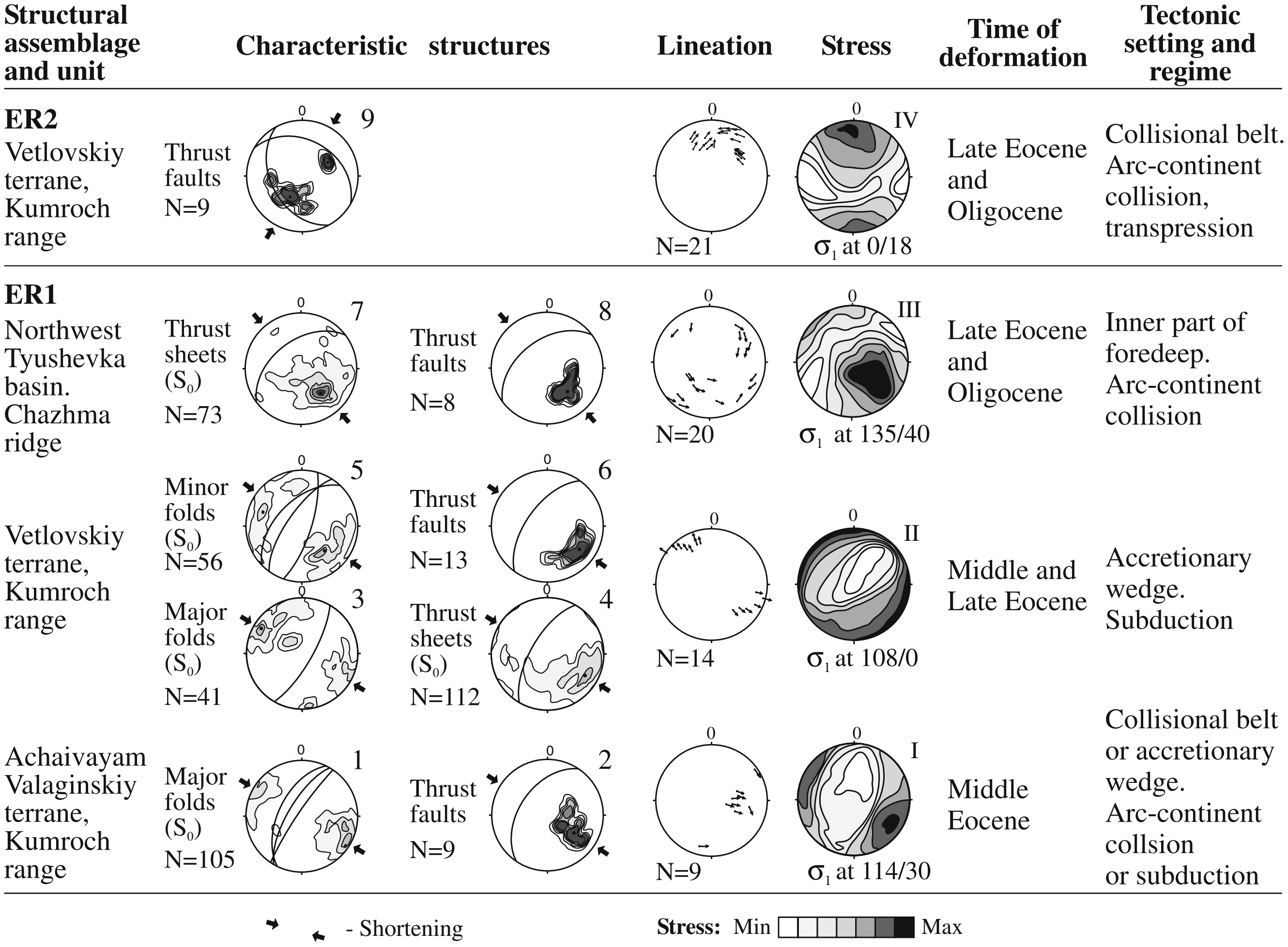


Fig. 7 Deformational styles and paleostress patterns in the Eastern Ranges Zone. Diagrams are in the equal area lower hemisphere projection. *Contours* on structural diagrams are at 1, 4, 7, 10, and 13% of total data points per 1% area of the net. *Diagram numbers* correspond to location numbers in Fig. 4. Paleostress data were processed with StereoNett 2.46 software

In the *Tyushevka basin* the SE-directed thrusts develop along contact with Vetlovskiy terrane, in a narrow zone, which reaches a maximum width of 15 km in Chazhma ridge (Fig. 6). In the latter area the thrusts develop in the Upper Eocene and Miocene rocks and dip NW (~320°) with the average angles of 40–50° (Fig. 7-8). Thrust sheets changes from several hundred meters to 1.5 km in thickness; their internal structures are monoclines (Fig. 7-7) and relatively few closed folds overturned towards SE (Bakhteiev et al. 1997). General degree of deformation is moderate: pinch-and-swell structures are common but boudinage develops only close to major faults. Outside Chazhma ridge the deformed zone rarely exceeds 1 km width, and in many cases it is limited to narrow fault zone of the singular Grechishkin thrust (Shapiro 1980).

Thrust fold deformations in the Eastern Ranges belt occurred in the uppermost crust levels; mineralogical study indicates very low grade metamorphic (zeolite facies) and high-grade diagenetic *P*–*T* conditions: from 100 to 230°C and 0.5 up to maximum 2 kbar (Lewerenz et al. 1999).

Paleostress tensors related to ER1 structures were reconstructed in different parts of the belt: in AV terrane, in Vetlovskiy terranes, and in the NW of Tyushevka basin. In all cases the tensors are consistent with shortening in NW–SE direction (Fig. 7). In the AV and Vetlovskiy terranes the tensors demonstrate sub-horizontal σ_1 axes (maximum stress) and sub-vertical σ_3 axes (minimum stress) (Fig. 7-I, 7-II). Tensors indicate pure thrust mechanism and it well corresponds to general style of deformation in these two terranes (Gaedicke et al. 1998; Freitag et al. 1999). In the NW of the Tyushevka basin the tensor demonstrates σ_1 dipping SE with an angle of 40° (Fig. 7-III). Tilt of the tensor can reflect shallower dip angles of the thrust faults, which are documented in the frontal part of the thrust belt.

Deformation in the ER1 complex developed from Early or Middle Eocene to Late Miocene, propagating with time from the NW to SE (Soloviev et al. 2006). In the NW of the belt, deformation started in the latest Early Eocene or earliest Middle Eocene based on the age of angular unconformity in the Valaginskiy ridge

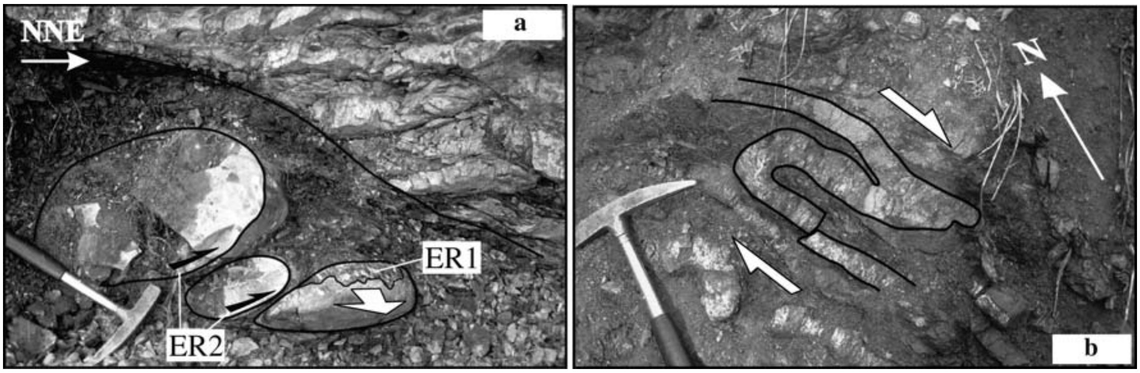
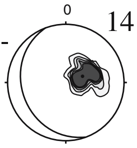
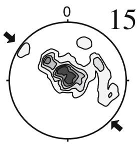
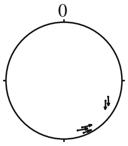
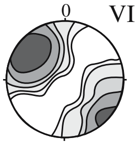
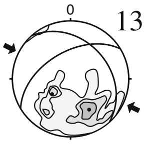
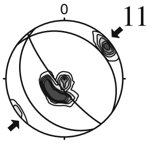
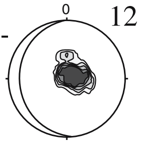
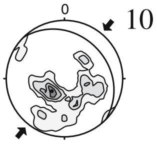
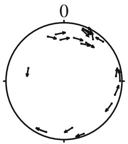
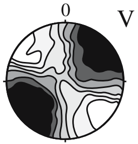


Fig. 8 Examples of the ER2 structures in Vetlovskiy terrane: **a** calcareous concretions imbricated with the motion towards NNE: Slicken-sided surface of the ER1 thrust with SE-directed motion (*oblique white arrow*) and ER2 minor thrusts. **b** Steeply plunging drag folds in the NW-trending right-lateral strike slip fault zone

(Bakhteiev et al. 1994). Coeval motions can also be inferred in Kumroch range, as Vetlovskiy thrust is traced there by olistostrome horizons in the Paleocene to Middle Eocene Stanislavskaya formation (Soloviev et al. 2006). Thrust motions in Kumroch range continued in post-Bartonian time, based on the age of youngest rocks in Stanislavskaya formation affected by thrusts (Soloviev et al. 2006). In frontal part of the thrust belt in Chazhma ridge deformation can be dated as the Late Eocene, based on the age of olistostroms associated with thrusts (Bakhteiev et al. 1997). Deformation is likely to have continued there during the Oligocene, as is evidenced by a break in sedimentation at that time. No active deformation and uplift apparently occurred during the Early and Middle Miocene, as far as diatomic facies of the Miocene age indicate open marine basin with flattened relief. Thrust motions along the north-western flank of the Tyushevka basin were renewed in

Structural assemblage and unit	**Characteristic structures**		**Lineation**	**Stress**	**Time of deformation**	**Tectonic setting and regime**
EP4 Tyushevka basin Kumroch (14); Kronotskiy Peninsula (15)	Mono-clines (S$_0$) N=31 	Folds (S$_0$) N=38 	 N=5	 σ_1 at 310/30	Late Miocene	Foreland basin. Arc-continent collision
EP3 Kronotskiy terrane Cape Kamchatka	Plunging Folds (S$_0$) N=50 		No data		Late Eocene and Oligocene	Island arc terrane. Arc-continent collision
EP2 Kronotskiy terrane North Cape Kamchatka (11); Kronotskiy Peninsula (12)	Folds (S$_0$) N=41 	Mono-clines (S$_0$) N=15 	No data		Late Eocene	Arc and Fore-arc basin. Blocking of subduction?
EP1 Kronotskiy terrane South Cape Kamchatka	Thrust sheets (S$_0$) N=35 		 N=21	 σ_1 at 210/5	Late Cretaceous through Middle Eocene	Fore-arc accretionary wedge. Subduction

➘ ⬉ - Shortening **Stress:** Min ☐☐☐▨▨■ Max

Fig. 9 Deformational styles and paleostress patterns in the Eastern Peninsulas zone. *Diagram numbers* correspond to *location numbers* in Fig. 4

the Late Miocene. Deformation had ceased by the Pliocene, based on the age of regional angular unconformity (Shapiro 1976, 1980; Shapiro et al. 1987; Zinkevich et al. 1993; Soloviev et al. 2006).

ER2 structures, which are characterized by shortening in the north–south direction were documented in the Vetlovskiy terrane (Gaedicke et al. 1998; Freitag et al. 1999). They comprise east–west trending thrusts and folds; left-lateral and right-lateral strike-slip faults, striking NE and NW, respectively, and numerous small plunging folds.

Sub-latitudinal thrusts are directed both north and south (Fig. 7-9). They develop either as singular faults or imbricate packages (Fig. 8a) and displace older ER1 structures with the amplitudes of up to first hundreds of meters. East–west trending folds represent open and low angle structures with sub-horizontal hinges, ranging from tens to hundred meters wide. The NE trending left-lateral strike-slip faults and the NW trending right-lateral ones develop as conjugated shears and are accompanied by steeply plunging tight and isoclinal drag folds (Fig. 8b).

Shortening in the north–south direction in Vetlovskiy terrane is well documented by paleostress data. Stress field, correlative with ER2 structures, is clearly distinctive from ER1 ones. The ER2 tensor is characterized by σ_1 axis dipping north with an angle of 15°, σ_2 axis steeply dipping south and sub-horizontal σ_3 (Fig. 7-IV). Steeply dipping σ_2 axis implies, that shortening in the N-to-S direction resulted mainly in strike-slip deformation (Gaedicke et al. 1998; Freitag et al. 1999).

The time of the ER2 deformation is post-Bartonian, based on the age of youngest deformed rocks, and pre-Pliocene according to the age of regional structural unconformity. Taking into account that the ER2 structures are not documented in Miocene rocks, the deformation is likely to occur during the Late Eocene and/or Oligocene.

East Peninsulas (EP) zone embraces Kronotskiy terrane and major part of the Tyushevka basin. Four structural assemblages, EP1–EP4 from older to younger ones, are recognized in this zone. EP1 structures are characteristic of the accretionary wedge of the Kronotskiy arc, EP2 define structural patterns of the fore-arc basin and volcanic belt, EP3 structures are large plunging folds, which affect entire Kronotskiy terrane, and EP4 assemblage unite syn-collisional folds and faults, developed mainly in the Tyushevka basin.

EP1 structures develop in the Cretaceous and Paleogene rocks within the accretionary wedge of the Kronotskiy arc (Figs. 6, 10). The wedge comprises south and southwest vergent thrust sheet package. It consists of four major thrust bodies, which represent either singular thrusts, or packages formed by smaller scale thrust sheets. From lower to upper the thrust bodies are comprised of (1) MORB gabbros and diabases, (2) deeper marine sedimentary and volcanic rocks, ranging from Early Cretaceous to Eocene in age, (3) upper mantle peridotites, and (4) Upper Cretaceous sedimentary rocks; ultramafic rocks, and boninitic gabbros (Figs. 3, 4) (Khotin 1976; Zinkevich et al. 1985, 1993; Fedorchuk 1989; Boyarinova et al. 1999).

Thrust sheets range in thickness from hundreds of meters to 1–2 km and dip N and NE with the angles ranging from 20° to 60° (Figs. 4, 9-10) (Khotin 1976; Zinkevich et al. 1985, 1993). Monoclinal structures prevail in the thrust packages; fold structures are rather few and presented by tight and isoclinal structures, either upright or overturned towards the S and SE. The rocks, though generally unmetamorphized, demonstrate a very high degree of deformation. Intensive boudinage, with the rate of the layer-parallel extension of up to 100%, and several systems of cleavage are characteristic of the EP1 structures. Main cleavage system is sub-parallel to principal thrusts and formed apparently due to thrust motions.

Major thrusts faults and high angle faults in the wedge are traced by terrigenous and serpentinite mélanges, which are characterized by chaotic structure and block-in-matrix fabric. Mélange blocks range in size from centimeters to first hundreds of meters. They are

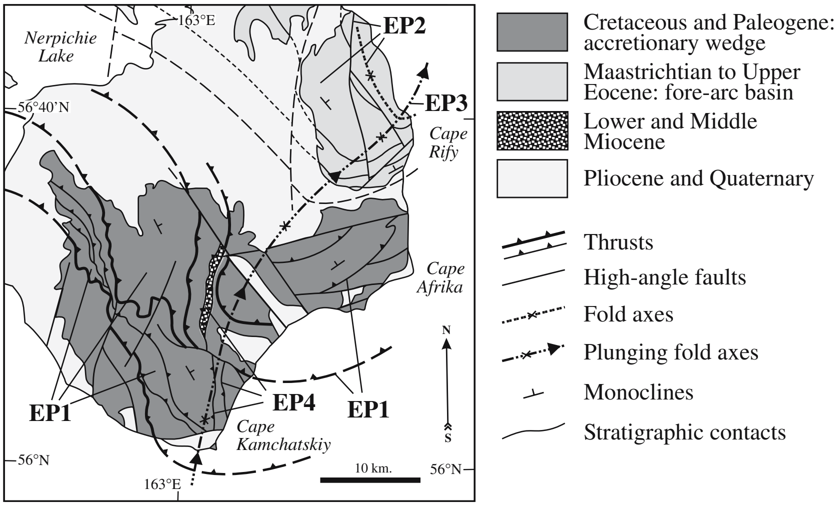


Fig. 10 Relations of the *EP1*, *EP2*, *EP3*, and *EP4* structures in the south of the Cape Kamchatka

comprised of gabbros, ultramafic and sedimentary rocks, derived from surrounding ophiolites, as well as by “exotic” rocks such as high-pressure crystalline schists, garnet-micaceous schists, and amphibolites (Boyarinova et al. 1999). Both upper mantle ultramafic rocks, which form individual thrust sheets, and high-pressure schists found in melange blocks imply that accretionary wedge formed close to master subduction zone, which reached as deep as to the upper mantle.

General orientation of the EP1 structures indicates that shortening during subduction occurred sub-perpendicular to the trend of the arc. Paleostress patterns in the accretionary wedge appear rather chaotic, and apparently reflect several deformational events, successively overprinting one another. A distinct tensor was isolated only for the latest generation of slicken-sided faults, which display well-preserved striations in calcite veins. Stress tensor is characterized by σ_1 axis dipping SW 210/5, sub-vertical σ_2, and horizontal σ_3 (Fig. 9-V). It is consistent with principal direction of shortening in the EP1 complex, and indicates strike-slip mechanism of deformation which can be correlated with the latest diagonal strike-slip faults.

Accretionary wedge dips north and underlies southern part of the fore-arc basin (Shapiro et al. 1997) (Fig. 4). The EP1 structures are not developed in the fore-arc basin, where oldest deposits are dated as the late Maastrichtian, and the deformation in the north of the accretionary wedge therefore predates late Maastrichtian (Khotin 1976). On the other hand, thrust sheets composed by Paleocene and Eocene rocks are found in the south of the wedge (Fedorchuk 1989; Vysotskiy 1989) and it indicates that active thrust faulting continued there until Early Eocene at least. We conclude from these facts that the wedge developed from Late Cretaceous to Eocene sub-synchronously with sedimentation in the fore-arc basin, and thrust sheets composed by younger rocks successively accreted in front of the older ones. Same style of deformation is broadly documented in accretionary wedges over the world and considered typical of such structures (Kennett 1982).

EP2 structures are characteristic of the volcanic belt and fore-arc basins of the Kronotskiy arc. They are presented by monoclines, relatively few folds, reverse faults sub-parallel to fold axes, and diagonal strike-slip faults (Khotin 1976; Shapiro et al. 1987). The monoclines occupy wide areas both on the Kronotskiy peninsula and Cape Kamchatka and are characterized by dip angles ranging from sub-horizontal to 50°–60°. Fold structures developed mainly in the north of the Cape Kamchatka. They are upright and inclined linear and brachy-form structures, ranging from low angle to closed in shape and from 1 to 8 km in width (Figs. 4, 9-11, 9-12).

The EP2 folds and monoclines change their strikes from toward NW on Cape Kamchatka (Fig. 9-11) to towards the NE on Kronotskiy peninsula (Fig. 9-12) in agreement with deformation of the entire Kronotskiy terrane in plunging folds (see EP3 structures). Restoration of the EP3 plunging folds suggests that the EP2 folds were initially trending from east to west, sub-parallel to the original strike of the Kronotskiy arc and sharply discordant to the trend of the East Kamchatka collisional belt. Shortening occurred in the north to south direction, sub-perpendicular to strike of the arc. This implies that EP2 deformation was not connected with collision of the Kronotskiy arc and Kamchatka and reflects an individual compressional episode. The time of EP2 deformation is constrained by the early Late Eocene age of youngest deformed rocks and Oligocene age of sub-volcanic bodies (Boyarinova et al. 1999), which cut fold structures in the north of the Cape Kamchatka (Fig. 4). Most probable age of deformation is the beginning of the Late Eocene, since cessation of sedimentation and volcanism in Kronotskiy arc point at major tectonic reorganization namely at that time.

EP3 structures. It has been proven by paleomagnetic data, that the knee-like bend of the Kronotskiy terrane (Figs. 1, 6) formed due to western part of the terrane rotated up to 90° counterclockwise with respect to the eastern part (Bazhenov et al. 1992). It remained unclear, however, whether the terrane was bent in plunging folds or was broken in smaller blocks, which rotated independently. Our observations argue in favor of the first mechanism of deformation.

Two major plunging folds dominate the overall structure of Cape Kamchatka peninsula. Fold axes, trending NNE are located at a distance of 40 km from one another. The axis of the anticline can be traced from the Nerpichie lake to Stolbovaya river, axis of syncline goes from the cape Kamchatskiy to the area in the north of the cape Rify (Figs. 4, 10). Within the syncline the older structures (EP1 and EP2) change their strikes from SW azimuth 230°–250° to NW 300°–315° (Figs. 4, 10) and they turn back from NW 300° to WSW 240°–250° within anticline (Fig. 4). The bend within the anticline is also well outlined by magnetic anomaly, related to ophiolites in deformed accretionary wedge (Fig. 6). Folds axes plunge towards NNE with the angles ranging from 20° to 70°. Steeper angles are characteristic in the south of the Cape Kamchatka and shallower angles prevail in the north. Fold axial plains are sub-vertical or dip ESE with the angles of 70°–80° (Fig. 9-13).

Bending of the Kronotskiy arc is interpreted to result from arc–continent collision (Bazhenov et al. 1992) and time of this deformation is essential for dating the age of the collision. The age of deformation can be deduced from the fact that Tyushevka basin discordantly truncates plunging folds and lacks any signs of such deformation (Fig. 6), and therefore the folds pre-date formation of the basin. Since the Tyushevka basin was finally formed in the Early Miocene, the age of plunging folds can be constrained between the Late Eocene (based on the age of the youngest rocks involved in folds) and earliest Miocene (based on the age of the basin, which seals these structures).

EP4 structures are documented mainly in the Oligocene and Miocene rocks in Tyushevka basin, and

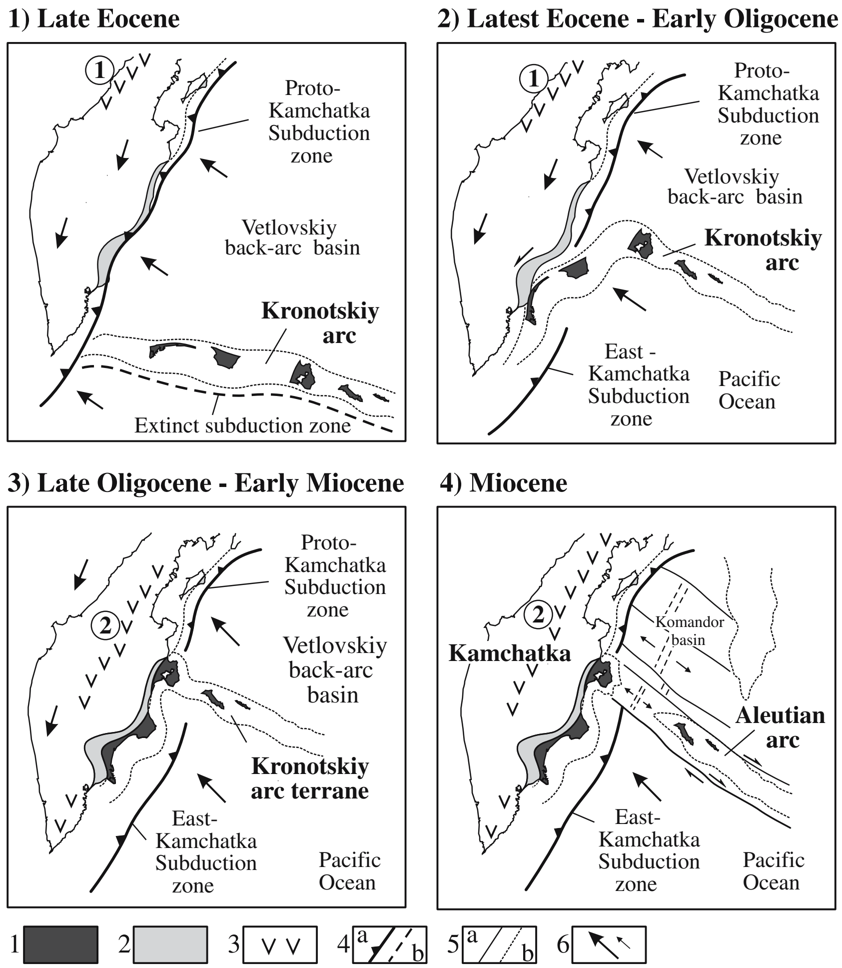


Fig. 11 Plate tectonic evolution of the Kamchatka–Aleutian junction area. *1* Kronotskiy arc, *2* Vetlovskiy terrane, *3* subductional volcanic belts: Kinkil (*1*) and Central Kamchatka (*2*), *4* subduction zones: *a* active and *b* extinct, *5* terrane boundaries *a* on land and *b* offshore, *6* directions of the plate motion

represent monoclines, flexures, low angle folds, reverse faults and thrusts. The monoclines are dominating and characterized by general dip towards the W and NW. Dip angles range from 5° to 30° and increase up to 60°–80° in flexures. Relatively few folds represent broad low angle structures, trending N and NE sub-parallel to the trend of the basin and ranging from 1 to 3 km in width (Figs. 4, 9-14, 9-15). NE trending reverse faults and thrusts develop mainly in the NW of the basin, close to the thrust folded belt of the Eastern Ranges. Principal direction of motion is toward the SE; opposite direction was documented only for a few thrusts on Kronotskiy peninsula (Bakhteiev et al. 1997). Outside Tyushevka basin the NE-trending reverse faults in Miocene rocks develop locally on the Cape Kamchatka (Khotin 1976) (Figs. 4, 10).

General strike of the EP4 structures towards the N and NE implies shortening in the E and SE directions, azimuths 90°–130°. A few displacement measurements, obtained for the Miocene rocks in Ust'-Kamchatsk area are in agreement with this vector: the σ_1 axis of the stress ellipsoid is reconstructed like dipping towards NW (310°) with an angle of 30° (Fig. 9-VI). The time of deformation is given by the post-Middle Miocene–pre-Pliocene angular unconformity, which is broadly documented within the Eastern Kamchatka. EP4 structures formed sub-synchronously with the latest ER1 thrusts in the Eastern Ranges zone (Shapiro 1976; Shapiro et al. 1987; Zinkevich et al. 1993; Bakhteiev et al. 1997).

Discussion

Reconstruction of the Kronotskiy arc

Analysis of paleomagnetic declinations in Cretaceous and Paleogene rocks versus present day structural strikes suggests that originally the Kronotskiy arc was linear and trended from west to east with an azimuth of 80°–100° (Bazhenov et al. 1992; Levashova et al. 2000a, b). The subduction zone (in paleocordinates) was located south of the arc. This is evidenced by the relative position of the accretionary wedge, the fore-arc basin, and the volcanic belt (Fig. 4 section I, and Fig. 6) as well as by the north dip direction of thrust planes in the accretionary wedge. The accretionary wedge developed from Late Cretaceous through the Middle Eocene (see EP1 structures) and it indicates that the subduction zone maintained its direction and position during this time.

Therefore, until the Middle Eocene the Kronotskiy arc was neither a part of the Pacific or Kula plates, which is situated further to the south. The arc located on a smaller plate (Vetlovka plate); the latter included the arc and Vetlovka back-arc basin.

Global reconstruction of the plate motion suggests that from the Cretaceous to Middle Eocene the Pacific and Kula plates were moving northward (Engebretson et al. 1987; Kononov 1989) and, subduction therefore occurred at an almost right angle to the strike of the east–west trending Kronotskiy arc. This statement is in good agreement with structural and paleostress data for the accretionary wedge of the Kronotskiy arc (EP1 structures), which also indicate shortening sub-perpendicular to the strike of the arc (Fig. 9-10, V). In the Middle Eocene (42–44 Ma) vector of the Pacific plate motion changed towards the NW (Az 290°) (Engebretson et al. 1987; Kononov 1989). A northwest dipping subduction zone was initiated along the Kamchatka margin and an accretionary wedge started to form within Vetlovskiy terrane (Tsukanov and Fedorchuk 1989; Tsukanov 1991; Konstantinovskaia 2001). Correlative volcanic belt formed in the NW of Kamchatka, where island arc volcanic rocks developed in Kinkil' formation of the Middle and Upper Eocene age (Fig. 11-1).

Continued volcanism in Kronotskiy arc is evidence that relative plate convergence was lasting at a very oblique angle of 10°–30° to the strike of the arc until Late Eocene. Cessation of the volcanism and subduction in the Priabonian age was followed by deformational episode with shortening sub-perpendicular to the strike of the arc (EP2 structures). The latter can be connected with subduction of an oceanic rise or spreading ridge (Kula-Pacific ridge?) or with locking of subduction zone. Either during the time of oblique subduction, same as the western part of the present day Aleutian arc (Lallemant and Oldow 2000), or after the cessation of subduction, the Kronotskiy arc was moved to the NW with the Pacific plate towards Kamchatka.

Arc–continent collision

Collision of the Kronotskiy arc with Kamchatka was previously dated as starting either in the Middle Eocene (Tsukanov 1991; Zinkevich and Tsukanov 1992) or in the Late Miocene (Kononov 1989; Bakhteiev et al. 1997; Levashova et al. 2000a, b; Konstantinovskaia 2001). Our data allow us to constrain the main episode of collision between the latest Eocene and earliest Miocene. This is based on the age of syn-collisional plunging folds in the Kronotskiy terrane (see EP3 structures), and on the provenance data for the Upper Eocene to Miocene Tyushevka basin, which indicate that the basin developed "in situ" with respect to Kamchatka (see Tyushevka basin).

Appearance of the fluvial conglomerates and proximal turbidites in the Upper Eocene in the NW of the Tyushevka basin (Shapiro 1976) apparently reflects the earliest stages of the arc–continent collision, which led to the change from the deeper marine trench setting to a shallow marine foreland basin. Active thrust motions in the NW of the Tyushevka basin in the Late Eocene (Bakhteiev et al. 1997) indicate active ongoing convergence and suggest that Kronotskiy terrane was not finally welded with Kamchatka at that time (Fig. 11-2).

Both plunging folds (EP3 structures) and syn-collisional thrusts (late ER1 structures) document shortening in the NW–SE direction, which imply that the collision was generally controlled by the NW motion of the Pacific plate. Since the motion occurred at an almost right angle to the strike of Kamchatka margin it could not cause deflection of the western part of the Kronotskiy terrane toward the south. This deflection rather reflects southward translation of the NE Eurasia margin, which took place during the Tertiary (Engebretson et al. 1987; Jolivet et al. 1987). Such southward motion of the Eurasia margin can also explain ER2 structures in collisional belt, which document shortening in the north-to-south direction (Fig. 11-2). Assuming an average rate of convergence of the Pacific Plate and Kamchatka of about 6 cm/yr in middle Tertiary, convergence must have lasted 8–9 Ma to accrete the length of the rotated part of the Kronotskiy arc (about 500 km) against Kamchatka. The terrane was deformed, as evidenced by plunging folds, and finally placed to Kamchatka margin by Early Miocene, when Tyushevka basin extended along the entire length of the collisional thrust belt. Accretion of the Kronotskiy arc to continent apparently caused jumping of the subductional volcanic belt from the NW of Kamchatka to Central Kamchatka, where active volcanism began in the latest Oiligocene (?) and Early Miocene (Fig. 11-3).

Active subsidence in Tyushevka foredeep implies that some convergence between Kronotskiy terrane and Kamchatka might have continued in the Miocene, when principal motion between Pacific plate and Eurasia was already concentrated in the East Kamchatka subduction zone (Fig. 11-4). Late Miocene deformational episode (latest ER1 and EP4 structures) can represent either the last phase of the arc–continent collision, or an independent event, connected with steepening of the East Kamchatka subduction zone (Seliverstov 1998). The eastern part of the Kronotskiy terrane (Komandor islands) did not collide with Kamchatka in the Tertiary. The convergence apparently ceased when this block was separated from Pacific plate by the Aleutian transform fault. Then the block moved to the SE due to opening of the Kamchatka strait, which most likely was connected with spreading in the Komandor basin in the Miocene (Fig. 11-4). NW motion of the Komandor islands was renewed in Pliocene and Quaternary (Oldow et al. 1999; Gaedicke et al. 2000; Freitag et al. 2001).

This reconstruction of regional plate tectonic patterns suggests that the continentward motion of the Kronotskiy arc was connected only with NW-directed subduction at Kamchatka margin since the Middle Eocene. A relatively short period of precollisional convergence (about 10 Ma) implies that in the Middle Eocene the arc was situated not more than 2°–3° south of its present day position. This contradicts paleomagnetic data, which indicate a location of the arc some 1,300–1,500 km south of Kamchatka in the Bartonian and Lutetian (Levashova et al. 2000a, b). Similar discrepancies between geological and paleomagnetic data in Tertiary formations were documented in many regions over the world, as magnetic inclinations both in sedimentary and volcanic rocks are found up to 20° shallower than can be expected (Westphal et al. 1986, 1993; Gilder et al. 1996; Cogne et al. 1999). Undetected intra-plate movements, poorly constrained reference poles, a nonaxial magnetic field, and a non-dipolar magnetic field were discussed as possible explanations of this phenomenon, but its nature still remains rather unclear (Westphal 1993). Resolving this uncertainty is of a more global scale and beyond the scope of current article. We can only state that magnetization in the Eocene rocks of Kronotskiy arc appears anomalously shallow, and a more detailed study need to be addressed to this question.

Conclusions

Structural evolution of the Kamchatka–Aleutian junction area in late Mesozoic and Tertiary was controlled by (1) the processes of subduction in Kronotskiy and Proto-Kamchatka subduction zones, and (2) collision of the Kronotskiy arc against Kamchatka. During the Late Cretaceous through the Middle Eocene the Kronotskiy arc was located at a smaller scale Vetlovka plate, and north-dipping subduction zone evolved south of the arc. The Kronotskiy subduction zone maintained its direction and position during this time and consumed northward motion of the Pacific and Kula plates. Convergence between the Kronotskiy arc and Eurasia occurred only due to NW-directed subduction at Kamchatka margin since the Middle Eocene (42–44 Ma).

Kronotskiy arc welded with Kamchatka between the Late Eocene and Early Miocene and minor shortening continued in the Miocene. Collision was controlled by the NW motion of the arc with Pacific plate and by the south-directed motion of the Eurasia margin. The latter component caused (1) deflection of the western part of the Kronotskiy arc toward the south, and (2) development of the transpressional structures in collisional belt.

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