International Geology Review, Vol. 37, 1995, p. 584–600.

Petrotectonic Evolution of the Maksyutov Complex, Southern Urals, Russia: Implications for Ultrahigh-Pressure Metamorphism

V. I. LENNYKH,
Urals Institute of Geology and Geochemistry, Urals Branch, Russian Academy of Sciences, Yekaterinburg, Russia

P. M. VALIZER,
Miass Institute of Mineralogy, Urals Branch, Russian Academy of Sciences, Miass, Russia

RACHEL BEANE, MARY LEECH, AND W. G. ERNST
Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305-2115

Abstract

The Maksyutov Complex consists of two juxtaposed lithotectonic units—Unit #1 of probable Late Proterozoic formation age, and Unit #2, apparently generated in Cambro-Ordovician time. The eclogite-facies metamorphism of Unit #1 occurred prior to 370–380 Ma, when this unit was subjected to blueschist-facies overprinting. Unit #2 displays the effects of a somewhat similar blueschist- or high-pressure greenschist-facies recrystallization, indicating that it may have been metamorphosed contemporaneously with Unit #1. Our field work and geochemical studies have focused on the Sakmara River area. Preliminary conclusions are as follows: (1) Unit #1 was subjected to metamorphic temperatures of 620 ± 70° C and minimum pressures of 1.5 GPa, or 2.7 GPa if the previously reported interpretation of coesite pseudomorphs from similar rocks exposed near the village of Shubino, 75 km to the south (Chesnokov and Popov, 1965), is correct. Peak metamorphic pressures would have reached at least 3.2 GPa if blocky graphite described in this report from a Sakmara River eclogitic mica schist has replaced neoblastic diamond; (2) Unit #2 experienced much lower maximum metamorphic pressures, on the order of 0.5 to 0.6 GPa; (3) Unit #2 was variably but intensely metasomatized, indicating the presence of an aqueous fluid during the Early Devonian blueschist/greenschist-facies metamorphism; (4) tectonic parallelism of the lithostratigraphic units and their bounding sutures, combined with P-T conditions of recrystallization, suggest assembly of the Maksyutov Complex in an intra-oceanic subduction zone. This process was followed by exhumation and suturing against the more easterly Middle Paleozoic unmetamorphosed ophiolitic (oceanic) basement and superjacent calc-alkaline Magnitogorsk island arc. The Late Proterozoic-Ordovician Mugodzhar and Ilmen microcontinents subsequently were thrust beneath the eastern edge of the Devonian Magnitogorsk Arc. Collision of the entire complex with the Ordovician–Lower Carboniferous continental-margin Suvanjak-Sakmara accretionary complex, lying to the west on the Russian Platform, also occurred during Middle Paleozoic time. Finally, (5), the tectonic imbrication of the several units within and adjoining the Maksyutov Complex was itself truncated and deformed into N–S parallelism by postulated Late Paleozoic postcollisional strike-slip movement (Dobretsov et al., in review).

Introduction and Plate-Tectonic Settings

THE HIGH-PRESSURE/ULTRAHIGH-PRESSURE (HP/UHP) metamorphosed Maksyutov Complex, situated in the southern Ural Mountains of Russia, is part of the larger Paleozoic Ural-Mongolian fold-belt system (Sengör et al., 1993). The general geography is presented in the index map of Figure 1. The Urals constitute an elongated N-S belt along the boundary between the easterly Siberian-Kazakhstan-North Tienshan cratons and the westerly Russian Platform (Zonenshain et al., 1984, 1990). As shown in Figure 2, the HP/UHP metamorphic complex is bounded on the east by the steeply east-dipping Main Ural thrust fault, juxtaposing it beneath feebly or unrecrystallized Upper Ordovician–Silurian ophiolites and associated flysch that form the oceanic crustal basement for the Devonian Magnitogorsk calc-alkaline island arc (Puchkov, 1993; Zakharov

0020-6814/95/137/584-17 $10.00

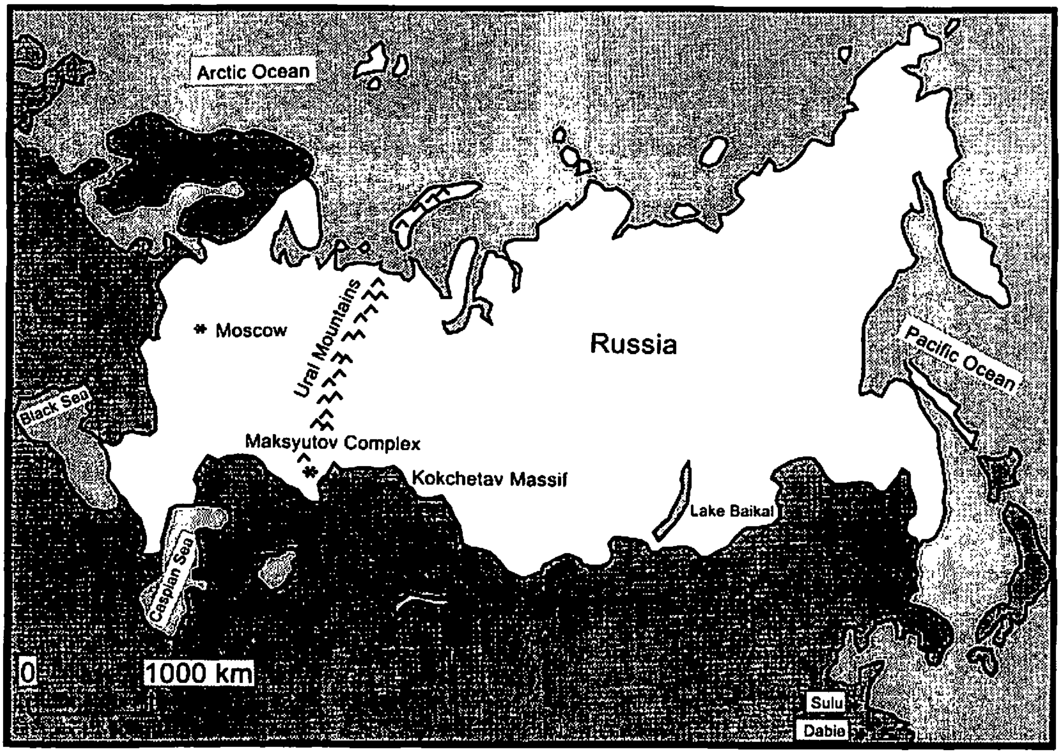


FIG. 1. Index map of Russia showing the location of the Ural Mountain belt, the Maksyutov and Kokchetav HP/UHP metamorphic complexes, and the Chinese Dabie and Sulu HP/UHP localities.

and Puchkov, 1994). On the west, the Maksyutov Complex tectonically underlies the Lower Paleozoic Suvanjak continental-margin sedimentary terrane. Farther west, Upper Ordovician-Lower Carboniferous clastic-wedge deposits of the Sakmara zone are draped along the edge of the Russian Platform and its frontal basin (Peyve et al., 1977).

The Shubino Village locality (Fig. 2) of the Maksyutov Complex represents the first locality where quartz intergrowths encapsulated in radially fractured garnets from eclogites were interpreted as coesite pseudomorphs (Chesnokov and Popov, 1965). This report was not widely read; moreover, most petrologists remained unconvinced by the textural interpretation. Thus the potential significance of this occurrence went unrecognized. The possibility of a return to the surface by ultrahigh-pressure metamorphic terranes was accepted only after independent discoveries of relict coesite in the Dora Maira Massif of the Western Alps (Chopin, 1984) and in the Western Gneiss Region of Norway (Smith, 1984); relict coesite ultimately was reported from quartz + almandine + jadeite rocks in the Maksyutov Complex (Dobretsov and Dobretsova, 1988). Thus far we have been unable to duplicate this observation, but, if it is correct, the presence of neoblastic coesite would require that the eclogitic unit have undergone UHP metamorphism at subduction-zone depths exceeding 90 km.

The Maksyutov Complex (Lennykh, 1977; Moskovchenko, 1982; Dobretsov and Dobretsova, 1988; Valizer and Lennykh, 1988) consists of two main superimposed tectonic units, which together constitute a composite structural slab approximately 5 to 10 km thick, and about 150 km or more in length (Fig. 2). These lithotectonic units exhibit contrasting mineral parageneses: the polymetamorphic eclogitic mica schist, Unit #1, underwent HP/UHP metamorphism, partially retrograded to blueschist assemblages, whereas the meta-ophiolite, Unit #2, was subjected only to blueschist or relatively high-pressure greenschist-facies

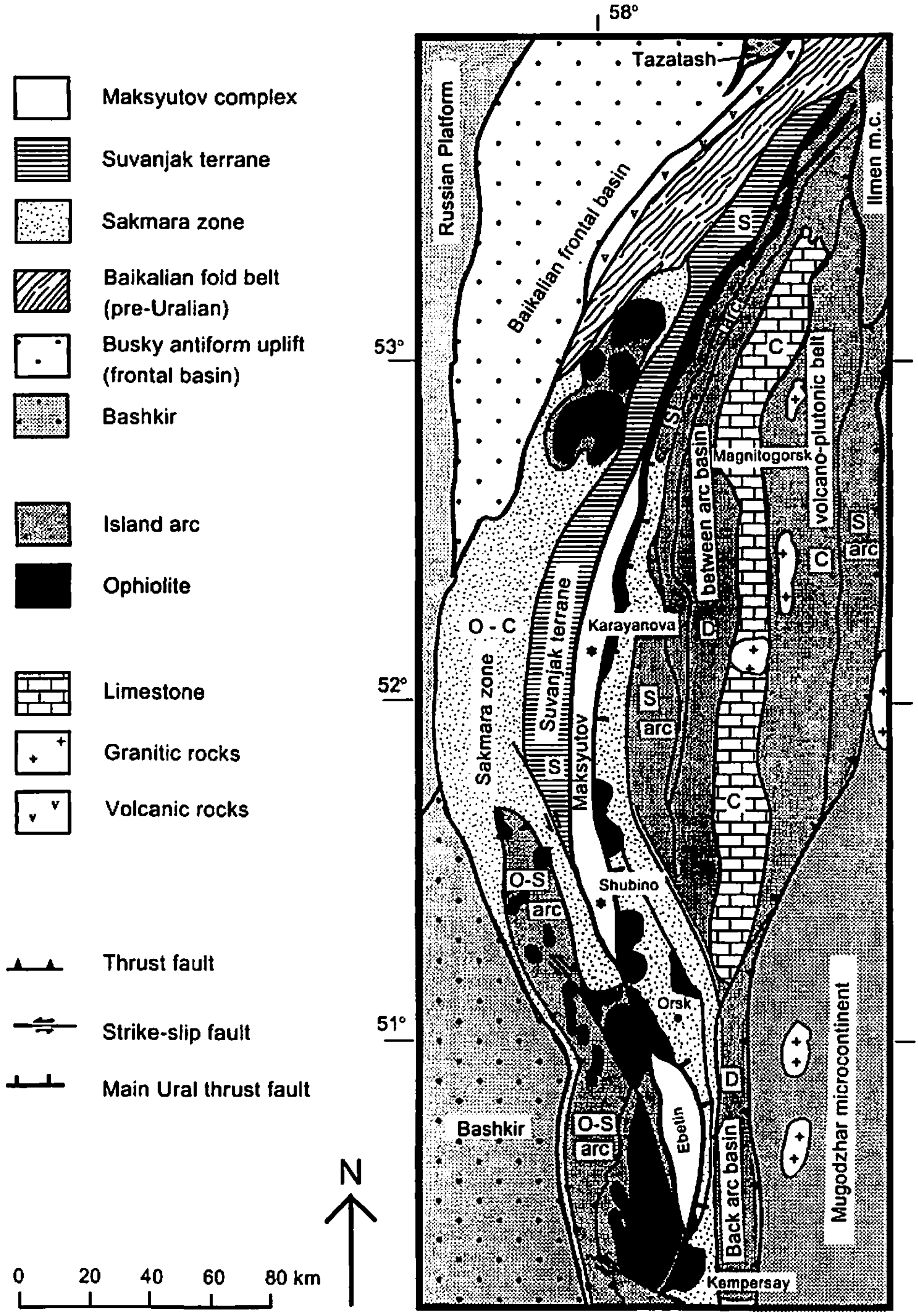


FIG. 2. Geology of the Maksyutov Complex, southern Urals, somewhat modified by Dobretsov et al. (in review), and Beane et al. (1995), from primary data by Sobolev (1975), Peyve et al. (1977), Lennykh (1977), Moskovchenko (1982), Valizer and Lennykh (1988), Dobretsov and Dobretsova (1988), and compiled by R. G. Coleman. The former village of Karayanova lies within the presently studied Sakmara River area. The original report of coesite pseudomorphs by Chesnokov and Popov (1965) was from Maksyutov Complex rocks located 75 km south near the village of Shubino.

metamorphism (Beane et al., 1995). The eclogitic mica schist unit possibly represents part of a disrupted craton of Late Proterozoic (1150 to 1200 Ma) formational age, based on U-Pb zircon ages from metavolcanics (Dobretsov and Sobolev, 1984); it consists of supracrustal lithologies—dominantly micaceous, quartzitic ± graphitic metasediments—with interlayered boudins and tectonic blocks of mafic + ultramafic compositions. High-pressure/ultrahigh-pressure metamorphic mineral assemblages for the various rock types of this unit, as described by Dobretsov et al. (in review), consist of: (a) quartz (coesite pseudomorphs) + garnet + omphacite + rutile + zoisite; (b) jadeite + quartz + garnet + kyanite + paragonite; (c) garnet + omphacite + barroisite; and (d) garnet + glaucophane ± lawsonite. Recorded peak conditions of the eclogitic phase assemblages were 1.5 to 2.7 GPa at about 550 to 690° C. Retrogression involving production of garnet-glaucophane schists, then greenschists, suggests a clockwise P-T trajectory, with the late-stage blueschist/greenschist assemblages produced at approximately 0.5 to 0.6 GPa (Beane et al., 1995). The ophiolitic unit may be of Cambro-Ordovician formation age, provided it is related to analogous rocks constituting the serpentinite-rich melanged oceanic basement of the adjacent Magnitogorsk island arc. The Maksyutov ophiolitic unit is characterized by sheets of serpentinite containing blocks of lawsonite-bearing meta-igneous rock. Dobretsov et al. (in review) also report the occurrence of rare hornblendite inclusions. Tabular lawsonite porphyroblasts typically have been completely replaced by clinozoisite and/or white mica.

All rocks in Unit #1 of the Maksyutov Complex exhibit the effects of multiple stages of deformation and recrystallization. Recumbent folds and shear zones within the eclogitic portion of the complex developed during and after the HP/UHP metamorphic event. The time of this subduction-zone metamorphism, however, is poorly constrained: it evidently preceded the subsolidus recrystallization of Unit #2 ophiolites, and possibly occurred prior to both the igneous generation of Unit #2 and the structurally overlying, virtually unmetamorphosed Ordovician-Silurian ophiolitic basement of the juxtaposed Devonian Magnitogorsk calc-alkaline island arc on the east. Metamorphism of Unit #2 also apparently pre-dated the suturing of the complex against the essentially unmetamorphosed Early-Middle Paleozoic Suvanjak and Sakmara terranes on the west.

The UHP recrystallization of the Maksyutov Complex may be related to the inferred Early Paleozoic eastward descent and collision of a microcontinental fragment of the Russian craton with a west-extending salient of the Kazakhstan-North Tienshan microcontinental assembly on the southeast (Shatsky et al., 1995) or, more probably, its subduction beneath an intra-oceanic arc. The terminal stage of penetrative deformation and blueschist/greenschist facies annealing of Maksyutov Unit #1 may have occurred at approximately 380 Ma ($^{40}Ar/^{39}Ar$ data of Matte et al., 1993). New ages obtained for white micas from eclogite and quartz-mica schist using $^{40}Ar/^{39}Ar$ methods correspond closely to the ages previously determined by Matte et al. (1993). As shown in Figure 3, the weighted mean plateau, isochron, and total fusion ages for recently analyzed phengites agree, indicating a 375.5 ± 1.7 Ma crystallization age for phengite from the eclogite, and a 365.5 ± 1.7 Ma age for white mica from the quartzite. The cooling ages of the phengites probably date a period in the exhumation history of the eclogites and quartz-mica schists characterized by attainment of the approximately 350° C closure temperature for white mica (McDougall and Harrison, 1988), not necessarily the time of deformation and blueschist/greenschist-facies recrystallization. This thermal relaxation was roughly contemporaneous with the subduction and accretion of intervening intracontinental ocean crust as young as Early Devonian (397 ± 20 Ma age of extrusion, Sm-Nd bulk-rock isochron measured by Edwards and Wasserburg, 1985). Of course, our dates indicate only the time in the exhumation process when the pre-Devonian HP/UHP Unit #1 eclogitic mica schists reached midcrustal levels and last re-equilibrated isotopically at about 350° C. Unit #2 displays a somewhat similar blueschist/greenschist-facies recrystallization and possesses foliations and lineations compatible with the late penetrative deformation recorded in the eclogitic mica schist unit, suggesting that Unit #2 also participated in the 370 to 380 Ma metamorphic event.

The Late Proterozoic-Ordovician Mugodzhar and Ilmen microcontinents consist of migmatites and granulites that were thrust beneath

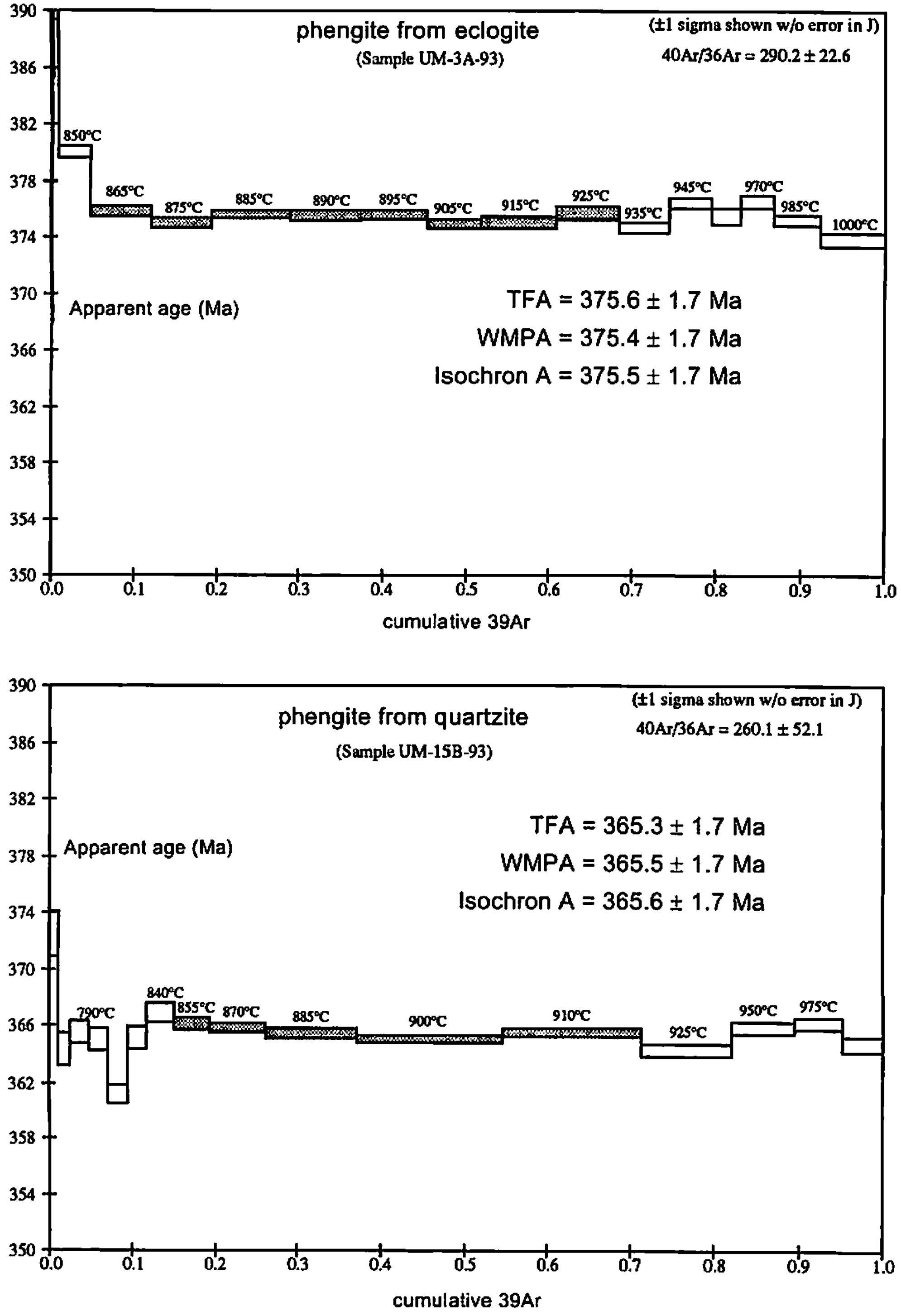


FIG. 3. New argon spectra for phengite from the Maksyutov Complex measured at the Stanford Geochronology Laboratory. Abbreviations: TFA = total fusion age; WMPA = weighted mean plateau age; Isochron A = isochron age.

the eastern edge of the Devonian Magnitogorsk island arc, which itself tectonically overlies the Maksyutov Complex. Thus, by this stage, subduction polarity had reversed, and the intervening oceanic-crust-capped lithosphere located immediately to the east of the Devonian–Carboniferous island arc was consumed during westward underflow. Continuing deformation of the Maksyutov Complex was related to conjectured Late Paleozoic left-lateral strike-slip movement along the Main Uralian fault (Dobretsov et al., in review). This large-scale sinistral motion could reflect a change in Paleozoic lithospheric plate kinematics that eventually led to the surface exposure of the subducted but buoyant Maksyutov HP/UHP continental crustal rocks.

Petrology and Structural Geology

General statement

As previously noted, two fault-bounded lithotectonic entities constitute the Maksyutov Complex—a layered eclogitic mica schist, Unit #1, and a structurally juxtaposed intermediate greenschist/blueschist assembly, Unit #2. Geologic relations near the former village of Karayanova along the Sakmara River are shown schematically in Figure 4. This study area lies 75 km north of Shubino Village, where coesite pseudomorphs first were described (Chesnokov and Popov, 1965).

Locally, Unit #2 appears to tectonically overlie Unit #1 (Lennykh, 1977; Valizer and Lennykh, 1988), but this interpretation may not be secure because top indicators are lacking in these intensely recrystallized rocks. The portion of Unit #1 adjacent to Unit #2 consists of extremely well-bedded, micaceous orthoquartzites of the Yumaguzinskaya subunit. A serpentinite-matrix melange containing numerous metasomatized, chiefly mafic, blocks and pods is situated within Unit #2, but in most cases lies near the contact with eclogitic mica schist and Yumaguzinskaya subunits. Along the Sakmara River, the Maksyutov Complex is characterized by remarkable continuity of compositional layering and invariant, layer-parallel schistosity. Both Yumaguzinskaya and serpentinite melange subunits occur near the contact between Units #1 and #2, but are discontinuous on a regional scale.

Unit #1

Well-laminated, garnetiferous quartz-mica schists make up most of the eclogite-bearing unit. Distinctive black graphitic quartzites and quartz-jadeite metagraywackes are minor but stratigraphically important components in the metaclastic section. Conformable mafic eclogite layers, lenses, and boudins are interstratified with the metasedimentary rocks. Of roughly basaltic composition, most eclogites contain important amounts of white mica in addition to garnet + omphacite + Na-amphibole + rutile. Distinct compositional layering gives the eclogitic horizons a laminated aspect almost as pronounced as that of the enclosing garnet-bearing pelitic schists. Although the thicker eclogite bodies have behaved competently during shearing, most exhibit the foliation of the enclosing paraschists and have been penetratively deformed. Thinner metamorphic layers show the effects of more extreme boudinage, and, in some localities, isolated lenses and blocks of micaceous eclogite 10 cm to 2.5 m in length are encased in garnetiferous mica schist. Coeval and/or later sodic amphibole is an accessory phase in some of the paraschists, but ranges from absent to high concentrations in the eclogites. Metamorphic mineral assemblages, now variably overprinted, attest to HP/UHP prograde metamorphic conditions. Multiple stages of deformation are present throughout this lithotectonic unit.

Yumaguzinskaya subunit

Where present, the distinctive white quartzite of the Yumaguzinskaya subunit ranges up to 300 m in thickness, but is generally thinner. Phengitic mica is an important neoblastic phase and in various horizons may be joined by chlorite, stilpnomelane, or, more rarely, blue amphibole. Relics of eclogitic assemblages are not preserved in this blueschist/greenschist-facies assemblage, possibly because of inappropriate bulk-rock compositions, complete retrograde reaction, or the lack of attendance of HP/UHP conditions. The Yumaguzinskaya member exhibits the effects of multiple stages of deformation in terms of disharmonic, isoclinal folds in several orientations as well as late, broad, open folding. The contact between the eclogitic mica schist and the Yumaguzinskaya is subparallel to the foliation and suggests a low-angle

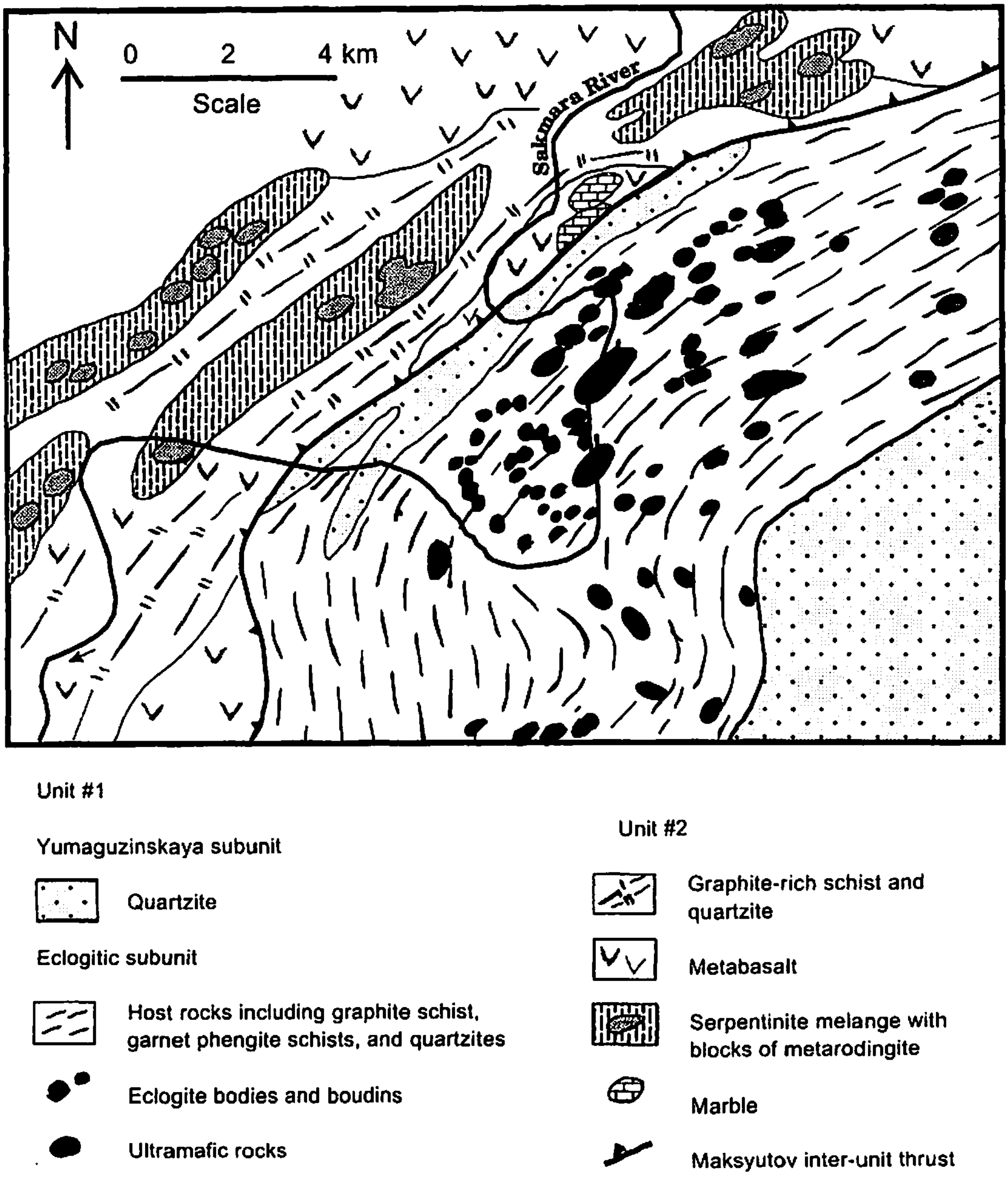


FIG. 4. Local geology of the Sakmara River area, Maksyutov Complex, southern Urals, from Valizer and Lennykh (1988, Fig. 39) and ongoing collaborative work.

thrust contact that probably juxtaposed the two subunits after the HP/UHP metamorphic event that produced the eclogites. However, because of strong bulk-chemical contrasts in the lithologies, the Yumaguzinskaya subunit and Unit #1 *sensu stricto* might be isofacial, in which case their mutual contact equally well could be an unconformity.

Unit #2

A series of interstratified, medium- to coarse-grained granoblastic calcite marbles, black graphitic quartzites, quartz-mica paraschists, greenstones, and microgabbros make up Unit #2. Lithologies of metabasaltic composition include neoblastic mineral assemblages consisting of albite + epidote + chlorite + actinolite + sphene ± lawsonite. The unit is penetratively deformed, but much less intensely than Unit #1. Bedding-plane cleavage in Unit #2 parallels that in the eclogitic mica schist. Physical conditions were transitional between those of the greenschist and blueschist metamorphic facies, judging from the crystallization of lawsonite, combined with the absence of sodic amphibole and/or sodic pyroxene.

Serpentinite metamelange

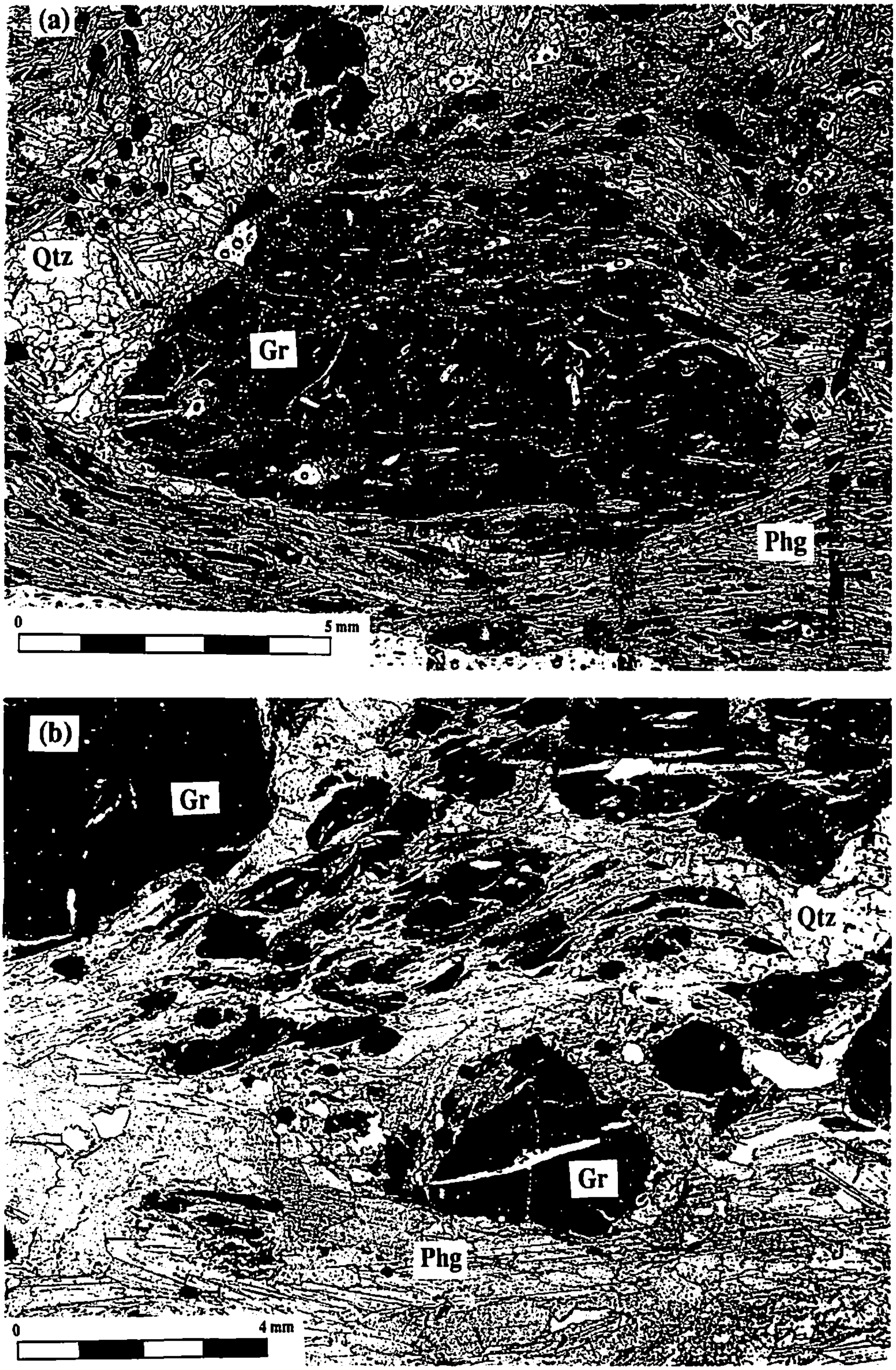
The discontinuous serpentinite-matrix melange consists dominantly of antigorite, with veins, sprays, and irregular stringers of later talc crosscutting the serpentinite. Patchy, "black-wall" rinds of chlorite ± actinolite ± talc separate included country-rock blocks from the ultramafic host, and attest to chemical reaction between chemically incompatible rock types. A variety of inclusions are present in the metamelange. Protoliths, now extensively altered, include blocks and slabs of metabasalt, metagabbro, and quartz-mica schist presumably derived from Unit #2; fragments of the Yumaguzinskaya subunit are not present in the serpentinized peridotite. All inclusions have been variably altered by metasomatic reaction with the enclosing antigorite schists and, accordingly, have been relatively enriched in Mg + Al + Ca and depleted in alkalis + silica. Zoisite ± white mica pseudomorphs after lawsonite are abundant. The foliation of the serpentinite matrix parallel to layering in both Units #1 and #2 and the presence of antigorite rather than lizardite or chrysotile indicate a metamorphic overprint of this melange.

Structural geology

All units and subunits have been penetratively deformed, but Unit #1 clearly has been more intensely sheared during and after HP/UHP metamorphism than the substantially lower-pressure Unit #2. Compositional layering and schistosities of rock types from the eclogitic unit and most of the ophiolitic unit dip to the northwest or southeast, folded about gently plunging fold axes that trend NE-SW. The tectonic juxtaposition of Units #1 and #2 allowed the apparently isofacial overprinting of blueschist/greenschist-facies metamorphism—retrograde for Unit #1, but prograde for Unit #2. Tectonic imbrication also is suggested by the presence of several harzburgite pods as tectonic blocks in Unit #1 *sensu stricto* (not in the Yumaguzinskaya subunit), and by the abundance of well-foliated serpentinite in the metamelange of Unit #2.

The N-S-trending eastern tectonic contact of the Maksyutov Complex with the unmetamorphosed Upper Ordovician-Silurian ophiolites and overlying Devonian island arc represents the Main Ural thrust fault (Fig. 2). This break dips eastward under the Magnitogorsk island arc (Echtler et al., 1995). On the west, the Maksyutov Complex is juxtaposed against and tectonically underlies the Lower Paleozoic Suvanjak terrane and the more westerly, Upper Ordovician-Lower Carboniferous Sakmara clastic-wedge sediments of the accreting East European (Russian) craton. Thus the Maksyutov Complex appears to represent a composite slab that roots to the east, bounded above (and doubtless below) by profound structural discontinuities. Its internal fabric predominantly strikes northeast and most structural elements are inclined to the west. Clearly, slab-bounding faults truncate the internal structures of the Maksyutov composite terrane. Based on outward-inclined foliations and compositional layering roughly symmetrical to axial portions of the complex, the metamorphic terrane has been interpreted as an antiformal structure, termed the Uraltau ridge (Brown et al., 1995).

Because the N-trending Maksyutov Complex is structurally terminated and flanked on both west and east by younger accretionary and island-arc massifs, it seems likely that the conjectured subduction event responsible for the studied HP/UHP metamorphism and perhaps the later (Early Devonian ?) blueschist/greenschist-facies recrystallization took place within a long-lived intra-oceanic subduction zone prior to exhumation and collision with the more easterly ophiolitic island arc, followed by suturing against the Russian Platform and its marginal Suvanjak-Sakmara accretionary prism on the west. The N-S trend of the tectonic contacts bounding and truncating the Maksyutov Complex suggests important post-suturing strike-slip (Dobretsov et al., in review).


(a)
Qtz
Gr
Phg
0
5 mm
(b)
Gr
Qtz
Gr
Phg
0
4 mm

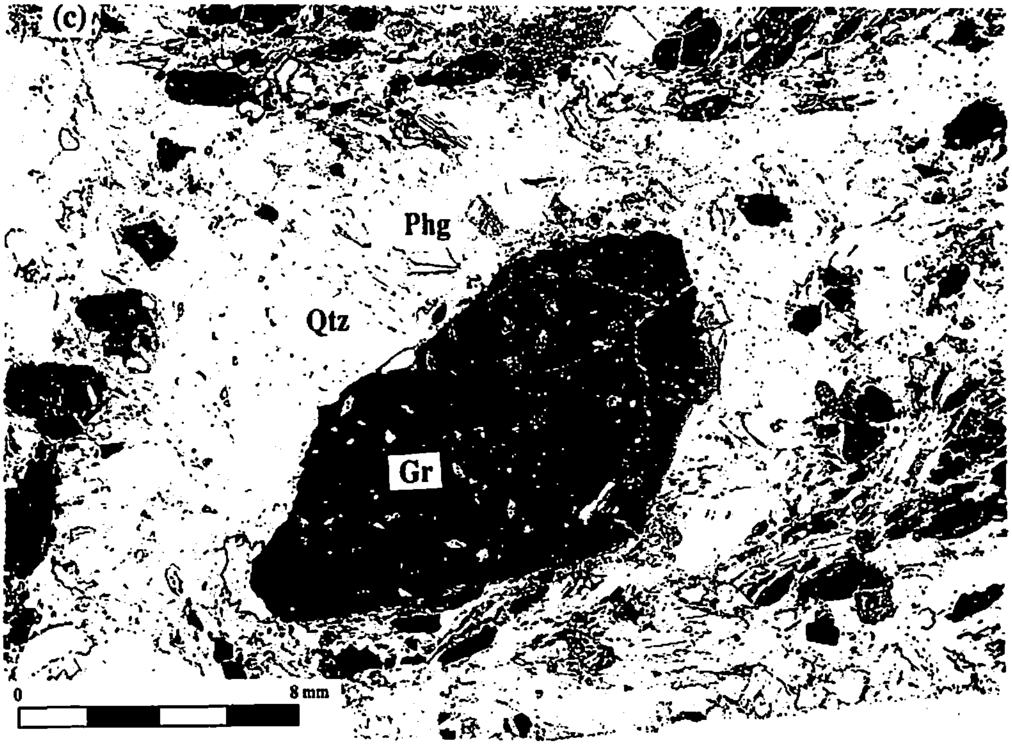


FIG. 5 (see also facing page). Textures of blocky graphite grains from quartz + white mica + rutile ± garnet ± clinozoisite ± zircon ± sphene paraschist from Unit #1, Sakmara River locality. Abbreviations: Gr = graphite; Phg = phengite; and Qtz = quartz.

Mineral Paragenesis of Unit #1

Three stages of metamorphism (M_{1-3}) of mafic rocks from Unit #1 were observed in hand specimens and thin sections, and are reported here: M_1 (eclogite facies), garnet (Alm_{55-60} Prp_{22-28} Grs_{16-20}) + omphacite (Jd_{46-56}) + phengite (Si ~3.50) + rutile; M_2 (blueschist facies), garnet + crossite-glaucophane ± lawsonite + white mica + clinopyroxene ± clinozoisite; and M_3 (greenschist facies), epidote + chlorite + white mica ± albite ± actinolite ± sphene. A minimum peak pressure for eclogite-facies metamorphism is ~1.5 GPa, as determined by the jadeite content of omphacite using the sliding equilibrium ab = jd + qtz (Holland, 1980). The nominal equilibrium temperature for such eclogite-facies metamorphism at 1.5 GPa P_{total} is ~600° C, computed employing Fe-Mg exchange thermometry between coexisting clinopyroxene and garnet (Beane et al., 1995). The calculated equilibrium temperature for eclogite from the Shubino Village locality would be approximately 680° C, assuming the presence of coesite, as reported by Chesnokov and Popov (1965) and Dobretsov and Dobretsova (1988).

Graphite-bearing mica schist (Sample M-16) from near the former village of Karayanova (see Fig. 2) contains 40% white mica, 38% graphite, 19% quartz, 1% rutile, and <1% feldspar, iron oxide, and zircon. A single cleavage, defined by aligned white mica and elongated graphite flakes, wraps around large, subangular, blocky graphite aggregates (up to 1.3 × 1.0 cm). These aggregates contain straight-aligned inclusions of white mica and quartz that are subparallel to the cleavage; graphite preserves a crenulation cleavage in the aligned inclusions. Pressure shadows containing quartz and coarse-grained phengite have developed around the subangular, centimeter-sized graphite aggregates, as discussed below.

Blocky Granite in Unit #1—Possible Pseudomorphs After Diamond?

Thin layers of unusually coarse-grained graphitic quartz + white mica (Si ~3.3 to 3.5) ± garnet ± clinozoisite ± zircon, sphene, and rutile-bearing paraschists of Unit #1 are distinctive by virtue of the remarkable concentration of graphite in these strata—on the order of 30 to 50 vol% in some specimens. Clearly the protolithic strata must have been extremely rich in carbon. Its organic nature is indicated by strongly negative $^{13}C/^{12}C$ values (unpubl. data). The rocks have been multiply deformed and intensely sheared, as attested to by the strong compositional layer-parallel alignment of phengite and some graphite flakes. These phases lie in the plane of foliation defined by the eclogitic and blueschist/greenschist overprint.

Other graphite grains, however, possess an extraordinary external morphology, being roughly blocky, tabular, or equant in outline. Petrographic studies demonstrate that these *blocky graphite crystals* are not simply molded around precursor phases of different mineralogy, but are 100% carbon. Equally surprisingly, the foliation planes defined by the white mica and platy graphite described above bend around the blocky carbon, and leave quartz-rich pressure shadows, as if the latter had behaved as rigid, competent crystals during HP/UHP ductile deformation. Textural relations are illustrated in Figure 5. What could have been the nature of such crystals? Although their blocky appearance does not evoke the image of newly grown diamond in particular, their rigidity during deformation and elemental composition suggests cubic carbon as a logical precursor. If so, the neoblastic diamond grew in the solid state when the carbonaceous quartz-mica schists were subjected to ultrahigh pressures, close to but below solidus temperatures. Subsequently, the putative diamond has been totally back-reacted due to retrograde metamorphism. Accordingly, investigation of the blocky graphite from the Maksyutov Unit #1 paraschists is continuing: studies include $^{13}C/^{12}C$ isotope geochemistry, petrographic examination of serial thin sections, and SEM imaging of carefully disaggregated materials (see Pearson et al., 1995).

Provided this speculation is correct, Unit #1 of the Maksyutov Complex must have been subjected to minimal pressures of approximately 3.2 GPa, even more than the 2.7 GPa that would be required to explain the pseudomorphs after coesite, described by Chesnokov and Popov (1965). Phase relations are depicted in Figure 6. At the least, 1.5 GPa seems to be required by mineralogic thermobarometric studies of the eclogite (Beane et al., 1995; Dobretsov et al., in review). As is evident from other UHP belts—such as the Kokchetav, Dora Maira, Western Gneiss Region, and Dabie-Sulu terranes—rather similar pressures have been verified elsewhere in continental collision zones (Ernst and Peacock, in press; Liou et al., in press).

Mineral Paragenesis of Unit #2

Unit #2 of the Maksyutov Complex consists primarily of metabasalt, chlorite schist, stilpnomelane schist, graphitic quartzite, and lenses of serpentinite metamelange. The latter possess a matrix of antigorite serpentinite and include blocks of metasomatically altered igneous rocks, largely metagabbro, graphitic quartzite, metagraywacke, and metabasalt. Some metasomatized rocks exhibit well-defined mineralogic zoning from the contact with the serpentinite to the core, as follows: (1) chlorite; (2) chlorite and lawsonite; and (3) grossular + chlorite ± lawsonite. Blocks of altered meta-igneous rock tend to be heterogeneous, reflecting the capricious nature of metasomatic fluids. The minerals of these inclusions vary, consisting of garnet ($Grs_{35\text{-}55}$ Prp_{02} $Alm_{33\text{-}55}$ $Sps_{02\text{-}50}$) + lawsonite + chlorite ± epidote-clinozoisite ± albite ± white mica ± clinopyroxene ± actinolite ± graphite ± sphene ± apatite ± chromite. Lawsonite tablets up to 5 cm in length have been completely pseudomorphosed by clinozoisite, white mica, and garnet. Garnets are typically zoned, with Alm and Grs components increasing and Sps decreasing from core to rim.

The serpentinite metamelanges are hypothesized to have formed by: (1) tectonic inclusion of blocks of mafic and felsic rocks in precursor solid-state peridotites; (2) production of chemically altered rocks by Ca-metasomatism during serpentinization of the enclosing ultramafics; (3) possible olistostromal emplacement or tec-

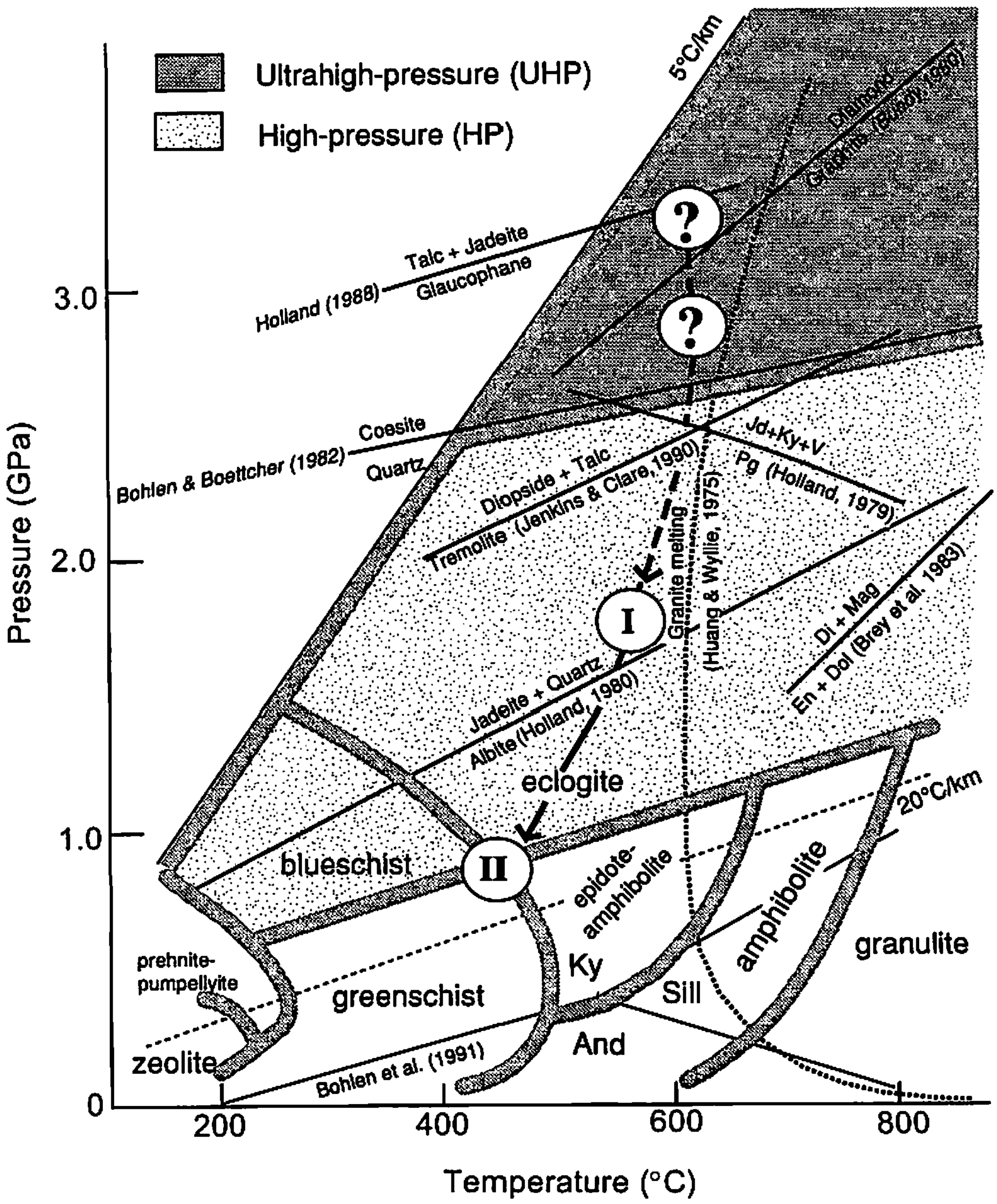


FIG. 6. Petrogenetic grid for high- and ultrahigh-pressure metamorphic P-T environments, modified from Liou et al. (1994). Experimentally determined phase equilibria for end-member systems also are indicated. The facies boundaries are shown for crustal conditions after Spear (1993). Estimated conditions of metamorphism for the eclogitic mica schists and the Early Devonian blueschist/greenschist-facies recrystallization are indicated, along with minimum P-T values required if the tentative interpretations of neoblastic coesite and diamond are correct.

tonic insertion of melanges within Unit #2 rocks; (4) subduction of Unit #2, resulting in the HP metamorphism of melanges and crystallization of lawsonite and associated mineral assemblages, probably concurrent with blueschist-facies retrogression of Unit #1; and (5) exhumation and greenschist-facies overprint (lawsonite replacement).

Tentative Petrotectonic Conclusions

Although field work only recently has been completed, and laboratory studies are in progress, several conclusions appear reasonable. (1) Unit #1 was subjected to minimum metamorphic pressures of at least 1.5 GPa—2.7 GPa if the interpretation of pseudomorphic coesite is correct, or 3.2 GPa if blocky graphite represents original neoblastic diamond. (2) Blueschist/greenschist-facies conditions, possibly at 370 to 380 Ma, attended progressive metamorphism of Unit #2 and the retrogression of Unit #1. (3) Unit #2 has been variably metasomatized, suggesting at least intermittent presence of an active aqueous fluid during recrystallization; this conclusion is supported by the presence of H_2O-bearing minerals that typify the blueschist/greenschist-facies overprinting. (4) The tectonic parallelism of all lithostratigraphic units and the E-dipping bounding Main Uralian suture, combined with HP/UHP conditions of recrystallization and available geochronologic data, argue for Silurian or older (Unit #1) and Early Devonian (Units #1 and #2) intra-oceanic subduction-metamorphism events. Underflow evidently alternated with periods of terrane ascent followed by final exhumation. In Late Devonian time, the Maksyutov terrane amalgam collided with the younger, more easterly, unrecrystallized ophiolitic basement + calc-alkaline island arc, followed by Carboniferous suturing of the terrane complex against the accretionary complex of the Russian Platform on the west. During this same period, the Ilmen and Mugodzhar microcontinents were accreted on the eastern side of the Magnitogorsk Arc through westward underflow and consumption of the intervening oceanic-crust-capped lithosphere (Zonenshain et al., 1984). Finally (5), the structural imbrication of the various units within and bounding the Maksyutov Complex were partially excised and sheared into N-S alignment by a hypothesized Late Paleozoic postcollisional strike-slip motion (Dobretsov et al., in review).

Several stages in a provisional plate-tectonic scenario for the southern Urals are illustrated schematically in Figure 7. The proposed lithotectonic evolution is rather similar to that proposed by Matte et al. (1993), except that we regard the time of generation of the HP/UHP mineral assemblages of Unit #1 as pre-Early Devonian—possibly Early Paleozoic. It also should be noted that this plate-tectonic model for development of the Maksyutov Complex requires that Unit #1 tectonically overlie Unit #2 during terrane accretion, and that their internal tectonic contact dip eastward subparallel to the Main Uralian thrust fault; furthermore, the scenario does not explain the antiformal nature of the UHP/HP terrane itself, nor the W-dipping adjacent Suvanjak and Sakmara superjacent section. Another tectonic alternative is discussed below.

A schematic cross-section is presented as Figure 8, modeled after Matte et al. (1993), Brown et al. (1995), and Echtler et al. (1995). In simplified fashion, it depicts the principal geologic features of the southern Urals collage in topologically correct position; constraints include the Main Ural thrust fault, the Sakmara continental-margin sediments onlapping both the Russian Platform and the Suvanjak + Maksyutov amalgamated assembly (the former tectonically emplaced over the latter), and a structurally higher Maksyutov Unit #2 in normal fault contact over Unit #1. The size of the HP/UHP composite terrane is exaggerated for clarity. The antiformal core of the Maksyutov Complex appears to have been produced by the westward ramp emplacement of the Uraltau ridge—possibly the hypothesized Russian microcontinental fragment that was subducted along with the associated Maksyutov Unit #1 cover series; both of these entities would have been subjected to HP/UHP recrystallization. The ramp-induced folding could have been responsible for formation of the marginal syncline developed in the Sakmara strata to the west, as well as the westward vergence of folds (Matte et al., 1993; Brown et al., 1995). The return of Unit #1 from mantle depths toward mid-crustal levels must have occurred before or during its juxtaposition against overlying Unit #2, and the composite terrane ascended relative to the essentially unmetamorphosed Suvanjak terrane. Westward relative movement of the Uraltau basement sliver must have been a very late (Late Paleozoic?) event in the evolution of the orogenic belt for it to have caused the open folding illustrated in Figure 8.

As a cautionary note, we observe that if the eclogitic mica schists of Unit #1 were recrystallized in Early Paleozoic time and stored at

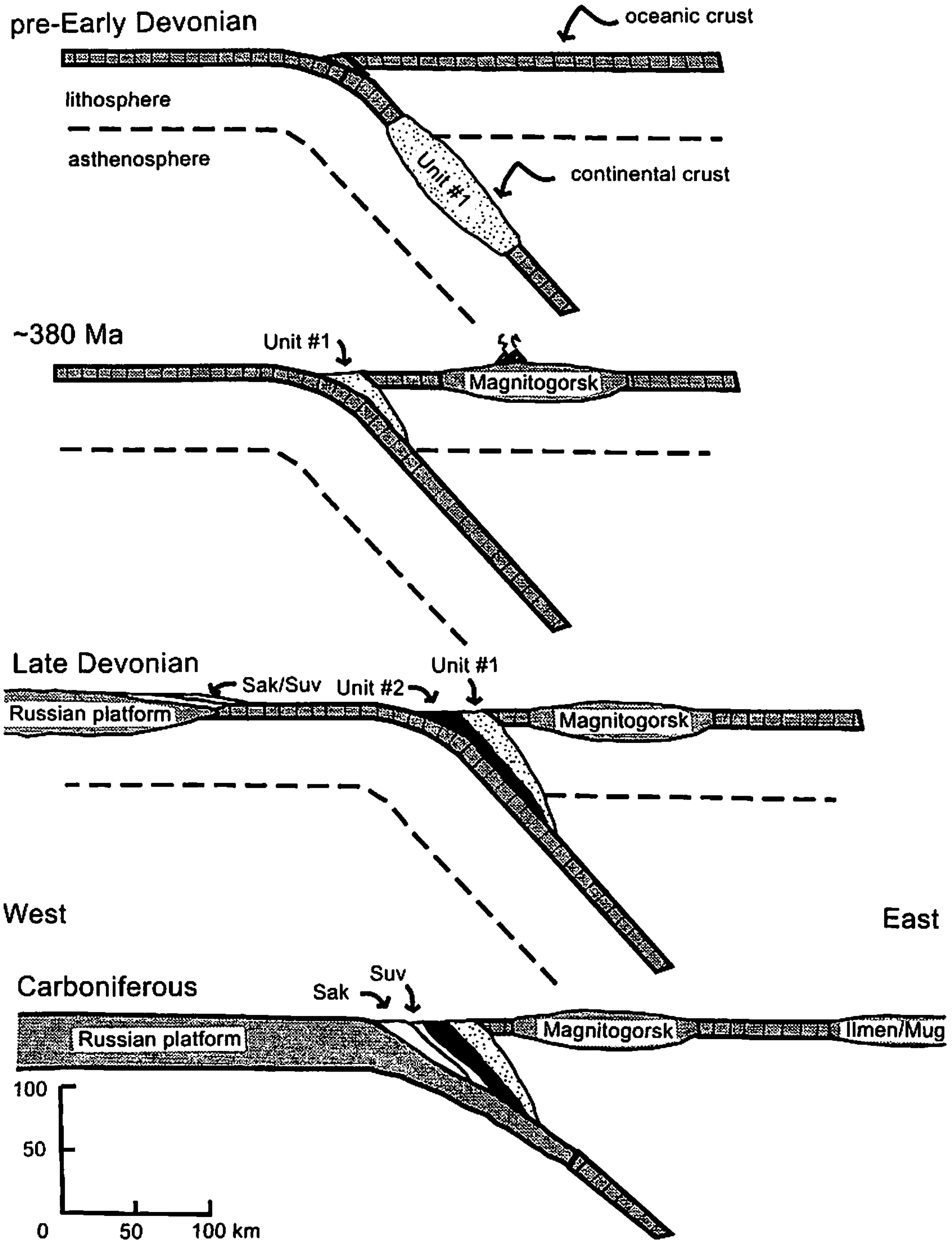


FIG. 7. Speculative plate-tectonic evolution of the southern Urals, approximately to scale, with special emphasis on the Maksyutov Complex, Units #1 and #2. Abbreviations: Ilmen/Mug = Ilmen and Mugodzhar microcontinental blocks; Sak = Sakmara clastic-wedge (miogeoclinal ?) terrane; Suv = Suvanjak continental-margin (eugeoclinal ?) terrane. For discussion, see text and Matte et al. (1993).

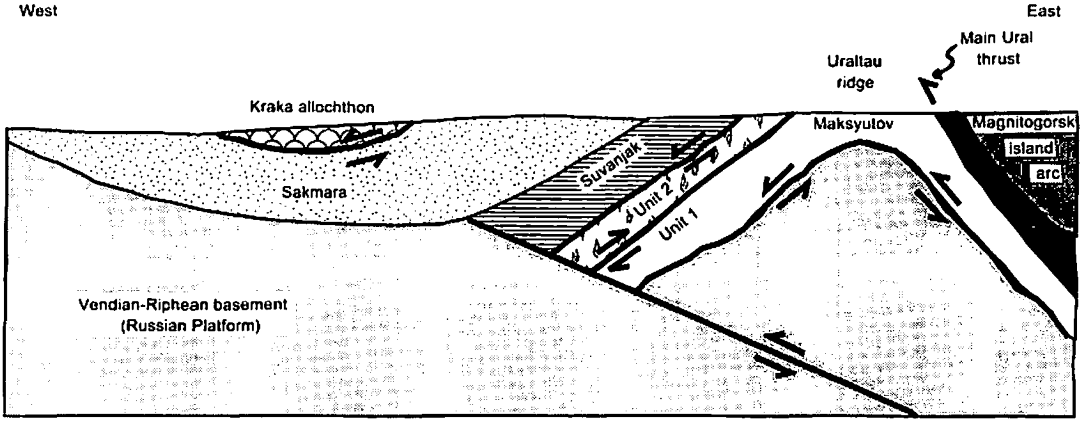


FIG. 8. Schematic cross-section illustrating geologic constraints regarding structure and history of the southern Ural Mountains. Thicknesses of the Maksyutov units are exaggerated and not to scale. Relationships summarized and modified from Peyve et al. (1977), Lennykh (1977), Moskovchenko (1982), Valizer and Lennykh (1988), Dobretsov and Dobretsova (1988), Matte et al. (1993), Brown et al. (1995), and Echtler et al. (1995). Major thrust faults and trends of motion are depicted in heavy lines, ground surface and depositional contacts in light lines. *Patterns:* dashed and dotted = sedimentary strata; random dashes + Precambrian continental crust; closely spaced lines = oceanic crust. In this tectonic model, the Kraka ophiolitic allochthon is correlated with the oceanic basement of the Magnitogorsk island arc. The Uraltau ridge is nowhere exposed in the southern Urals.

intermediate depths in a long-lived intraoceanic island-arc environment (at ~600° C and 1.5 GPa) until Early Devonian amalgamation with the metaophiolite unit, ample time would seem to have been available for backreaction of the putative diamond and coesite; however, active subduction over an extended time interval would be expected to have generated a massive coeval calc-alkaline volcanic/plutonic arc, and none is evident. On the other hand, if Unit #1 lithologies were stored at upper mantle/lower crustal depths for only an abbreviated period of time, preserved relics of coesite and coarse-grained diamond would be expected. Clearly, the postulated UHP nature of the eclogitic mica schists must be considered as equivocal.

Nevertheless, although much remains to be investigated in the region, the mineralogic, petrologic, and structural relations described in this report demonstrate that the tectonic assembly of the southern Urals comprised a long and complicated series of events spanning important intervals of the entire Paleozoic Era. The special significance of the Maksyutov Complex is that important episodes of profound subduction of continental crust and HP/UHP metamorphism may have attended early stages of growth; mineralogic effects of these events have been interpreted as preserved and detected by virtue of the large-scale exhumation that occurred during early stages of the continental assembly.

Acknowledgments

The authors are grateful for support by the Urals Institute of Geology and Geochemistry, Yekaterinburg, the Miass Institute of Mineralogy, and Stanford University. Funding also was provided by the U. S. National Science Foundation through grant EAR93-04480/Coleman, and NSF predoctoral fellowships to both Beane and Leech. Beane and Leech also received research grants from the Scientific Research Society, Sigma Xi, as well as from the Geological Society of America. First-draft versions of the manuscript were reviewed and materially improved by R. G. Coleman, J. H. Knapp, J. G. Liou, and I. Sunagawa.

REFERENCES

Beane, R. J., Liou, J. G., Coleman, R. G., and Leech, M. L., 1995, Petrology and retrograde P-T path for eclogite of the Maksyutov Complex, southern Ural Mountains, Russia: The Island Arc, v. 4, p. 254-266.

Bohlen, S. R., and Boettcher, A. L., 1982, The quartz-coesite transformation: a pressure determination and the effects of other components: Jour. Geophys. Res., v. 87, p. 7073-7078.

Bohlen, S. R., Montana, A., and Kerrick, D. M., 1991, Precise determinations of the equilibria kyanite = sillimanite and kyanite = andalusite and a revised triple point for Al_2SiO_5 polymorphs: Amer. Mineral., v. 76, p. 677-680.

Brey, G., Brice, W. R., Ellis, D. J., Green, D. H., Harris, K. L., and Ryabchikov, I. D., 1983, Pyroxene-carbonate reactions in the upper mantle: Earth Planet. Sci. Lett., v. 65, p. 63-74.

Brown, D., Puchkov, V., Alvarez-Marron, J., and Perez-Estaun, A., 1995, The structural architecture of the footwall to the Main Uralian fault, southern Urals: Earth Sci. Rev. (in press).

Bundy, F. P., 1980, The P, T phase and reaction diagram for elemental carbon: Jour. Geophys. Res., v. 85, p. 6930-6936.

Chesnokov, B. V., and Popov, V. A., 1965, Increasing volume of quartz grains in eclogites of the South Urals: Doklady Akademii Nauk, v. 62, p. 909-910 (in Russian).

Chopin, C., 1984, Coesite and pure pyrope in high-grade blueschists of the Western Alps. A first record and some consequences: Contrib. Mineral. Petrol., v. 86, p. 107-118.

Dobretsov, N. L., and Dobretsova, L. V., 1988, New mineralogic data on the Maksyutov eclogite-glaucophane schist complex, Southern Urals: Trans. U.S.S.R. Acad. Sci., Earth Sci. Section, v. 300, p. 111-116.

Dobretsov, N. L., and Sobolev, N. V., 1984, Glaucophane schists and eclogites in the folded systems of northern Asia: Ofioliti, v. 9, p. 401-424.

Dobretsov, N. L., Shatsky, V. S., Coleman, R. G., Lennykh, V. I., Valizer, P. M., Liou, J. G., Zhang, R., and Beane, R. J., in review, Tectonic setting and petrology of ultrahigh-pressure metamorphic rocks in the Maksyutov complex, Ural Mountains, Russia: Jour. Metamor. Geol.

Echtler, H. P., Stiller, M., Steinhoff, F., Krawczyk, C. M., Panov, V. D., Lipovetsky, I. A., Knapp, J. H., Perez-Estaun, A., and Hismatulin, T., 1995, URSEIS '95: Vibroseis deep reflection profiling of the southern Urals, central Russia [abs.]: EOS (Trans. Amer. Geophys. Union), v. 76, p. 550.

Edwards, R. L., and Wasserburg, G. J., 1985, The age and emplacement of obducted oceanic crust in the Urals from Sm-Nd and Rb-Sr systematics: Earth Planet. Sci. Lett., v. 72, p. 389-404.

Ernst, W. G., and Peacock, S., in press, A thermotectonic model for preservation of ultrahigh-pressure mineralogic relics in metamorphosed continental crust: Washington, DC: Amer. Geophys. Union, Geophysical Monograph series.

Holland, T. J. B., 1979, Experimental determination of the reaction paragonite = jadeite + kyanite + water, internally consistent thermodynamic data for part of the system Na_2O-Al_2O_3-SiO_2-H_2O, with applications to eclogites and blueschists: Contrib. Mineral. Petrol., v. 68, p. 293-301.

————, 1980, The reaction albite = jadeite + quartz determined experimentally in the range 600-1200° C: Amer. Mineral., v. 65, p. 129-134.

————, 1988, Preliminary phase relations involving glaucophane and applications to high pressure petrology: New heat capacity and thermodynamic data: Contrib. Mineral. Petrol., v. 99, p. 134-142.

Huang, W. L., and Wyllie, P. J., 1975, Melting reactions in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2 to 35 kilobars, dry and with excess water: Jour. Geol., v. 83, p. 737-748.

Jenkins, D. M., and Clare, A. K., 1990, Comparison of the high-temperature and high-pressure *stability* limits of synthetic and natural tremolite: Amer. Mineral., v. 75, p. 358-366.

Lennykh, V. I., 1977, The eclogite-glaucophane belt of the Southern Urals: Moscow, Nauka Press, 158 p. (in Russian).

Liou, J. G., Zhang, R., and Ernst, W. G., 1994, An introduction to ultrahigh-pressure metamorphism: The Island Arc, v. 3, p. 1-24.

Liou, J. G., Zhang, R. Y., Wang, X., Eide, E. A., Ernst, W. G., and Maruyama, S., in press, *Metamorphism* and tectonics of high-P and ultrahigh-P belts in the Dabie-Sulu region, eastern central China, *in* Harrison, M. P., and Yin, A., eds., Rubey volume VIII: The tectonic development of Asia: New York, Cambridge University Press, p. 300-344.

Matte, P., Maluski, H., Caby, R., Nicholas, A., Kepezhinkskas, P., and Sobolev, S., 1993, Geodynamic model and $^{39}Ar/^{40}Ar$ dating for the generation and emplacement of the high pressure metamorphic rocks in the SW Urals: Paris, C. R. Academie des Sciences, v. 317, Serie II, p. 1667-1674.

McDougall, I., and Harrison, T. M., 1988, Geochronology and thermochronology by the $^{40}Ar/^{39}Ar$ method: New York, Oxford University Press, 212 p.

Moskovchenko, N. I., 1982, Precambrian high-pressure complexes in Phanerozoic folded belts: Moscow, Nauka Press, 161 p. (in Russian).

Pearson, D. G., Davies, G. R., and Nixon, P. H., 1995, Origin of ultramafic rocks of UHP (diamond facies) origin, *in* Coleman, R. G., and Wang, X., eds., Ultrahigh-pressure metamorphism: New York, Cambridge University Press, p. 456-510.

Peyve, A. V., Ivanov, S. N., Lanchenov, V. M., and Perfiliev, A. C., eds., 1977, Tectonic map of the Ural Mountains: Scale 1:1,000,000: Moscow, USSR Academy of Sciences, Institute of Mineral Resources and Geology (in Russian).

Puchkov, V. N., 1993, Paleooceanic structures of the Ural Mountains: Geotectonics, v. 27, p. 184-196 (English translation).

Schertl, H. P., Schreyer, W., and Chopin, C., 1991, The pyrope-coesite rocks and their country rocks at Parigi, Dora-Maira Massif, Western Alps; detailed petrography, mineral chemistry and PT-path: Contrib. Mineral. Petrol., v. 108, p. 1-21.

Sengör, A. M. C., Natal'in, B. A., and Burtman, V. S., 1993, Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia: Nature, v. 364, p. 299-307.

Shatsky, V. S., Sobolev, N. V., and Vavilov, M. A., 1995, Diamond-bearing metamorphic rocks of the Kokchetav massif (northern Kazakhstan), *in* Coleman, R. G., and Wang, X., eds., Ultrahigh-pressure metamorphism: New York, Cambridge University Press, p. 427-455.

Smith, D. C., 1984, Coesite in clinopyroxene in the Caledonides and its implications for geodynamics: Nature, v. 310, p. 641-644.

Sobolev, L. D., ed., 1975, Geologic map of the Ural Mountains: Scale 1:1,000,000: Moscow, Nauka Press (in Russian).

Spear, F. S., 1993, Metamorphic phase equilibria and pressure-temperature-time paths: Washington, DC, Mineral. Soc. Amer. Monograph, 799 p.

Valizer, P. M., and Lennykh, V. I., 1988, Amphiboles of blueschists of the Urals: Moscow, Nauka Press, 202 p.

Zakharov, O. A., and Puchkov, V. N., 1994, The collisional origin of the eclogite-glaucophane-schist belt of the Uraltau zone: Ufa, Russian Academy of Sciences, 29 p. (in Russian).

Zonenshain, L. P., Korinevsky, V. G., Kazmin, V. G., Pecherskiy, D. M., Khain, V. V. and Matveyenkov, V. V., 1984, Plate tectonic model of the development of the Southern Urals: Tectonophysics, v. 109, p. 95-135.

Zonenshain, L. P., Kuzmin, M. I., and Natapov, L. M., 1990, Geology of the USSR: A plate-tectonic synthesis: Washington, DC, Amer. Geophys. Union Geodynamics Series, v. 21, 242 p.