Russian Geology
and Geophysics
Vol. 44, No. 12, pp. 1321-1338, 2003

Geologiya
i Geofizika
UDC 551.24

GEODYNAMICS AND GRANITOID MAGMATISM OF COLLISIONAL OROGENS

A.G. Vladimirov, N.N. Kruk, S.N. Rudnev, and S.V. Khromykh

Institute of Geology, Siberian Branch of the RAS,
3 prosp. Akad. Koptyuga, Novosibirsk, 630090, Russia

The Pamir-Himalayan and Central Asian intracontinental fold belts developed to follow different eodynamic scenarios. In the first case, it was an ultimate version of hard collision, when cratons directly interacted with the Early Precambrian crust and thick lithosphere mantle. The second case was a soft collision, which came to an end in Late Paleozoic-Early Mesozoic time, without reachin the sta e when the Siberian, Sino-Korean, and Tarim cratons would be struck. Direct eophysical observations cannot be used for ancient epochs, but the thickness of lithosphere of collidin plates and microplates can be inferred from Sr-Nd isotope characteristics of ranitoid batholiths, which depend on avera e composition and a e of the crust, thus indirectly indicatin the thickness of a enetically related underlyin lithosphere mantle. The upper mantle dynamics has been analyzed for different sta es of collisional oro eny. It has been concluded that at the moment of inversion (the be innin of the early collision sta e), a slab is detached and an asthenosphere swell appears in the vicinity of the future collisional buildin immediately beneath the Moho discontinuity. As a result, short-term anomalous temperature radients appear in the lower crust, lar e-scale meltin occurs, and bimodal volcanic series form, which, on the one hand, still retain suprasubduction eochemical labels but, on the other hand, reflect the composition of the lower crust subjected to advanced meltin . Then the collisional oro eny follows the classical scenario of the thickenin of the crust and its lithosphere root, coverin the period from the end of the early oro eny sta e throu h the late oro eny sta e. The time of formation and extent of an oro en depend on the thickness of collidin plates, and the composition of ranitoid batholiths is directly correlated with the composition of the eolo ic environment. The relationship with the mantle, if any, is expressed in specific forms, e. ., in the form of rifts in the oro en foreland durin a frontal collision or in the form of featherin conver ent and diver ent strike-slip faults when the collision is oblique. The dynamics of development of collisional oro ens radically chan es at the postcollision (taphro enic) sta e. With a reater thickness of the lithosphere root (Pamirs-Himalayas), the density instability causes the lithosphere delamination, and asthenosphere flows move beneath the Moho, thus causin a drastic rise in relief, followed by the oro en's collapse. With a smaller thickness of the lithosphere (arc-arc, arc-seamount, arc-microcontinent, and other collisions), there is no delamination, and the oro en's breakup is due only to ravitation landslides and detachments in the crust. Central Asia is unique for the presence of a lar e lower-mantle plume. Therefore, the processes of the seemin ly classical soft collision actually led there to the initiation of local plumes beneath folded oro ens. A model is proposed for the induced plumes that permits the formation of iant ranitoid batholiths or their source areas at the postcollision sta e, as well as their specific composition combinin plume and collision characteristics.

Geodynamics, plate and plume tectonics, granite magmatism, Pamirs-Himalayan and Central Asian fold belts

PROBLEM BACKGROUND

Granitoid magmatism and orogeny are intimately involved with each other, reflecting various aspects of the same geologic phenomenon. Until the 1970s, this empirical regularity was explained from the point of view of the orogen-geosynclinal concept, though even at that time, some geologic discrepancies were known. In 1967, Kuznetsov and Yanshin [1] generalized the contradicting facts and came to the conclusion that granitoid batholiths are often beyond the geosynclinal troughs proper and have a specific composition (e.g., the Kalba-type granites in Gorny Altai, etc.). Later on, these batholiths were localized in areas of joint or autonomous tectonomagmatic activity, and their origin was supposed to be linked to intratelluric flows of fluids and heat, responsible for the lateral-time zoning and specific composition in orogenic belts and beyond them [2–4]. This approach was paralleled by alternative ideas of isochemical anatexis in the Earth's crust and formation of gabbro-granite series in fold belts by syntexis and/or fluid syntexis of mantle and crustal magmas (see, e.g. the review [5]).

The problem of orogenic and nonorogenic granitoid batholiths is hotly debated in terms of plate tectonics. In particular, the model of frontal impact of continents associated with crust thickening, metamorphism, and granite formation [6], subduction of a mid-oceanic ridge beneath the margin of one of the colliding continents and/or microcontinents [7], intracontinental subduction and rheological layering of the lithosphere [8], detachment of a slab in zones of collision [9, 10], and, finally, delamination of the lithosphere and intracontinental extension involved with the orogen collapse [11]. All these models make an attempt to describe, in terms of plate tectonics, the within-lithosphere and asthenosphere power sources responsible for the appearance of mantle magmas beneath the collision "sutures" and, as a result, anomalous temperature gradients and large-scale granite formation at the level of the Earth's crust. Simultaneously, many geologists accept the idea that a superplume (lower-mantle hot spot) existed in North America, which acted throughout the Phanerozoic and was responsible for the formation of the Permian-Triassic traps of Siberia and coeval granitoids of Central Asia [12, 13]. The revived "granite" discussion finally reduces to the estimation of the contribution of the collision and plumes to the formation of giant granitoid batholiths of Central Asia. Our paper is aimed at unravelling this problem. Emphasis is placed upon the plate-tectonic factors and boundary conditions of their application in analysis of geodynamics and magmatism of collisional orogens, as the plume-tectonic and their interpretation with respect to granitoid magmatism have been considered elsewhere [14, 15].

MAIN STAGES OF COLLISIONAL OROGENY

Collisional orogens appear by collision of two continental lithosphere plates, which could be of varying scale: continent-continent or continent-microcontinent. Since initially the lithosphere plates are separated by a basin with the oceanic-type crust, the collision is preceded by the subduction of this crust, with the formation of an accretionary wedge, or "pseudosubduction", reflecting the thrust of continental masses over the sea-margin basin, which has lost the relation with convection in the upper mantle [16, 17]. A special place is occupied by transpressional orogens and orogens related to local collisions of an arc with a protrusion of continent, with a microcontinent, oceanic uplift and/or a fragment of another arc. These versions occur chiefly in the accretionary (subduction) fold belts but can be also expressed in the intracontinental belts like the Central Asian fold belt [18–20]. In classifications of fold belts these are lower-rank structures [19], which can replace one another laterally in the same zone, depending on the angle of collision and plate configuration, or in time, reflecting different stages of orogeny [21]. It is not a sheer coincidence that a compromise term is introduced for them, "accretion-collisional orogens", which becomes increasingly more popular in the geological literature on Central Asia [22]. A common feature of accretion-collisional orogens is a more important role of basite magmatism, which still retain subduction-related isotope-geochemical characteristics [23] as well as specific composition of batholiths often coexisting with granitoids, $+\varepsilon_{Nd}(T)$ [24–26].

Before the plate tectonics was proposed, it had been known that the collisional orogens, which together with accretionary wedges were called then epigeosynclinal orogens, experience three stages in their development: early-, late-, and postorogenic (taphrogenic) stages. Each of them is characterized by its own specific morphology and deformations in the Earth's crust, which is expressed in correlative sedimentary, metamorphic, and igneous formations. The total duration of orogeny makes up tens of millions of years, demonstrating a direct dependence on scales of colliding plates, the first stage taking no less than 15–20 myr.

The main stages of development of collisional orogens by continent-continent collision are characterized by Khain [10] and Dewey [27]. Khain's scenario is based on a comparative tectonic analysis of the Mediterranean and Pamirs-Himalayan sector of a giant (more than 16,000 km long) Alpine fold belt, whose formation began as a result of collision of three continents – Europe, Africa, and Asia. These sectors are found at different stages of

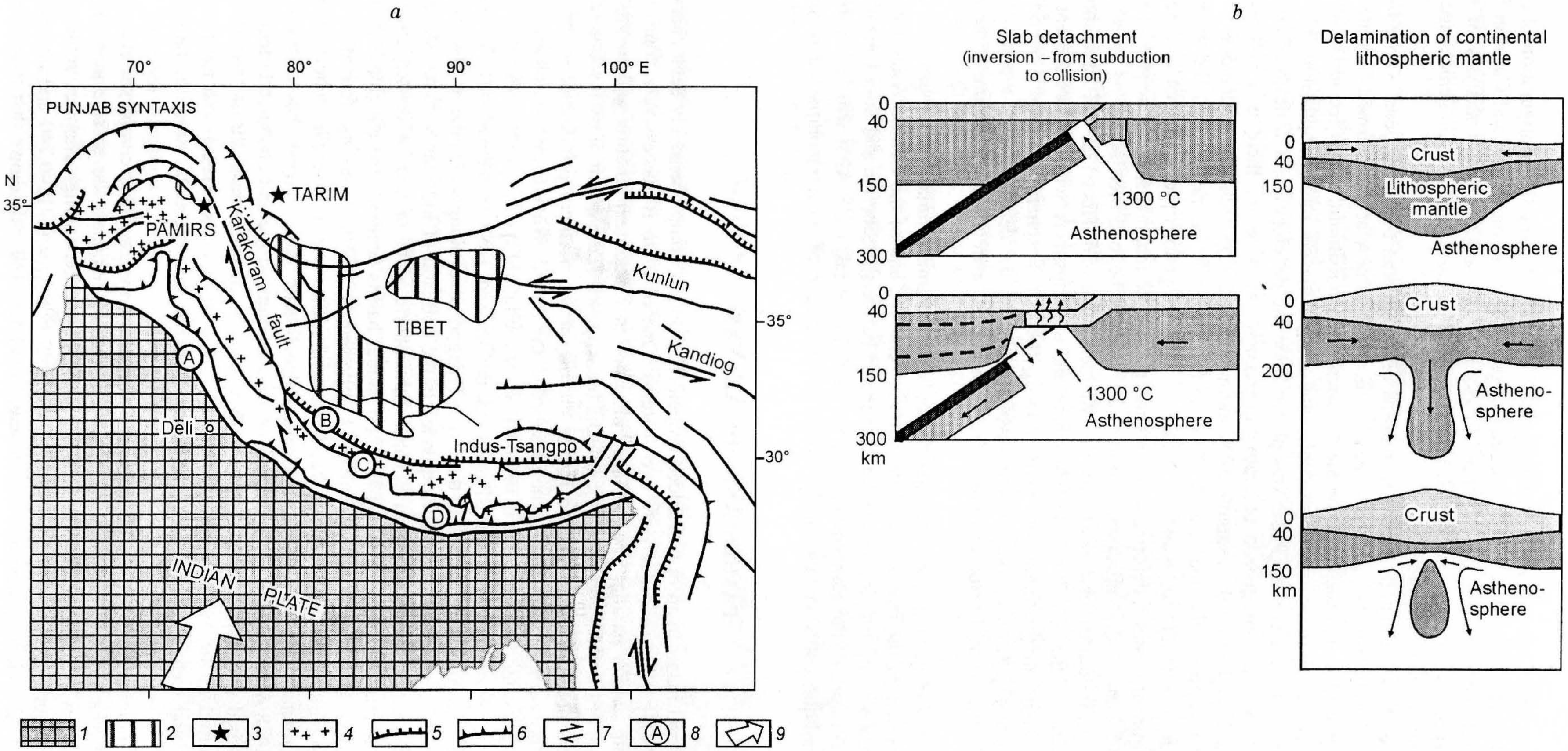

Fig. 1. Structural scheme of the Pamir-Himalayas and Tibet (*a*) and geodynamic models (*b*) in the "continent–continent" version reflecting the early-orogenic stage of collision tectogenesis, accompanied with slab detachment [9, 10] and late-orogenic, related to the mantle-lithosphere detachment above the collision suture because of density instability [11, 48]. ***1*** **— crystalline shield of Indostan;** ***2, 3*** **— areas of volcanism:** ***2*** **— bimodal K-calc-alkaline (Paleocene–Miocene),** ***3*** **— alkaline-basalt (Pleistocene);** ***4*** **— areas of leucogranite massifs (Eocene–Miocene);** ***5*** **— ophiolite-labelled ancient subduction crusts;** ***6*** **— thrusts;** ***7*** **— strike-slip faults;** ***8*** **— largest ruptures: A — Himalayan frontal fault, B — Indus-Tsangpo suture, C — Major central thrust, D — Major marginal thrust;** ***9*** **— direction of migration of the Indian Plate.**

out under conditions of adiabatic decompression from metapelites at the expense of muscovite dehydration at T = 750–770 °C, P = 5–8 kbar (at T < 650 °C in fluid-saturated conditions).

The transversal compression of the space initially occupied by the Himalayas is estimated at hundreds of kilometers [36]. The thickness of the upper-crustal nappe-thrust complexes is no less than 70 km, whereas the lower-crustal complexes extruded beneath the Moho discontinuity evidently experienced granulitization, eclogitization, and melting, which led to the appearance of physical properties undistinguishable from the properties of the lithosphere mantle. The basite magmatism of Cenozoic age is absent from the Himalayas. North of the collisional suture (Tibet Plateau), on the contrary, an asthenosphere window is inferred from geophysical data and wide occurrence of volcanism represented by the potassium series (shoshonites, latites, tephrophonolites and K-rhyodacites with an Ar-Ar age of 18±0.5 Ma). Judging from the contribution of the subduction component (no less than 20%), these volcanites cannot be interpreted as of pure plume origin [41].

The Punjab syntaxis and Pamirs. In the frontal part of the protrusion the early-orogen conglomerate molasses are represented by separate wedges, lithoslabs, and dislocated sequences whose age, according to stratigraphic observations, is not younger than Early Paleogene and the associated volcanism in the Ladakh and Kohistan corresponds to the calc-alkaline series [33].

The late-orogen tectonic stage (early phase) includes the Paleocene Bartang volcanites of the Central Pamirs, whose composition varies from bimodal shoshonite to higher-K calc-alkaline series [42]. In the South Pamirs, compositionally close volcanites make up the Kyzyl-Rabat structure whose Eocene age was established by biostratigraphic methods [34]. According to Titov et al. [43], shoshonites were primary magmas initially enriched in F and Cl; their contamination occurred under the lower-crustal conditions (>10 kbar), and differentiation of hybrid latite melts, in the intermediate chambers (<3.5 kbar). Potassium rhyolites corresponded to low-temperature anatectic melts. Primary Sr isotope ratios vary from 0.706–0.708 (shoshonites-latites) to 0.712 (K-rhyolites); the basic varieties retain the Nb-Ta minimum.

A specific tectonic position is occupied by Cenozoic biotite-muscovite(±garnet) leucogranites of stress-type, circumventing and simultaneously penetrating the Nuristan-Badakhshan crystalline massif of Early Cambrian age [44]. Analysis of structural data [45] shows that at the climax of metamorphism, this zone was dominated by radial stresses and dislocations, which can be linked to the frontal load off the Punjab syntaxis. The leucogranites are persistently associated with blastomylonites of pre-, syn-, and postgranitic age. The morphology of individual bodies is tabular in large massifs, e.g., in the South Pamirs, and corresponds to the deformed domes, extruded onto the nonmetamorphosed complexes of the Southeastern Pamirs. Generation of these melts began at the early-orogen stage 38–33 myr ago, with its climax dated at 25–13 Ma [38, 46]. Remarkably, the leucogranites of the Pamirs had already experienced the tectonic extrusion, but in the rear of the Punjab protrusion the granite formation had not finished yet (2.7±1.2 Ma, U-Pb). As inferred from composition [38, 44], they are close to the Himalayan leucogranites $(^{87}Sr/^{86}Sr)_0$ = 0.715–0.723, $\varepsilon_{Nd}(T)$ varies from –10 to –18; the model ages T_{Nd}(DM) exceed 1.8–2.0 Ga.

Worthy of note are explosion pipes made up of alkaline basalts, picrites, and ankaramites of the Dunkel'dyk complex [34]. In the Pamirs, they belong to magmatites of Quaternary age. The xenoliths of garnet granulites found in them contain melt inclusions and must be considered as S-type acid magmas having crystallized at the lower-crustal depths (no less than 12 kbar). They are correlated with the Quaternary alkali basalts and basanites of the Toyun trough (Tarim).

Geophysical data are bearing on the existence of a large lithospheric wedge beneath Hindukush, which marks the northwestern seismic boundary of the Nuristan-Badakhshan Massif and has no counterparts in the East Pamirs and Karakoram [47]. The Himalayas and Tibet are, on the contrary, characterized by a deep asymmetry with the northern vergence of seismofocal plane, which is generally in agreement with the recentmost deformations in the Earth's crust. To follow Khain [10, 16], we suppose that these geological examples correspond to two extremal versions of collisional tectogenesis owing to the plate geometry. Hindukush, Pamirs, and partly Karakoram were related to the pseudosubduction at the early-orogen stage and frontal impact at the late-orogen stage; the Himalayas and Tibet are associated with the slab detachment at the early-orogen stage (Kardung formation) and intracontinental subduction at the late-orogen stage, which led to the doubling of the lithosphere thickness (up to 300–400 km).

According to some estimates [11, 48], with the thickness of the compressed plastic lithosphere more than 350 km, its decollement occurs because of density instability. As a result, the abnormally hot asthenosphere mantle moves beneath the collision orogen and causes a drastic rise in relief (see Fig. 1). It is not ruled out that the Pamirs experiences just the same phenomenon, when in the west the mantle lithosphere root is still beneath the Hindukush Ridge whereas in the east, beneath the Karakoram and Tibet Ridges it disappeared 10–8 myr ago. A direct indication of this process seems to be explosion pipes of the Dunkel'dyk type in the Pamirs and recent volcanism in the Tarim basin. In this context, the seismotomographic data by Kulakov et al. [47] intrigue us, suggesting a nonordered structure of the upper mantle beneath the East Pamirs, Karakoram, and Himalayas, possibly, related to the active phase of orogeny, with the stationary convective currents in the upper mantle being still unstable.

The deep-seated mantle processes and magmatism of the Pamirs and Himalayas can also be specified in the context of estimation of the rate of continent convergence. The maximum rate was evidently typical of the Punjab syntaxis, which was involved in collision 20–15 myr before the Indo-Eurasian collision took place but the late-orogenic stage has not been completed yet. Indirect support comes from the fact that the Nuristan-Badakhshan Massif, situated in the frontal part of the syntaxis, experiences shearing and rotation without marked motion northward. According to estimated rates of tectonic exposure of metamorphic complexes [6], the maximum rate of convergence (up to 5 cm/year) was in the Himalayas, which was favored by a gentle dip of the seismofocal plane and intracontinental subduction. With the Pamirs and Himalayas considered as a single collision system, shoshonite volcanism may be explained as a result of successive origination of transverse convergent and divergent rifts in the orogen foreland first in the Central Pamirs (Paleocene), then in the Southeastern Pamirs (Eocene), and, finally, in the Tibet (Miocene).

CENTRAL ASIA AND ALTAI

The geodynamic evolution and history of formation of the CAFB are described elsewhere [20, 22, 49]. In the context of the problem under consideration, the most important achievements of the past decade are as follows:

On the basis of U-Pb, Rb-Sr, and Ar-Ar isotope dating and structural-petrological studies, Neoproterozoic, Caledonian, Hercynian, and even Mesozoic ages have been proven for some metamorphic sequences, including granulites [50–52]. Systematic Sm-Nd isotope studies have shown that the CAFB is dominated by the juvenile crust with T_{Nd}(DM) (2-st) of granitoid protoliths of 950–760 and 750–550 Ma ("Caledonian" and "Hercynian" isotopic granitoid provinces, respectively [26]). More ancient terranes (Hangayn, Barguzin, Sangilen, Altai-Mongolian, etc.) with T_{Nd}(DM) (2-st) of granitoid protoliths dated at 1700–1000 Ma are of restricted occurrence, and only few microcontinents have the Early Precambrian protolith [24, 26, 53]. The predominance of ensimatic arcs, fragments of sea-margin basins, paleoseamounts, and "juvenile" accretionary prisms in the Caledonian accretion-collision collage of the CAFB with an insignificant contribution from Early Cambrian sourcelands led to the wide development of granitoids with $+\varepsilon_{Nd}(T)$ [24, 26]. The highest positive values of $\varepsilon_{Nd}(T)$, comparable to the DM characteristics, and the youngest model ages of granitoid protoliths have been established for Junggaria and Kuznetsk Alatau (Fig. 2). These regions are now interpreted as large fragments of Neoproterozoic paleo-oceanic rises and seamounts preserved in the CAFB structure [51, 54].

Within the CAFB, there are Caledonian (Kuznetsk Alatau, Bateny, Sangilen, Western Baikal region) and Hercynian (Altai) paleotransform margins, along which oblique collisions with microcontinents and terranes of different genesis occurred [17, 18, 32, 49, 55, 56]. The resulting transpressional orogens (in terms of [19]) are usually characterized by an intimate connection of thrust deformations with progressive HT/LP metamorphism and large-scale granite formation at the late- and postorogenic stages of tectogenesis. Taking into account the persistent conjunction with dike belts of higher-alkalinity basites, which mark the main convergent and divergent "shear"-zones, they were termed "hot shear systems" [17]. Consider the evolution of granitoid magmatism of such structures by the example of the Altai tectonotype (Fig. 3).

Altai. The geodynamic evolution of Altai is now interpreted in the context of gradual approaching of the Kazakhstan and Siberian plates, with their clockwise rotation relative to each other and simultaneous decline of the Ob'-Zaisan paleo-oceanic basin [20, 22]. It is supposed that the precollisional Altai and Kazakhstan margins (D_{1-2}) were transform boundaries separated by the oceanic basin with mid-oceanic ridge. The Altai-Mongolian microcontinent, sliding along the Siberian continent, had the Neoproterozoic crust (T_{Nd}(2-st) = 1500–1000 Ma) [18, 56]. In this period, the Ob'-Zaisan paleo-oceanic basin interacted with the Kazakhstan and Siberian continents in the form of two oblique subduction zones (Zharma-Saur and Rudny-Altai island arcs). By the middle Carboniferous, the ocean was completely closed and the further evolution of the orogen proceeded against the background of general left-hand strike-slip deformations [57]. The main ones are the Zharma-Saur, Char, and Irtysh strike-slip faults (see Fig. 3). As noted above, the orogen also included the Kuznetsk-Alatau and Junggarian terranes, fragments of paleo-oceanic rises with the protolith dated at T_{Nd}(2-st) = 850–650 Ma. The evolution history of Altai includes three orogenic stages, for each of which time sections are given, with outlines of the belts and chamber areas of granitoid magmatism shown separately (Fig. 4).

The inversion phase (onset of the early-orogenic stage) also encompasses eroded central-type volcanoes (C_3-P_1) the chains of which most probably reflect the detachment and oblique subduction of paleoslabs beneath the Kazakhstan and Siberian continents. The U-Pb isotope age of this volcanism was 301±7 Ma [58]. A

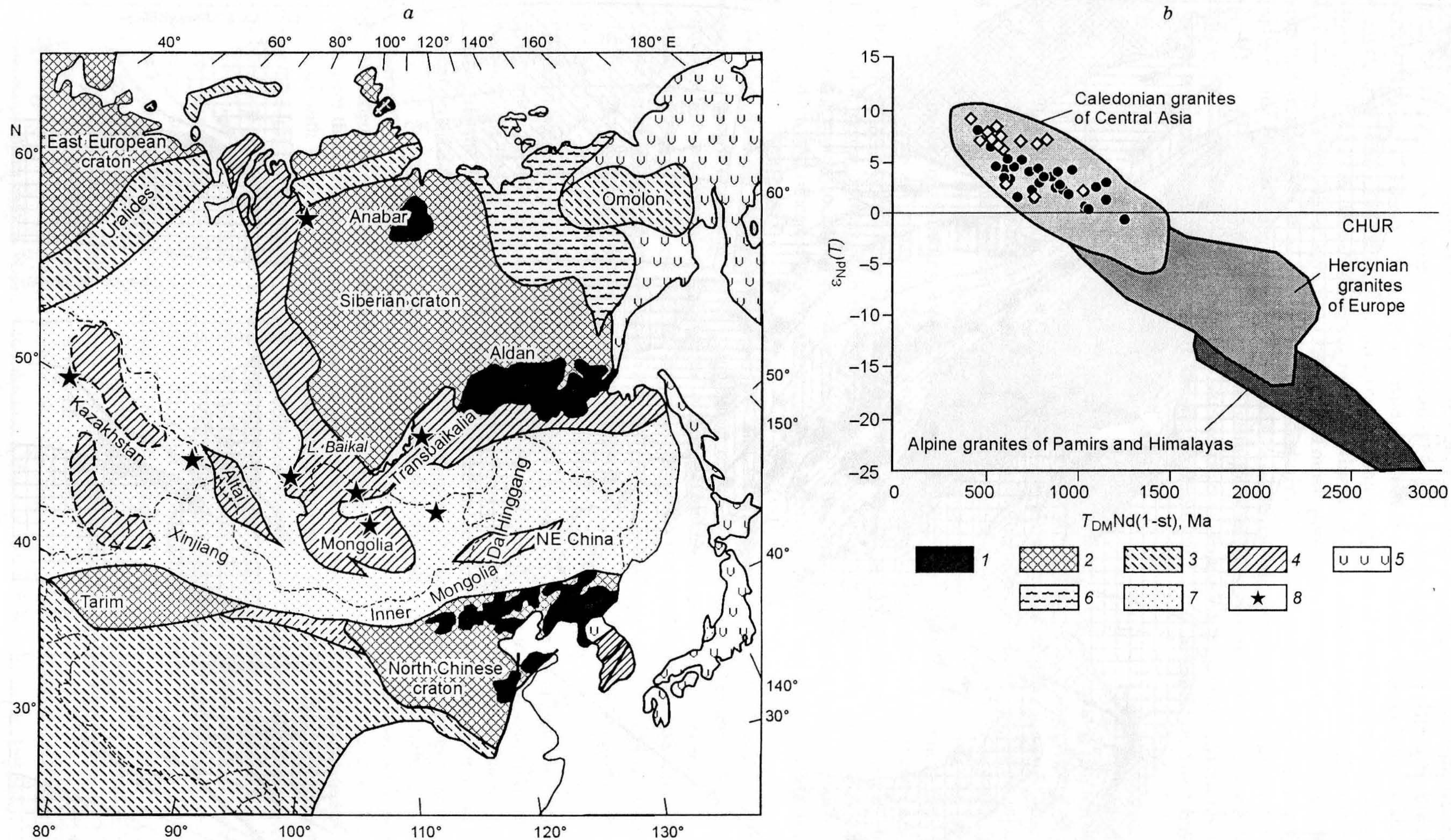

Fig. 2. Central Asian Fold Belt. ***a*** **— Tectonic scheme constructed with Nd-isotope provinces taken into account [24, 26, 53, 63];** ***b*** **— Nd-isotope diagram for granitoids [24, 26].** ***1*** **— shields;** ***2–4*** **— areas with the crust of Archean–Early Proterozoic age (*2*), Middle Proterozoic age (*3*), and Neoproterozoic age (*4*);** ***5–7*** **— geological structures of the Pacific (*5*), Yana-Kolyma (*6*), and Central Asian (*7*) fold belts;** ***8*** **— hot spots of Late Paleozoic–Mesozoic age.**

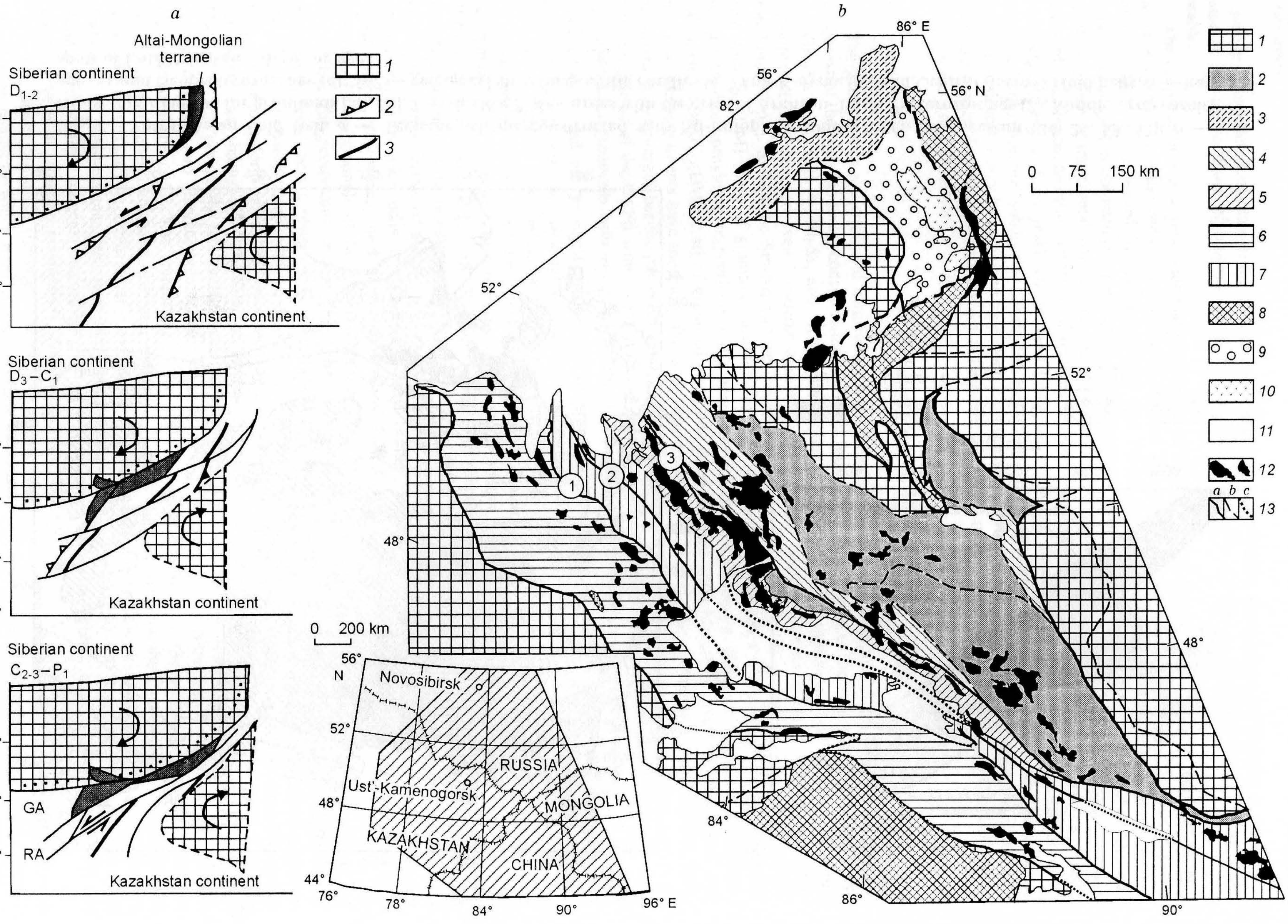
a
Altai-Mongolian terrane
Siberian continent
D1-2
Kazakhstan continent
Siberian continent
D3–C1
Kazakhstan continent
Siberian continent
C2-3–P1
GA
RA
Kazakhstan continent
1
2
3
b
86° E
56°
56° N
82°
52°
52°
48°
48°
84°
86°
90°
0 75 150 km
0 200 km
N
Novosibirsk
RUSSIA
Ust'-Kamenogorsk
MONGOLIA
KAZAKHSTAN
CHINA
76°
78°
84°
90°
96° E
44°
1
2
3
4
5
6
7
8
9
10
11
12
a b c
13

Fig. 3. Generalized tectonic scheme of the Altai collision-shift orogen. *a* — Palinspastic reconstructions (data borrowed from [79] with author's modifications): *1* — continents, *2* — subduction zones, *3* — MOR or paleoMOR; GA — Gorny Altai, RA — Rudny Altai. *b* — Tectonic scheme (localized in the inset): *1* — Neoproterozoic-Early Paleozoic structure-composition complexes of the Siberian and Kazakhstan continents, undifferentiated; *2* — Altai-Mongolian microcontinent; *3–8* — continental-margin and oceanic terranes of Middle and Late Paleozoic age: *3* — Kolyvan'-Tomsk passive(?) margin, *4* — Rudny-Altai island-arc, *5* — Kalba-Narym turbidite, *6* — Zharma-Saur island-arc, *7* — Char oceanic, *8* — Kuznetsk-Alatau and Junggarian oceanic rise and/or groups of seamounts; *9* — Kuznetsk sedimentary basin, including: *10* — traps of Triassic age; *11* — Cenozoic deposits; *12* — granitoids in the age range from Carboniferous through Early Jurassic; *13* — faults: *a* — proved, *b* — supposed, *c* — supposed beneath Quaternary deposits. Encircled numerals are main strike-slip faults with sinistral kinematics: 1 — Zharma-Saur, 2 — Char, 3 — Irtysh.

distinguishing feature of volcanism is low abundance of water and abnormally high (more than 1000 °C) temperatures of acid melt crystallization. The rocks contain xenoliths and xenocrysts of metamorphic rocks of granulite facies, which is indicative of great (30 km and more) depths of generation of silica magmas [59].

Granitoid magmatism of the Kalba and Zharma batholith belts (P_{1-2}) falls on the boundary of the early- and late-orogenic stages. The batholiths are made up of granodiorite-granite associations enriched in alumina and potassium, and time of their emplacement is synchronized with pulses of reactivation of sinistral strike-slip deformations in the Irtysh folding zone (283–276 and 273–265 Ma, Ar-Ar ages of micas from blastomylonites and U-Pb ages of zircons and monazites from granitoids, respectively) [60]. At the late-orogenic stage (P_2-T_1) granitoid magmatism covered considerably larger areas, retaining coarse-conform outlines relative to the boundaries of the collision-shift system. Along with the *S*-type granitoids, rare metal-plumasite, granite-leucogranite, and syenite-granosyenite-granite associations are widespread there. The former correspond to the mesabyssal facies (Monastyrka, Belokurikha, and other batholiths, and the latter, to the subvolcanic and hypabyssal facies (paleovolcanoes of the Semeitau or Aya types).

For the granitoid batholiths of the early- and late-orogenic stage, the Nd and Sr isotope composition is convincingly shown to depend on the composition of the host terranes. For example, the Kalba and Monastyrka granitoids, which are formed at the expense of the metapelite deposits of the fore-arc basin (Takyr Black-Shale Formation) have $\varepsilon_{Nd}(T) = -2...+2$, $(^{87}Sr/^{86}Sr)_0 = 0.705–0.706$. The granitoid batholiths of the Tigirets-Savvushinsky belt crossing the Rudny Altai structures with the ensimatic basement and the Gorny Altai structures with the ensialic basement display a drastic jump in isotopic parameters of Nd and Sr: $\varepsilon_{Nd}(T) = +2...-1$, $(^{87}Sr/^{86}Sr)_0 =$ 0.7051; $\varepsilon_{Nd}(T) = -0.5...+1$, $(^{87}Sr/^{86}Sr)_0 = 0.7061–0.7071$, respectively [61].

The post-orogenic (within-plate) stage (T_2–J_1) is characterized by an ultimately wide diversity of geochemical types of granitoids (from plumasite and rare metal-plumasite to K-high calc-alkaline and subalkaline). This stage also encompasses the Kuznetsk basin traps corresponding, in isotope-geochemical characteristics and age, to the initial rifting on the Siberian Platform [14, 62], as well as dike belts of alkaline basalts and lamprophyres.

The reported factual data on the structure of magma chambers and isotope-geochemical characteristics of granitoids may be reasonably explained if we recall that the Altai orogen was formed by collision of terranes whose thickness of lithosphere was commensurate (Junggarian and Kuznetsk-Alatau paleo-oceanic terranes) to or slightly exceeded (terranes of transform margins, obliquely oriented island arcs, and juvenile accretionary prisms) the lithosphere thickness in the modern sea-margin—island-arc settings. This is corroborated by a wide occurrence of granitoids with $+\varepsilon_{Nd}(T)$, which not only indicate the age and "maturity" of the crust but are directly correlated with the lithosphere thickness. During the collision compression with respect to relatively thin lithosphere microplates and plates under the intense strike-slip tectonics, the uplift of the Altai relief seemed to be no more than 2–4 km, and accordingly the lithosphere thickening did not exceed 150–200 km. Being of oblique orientation, the Zharma-Saur and Rudny Altai paleoslabs hardly had any effect on the structure during their detachment at the early-orogenic stage. This is confirmed by small thickness (initial hundreds of meters) of molassa. It is not by chance that some authors [49] negate the collisional nature of this folded system, whose evolution is related to the Irtysh intracontinental strike-slip fault. During this period corresponding to the inversion of the geodynamic regime (from subduction to collision), only contrasting basalt-rhyolite and/or basalt-latite-K-rhyolite series as well as the comagmatic hypabyssal intrusions formed.

Delamination of the lithosphere mantle, like the delamination observed now beneath the Himalayan orogen, could not occur there either, because the thickness did not reach a threshold of 350 km [11, 48]. Under these

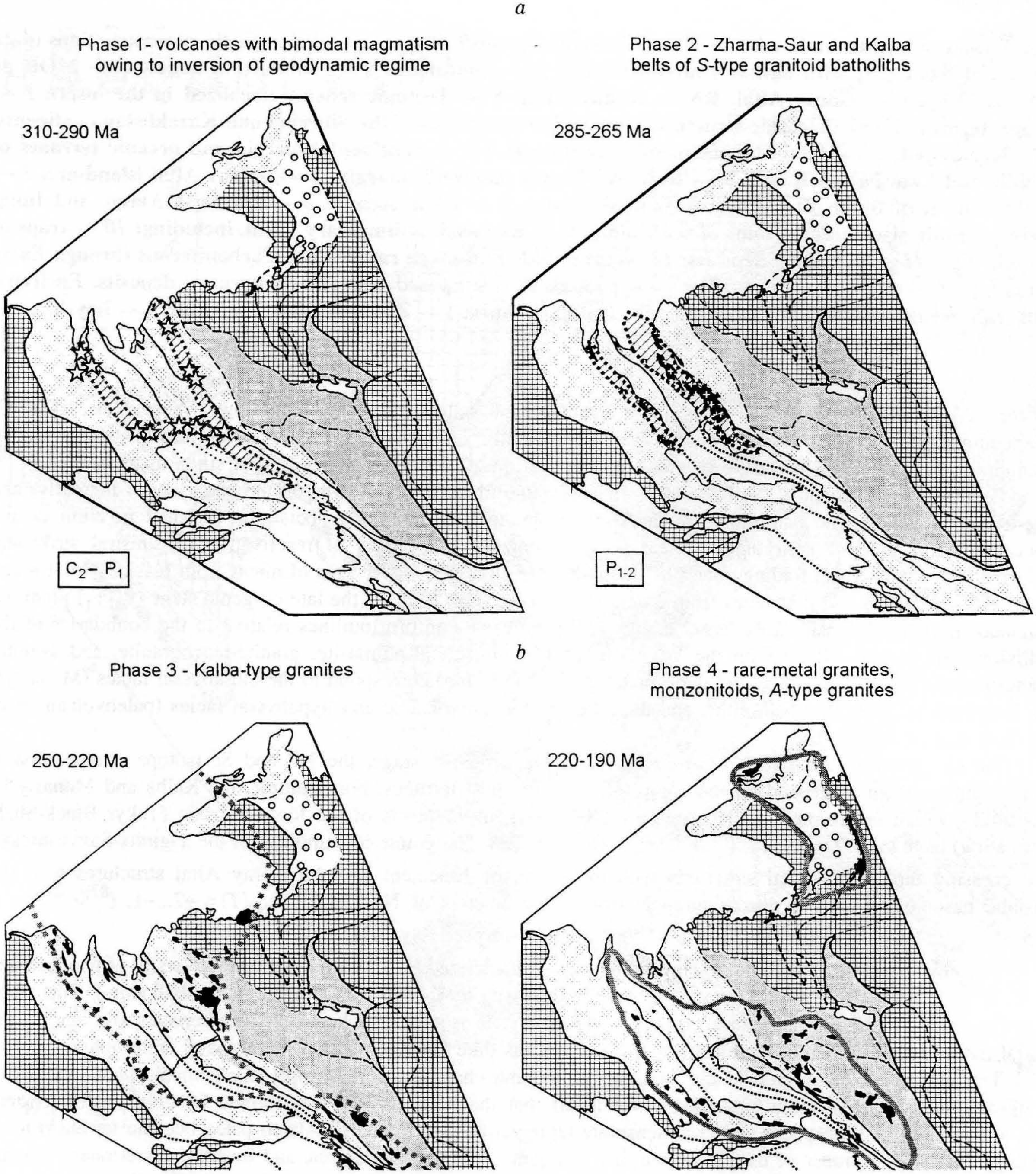

Fig. 4. Extents and structure of magma chambers of Altai at time sections reflecting the dynamics of development of collisional orogen and influence of plume-tectonics. Stages of collisional tectogenesis on Altai: *a* — early-orogenic, *b* — late- and post-orogenic. *1* — Neoproterozoic-Early Paleozoic structure-compositional complexes of the Siberian and Kazakhstan continents, undifferentiated; *2* — Altai-Mongolian microcontinent and its fragments; *3* — continental-margin and oceanic formations of Middle and Late Paleozoic age, undifferentiated; *4* — Kuznetsk sedimentary basin, including traps of Triassic age and Jurassic superimposed troughs; *5* — Cenozoic deposits; *6* — volcanic belts and their paleovolcanoes as indicators of the inversion of geodynamic regime; *7* — outlines of magma chambers of the early-orogenic stage; *8* — granitoid batholiths; *9* — outlines of chamber zones of the late- (P_2-T_1) and post-orogenic (T_2-J_1) stages; *10* — master faults: *a* — proved, *b* — supposed.

boundary conditions, a source of energy providing the heating of the thickened crust and their partial melting could be a thermal anomaly remained after the paleo-MOR had been overlapped by a continental plate. It is specific for the Altai orogen that the paleo-MOR, whose expression is the Char ophiolite belt, owing to the symmetrical position of the Zharma-Saur and Rudny Altai obliquely oriented island arcs did not submerge beneath the margin of one of the continental plates but remained beneath the axial part of the orogen (see Fig. 3). The most debatable is the geodynamic interpretation of the postorogenic stage whose magmatism reveals signs of the influence of plume source. According to [12, 61], granitoid magmatism of this stage was controlled on Altai by the uplift of mantle magmas or their derivates to the decompression zones associated with intense convergent and divergent strike-slip deformations.

DISCUSSION

Thickness and maturity of lithosphere and their importance for collision-related orogeny. The classification of collisional and postcollisional processes based on the thickness of the lithosphere of colliding geoblocks is given in Table 1. The tectonic types are chosen so that the effect of plume sources is minimal. Worthy of note is the systematic variation of $\varepsilon_{Nd}(T)$-characteristics of granitoids, depending chiefly on the maturity and age of the crustal substratum [24, 26, 51, 53] and, therefore, on the lithosphere thickening within a folded orogen. In the Pamirs and Himalyas the values of $\varepsilon_{Nd}(T)$ for granite-leucogranites are not higher than –15, which is typical of the cratons with the Early Precambrian crust; in Central Asia, they only extremely rarely reach values of –13...–10 by the collision of cratons with microcontinents having the Early Precambrian crust (Siberian craton–Barguzin microcontinent [53], Sino-Korean craton — its "fragments" [24]). In general, it may be thought proven [26, 53, 63] that the greatest contribution to the formation of accretionary-collisional and collisional granitoids of the CAFB comes from the young juvenile crust, whose isotope characteristics correspond to the Caledonian structure-material complexes (young and mature island arcs, accretionary prisms with ophiolites, paleo-oceanic rises and seamounts). It is for this reason that granitoids with $+\varepsilon_{Nd}(T)$ are abundant there, with their share, the greatest in the Caledonian accretionary-collisional structures, being gradually declined in the transition to the Hercynides and Cimmerides. The formation of granitoids with lower $\varepsilon_{Nd}(T)$ and older model ages is explained by a pelitic impurity (no more than 30% as estimated in [53]) of the ancient continental crust in accretionary prisms, which is the substratum for most orogenic granitoids. In some, rather rare, cases, the older model Nd ages of granitoids relatively to their geological ages (Kuznetsk Alatau and Bateny Ridge) are well explained by the specific composition of paleo-oceanic rises and seamounts, having blocked the subduction zones, because along with MOR basalts they abound in rocks with isotope characteristics of OIB [51, 63].

The tabulated data can also be analyzed in another way, considering the crust growth of Asia as a single continent. Unlike other continents, Asia has two cores and some smaller Early Precambrian fragments whose consolidation, accompanied by orogeny in Central Asia and Pamirs-Himalayas, was drastically different. In the Pamirs-Himalayan intracontinental fold belt, the orogeny has not completed yet but, owing to a high rate and intensity of plate convergence, reached the stage of direct interaction of cratons. In this version, the thicknes of the lithosphere of colliding plates was ultimately high, and the core of orogen is represented by Early Precambrian complexes with abnormally low $\varepsilon_{Nd}(T)$ and high I_0^{Sr} isotope parameters. The Central Asian Fold Belt, on the contrary, already completed its orogenic development, but there the orogeny had never reached the stage of direct interaction of cratons, therefore, collisions of geoblocks (terranes) with a relatively thin lithosphere and juvenile type of crust played a leading role; they have high, often positive, $\varepsilon_{Nd}(T)$ and lower I_0^{Sr} isotope characteristics, respectively.

Intralithospheric and sublithospheric power sources, responsible for magmatism at different stages of collision-related orogeny. A comparative analysis of the Pamirs-Himalayas and Central Asia reported there, and the literature data [17–22, 38, 64–66] shows that the early-orogenic stage of collision-related tectogenesis is composed of two essentially independent phases: inversion (subsequent, after H.Stille), reflecting the moment of transition from subduction to collision, and early-orogenic phase proper. Indicators of the inversion phase connected with the slab decollement and intrusion of mantle diapirs immediately beneath the Moho discontinuity and into the lower crust of collision zones are bimodal monzogabbro-monzonite-granosyenite-K-granite (K-basalt-latite-rhyolitic) and calc-alkaline gabbro-granite (basalt-rhyolite) volcanoplutonic formations. Basic rocks of these formational series, as a rule, retain subduction-related characteristics, whereas granitoids are distinguished by abnormally high temperatures of crystallization (≥1000 °C).

The second-phase granitoid associations usually correspond to the transition from early- to late-orogenic stage

Table 1

Classification of Collisional and Postcollisional Processes

	GEODYNAMIC PROCESSES AND TECTONOTYPES OF ASIA			+4...+9
Thickness of lithosphere of colliding geoblocks (↓)	**Accretion-collisional processes** Variants of collision of geoblocks: continent–arc fragment, arc–arc, arc–microcontinent, arc–seamount			$+\varepsilon_{Nd}(T)$ granites (↑)
	Continent–microcontinent (superterrane) collision Soft interaction of active continental margins with microcontinents			
	Chersky tectonotype Soft collision with pseudosubduction at the precollision stage (J_3–K)	*Transbaikalian (Cordilleran) tectonotype* Soft collision with paleoMOR beneath the continent and/or microcontinent margin (J_3–K)	*Altai (Scottish) tectonotype* Shift interaction with paleoMOR beneath the collision suture (C_{2-3}–J_1)	+2...–2
	Continent–continent collision Hard interaction of cratons			$-\varepsilon_{Nd}(T)$ granites (↓)
	Pamir tectonotype Hard collision, with pseudosubduction, at the precollision stage (Alpides)	*Himalayan tectonotype* Frontal compression, with intracontinental subduction (Alpides)	*Scandinavian tectonotype* Frontal compression (Caledonides)	–10...–40

which takes little time (1–2 myr) and is 20–25 myr apart from the onset of the collision. In the Pamirs and Himalayas, owing to the anomalous compression of cratons and intracontinental subduction, there is no relationship with the mantle, and intralithosphere sources of energy produced by increased temperature gradient on crust thickening and radioactive heating begin to play a leading role [6]. A certain contribution is made by dissipative heat, e.g., on collisional indention of structures of the Punjab-syntaxis type [44]. The *S*-type granite-leucogranites formed under these conditions have abnormally low $\varepsilon_{Nd}(T) = -10...-40$ and high $I_0^{Sr} > 0.710$–0.715 characteristics, since the melting affected the Early Precambrian substratum. The above-characterized intralithospheric sources of energy evidently little contributed to the CAFB; of most importance are there ascending mantle flows and asthenosphere anomalies linked to the overlapping of the paleoMOR by a continental lithosphere plate in the course of collision-related tectogenesis. Geodynamic models (Fig. 5) reflect the formation of collisional orogens in the case of axial arrangement of paleoMOR (Altai tectonotype, see description above in the text) and in the case of overlapping of the paleoMOR by the edge of the continental plate in the precollision stage (Californian and/or Transbaikalian tectonotype, after [17, 50]). This is to be contrasted with the geodynamic model for collision-related tectogenesis implemented in the form of pseudosubduction, when the peri-oceanic basin was closed, which had before lost the relationship with spreading centers and subduction [16]. Exemplified by the collisional belt of the Chersky Ridge [17, 67], it was shown that there is no paleoMOR beneath the collisional orogen and, as a result, the mantle magmatism is suppressed and the granitoid one is represented by *S*-type. In general, the granitoid batholiths of this stage display a distinct dependence of their composition on the host terrane. For example, in the Kuznetsk Alatau and Bateny Ridge, this stage corresponds to the Early Caledonian diorite-granodiorite-granitoid batholiths [25, 68]. They belong to the calc-alkaline series and have ultimately high parameters $\varepsilon_{Nd}(T) = 2.0...+6.5$; $T_{DM}(2\text{-st}) = 0.65$–$1.05$ Ga, as they were produced by the collision of paleo-oceanic rises and seamounts of Neoproterozoic age with a Vendian-Early Cambrian island arc (North Sayan). Kuznetsov [69] was the first to notice this relationship, and the systematic evidence of the dependence of the batholith composition on the composition of the host middle and lower crust is considered by Kovalenko et al. [26] by the example of Central Asian Caledonides.

It is most difficult to give a geodynamic interpretation to the post-orogenic (taphrogenic) stage of collisional tectogenesis whose magmatism in Central Asia displays direct evidence of existence of a plume source. The most illustrative features are Late Paleozoic-Early Mesozoic granitoid batholiths roughly coeval with the Permo-Triassic traps of Siberia and Kuznetsk Basin. Some authors explain this spatial-temporal conjunction by a pure plume source of traps and granites equally [12–15]. Not repeating their argumentation, we will emphasize two issues. The total period of formation of the batholiths in Transbaikalia, Mongolia, and Altai coincides completely

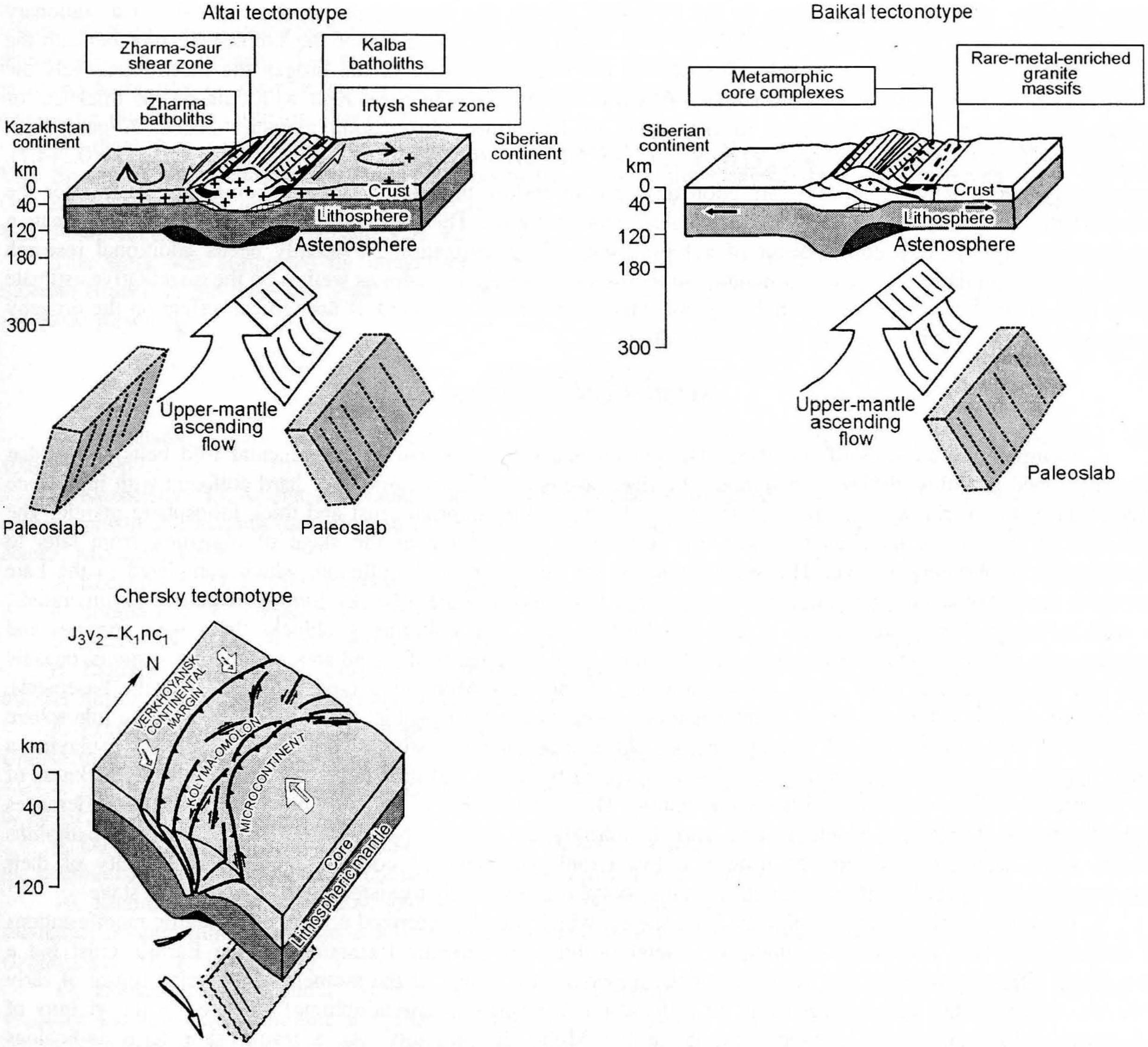

Fig. 5. Geodynamic models of evolution of collisional orogens in the continent-microcontinent (superterrane) variants. For explanations see the text.

(320–190 Ma), and in each case the mantle plume spatially coincides with the collisional orogen, i.e., is associated with the orogenic thickening of the lithosphere. According to Yarmolyuk and Kovalenko [15], this spatial-temporal conjugation is due to the movement of the margin of the Siberian continent over the same hot spot (Angara-Vitim batholith, 320–290 Ma → Hangayn, 250–235 Ma → Henteyn, 225–195 Ma), and the extensive crust remelting in the cores of orogens is connected with strong compression preventing the intrusion of basite magmas of plume genesis and, hence, with rifting around the batholiths, with bimodal alkaline and ultra-alkaline series. This hypothesis is in discordance with the location of the Altai and Central Kazakhstan chambers with intense rare-metal granitoid magmatism, which are synchronous with the Henteyn and Angara-Vitim batholiths, respectively (see Fig. 2). If we connect them with another hot spot, its track with younger magmatism from west to east (in the modern reference framework) contradicts palinspastic reconstructions indicating the oppositely directed migration of the Kazakhstan plate.

The geodynamic model of induced plumes seems to be more preferable. It explains the inevitable appearance of ascending upper-mantle flows beneath the collisional sutures by extrusion of the asthenosphere matter beneath the flanks of orogens during the growth of the lithosphere root. These flows, in turn, provoke the rise of abnormally hot matter from the 670–700 km phase boundary, under which the main reservoir of a lower-mantle plume (North

Asian [12–15]) is situated. According to the supposed model, the time taken for the come-up to a stationary ascending flow must directly correlate with the time taken for the formation of the lithosphere root beneath the folded orogens to follow a simple rule: The thicker the lithosphere root of the orogen the more intensively the induced plume forms. Nd-isotope data suggest that this hypothesis is in agreement with data on the thickness of colliding geoblocks, which decreases in the series of batholiths and magma chamber zones: Angara-Vitim ($\varepsilon_{Nd}(T) = -13...-2$) → Hangayn ($\varepsilon_{Nd}(T) = -8...-1$) → Henteyn ($\varepsilon_{Nd}(T) = 1.4...+2$) → Altai ($\varepsilon_{Nd}(T) = 0...+4.7$). Remarkably, the extents of granite formation decrease to follow this series as well, being the greatest for the Angara-Vitim batholith and the smallest, for the Altai chamber zone. The choice and substantiation of the alternative geodynamic models, as a continuation of a long-discussed "granitization", evidently needs additional research bearing on 3D simulation of the lower mantle—upper mantle—orogen system as well as on the quantitative estimate of the role of fluid regime of collisional orogens, which can have a profound, if not critical, effect on the orogeny dynamics and specific character of granite formation.

MAIN CONCLUSIONS

1. Comparative analysis of the Pamir-Himalayan and Central Asian intracontinental fold belts shows that they developed to follow different scenarios. The first case is an ultimate version of hard collision with immediate interaction of the Tarim and Indian cratons having the Early Precambrian crust and thick lithosphere mantle. The processes of collisional tectogenesis have not completed yet and are at the stage of transition from late- to postorogenic (taphrogenic) stage. The second case is the version of soft collision, which completed in the Late Paleozoic-Early Mesozoic having not reached the stage of collision of the Siberian, Sino-Korean, and Tarim cratons, as well as Early Precambrian cores of the Kazakhstan plate. The colliding geoblocks there were terranes and superterranes with the thinned lithosphere and unmature crust (fragments of island arcs, sea-margin systems, oceanic rises and seamounts and only rarely microcontinents of the Altai-Mongolian type with the Grenville basement). For ancient epochs, where the direct geophysical observations are not possible, the only indicator of the lithosphere thickness of colliding plates and microplates are Nd-isotope characteristics of granitoid batholiths, displaying a direct dependence on the average composition and age of the crust and thus indirectly indicating the thickness of the genetically related underlying lithosphere mantle. The classification of collision processes based on differences in the thickness of colliding geoblocks and, correspondingly, on different Nd characteristics of granitoid batholiths reveals some tectonotypes using as criteria a lower-rank geometry of colliding geoblocks, velocity of their convergence, and spatial relationship with oceanic morphostructures that existed at the precollision stage.

2. The collisional orogens develop in three stages, which are characterized not only by specific manifestations of deformations and correlated sedimentary, metamorphic, and igneous formations in the Earth's crust but a principally different structure and dynamics of the upper-mantle flows. At the moment of inversion (onset of early collision stage), a slab was detached and an asthenosphere protrusion (pseudoplume) appeared in the vicinity of the future collisional orogen immediately above the Moho discontinuity. As a result, short-term anomalous temperature gradients appear in the lower crust, extensive melting occurs, and bimodal volcanic series form, which, on the one hand, retains subduction-related geochemical "labels" and, on the other hand, reflect the lower-crust composition subjected to advanced melting. Of wide occurrence are contamination of basites with crustal material and syntexis of compositionally contrasting magmas, which finally led to the formation of hybrid series, of the shoshonite and/or latite type. Then the collision-related tectogenesis that follows the classical scenario of thickening of the crust and its lithosphere root covers the end of the early- and late-orogenic stages. The time of formation and size of an orogen depend, first of all, on the thickness of the colliding plates, and the composition of granitoid batholiths is directly correlated with the composition of the host geological medium. There is either no relationship with the mantle or it is displayed in specific forms, e.g., in the form of rifts in the orogen foreland by the frontal collision or in the form of feathering convergent and divergent strike-slip faults on oblique collision.

3. The dynamics of developemnt of collisional orogens radically changes at the postcollision (taphrogenic) stage. With the thickened lithosphere, when the collision reaches the utmost interaction of cratons, the depth of the lithosphere root reaches the critical level (350–400 km). As a result, the density instability leads to the delamination of the lithosphere, and the asthenosphere flows appear beneath the Moho discontinuity, causing a drastic rise in relief and then the collapse of the orogen. Magmatism is like the magmatism observed at the above-described stage of slab detachment in the transition from subduction to collision, but its extent is considerably greater, subduction-related geochemical "labels" are absent, and not only volcanoes but also large granitoid batholiths form. With the thinned lithosphere (collision of the types arc—arc, arc—seamount, arc—microcontinent, etc.), delamination did not occur, and the orogen cave-in is linked only to gravitational slides and decollements in the crust. Magmatism is either suppressed or absent. The unique character of the CAFB implies that there was

a large lower-mantle plume and therefore the processes of seemingly classical soft collision actually induced local plumes beneath the orogens. The proposed model of induced plumes permits us to explain the formation of giant granitoid batholiths or their magma chambers at the postcollision stage as well as their specific composition combining plume and collision characteristics.

We thank N.L. Dobretsov, V.I. Kovalenko, F.A. Letnikov, Ye.V. Sklyarov, V.V. Yarmolyuk, S.A. Tychkov, V.N. Sharapov, Yu.V. Perepechko, and O.P. Polyansky, participating in discussions and promoting these studies. Our thanks also go to analysts Ye.V. Bibikova, A.B. Kotov, D.Z. Zhuravlev, V.P. Kovach, Ye.B. Sal'nikova, V.A. Ponomarchuk, A.V. Travin, and V.A. Khalilov.

This work was supported by Integration grants 30/1998, 106/2003, 672/2003 from the Presidium of the Siberian Branch of the RAS and grants 03-05-65099, 03-05-65081, and 02-05-65091 from the Russian Foundation for Basic Research.

REFERENCES

1. Kuznetsov, Yu.A., and A.L. Yanshin, Granitoid magmatism and tectonics, *Geologiya i Geofizika*, 10, 108–121, 1967.

2. Kuznetsov, Yu.A, and E.P. Izokh, Geological evidence of intratelluric heat and mass flows as agents of metamorphism and magma formation, in *Problems of petrology and genetic mineralogy. Vol. 1* [in Russian], 7–20, Nauka, Moscow, 1969.

3. Korzhinsky, D.S., Metamagmatic processes, *Izv. AN SSSR. Ser. Geol.*, 12, 3–6, 1973.

4. Letnikov, F.A., *Granitoids of block regions* [in Russian], 218 pp., Nauka, Novosibisrk, 1975.

5. Dobretsov, N.L., *Global petrological processes* [in Russian], 235 pp., Nedra, Moscow, 1981.

6. England, P.C., and B. Thompson, Pressure-temperature-time parths of regional metamorphism I: Heat transfer during the evolution of regions of thickened continental crust, *J. Petrol.*, **25**, 894–928, 1984.

7. Ernst, W.G., and C.A. Nelson (Eds.), *Integrated Earth and environmetal evolution of the southwestern United States*, 501 pp., California, Geol. Soc. of America, Bellwether publishing, 1998.

8. Khain, V.E., and L.I. Lobkovsky, Specific features of the formation of collisional orogens, *Geotektonika*, 6, 20–31, 1990.

9. Davies, J.L., and F. von Blanckenburg, Slab breakoff: A model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens, *Earth Planet. Sci. Lett.*, **129**, 85–102, 1995.

10. Khain, V.E., S.A. Tychkov, and A.G. Vladimirov, Collision orogeny: a model for the detachment of a subducted oceanic lithospere plate as a result of continental collision, *Geologiya i Geofizika (Russian Geology and Geophysics)*, **37**, 1, 5–16(3–13), 1996.

11. Houseman, G.A., and P. Molnar, Gravitational (Rayleigh-Taylor) instability of a layer with non-linear viscosity and convective thinning of continental lithosphere, *Geophys. J. Int.*, **128**, 1, 125–156, 1997.

12. Dobretsov, N.L., Permo-Triassic magmatism and sedimentation in Eurasia as expression of a superplume, *Dokl. RAN*, **354**, 2, 220–223, 1997.

13. Yarmolyuk, V.V., V.I. Kovalenko, and M.I. Kuz'min, The North Asian superplume in the Phanerozoic: magmatism and deep-level geodynamics, *Geotektonika*, 5, 3–29, 2000.

14. Dobretsov, N.L., Mantle plumes and their role in the formation of anorogenic granitoids, *Geologiya i Geofizika (Russian Geology and Geophysics)*, **44**, 12, 1243–1261(1199–1218), 2003.

15. Yarmolyuk, V.V., and V.I. Kovalenko, Geodynamic settings of batholith formation in the Central Asian fold belt, *Geologiya i Geofizika (Russian Geology and Geophysics)*, **44**, 12, 1305–1320(1260–1274), 2003.

16. Khain, V.E., Pseudosubduction and its role in the development of orogenic belts, in *Tectonics and geodynamics of continental lithosphere. Vol. 2* [in Russian], 270–271, Geos, Moscow, 2003.

17. Vladimirov, A.G., Main factors controlling magmatism in collision geodynamic settings, in *Proceedings of All-Russian Scientific Conference "Petrology of magmatic and metamorphic complexes". Vol. 1* [in Russian], 177–181, Tomsk, 2002.

18. Khanchuk, A.I., L.M. Parfenov, G. Badarch, et al., Geodynamic map of Northeastern Asia, in *Tectonics and metallogeny of Central and Northeastern Asia. Abstracts of International Conference* [in Russian], 15–17, Izd-vo SO RAN, filial "Geo", Novosibirsk, 2002.

19. Sengör, A.M.C., Plate tectonics and orogenic research after 25 years: synopsis of a Tethyan perspective, *Tectonophysics*, **187**, 315–344, 1991.

20. Mossakovsky, A.A., S.V. Ruzhentsev, S.G. Samygin, and T.N. Kheraskova, Central Asian Fold Belt: geodynamic evolution and history of formation, *Geotektonika*, 6, 3–33, 1993.

21. Sokolov, S.D., V.S. Oksman, and G.E. Bondarenko, Accretionary and collision fold belts, in *Proceedings*

of the Meeting "Tectonics and geodynamics of continental lithosphere". Vol. 2 [in Russian], 201–204, Moscow, 2003.

22. Dobretsov, N.L., R.G. Coleman, and N.A. Berzin (Eds.), Geodynamic evolution of Paleoasian Ocean: Reports of IV Internatoional Symposium on IGCP-283 Project, *Geologiya i Gefiizka (Russian Geology and Geophysics)*, **35**, 7–8, 269 pp., 1994.

23. Izokh, A.E., G.V. Polyakov, A.S. Gibsher, P.A. Balykin, D.Z. Zhuravlev, and V.A. Parkhomenko, High-alumina stratified gabbroids of the Central-Asian fold belt: geochemistry, Sm-Nd isotopic age, and geodynamic conditions of formation, *Geologiya i Geofizika (Russian Geology and Geophysics)*, **39**, 11, 1565–1577(1565–1577), 1998.

24. Jahn Bor-ming, F.Y. Wu F.Y., and B. Chen, Massive granitoid generation in Central Asia: Nd isotope evidence and implication for continental growth in the Phanerozoic, *Episodes*, **23**, 82–92, 2002.

25. Vladimirov, A.G., A.S Gibsher, A.E. Izokh, and S.N. Rudnev, Early Paleozoic granitoid batholiths of Central Asia: extents, sources, and geodynamic conditions of formation, *Dokl. RAN*, **369**, 6, 795–798, 1999.

26. Kovalenko, V.I., V.V. Yarmolyuk, and V.P. Kovach, Sources of Phanerozoic granitoids of Central Asia: Sm-Nd isotope data, *Geokhimiya*, 8, 699–712, 1996.

27. Dewey, J.F., Extensional collapse of orogenes, *Tectonics*, **7**, 1123–1139, 1988.

28. Kopp, M.L., *Structures of lateral extrusion in the Alpine-Himalayan collision belt* [in Russian], 314 pp., Nauchny Mir, Moscow, 1997.

29. Blanco, M.J., and W. Spakman, The *P*-wave velocity structure of the mantle below the Iberian Peninsula: evidence for subducted lithosphere below southern Spain, *Tectonophysics*, **221**, 13–34, 1993.

30. Willett, S.D., and C. Beaumont, Subduction of Asian lithosphere beneath Tibet inferred from models of continental collision, *Nature*, **369**, 642–645, 1994.

31. Dobretsov, N.L., M.M. Buslov, D. Delvaux, et al., Meso- and Cenozoic tectonics of the Central Asia mountain belt: effect of lithospheric plate interaction and mantle plumes, *Int. Geol. Rev.*, **38**, 5, 430–466, 1996.

32. Rosen, O.M., and V.S. Fedorovsky, *Collision granitoids and delamination of the Earth's crust (examples of Cenozoic, Paleozoic, and Proterozoic collision systems)* [in Russian], 188 pp., Nauchny Mir, Moscow, 2001.

33. Ruzhentsev, S.V., V.A. Shvol'man, B.R. Pashkov, and I.I. Pospelov, Tectonic development of the Pamir-Himalayan segment of the Alpine fold belt, in *Tectonics of the Tien Shan and Pamirs* [in Russian], 167–175, Nauka, Moscow, 1983.

34. Budanov, V.I., *Endogenous formations of the Pamirs* [in Russian], 299 pp., Dinish, Dushanbe, 1993.

35. Debon, F., P. Le Fort, D. Dautel, J. Sonet, and J.L. Zimmerman, Granites of western Karakorum and northern Kohistan (Pakistan): a composite mid-cretaceous to Upper Cenozoic magmatism, *Lithos*, **20**, 1, 19–40, 1987.

36. Gansser, A., Facts and theories on the Himalayas, *J. Geol. Soc. India*, **41**, 487–508, 1993.

37. Vladimirov, A.G., Correlation of magmatic events of Late Mesozoic—Cenozoic and problem of geodynamics of Pamirs-Himalayas region, *Dokl. RAN*, **326**, 3, 489–492, 1992.

38. Khain, V.E., *Tectonics of continents and oceans (the year 2000)* [in Russian], 604 pp., Nauchny Mir, Moscow, 2001.

39. Douce, A.E.P., and N. Harris, Experimental Constraints on Himalayan Anatexis, *J. Petrol.*, **39**, 4, 689–710, 1998.

40. Searle, M.P., Emplacement of Himalayan leucogranites by magma injection along giant sill complexes: examples from the Cho Oyu, Gyachung 'Kang and Everest leucogranites (Nepal Himalaya), *J. Asian Earth Sci.*, **17**, 5–6, 773–783, 1999.

41. Arnaud, N.O., Ph. Vidal, P. Tapponier, et al., The high K_2O volcanism of northwestern Tibet: Geochemistry and tectonic implication, *Earth Planet. Sci. Lett.*, **111**, 351–367, 1992.

42. Budanov, V.I., N.I. Volkova, and V.I. Dronov, Palaeogene mugearite-shoshonite volcanism (the Bartang Complex) as a reflection of collisional events in the Pamirs, in *Continental growth in the Phanerozoic: evidence from Central Asia (Abstracts of the IV Workshop IGCP-420, August 5–14, 2002)*, 19–24, Changchun, China, 2002.

43. Titov, A.V., A.G. Vladimirov, V.P. Chupin, and O.N. Mayorova, Evolution of shoshonite-latite melts and conditions of their crystallization (by the example of the Kyzyl-Rabat volcanic structure, South Pamirs), *Dokl. RAN*, **327**, 1, 121–125, 1992.

44. Vladimirov, A.G., S.N. Rudnev, V.P. Chupin, O.N. Maiorova, and Yu.G. Shipitsin, Petrology of highly aluminous granites of the Pamir complex (Southwestern Pamir), *Geologiya i Geofizika (Soviet Geology and Geophysics)*, **29**, 12, 87–95(77–76), 1988.

45. Glebovitsky, V.A., I.S. Sedova, M.S. Dufur, et al., *Evolution of Alpine-type metamorphic belts* [in Russian], 308 pp., Nauka, Leningrad, 1981.

Folded Area, in *Petrology of igneous and metamorphic complexes. Proceedings of the Scientific Conference. Vol. 1* [in Russian], 201–208, Tomsk, 2002.

69. Kuznetsov, Yu.A., *Main types of igneous formations* [in Russian], 392 pp., Nedra, Moscow, 1964.

70. Letnikov, F.A., Magma-forming fluid systems of continental lithosphere, *Geologiya i Geofizika (Russian Geology and Geophysics)*, **44**, 12, 1262–1269(1219–1225), 2003.

71. Sharapov, V.N., and Yu.V. Perepechko, Dynamic characteristics of basite within-plate magmatic facies and formations and 3D models of lithosphere-upper mantle interaction, in *Present-day problems of formational analysis, petrology, and mineralization of igneous complexes (Abstracts of the All-Russian Conference, Novosibirsk, 16–19 April, 2003)* [in Russian], 379–380, Izd-vo SO RAN, filial "Geo", Novosibisrk, 2003.

72. Sharapov, V.N., and Yu.V. Perepechko, Correct mathematical models for melt generation of within-plate basite formations, *ibid.*, 380–381.

Received 14 May 2003