Available online at www.sciencedirect.com

SCIENCE DIRECT®

Tectonophysics 365 (2003) 45–76

TECTONOPHYSICS

www.elsevier.com/locate/tecto

Tectonic evolution of the Mesozoic Verkhoyansk–Kolyma belt (NE Asia)

Vladimir S. Oxman*

Institute of Diamond and Precious Metal Geology SO RAN, 677001, 39 Lenin pr., Yakutsk, Russia

Received 5 March 2002; accepted 10 February 2003

Abstract

The Verkhoyansk–Kolyma belt (VK) forms the western part of the Verkhoyansk–Chukotka Mesozoic orogen (NE Asia) and lies between the Siberian craton on the western side, the Mesozoic–Cenozoic Koryak–Kamchatka accretionary orogen on the eastern side, and the Arctic Alaskan craton to the north. The VK results from the collision of the Siberian craton and the Kolyma–Omolon composite terrane (KO), which acted as an indentor resulting the Kolyma orocline. The KO is made up of ophiolite and olistostromal and schistose units that were amalgamated during the Middle–Late Jurassic by thrust and nappe tectonics under greenschist facies metamorphism. This was followed in Latest Jurassic by thrusting and strike-slip faulting related to the collision of the KO composite terrane with the Siberian craton. This collision also produced the Verkhoyansk fold-and-thrust belt in the Siberian continental margin. In the earliest Cretaceous, collision of the Alaskan and Siberian margins resulted in further thrust and strike-slip tectonism.

Keywords: Tectonics; Verkhoyansk–Kolyma orogenic belt; Mesozoic

---

1. Introduction

A large orogenic area occurs in northeastern Asia to the east of the older Siberian platform. This area is underlain by the Mesozoic Verkhoyansk–Chukotka collision zone and the Mesozoic–Cenozoic Koryak–Kamchatka accretion fold zone (Fig. 1). The Verkhoyansk–Chukotka collision zone is traditionally subdivided into Verkhoyansk–Kolyma and Novosibirsk–Chukotka (Chukotka–Arctic Alaska) collisional orogens (Fujita and Newberry, 1982; Fujuta and Newberry, 1983; Zonenshain et al., 1990; Parfenov, 1991; Sokolov et al., 1997; Natal'in et al., 1999; Tectonics, Geodynamics and Metallogeny of the Sakha Republic (Yakutia), 2001).

The Verkhoyansk–Kolyma orogen results from the Mesozoic collision of the Verkhoyansk continental margin of the north Asian (Siberian or Angarian; Sengor and Natal'in, 1996) craton and the Kolyma–Omolon microcontinent (Parfenov, 1991). Tectonic structures in the orogen are westerly facing, and vary in orientation from typically northwesterly striking in the southwest and northeasterly striking in the northwest (Figs. 1–3), a feature known as the Kolyma "loop" (Zonenshain et al., 1990). The Priverkhoyansk

---

* Tel.: +7-8411-2445811.

E-mail address: oxman@diamond.ysn.ru (V.S. Oxman).

0040-1951/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0040-1951(03)00064-7

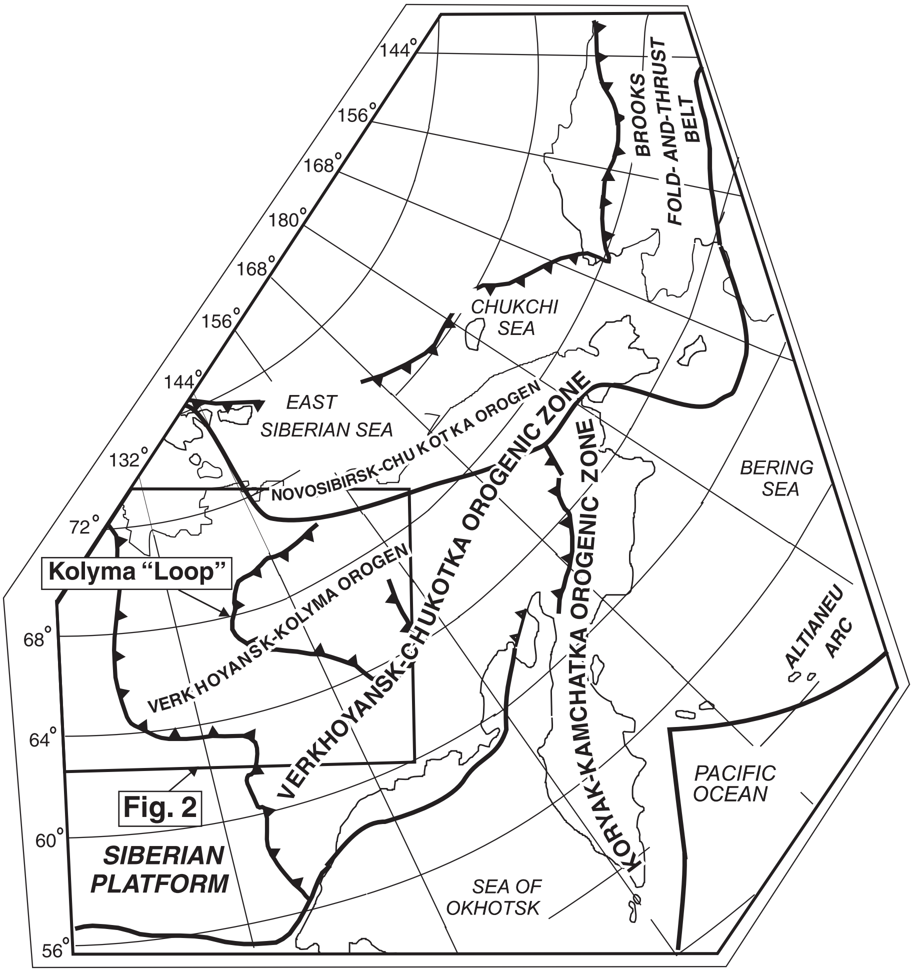


Fig. 1. The major tectonic divisions in northeast Asia.

foredeep basin occurs along the contact between the Verkhoyansk–Kolyma orogen and the ancient Siberian platform and can be traced along the external part of orogen.

The Verkhoyansk continental margin consists of Paleozoic to Mesozoic shelf sediments and turbidites of the north Asian craton that were subsequently deformed into the Verkhoyansk fold-and-thrust belt, and represents foreland of the orogen (Parfenov, 1991; Parfenov et al., 1995; Prokopiev, 1998). The inner part of the Verkhoyansk–Kolyma orogen constitutes the Chersky collisional belt (Oxman, 1998) (Figs. 2 and 3). The hinterland of the orogen includes deformed Paleozoic–Early Mesozoic sediments of the Alazeya block and synorogenic and postorogenic Mesozoic terrigenous rocks of the Ilin–Tass anticlinorium and Indigirka–Zyryanka basin.

The objectives of this article are to investigate the structural and geodynamic evolution of the inner part of collisional orogen, to discuss the origin of the Kolyma loop, and to examine the varying styles of early accretion and subsequent collisional deformation in various regions of the inner part of the Verkhoyansk–Kolyma orogen. The study area is an example of accretionary and collision deformation along and across a Mesozoic orogenic arcuate belt.

This article is based on results from long-term geological mapping, detailed structural profiles in

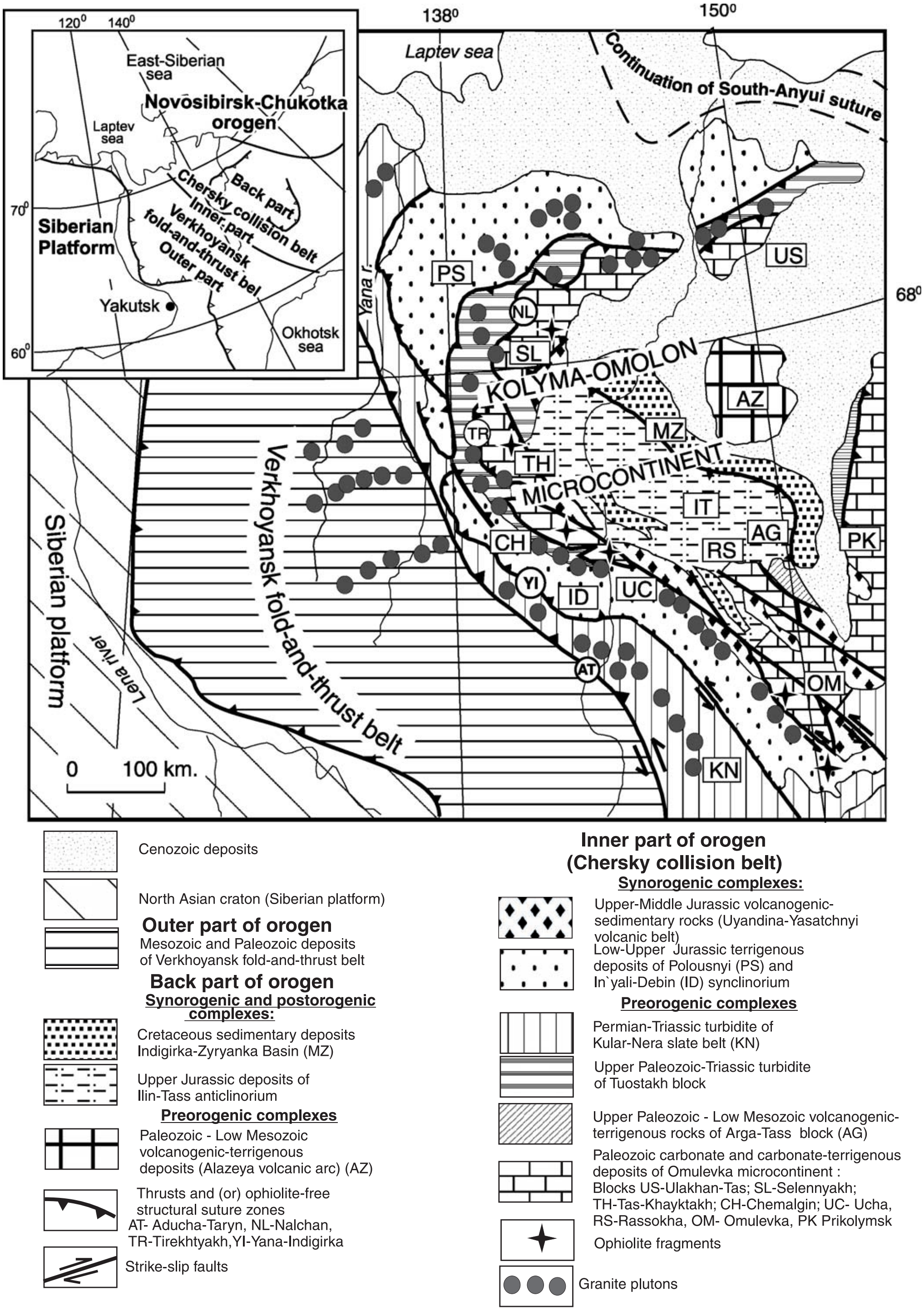


Fig. 2. Generalized tectonic map of central part of the Verkhoyansk–Kolyma collision orogen. Inset: Main tectonic zones of the Verkhoyansk–Kolyma orogen.

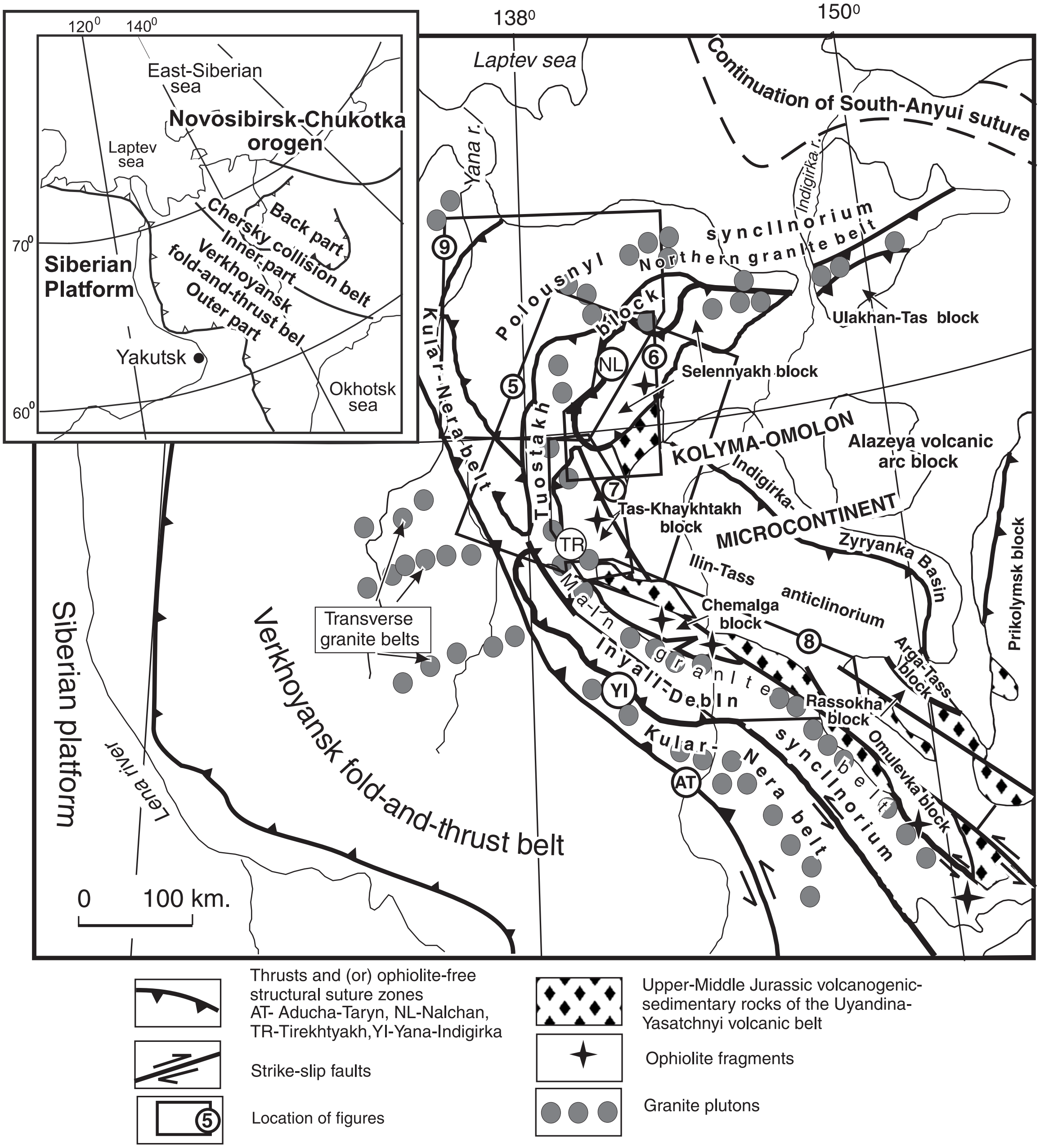


Fig. 3. Main tectono-stratigraphic units of central part of the Verkhoyansk–Kolyma collision orogen. Inset: Main tectonic zones of the Verkhoyansk–Kolyma orogen.

the north of the Verkhoyansk–Kolyma orogen, and detailed structural studies in key areas in central and southern parts of this orogen. Further details may be found in a monograph (Oxman, 2000) and in notes accompanying geological maps (scale 1: 50,000 and 1:200,000).

2. Main tectono-stratigraphic units of the Verkhoyansk–Kolyma orogen

2.1. Outer part of orogen

The *Verkhoyansk fold-and-thrust belt* represents the external (foreland) part of the Verkhoyansk–Kolyma orogen (Parfenov, 1991; Parfenov et al., 1995; Prokopiev, 1998), and is thought to represent the vestige of the Verkhoyansk continental margin. The belt consists of Paleozoic to Mesozoic shelf sediments and turbidites deposited on the eastern margin of the north Asian craton (Fig. 4) and is subdivided into zones and segments (see Figs. 3 and 4 in Parfenov, 1991). Early and Middle Paleozoic deposits, exposed in the western part of the belt, accumulated on the ancient Precambrian crystalline basement of the northeast Asian craton. Rock units include Devonian–Early Carboniferous rift-related gabbro, basalt, basaltic tuff, with interlayered gypsum and anhydrite (Parfenov, 1991). Carboniferous–Permian and Triassic–Middle Jurassic strata consist of shallow marine and deltaic facies deposits which form progradational prisms in central and eastern parts of the Verkhoyansk margin (Fig. 4) and are thought to postdate a rifting event. Cretaceous syn- and postorogenic terrigenous deposits occur locally (Parfenov, 1991; Prokopiev, 1998).

2.2. Inner part of orogen

Located to the east of the Verkhoyansk fold-and-thrust belt, the Chersky collisional belt represents inner part of the Verkhoyansk–Kolyma orogen. This belt (Figs. 2 and 3) consists of (from west to east), the *Kular–Nera slate belt* (Kular–Nera terrane of Nokleberg et al., 2001), the Late Paleozoic–Early Mesozoic *Tuostakh block* (Nagondza terrane in Nokleberg et al., 2001), several Paleozoic fault-bounded blocks of Paleozoic age in the central part of the belt (*Omulevka microcontinent* in Nokleberg et al., 2001), and stacked allochthons of *ophiolite* and variably *metamorphosed blocks*. Late Mesozoic synorogenic sedimentary and volcaniclastic rocks are also recognized in this belt.

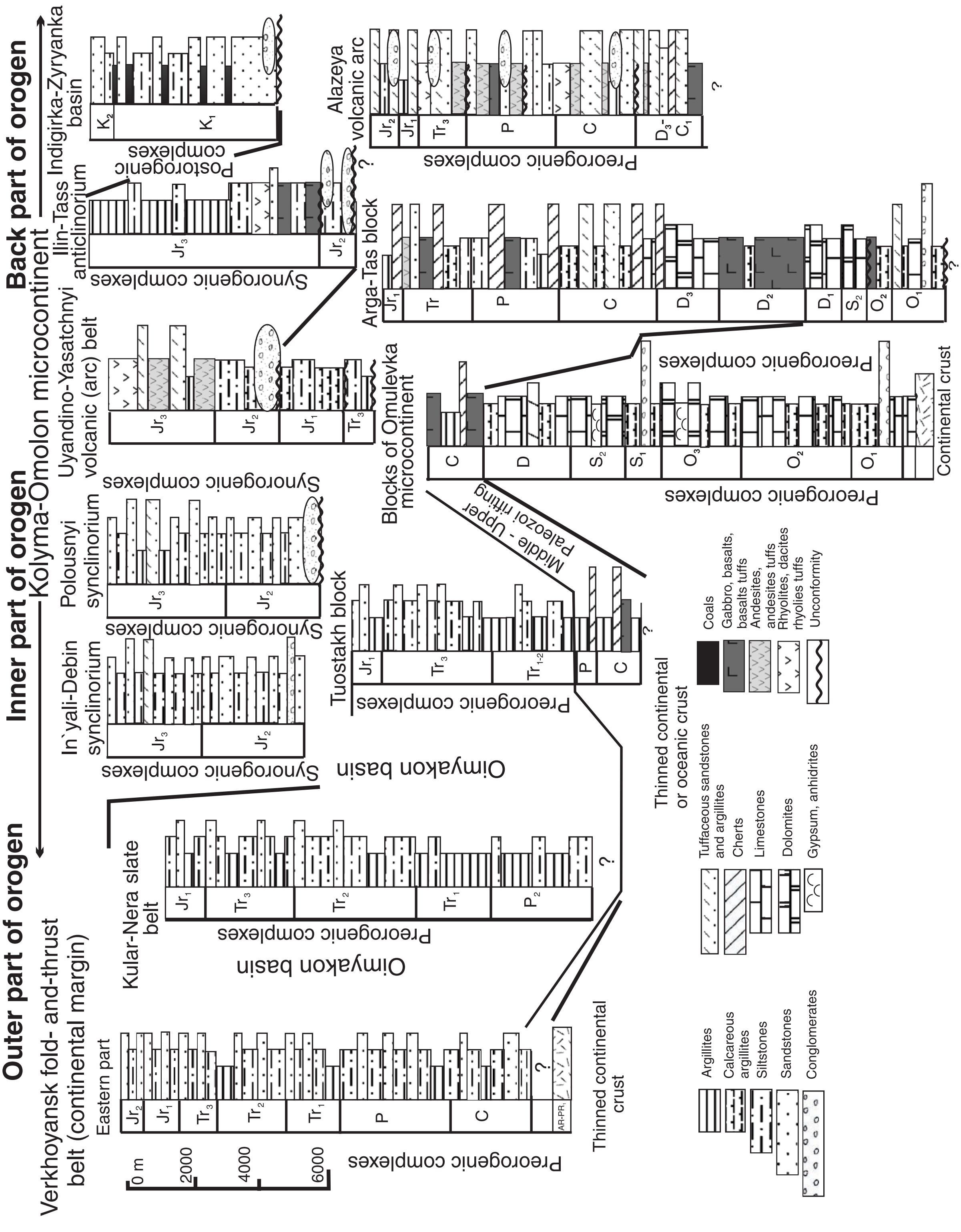
2.2.1. Preorogenic complexes

The *Kular–Nera slate belt* occurs in a relatively narrow zone but extends for more than 900 km along strike (Figs. 2 and 3). It consists of tectonic slices of Late Permian to Early Jurassic black shales and turbidite deposits which are interpreted as continental basin slope deep-water fan deposits (Fig. 4). These deposits accumulated on thinned continental or oceanic crust of the Oimyakon sedimentary basin, which formed as a result of Middle–Late Paleozoic rifting (Parfenov, 1991). The belt is bounded to the west by the Adycha–Taryn fault, which is also the location of an abrupt facies change in Triassic and Low Jurassic deposits that extend for more than 450 km (Natal'in and Parfenov, 1989).

The *Tuostakh block* is composed of polydeformed Late Paleozoic and Early Mesozoic deposits (Fig. 4). The block is dissected by a series of faults with thrust and strike-slip kinematics (Fig. 5). Permo-Carboniferous deposits occur in a series of small lenses and thin sheets along the eastern border of the block (Oxman et al., 1998a) and consist of condensed sections of hemipelagic volcanogenic–terrigenous–siliceous and carbonate–terrigenous deposits and interbedded pillow-basalts that are interpreted as syn-rift assemblages. Taken together, the Kular–Nera belt and the Tuostakh block could represent the central and eastern parts, respectively, of the Oimyakon sedimentary basin.

The *Omulevka microcontinent* occurs in the eastern portion of the Chersky collision belt and consists of the *Selennyakh* (Fig. 6), *Tas–Khayakhtakh* (Fig. 7) and smaller fault-bounded blocks (Figs. 2, 3 and 8). These blocks are predominantly composed of Ordovician–Devonian strata thought to have accumulated on thinned continental crust along eastern portion of the Verkhoyansk continental margin. The strata consist of fossiliferous carbonate and carbonate–terrigenous shelf deposits, with relatively minor interbedded gypsum, anhydrite and red-beds (Bogdanov, 1963; Bulgakova, 1986; Alkhovik and Baranov, 1989). Carbonate turbidites and olistostromes, which are associated with siliceous–terrigenous and volcanic formations (basalts and basalts tuffs), also occur.

Late Paleozoic (Early Carboniferous, Tournaisian–Visean) assemblages comprise relatively deep-water siliceous and volcanogenic mafic rocks, and by hemipelagic condensed sections (Bulgakova and Kolodeznikov, 1990; Oxman et al., 1998a,b). Volcanic and volcano-sedimentary rocks, with voluminous pillow-basalts, formed in a rift environment. Late Permian


Outer part of orogen
Inner part of orogen
Back part of orogen
Kolyma-Omolon microcontinent
Verkhoyansk fold- and-thrust belt (continental margin)
Eastern part
Preorogenic complexes
0 m
2000
4000
6000
Jr2
Jr1
Tr3
Tr2
Tr1
P
C
AR-PR1
?
Thinned continental crust
Kular-Nera slate belt
Preorogenic complexes
Oimyakon basin
P2
In`yali-Debin synclinorium
Synorogenic complexes
Oimyakon basin
Jr3
Polousnyi synclinorium
Uyandino-Yasatchnyi volcanic (arc) belt
Ilin-Tass anticlinorium
Postorogenic complexes
Indigirka-Zyryanka basin
K2
K1
Tuostakh block
Tr1-2
Thinned continental or oceanic crust
Middle - Upper Paleozoi rifting
Blocks of Omulevka microcontinent
D
S2
S1
O3
O2
O1
Continental crust
Arga-Tas block
Tr
D3
D2
D1
Alazeya volcanic arc
D3-C1
Argillites
Calcareous argillites
Siltstones
Sandstones
Conglomerates
Tuffaceous sandstones and argillites
Cherts
Limestones
Dolomites
Gypsum, anhidrites
Coals
Gabbro, basalts, basalts tuffs
Andesites, andesites tuffs
Rhyolites, dacites rhyolies tuffs
Unconformity

deposits unconformably overlie Ordovician–Devonian strata and include interbedded sandstone, conglomerate, calcarenite and micrite.

Ordovician–Early Carboniferous sedimentary and volcano-sedimentary rocks of the blocks of the *Omulevka microcontinent* overthrusted formations of the Tuostakh block (in the north and northwest), and Middle Jurassic deposits of the In'yali–Debin synclinorium, etc. (in the south) (Figs. 2 and 3). Faults that bound blocks composed of Paleozoic rocks have complex kinematics. To the south, faults are predominantly NW–SE and are sinistral, and to the north, faults are predominantly NE–SW and dextral.

2.2.2. Ophiolite and metamorphic rocks

In the central part of Chersky collisional belt, ophiolitic and metasedimentary rocks (Figs. 2, 3, 5–8) occur as allochthons tectonic sheets thrust on Paleozoic deposits, or form small lenses along strike-slip fault zones. The ophiolites contain serpentine harzburgites and dunites, gabbro and gabbro–amphibolites of cumulate origin, metabasalts, ophicalcite breccias and ophiolite-clasts. Geochemical and geological data imply that the ophiolites formed in a suprasubduction zone environment (Oxman et al., 1995).

The grade of metamorphism varies from upper amphibolite to lower greenschist facies (Oxman, 1996, 1998). The first phase of metamorphism is recorded only in the ophiolites and is characterized by temperatures between 450 and 500 °C and pressures of less than 2.0 kbar, which is typical of elevated geothermal gradients near spreading centres. This metamorphism was not accompanied by deformation and is dated at 419–430 Ma (^{40}Ar–^{39}Ar on actinolitic hornblendes, Layer et al., 1993; Oxman et al., 1995). The second phase of metamorphism occurred under Barrovian-type conditions ($T = 450$–620 °C, $P = 4.0$–6.0 kbar) and ^{40}Ar–^{39}Ar analyses of biotite in the metasediments yielded an age of 370 Ma (Layer et al., 1993; Oxman et al., 1995). A third phase of metamorphism, under greenschist facies conditions occurred lower pressures in the northern part of the belt (2.0–4.0 kbar) and medium pressures in the southern part of the belt (4.0–6.0 kbar) (Oxman et al., 1998b). This event is dated at 174 Ma by muscovite from schists using ^{40}Ar–^{39}Ar method (Layer et al., 1993).

2.2.3. Synorogenic and postorogenic complexes

Middle–Late Jurassic lithostratigraphically correlative volcano-sedimentary units occur in several parts of the Verkhoynsk–Kolyma orogen; in the *In'yali–Debin* and *Polousnyi synclinoria*, the *Uyandina–Yasatchnyi belt* (Parfenov, 1984;Trunilina et al., 1999; Oxman, 2000). Middle–Late Jurassic (Bajocian–Early Volgian) turbidites in the synclinorium are characterized large horizons of olistrostromes, tectono-sedimentary mélanges containing fragments of igneous rocks, tuffs, synsedimentary folds and thrusts. (Natapov and Surmilova, 1986; Parfenov, 1984; Trunilina et al., 1999). These units are unconformably overlain by post-tectonic Late Cretaceous strata (Natapov and Surmilova, 1986; Parfenov, 1984, 1991). The Uyandina–Yasatchnyi belt is characterized by arc-related volcano-sedimentary (Trunilina et al., 1999).

The *Polousnyi and In'yali–Debin syclinoria* (Figs. 2, 3, 8 and 9) are composed of Middle–Late Jurassic synorogenic deposits, flanked by Triassic–Early Jurassic rocks of Kular–Nera belt and Tuostakh block (Fig. 9) (Gusev, 1979). Fold–thrust structures in the Polousnyi synclinorium are the result of several episodes of deformation and have northwestern vergence in central and southern parts, and southeastern vergence in northern part. The lowest units in the In'yali–Debin synclinorium formations are characterized by Middle–Late Jurassic rhythmically alternating beds of siltstones, mudstones, sandstones and olistostromes. Late Jurassic strata are composed of siltstones, mudstones, argillaceous shales, polymictic and calcareous sandstones, with interbedded tuffaceous mudstones, tuffaceous sandstones and conglomerates (Parfenov, 1984; Oxman, 2000). Structures in

Fig. 4. Synthetic lithostratigraphic columns of main tectono-stratigraphic units of the Verkhoyansk–Kolyma orogen. Age symbols: K_2—Upper Cretaceous; K_1—Lower Cretaceous; Jr_3—Upper Jurassic; Jr_2—Middle Jurassic; Jr_1—Lower Jurassic; Tr—Triassic; Tr_1—Upper Triassic; Tr_2—Middle Triassic; Tr_3—Lower Triassic; P—Permian; P_2—Upper Permian; C—Carboniferous; C_1–D_3—Lower Carboniferous–Upper Devonian; D—Devonian; D_3—Upper Devonian; D_2—Middle Devonian; D_1—Lower Devonian; S_1—Upper Silurian; S_2—Lower Silurian; O_3—Upper Ordovician; O_2—Middle Ordovician; O_1—Lower Ordovician; C—Cambrian; Ar_3–Pr_1—Upper Archean–Lower Proterozoic.

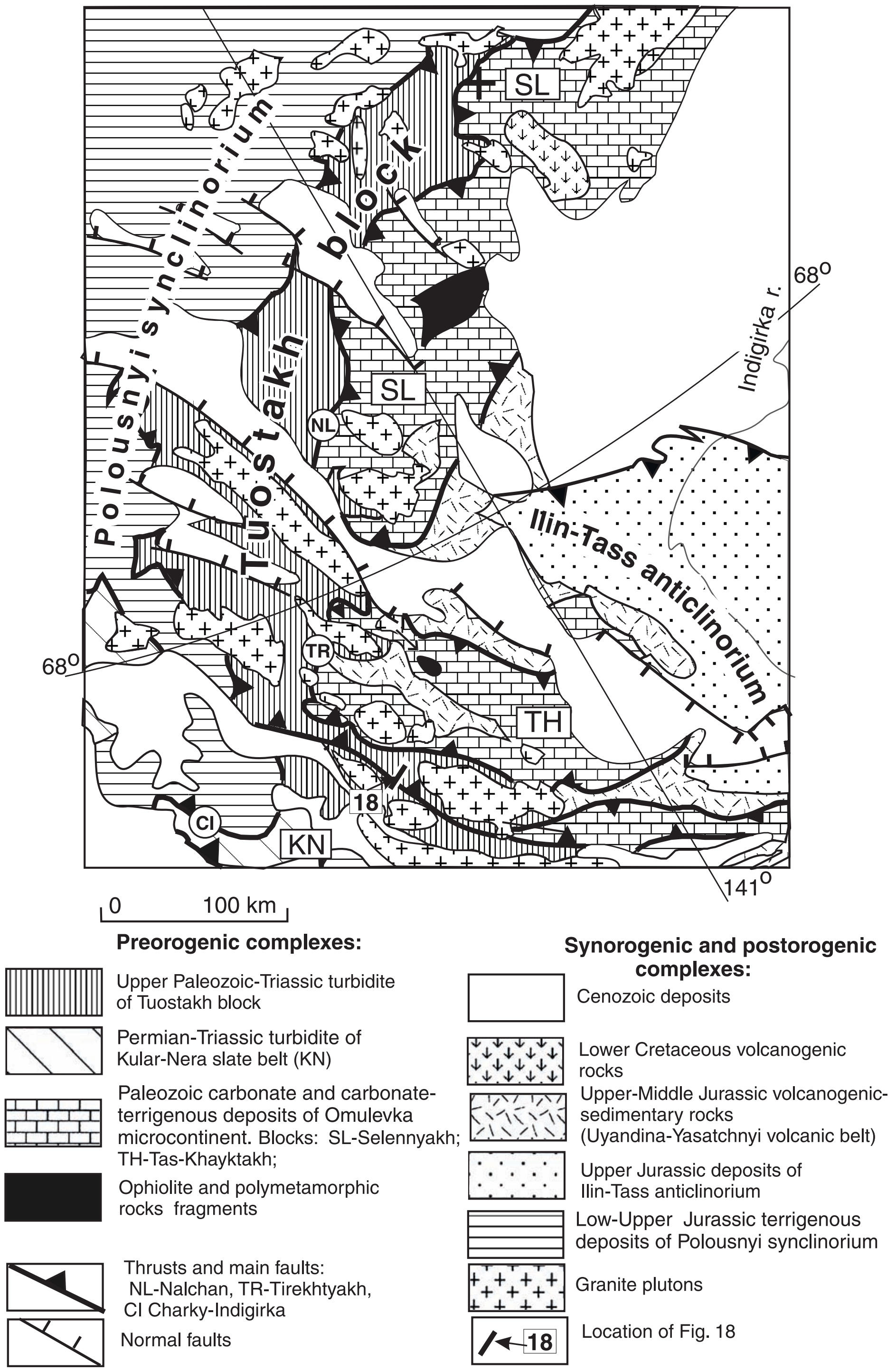


Fig. 5. Tectonic setting and generalized tectonic map of the Tuostakh block (compiled by V.S. Oxman (Oxman, 2000; Tectonics, Geodynamics and Metallogeny of the Sakha Republic (Yakutia), 2001)). See Fig. 3 for locations.

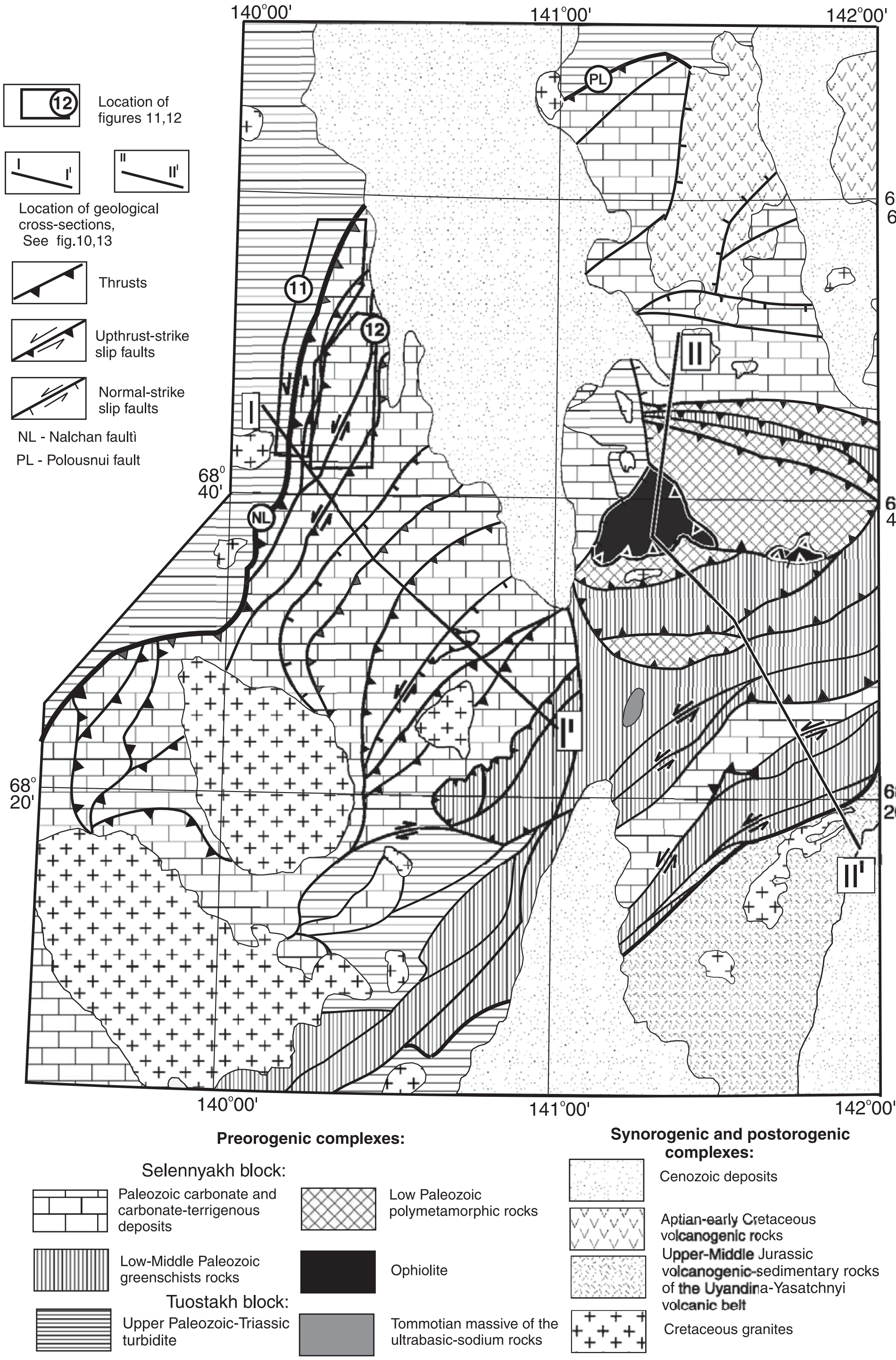


Fig. 6. Structure of the Selennyakh block of Omulevka microcontinent (compiled by V.S. Oxman (Oxman, 2000; Tectonics, Geodynamics and Metallogeny of the Sakha Republic (Yakutia), 2001)). See Fig. 3 for locations.

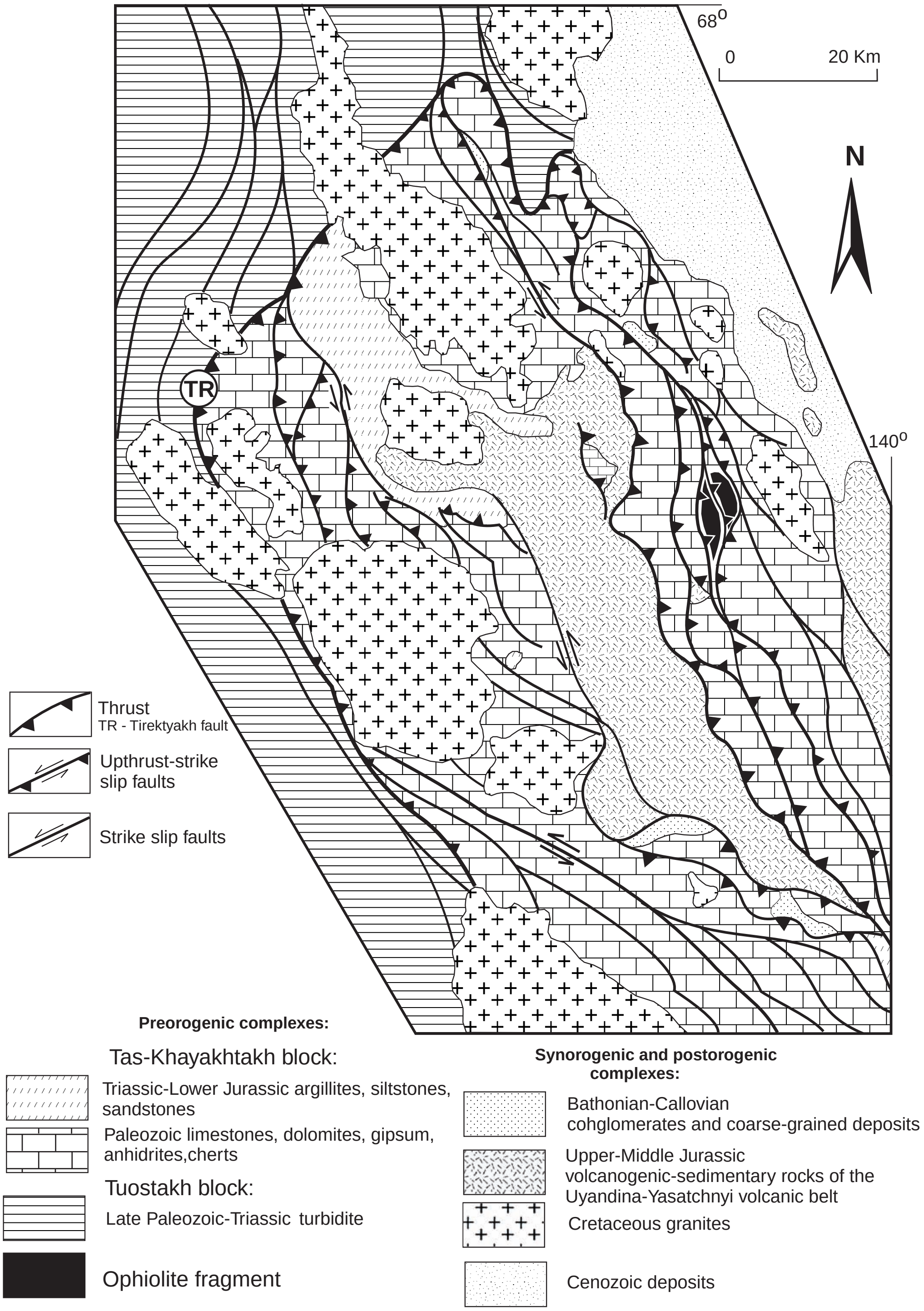


Fig. 7. Structure of the Tas–Khayakhtakh block of Omulevka microcontinent (compiled by V.S. Oxman (Oxman, 2000; Tectonics, Geodynamics and Metallogeny of the Sakha Republic (Yakutia), 2001)). See Fig. 3 for locations.

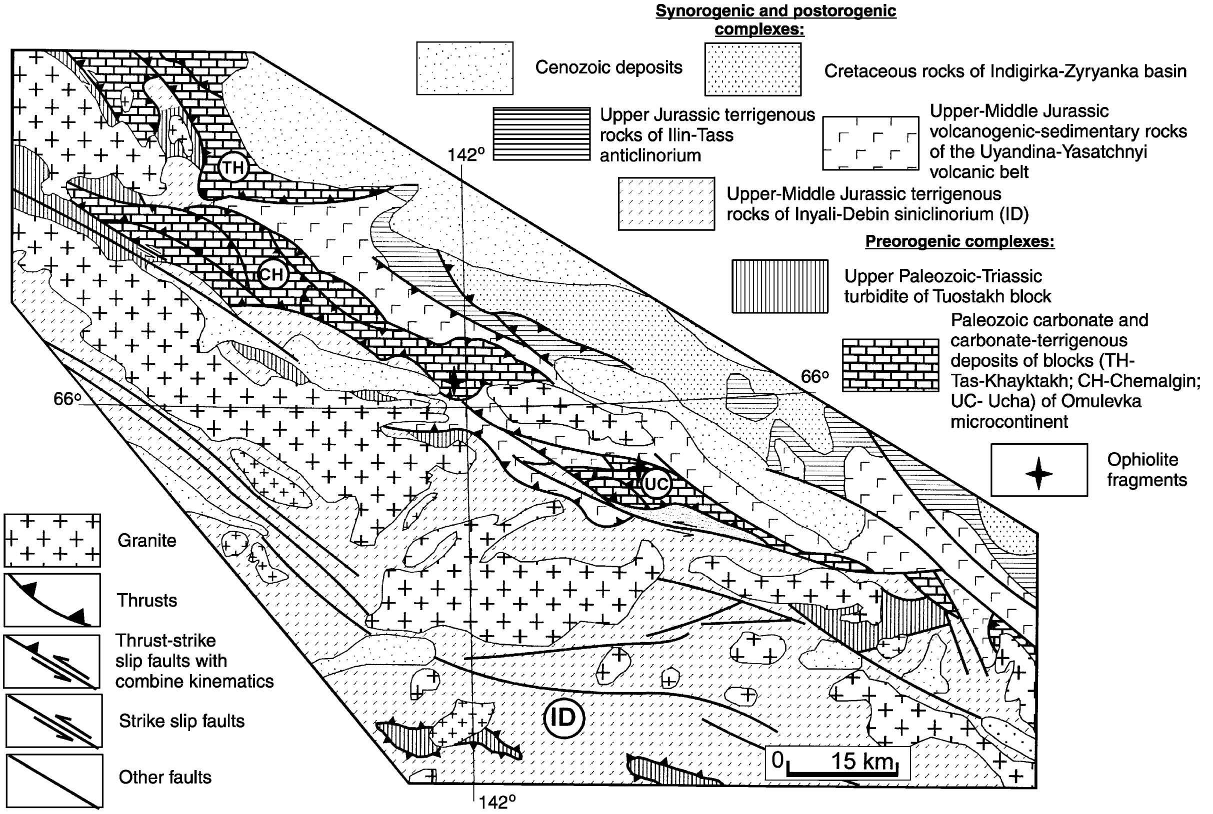


Fig. 8. Structural map of the central part of the Chersky collision belt (compiled by V.S. Oxman (Oxman, 2000)). See Fig. 3 for locations.

In'yali–Debin synclinorium have a predominantly northwestern trend. In the central part of this synclinorium, there is a large S-like sigmoidal fold. The overall structure of the synclinorium is asymmetric, with a steep to vertical eastern and northeastern limb, and a gentle to subhorizontal western and southwestern limb. Synclinorium deposits consist of sedimentary rocks that were deposited synchronously with the accretion of the Kolyma–Omolon microcontinent to the north Asian craton.

Middle and Late Jurassic and Cretaceous rocks occur between and within blocks of the Omulevka microcontinent, and Tuostakh block. They consist of conglomerate, psammite and argillaceous molasse and grade along strike into olistostromal deposits (see Figs. 5.3 and 5.4 in Oxman, 2000). Middle and Late Jurassic (Bathonian–Kimmeridgian) sedimentary deposits unconformably overlie Ordovician and Devonian sediments. Middle Jurassic molasse and olistostromal deposits are related to the accretion of these various blocks into the composite Kolyma–Omolon microcontinent (Parfenov, 1995; Oxman, 2000; Nokleberg et al., 2001).

The *Uyandina–Yasatchnyi belt* (Figs. 2–4) is composed of synorogenic Middle Jurassic sedimentary and Late Jurassic volcano-sedimentary deposits, which unconformably overlie Early Middle Paleozoic (Ordovician–Devonian) carbonate and carbonate–terrigenous rocks and metamorphic assemblages. Middle Jurassic (Bathonian–Callovian) poorly sorted conglomerates, breccias and micrites grade into olistostromal deposits along strike. Late Jurassic (Oxfordian–Kimmeridgian) deposits consist of pillow-basalts, spilite, basaltic andesites, andesites and intermediate tuffs, and are exposed in nappes that are unconformably overlain by Volgian-age dacites, rhyolites, felsic tuffs and interbedded clastic rocks (Trunilina et al., 1999).

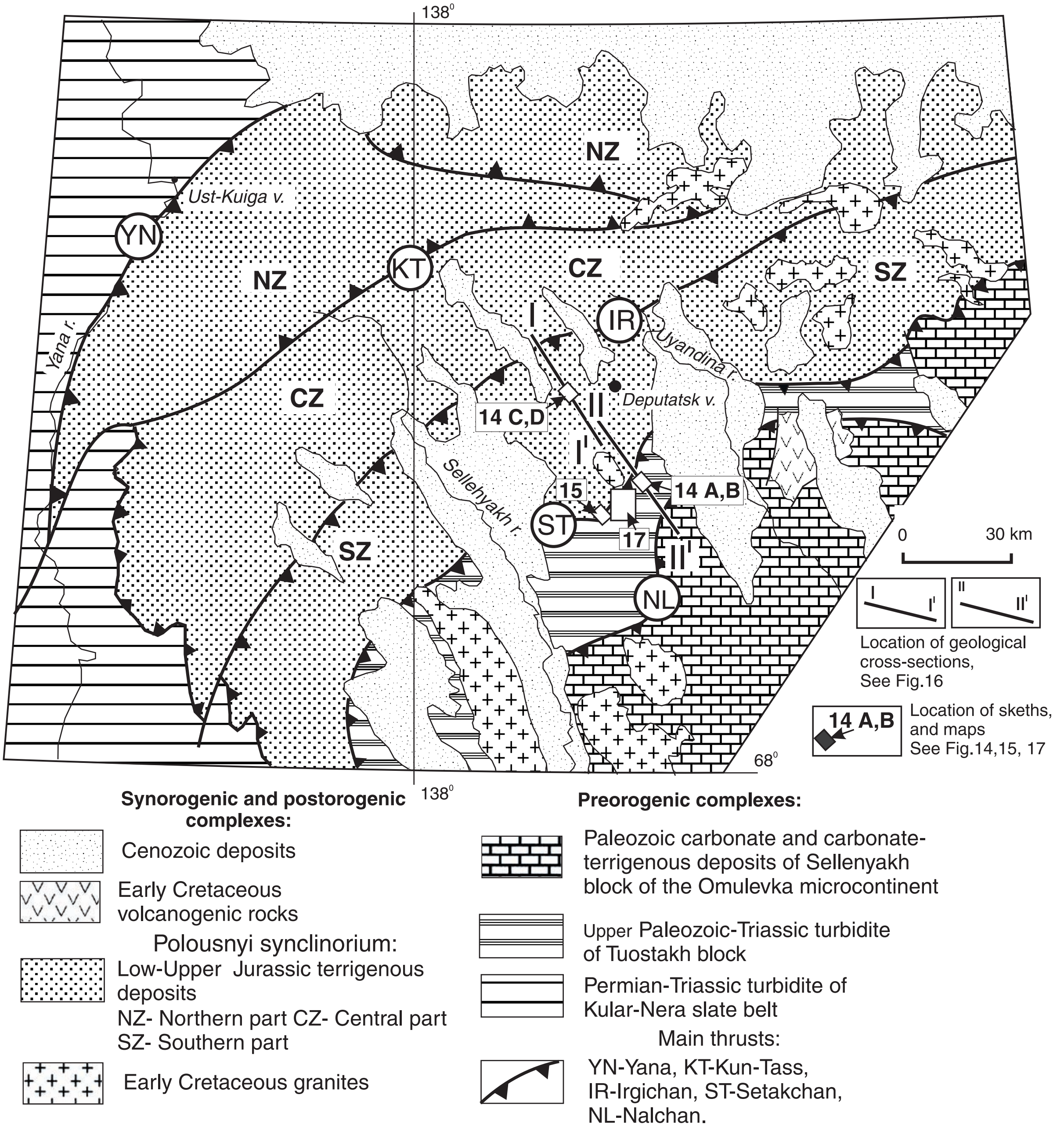


Fig. 9. Structural map of the Polousnyi synclinorium (compiled by V.S. Oxman (Oxman, 2000; Tectonics, Geodynamics and Metallogeny of the Sakha Republic (Yakutia), 2001)) See Fig. 3 for locations.

2.2.4. Granite belts

Granite batholiths are common in many parts of the Verkhoyansk–Kolyma orogen (Figs. 2 and 3) (Parfenov, 1991; Trunilina et al., 1999; Layer et al., 2001; Nokleberg et al., 2001) and occur in quasi-arcuate patterns. In general, the age of the granite plutons is progressively younger from south to north, and from east to west. ^{40}Ar–^{39}Ar dating has identified distinct phases of granitoid magmatism (Layer et al., 2001). Early pre-collisional plutons occur predominantly in the southern and eastern parts of Main belt. These plutons have apparent ages of ca. 160–140 Ma, are metaluminous to peraluminous quartz diorites, granodiorites and monzogranites, and reflect subduction along the southwest margin of the Kolyma–Omolon microcontinent (Layer et al., 2001). These plutons are broadly coeval with the formation of the Uyandina–Yasatchnyi belt.

Plutons in the central and northern parts of Main belt (Fig. 3) are ca. 143–138 Ma in age. They consist of strongly peraluminous muscovite–biotite granites, and are thought to have been generated during a collisional event (Trunilina et al., 1999). In the north, tonalites, granodiorites, granites and syenites dated at ca. 130–123 Ma are interpreted to reflect subduction along the northern margin of the Kolyma–Omolon microcontinent (Layer et al., 2001).

Granitoid intrusions along the Transverse belts consist of diorite to granodiorite, quartz monzodiorite, with small bodies alkali granite, syenite (Trunilina et al., 1999). These intrusions are dated at ca. 106–92 Ma and are associated with post-collisional east–west extension (Layer et al., 2001).

2.3. Hinterland part of orogen

The *Alazeya block* (Figs. 2 and 3) occurs in the hinterland of the Verkhoynsk–Kolyma orogen and is separated from tectono-stratigraphic units in the central part of the belt by the northeasterly striking Ozhoginskaya positive magnetic anomaly, which is interpreted as a suture formed by the collision of the Alazeya arc with the Omulevka microcontinent (Parfenov, 1991). Possible fragments of this suture are exposed in Arga–Tass block, in the southeastern portion of the collisional zone (Figs. 2 and 3). The Alazeya block is composed of Devonian–Carboniferous, Permian, Late Triassic and Early Jurassic arc-related volcano-sedimentary deposits, tuffs of intermediate to felsic composition, basaltic andesite and andesite with interbedded conglomerate, siliceous and siliceous–argillaceous rocks (Grinberg et al., 1981). In addition, isolated lenses of glaucophane and glaucophane–lawsonite schists, oceanic tholeiitic basalts, quartzites, and marbles occur (Grinberg et al., 1981).

Late Mesozoic overlapping sedimentary complexes of the eastern hinterland part of the Verkhoyansk–Kolyma orogen are developed in the *Ilin–Tass anticlinorium* and *Indigirka–Zyryanka* basin. The *Ilin–Tass anticlinorium* (Figs. 2–4) is composed of homogeneous beds of interbedded siltstones and mudstones of Late Jurassic age (Gusev, 1979; Prokopiev, 1998). These formations are deformed into a system of tight folds and thrusts. To the east, these formations allochthonously overlie Cretaceous deposits of the Indigirka–Zyryanka basin (Parfenov, 1991).

3. Regional structures in the inner part of the Verkhoyansk–Kolyma belt

Major tectonic-stratigraphic units of the inner part of the Verkhoyansk–Kolyma orogen occur in a fold-and-thrust belt. Detailed descriptions of these structures are given elsewhere (e.g. Oxman et al., 1995; Oxman and Prokopiev, 1995, 2000; Parfenov et al., 1989; Oxman, 2000). In this article, these structures are summarized in figures highlighting the northwestern part of orogen, including the Selennyakh block of Omulevka microcontinent, Tuostakh block, ophiolites and synorogenic deposits of Polousnyi synclinorium.

3.1. Devonian deformation

The earliest, supposedly Devonian deformation, is recorded only in ophiolites and polymetamorphic rocks. This event is represented by asymmetric, isoclinal, commonly intrafolial and “sheath” folds of F_{n-1} and F_n (n, $n-1$ are designated as Devonian deformation), accompanied by ductile thrusts that are subparallel to primary “stratification”, development of a foliation and metamorphic banding (S_n, S_{n-1}), and high temperature mylonites (Oxman et al., 1995, 1998b). This deformation reflects Barrovian-type metamorphism, and is dated at 370 Ma (^{40}Ar–^{39}Ar, biotite, Layer et al., 1993). The dated biotite occurs in a schistosity that is subparallel to axial surfaces of the early recumbent folds in the polymetamorphic rocks. Ophiolite and polymetamorphic rocks are stacked above deep-seated thrusts and represent tectonic detachment of oceanic crust (Oxman, 1998, 2000; Oxman et al., 1995, 1998b).

3.2. Late Mesozoic (Middle Jurassic–Cretaceous) deformation

3.2.1. D_1—mainly thrust deformation

Late Mesozoic D_1 deformation in ophiolites and metamorphic rocks produced regional- and outcrop-scale F_1 concentric gently plunging folds. Ophiolites typically occur in synforms, and metamorphic rocks are exposed in the cores of regional antiforms (Oxman, 2000) (Fig. 10). D_1 also produced thrusts and metamorphism which is dated at 174 Ma ($^{40}Ar-^{39}Ar$, muscovite, Layer et al., 1993).

D_1 fold structures in the Selennyakh block of the Omulevka microcontinent are characterized by asymmetric, periclinal sub-recumbent regional- and outcrop-scale F_1 folds (Figs. 11 and 12). Axial surfaces of folds gently dip to the east, and fold axes gently plunge to the northeast and southwest (Fig. 11, equal area nets: 1, 4, 5, 7, 8, 10 and 12). S_1 foliation is developed subparallel to the axial planes and is defined by muscovite and chlorite. $^{40}Ar/^{39}Ar$ dating of muscovite yields a cooling age of 174 Ma (Layer et al., 1993), implying a Middle Jurassic (pre-Kimmeridgian) age. Along the regional-scale Seimchan thrust in the Sellenyakh block, middle Ordovician strata are thrust over Late Paleozoic deposits (Fig. 13). Thrust displacements also occur along the Nalchan fault, where Paleozoic deposits structurally overlie onto Mesozoic rocks (Figs. 11 and 13). Horizontal displacements on the order of tens to hundreds of km were obtained by determining the offset of originally continuous contemporaneous facies in allochthons and paraautochthons. Calculated values of horizontal shortening are estimated at 55–65% (Fig. 12; Oxman, 2000). Regional detachments occur in strata representing the boundary between the Ordovician and Silurian, within Middle and Late Ordovician deposits (Fig. 12).

Thrusts also occur in other blocks of the Omulevka microcontinent (Bogdanov, 1963; Gusev, 1979; Parfenov et al., 1989). Regional faults divide the Sellennyakh, Tas–Khaykhtakh and others blocks of Omulevka microcontinent (Figs. 6–8). In Tas–Khayahtakh block, early thrusting and associated zones of tectonic melange are preserved in all tectonic sheets and in the Tirekhtyakh fault zone (see Figs. 8.1–8.5 in Oxman, 2000). The matrix of olistostromal deposits contains remains of Middle Jurassic fauna,

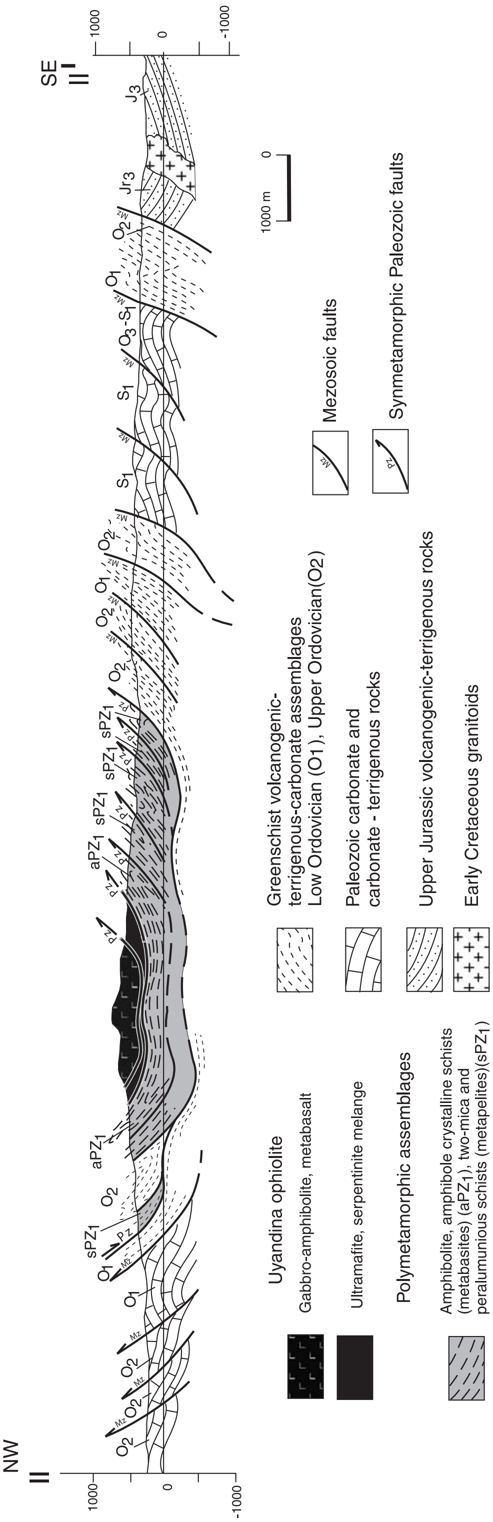


Fig. 10. Geological cross section of Uyandina ophiolites (for location, see Fig. 6).

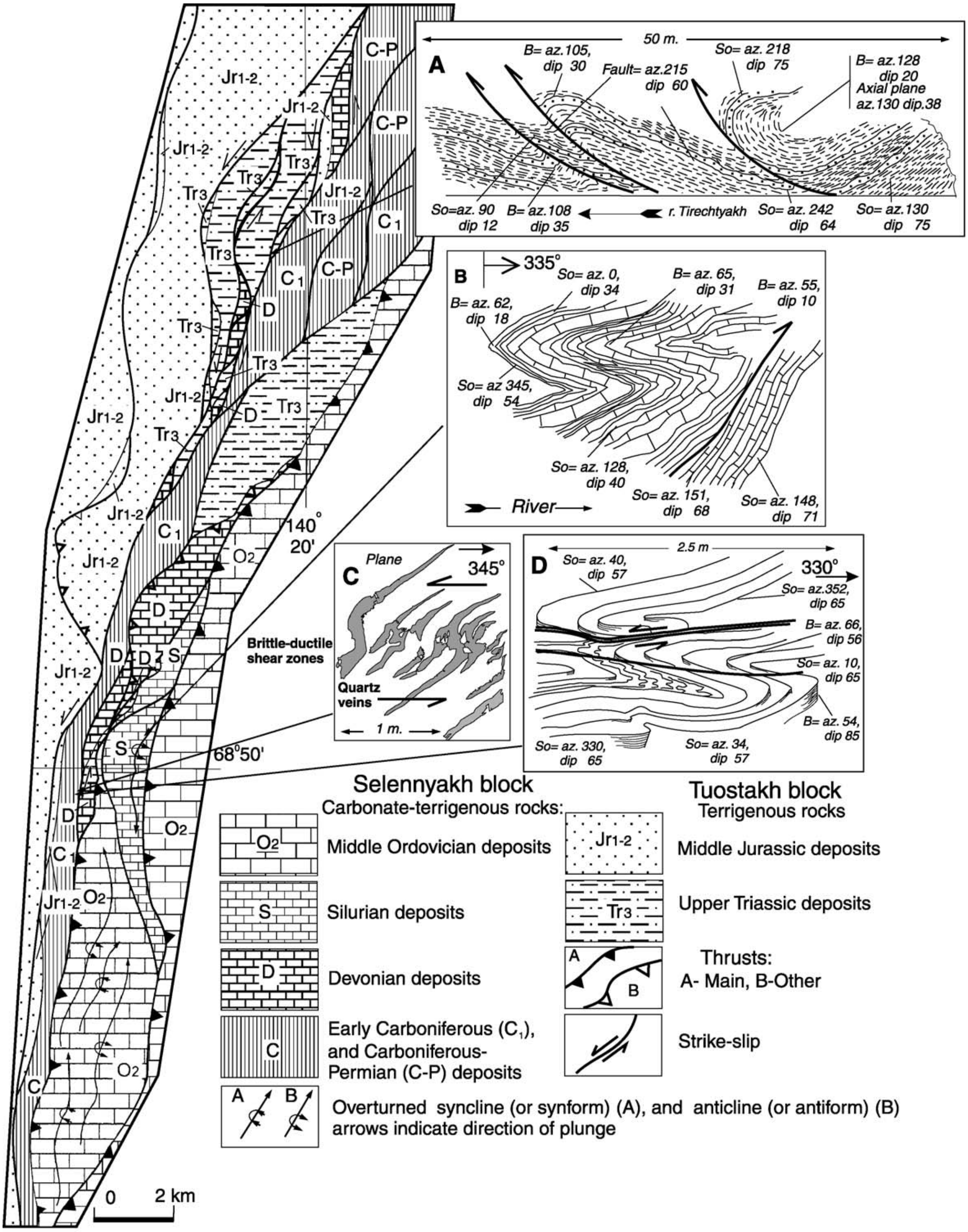


Fig. 11. Geological map of the Nalchan fault zone (western part of the Selennyakh block). Insert (sketches after photos): A–D_1, thrust deformations in the Triassic rocks of the Tuostakh block; B–D_1, thrust deformations in the Paleozoic rocks of the Selennyakh block; C, D–D_2, strike-slip deformations in the Selennyakh block deposits.

and clasts of serpentinites, derived from ophiolitic complexes. These olistrostromes are thought to herald nappe–thrust development (Oxman, 2000). In the Chemalgin block, allochthonous sheets are described by Parfenov et al. (1989).

D_1 thrusts also occur in the *Tuostakh block* (Fig. 14a,b). Duplexes, imbricate and "pop-up" structures, passive roof thrusts, etc. are all described in Oxman (2000). Large klippes (up to 5 km wide) occur to the west of the major thrust front (Fig. 15). Thrusts are expressed by terrigenous tectonic melange zones, and are confined to the horizons of argillaceous rocks, and the regional thrust-detachment is placed along the base of the Triassic deposits (Oxman and Prokopiev, 2000). Early (Mesozoic) deformation is represented by F_1 recumbent, tight to isoclinal folds that are overturned and inclined to the west or northwest (Fig. 11, insert A; Fig. 16). These folds are genetically related to a series of blind and emergent thrusts of western or northwestern vergence. In general, the Tuostakh block has an imbricate structure (Fig. 17), and the amount of shortening for the central part of the block is estimated at ~ 55%. This deformation is pre-Early Cretaceous in age, because the thrusts are post-tectonically intruded by granitoids dated at 127 Ma (^{40}Ar/^{39}Ar method, Layer et al., 2001).

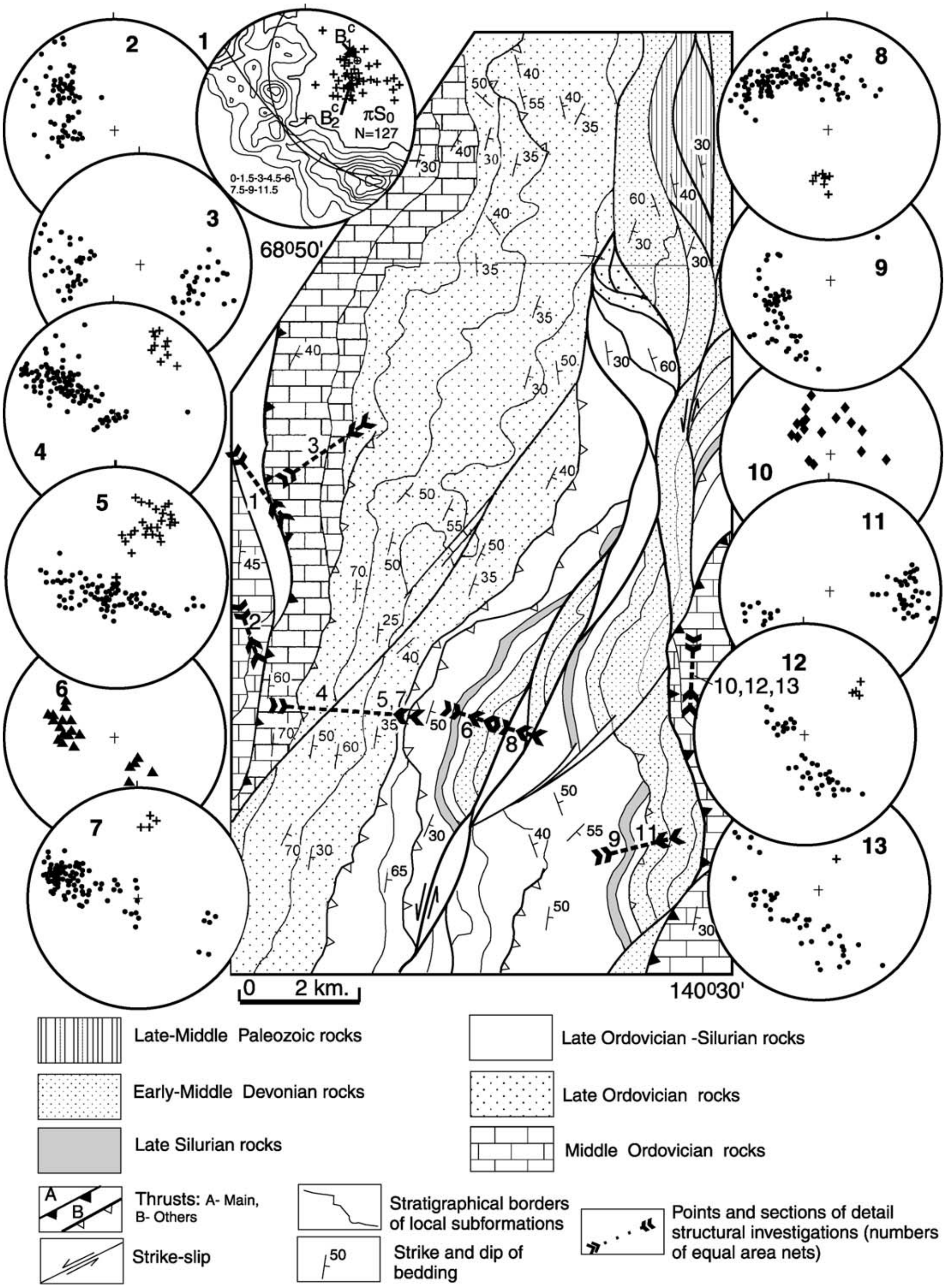
D_1 nappe and thrust deformation produce recumbent, and inclined F_1 folds in the *Polousnyi synclinorium*. Passive roof duplex structures and imbricate thrust fans were formed (Fig. 17). The calculated value of shortening for the southern part of Polousnyi synclinorium is ~ 30% (Oxman, 2000). The fold–thrust front reflects westerly to northwesterly tectonic transport, and is cut by lateral, oblique or truncated ramps in the north. The age of the nappe–thrust structures is similar to that of the strata. The age of D_1 deformation in the synclinorium is thought to gradually decrease from south to north. Thrusting is Late Oxfordian–Kimmeridgian in age in the south, Latest Jurassic in the central synclinorium, and Latest Jurassic–Cretaceous in the north (Layer et al., 2001). This progression is suggested by the gradual the decreasing age of the rocks participating in nappe–thrust deformation from south to north, and by a similar trend in the ages of the Transverse belt granites (Layer et al., 2001), which intrude these structures. In the para-autochthonous zones, a tectono-sedimentary terrigenous melange is developed (Oxman, 2000; Oxman and Prokopiev, 2000).

Thus, D_1 Jurassic–Cretaceous deformation consists of thrusts and F_1 folds that are recumbent and overturned to the west and the Middle Jurassic age of the olistostromal deposits marks the beginning of this deformation. Rejuvenation of the thrusts is recorded from east to west and from north to south.

Similar thrusting is also typical of other tectonostratigraphic units of the inner part of the Verkhoyansk–Kolyma orogen. In the Kular–Nera slate belt, D_1 is represented by folds and thrusts and a series of en echelon regional-scale anticlines and synclines (Gusev, 1979; Oxman, 2000) that are intruded by granites of the Major and Transverse belts. Early F_1 folds are recumbent and overturned to the northwest, and coeval thrusts contain slices of Triassic–Lower Jurassic strata. To the west in the Adycha–Taryn zone, Triassic deposits are detached from their basement and occur in discrete thrust slices (Parfenov et al., 1988).

A similar style of D_1 deformation occurs in the In'yali–Debin synclinorium (Gusev, 1979; Parfenov, 1984; Parfenov et al., 1988; Oxman, 2000, Figs. 10.6 and 10.7). Along eastern flank of In'yali–Debin synclinorium, thrusts are intruded by granite batholiths whose age, according to ^{40}Ar/^{39}Ar dating of hornblende and biotite, varies from 139 to 143 Ma (Layer et al., 2001). The deformation is thought to be Middle–Upper Jurassic, as indicated by abundant olistostromal deposits of this age (Parfenov, 1991). Horizontal shortening of 30–40% is similar to values calculated for southeastern part of Polousnyi synclinorium (Fig. 17). The largest horizontal displacement (more than 400 km) occurs along the Charky–Indigirka thrust zone, which defines the southwestern border of In'yali–Debin synclinorium, and along which Middle–Late Jurassic deposits are detached

Fig. 12. Geological–structural map of the western part of the Selennyakh block (compiled by the author and geologists from GGP "Lenskoe"). Symbols on the equal area plots (equal area lower hemisphere): points—poles to bedding (πS_0); crosses—measured hinges of folds and its generations; crosses in circles—inferred fold axes of first (B^c_1) and second generations (B^c_2); triangle—poles axial planes of folds; rhombs—deformational lineations. Contours are in percent of total data points per 1% area of net.


1
2
3
4
5
6
7
8
9
10
11
12
13
B₁ᶜ
B₂ᶜ
πS₀
N=127
0-1.5-3-4.5-6-7.5-9-11.5
68⁰50'
140⁰30'
0 2 km.
10,12,13
5,7
Late-Middle Paleozoic rocks
Early-Middle Devonian rocks
Late Silurian rocks
Late Ordovician -Silurian rocks
Late Ordovician rocks
Middle Ordovician rocks
Thrusts: A- Main, B- Others
Strike-slip
Stratigraphical borders of local subformations
Strike and dip of bedding
Points and sections of detail structural investigations (numbers of equal area nets)

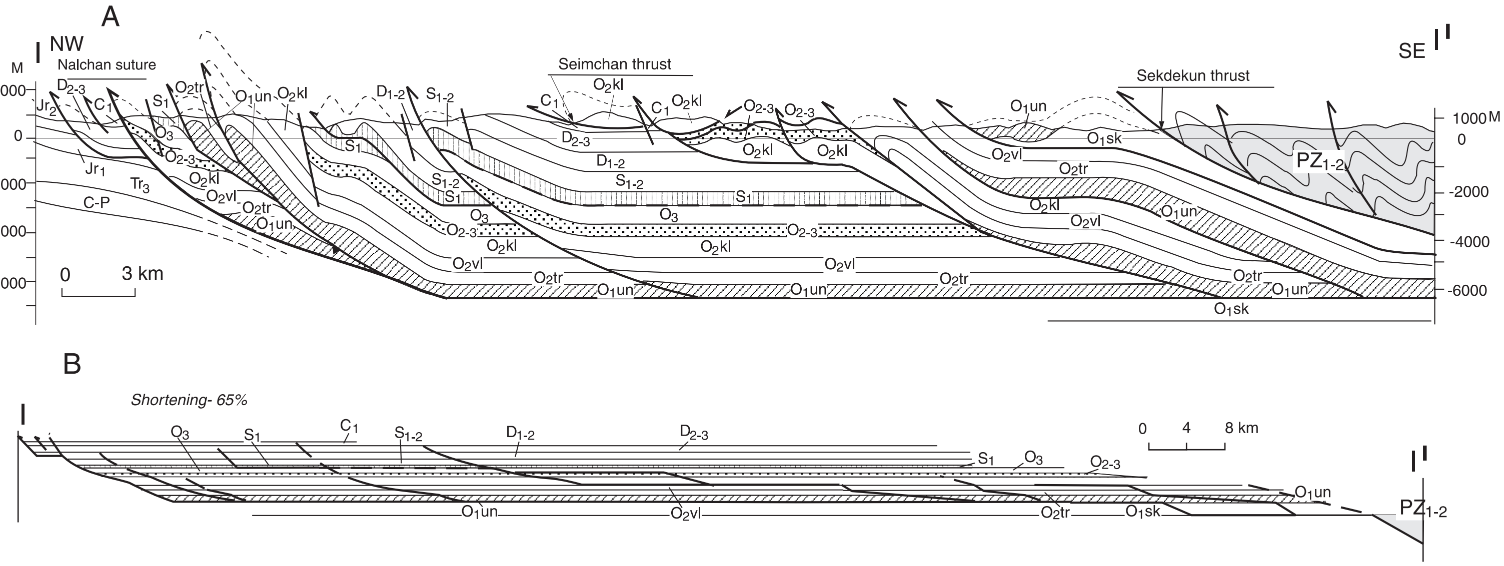


Fig. 13. Balanced (A) and reconstructed (B) sections of west part of Selennyakh block. For location of section, see Fig. 6. Assemblages of Polousnyi synclinorium and Tuostakh block: Middle Jurassic (Jr_2), Lower Jurassic (Jr_1), Triassic (Tr_3), Permian–Carboniferous (C–P); carbonate and carbonate–terrigenous deposits of Selennyakh block: Lower Carboniferous (C_1), Middle–Upper Devonian (D_{2-3}), Lower–Middle Devonian (D_{1-2}), Silurian (S_{1-2}); Inach Formation Lower Silurian (S_1in), Upper Ordovician (O_3), Middle–Upper Ordovician (O_{2-3}), Middle Ordovician, Kaluchan Formation (O_2kl), Volchin Formation (O_2vl), Taryng–Uriakh Formation (O_2tr), Lower Ordovician: Ungin Formation (O_1un), Sekdekun Formation (O_1sk); Paleozoic greenschist assemblages (PZ_{1-2}).

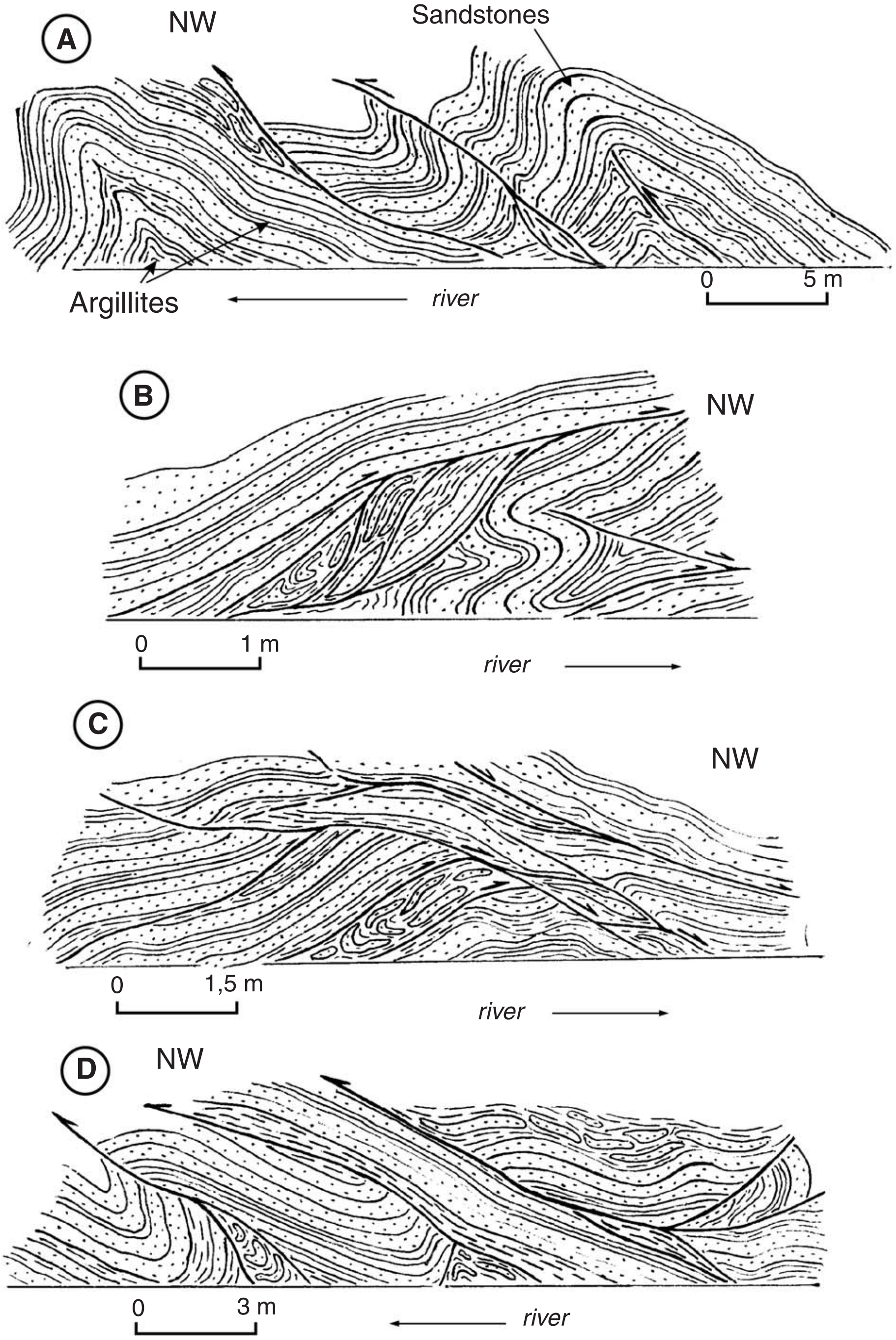
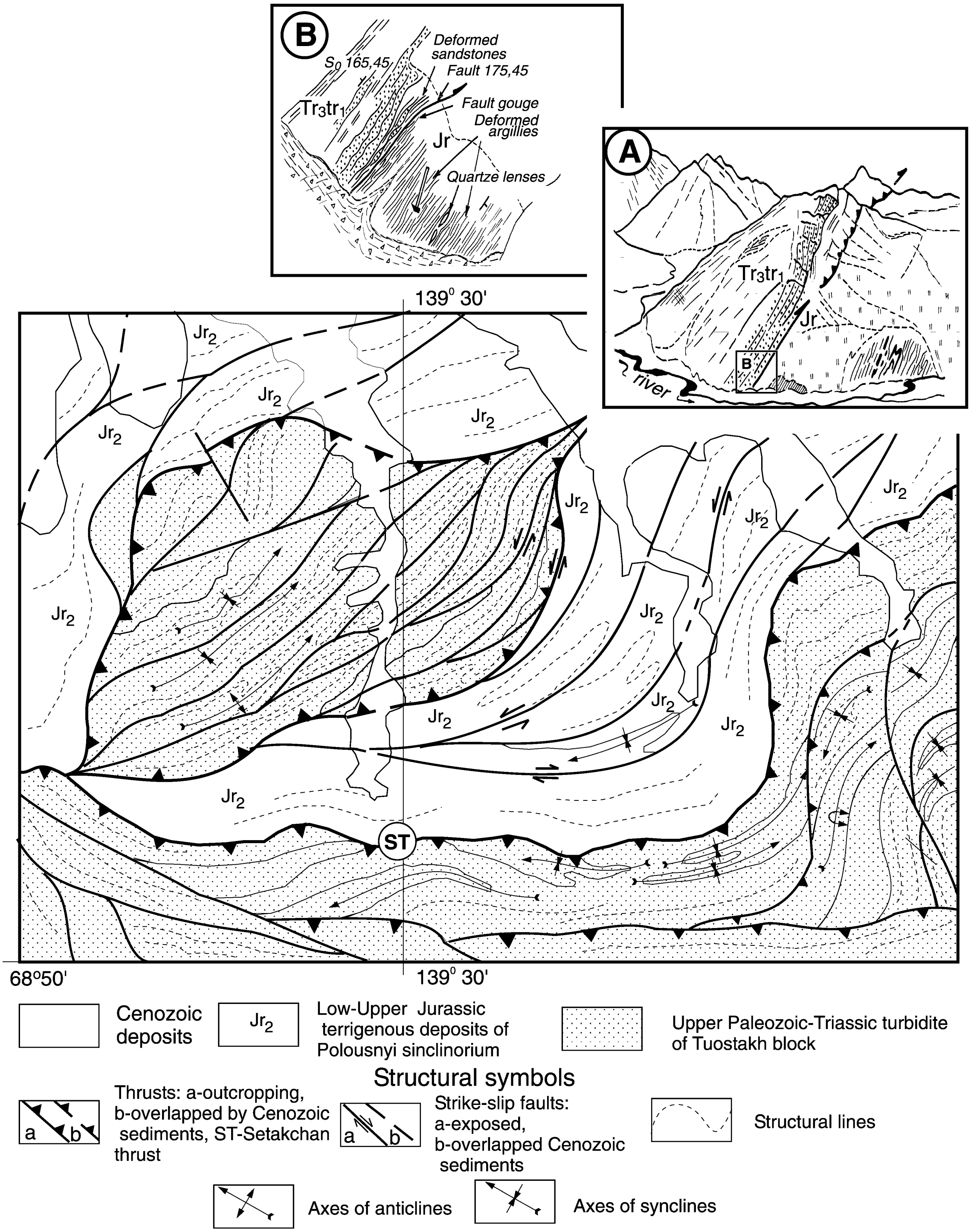


Fig. 14. Outcrop-scale D_1 deformation in the Upper Triassic rocks of the Tuostakh block (A, B), and Low–Middle Jurassic rocks of Polousnyi synclinorium (C, D) (sketches after photo). The deformation includes various types of thrusts and F_1 overturned and inclined to the northwest. See Fig. 9 for location.


B
S0 165,45
Deformed sandstones
Fault 175,45
Fault gouge
Deformed argillies
Quartze lenses
Tr3tr1
Jr
A
Tr3tr1
Jr
B
river
139° 30'
Jr2
ST
68°50'
139° 30'
Cenozoic deposits
Jr2
Low-Upper Jurassic terrigenous deposits of Polousnyi sinclinorium
Upper Paleozoic-Triassic turbidite of Tuostakh block
Structural symbols
a b
Thrusts: a-outcropping, b-overlapped by Cenozoic sediments, ST-Setakchan thrust
a b
Strike-slip faults: a-exposed, b-overlapped Cenozoic sediments
Structural lines
Axes of anticlines
Axes of synclines

and overthrust onto Late Triassic formations (Gusev, 1979; Parfenov, 1984).

3.2.2. D_2—transpressional deformation

Late Mesozoic D_2 deformation in ophiolites and metamorphic rocks produced F_2 folds characterized by steep hinges that are thought to be related to transpressional tectonics (Oxman et al., 1995, 1998b). F_2 folds in the Selennyakh and other blocks of the Omulevka microcontinent occur as en echelon non-cylindrical and cylindrical folds with moderately to steeply plunging hinge lines (Fig. 11, insert D; Fig. 12, equal area net 1). Regional-scale and outcrop-scale F_2 folds deform and rotate D_1 structures. D_2 deformation is associated with steep faults (some are reactivated D_1 thrusts) with strike-slip, normal-strike-slip, and thrust-strike-slip kinematics. A sinistral strike-slip component is expressed by displacement of some stratigraphic markers and other shear-sense indicators (slickenside lineation, brittle–ductile en echelon quartz-vein shear zones (Fig. 11, insert C), drag folds and others (Oxman, 2000). The largest faults, such as Nalchan Fault, have structures typical of strike-slip duplexes and imbricate (accordingly to the terminology of Woodcock and Fisher, 1986; Figs. 6, 11 and 12)).

Similar D_2 structures occur in the other blocks of the Omulevka microcontinent (Figs. 7 and 8; see also Figs. 8.14, 8.23, 8.25 and 9.8–9.12 in Oxman, 2000; Gusev, 1979). The second stage of deformation of Tuostakh block produced conjugate brittle–ductile shear zones with strike-slip, oblique thrust-strike-slip with right- and left-lateral components. Structures such as horsetail splay, strike-slip fans duplexes are similar to those described by Woodcock and Fisher (1986) (Fig. 15). Coeval F_2 folds have outcrop-scale steeply and moderately plunging hinges and sub-vertical or steep southwesterly dipping northwest-striking axial surfaces (Fig. 18, insets) with an axial planar S_1 cleavage (Fig. 18, inset A) and an S_2 crenulation cleavage. The intersection of S_1 and S_2 produced an L_2 lineation which is parallel to the axes of associated small-scale F_2 folds. F_2 folds are en echelon, and asymmetric with S- or Z-like patterns (Fig. 18). They are superposed on earlier D_1 thrusts and folds (Fig. 16).

D_2 structures in the Polousnyi synclinorium also produced left-lateral strike-slip faults. During this stage, shortening of older fold structures and curving into large sigmoidal folds that re-oriented and transposed earlier structures. In the Polousnyi synclinorium, strike-slip faults have displacements varying from tens of centimeters to more than 10 m. Transpression resulted in the formation of duplexes and fans. Faults are expressed by mylonites, cataclasites and breccias. Slickenlines on the fault planes, and other kinematics indicators exhibit sinistral strike-slip and reverse-strike-slip kinematics.

D_2 is also expressed in the inner part of Verkhoyansk–Kolyma orogen, producing thrusts and nappes in the In'yali–Debin sinclinorium and regional- to outcrop-scale F_2 folds, which are coeval with strike-slip and normal faults (Fig. 8) (Oxman, 2000; Oxman and Prokopiev, 2000; Parfenov, 1991). The relationship between D_2 and the granite plutons is unclear, and although the age of this deformation is uncertain, it is inferred to be Late Volgian–Early Cretaceous in age (Oxman, 2000).

3.2.3. D_3—transtension

D_3 structures occur in the all units of the inner part of the Verkhoyansk–Kolyma orogen. Although not as widespread as D_1 and D_2, they are expressed by regional- to outcrop-scale steep faults, mostly with combined strike-slip-normal and normal fault kinematics (Oxman, 1998; Figs. 5–8, 16). In the central and southeastern part of the orogen, D_3 faults are predominantly NW-striking, i.e. similar in orientation to earlier structures. In the northwestern flank of orogen, faults with thrust- and sinistral-thrust components are developed (Oxman and Prokopiev, 1993a, 1995; Wallace et al., 1995). F_3 folds with

Fig. 15. Structural map of the junction Tuostakh block and Polousnyi synclinorium (compiled by V.S. Oxman, after unpublished data of the GGP "Lenskoe" and personal data) For location, see Fig. 9. Large klippe of the Triassic rocks (up to 5 km wide) are mapped westward of the major thrust front. Early (Mesozoic) deformation is represented by F_1 recumbent, tight to isoclinal folds that are overturned and inclined to the west or northwest, and by genetically related thrusts. Early thrusts were transposed into left-lateral strike-slip faults. Strike-slip faults form fan and duplex structures. Insets (sketches after photo): A—Setakchan thrusts Triassic rocks of preorogenic Tuostakh block; B—outcrop-scale fragment of the Setakchan thrust (see insert A for location).

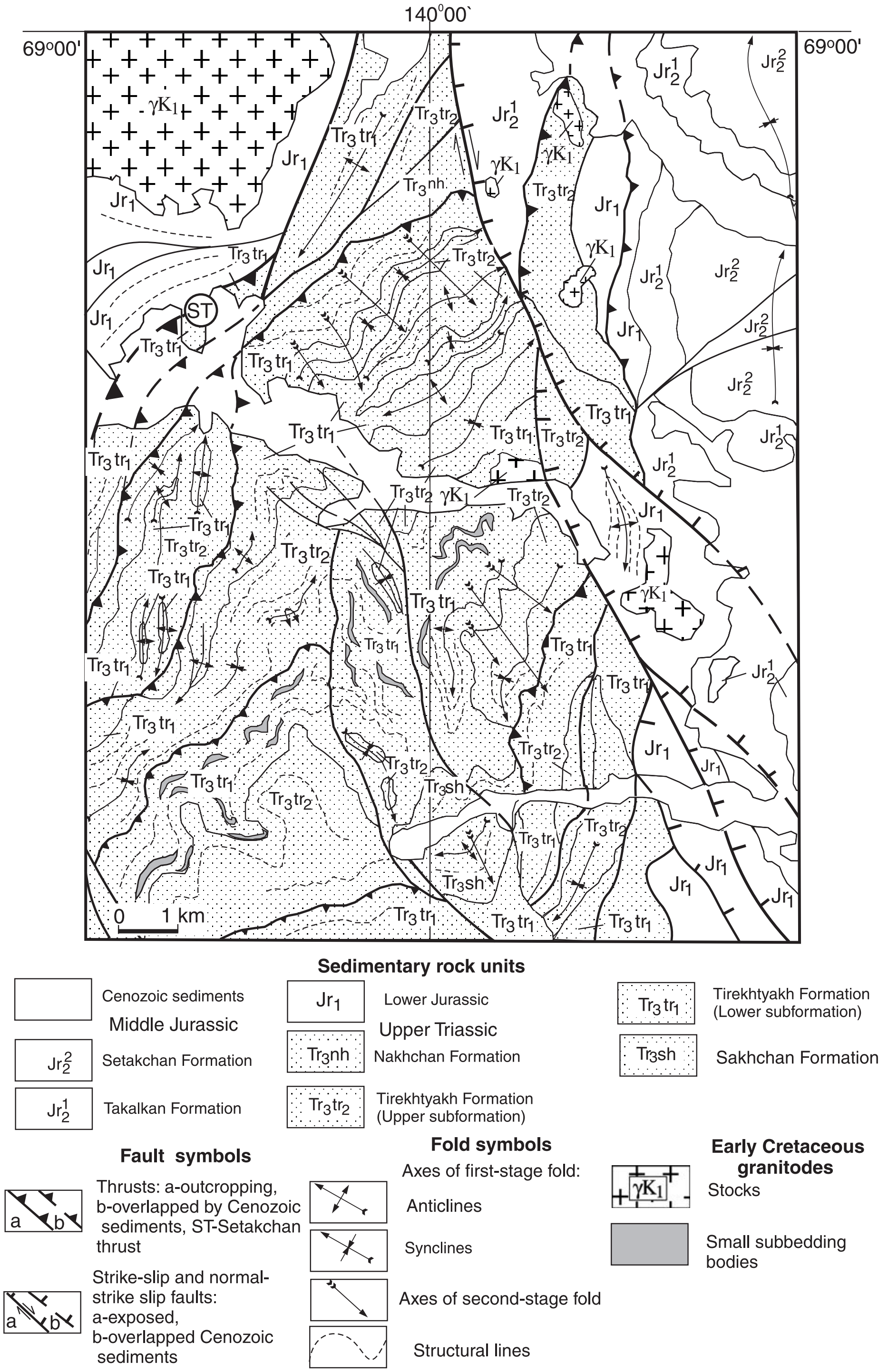


Fig. 16. Structural map of northwestern part of Tuostakh block (compiled by V.S. Oxman after unpublished data of the GGP "Lenskoe", and personal dates). For location, see Fig. 9.

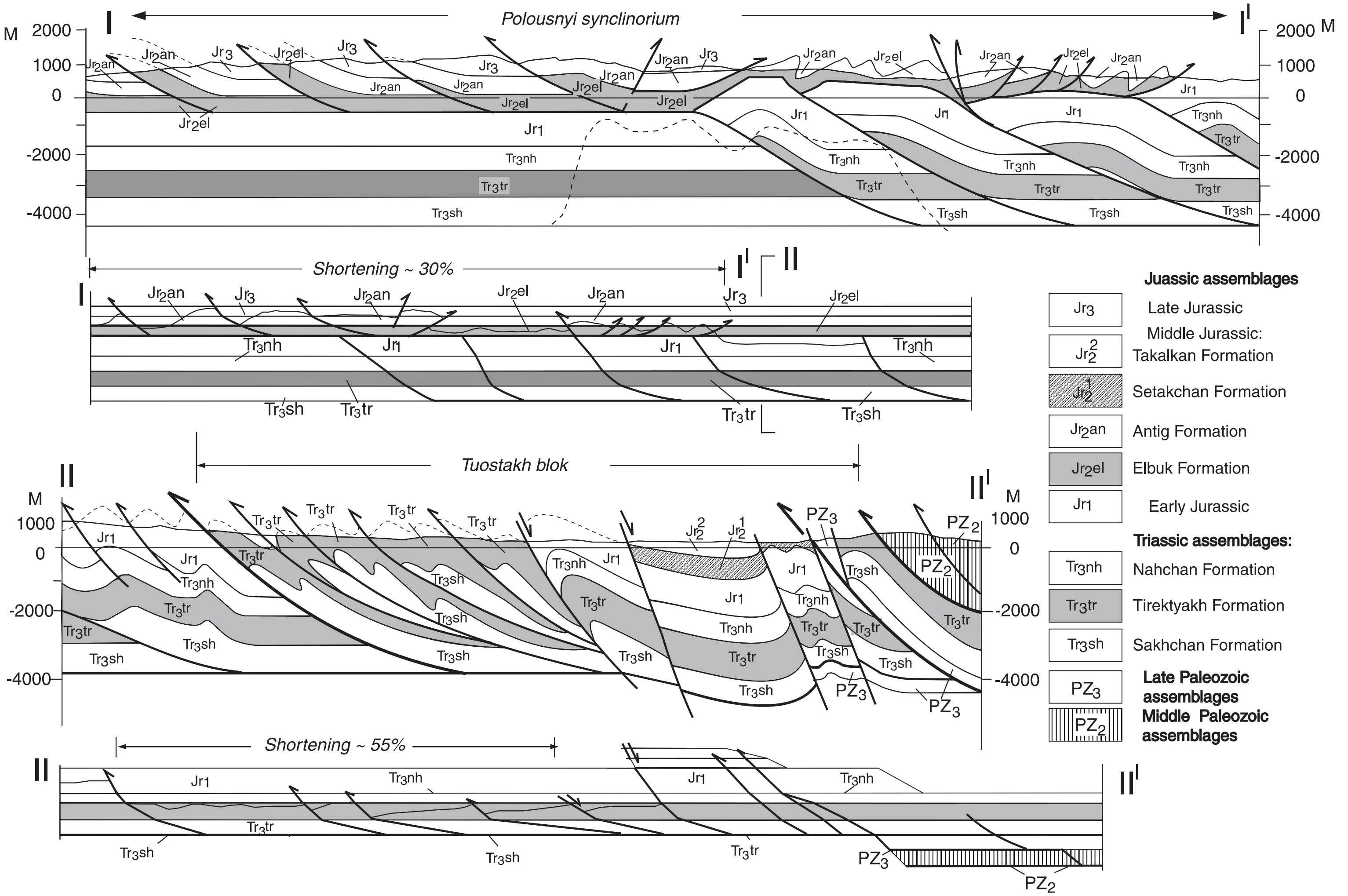


Fig. 17. Balanced and reconstructed sections of the southern zone of the Polousnyi synclinorium (for location of sections, see Fig. 9). Dashed line on section I–I′ shows outlines of the Deputatskiy granitoid pluton.

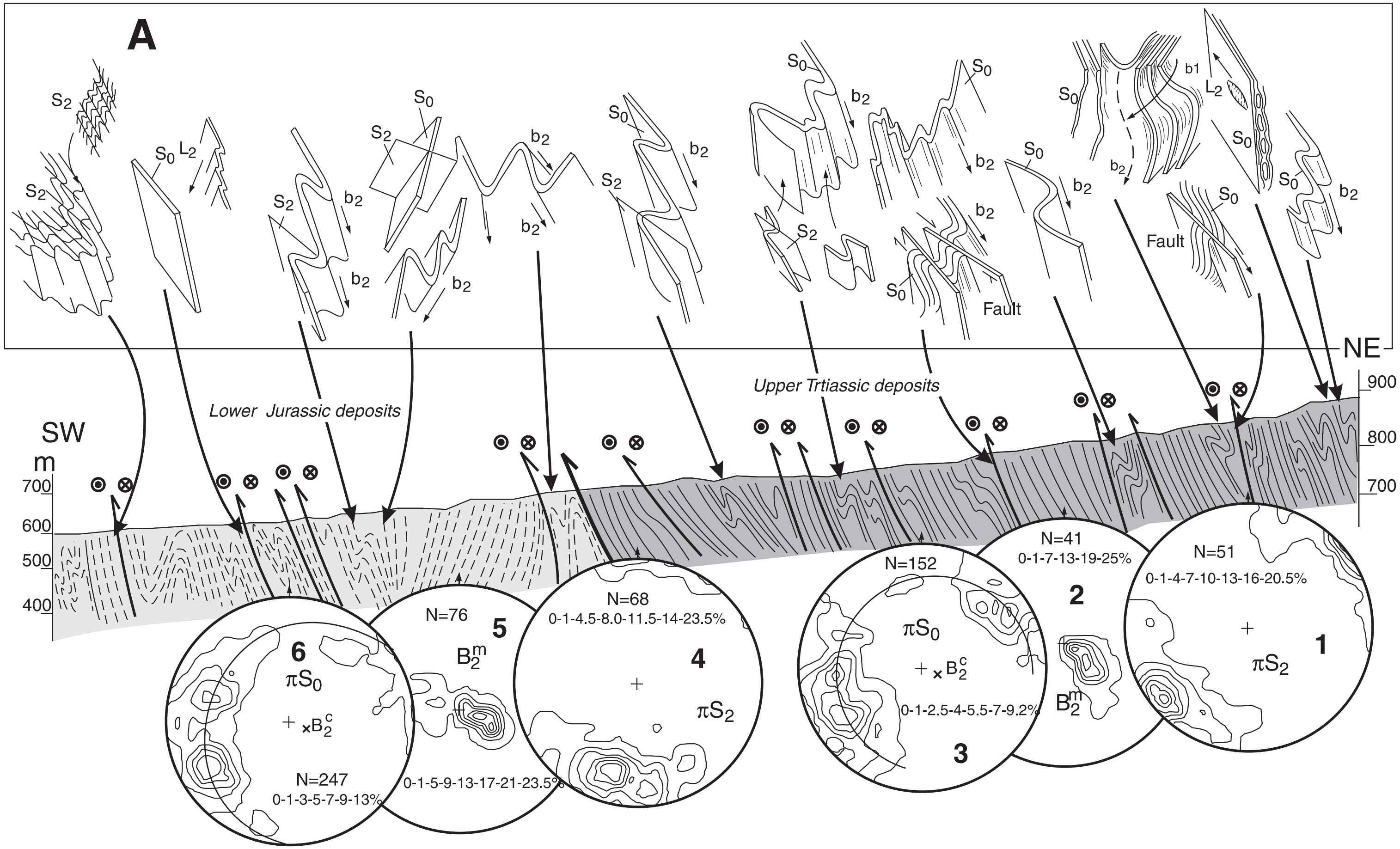


Fig. 18. Fragment of structural–kinematic section of joining tectonic zone of Polousnyi synclinorium and Tuostakh block. Strike-slip faults: open circle with a point inside denotes block movement away from viewer; circle with an × denotes block movement towards viewer. See Fig. 5 for location. Inset A above section: small- and outcrop-scale structural forms (sketches after photos), arrows show places of the photos. Structural symbols: S_0, πS_0—bedding and poles to bedding; $S_2 \pi S_2$—cleavage of axial plane and their generations, poles to cleavage plane and their generations; Fold axes and their generations: $b^{c}_{1,2}$—calculated, b^{m}_{2}—measured; L_2—lineation and their generation. Equal area plots (lower hemisphere projections): 1–3, for the Triassic deposits of the Tuostakh block; 4–6, for Lower Jurassic deposits of the Polousnyi synclinorium. Contours are in percent of total data points per 1% area of net.

steeply plunging hinges are associated with normal-strike-slip faults. Small-scale kink-folds are also recognized.

Taken together, these regional strike-slip faults display synthetic and antithetic shears similar to those formed in the strike-slip regimes (Sylvester, 1988). Numerous small bodies and stocks of the Transverse granite belts are coeval with D_3 faults (Trunilina et al., 1999). The age of these granites is ranges from 130 to 120 Ma (i.e. Late Neocomian) with the younger plutons occurring in the west.

In the central part of the orogen, Cenozoic deformation is evident (Parfenov, 1991, 1995; Nokleberg et al., 2001). Tectono-stratigraphic units, located in the outer part (Verkhoyansk fold-and-thrust belt) and in the hinterland of the orogen (Ilin–Tass anticlinorium, Alazeya block), also have fold–thrust structures, thought to have formed from reactivation of Mesozoic structures (Parfenov et al., 1995; Prokopiev, 1998).

4. Geodynamic evolution and discussion

There are several model for the Mesozoic development of northeastern Asia, which, to some extent, provide the context for interpretations on the tectonic and geodynamic evolution of the studied region (Gusev, 1979; Parfenov, 1984, 1995; Sengor and Natal'in, 1996; Zonenshain et al., 1990; Bogdanov and Tilman, 1992; Oxman, 2000; Oxman et al., 1995; Parfenov et al., 1993; Sokolov, 1992; Sokolov et al., 1997; Khudoley and Sokolov, 1998; Nokleberg et al., 2001; Tectonics, Geodynamics and Metallogeny of the Sakha Republic (Yakutia), 2001; and others).

Ordovician–Devonian strata of the inner part of the Verkhoyansk–Kolyma orogen (the Omulevka microcontinent) were deposited along the eastern flank of the Verkhoyansk passive margin (modern coordinates, Natapov and Surmilova, 1986; Zonenshain et al., 1990; Parfenov, 1991). According to these authors, "Paleozoic" blocks were separated from Verkhoyansk continental margin as a result of Late Paleozoic rifting. Parfenov (1995) and Nokleberg et al. (2001) interpret these blocks of Paleozoic rocks as pericratonic (i.e. proximal) terranes. Bulgakova (1997) supposes that these blocks were separated from eastern part of Verkhoyansk margin in Early Ordovician. Other researchers, however (Natapov and Surmilova, 1986; Zonenshain et al., 1990), consider only the Arga–Tass and Rassokha blocks as discrete terranes that are composed mainly of deep-water deposits.

Alternatively, Bogdanov and Tilman (1992) interpret these blocks as exotic terranes that represent Paleozoic fragments of Arctic passive margin displaced in a southwestern direction to the Siberian continent.

The Late Devonian is characterized by abrupt changes in geodynamic environments in northeastern Asia and by variations in the orientations of compressional and extensional vectors (Fig. 20). As a result of rifting, fault-bounded blocks of the Paleozoic Omulevka microcontinent were severed from eastern edge of Verkhoyansk margin, and opening of Oimyakon basin occurred which was underlain by oceanic or thinned continental crust (Parfenov, 1991; Sengor and Natal'in, 1996; Oxman, 1998). Late Devonian to Permian volcanogenic–siliceous–terrigenous hemipelagic and condensed sections were developed along western margins of the Paleozoic blocks. A back-arc basin associated with the Alazeya island arc system is thought to be located east of the Omulevka microcontinent (in modern coordinates) and relics of this back-arc basin are represented by fragments of ophiolites that occur along the axial part of collision belt of Chersky (Oxman et al., 1995; Oxman, 1996).

The following Late Paleozoic tectonic regimes are proposed (from west to east, in modern coordinates) to the east of Verkhoyansk continental margin of the north Asian craton: Oimyakon sedimentary basin, Omulevka microcontinent, back-arc basin, Alazeya island arc system.

The Late Triassic–Early Jurassic is characterized by recurrent displacements of the blocks along the edge of north Asian craton (Parfenov, 1991; Neustroev et al., 1993). Progressive shortening and shallowing of Oimyakon basin are documented. Calcareous flysch that contain a volcanogenic component began to accumulate in the eastern part of this basin.

In the Late Mesozoic, three main stages of deformation are distinguished and occur in almost all parts of the belt (Oxman and Prokopiev, 1993a,b, 1995; see also Fujita and Newberry, 1982; Fujuta and Newberry, 1983).

Many models propose the existence of a subduction zone dipping beneath the Omulevka microcontinent and north Asian craton (Natapov and Surmilova, 1986; Zonenshain et al., 1990; and others). The abundance of Cretaceous granitoid in the inner parts of Verkhoyansk–Kolyma orogen supports this model. An alternative hypothesis that there were two subduction zones, an early zone dipping westwards resulted in the accretion of the Alazeya island arc and Omulevka microcontinent (terrane) and the formation of Kolyma–Omolon microcontinent, and late zone, of opposite polarity, whose origin is attributed to the accretion of Kolyma–Omolon microcontinent to the Verkhoyansk continental margin (Parfenov, 1995). The data presented in this article favour the latter model.

In the Early–Middle Jurassic, accretion and collision of Omulevka microcontinent and Alazeya arc were related to closure of the intervening back-arc basin forming the composite Kolyma–Omolon microcontinent or superterrane (Parfenov, 1995; Nokleberg et al., 2001) was formed. Obduction of metamorphized ophiolites and metamorphic rocks occurred in the initial stages of accretion. This accretion caused additional crustal-scale buckling along the eastern flank of the Oimyakon basin. The In'yali–Debin and Polousnyi synclinoria were located above the thinned crust of this basin. These synclinoria are typically linear, asymmetric structures with gentle western and steep eastern limbs. Collision between the composite Kolyma–Omolon microcontinent and the Verkhoyansk continental margin caused the generation of a new subduction zone with opposite polarity (Figs. 19 and 20).

Nappes containing ophiolite and polymetamorphic schists were thrust over Paleozoic carbonate–terrigenous deposits of Omulevka microcontinent. Various types of olistostromes were formed (Parfenov et al., 1989; Oxman, 2000) and turbidites accumulated in Polousnyi and In'yali–Debin synclinoria. Deformation with very similar styles occurs in preorogenic and synorogenic deposits of the inner part of the Verkhoyansk–Kolyma orogen and is represented by nappes, thrusts, thrust duplexes and imbricate fan structures, F_1 recumbent and overturned folds. Shear sense indicators indicate that the thrust front verged from east to west. In the preorogenic deposits of the Omulevka microcontinent and Tuostakh block, the nappe–thrust front is classified as an emergent thrust front type (Morley, 1986), and to the west within the

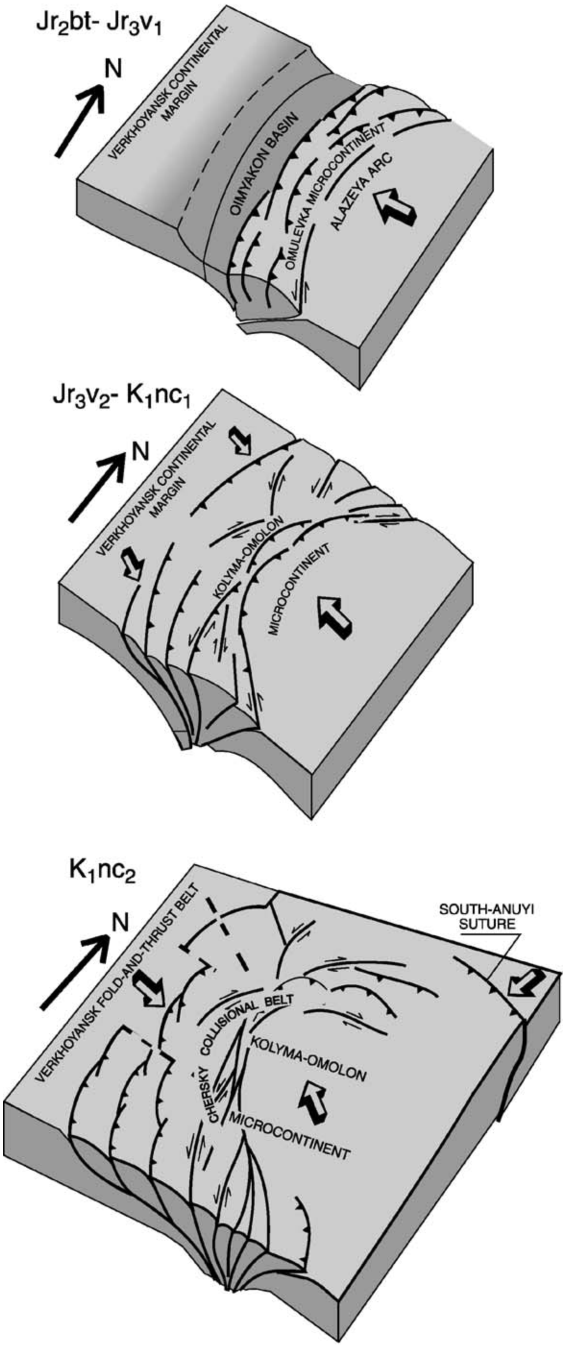


Fig. 19. Scheme of evolution of inner part of Verkhoyansk–Kolyma orogenic area ("Kolyma Loop") (arc Chersky collision belt).

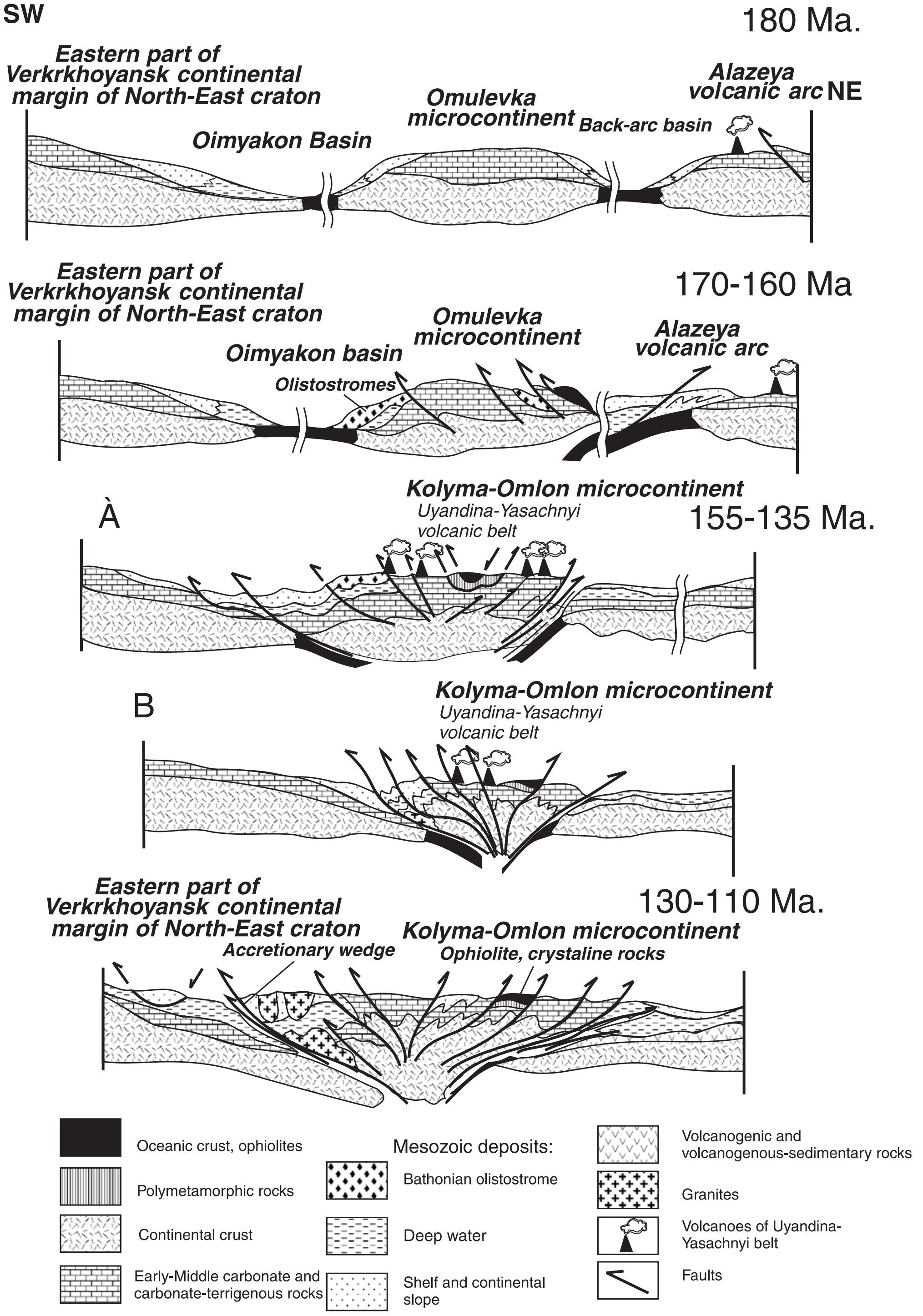


Fig. 20. Model of geodynamic evolution of the Chersky collisional belt: A — northern part of belt; B — southern part of belt.

In'yali–Debin and Polousnyi syclinoria, similar thrusts were synchronous with sedimentation. The style of deformation of these synorogenic deposits is similar to that observed in modern accretionary prisms (Oxman, 1998; Prokopiev, 1998; Oxman, 2000). They are represented by thrust and nappe deformation involving slightly lithified turbidites and olistostromal horizons (Oxman, 2000). The age of the rocks and the thrusts are older to the east, and to the west, regional thrusts cut into higher stratigraphic levels. Thrust fronts, developed in synorogenic rocks of the Polousnyi and In'yali–debin synclinoria, belong to emergent or a buried thrust front type. Considerable crustal thickening is related to regional thrust and nappe development. Low pressure greenschist facies metamorphism ($T = 300-450$ °C, $P \sim 2.0$ kbar) is recorded in the northern and central parts of the belt. Medium pressure (Barrovian-type, $P = 4.5-6.0$ kbar) metamorphism (e.g. Thompson et al., 1997) is registered in more southern regions (Oxman et al., 1998b).

Convergence and accretion of Kolyma–Omolon microcontinent with the northeast Asian craton, and progressive narrowing and closing of Oimyakon sedimentary basin occurred in the Oxfordian–Early Tithonian (Volgian) (Nokleberg et al., 2001). Deposition of turbidites and shelf complexes continued in Polousnyi and In'yali–Debin synclinoria. Progradation of a synsedimentary thrust front and related folding occurred in the west.

The Ilin–Tass trough, which is dominated by turbidites, is located in the hinterland of the collisional belt (Parfenov, 1991). Formation of this basin is might be connected with decoupling in the hinterland of the collision belt when the Ilin–Tass trough was transformed into Indigirka–Zyryanka sedimentary basin.

Accretion of the Kolyma–Omolon composite microcontinent to the Verkhoyansk continental margin took place in the Late Tithonian (Volgian) to Early Neocomian (Figs. 19 and 20). The Kolyma–Omolon microcontinent is inferred to represent an indentor, and was partly composed of poorly lithified Mesozoic sediments of the eastern Verkhoyansk continental margin. Paleozoic rocks, which comprise the Omulevka microcontinent, are deformed into discrete, en echelon, lenses that are bounded by faults with complex kinematics. In the southern part of the region, the faults are NW-striking. In the northern part, these faults are NE-striking and dextral. In the Tuostakh block, conjugate left-lateral and right-lateral faults occur in front of regional thrusts (Oxman, 2000). Transpressional duplexes are formed (which grade into fans along strike) where there are abrupt changes in strike of structures from northwest to northeast. Local transtensional structures form "pull-apart" basins, bounded by strike-slip extensional duplexes and fans (in terminology by Woodcock and Fisher, 1986; Sylvester, 1988).

Early thrusts, located in axial part of the collision belt, transform into combined oblique thrust, and transpressional structures. Coeval F_2 folds deform early thrusts, recumbent folds, olistostromes, and ophiolitic sheets. They are distributed in en echelon arrays and are periclinal, with their plunge affected by changes in fault orientations. Calculated values of shortening for central part of collision belt are 55–65%, and for both the Polousnyi synclinorium and Tuostakh block are 35–45%.

In western regions, thrusting continued and prograded towards north Asian craton and Verkhoyansk continental margin, i.e. to the foreland of the orogen. Late Mesozoic deposits, probably, were detached from the basement. The thrust front was bound by lateral oblique or truncated ramps. Formation of nappe–thrust structures was close to sedimentation age with basal detachments probably located at the contact between the underlying Middle and Early Jurassic rocks.

The most important faults (Adycha–Tarun, Charky–Ingigirka, etc.) divide assemblages that formed in different geodynamic conditions at a great distance from each other and can be considered as "ophiolite-free suture zones" (Dewey, 1977; Natal'in and Parfenov, 1989; Leonov, 1993). The Adycha–Tarun "ophiolite-free" suture zone separates the Verkhoyansk continental margin and rocks of Kular–Nera slate belt (i.e. the deep deposits of Oimyakon basin) (Parfenov et al., 1988).

D_2 deformation is Late Volgian in age in the eastern part of the Verkhoyansk–Kolyma collision belt) and Early Neocomian in the southwestern and northeastern parts. This interpretation is supported by progressive younging to the west and north of the rocks that participated in nappe–thrust tectonics, and also by gradual younging in the age of granites that crosscut these deformations. Frontal thrust structures of Verkhoyansk fold–thrust belt were formed in Cretaceous times. Calculated values of horizontal shortening for other segments of Verkhoyansk fold-and-thrust belt vary from 21% to 48% (Parfenov et al., 1995). The rate of lateral migration of folding in southwestern and northeastern directions was probably 1–3 cm/year.

Changes in kinematics and orientation of coeval faults and folds are probably connected with the rotation of north Asian craton (as evidenced by paleomagnetic data, Bondarenko and Didenko, 1997; Sokolov et al., 1997). The age of deformation is determined by the relationship of the faulted and folded structures with the granitic plutons. These plutons are Late Jurassic in age in southeastern parts of collision belt, and are progressively younger to the north and west (Layer et al., 2001). The overall kinematics of faults in central part of the collision belt and the strike-slip dislocations in other parts of the belt are related to oblique collision between Kolyma–Omolon microcontinent and Verkhoyansk continental margin of the north Asian craton.

Gradual changes in the displacement direction of the Kolyma–Omolon microcontinent from the southwest to the northwest occurs in the Late Neocomian, and caused transpressional–collisional deformation. Faults with strike-slip and oblique-slip kinematics have similar orientations to earlier structures in the southeastern and central segments of collision belt. In northeastern part of the region, thrust-, oblique-slip with mainly sinistral displacements followed by granitic intrusions occurred (Layer et al., 2001). F_1 and F_2 folds are deformed into F_3 noncylindric folds with steep hinges and axial surfaces. Additional rotation of the collisional belt by northeastern and southwestern compression was connected with collision of continental margin of Novosibirsk–Chukotka microcontinent or the Chukotka–Arctic Alaska block (Natal'in et al., 1999) and north Asian (Siberian) craton, and with the closing Anyui–Angayucham (South-Anyiu) basin (Wallace et al., 1995; Sokolov et al., 1997; Nokleberg et al., 2001).

The Mesozoic Verkhoyansk–Kolyma orogenic belt of northeast Asia was formed as a result of the closure of a small ocean or a marginal basin. Early faults and folds formed as a result of the oblique collision and are represented by accretionary, subduction-related nappes and thrusts, and by late transpression–collisional structures. The Verkhoyansk–Kolyma and Novosibirsk (Arctic Alaska)–Chukotka orogens of northeast Asia are attributed to the accretion and late collision of microcontinents (Kolyma–Omolon and Chukotka, respectively) and long-lasting existing convergent margins of Siberian craton.

Geodynamic models for the early stages of evolution of Mesozoic orogenic belts of northeastern Asia can be compared with modern environments, such as the continental convergent margins of the northern part of Paleo-Pacific, particularly in Bering or Okhotsk seas. Models for rotation of the Verkhoyansk–Kolyma orogen can be also compared with modern situations of Indonesian archipelago, where northern Australia is colliding with the Banda arc. One of the further goals of IGCP 453 is to resolve these problems and refine these models.

5. Conclusion

The Verkhoyansk–Kolyma belt lies in the western portion of the Verkhoyansk–Chukotka Mesozoic orogenic zone of northeastern Asia between the ancient Siberian platform and Mesozoic–Cenozoic Koryak–Kamchatka accretionary system. The Verkhoyansk continental margin is the external (foreland) part of Verkhoyansk–Kolyma orogen whereas the Chersky collisional belt is the inner part of the orogen and includes stacked allochthons of ophiolite, a number of variably metamorphosed and deformed fault-bounded blocks, consisting of Paleozoic–Early Mesozoic pre-orogenic rocks, synorogenic Mesozoic sedimentary rocks, Main, Northern and Transverse granite and Uyandina–Yasatchnyi volcano-sedimentary belts. The inner part of the Verkhoyansk–Kolyma orogen is a collage of terranes that combined to form the composite Kolyma–Omolon microcontinent. The hinterland of the orogen includes polydeformed Paleozoic–Early Mesozoic complexes of the Alazeya block and synorogenic and postorogenic Mesozoic complexes of terrigenous rocks of the Ilin–Tass anticlinorium and Indigirka–Zyryanka basin.

The earliest, supposedly Paleozoic deformation, is recorded only in ophiolites and polymetamorphic rocks. These deformations were connected with Barrovian-type metamorphism dated at 370 Ma. Ophiolite and polymetamorphic rocks are stacked on deep-seated thrusts and represent tectonic detachment of oceanic crust.

The main stages of accretion are defined in central part of the Verkhoyansk–Kolyma belt. A Middle–Later Jurassic stage is connected with the coupling of separate structures into composite Kolyma–Omolon microcontinent. Late Jurassic–Early Cretaceous collision of Kolyma–Omolon microcontinent with Verkhoyansk continental margin. A Cretaceous stage is connected with the accretion and collision Chukotka microcontinent to north Asian (Siberian) craton.

Regional structures of the central part of the Verkhoyansk–Kolyma orogen formed during these three stages, and reflect changes in the displacement direction of the Kolyma–Omolon microcontinent from E–W to N–S. Fold and thrust deformation occurred along the entire belt in the Bathonian–Early Volgian. Obduction of ophiolitic sheets, schists, olistostrome formation, greenschist facies metamorphism are connected with early deformation. In the Late Volgian–Early Neocomian, in central part of collision belt, D_2 faults with mainly thrust kinematics are formed, which become lateral and oblique thrust, and oblique-slip faults in the northeastern and southwestern segments. In the Late Neocomian, D_3 faults with sinistral and reverse-sinistral kinematics occurred in southwestern and central parts of the belt. Thrust- and upthrust-strike slips with mainly dextral displacements occurred in northwestern segment.

The first stage of accretion caused buckling of crust at the thinned and weakened eastern edge of Oimyakon sedimentary basin in front of the orogenic wedge of the composite Kolyma–Omolon microcontinent. The Omulevka microcontinent could have acted as an impediment to the subduction of back-arc basin of the Alazeya arcs. Amalgamation structures in the composite Kolyma–Omolon microcontinent and its convergence to the Verkhoyansk continental margin resulted in the generation of a new subduction zone of opposite polarity. The second stage collision in its early stages occurred only at upper crustal levels. As a result, various sedimentary thrust fronts were formed in sedimentary cover of Oimyakon basin. The main faults, boundary thrust fronts, are considered as ophiolite-free suture zones. They separate different geodynamic complexes and structures.

As the collision progressed, the Kolyma–Omolon microcontinent acted as indentor, and caused additional rotation of orogenic structures, and the formation of the "Kolyma loop". Thrust fronts moved in the direction of the orogenic foreland forming the Verkhoyansk fold-and-thrust belt. Deformation occurred in the central part of the orogen at that time. The Ilin–Tass trough is located in the hinterland of collision belt. Probably, the formation of this basin is connected with decoupling in the hinterland of the collision belt. The Ilin–Tass trough was subsequently transformed into Indigirka–Zyrianka sedimentary basin.

Acknowledgements

I appreciate my colleagues, Profs. L.M. Parfenov, P.W. Layer, W.K. Wallace and K. Fujta, and Drs. A.V. Prokopiev, F.F. Tret'yakov, Yu V. Karyakin and V.F. Timofeev, with whom I studied the structures of the inner part of the Verkhoyansk–Kolyma orogen and discussed various questions of its evolution. I also would like to thank the geologists from GGP "Lenskoe" for assistance in field researches.

I appreciate J.B. Murphy and J.D. Keppie, managing editors of Special Issue and heads of IGCP 453 "Uniformitarianism revisited: a comparison between modern and ancient orogens", for their interest in my report at the conference that was held in September 2001 in Sion at the Universitary Institute Kurt Bösch (IUKB). Reviews by M. Cecile and A. Khudoley also provided very helpful comments. Report materials were also used partially while preparing the article at the meeting: "Continental Collision and Tectonosedimentary Evolution of Forelands: Mechanics of Coupling and Far-Field Deformation", arranged by Profs. G. Bertotti, K. Schulmann, S. Cloetingh, whom I appreciate so much, as well as my reviewers.

This work was supported by RFBR (grants 00-05-65105 and 03-05-64915) and RFBR-Arctic (grants 00-05-96227 and 03-05-96015), UROG, 09-01-033, VI Foundation of Young Scientists Projects of Russian Academy of Science grant no. 340. I also appreciate A. Shulyak for his help in preparing the English version of the paper.

References

Alkhovik, T.S., Baranov, V.V., 1989. Stratigraphy of Silurian deposits of north-eastern Yakutia. Geology and Ore Content in Yakutia. Yakutian Scientific Centre SO RAN, Yakutsk, pp. 105–111 (in Russian).

Bogdanov, N.A., 1963. Tectonic Evolution in Paleozoic Stage of the Kolyma Massif and Eastern Arctic. AN SSSR publishing house, Moscow (in Russian).

Bogdanov, N.A., Tilman, S.M., 1992. Tectonics and geodynamics of the north-east of Asia (explanatory note for tectonic map of the north-east of Asia, scale 1: 500,000). IL RAN, Moscow (in Russian).

Bondarenko, G.E., Didenko, A.E., 1997. New geological and paleomagnetic data on Jurassic–Cretaceous history of the Omolon massif. Geotectonics 2, 14–27 (in Russian).

Bulgakova, M.D., 1986. Lithology of Ordovician Deposits in the Northeastern USSR. Nauka, Moscow (in Russian).

Bulgakova, M.D., 1997. Paleogeographia of Yakutia in Early–Middle Paleozoic. Yakutian Scientific Centre SO RAN, Yakutsk (in Russian).

Bulgakova, M.D., Kolodeznikov, I.I., 1990. Middle Paleozoic Rifting on the north-east of USSR: sedimentogenesis and volcanism. Nauka, Moscow (in Russian).

Dewey, J.F., 1977. Suture zone complexities: a review. Tectonophysics 40 (1/2), 53–67.

Fujita, K., Newberry, T., 1982. Tectonic evolution of northeastern Siberia and adjacent regions. Tectonophysics 89 (1–3), 337–357.

Fujuta, K., Newberry, T., 1983. Accretionary and tectonic evolution of Northeast Siberia. In: Hashimoto, M., Uyeda, S. (Eds.), Accretion Tectonics in the Circum-Pacific Regions. Terra Pub., Tokyo, pp. 43–57.

Grinberg, G.A., Gusev, G.S., Bakharev, A.G., Bukgakova, M.D., Ipatieva, I.S., Nedosekin, Y.D., Rukovich, V.N., Soloviev, V.I., Surnin, A.A., 1981. Tectonics and Magmatic and Metamorphic Complexes of the Kolyma–Omolon Massif. Nauka, Moscow (in Russian).

Gusev, G.S., 1979. Fold Structures and Faults of the Verkhoyansk–Kolyma Mesozoide System. Nauka, Moscow (in Russian).

Khudoley, A.K., Sokolov, S.D., 1998. Structural evolution of the northeast Asian continental margin: an example from the western Koryak fold and thrust belt (northeast Russia). Geol. Mag. 135 (3), 311–330.

Layer, P.W., Parfenov, L.M., Surnin, A.A., Timofeev, V.F., 1993. First 40Ar/39Ar Definitions of the Age of Magmatic and Metamorphic Rocks of Verkhoyansk–Kolyma Mesozoides, vol. 329.5. AN SSSR, Doklady, pp. 621–624 (in Russian).

Layer, P.W., Newberry, R., Fujita, K., Parfenov, L.M., Trunilina, V.A., Bakharev, A.G., 2001. Tectonic setting of the plutonic belts of Yakutia, northeast Russia, based on ^{40}Ar/^{39}Ar geochronology and trace element geochemistry. Geology 29 (2), 167–170.

Leonov, M.G., 1993. Structural Groups of Nappe-folded Zones. Nauka, Moscow (in Russian).

Morley, C.K., 1986. A classification of thrust fronts. Am. Assoc. Pet. Geol. Bull. 70 (1), 12–25.

Natal'in, B.A., Parfenov, L.M., 1989. Structural geology of suture zones (on example of South-Anuyiskaya, Mongolo-Okhotskaya and Adycha–Tarynskaya). In: Pusharovskyi, Yu.M. (Ed.), Tectonic Researches in Connection with Medium–Large-Scale Geological Mapping. Nauka, Moscow, pp. 69–88 (in Russian).

Natal'in, B.M., Amatj, J.F., Toro, J., Wright, J.E., 1999. Paleozoic rocks of northern Chukotka Peninsula, Russian Far East: implications for the tectonics of the Arctic region. Tectonics 18, 977–1003.

Natapov, L.M., Surmilova, E.P. (Eds.), 1986. Geological map of the USSR. Scale, 1:1.000.000. Explanatory note. Sheet Q-54-55-Khonuu. PGO "Aerogeologiya", Leningrad (in Russian).

Neustroev, A.P., Parfenov, L.M., Rodionov, V.P., 1993. Paleomagnetic data and the nature of the Tas–Khayakhtakh terrane (Verkhoyansk region). Geol. Geofiz. 8, 25–37 (in Russian).

Nokleberg, W.J., Parfenov, L.M., Monger, J.W.H., Norton, I.O., Khanchuk A.I., Stone, D.B., Scotese, C.R., Scholl, D.W., Fujita, K., 2001. Phanerozoic Tectonic Evolution of the Circium-North Pacific. US Geological Survey. Professional Paper 1626, US Departament of the Interior.

Oxman (Oksman), V.S., 1996. Tectonic evolution and ophiolites of the orogenic belt of the Chersky Range. 30th International Geological Congress, Bejing, China, Abstracts, vol. 1, p. 299.

Oxman, V.S., 1998. Geodynamic evolution of collision belt of the Chersky mountain system (north-east of Asia). Geotectonics 1, 56–70 (in Russian).

Oxman, V.S., 2000. Tectonics of Chersky Range Collision Belt (North-east Russia). GEOS, Moscow (in Russian).

Oxman, V.S., Prokopiev, A.V., 1993a. Oblique collisional structures of the Chersky Range, northeastern Russia. AGU, Fall Meeting, Abstracts, San Francisco, p. 545.

Oxman, V.S., Prokopiev, A.V., 1993b. Transpression and collisional structures of the Chersky Range. L.P. Zonenshain Memorial Conf. of Plate Tectonics, Moscow, p. 112.

Oxman, V.S., Prokopiev, A.V., 1995. Structural–kinematic evolution of the arcuate orogenic belt of the Chersky mountain system. "Curved orogenic belts: their nature and significance". Buenos-Aires, 27–31.

Oxman, V.S., Prokopiev, A.V., 2000. Terrigenous tectonic melanges within the Polousnenskyi sinclinorium. Otecestv. Geol. 5, 47–51 (in Russian).

Oxman, V.S., Parfenov, L.M., Prokopiev, A.V., Timofeev, V.F., Tretyakov, F.F., Nedosekin, Y.D., Layer, P.W., Fujita, K., 1995. The Chersky Range ophiolite belt, northeast Russia. J. Geol. 103 (5), 539–556.

Oxman, V.S., Prokopiev, A.V., Karyakin, Y.V., Tarabukin, V.P., 1998a. Fragments of Oimyakon paleoocean in collision belt of the Chersky (north-east of Asia). Tectonics and Geodynamics: General and Regional Aspects, vol. 2. GEOS, Moscow, pp. 69–72 (in Russian).

Oxman, V.S., Timofeev, V.F., Tretyakov, F.F., 1998b. Uyandinsky complex of polymetamorphic rocks: $P–T–t$ evolution and geodynamic interpretation. Otecestv. Geol. 6, 10–14 (in Russian).

Parfenov, L.M., 1984. Continental Margins and Island Arcs of the Mesozoides of Northeast Asia. Nauka, Novosibirsk (in Russian).

Parfenov, L.M., 1991. Tectonics of the Verkhoyansk–Kolyma Mesozoides in the context of plate tectonics. Tectonophysics 199, 319–342.

Parfenov, L.M., 1995. Terranes and the history of Mesozoic Orogenic belts in East Yakutia. Geol. Pac. Ocean 12, 977–994.

Parfenov, L.M., Rozhin, S.S., Tretyakov, F.F., 1988. Character of the Adycha–Tarun zone of faults (eastern Verckhoyansk). Geotectonics 22, 356–366 (in Russian).

Parfenov, L.M., Oxman, V.S., Shashkin, M.M., 1989. Mid- to Late Jurassic tectonic nappes of the Tas–Khayahtakh zone. Geol. Geofiz. 1, 130–134 (in Russian).

Parfenov, L.M., Natapov, L.M., Sokolov, S.D., Tsukanov, N.V., 1993. Terranes analysis and accretion in northeast Asia. Isl. Arc 2, 35–54.

Parfenov, L.M., Prokopiev, A.V., Gaiduk, V.V., 1995. Cretaceous frontal thrusts of the Eastern Siberia. Tectonics 14 (2), 342–358.

Prokopiev, A.V., 1998. Verkhoyansk–Chersky collisional orogen. Geol. Pac. Ocean 4, 15–28 (in Russian).

Sengor, A.M.C., Natal'in, B.A., 1996. Paleotectonics of Asia: fragments of a synthesis. In: Yun, A., Harrison, M.T. (Eds.), Tectonic Evolution of Asia, Rubey Colloq. Cambridge Univ. Press, pp. 486–640.

Sokolov, S.D., 1992. Accretionary Tectonics of the Koryak–Chukotka Segment of the Pacific Belt. Nauka, Moscow (in Russian).

Sokolov, S.D., Didenko, A.N., Grigoriev, V.N., Aleksutin, M.V., Bondarenko, G.E., Krylov, K.A., 1997. Paleotectonic reconstructions of the north-east of Russia: problems and uncertainties. Geotectonics 6, 72–90 (in Russian).

Sylvester, A.G., 1988. Strike-slip faults. Geol. Soc. Amer. Bull. 100, 1666–1703.

Tectonics, Geodynamics and Metallogeny of the Sakha Republic (Yakutia), 2001. MAIK ''Nauka/Interperiodica'', Moscow (in Russian).

Thompson, A.B., Schulman, K., Jezek, J., 1997. Thermal evolution and exhumation in obliquely convergent (transpressive) orogens. Tectonophysics 280, 171–184.

Trunilina, V.A., Orlov, Y.S., Roev, S.P., Oxman, V.S., Ivanov, P.O., Khabibulina, T.S., Karyakin, Y.V., 1999. Magmatism of Different Geodynamic Environments (Truncation Zone the Verkhoyansk Passive Margin and Kolyma–Omolon Microcontinent). Yakutian Scientific Centre SO RAN, Yakutsk.

Wallace, W.K., Oxman, V.S., Prokopiev, A.V., Parfenov, L.M., 1995. Origin of arcuate structural trends at the boundary between the Siberian Platform and accreted terranes, Chersky Range, northeastern Yakutia. GSA Abstracts with Programs. 91st Annual Cordilleran Section 27 (5), 82.

Woodcock, N.H., Fisher, M., 1986. Strike-slip duplexes. J. Struct. Geol. 8 (7), 725–735.

Zonenshain, L.P., Kuzmin, M.L., Natapov, L.M., 1990. Geology of the USSR: a plate tectonic synthesis. Am. Geophys. Union, Geodyn. Ser., 21.