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Lateral Structural Variability in Zone of Eocene Island-Arc–Continent Collision, Kamchatka

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Abstract—The lateral variability of structural elements in the collision zone of the Cretaceous–Paleocene Achaivayam–Valagin island arc with the northeastern Asian margin is considered. The similarity and difference of Eocene collision structural elements in the north and the south of Kamchatka are shown. In northern Kamchatka, the continent–arc boundary is traced along the Lesnaya–Vatyn Thrust Fault, which completed its evolution about 45 Ma ago. The thin, near-horizontal allochthon of this thrust, composed of island-arc rocks, overlies the deformed but unmetamorphosed terrigeneous sequences of the Asian margin. The general structure of this suture in the Kamchatka Isthmus and southern Koryakia is comparable with the uppermost subduction zone, where a thin lithospheric wedge overlaps intensely deformed sediments detached from the plunging plate. In southern Kamchatka (Malka Uplift of the Sredinny Range), the arc–continent collision started 55–53 Ma ago with thrusting of island-arc complexes over terrigenous rocks of continental margin. However, the thickness of the allochthon was much greater than in the north. Immediately after this event, both the autochthon and lower part of allochthon were deformed and subsided to a significant depth. This subsidence gave rise to metamorphism of both the autochthon (Kolpakov and Kamchatka groups, Kheivan Formation) and lower allochthon (Andrianovka and Khimka formations). The anomalously fast heating of the crust was most likely related to the ascent of asthenospheric masses due to slab breakoff, when the Eurasian Plate was plunging beneath the Achaivayam–Valagin arc.

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INTRODUCTION

Over most of the territory of the Olyutor–Kamchatka Tectonic Domain (Fig. 1), including the Olyutor Zone, Karaginsky Island, the Kamchatka Isthmus (Fig. 2), and the eastern ranges of Kamchatka, as well as the southern Sredinny Range (Fig. 5), the Campanian–Maastrichtian and lower Paleocene sequences are composed of volcanic, volcanosedimentary, and cherty rocks with geochemical and facies attributes of ensimatic island-arc complexes [4, 13, 50, 55].

In the Olyutor Zone (Fig. 1), Kamchatka Isthmus (Fig. 2), and southern Sredinny Range (Fig. 5), the Cretaceous–Paleocene oceanic and island-arc complexes are thrust over the coeval terrigenous rocks, whose clastic material was derived from northeastern Asia [8, 34, 56, 59]. It is suggested that the most southeastern part of the Kamchatka–Olyutor Zone (except the eastern peninsulas of Kamchatka) is made up of fragments of a large ensimatic island arc, which had originated in the ocean and then was attached to the continent [14, 19, 36, 54]. This suggestion is consistent with the paleomagnetic data on northward drift of most Cretaceous and lower Paleocene rocks by 10–15° [18, 23, 29]. The existence of such an arc was noted in [9], and in [14] it was called the Achaivayam–Ozerny–Valagin arc. In this paper, we name it as the Achaivayam–Valagin arc [54]. The structural elements related to the attachment of this arc to the Asian margin were studied most thoroughly in the Olyutor Zone (Olyutor and Vetvei ranges) [35, 39], the Kamchatka Isthmus (Lesnaya Uplift) (Fig. 2) [42], and in the southern Sredinny Range (Malka Uplift) (Fig. 5) [17].

In this paper, we characterize the lateral structural variability in the zone of collision between the Achaivayam–Valagin arc and the northeastern Asian margin.

HISTORICAL OVERVIEW AND SETTING OF PROBLEM

Mitrofanov [27] was the first to publish evidence for the tectonic nappe composed of the Upper Cretaceous cherty–volcanic sequences of the Vatyn Group and thrust over terrigenous sequences of the Central Koryak (Ukelayat) Group in the Olyutor Zone. The general geometry of this nappe was ascertained earlier in the course of geological mapping on scales of 1 : 1000000 and 1 : 200000, when the thrust fault was regarded as a stratigraphic boundary. During the subsequent three decades, the contours of this structural unit were speci-

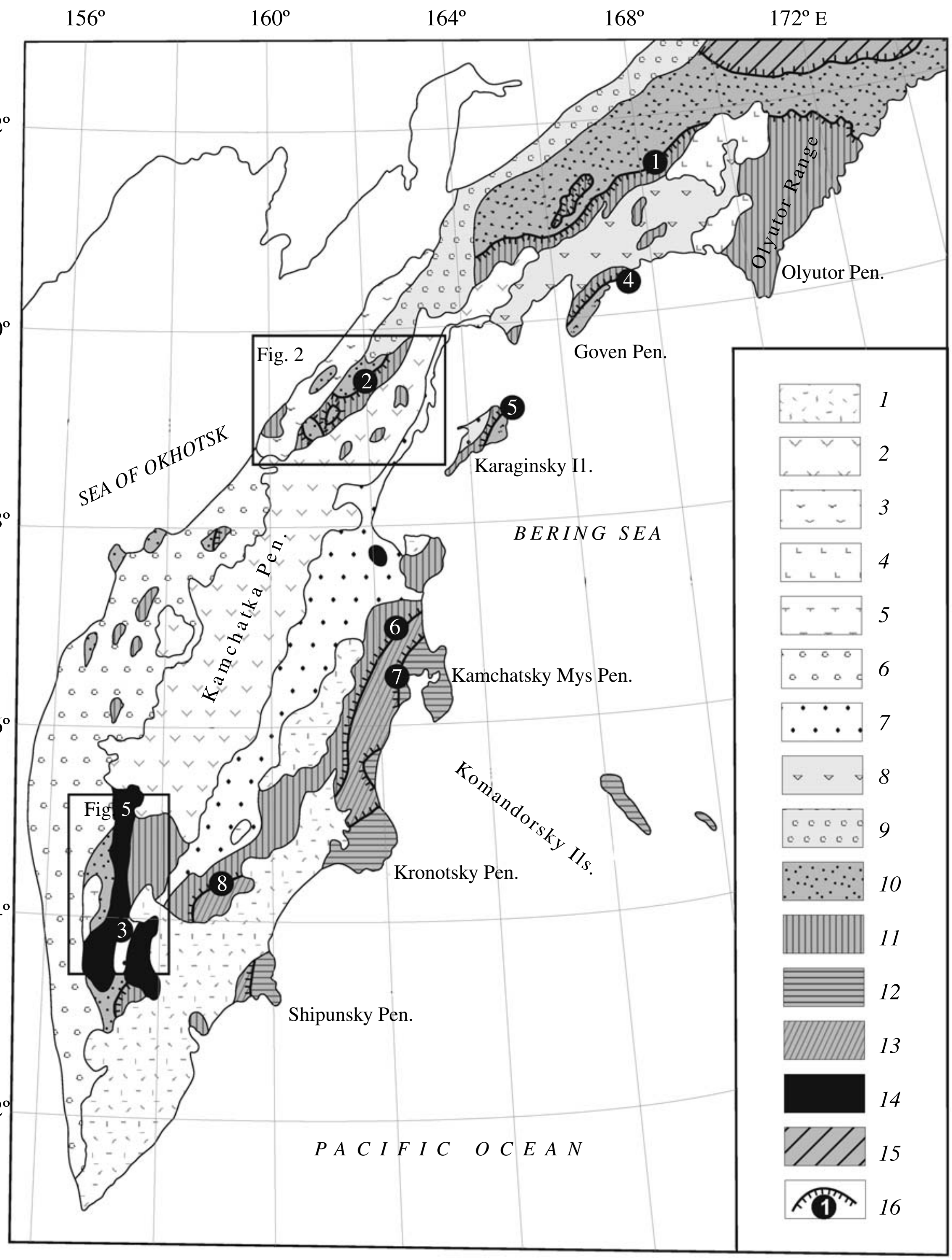


Fig. 1. Tectonic units of Kamchatka and southern Koryakia. (*1–9*) Tectonic units of cover. (*1–5*) Subaerial belts and fields: (*1*) East Kamchatka (Pliocene–Quaternary), (*2*) Central Kamchatka (Oligocene (?) –Quaternary), (*3*) Kinkil (West Kamchatka–Koryakia) (Eocene–Oligocene), (*4*) Apuka–Vevenka (Pliocene–Quaternary), (*5*) Cherepanovsky (Paleocene–Eocene); (*6–9*) sedimentary troughs and depressions: (*6*) West Kamchatka (Eocene–Pliocene), (*7*) Central Kamchatka Depression (Pliocene–Quaternary), (*8*) Il'pi–Pakhacha Trough (Eocene–Miocene), (*9*) Pustoretsk–Parapol Trough (Miocene–Quaternary); (*10–15*) basement terranes: (*10*) Omgon–Ukelayat Terrane, terrigenous sediments of continental rise (Late Cretaceous–Eocene), (*11*) Achaivayam–Valagin paleoisland arc (Late Cretaceous–Paleocene), (*12*) Vetlov–Goven accretionary prism (Eocene–Miocene), (*13*) Kronotsky–Komandorsky paleoisland arc (Late Cretaceous–Oligocene), (*14*) metamorphic rocks developed after the rocks of Omgon–Ukelayat and Achaivayam–Valagin terranes, (*15*) terranes of northern Koryakia; (*16*) tectonic sutures–thrust faults (numerals in circles): (1) Vatyn–Vyvenka, (2) Lesnaya, (3) Andrianovka, (4) Goven, (5) Karaginsky, (6) Vetlov, (7) Grechishkin, (8) Valagin.

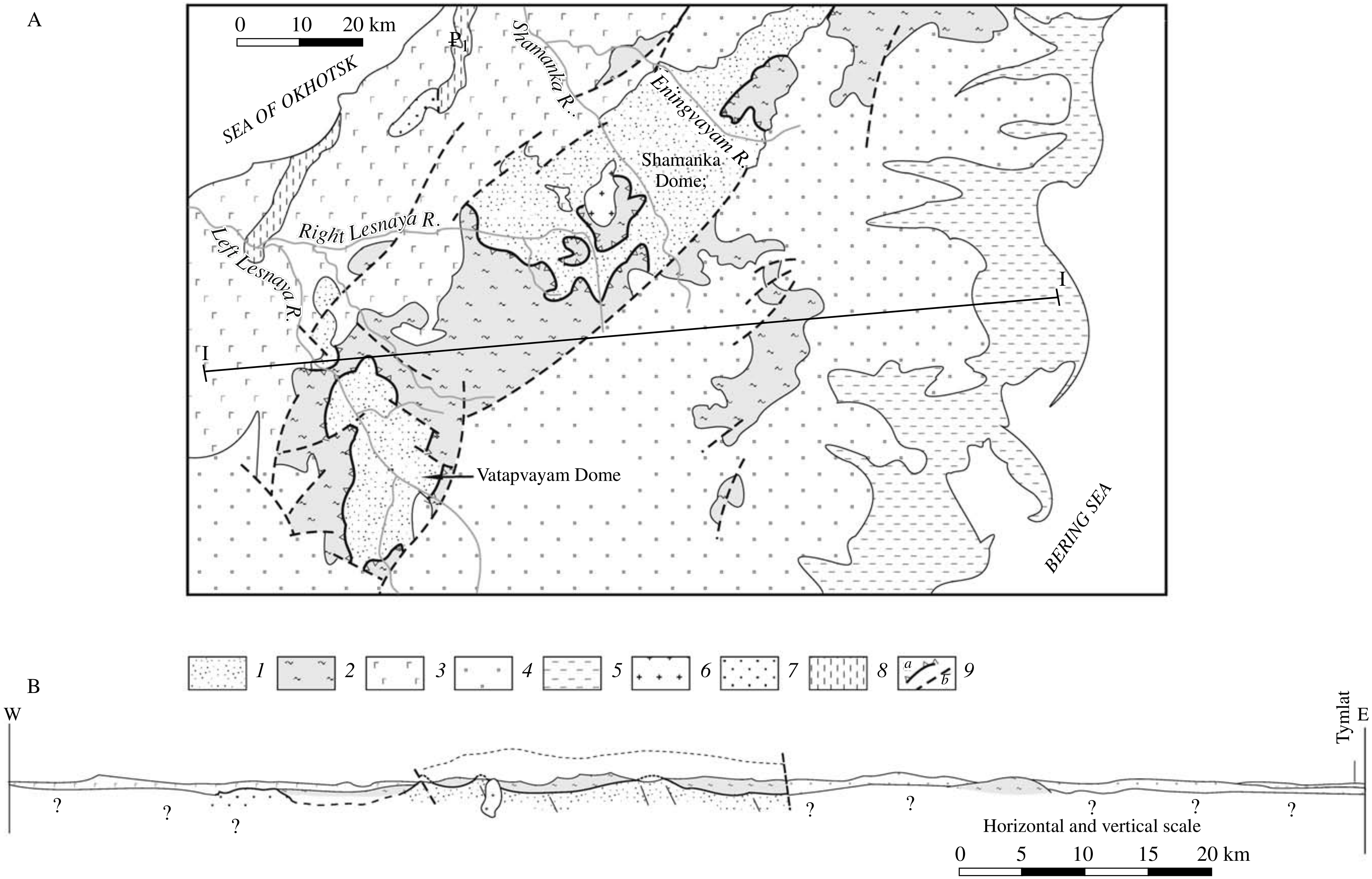


Fig. 2. Geological sketch map of the Kamchatka Isthmus: (a) after [42] using the data reported in [7] and (b) geological section. (*1*) Autochthonous complex, Lesnaya Group (Upper Cretaceous (?)–middle Eocene; (*2*) allochtonous complex, Irunei Formation (Upper Cretaceous); (*3–6*) neoautochthonous complex: (*3*) volcanic rocks of the middle–upper Eocene Kinkil Formation (West Kamchatka volcanic belt), (*4*) upper Eocene–lower Miocene sedimentary rocks and Miocene–Pliocene volcanic rocks, (*5*) Quaternary loose sediments, (*6*) Shamanka granitoid pluton; (*7, 8*) terrigenous complexes of western Kamchatka: (*7*) Tal'niki Formation (Upper Cretaceous), (8) Getkil Formation (Paleocene); (9) tectonic boundaries: (a) Lesnaya Thrust Fault and (b) other faults.

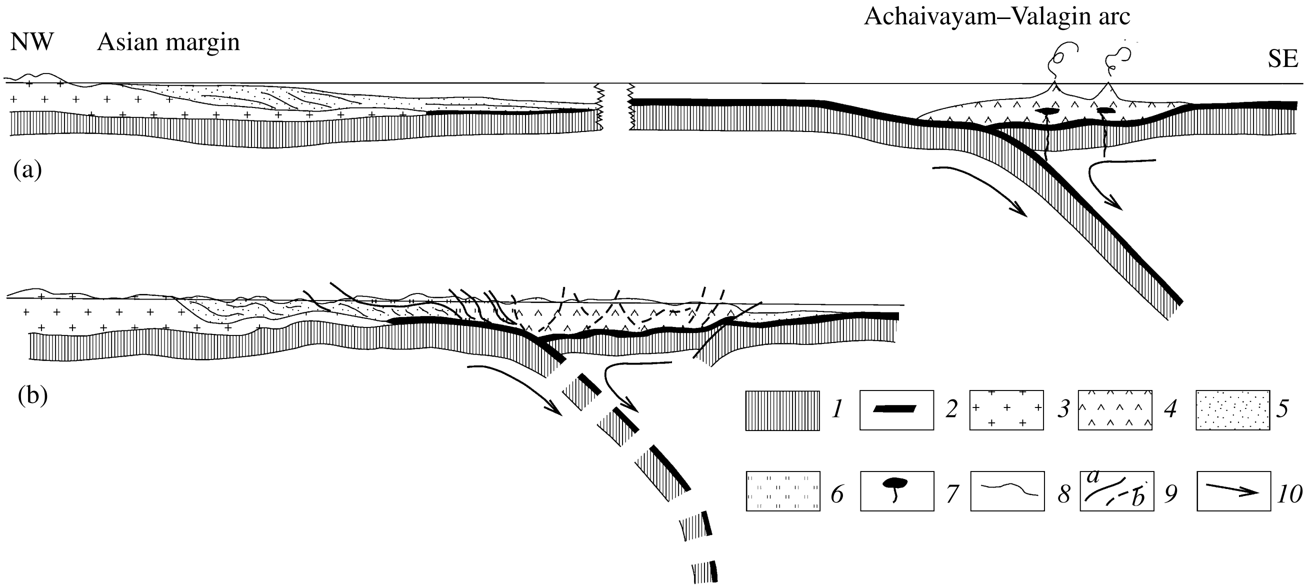


Fig. 3. A model of collision of the northern segment of the Achaivayam–Valagin arc with the northeastern Asian margin: (a) late Campanian (~75 Ma ago) and (b) middle Lutetian (~46 Ma ago). (*1*) Lithospheric mantle, (*2*) oceanic crust, (*3*) continental crust, (*4*) crust of ensimatic island arc, (*5*) terrigenous rocks, (*6*) volcanic rocks, (*7*) precollision island-arc magma chambers, (*8*) bedding in terrigenous complex, (*9*) faults: (a) major and (b) auxiliary; (*10*) asthenospheric flow.

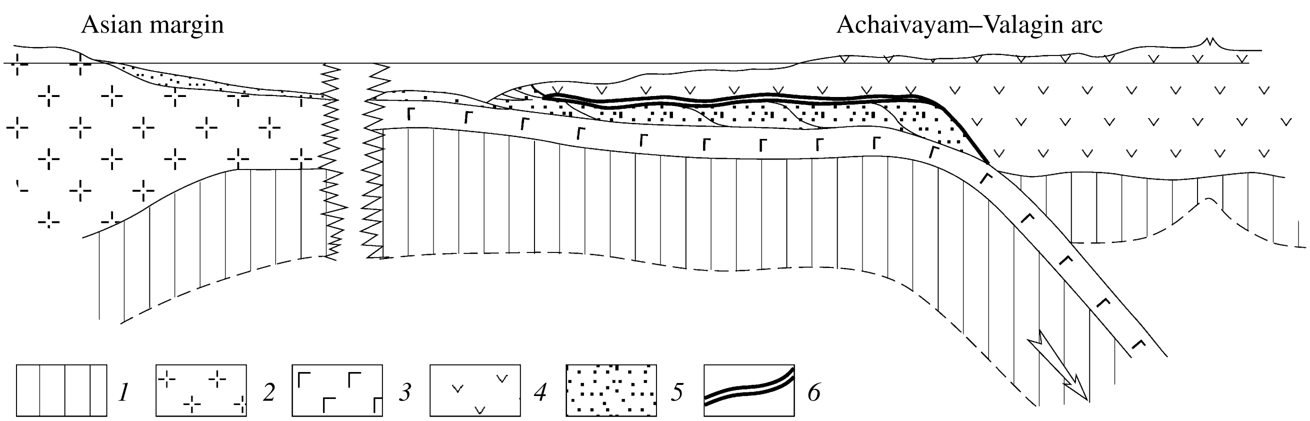
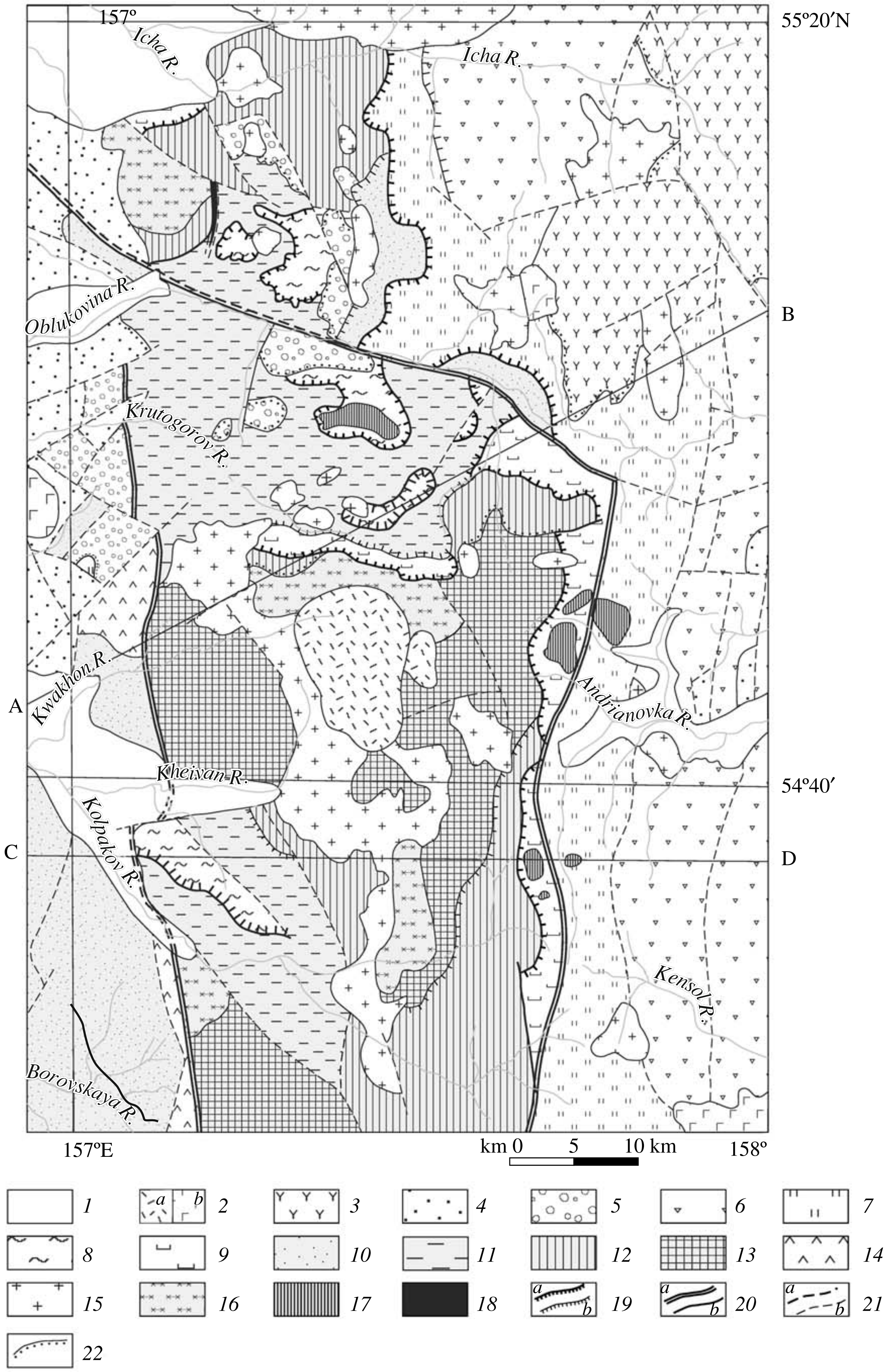


Fig. 4. A reconstruction of the zone of conjugation of the northern segment of the Achaivayam–Valagin arc with the Asian margin before the Lutetian (~48 Ma ago). (*1*) Lithospheric mantle, (*2*) continental crust, (*3*) oceanic crust, (*4*) crust of ensimatic island arc, (*5*) terrigenous rocks, (*6*) main surface of the Vatyn–Lesnaya Thrust Fault.

Fig. 5. Geological sketch map of the southern Sredinny Range of Kamchatka, modified after [15]. (*1*) Quaternary sediments; (*2*) Quaternary volcanics: (a) rhyolite and (b) basalt; (*3*) Miocene and Pliocene volcanic rocks; (*4*) upper Eocene and Oligocene marine sedimentary rocks; (*5*) lower Eocene continental molasse (Baraba and Khulgun formations); (*6*) Maastrichtian–Paleocene volcanic and volcanosedimentary rocks (Kirganik Formation); (*7–9*) Santonian–Campanian cherty and volcanic rocks and their metamorphosed analogues: (*7*) Irunei Formation, (*8*) Khimka Formation, (*9*) Andrianovka Formation; (*10–12*) Upper Cretaceous–Paleocene terrigenous rocks and their metamorphosed analogues: (*10*) Khozgon Formation, (*11*) Kheivan and Stopol'nik formations, (*12*) Kamchatka Group (Shikhta Formation); (*13*) Lower and Upper Cretaceous metamorphic rocks of the Kolpakov Group; (*14*) Upper Jurassic–Lower Cretaceous (?) volcanic rocks of the Kwakhon Formation; (*15*) Eocene anatectic granitoids; (*16*) Late Cretaceous gneissose granite and granite gneiss of the Krutogorov Complex; (*17*) Late Cretaceous (Campanian–Maastrichtian) pyroxenite–gabbro–syenite intrusions; (*18*) serpentinite of unknown age; (*19*) thrust faults: (a) major, separating autochton and allochthon and (b) auxiliary; (*20*) nearly vertical faults: (a) major and (b) auxiliary; (*21*) inferred faults: (a) major and (b) auxiliary; (*22*) unconformable onlap. AB and CD are lines of sections shown in Fig. 6.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fied largely as a result of thematic studies performed by geologists from the Institute of Lithosphere and Geological Institute of the Russian Academy of Sciences [1, 2, 4, 35, etc.]. The frontal part of the allochthon is mapped as a gently dipping and slightly deformed sheet a few kilometers thick and 30–40 km wide [15]. The Vatyn–Vyvenka Allochthon is composed of several intensely deformed complexes of volcanic and sedimentary rocks, some of which are close to oceanic rocks in composition, whereas the others are similar to island-arc sequences [1, 4]. Paleomagnetic data indicate an appreciable northward drift of allochthonous complexes before their attachment to the continent [18]. However, the suggestion that cherty–volcanic allochthonous complexes of the Olyutor Zone are large fragments of the Late Cretaceous intraoceanic island arc attached to northeastern Asia as a result of Cenozoic drifting of Pacific oceanic plates was set forth [44] much earlier than these data became available. In terms of terrane tectonics, these fragments are related to the youngest exotic terranes of the Koryak Highland [34]. The Vatyn–Vyvenka Thrust Fault may be regarded as a tectonic suture that bounds the Olyutor island-arc terrane.

In the Kamchatka Isthmus (Lesnaya Uplift), a low-angle and thin allochthonous sheet of island-arc and oceanic (?) volcanic and sedimentary rocks (Irunei Formation) overlies the intensely deformed Lesnaya Group, a complete analogue of the Ukelayat Flysch [53, 58]. The paleomagnetic study of the Upper Cretaceous island-arc rocks of the allochthon confirmed their considerable northward drift relative to northeastern Asia [23]. The structural features of the Vatyn–Vyvenka and Lesnaya thrust faults (mylonites, tectonic melanges, mesostructural elements) are almost identical, and this similarity allows us to regard these faults as segments of a single thrust separated by outcrops of Late Cenozoic volcanic rocks. The Upper Cretaceous cherty–volcanic complexes of the Lesnaya Uplift are referred to the same paleoarc as similar sequences in the Olyutor Zone [10, 54].

The Upper Cretaceous and Paleocene sedimentary and volcanic rocks that extend from Karaginsky Island via Ozerny Peninsula toward the eastern ranges of Kamchatka from the Kumroch Range in the north to the Ganal Range in the south are related to this paleoarc as well [9, 13]. Paleomagnetic data have shown that the Late Cretaceous volcanics of Karaginsky Island and the Kumroch Range were formed at latitudes close to those of coeval rocks in the Olyutor Zone [18, 29]. All this led to the concept of the single Late Cretaceous–Paleocene Achaivayam–Ozerny–Valagin paleoarc, whose evolution completed by collision with the continent [14, 54].

To the south of the Lesnaya Uplift, the collision structural units are overlapped by Miocene and Pliocene–Quaternary sediments and volcanic rocks. Therefore, direct evidence for collision of the Achaivayam–Valagin arc with continent should be looked for in the southern Sredinny Range of Kamchatka, in the Malka Uplift composed of metamorphic rocks that divide the Upper Cretaceous volcanic and sedimentary sequences of the Irunei and Kirganik formations in the east and the Cretaceous–Paleocene sand-shale sequences of the Kikhchik Group in the west. The former are close to the coeval rocks of the eastern ranges, while the latter, to the terrigenous rocks of the Lesnaya Group in the Kamchatka Isthmus and the Ukelayat Group of southern Koryakia. The key tectonic problem of this area and Kamchatka as a whole is the age, structure, and nature of metamorphic complexes.

The two main viewpoints on the nature of metamorphic rocks of the Malka Uplift competed for almost half of century. According to the one concept [26, 47], the metamorphic rocks are the oldest in the peninsula and compose inliers of the pre-Upper Cretaceous (mainly Precambrian) basement. In the alternative opinion, these rocks are metamorphosed analogues of Cretaceous sequences [22]. It is evident that the models of tectonic evolution of the Olyutor–Kamchatka region substantially depend on the choice of one of these hypotheses.

The determination of the age of particular zircon grains or their fragments from gneisses and migmatites of the Kolpakov and Kamchatka groups [36, 67] has shown that the deposition of the terrigenous sequence as a protolith of the Kolpakov and Kamchatka groups continued to the Late Cretaceous and early Eocene, respectively. The age of the last and most intense metamorphism of the Kolpakov Group is early Eocene as well. It was ascertained also that at least a part of metamorphosed volcanic and cherty rocks of the Andrianovka Formation in the framework of the uplift contains Late Cretaceous radiolarians similar to those from the Irunei Formation [40]. These data, together with the results of structural study [17], indicate that the overwhelming majority of metamorphic rocks in the Malka Uplift are analogues of unmetamorphosed rocks of its framework. Therefore, the western boundary of the Achaivayam–Valangin island-arc terrane should be drawn within the metamorphic complex.

Thus, the morphological and geodynamic manifestation of the largest tectonic suture of the Olyutor–Kamchatka region turned out to be quite different in its the northern and southern parts. In this paper, we state these differences and interpret them in terms of a simple kinematic model of the collision of the Achaivayam–Valangin arc with the northeastern margin of Asia.

Despite its obviousness, this problem was not specially discussed in the literature.

The only exception is the monograph by Konstantinovskaya [19], where a number of important questions were brought up, including the causes of precollision termination of island-arc volcanic activity, the mechanisms of emplacement of heavy mafic and ultramafic igenous rocks, and the nature of opposite vergence of minor folds in the autochthon of the Vatynka Nappe. The nature of this nappe itself and the cause of the absense of such structural elements in southern Kamchatka were not discussed. Konstantinovskaya reasonably deems that the main difference between the northern and southern segments of the collision zone consists in the formation of the metamorphic core in the south and its absence in the north.[1] The cause of the wide development of metamorphic rocks in the south and their absence in the north is perceived in different ...structure of the continental crust of the Asian margin in its frontal portion. The heterogeneous nappe–fold structure of the basement in southern Kamchatka decreased the strength of the crust and predetermined deformation of the margin at the early stage of its collision with the arc, including tectonic delamination of the continental crust beneath the margin along the crust–mantle interface, detachment, and exhumation of crustal blocks at the front of the overthrusting arc. The continental margin of Asia in the north of Kamchatka and in the Olyutor region apparently was stronger, and this circumstance prevented deformation of the margin at the early stages of collision with the northern segment of the Achaivayam–Valangin arc [19, p. 144]. In fact, the high strength of the lithosphere and low degree of deformation of the continental margin in the north are rather doubtful, if we remember that tectonic nappes and large recumbent folds of the Ekonai and Pikas'vayam–Evravaam zones of the island-arc and oceanic nature occur to the north of the Central Koryak Trough. These structural elements were attached to the continent only in the Early Cretaceous. Konstantinovskaya [19] does not emphasize a difference in *PT* conditions during formation of tectonic suture, which gave rise to the widespread syncollision metamorphism in southern Kamchatka in contrast to the complete absence of such process in the north of the peninsula and in the Olyutor Zone. This omission can be understood, because the model stated in [19] was elaborated before publication of the data concerning the age of zircons from gneisses and schists of the Kolpakov and Kamchatka groups.

The pivotal place in the concept developed by Konstantinovskaya [19] is occupied by the hypothesis of complete submergence of the crust of forearc block into a subduction zone; this conclusion is based on the results of physical modeling. No specific features of this conjectural process in the northern and southern segments of the zone of collision with Achaivayam–Valagin are mentioned. Therefore, in this paper we call special attention to the fundamentally different structure in the northern and southern segments of the tectonic suture that bounds the Achaivayam–Valagin Terrane in the northwest.

COLLISION STRUCTURAL ELEMENTS IN THE NORTHERN PART OF THE OLYUTOR–KAMCHATKA ZONE

The Vatyn–Vyvenka Thrust Fault is the northwestern boundary of the Achaivayam–Valagin arc in the Olyutor Zone (Fig. 1) [4, 34, 35]. The terrigenous sequences of the Upper Cretaceous–middle Eocene Ukelayat Flysch occur in the autochthon [8, 9, 11, 34, 38, 65]. Sandstones of this stratigraphic unit are classed with quartz–feldspar graywacke, a product of erosion of the northeastern margin of Asia [8, 9, 11, 34, 59]. The allochthon is a relatively thick (up to 5 km) near-horizontal sheet complicated by younger faults [1, 39]. This sheet consists of the cherty–volcanic Vatyn Formation, lavas and tuffs of the Achaivayam Formation, and related PGM-bearing pyroxenite–gabbro intrusions [2, 4, 25]. The autochthonous sequences beneath the thrust fault are deformed into small folds overturned to the northwest [39]. The observed lateral overlapping reaches 40 km. The Vatyn–Vyvenka Thrust Fault was formed as early as 45 Ma ago, because the age of the youngest population of zircons in one sandstone sample from the autochthonous Ukelayat Group is 43.9 ± 3.6 Ma [36, 38]. The oldest units of the neoautochthon pertain to the upper Miocene [5, 16].

The Cretaceous–lower Paleocene island-arc section is conformably built up by the upper Paleocene–lower Miocene sedimentary rocks of the Il'pi–Pakhacha Trough [50]. Southward, this trough likely narrows and extends beneath the Litke Strait. In the Il'pi Peninsula and Ivtygin and Mainy-Kakyine ranges, the well-studied Cenozoic sections do not reveal an unconformity in pre-Miocene sequences [6, 15]. The Upper Cretaceous and Cenozoic rocks of the Pakhacha Trough were deformed in open faults much later, in the middle–late Miocene.

The structure of the Kamchatka Isthmus (Lesnaya Uplift) (Fig. 2) was considered in a series of publications [10, 39, 42, 53, 58]. The rocks pertaining to the Achaivayam–Valagin arc are recognized here as the Irunei Formation and subdivided into several sequences with poorly known mutual stratigraphic relationships. In the axial zone of the range and on its eastern slope, the Irunei Formation is exposed as relatively small inliers unconformably overlapped by Cenozoic sediments and volcanic rocks; the oldest of them pertain to the middle Eocene Snatol and Kinkil formations. On the western slope of the range, the Irunei Formation composes the allochthon of the Lesnaya Thrust Fault (Fig. 2a). The extreme northeastern point, where the Lesnaya Thrust Fault is observed, is separated from the extreme southwestern outcrop of the Vatyn–Vyvenka Thrust Fault only by a hundred kilometers (Fig. 1). Both thrust faults are similar in morphology and may be regarded as segments of a single structural unit. As in

[1] In the opinion of Konstantinovskaya, another important distinguishing feature of the northern segment is the development of the thick accretionary wedge at the arc–continental margin interface, keeping in mind the thick, strongly deformed terrigenous sequences of the Lesnaya and Ukelayat Groups. This statement may be contested, because the thick terrigenous sequences of the Kikhchik Group differs little from the Upper Cretaceous–Paleocene terrigenous complexes of the Olyutor Zone and the assignment of these complexes to accretionary wedges is only one possible interpretation, and not the most convincing if sandstone composition is taken into account.

the Olyutor Zone, in the Lesnaya Uplift, the allochthonous complexes occur as a thin near-horizontal sheet (Fig. 2b) consisting of low-angle tectonic slices. In the outcrops on the western slope of the Sredinny Range, high-Ti and low-K basalts intercalate with red jasper containing fragments of inoceramide shells. The overlying thick sequence of psammitic green tuff, tuffite, and chert also contains inoceramide fragments. Lenses of psephitic tuff and tuffaceous breccia, as well as flows of pyroxene pillow basalt are sporadic. On the eastern slope of the Sredinny Range, the section of the Irunei Formation consists of the lower tuffite–cherty sequence and the upper sequence of tuffs and lavas corresponding to andesitic dacite in composition. A member of cherty tuffite with numerous inoceramide fragments is mapped at the boundary of these sequences. Occasional radiolarians separated from cherts of the Irunei Formation belong to the Campanian and Maastrichtian [28]. In the Kamchatka Isthmus, the Irunei Formation is cut through by minor pyroxenite–gabbro–syenite intrusions correlated with PGM-bearing intrusions of the Olyutor Zone [20]. In some tectonic slices, the Irunei Formation is metamorphosed up to the grade of greenschist facies [58].

The autochthon is composed of flysch pertaining to the Lesnaya Group; these rocks are deformed into small folds overturned to the west. Sandstones are classified as quartz–feldspar graywacke; the clastic material was supplied from the northeastern Asian margin [8, 59]. A mylonite zone varying in thickness from a few meters to tens of meters is traced along the thrust fault surface [53] complicated by later domelike folds and numerous faults. The amplitude of these dislocations is comparable with a range of present-day topography. Most likely, at the time of its formation, the thrust fault surface was close to the horizontal plane, and the thickness of the allochthon did not exceed a few kilometers (Fig. 2b). The thrust fault is overlain by volcanic rocks of the Kinkil Formation and cut through by the Shamanka granodiorite pluton. On the basis of fission-track dating of detrital zircon in sandstones and nannoplankton from mudstones, the upper age limit of the Lesnaya Group is determined not older than the middle Lutetian (~46 Ma) [42]. The age of the oldest neoautochthonous complexes (lower part of Kinkil volcanic rocks and granite) is not younger than 45–44 Ma (U–Pb, Rb–Sr, R–Ar, fission track dating) [42].

On Karaginsky Island and the Goven Peninsula, the Cretaceous and Paleocene–Eocene sequences are strongly deformed into a series of steeply dipping imbricate thrust faults and NE-verging recumbent folds [50, 60]. In regard to their structure, they may be interpreted as a back zone of accretionary wedge above the late Eocene–Miocene subduction zone plunging beneath the continent; this zone is considered to have arose after the attachment of the Achaivaym–Valagin arc to continent [43, 50].

ON THE NATURE OF THE VATYN–LESNAYA THRUST FAULT

The allochthon of the Vatyn–Lesnaya Thrust Fault is a thin (1–2 km, occasionally up to 5 km), almost horizontal sheet (Fig. 2b). The amplitude of nappe is more than 30 km (up to 100 km, according to other estimates). The complex internal structure of the allochthonous sheet [1, 2] is cut off by its lower edge. After the thrusting, this sheet was slightly deformed with the formation of gentle domelike folds, small flexures, and steps related to faults [39]. The vertical separation of these dislocations did not exceed a few kilometers.

Tuffs, silicites, and gabbroids metamorphosed under conditions of greenschist facies occur in the allochthon of the Vatyn–Lesnaya Thrust Fault in the Kamchatka Isthmus [58]. However, the autochthonous sequences of the Ukelayat and Lesnaya groups underlying the allochthon were heated to a temperature below 100°C. The tracks of spontaneous uranium decay in zircons were not annealed; in apatite, they were annealed only in particular samples [42]. The thrust fault was formed very quickly. The autochthonous sequences were deposited at least until the middle Lutetian, and the bottom of the neoautochton is dated at the same age. The minimum rate of thrusting is determined by the distance from the thrust front to the location of sampling divided by the time of motion. The minimum rate of thrusting in the direction perpendicular to the thrust front is estimated at 2 cm/yr (20 km/Ma) and thus is comparable with the velocity of Pacific Plate motion relative to Eurasia in the middle Eocene (5 cm/yr) [64].

The formation of the Vatyn–Lesnaya Thrust Fault was predated by a long (from 75 to 55 Ma ago) period of the independent evolution of the Achaivayam–Valagin island arc, which was drifting to the northwest along with Pacific plates [18, 45, 54]. The terrigenous sediments of the Lesnaya and Ukelayat groups were deposited at the continental rise along the northeastern Asian margin (Fig. 3a). On approach of the arc to the continent, the frontal portions of fans started to subside into the deepwater trench and further into the subduction zone (Fig. 3b). This subduction zone, like most of its modern analogues, is divided into two parts. The upper, low-angle and locally almost horizontal part was 50–100 km wide and separated from the lower part by a sharp bend. The upper plate above the upper low-angle part of the subduction zone had the shape of a thin wedge faced by its edge toward the plunging plate. This initial wedge composed of intensely deformed oceanic and island-arc sequences was probably formed at the early stage of arc evolution under the effect of subduction erosion. With the onset of consumption of turbidites much thicker than pelagic sediments, the subduction erosion gave way to accretion in the form of underplating the initial wedge (composed of backarc and arc sequences) by turbidites (Fig. 4). The plate boundary in the low-angle portion of the subduction zone could repeatedly have shifted downward as the layer of deformed turbidites at the bottom of the upper plate continued to accrete. As a result, the suprasubduction wedge acquired a two-stage structure with deformed turbidites at the base and no less deformed island-arc sequences above the nearly horizontal surface of the thrust fault (Fig. 4).

The latter sentence describes adequately the main features of the structure of the Vatyn–Lesnaya Thrust Fault. The point is that in this model the autochthon structure continues to form after cessation of motion along the main plane of the Vatyn–Lesnaya Thrust Fault. In some publications, this thrust fault was named an obduction structure [32, 34]. The motion along this suture terminated because of the rearrangement of plate motions [14, 33, 34, 36] or owing to blockage in another segment of plate boundary, rather than by arc–continent collision in the given place. The Malka Uplift, where collision structure is superimposed on a low-angle thrust similar to the Vatyn–Lesnaya Fault, is the most probable blocking structural element.

COLLISION STRUCTURAL ELEMENTS IN SOUTHERN KAMCHATKA

The southern Sredinny Range of Kamchatka (Malka Uplift) is another site where the structural elements that arose as a result of attachment of the arc to the continent have been studied rather thoroughly (Figs. 5, 6). The structure of this area is much more complex than in the Kamchatka Isthmus, but some similar features are retained.

On the eastern slope of the range from the Andrianovka River in the north to the Ozernaya Kamchatka River in the south, the Cretaceous–Paleogene volcanic and sedimentary sequences occur as several steeply dipping sheets trending in the near-meridional direction. The easternmost sheets, mainly composed of tuffaceous breccias and lavas, are recognized as the Kirganik Formation, while the westernmost sheets, consisting of chert with inoceramides and cherty tuffite with lenses of basalt, pertain to the Irunei Formation. The Irunei Formation contains Santonian and Campanian radiolarians; in the upper portion of the Kirganik Formation, ragiolarians are Maastrichtian and Danian in age [12]. The rocks of the Kirganik and Irunei formations are cut through by pyroxenite–gabbro–syenite intrusions comparable to PGM-bearing intrusions of the Olyutor Zone [2, 20, 46].

A vertical fault clearly expressed in topography (Fig. 5) separates the rocks of the Irunei Formation from metavolcanic rocks of the Andrianovka Formation. Immediately west of the fault, the Andrianovka Formation consists of greenschist grading westward into amphibolite with foliation steeply dipping eastward [17]. The Andrianovka Formation is cut through by pyroxenite, gabbro, and syenite. The marginal parts of intrusive bodies were involved in metamorphism and underwent structural reworking. Magmatic zircon from syenite is dated at 70–63 Ma (Maasrichtian–Danian) [48]. The Late Cretaceous radiolarians were found in silicites of the Andrianovka Formation [40].

The metaterrigenous crystalline schists of the Kamchatka Group underlie the Andrianovka Formation, being separated from the latter by a blastomylonitic zone [17]. Another fault zone separates schist from the underlying gneiss of the Kolpakov Group, a high-grade metamorphic complex that occupies a large area in the axial zone of the Malka Range [15].

To the north of the Andrianovka River, in the basins of the Oblukovina and Icha rivers, the trends of the Irunei and Kirganik formations turn to the west, and the vertical boundaries of the tectonic sheets are transformed into westward verging thrust faults [57]. At the Oblukovina–Icha interfluve, the rocks of the Irunei Formation are thrust over the intensely deformed sandstone and siltstone of the flyschoid Khozgon Formation containing middle Campanian radiolarians [57]. At the contact of the Khozgon and Irunei formations, thin mylonitic zones with flaser structure are observed. Northerly, a sheet of rocks belonging to the Khozgon Formation pinches out, and the Irunei Formation is thrust over metamorphic rocks. At the interfluve of the Oblukovina and Khimka rivers, the Malka Group and the Khozgon Formation are separated by a thick lens of the Baraba continental conglomerate and sandstone that contain plant remains and overlap unconformably metamorphic rocks, in turn, being tectonically overthrust by the Khozgon Formation. The flora of the Baraba Formation has been described as late Campanian [51, 52]. At the same time, the U–Pb age of zircons from a tuff close to the bottom of this sequence yielded 50 Ma, corresponding to the early Eocene [41].

The Malka Group, occupying a lower structural position relative to unmetamorphosed rocks, consists of three formations. Structurally from top to bottom these are the Chimka Formation (greenschists after tuffs and cherts), the Kheivan Formation (slates and phyllites after mudstones and quartz–feldspar graywackes close to the Khozgon sandstones in composition), and the Andrianovka Formation (epidote–actinolite schists and amphibolites) [47].

Somewhat to the south, at the headwater of the Krutogorov River, the Malka Group crops out as several tectonic sheets with metaultramafic lenses at their boundaries, which are thrust over metaterrigenous crystalline schists of the Kamchatka Group [30]. The rocks of the Kamchatka Group overlie with unconformity and conglomerate at the base the Krutogorov gneissose granite [30, 47] that cuts through gneiss and migmatite of the Kolpakov Group.

In the west, metamorphic rocks of the Malka Range contact along a series of steeply dipping faults with terrigenous rocks of the Kikhchik Group, which are close in stratigraphic position and lithology to the Omgon and Lesnaya groups of western and northern Kam-

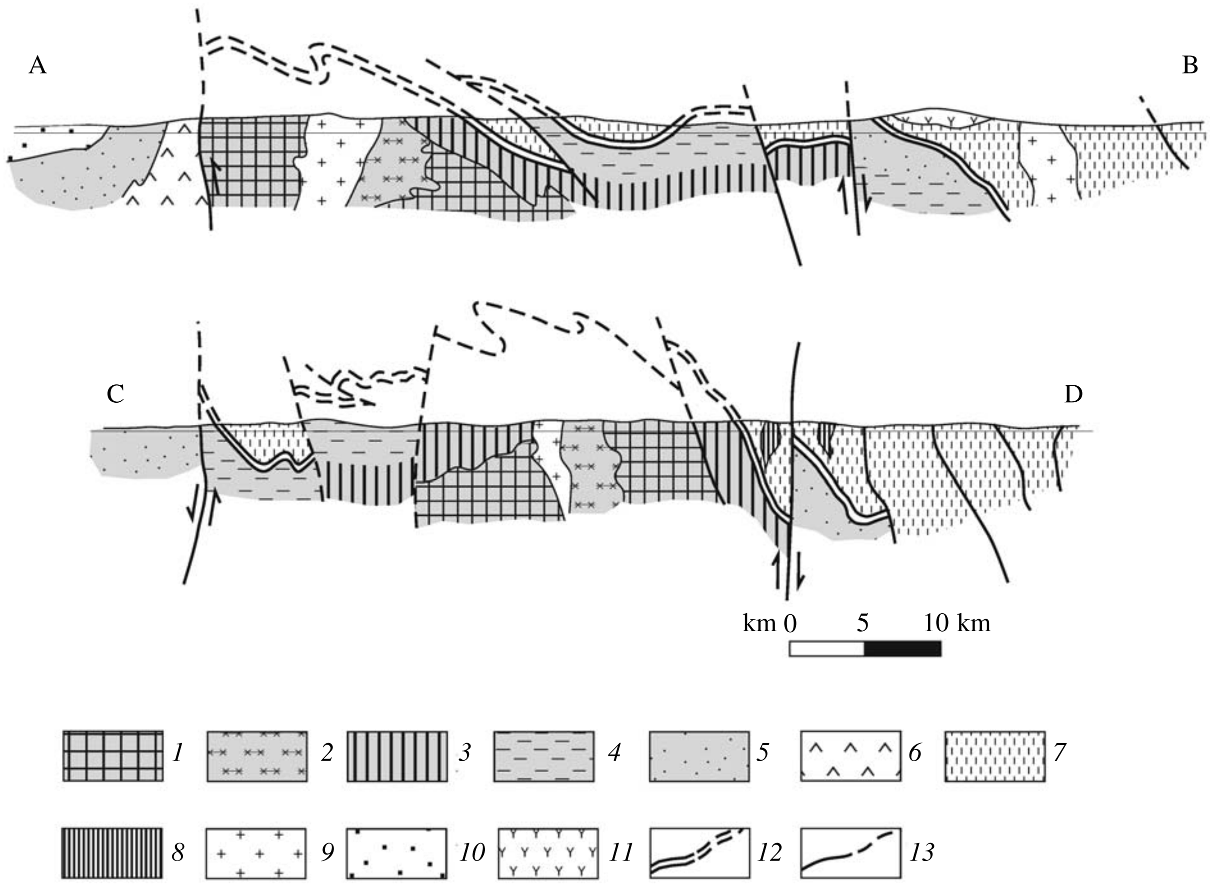

Fig. 6. Schematic geological sections along line AB and CD (Fig. 5). Metamorphic rocks of autochthon (patterns on gray background): (*1*) Kolpakov Group, (*2*) gneissose granite of the Krutogorov Complex, (*3*) Kamchatka Group (Shikhta Formation), (*4*) Kheivan and Stopol'nik formations; unmetamorphosed rocks of autochthon: (*5*) Khozgon Formation; units of indefinite structural position: (*6*) Kwakhon Formation; metamorphosed and unmetamorphosed rocks of allochthon (patterns on white background): (*7*) Andrianovka, Khimka, Irunei, and Kirganik formations; (*8*) syenite intrusions cutting through allochthon only; (*9*) Eocene anatectic granite; (*10*) Tertiary sedimentary rocks on the western slope of the Sredinny Range; (*11*) Miocene and Pliocene volcanic rocks; (*12*) main tectonic suture of the Sredinny Range; (*13*) other faults.

chatka [37]. The Khozgon Formation is regarded here as a lower part of the Kikhchik Group. A few tectonic blocks of the Irunei Formation composed of cherty rocks with innoceramide were mapped along the western contact of metamorphic rocks of the Malka Range with the Kikhchik Group [15].

Thus, as a first approximation, the southern Sredinny Range may be regarded as a near-meridional horst, whose uplifted core consists of metamorphic rocks, while the limbs are composed of unmetamorphosed Upper Cretaceous and Paleocene rocks, mainly volcanic in the east and terrigenous in the west. Such a structure was one of the arguments for considering metamorphic rocks as a pre-Late Cretaceous basement. In recent years, the age of metamorphic rocks in the Sredinny Range was refined by dating of zircon and monazite with the U–Pb method (SHRIMP) [36, 62, 66, 67]. The age of the zircon and monazite from the Kolpakov and Kamchatka groups and the Krutogorov Granite was estimated. The U–Pb dating of detrital zircons shows that the age of the protolith of the Kolpakov Group corresponds to the Mid-Cretaceous, whereas the age of the protolith of the Kamchatka Group is Paleocene [36, 37]. The Kolpakov Group was cut through by the Krutogorov Granite in the Campanian (78.5 ± 1.2 Ma) [67].

Metamorphism of rocks in the Sredinny Range should be younger than 55 ± 3 Ma, which is the age of the youngest detrital zircon grain from schist of the Kamchatka Group. The U–Pb SHRIMP dating of the outer zones in zircon from leucosome and melanosome of Kolpakov migmatites and the dating of metamorphic monazite show that a peak of metamorphism and anatexis falls on the early Eocene (52 ± 2 Ma ago) [66, 67].

The age of zircons from pegmatite veins and granites shows that they crystallized contemporaneously with the peak of metamorphism. Synkinematic granite cuts through the Andrianovka Thrust Fault 51.5 ± 0.7 Ma ago, synchronously with the peak of metamorphism [36].

Thus, gneisses of the Kolpakov Group that occupy the lowermost structural position in the Malka Uplift cannot be older than Mid-Cretaceous, whereas schists of the Kamchatka Group include Paleocene rocks. In general, these groups are analogues of the Upper Cretaceous and Paleocene terrigenous rocks of the Kikhchik Group and the Khozgon Formation. The statistical comparison of age distributions of zircons from schists of the Kamchatka Group and sandstones of the Khozgon and Ukelayat formations has shown that they are identical [67]. The Cretaceous and Paleogene sedimentary rocks, as products of erosion of the northeastern Asian margin, most likely were a protolith of the Kolpakov and Kamchatka groups.

The structurally higher Andrianovka Formation (amphibolite, greenschist) includes low-grade quartzites that contain Late Cretaceous radiolarians [40] and is cut through by Cretaceous–Paleogene intrusions [48]. There are grounds to correlate the Andrianovka Formation with the Irunei and Kirganik formations in the eastern framework of the metamorphic complex.

The Kheivan and Khimka formations unconformably overlain by the middle Eocene Baraba Formation are obviously older [41]. No other evidence for the age of these formations is available. They occupy a transitional structural position between the Andrianovka Formation below and unmetamorphosed Cretaceous–Paleocene rocks above. The grade of metamorphism decreases in the direction Andrianovka–Kheivan–Khimka formations. Metasandstones of the Kheivan Formation are close in composition to the Khozgon sandstones, and this similarity hinders their discrimination in the course of geological mapping. Most likely, the metaterrigenous rocks of the Kheivan Formation are a metamorphosed analogue of the Kikhchik Group, whereas the metavolcanic rocks of the Khimka Formation are an analogue of the Irunei Formation. The overlapping of the Kamchatka Group by the Andianovka Formation and the same relationships between the Kheivan and Khimka formations should be regarded as a result of the same tectonic juxtaposition as overlying of the Khozgon Formation by the Irunei Formation or as the thrusting of the Vatyn Group over the Ukelayat Flysch in the Olyutor Zone. In some cases, such relationships are confirmed by field observations. Lenses of metaultramafic rocks are mapped at the base of the Andrianovka Formation at the headwater of the Krutogorov River [30]. A blasomylonite zone was traced along the boundary of the Kamchatka Group and Andrianovka Formation in the Left Andrianovka River valley [17].

The near-horizontal boundary between the Kheivan and Khimka formations to the west of Mount Baraba is discordant to the internal structure of both formations. In some other places, where the Kheivan Formation or its analogues, e.g., the Stopol'nik Formation, are overlain by the Khimka Formations or its analogues, e.g., the Alistor Formation, the boundary may also be interpreted as tectonic. Therefore, our basic concept taking these relationships into account and being supported by recently obtained geochronological data contends that the tectonic surfaces separating the Kamchatka Group and the Andrianovka Formation, on the one hand, and the Kheivan and Khimka formations, on the other, and finally, the Khozgon and Irunei formations, are segments of an initially continuous thrust fault, which was similar in morphology to the Lesnaya and Vatyn–Vyvenka thrust faults in the north of the region. In the north, the thrusting of the Achaivayam–Valagin arc over the terrigenous rocks of the Asian margin was not disturbed markedly by the subsequent motions and accompanied by deep submergence and heating of autochthonous complexes. In contrast, the autochthonous terrigenous sequences in the southern Sredinny Range were metamorphosed along with the lower part of the allochthonous complex. Metamorphism was conjugated with intense deformation, so that the lower edge of the allochthonous complex, as the master structural surface, was fragmented (Fig. 6), partly emerged and eroded (in the axial zone of the Malka Uplift and on its western limb), and partly (on the eastern limb) deeply submerged, thus becoming inaccessible for observation.

The first stage of metamorphism, probably still unrelated to collision of the Achaivayam–Valagin arc (?) and affecting only the Kolpakov Group, occurred in the Mid-Campanian and was accompanied by emplacement of the Krutogorov Granite. The subsequent erosion was short-term and gave way to the deposition of the Kamchatka Group up to the end of the Paleocene. The process was interrupted by thrusting of the Cretaceous–Paleocene complexes of the Achaivayam–Valagin arc and the following major metamorpic event.

The isotopic age of the Kamchatka Group and the bottom of the Baraba Formation, the oldest neoautochthonous stratigraphic unit, showed that the transformation of terrigenous sediments into metamorphic rocks and exhumation of them took less than 5 Ma. Metamorphism of the allochthonous Andrianovka and Khimka formations was as short-term as the above event. These conclusions are based on the following reference points. The age of the youngest detrital zircon from schists of the Kamchatka Group is 55 ± 3 Ma and may be regarded as a protolith age. The age of metamorphism is 52 ± 2 Ma [36, 66]. Zircons from a tuff at the bottom of the Baraba Formation are dated at 50.5 ± 0.9 Ma. Pebbles of metamorphic rocks were found in the upper sequence of the Baraba Formation; hence, at that time the metamorphic rocks were already exposed at the surface. A later phase of westward thrusting of the Khozgon and Irunei rocks pertains to the post-Barbara time [57]. The backarc zone of the Achaivayam–Valagin arc in southern Kamchatka is exposed in the eastern ranges. One of the most complete section of the upper part of the island-arc complex has been described in the Valagin Range separated from the Malka Uplift by the Central Kamchatka Depression [3]. The section begins with tuffaceous and cherty rocks of the Golubovsky Formation and is built up by tuffs and lavas of the Kitil'ga Formation, which, in turn, grades upsection into the terrigenous flyschoid sequence of the Tal'niki Formation that contains planktonic foraminifera of the early Paleocene–lower Eocene. These rocks are overlapped with sharp unconformity by shelf sediments of the Lutetian Snatol Formation. Upper Cretaceous–lower Eocene sections of similar structure were described in the Kumroch Range, where the volcanic sequence is referred to the Khapitsa Formation and the terrigenous sequence to the Drozdovsky Formation [43, 49]. These sections demonstrate that the volcanic activity in the eastern ranges somewhat predated the formation of the thrust fault system in the Malka Range, whereas the first tectonic deformation postdated this event. In other words, the deformation of the Achaivayam–Valagin arc that collided with the continent was localized, as in the north, within a relatively narrow frontal zone.

Soon after the collision, the SE-verging Vetlov accretionary wedge started to form in the backarc zone of the Achaivayam–Valagin arc from the Kumroch Range in the north to the Vakhil Uplift in the south [24, 43, 49]. Likely, this accretionary wedge marks a subduction zone that arose owing to blockage of such a zone at the front of the Achaivayam–Valagin arc, and in this relationship we also see a similarity with the structure of northern Kamchatka and the southern Olyutor Zone.

ON THE NATURE OF EOCENE METAMORPHISM IN THE MALKA RANGE

Intense and fast transformation of the structure, including deep submergence, rapid heating of the crust accompanied by metamorphism of moderate pressure and high temperature, and the subsequent emergence of metamorphic rocks and overlapping of them by discontinuous neoautochthonous complex occurred in the Malka Uplift immediately after thrusting of the Achaivayam–Valagin arc over terrigenous rocks of the Kikhchik Group (Fig. 7). Rather arbitrarily, these processes may be regarded as three consecutive evolutional stages.

The first stage is the submergence of the autochthon and the lower parts of the allochthon to a depth that corresponds to the pressure of 6–9 kbar necessary for the formation of gneisses, crystalline schists, and amphibolites. Such submergence was caused by thickening of the crust due to its lateral shortening induced by the initial arc–continent collision (Fig. 7a). The main deformation—thrusts and west-verging folding—were localized in the suprasubduction lithospheric wedge of the upper plate. The substantial increase in the crust's thickness brought about by deformation was compensated by shallowing of the basin, rising topography, and isostatic subsidence of the crust and lithosphere bottom. The joint imbricate thrusting of the allochthon and autochthon at this stage created the prerequisites for repetition of coeval but variously metamorphosed sequences in the vertical section (Fig. 8).

The second stage is characterized by rapid (no longer than 3–5 Ma) heating of the autochthon and the lower part of the allochthon up to 550–650°C, sufficient for gneiss and amphibolite formation (Fig. 7b). Such heating was hardly possible as a result of conductive heat transfer from the lower crust to the terrigenous and volcanic rocks buried beneath a pile of nappes. An additional powerful source of heat in the form of ascent of hot asthenospheric mantle to a high level was required (Fig. 7b). As was shown recently by numerous examples, such ascent occurs in collision zones owing to slab breakoff [61, 63, 71].

The arc–continent collision is always predated by consumption of the lithosphere in the separating ocean basin. In our case, the lithosphere was consumed beneath the Achaivayam–Valagin arc (Fig. 3a). The collision proper starts when, after the oceanic crust, the thinned continental (transitional, intermediate) crust that initially occurred in the uppermost part of the lithospheric plate and only insignificantly diminished its average density submerges into the subduction zone (Fig. 7a). However, on convergence of the arc and continent, the thickness of the consumed, relatively light crust and its share in the litosphere's thickness increases. The density of the submerged lithosphere decreases and becomes less than the density of the adjacent asthenosphere. Therefore, compression of accretionary wedge induces tensile stresses in the upper part of the slab to break it off (Fig. 7b). The arising gap is filled with asthenospheric mantle, decompression of which gives birth to basaltic melts that provide fast heating, metamorphism, and partial selective melting of the upper and lower crust [61]. The complete breakoff of the slab results in its submergence into the mantle, the fast isostatic rise of the crust above the breakoff zone, and the deep erosion of the crust. A trap for anomalously hot mantle appears at the bottom of the thinned crust, facilitating uplift of the collision zone and active crustal magmatism. The cessation of subduction, while the counter motion of plates is retained, gives rise to the origination of a new zone of consumption. In Kamchatka, such a zone, in the form of the Vetlov Thrust Fault [19], arose in the backarc zone of the Achaivayam–Valagin arc attached to the continent.

This model describes satisfactorily the main features of the Malka Ridge, where the Kolpakov Group may be regarded as the upper part of precollision sialic crust, the involvement of which in the Eocene subduction zone about 54 Ma ago led to the slab breakoff. According to the classical model [63], slab breakoff is

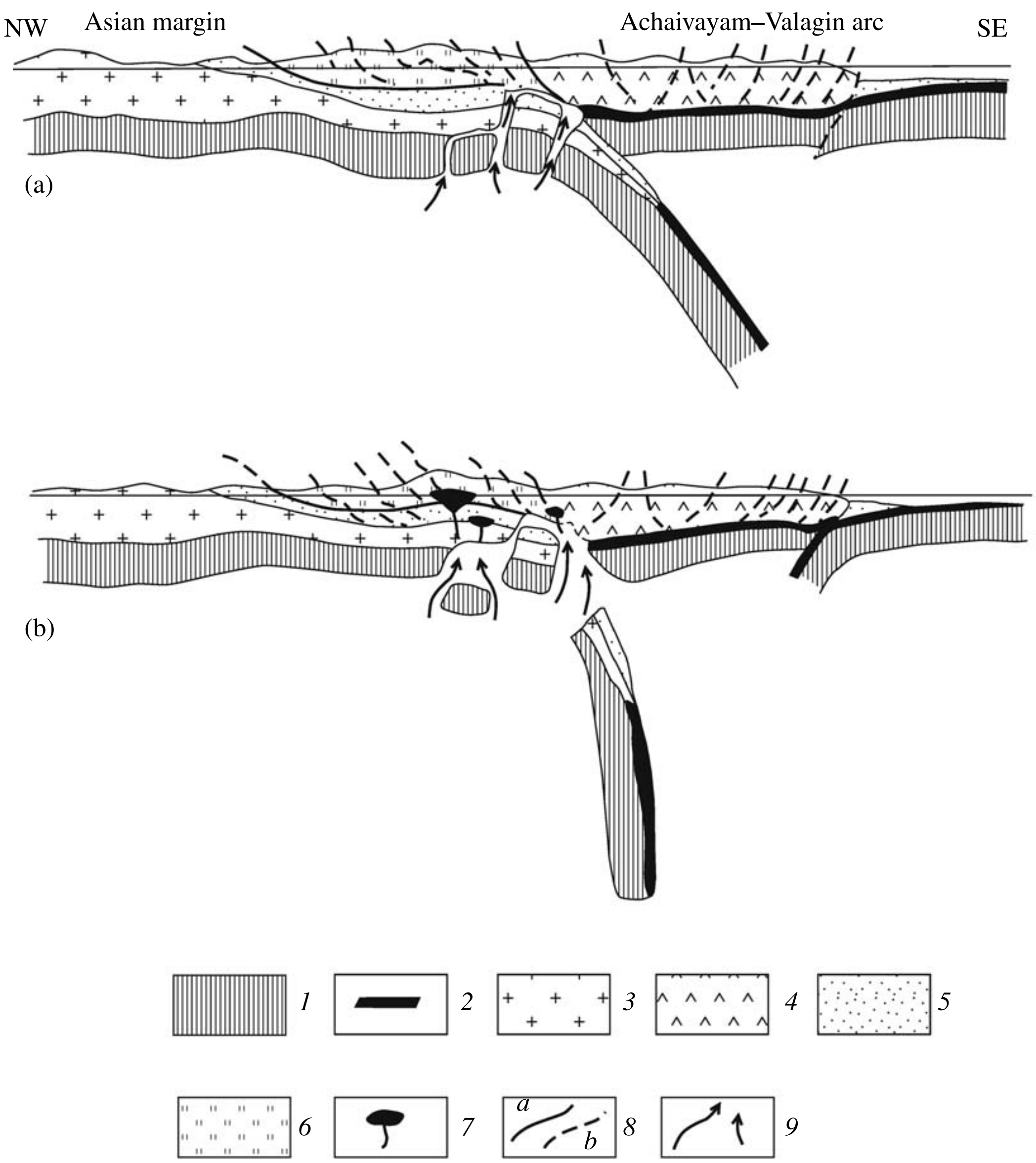

Fig. 7. A model of collision of the southern segment of the Achaivayam–Valagin arc with the northeastern Asian margin: (a) early Ypresian (~54 Ma ago) and (b) middle Ypresian (~52 Ma ago). (*1*) Lithospheric mantle, (*2*) oceanic crust, (*3*) continental crust, (*4*) crust of ensimatic island arc, (*5*) terrigenous rocks, (*6*) volcanic rocks, (*7*) syncollision anatectic magma chambers, (*8*) faults: (a) major and (b) auxiliary; (*9*) ascending mantle flows.

suggested somewhat below the main bend of plunging plate, so that the main thermal impact falls on the complexes of overriding plate. In a real plate, the place of breakoff probably is determined by lithospheric inhomogeneities, for example, by already existing faults. In any case, in the best-studied example of the arc–continent collision on Taiwan, the slab breakoff brings about metamorphism exactly in the complexes of the plunging plate [19, 71]. In addition, in our case, the island-arc complexes of the overriding plate undoubtedly underwent metamorphism in the Eocene, and products of this process are observable not only in the Sredinny Range but also in the Ganal Range [21, 31], where metavolcanic rocks may be compared with the Cretaceous–Paleocene sequences of the Valagin Range.

Other geomechanical models describing a breach that opens access of the hot asthenospheric mantle to the upper crust and its fast heating may be proposed. In particular, the subsidence of the lower plate under a load of syncollision nappes and corresponding increase in pressure may lead to eclogitization of the oceanic crust and increase in density of the lower plate with its

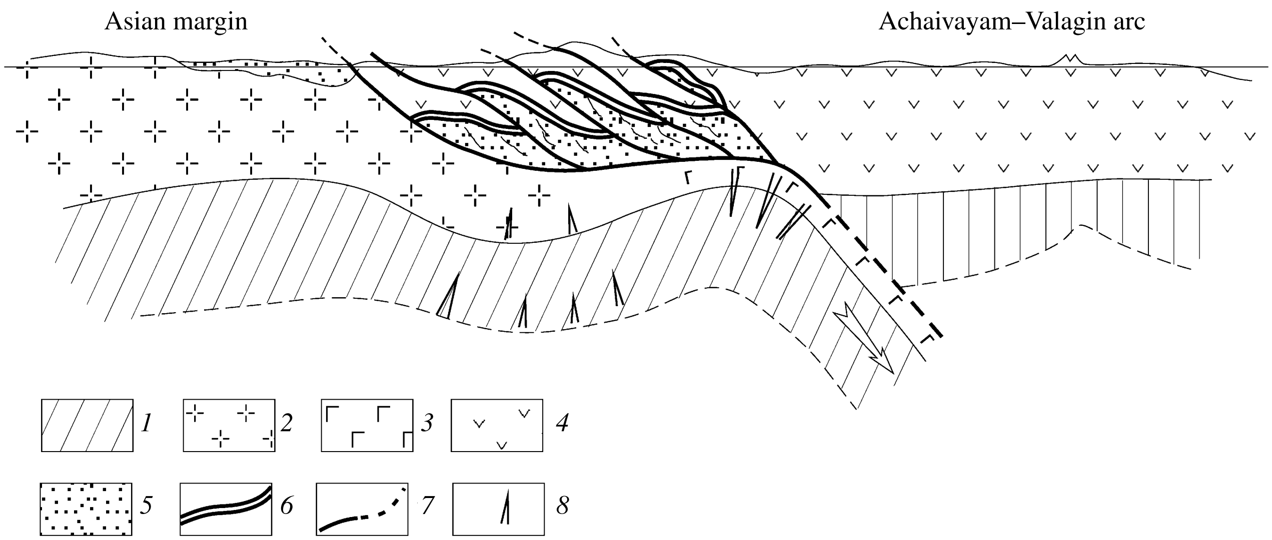

Fig. 8. A reconstruction of the zone of conjugation of the southern segment of the Achaivayam–Valagin arc with the Asian margin before the Ypresian (~54 Ma ago). (*1*) Lithospheric mantle, (*2*) continental crust, (*3*) oceanic crust, (*4*) crust of ensimatic island arc, (*5*) terrigenous rocks, (*6*) main surface of thrust fault (Andrianovka Suture), (*7*) other faults, (*8*) zone of plastic deformation and ascending heat flow.

fast destruction and submergence into the asthenosphere.

The third stage in the evolution of the Malka Uplift is manifested in exhumation of newly formed metamorphic rocks [17, 19]. This process most likely is related to isostatic growth of granite gneiss diapirs as a response to the density inversion in the region of thick packets of allochthonous sheets.

Each of the aforementioned stages in the evolution of the Malka Uplift was accompanied by intense tectonic deformations, which created the structure of this uplift with a core composed of gneiss and granite and framed by greenschist-facies metamorphic rocks giving way outward to Cretaceous–Paleocene unmetamorphosed rocks (Fig. 5). The rise of metamorphic complexes relative to their framework continued in the post-Eocene time along large near-meridional faults (Figs. 5, 6). As a result, the major thrust fault surface, emphasizing the internal structure of uplift, i.e., the roof of the terrigenous or metaterrigenous autochthon, turned out to be either eroded (in the core and on the western limb) or deeply subsided (on the eastern limb). Only at the northern periclinal closure of the uplift, can it be observed how this surface is cut by topography at the bottoms of the Andrianovka, Khimka, and Irunei formations. This implies that this surface is complexly deformed and destroyed by later faults in such a manner that the boundary between island-arc and terrigenous complexes repeats up to three times in the vertical section.

COMPARISON OF COLLISIONAL STRUCTURAL ELEMENTS IN NORTHERN AND SOUTHERN KAMCHATKA

On comparing of the structural elements arising as a result of collision between the Achaivayam–Valagin arc and the northeastern Asian margin in southern Kamchatka, the Kamchatka Isthmus, and the Olyutor Zone of the Koryak Highland, similar and obviously different features can be pointed out. In both northern and southern Kamchatka, the main structural elements in the conjugation zone were formed over relatively short time spans, no longer than 5 Ma. Taking into account the uncertainties in age determinations, deformation could have been still more transient. The deformation related to the arc–continent collision is confined to a rather narrow (<100 km) tract, beyond which no unconformities coeval to the movements at the northwestern boundary are noted.

The comparison of the Malka and Lesnaya uplifts shows that the structures at the arc–continent boundary were formed asynchronously: 55–50 Ma ago in the south and 48–45 Ma ago in the north. It is quite probable that similar structural elements in the Olyutor Zone were formed even later. The deformation at the arc–continental margin boundary started everywhere with low-angle thrusting of island-arc complexes over terrigenous sequences. In the northern part of the region, the deformation was practically terminated at this stage (Vatyn–Lesnaya Thrust Fault) (Figs 3b, 4), whereas the joint deformation of autochthon and allochthon begins after the thrusting along with fast heating of the crust

(Figs. 7, 8). As a result, both the terrigenous complexes of the Asian margin and the island-arc associations of the Achaivayam–Valagin arc underwent metamorphism.

The variability of the tectonic structures along the suture between the paleoarc and continent is a general rule, because the outlines of the arc and continental margin in plan view were formed independently and came into contact randomly. It is inevitable that segments of the arc contacted with the continent and were deformed earlier, hindering or even blocking the motion of the plate together with which they are drifting. In the segments between points of contact, the collision structures are expressed poorly or not formed at all. Simultaneously with blockage of the older subduction zone, a new trench arises in backarc zone of the attached arc, where the oceanic lithosphere, not having ceased its drift toward the continent, is consumed [19].

The specific feature of the considered example is expressed in the absence of synchronism in cessation of arc drifting in the south and north, most likely due to the division of the arc into two segments by the NW-trending transform fracture zone (Fig. 9). The collision of the southern segment in the early Eocene (Fig. 9b) did not stop the drift in the north, where a basin between arc and continent existed up to the middle Eocene and turbidites continued to accumulate therein (Figs. 9b, 9c). The lithosphere of this basin was slowly consumed in the subduction zone plunging beneath the arc (Figs. 9b, 9c). The cessation of this drift in the middle Eocene in the north of the region probably was a delayed reaction to the collision of the southern segment of the arc in the early Eocene and additionally was related to the general reorganization of plates in the North Pacific and its continental framework, when, in particular, a system of strike-slip faults separated the structural elements of northern Kamchatka and the Olyutor Zone from the Pacific Plate.

CONCLUSIONS

(1) In the northern Olyutor–Kamchatka Zone, the boundary of the Achaivayam–Valagin arc and the Asian margin is expressed in the Lesnaya–Vatyn Thrust Fault, along which a thin, low-angle sheet of strongly deformed Upper Cretaceous–lower Paleocene oceanic and island-arc rocks overlie the Upper Cretaceous–middle Eocene terrigenous sequences of the Ukelayat and Lesnaya groups. This structural unit formed at the stage of subduction beneath the Achaivayam–Valagin arc may be considered the upper portion of a low-angle suprasubduction lithospheric wedge. In the Kamchatka Isthmus, the thrusting ceased about 45 Ma ago, and after that, the thin and wide allochthonous sheet remained almost undeformed. In the Olyutor Zone, the final formation of the suture was probably related to younger time.

(2) In the southern part of the region (the Malka Uplift of the Sredinny Range), the arc–continent interaction also began with thrusting of the Cretaceous–Paleocene oceanic and island-arc rocks over the coeval terrigenous rocks of the continental margin about 55 Ma ago. However, the allochthonous sheet formed at that stage (probably, similar to the Lesnaya Vatyn Thrust) was intensely compressed and deformed along with autochthonous terrigenous complex in the course of collision. As a result, the allochthonous sheet was fragmented into tectonic slices, the thickness of the crust increased, and the bottom of the allochthonous complex was submerged to a depth of 15–20 km. Afterward, the crust was rapidly heated up, likely owing to the destruction of the lower lithosphere and invasion of asthenospheric masses (anomalous mantle) to the lower edge of the crust or even to the upper crust. This event occurred 52 ± 2 Ma ago and gave rise to metamorphism of high temperature and moderate pressure affecting the lower part of the collision zone and to the partial granitization of deeply subsided terrigenous rocks of the autochthon. Eventually, the light and plastic granite-gneiss masses buried beneath the packet of tectonic slices of relatively heavy island-arc rocks started to ascend as a core of rapidly rising and simultaneously eroded dome surrounded by low-grade metamorphic rocks. Only U–Pb (SHRIMP) dating of separate zircon grains from the rocks of the Kolpakov and Kamchatka groups made it possible to establish that these gneisses are products of metamorphism of the Cretaceous and Lower Paleogene terrigenous rocks, analogues of the Kikhchik Group.

(3) The sharp structural difference of different segments of the same arc–continent boundary may be caused by kinematics of the Achaivayam–Valagin arc at the final stage of its drifting toward Eurasia. It is suggested that this arc was segmented by a transform fracture zone, and when its southwestern segment had already collided with the continental margin, the northeastern segment still remained at a distance of a few hundred kilometers from it. Although this segment continued to approach the continent for a few million years, the arc did not collide with the continent because 43 Ma ago the proto-Komandorsky strike-slip fault separated northern Kamchatka and Koryakia from the Pacific Plate.

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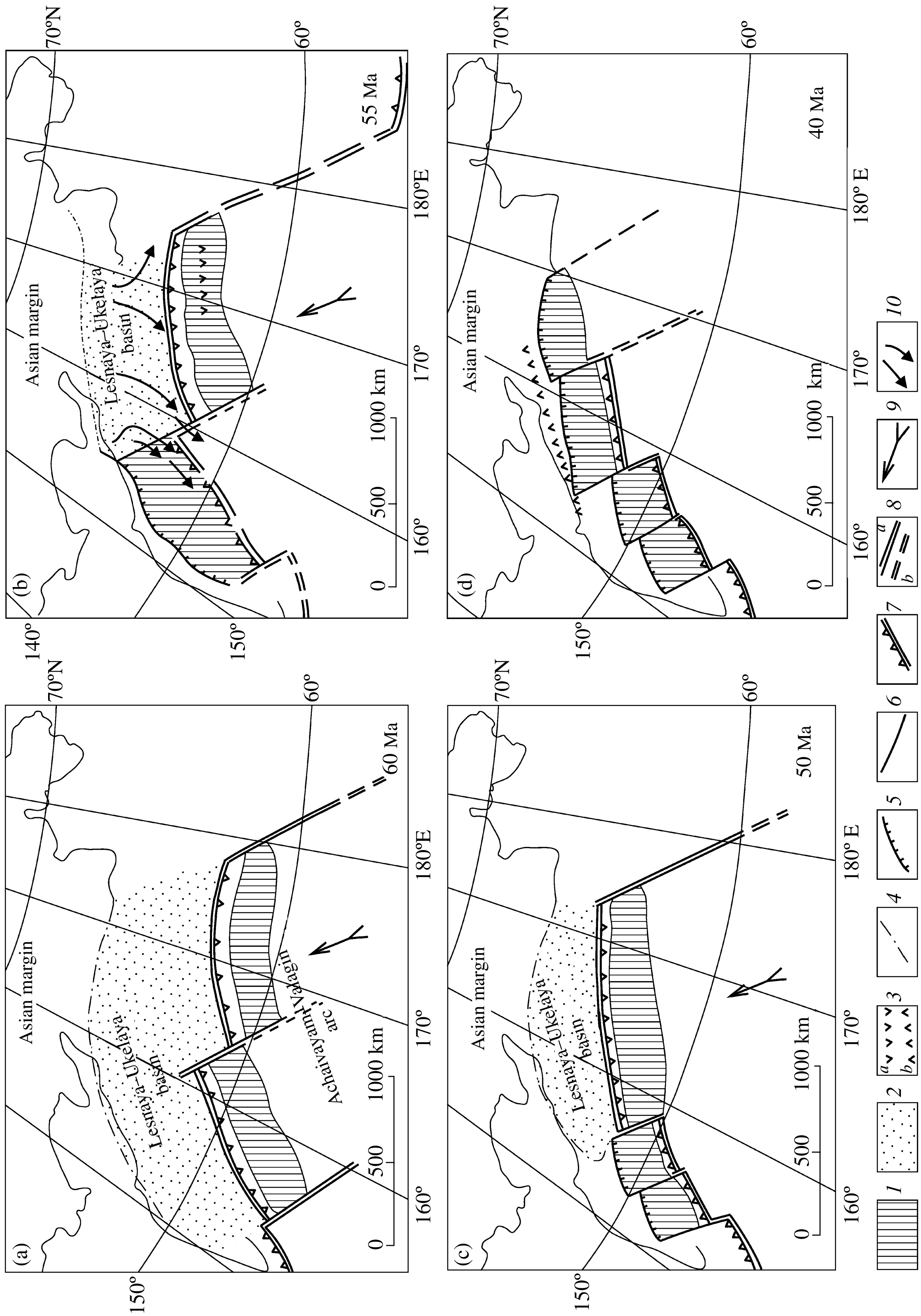

Fig. 9. Tectonic scheme of collision of the Achaivayam–Valagin arc with the Asian margin: reconstructions for (a) 60, (b) 55, (c) 50, and (d) 40 Ma ago, using paleomagnetic and kinematic data [18, 23, 24, 64, 68–70]. (*1*) Achaivayam–Valagin arc; (*2*) Lesnaya–Ukelayat sedimentary basin; (*3*) volcanic (a) Goven–Karaginsky arc and (b) Kinkil Belt; (*4*) arbitrary northwestern boundary of the Lesnaya–Ukelayat basin; (*5*) thrust fault of arc over continental margin; (*6*) strike-slip fault; (*7*) subduction zone; (*8*a) transform fracture zone; (*8*b) inferred tectonic zone; (*9*) direction of the oceanic lithosphere motion; (*10*) direction of terrigenous material transport 55 Ma ago.

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