Arc-continent collision and subduction reversal in the Cenozoic evolution of the Nortwest Pacific: An example from Kamchatka (NE Russia)

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Arc–continent collision and subduction reversal in the Cenozoic evolution of the Northwest Pacific: an example from Kamchatka (NE Russia)

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Abstract

The principal new feature in the Cenozoic evolution of the Northwest Pacific is based on the fact that two arc terranes of Upper Cretaceous–Paleogene age were incorporated in the Kamchatka orogen during the early Tertiary and at the end of the Miocene, respectively. These two arc terranes, so-called Achaivayam–Valaginskaya (Campanian–Lower Paleocene) and Kronotskaya (Coniacian–Eocene) arcs, are separated by a suture zone that contains deformed slices of young (Paleocene–Lower Eocene) oceanic crust. Paleomagnetic data on the original paleolatitudes of the arc positions as well as geochemical data characterized the arcs as intraoceanic, originated in the Northwest Pacific. The arcs were separated by the Vetlovka oceanic plate, suggested to be a trapped fragment of the Kula plate, in which a new spreading zone developed in the early Tertiary. The principal event in the reconstructed evolution is the Eocene collision of the extended Achaivayam–Valaginskaya arc terrane with the continental margin of Asia. The margin is interpreted as the southeastern (facing the Pacific) Cretaceous accretionary boundary of the Okhotsk microplate docked against the Asian continent at ~55–65 Ma. The arc–continent collision developed progressively northward from the end of the Paleocene–Early Eocene in Southern Kamchatka to the Middle Eocene in the Olutorka region. The different stages of the collision occurred simultaneously along strike of the Achaivayam–Valaginskaya arc. According to the geodynamic model based on geological data for Southern Kamchatka, collision included: (1) the entrance of the continental margin in the subduction zone, deformation of the overriding plate and subduction of fore-arc block; (2) arc obduction on the continental margin, blocking of continental margin subduction; and (3) subduction reversal with onset of oceanic subduction at the eastern side of the deformed arc. This subduction reversal produced deformation and reverse faulting along the eastern side of the arc, thus allowing accretion of tectonic slices of young oceanic crust of the Vetlovka plate, which began to subduct. During the subduction reversal, the subducted plate dipping to the southeast was broken off and detached at depth under the arc area. The subduction polarity reversal, the most characteristic feature of the collision model, is strongly supported by structural and geologic data of Southern Kamchatka and explains the main tectonic, metamorphic and magmatic events related to and postdating the collision. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: orogen tectonics; arc–continent collision; subduction reversal; plate kinematics; Pacific; Kamchatka

1. Introduction

Convergence between the Pacific plates and the continental plate of Northeast Asia is a history of accretion of arc terranes, oceanic plateau and

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microcontinents arriving from Pacific and docked to the continental margin (Engebretson et al., 1985; Zonenshain et al., 1990; Parfenov et al., 1993; Nokleberg et al., 1994; Sokolov and Byalobzheskiy, 1996). The volcanic–plutonic belts of Andean type consequently developed in time above growing accretionary continental margin of Northeast Asia (Fig. 1). The Uda–Murgal and Okhotsk–Chukotka belts developed above the Mesozoic active margin of Asia during the Late Jurassic–Neocomian and the Albian–Campanian, respectively (Filatova, 1988). During the Cenozoic, three volcanic belts developed in the Kamchatka orogen (Fig. 1): Koryak–Kamchatka (Middle Eocene–Oligocene), Central Kamchatka (Oligocene–Quaternary) and Eastern Kamchatka (Pliocene-today) belts (Shantzer et al., 1985; Filatova, 1988). The active volcanoes of the Eastern Kamchatka and the Kuril arc form above the northwest-dipping subduction zone of the Pacific plate (Fig. 2) (Gorbatov et al., 1999a).

The region of Sea of Okhotsk between the Mesozoic active margin of Northeast Asia and Kamchatka is underlain by the Okhotsk microplate lithosphere (Fig. 1) that contains several suboceanic or subcontinental blocks, which differ in crustal thickness and geophysical characteristics (Kharakhinov et al., 1996). The microplate moves slowly to the northwest relative to Eurasia and North America (Savostin et al., 1983; Cook et al., 1986; DeMets, 1992; Seno et al., 1996; Takahashi et al., 1999). Recent tomographic data of Bijwaard et al. (1998) and Gorbatov et al. (1999b, 2000) reveal the positive velocity perturbation feature beneath the northern Sea of Okhotsk.. This high-velocity anomaly extending to ~660 km of depth and then deflecting along the 660-km discontinuity was interpreted as a remnant slab of the Okhotsk microplate (Fig. 2) (Gorbatov et al., 1999b, 2000).

The Kamchatka orogen contains three accreted oceanic arc terranes and the Sredinny microcontinent (Fig. 1). West of Kamchatka, the orogen is composed of remnants of the Kvakhona arc (Jurassic–Lower Cretaceous) and the Sredinny microcontinent (Bondarenko and Sokolkov, 1990; Bondarenko, 1992; Rikhter, 1995). Within the central and eastern Kamchatka (Fig. 2), the orogen contains mainly fragments of the Achaivayam–Valaginskaya arc (Campanian–Lower Paleocene) (Zinkevich et al., 1990; Konstantinovskaya et al., 1993; Shapiro, 1995). On the Eastern Peninsulas of Kamchatka, the Kronotskaya arc (Coniacian–Eocene) is exposed (Raznitsin et al., 1985; Shapiro, 1995).

The Lesser Kuril islands represent recent nonvolcanic rise in front of the Kuril arc (Fig. 1). The rise is composed of Campanian–Lower Maastrichtian volcanites similar in geochemical composition to rocks of the Achaivayam–Valaginskaya arc (Geodekyan et al., 1976). The Lesser Kuril arc rocks are suggested to have originated on oceanic crust (Fedorchenko and Rodionova, 1975).

The Achaivayam–Valaginskaya and Kronotskaya arcs of the Kamchatka orogen are characterized in geochemical composition as intraoceanic (Khubunaya, 1987; Konstantinovskaya, 1992; Magakyan et al., 1993; Kamenetskiy et al., 1993). Paleomagnetic data on the original paleolatitudes of the arc positions (Table 1) suggest that both of the arc terranes originated in the Pacific, southeast from its current position. The different scenarios of the arcs transport and accretion to the Asian margin during the Cenozoic have been proposed (Worrall, 1991; Zinkevich and Tsukanov, 1992a; Nokleberg et al., 1994; Geist et al., 1994; Shapiro, 1995; Shapiro et al., 1997; Levachova, 1999). Nonetheless, one question relevant for paleo-reconstructions has not been answered: what is the nature of tectonic accretion or collision of the arcs with the Asian continental margin? This paper discusses the collision between the Achaivayam–Valaginskaya arc and the Asian margin. This arc terrane, which is 1000-km long, most likely played a significant role in the Cenozoic evolution of the northwestern Pacific. Tectonic structures formed during the arc–continent collision, including those from deep crustal levels, are now exposed, providing direct information about geodynamic processes involved in the collision. Although this event occurred during the Early Cenozoic, the syncollisional tectonic structures were not significantly modified. A geodynamic model for the arc–continent collision is proposed on the basis of new data on geology and tectonic structures of the Kamchatka orogen. To explain possible geodynamic context for the collision model, a new reconstruction of the Cenozoic evolution in the Northwest Pacific is discussed.

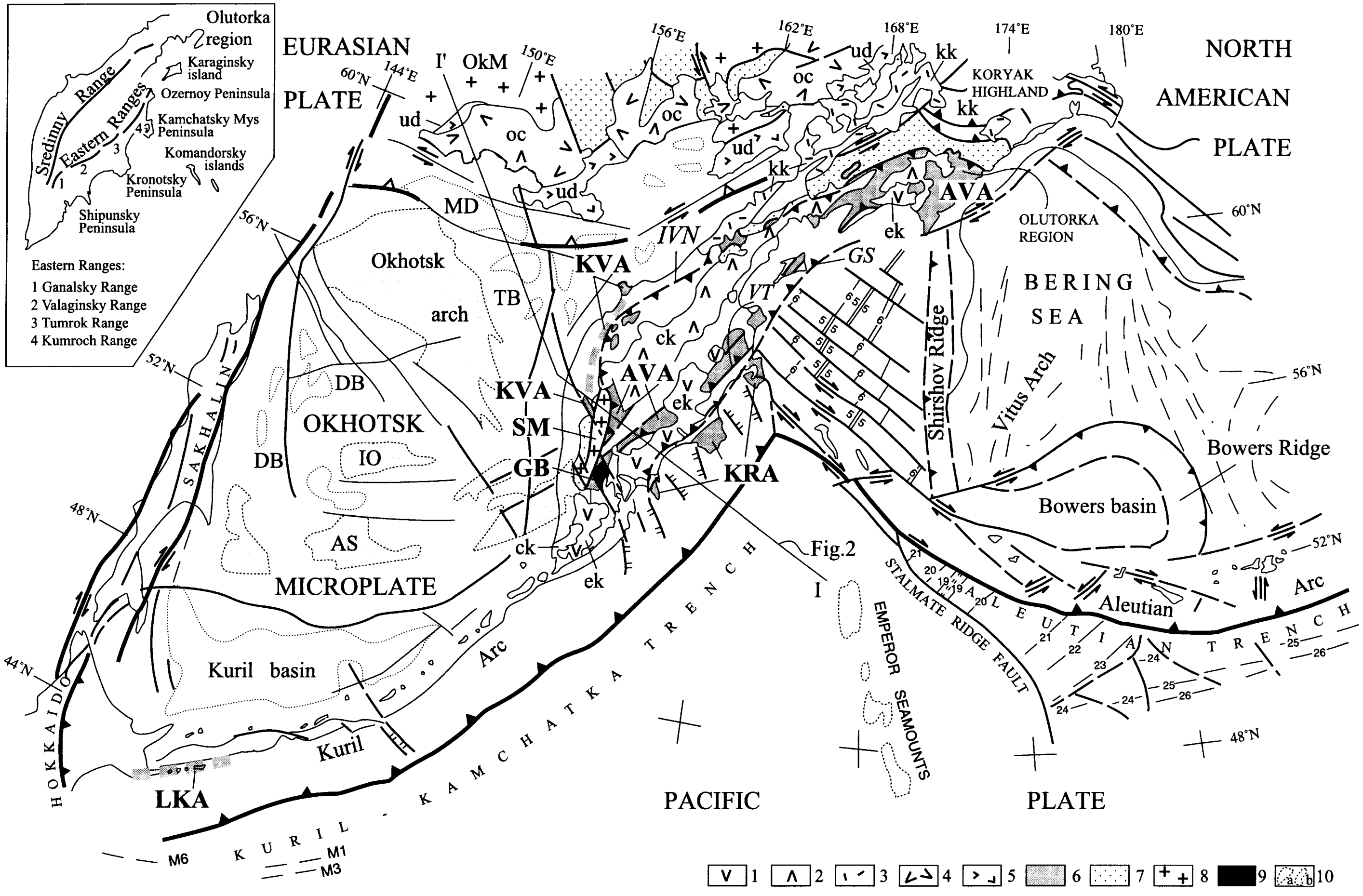


Fig. 1. Geodynamic setting of Kamchatka in framework of the Northwest Pacific. Modified after Nokleberg et al. (1994) and Kharakhinov (1996)). Simplified cross-section along line I–I′ is shown in Fig. 2. The inset shows location of Sredinny and Eastern Ranges.1–5 = Volcanic–plutonic belts of Andean type: 1 = Eastern Kamchatka (ek), 2 = Central Kamchatka (ck), 3 = Koryak–Kamchatka (kk), 4 = Okhotsk–Chukotka (oc), 5 = Uda-Murgal (ud); 6 = arc terranes: Kvakhona (KVA), Achaivayam–Valaginskaya (AVA), Kronotskaya (KRA), Lesser Kuril (LKA); 7 = continental-derived turbidites; 8 = microcontinents Okhotsk (OkM), Sredinny (SM); 9 = Ganalsky metamorphic block (GB); 10 = offshore rises of basement (a): Institute of Oceanology (IO), Academy of Sciences (AS), and deeps (b): Magadan deep (MD), Tinro basin (TB), Derugin basin (DB). In capital letters: IVN = Iruney–Vatuna nappe, VT = Vetlovka thrust, GS = Grechishkin collisional suture.

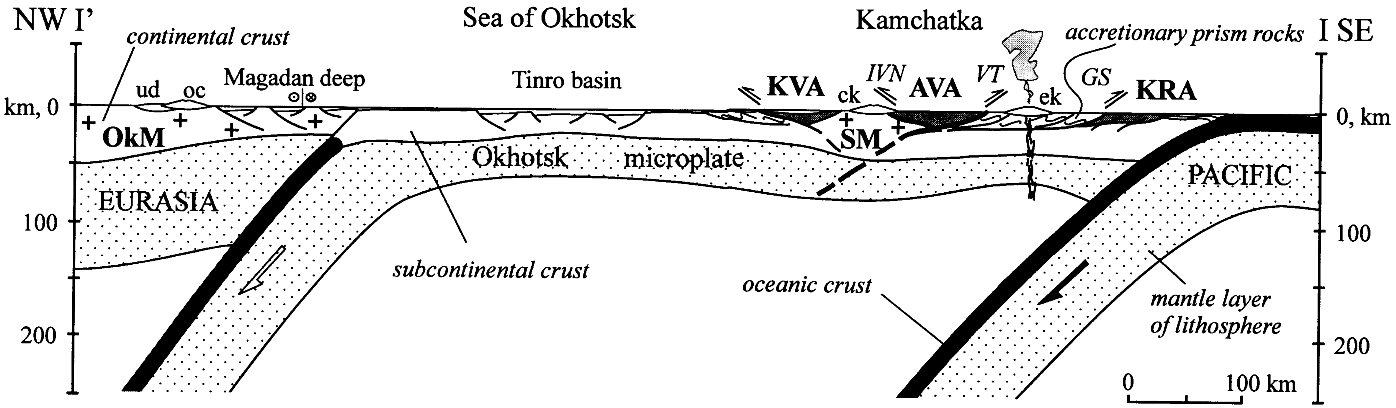


Fig. 2. Simplified cross-section locating in Fig. 1 of Northeast Sea of Okhotsk and Kamchatka. Data on type and thickness of crust are taken from Zhuravlev and Antipov (1993) and Kharakhinov et al. (1996). Subduction zones of the Okhotsk microplate and the Pacific plate are shown after Gorbatov et al. (1999a,b, 2000). Key symbols as in Fig. 1. Black and white arrows indicate active and inactive subduction, respectively.

Table 1
Paleolatitudes of the island arc terranes of the Kamchatka–Olutorka region

Age of volcanic units	Region of sampling	Paleolatitutes (°N)	References
Achaivayam–Valaginskaya arc			
Kamchatka segment			
Campanian	Sredinny Range	48.5 ± 8.4	Levachova et al., 1998
Campanian	Kumroch Range	48.7 ± 5.0	Levachova et al., 1997
Upper Campanian–Maastrichtian	Kumroch Range	30 ± 5	Shapiro et al., 1997
Maastrichtian	Kumroch Range	48 ± 5	Shapiro et al., 1997
Lower Paleocene	Kumroch Range	53 ± 10	Shapiro et al., 1997
Present position	Sredinny–Kumroch Ranges	53–57	
Olutorka region segment			
Maastrichtian–Lower Paleocene	Karaginsky island	44.5 ± 5.6	Kovalenko, 1990
Campanian–Maastrichtian	Olutorka region	42.1 ± 7.1	Kovalenko, 1993
Campanian–Maastrichtian	Olutorka region	49.0 ± 10.9	Kovalenko, 1992
Campanian–Maastrichtian	Olutorka region	47.0 ± 6.5	Kovalenko, 1992
Campanian–Maastrichtian	Olutorka region	51.1 ± 7.0	Kovalenko, 1992
Middle Eocene	Olutorka region	58.6 ± 15.8	Kovalenko, 1993
Eocene	Olutorka region	60.2 ± 6.8	Kovalenko, 1990
Present position	Olutorka region	60–62	
Kronotskaya arc			
Campanian–Maastrichtian	Kronotsky peninsula	44.8 ± 8.0	Levachova, 1999
Upper Paleocene	Kronotsky peninsula	38.6 ± 3.5	Levachova, 1999
Middle Eocene	Kronotsky peninsula	45.1 ± 7.0	Levachova, 1999
Middle Eocene	Kronotsky peninsula	41.0 ± 6.0	Bazhenov et al., 1992
Present position	Kronotsky peninsula	55	
Lower Paleocene	Kamchatsky Mys peninsula	38.1 ± 4.1	Pechersky et al., 1997
Middle–Upper Eocene	Kamchatsky Mys peninsula	47.0 ± 6.4	Pechersky et al., 1997
Middle–Upper Eocene	Kamchatsky Mys peninsula	47.0 ± 5	Shapiro et al., 1997
Middle–Upper Eocene	Kamchatsky Mys peninsula	48.0 ± 11	Bazhenov et al., 1992
Present position	Kamchatsky Mys peninsula	56.5	

2. Data on geology and tectonic structures

2.1. *Upper crustal tectonic structures related to arc–continent collision*

The Achaivayam–Valaginskaya arc is exposed in the Sredinny and Eastern Ranges of Kamchatka and in the Olutorka region (Fig. 1, inset). The arc was emplaced northwestward over the continental margin of Asia along the Iruney–Vatuna nappe (Shapiro, 1995), which extends ~1000 km through the entire Kamchatka peninsula to the Olutorka region (Fig. 1). This event is diachronous and youngs northward, thus supporting northward progressive collision of the arc and the margin.

In the north of Kamchatka and in the Olutorka region, the Achaivayam–Valaginskaya arc units obducted toward the northwest onto the Campanian–Early Eocene continental-derived turbidite formations (Fig. 3) (Fedorchuk and Izvekov, 1992; Solov'ev et al., 1997; Brandon et al., 1998). The leading edge of the arc is tectonically underlain by the tectonic slices of the Cretaceous oceanic crust that contains the Albian–Campanian MORB-type basalts and pelagic radiolarites (Krylov et al., 1989; Vishnevskaya, 1990). The nappe structures are unconformably covered by the Middle Eocene and Oligocene units of the Koryak–Kamchatka and Central Kamchatka volcanic belts (Fig. 3) (Shantzer et al., 1985), thus supporting the early Middle Eocene time of the collision in the region (Brandon et al., 1998). In Southern Kamchatka, the arc units thrust towards the northwest over the Sredinny microcontinent (Fig. 4) at the end of the Paleocene–Early Eocene (see below).

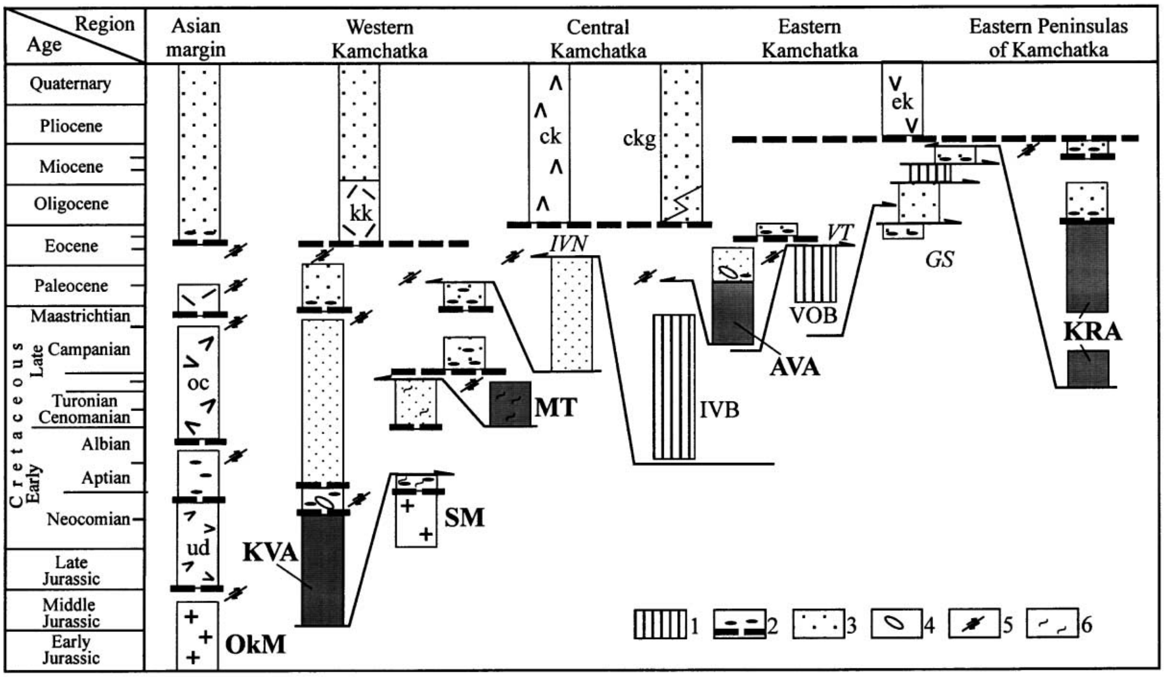


Fig. 3. Chronodiagram representing time vs. simplified lithologic units and major tectonic events for Kamchatka. 1 = Oceanic crust rocks (basalts, diabases and/or pelagic sediments); 2 = major inconformity and basal conglomerates; 3 = non-marine and/or shallow marine clastic deposits; 4 = olistostromal deposits; 5 = episode of accretion; 6 = penetratively deformed or regionally metamorphosed rocks. In capital letters: MT = Malkin terrane; IVB = units of the Iruney–Vatuna oceanic basin; VOB = units of the Vetlovka oceanic basin. Other symbols as in Fig. 1.

The eastern margin of the Achaivayam–Valaginskaya arc is marked by the Vetlovka thrust, which extends from the Shipunsky Peninsula in the south through the Eastern Ranges to the Karaginsky island and the Govena Peninsula in the north (Fig. 4). Along this fault, the arc was emplaced to the southeast over the Vetlovka oceanic unit of Paleocene–Early Eocene age (Fig. 3) (Tsukanov and Fedorchuk, 1989; Fedorchuk et al., 1990; Bakhteev et al., 1994). The northwest-dipping imbricate thrust faults associated with tight and isoclinal folding affected both the eastern margin of the arc and the Vetlovka unit during the Eocene (Chechovich et al., 1990; Geist et al., 1994; Kovalenko, 1992; Kravchenko-Bereznoy, Nazimova, 1991; Zinkevich and Tsukanov, 1992b).

The deformed rocks of the Achaivayam–Valaginskaya arc and the Vetlovka oceanic unit thrusted over the Upper Eocene–Upper Miocene sedimentary units exposed to the east in the Grechishkin collisional suture (Fig. 4). The suture extends along the Kamchatka ~300 km and represents a system of steep northwest-dipping synsedimentary thrusts developed in terrigenous deposits during the Late Eocene to terminal Miocene, when the Kronotskaya arc docked to Kamchatka (Fig. 3) (Bakhteev et al., 1997). Within the suture, the Miocene pelagic siliceous rocks occur in tectonic slices (Fig. 3) that contain Radiolaria groups similar to those of Japan and the Kuril Islands (Bakhteev et al., 1997). It is likely that the structure of the Vetlovka and Grechishkin thrusts represents an accretionary wedge developed from the Middle Eocene to the Late Miocene to the east of the coeval Central Kamchatka volcanic belt (Figs. 3, 4).

The southeast-dipping Iruney–Vatuna nappe converges with the northwest-dipping Vetlovka thrust in the vicinity of Govena Peninsula in the north and in the Southern Kamchatka in the south (Fig. 4) (Chechovich et al., 1990; Zonenshain et al., 1990).

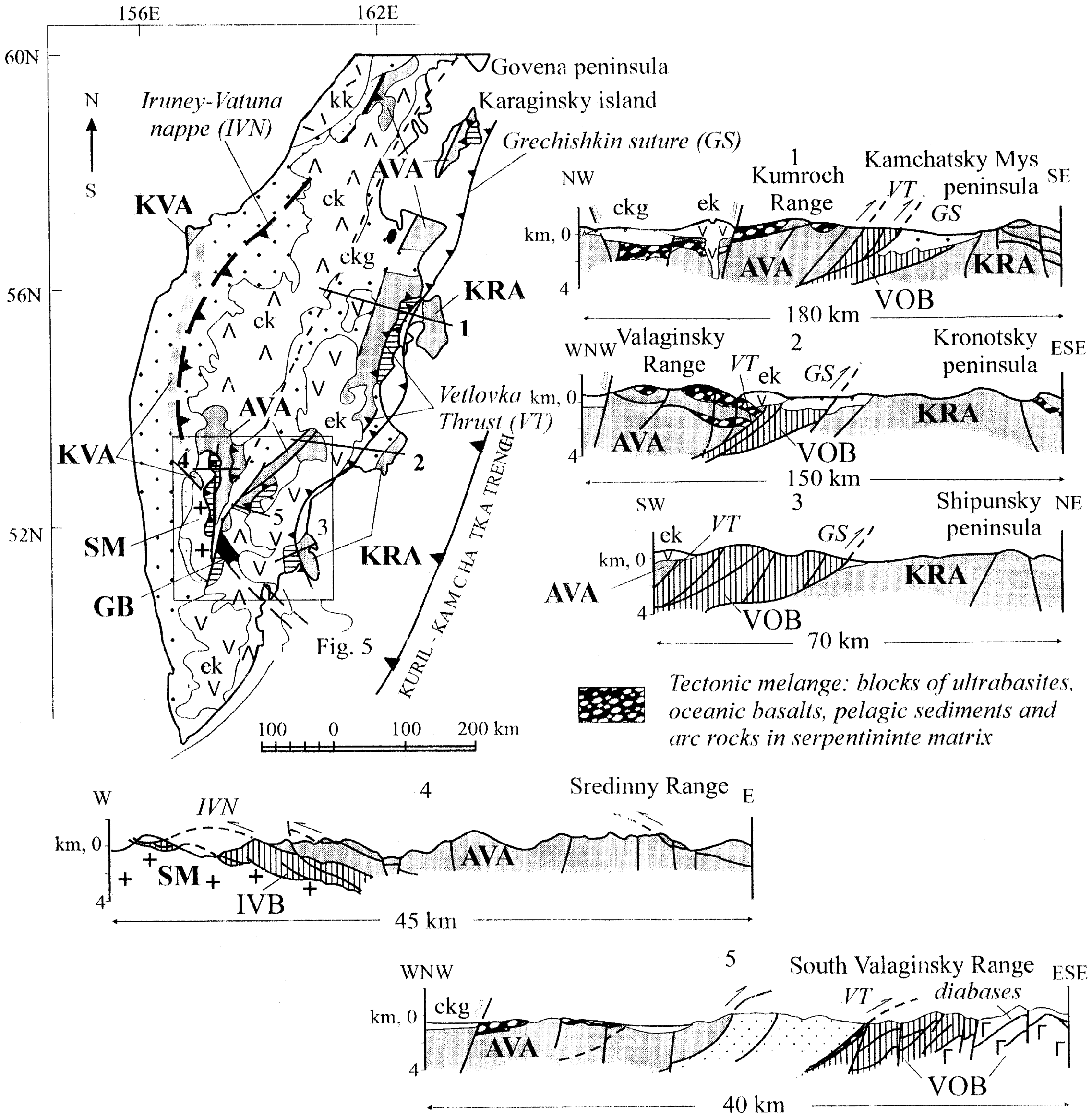


Fig. 4. Tectonic sketch and cross sections of Kamchatka. Modified after (Zinkevich and Tsukanov, 1992b; Zinkevich et al., 1994). Cadre shows location of Fig. 5a. Key symbols as in Figs. 1 and 3. Vertical hatched pattern in the cross-sections is horizontal on the map.

This paper focuses on the southern Kamchatka segment of the Achaivayam–Valaginskaya arc.

2.2. The Achaivayam–Valaginskaya arc in southern Kamchatka

The western and eastern sides of the Achaivayam–Valaginskaya arc are separated by the Central Kamchatka graben (Fig. 4), which is believed to have opened progressively along strike from north–northeast to south–southwest from Oligocene to Miocene times (Fig. 3) (Zinkevich et al., 1990). In Southern Kamchatka, its width is less than 20 km.

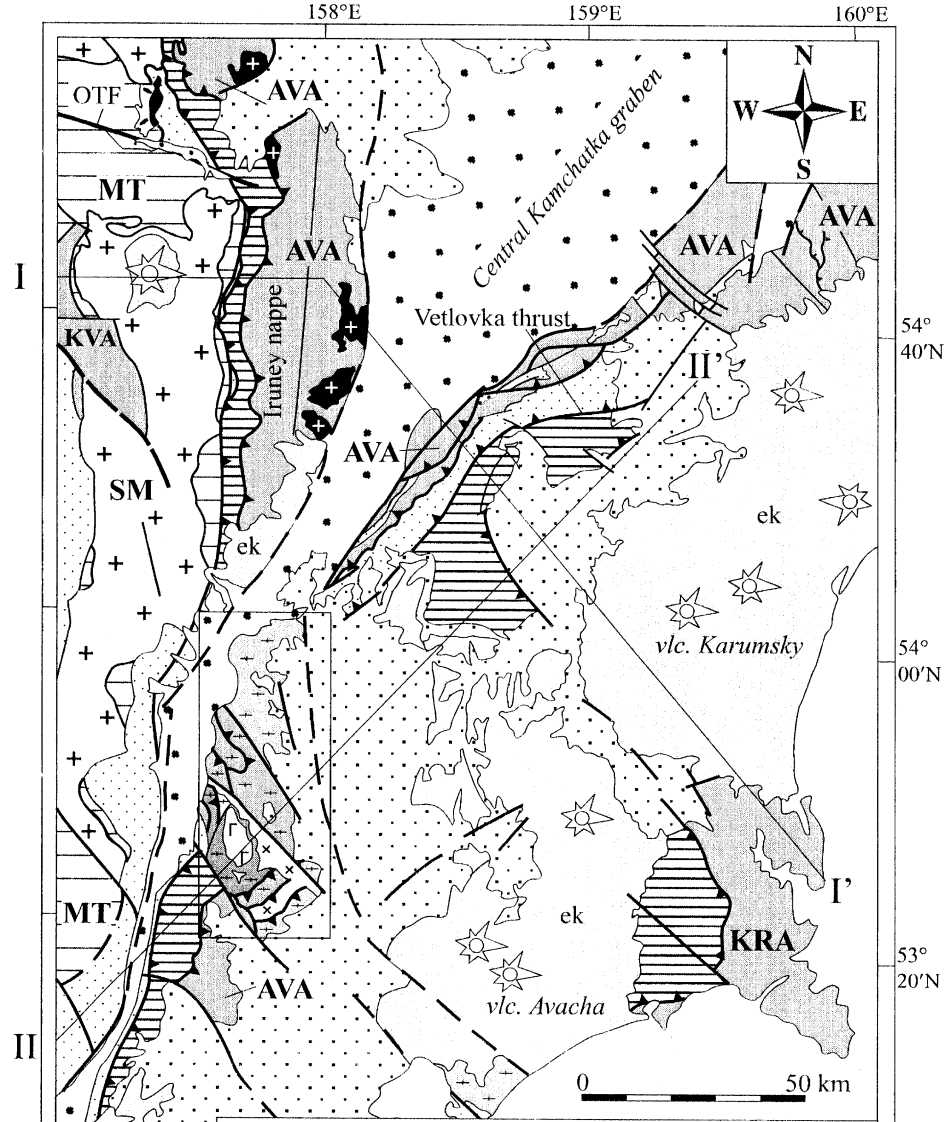


Fig. 5. (a) Tectonic map of Southern Kamchatka. Modified after (Geological map of Kamchatka, 1981; Rikhter, 1991). Cadre shows location of the Ganalsky metamorphic block. Cross-sections along lines I–I′ and II–II′ are shown in Fig. 5b. 1 = volcanic rocks of Pliocene–Quaternary age; 2–3 = rocks of the Ganalsky metamorphic block: 2 = phyllite to chlorite–biotite schists (a); greenschists to epidote–amphibolites (b), 3 = garnet amphibolites (a), granulites (b); 4 = gabbroic intrusive massif (a), synkinematic gabbro and plagiogranite intrusions (b), 5 = Malkin terrane, 6 = alkaline granites of Miocene age. In capital letters: OTF = Oblukovina transverse fault. Horizontal hatched patterns are vertical on cross-sections in Fig. 5b. Other symbols as in Fig. 1 and 3. (b) Cross-sections located in (a) of Southern Kamchatka. Key symbols as in (a).

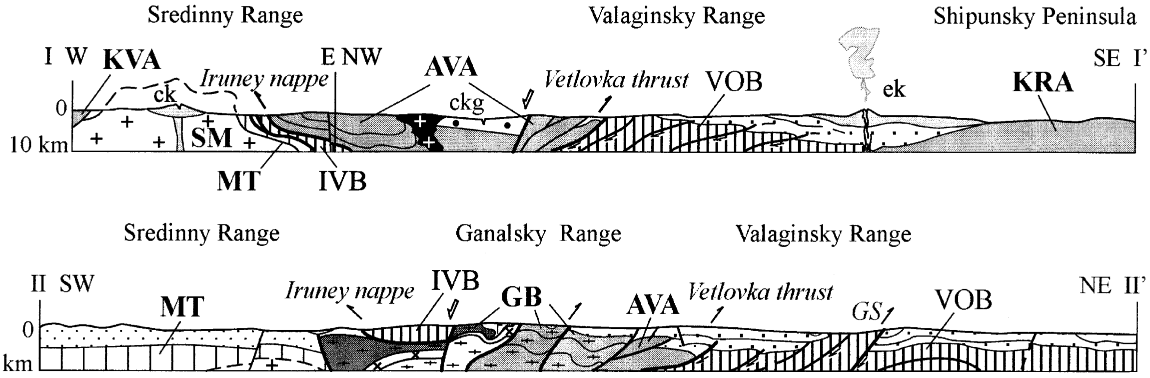


Fig. 5. (*continued*)

2.2.1. *The Iruney–Vatuna nappe*

The tectonic structure of the Iruney–Vatuna nappe in Southern Kamchatka crops out on the eastern slopes of the Sredinny Range (Fig. 5). The relative autochthon is composed of the Sredinny metamorphic block, which contains granulite facies rocks intruded by plagiogranites dated by Rb/Sr methods as 127 ± 6 Ma (Vinogradov et al., 1988, 1991; Rikhter, 1995). Remnants of the Kvakhona arc tectonically emplaced along the western margin of the Sredinny block at the end of the Early Cretaceous (Bondarenko, 1992). The arc and the metamorphic block are overlain by continental-derived turbidites of Middle–Later Cretaceous age (Fig. 3). The Malkin terrane thrust over the granulite basement of the Sredinny block along its eastern margin and in the periclinal zones (Fig. 5a). The Malkin terrane is composed of the amphibolite–facies metamorphic rocks that are recognized as originally arc-related volcanites (Rikhter, 1995). The non-metamorphosed molasse deposits of Campanian and Paleocene ages unconformably overlie the Malkin terrane and contain redeposited clastics of the metamorphic rocks (Fig. 3). The Campanian flora found in the molasse deposits (Shapiro et al., 1986) constrains the overthrusting and metamorphic events of the Malkin terrane to before 83 Ma (Rikhter, 1995).

The Iruney–Vatuna nappe is composed mostly of Campanian–Lower Paleocene volcanic and volcaniclastic rocks of the Achaivayam–Valaginskaya arc (Fig. 5b) (Zinkevich et al., 1994). The arc units are generally deformed in open folds. The frontal part of the nappe, where the deformation is more intense, is affected by west-vergent folding and thrusting. In front of the arc units, tectonic slices with total thickness not exceeding 1–2 km are observed. These slices consist pelagic cherts and radiolarites of Santonian–Lower Maastrichtian age (Fig. 3), which thrust over the distal continental-derived turbidites of the Campanian age (Konstantinovskaya, 1997). Within both units, MORB-like basalt occur (Fedorov, 1986).

The structural style of the frontal part of the Iruney–Vatuna nappe varies along strike. The low-angle thrusts occur north of the main outcrop of the Sredinny metamorphic block, north of the Oblukovina transverse fault (Fig. 5a). To the south of the fault, the frontal thrust is steep to near vertical (Fig. 5b). Along the basal thrust of the Iruney–Vatuna nappe, the rocks of the autochthonous molasse deposits display penetrative cleavage and are sheared, with top to the northwest kinematic indicators (Kolodyazhny et al., 1996). The rocks of the Iruney–Vatuna nappe thrust over the Sredinny metamorphic block at the end of the Paleocene–Early Eocene (Fig. 3). The Miocene alkaline granite intrusions occurred in the nappe (Fig. 5) mark continental crust formation.

2.2.2. *The Vetlovka thrust*

The eastern margin of the Achaivayam–Valaginzetaskaya arc is marked by the Vetlovka thrust (Fig. 5a). The eastern margin consists of series of tectonic slices bound by steeply northwest-dipping thrusts (Zinkevich et al., 1992). The western and structurally uppermost tectonic slices are composed of Campanian–Lower Paleocene volcanic and volcaniclastic rocks, which are overlain by Upper Paleocene–Lower Eocene continental-derived turbidites (Fig. 3) (Bakhteev et al., 1994). These rocks are jointly deformed into southeast-verging folds and thrust over the Vetlovka oceanic unit (Fig. 5b). The Vetlovka unit contains distal volcaniclastic rocks, pelagic radiolarites and limestones, MORB-like basalts and diabases of Paleocene–Early Eocene age (Zinkevich et al., 1992; Bakhteev et al., 1994). The rocks of the unit affected by northwest-dipping intensive isoclinal folding and steep thrusting and, in turn, thrust over the Upper Eocene–Miocene sedimentary units exposed to the east (Fig. 5b).

The deformed rocks of the Vetlovka oceanic unit are unconformably overlain by the Middle Eocene shallow-sea sedimentary rocks (Fig. 3) forming neoautochthon (Bakhteev et al., 1994). The southeastward thrusting along the eastern side of the Achaivayam–Valaginskaya arc and underthrusting of the oceanic rocks occurred in the Early Eocene (Fig. 3). This event cannot be associated with tectonic accretion of the Kronotskaya arc as it was supposed by Zinkevich and Tsukanov (1992a) because this arc docked to Kamchatka at the end of the Miocene (Fig. 3) (Bakhteev et al., 1997). Thus, both the tectonic events (i.e. northwestward thrusting of the Achaivayam–Valaginskaya arc over the Asian continental margin and southeastward reverse faulting along the eastern side of the arc accompanied by accretion of the Paleogene oceanic crust) may be assigned to the arc–continent collision event.

2.3. Ganalsky metamorphic block

The Ganalsky metamorphic block locates in front of the Achaivayam–Valaginskaya arc (Fig. 5a). The block is composed of three main allochthonous units emplaced to the northwest onto the granulite autochthon along the low-angle overthrusts (German, 1978; Rikhter, 1991). The allochthonous units consist phyllite and chlorite–biotite facies rocks in the upper tectonic slice, greenschists and epidote amphibolites in the middle slice and garnet amphibolites in the deeper slice (Rikhter, 1993). Isoclinal folds and ductile deformation developed in the rocks at deeper structural levels and synkinematic gabbro and plagiogranite intrusions occurred along the thrusts (Luchitskaya and Rikhter, 1989; Luchitskaya, 1998). Thin zones of serpentinized ultrabasites and pyroxenites define the base of major tectonic slices.

The steep northeast-verging thrusts with sinistral strike–slip component superimposed over the northwest directed overthrusts in structure of the Ganalsky metamorphic block (Fig. 5b) (Rikhter, 1991). Open folding and superimposed retrograde metamorphism are associated with these oblique slip faults (Rikhter, 1993). From north to south, lower structural levels are exposed in the block (Fig. 5a). The Middle Eocene shallow sea sedimentary rocks unconformably overlie the metamorphic rocks.

The protoliths for the rocks of the allochthonous units in the Ganalsky metamorphic block were volcanic and volcaniclastic arc rocks (Rikhter, 1993). The garnet amphibolites and marbles from the deeper tectonic slice represent metamorphosed oceanic basalts, pelagic siliceous rocks and limestones, which originally underlain the arc-related rocks (Rikhter, 1993). The rocks were metamorphosed under MP–HT conditions of amphibolite (6.8–7.3 kbar, 730–800°C) and greenschist (4.8–5.0 kbar, 530–560°C) facies (Mohammed et al., 1998). Ar/Ar data from the garnet amphibolites yields ages between 50.6 and 47 Ma (Zinkevich et al., 1993) that corresponds to the latest Early Eocene early Middle Eocene (Gradstein and Ogg, 1996). The synkinematic gabbro intrusion dated by the Ar/Ar method yields hornblende ages of 35.4 Ma and plagioclase ages of 42 Ma (Zinkevich et al., 1993).

The granulite facies rocks from the autochthon of the Ganalsky block were metamorphosed under MP–HT conditions (7.8 kbar, 730–850°C) and underwent two events of retrograde amphibolite and greenschist facies metamorphism (Mohammed et al., 1998). The origin of the granulites is disputable. Sm/Nd isotopic data from these rocks ($\varepsilon_{\mathrm{Nd}} = -4$) are consistent with a juvenile crust metamorphosed in Cenozoic time, most likely after 50 Ma (Vinogradov et al., 1991). These data are not consistent with existing Pb/Pb and U/Pb zircon data from the Ganalsky gneiss (1.6 b.y.) (L'vov et al., 1986). It allows comparing these rocks with granulites of the Sredinny metamorphic block (Rikhter, 1993, 1995) that locates in 10 km to the west (Fig. 5a). In this case, the autochthonous granulites of the Ganalsky block may represent margin of the Sredinny microcontinent overthrusted by the arc during the collision.

The island arc and oceanic rocks composing protoliths of the allochthonous metamorphic units of the Ganalsky block are suggested to represent basement of the Achaivayam–Valaginskaya arc (Rikhter, 1991, 1993) that locates in 15 km to the northeast (Fig. 5a). During collision between the arc and the Sredinny microcontinent, the arc basement and underlying oceanic crust underwent northwestward overthrusting and crustal thickening and progressively affected synkinematic MP–HT metamorphic event. Ar/Ar age data indicate that the amphibolite-grade metamorphism occurred before the latest Early Eocene. The later northeast-verging thrusting resulted in exhumation of the metamorphic rocks.

3. Geodynamic model of the Kamchatka arc–continent collision

The Achaivayam–Valaginskaya arc arrived to the Asian margin at the end of Early Paleocene time (Table 1) (Konstantinovskaia, 1999a). The Sredinny microcontinent and accreted Malkin metamorphic terrane formed the frontal part of the continental margin (Fig. 6a). The Campanian–Paleocene molasse deposits and continental-derived turbidites accumulated along the margin. These rocks composed also the accretionary prism in front of the arc formed in course of the northwestward migration of the arc (Fig. 6a).

Physical modeling experiments (Shemenda, 1994) show that as the buoyant continental crust of a margin began to subduct, subduction of the plate slowed down or stopped, producing a strong stress increase in the overriding plate. Deformation is localized in the weakest part of the plate — the arc area — producing a subsequent failure of the plate. One of the possible scenarios is that the failure initiates downward motion of fore-arc block under the arc, which experiences a high rate of subsidence. In contrast, the frontal parts of the fore-arc block non-isostatically uplifts (Fig. 6b). These results may be applied to the Kamchatka arc–continent collision. During the Late Paleocene, volcanism in the arc ceased and high-rate accumulation of continental-derived turbidites occurred in the arc area (Fig. 6b). The basal levels of the turbidite sequence contain olistostrome deposits (Fig. 3) that indicates unstable sedimentary environment at the beginning of the arc subsidence. The mineralogical composition of the Upper Paleocene turbidites overlying the arc rocks is similar to the Upper Cretaceous turbidites that found in front of the arc (Shapiro et al., 1992). The model explains accumulation of the Upper Paleocene turbidites in the area of arc subsidence as a result of erosion and redeposition of the Upper Cretaceous continental-derived turbidites from the accretionary prism of fore-arc block that rises up in response of the continental margin underthrusting (Fig. 6b).

Physical modeling suggests that subduction of the fore-arc block beneath the arc results in its complete disappearance in the subduction zone, deformation and obduction of the arc onto the continental margin (Chemenda et al., 2000). The margin of accretionary structure deforms and frontal blocks of light continental crust may be detached and exhumed (Konstantinovskaia, 1999b). During this stage in Kamchatka, the arc thrust over the Sredinny microcontinent (Fig. 6c). The arc basement and underlying oceanic crust were stripped, underthrust beneath the arc and subjected to synkinematic progressive amphibolite-grade metamorphism. The metamorphic Malkin terrane in frontal part of the Sredinny microcontinent is supposed to be detached and began to exhume (Fig. 6c). Unfortunately, lack of the Early Eocene sedimentary rocks in the region was a problem for precise dating of this event and new investigations on the exhumation process are needed.

Modeling indicates that after the strong mantle part of the fore-arc block descents, the subduction in this area may be blocked and continued convergence of the plates initiates a new subduction zone along the back side of the deformed arc (Fig. 6b–d). The evolution of this new established subduction zone result in detachment of the previously subducted plate (Chemenda et al., 2000; Konstantinovskaia, 2000). In Kamchatka, this stage may have led to the beginning of Vetlovka oceanic plate subduction and tectonic accretion of its crustal rocks (basalts and pelagic sediments) to the eastern side of the Achaivayam–Valaginskaya arc (Fig. 6d). Further evolution of the oceanic subduction under the newly formed margin from Late Eocene through Miocene times led to formation of the Central Kamchatka

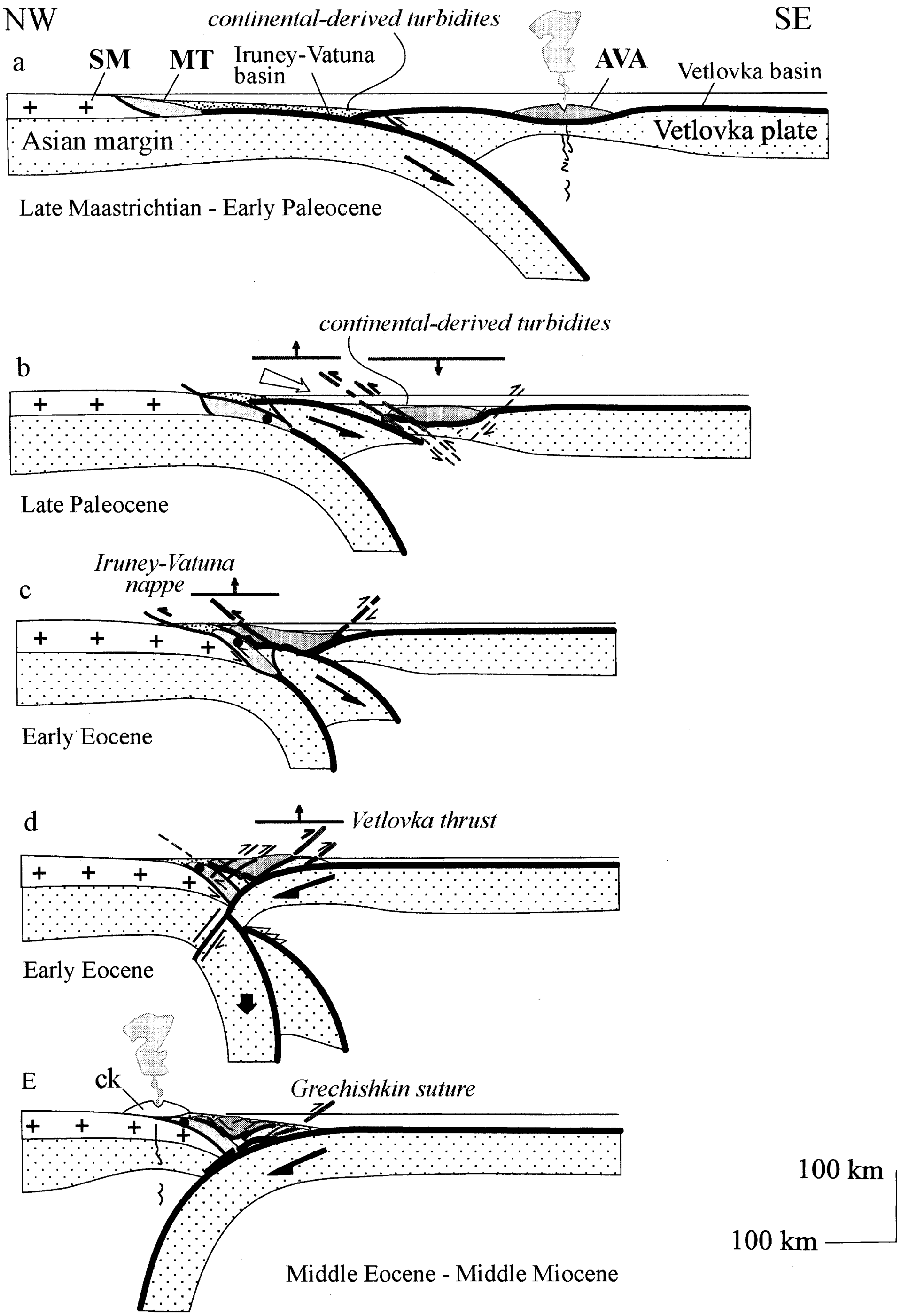


Fig. 6. Geodynamic model of the Kamchatka arc–continent collision. Key symbols as in Fig. 2. White arrow on profile (b) indicates erosion and redeposition of continental-derived turbidites from rising accretionary prism of fore-arc block in the area of arc subsidence.

volcanic belt and a growing accretionary prism to the east from the belt (Fig. 6e).

4. Reconstruction of the Cenozoic evolution in the northwest Pacific

The Mesozoic active continental margin of Northeast Asia was defined by the Okhotsk–Chukotka and Sikhote–Alin volcanic–plutonic belts (Fig. 7A) developed above the north and northwest-dipping subduction zones (Parfenov et al., 1981; Filatova, 1988; Zonenshain et al., 1990). The magmatic activity in the belts was ceased (Fig. 7A and B), when the Okhotsk microplate docked to Asia in ~55–65 Ma (Zonenshain et al., 1990; Kimura, 1994; Worrall et al., 1996). After this event, the southeastern boundary of the microplate formed the frontal, facing the Pacific, margin of Asia (Fig. 7B). The Kvakhona arc and the Sredinny microcontinent composed the accretionary structure of the margin from the Middle–Upper Cretaceous. The Iruney–Vatuna oceanic basin situated to the southeast of the margin (Fig. 7A).

The continental margin of North America was marked by volcanic activity developed during the Maastrichtian–Early Paleocene in the central Koryak Highland, on outer shelf of the Bering sea and along the southern Alaska Range (Fig. 7A) (Cooper et al., 1992; Sokolov and Byalobzheskiy, 1996). The Kula plate originated in the Pacific at about 85 Ma moved northward and subducted under the active margin (Engebretson et al., 1985). The boundary between the Kula and Pacific plates is interpreted to be either a single northwest-extended transform fault (Engebretson et al., 1985) or a series of short spreading centers divided by extended northwest transform zones (Lonsdale, 1988). There are no direct evidences on exact location of the boundary. Kimura et al. (1992) assumed the Kula–Pacific spreading ridge subducted under Hokkaido–Sakhalin active margin in ~65 Ma (Fig. 7A).

The Achaivayam–Valaginskaya arc originated in the Northwest Pacific area to the southeast of its current position (Fig. 7A). During the Campanian–Early Paleocene, the active arc migrated to the northwest toward the Asia that is supported by paleomagnetic data (Table 1). The lithosphere of the Iruney–Vatuna oceanic basin have been subducted in course of the arc migration (Fig. 7A–B). The Kronotskaya arc originally located not far from the Achaivayam–Valaginskaya arc and moved to the southeast during the Paleocene (Fig. 7A–B, Table 1). The relative motion of the arcs one away from other during the Paleocene–Early Eocene may cause extension and seafloor spreading with formation of new oceanic crust in the Vetlovka plate between the arcs (Fig. 7A–B).

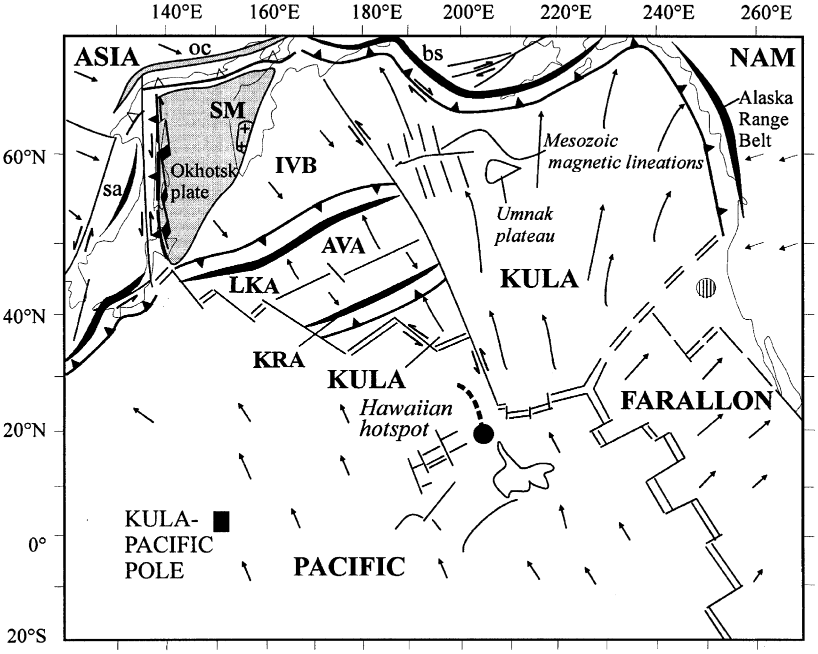
The Lesser Kuril arc is thought to have originated to the southeast from its present position at ~36°N (Bazhenov and Burtman, 1994), most likely to the southwest from the Achaivayam–Valaginskaya arc (Fig. 7A). The end of volcanic activity, thrusting and folding occurred in the Lesser Kuril arc in the Late Maastrichtian (Melankholina, 1978, 1988) most likely mark the beginning of collision between the arc and the Okhotsk microplate (Fig. 7A–B).

The collision of the Achaivayam–Valaginskaya arc with the southeastern margin of the Okhotsk microplate propagated northward from the end of the Late Paleocene–Early Eocene in Southern Kamchatka to the Middle Eocene in the Olutorka region (Fig. 7B). The subduction reversal occurred during the collision resulted in onset of the northwest-dipping oceanic subduction of the Vetlovka plate (Fig. 6). Evolution of the oceanic subduction resulted in formation of the Koryak–Kamchatka and Central Kamchatka volcanic belts developed above the new formed accretionary margin in the Middle Eocene and in the Oligocene, respectively (Fig. 7C). The Kronotskaya arc began to migrate northwestward with the Vetlovka oceanic plate since the Late Paleocene (Table 1).

The Kula–Pacific rotation pole shifted at ~55 Ma, causing counterclockwise rotation of the Kula plate velocity from north to north–northwest (310°N), and the Kula–Pacific boundary was reorganized into a left-lateral transform fault (Fig. 7B) (Lonsdale, 1988). Formation of the proto-Aleutians at ~55 Ma (Cooper et al., 1992) resulted in trapping of the Mesozoic oceanic crust of the Kula plate (Fig. 7B). Behind the western segment of the Aleutians (Fig. 7B–C), extension and back-arc spreading developed in 55–42 Ma in the Vitus arch and the Bowers basin, respectively (Cooper et al., 1992).

The new reorganization of plate motion occurred at ~43 Ma. The Asian plate velocity changed (Fig. 7C) from southeast to southwest (Engebretson et al.,

A. 65 Ma



B. 55 Ma

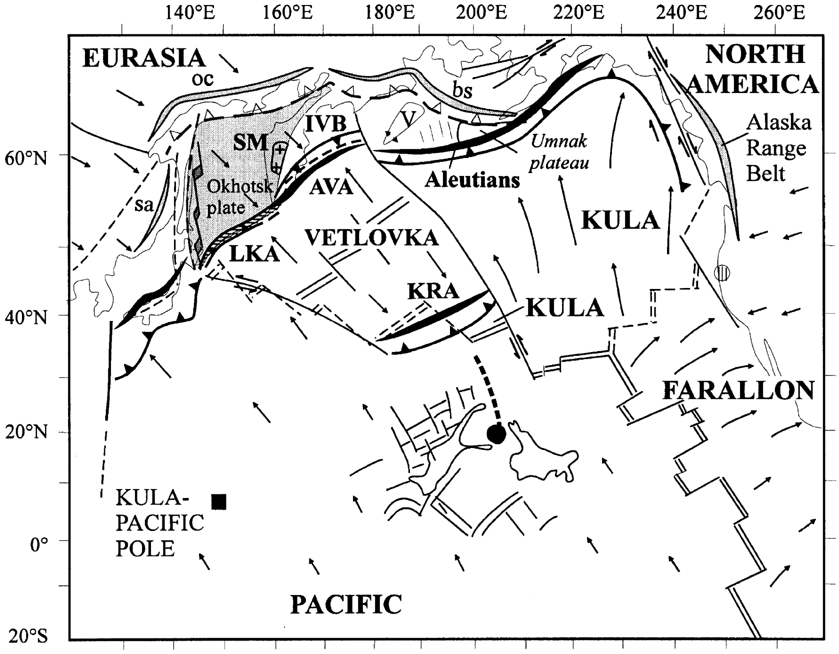
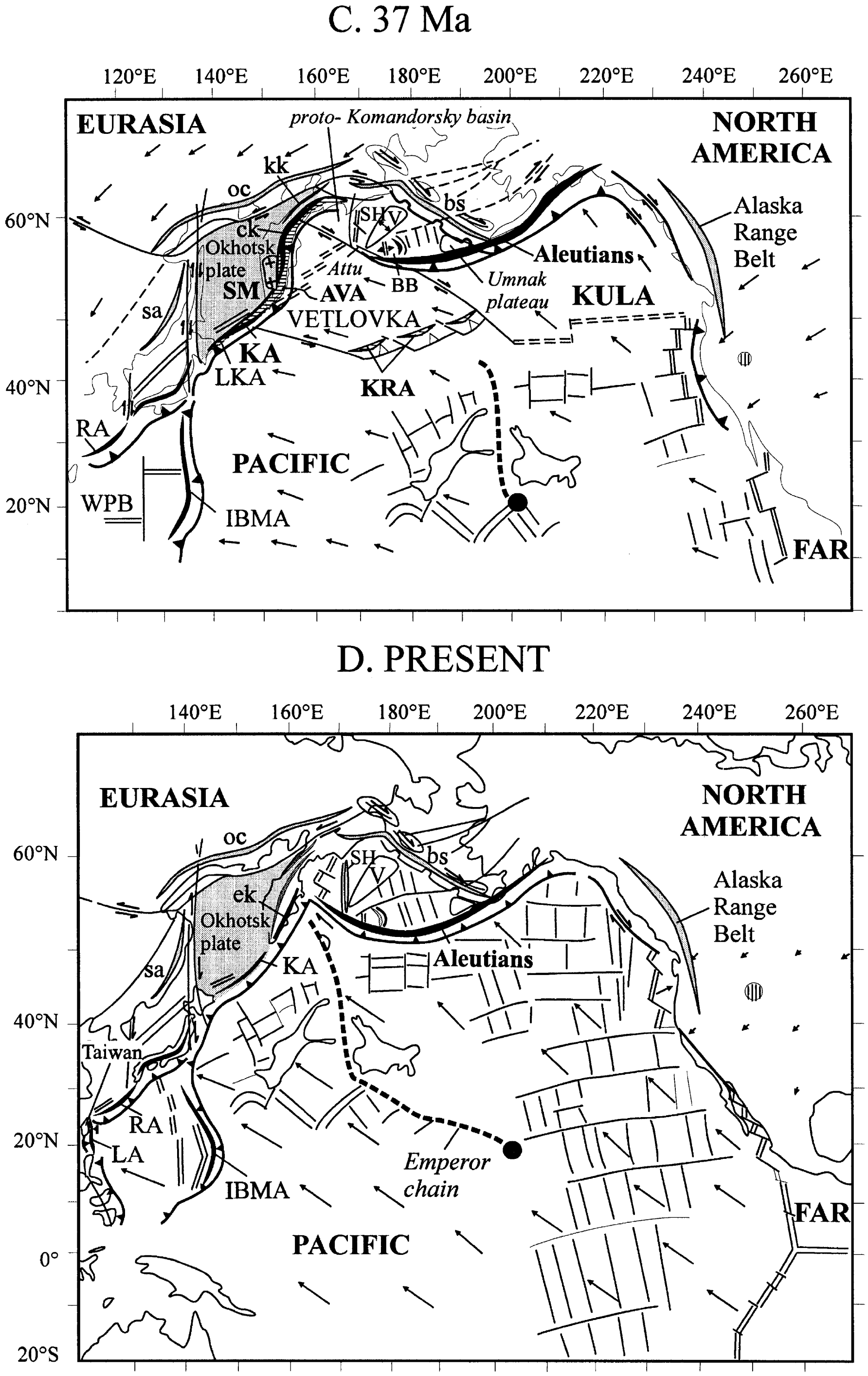


Fig. 7. The Cenozoic evolution in the Northwest Pacific. Plate kinematics is shown in hotspot reference frame after (Engebretson et al., 1985). Keys distinguish zones of active volcanism (thick black lines), inactive volcanic belts (thick gray lines), deformed arc terranes (hatched pattern), subduction zones: active (black triangles), inactive (empty triangles). In letters: sa = Sikhote-aline, bs = Bering shelf belts; SH = Shirshov Ridge; V = Vitus arch; KA = Kuril; RA = Ryukyu; LA = Luzon, IBMA = Izu–Bonin–Mariana arcs; WPB = Western Philippine, BB = Bowers basins. Other symbols as in Fig. 1.



C. 37 Ma

D. PRESENT

Fig. 7. (*continued*)

1985), the Kula–Pacific spreading was dead and the Kula plate was annexed to the Pacific plate (Engebretson et al., 1985; Lonsdale, 1988). The motion of both the plates changed from north–northwest to west–northwest (Fig. 7B–C), and the velocity decreased from 14 cm/yr to about 3 cm/yr (Engebretson et al., 1985).

As a result of the Kula–Pacific plate reorganization in ~43 Ma, subduction of the Pacific plate under the Kronotskaya arc became very oblique, leading to cessation of volcanism within the arc and perhaps segmentation of the arc along strike by oblique transform faults (Fig. 7C). After this event, the Kronotskaya arc continued to be passively transported to the northwest with the Vetlovka plate and, finally, at the end of Miocene time, docked to Kamchatka. The Vetlovka plate was detached and completely subducted. The Pacific plate subduction zone established under the newly formed accretionary margin resulting in formation of the Eastern Kamchatka volcanic belt in ~5 Ma (Fig. 7C–D). Thus, the present configuration of the Asia continental margin was acquired (Fig. 7D).

Along the western margin of the Pacific, the plate convergence became orthogonal at ~43 Ma. This reorganization caused a change of the Philippine–Pacific boundary from a transform fault to a west-dipping subduction zone (Fig. 7B–C) that was accompanied by formation of the Izu–Bonin–Mariana arc (Stern and Bloomer, 1992) and opening of the West Philippine back-arc basin (Rangin et al., 1990). In contrast, the eastern Pacific margin (Fig. 7C) was converted to purely strike–slip (Lonsdale, 1988). The change in the oceanic plate motion caused highly oblique subduction along the western Aleutians with formation of a system of strike–slip transform faults (Fig. 7C), separated the proto-Komandorsky basin from the oceanic basin (Cooper et al., 1992). Transtensional rifting and spreading-type tholeiitic magmatism occurred at about 43 Ma in the westernmost part of the Aleutians, on the Attu island (Fig. 7C) (Yogodzinski et al., 1993). Extensional faulting affected Shirshov ridge (Fig. 7C) behind the Aleutians (Cooper et al., 1992).

5. Discussion and conclusions

The subduction reversal occurred during the Kamchatka arc–continent collision is a principal event in the proposed reconstruction of the Cenozoic evolution in the Northwest Pacific. The Late Cenozoic examples of the comparable collision zones, where subduction reversal is suggested to occur during arc–continent collision, are reported from the Western Pacific in Timor (Price and Audley-Charles, 1987), Taiwan (Chemenda et al., 1997; Malavieille, 1999; Teng et al., 2000), southern Philippines and New Guinea (Pubellier and Cobbold, 1996; Pubellier et al., 1999). The reconstruction similar to the Kamchatka arc–continent collision model is proposed for the Ordovician Taconian orogen in the western New England (Karabinos et al., 1998).

The geodynamic setting established during the early Tertiary collision of the Achaivayam–Valaginskaya arc with the Okhotsk microplate margin (Fig. 7B) may be compared to the present framework in the Philippine Sea area (Konstantinovskaya, 1999c). After the northern Luzon arc thrust over the continental margin in the early Pliocene (Fig. 7D), the breakoff of the east-dipping Eurasian plate occurred and the new west-dipping subduction of the Philippine Sea plate began to propagate southward along the eastern side of the arc (Chemenda et al., 2000; Teng et al., 2000). It is most likely that this subduction zone may connect in time to the west-dipping subduction zone at the eastern side of the Philippine arc (Fig. 7D). If so, the Philippine Sea plate may completely subduct under the new formed active margin, as the Vetlovka plate in Kamchatka (Fig. 7B–D), and the Izu–Bonin–Mariana arc will be docked to the accretionary margin, as the Kronotskaya arc.

The principal difference between the models of Chemenda et al. (2000) and Teng et al. (2000) on the Taiwan arc–continent collision is concerned with a mechanism of subduction reversal. The 3D physical modeling experiments of Chemenda et al. (2000) show that a failure of the overriding Philippine Sea plate occurred along the west-dipping lithospheric fault at the eastern side of the Luzon arc, after the arc thrust over the margin. The failure is prepared by deformations propagating from the conjugate north-dipping subduction zone of the Philippine Sea plate under the Ryukyu arc. The failure of the plate initiates progressive west-dipping subduction of the plate and further evolution of the subduction results in detachment the Eurasian plate. In contrast, Teng et al. (2000)

suggested the breakoff of the east-dipping Eurasian plate beneath Taiwan orogen is a mechanism for the subduction reversal. The slab detachment has created a mantle window for the north-dipping Philippine Sea plate to move in laterally, causing a switch in the subduction polarity. Future investigations may test a leading mechanism of subduction reversal occurred during arc–continent collision.

The 3D reconstruction of the Cenozoic evolution in the Northwest Pacific discussed above led to suggest that during the Kamchatka arc–continent collision, subduction reversal most likely was produced the first causing the Asian slab detachment. After the Achaivayam–Valaginskaya arc thrust to the northwest over the continental margin, a failure of the overriding Vetlovka oceanic plate occurred in the south along the northwest-dipping lithospheric fault at the eastern side of the arc (Fig. 7B). This failure most likely was prepared by deformations propagating from the conjugate subduction zone dipping to the west under the Japan continental margin of Asia. The northward propagation of the Vetlovka plate subduction under the Kamchatka orogen resulted in progressive detachment of the previuosly subducted plate dipping to the southeast (Fig. 7B–C). As a hypothesis, subduction reversal provides a model for the deep lithospheric structure of Kamchatka that can be tested by future investigations.

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