Tectonics, geodynamics and gold mineralization of the eastern margin of the North Asia craton

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Abstract: The North Asia craton is a crustal block including the Siberian platform and marginal fold-and-thrust belts. On the eastern margin of the North Asia craton there is the Verkhoyansk fold-and-thrust belt making up the western part of the Verkhoyansk–Chersky collisional orogenic belt extending for 2000 km from the Laptev Sea in the north to the Sea of Okhotsk in the south. A system of frontal thrusts separates the belt from the platform structures. The frontal part of the belt is mainly made of Carboniferous and Permian terrigenous rocks of palaeodeltas and submarine fans which grade eastward into Triassic and Jurassic sediments of the continental slope. The front of the belt is characterized by thrusting and strike-slip faulting with large horizontal displacements. The largest anticlinoria at the front of the belt have a duplex structure. Formation of the major gold deposits and fold and fault structures, as well as igneous activity in the region, are related to the collision of the North Asia craton with the Kolyma–Omolon superterrane and the Okhotsk terrane in the Late Jurassic–Neocomian. The collision occurred in two stages: the early Neocomian frontal collision and the late Neocomian oblique collision.

The principal gold potential of the western part of the Verkhoyansk–Chersky orogen (Republic of Sakha, Yakutia, Russian Federation) was created during the late Mesozoic collision of the North Asia craton (Siberian platform and its Verkhoyansk passive margin in the east) with the Kolyma–Omolon microcontinent (large composite terrane, or superterrane) and the Okhotsk microcontinent (terrane with Archaean basement). The early frontal collision took place in the Late Jurassic and Neocomian and the late oblique collision occurred in the Early Cretaceous.

Two groups (early and late collisional) of gold–quartz deposits are recognized, localized in five metallogenic zones. The early collisional group is related to the Verkhoyansk, Alakh–Yun, and Kular metallogenic zones; the late collisional group is localized in the Adycha–Nera and South Verkhoyansk metallogenic zones. These metallogenic zones are within the Yana–Indigirka metallogenic belt (Fig. 1). Some of the deposits described in this paper were mentioned earlier in overviews by Nokleberg *et al.* (1996, 1997).

The formation of the early group was related to the tectono-metamorphic transformation of gold-bearing sedimentary rocks on the shelf of a passive continental margin and to the transport of ore components by solutions expelled from source rocks up to the ore-localizing barriers in shear zones of the thrust structures (Fridovsky & Prokopiev 1998). Deposits of the late group are considered to be derived from ore-magmatic systems related to the main granite batholith belt (Parfenov & Kuz'min 2001) and localized in the thrust and strike-slip zones. The deposits considered in this paper mainly belong to the type of 'Au deposits in shear zones and quartz veins' (after Nokleberg *et al.* 1996). The characteristics of the gold deposits are presented in Table 1.

Verkhoyansk–Chersky orogen

Main geological features of the orogen

Collisional orogens (orogenic belts) are mountain-fold structures resulting from collision of large continental blocks of the Earth's crust, such as continents and microcontinents or superterranes (Hatcher 1990; Twiss & Moores 1992). They are distinct from accretionary orogenic belts formed during accretion of comparatively small blocks of the Earth's crust of different origin to the continental or superterrane margin along the subduction zone.

The Verkhoyansk–Chersky orogen comprises all tectonic structures east of the Siberian platform including the Zyryanka Basin (Figs 2 and 3). It also covers the western part of the Verkhoyansk–

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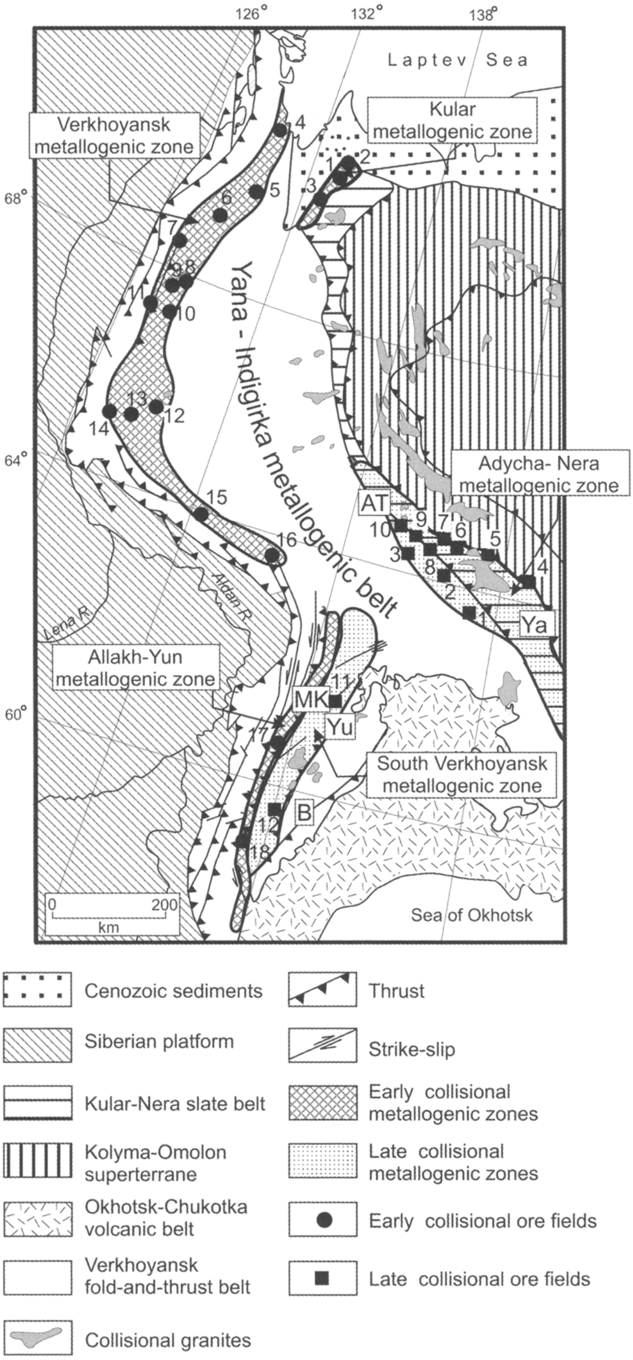

Fig. 1. Metallogenic zones of the Yana–Indigirka metallogenic belt.Faults (letters in boxes): Ya, Yana–Indigirka; AT, Adycha–Taryn; B, Billyakchan; MK, Minor,Kiderikin; Yu, Yudoma. Early collisional ore fields (numerals in figure): 1, Kyllakh; 2, Burguat; 3, Dzhuotuk; 4, Dyandi,Okhonosoi; 5, Meichan; 6, Dzhardzhan; 7, Balagannakh; 8, Sereginsky; 9, Aialyr; 10, Sudyandalakh; 11, Imtachan; 12, Kygyltas; 13, Sagandzha; 14, Kitin; 15, Barain; 16, Kharangak; 17, Bular–Onocholokh; 18, Yursky–Brindakit. Late collisional ore fields: 1, Yakutsky; 2, Saninsky; 3, Badran; 4, Kurun–Agalyk; 5, Sokh; 6, Tuora–Tas; 7, Ol'chan; 8, Talalakh; 9, Bazovsky; 10, Zhdaninsky; 11, Nezhdaninskoe; 12, Zaderzhinsky.

Table 1. *Significant gold deposits and occurrences of the Yana–Indigirka metallogenic belt*

Groups of gold deposits	Main fault kinematics	Orebody morphology	Mineral deposits and occurrences	Deposit type	Metallogenic zone	Ore field	Major metals
Early collisional	Thrust faults	Saddle veins at crests and sheet veins at limbs of the folds	Yurskoe*	Au in shear zone and quartz vein	Allakh–Yun	Yursky–Brindakit	Au
			Nekur		Allakh–Yun	Yursky–Brindakit	Au
			Duet		Allakh–Yun	Yursky–Brindakit	Au
		Sheet, lenticular, and ladder veins	Fin	Au in shear zone and quartz vein	Allakh–Yun	Yursky–Brindakit	Au
			Burguat		Kular	Burguat	Au
			Emelyanovskoe		Kular	Burguat	Au
			Kyllakh		Kular	Kyllakh	Au
			Estakadnoe		Kular	Kyllakh	Au
		Sheet and lenticular veins, stratiform stockwoks, mineralized crush zones	Srednee	Au in shear zone and quartz vein	Kular	Kyllakh	Au
			Kieng–Yuryakh		Kular	Dzhuotuk	Au
			Verkhnee		Kular	Dzhuotuk	Au
			Onocholokh		Allakh–Yun	Bular–Onocholokh	Au
			Dyandi		Verkhoyansk	Dyandi–Okhonosoi	Au
			Balbuk		Verkhoyansk	Barain	
			Anna–Emeskhin		Verkhoyansk	Meichan	
Late collisional	Thrust faults	Mineralized crush zones, concordant and cross-cutting veins, stockwoks, lenticular bodies	Mastakh	Au in shear zone and quartz vein	Adycha–Nera	Yakutsky	Au
			Yakutskoe		Adycha–Nera	Yakutsky	Au, Ag
	Strike-slip faults	Concordant lenticular bodies, cross-cutting veins and veinlets at limbs and crests of folds with steeply dipping hinges	Zhdannoe	Au quartz vein	Adycha–Nera	Zhdaninsky	Au
			Tuora–Tas		Adycha–Nera	Tuora–Tas	Au
			Sokhatinoe		Adycha–Nera	Tuora–Tas	
			Venera		Adycha–Nera	Tuora–Tas	
			Sokh–Bar		Adycha–Nera	Tuora–Tas	
			Kellyam		Adycha–Nera	Sokh	
		Mineralized crush zones, concordant and cross-cutting veins, stockwoks, lenticular bodies	Bazovskoe	Au in shear zone and quartz vein	Adycha–Nera	Bazovsky	Au
			Badran		Adycha–Nera	Badran	Au
			Nezhdaninka		South Verkhoyansk	Nezhdaninskoe	Au, Ag
			Zaderzhinskoe		South Verkhoyansk	Zaderzhinsky	Au

* Deposits in production

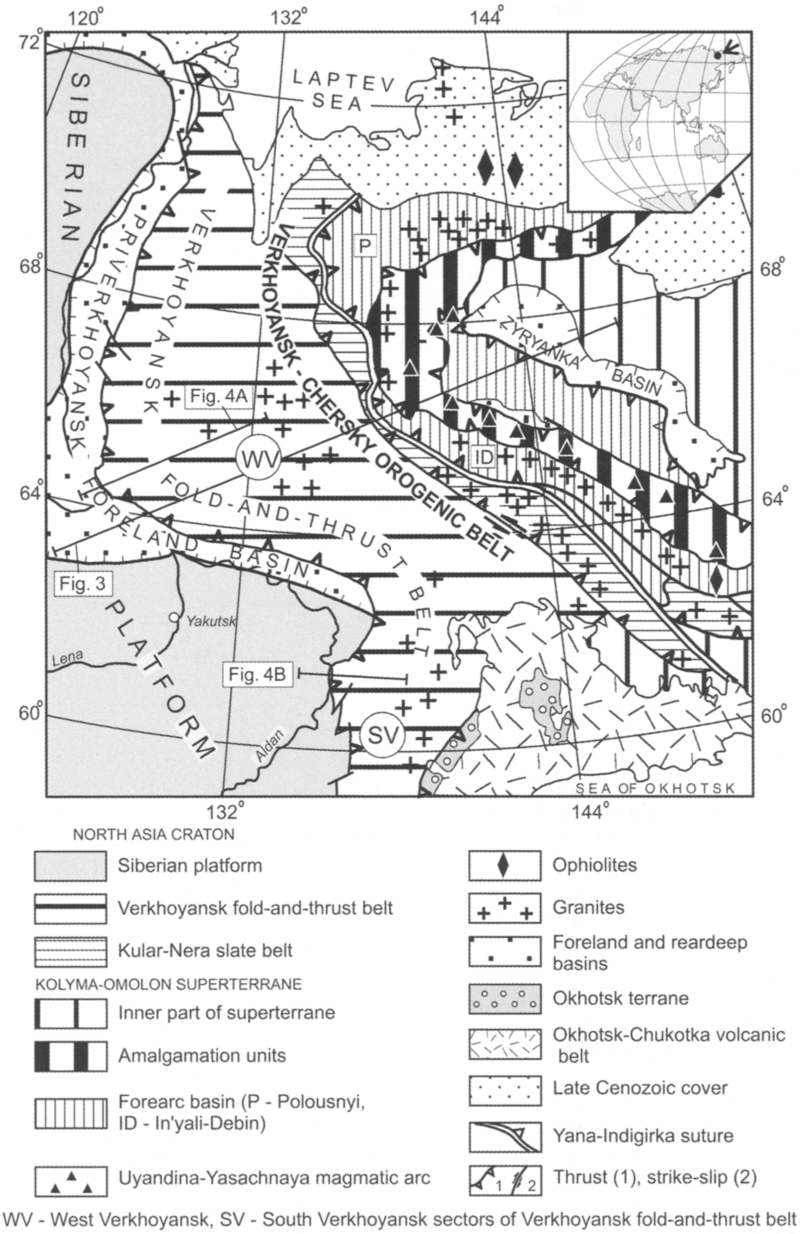

Fig. 2. Tectonic sketch-map of the Verkhoyansk–Chersky collisional orogen (orogenic belt).

Kolyma Mesozoides and resulted from collision between the North Asia craton and the Kolyma–Omolon superterrane at the end of the Late Jurassic–Neocomian, and from the closing of the smaller Oimyakon ocean basin. The formation of the Kolyma–Omolon superterrane (microcontinent) is linked to amalgamation of several terranes at the end of the Mid-Jurassic, part of which had been earlier separated from the North Asia craton in the course of Late Palaeozoic rifting (Parfenov 1991, 1995; Prokopiev 1998). The Verkhoyansk–Chersky orogen bears all the characteristic features found in collisional belts. The structure of the Verkhoyansk–Chersky collisional orogen has bean subdivided into outer, inner and rear zones (Prokopiev 1998; Fig. 3).

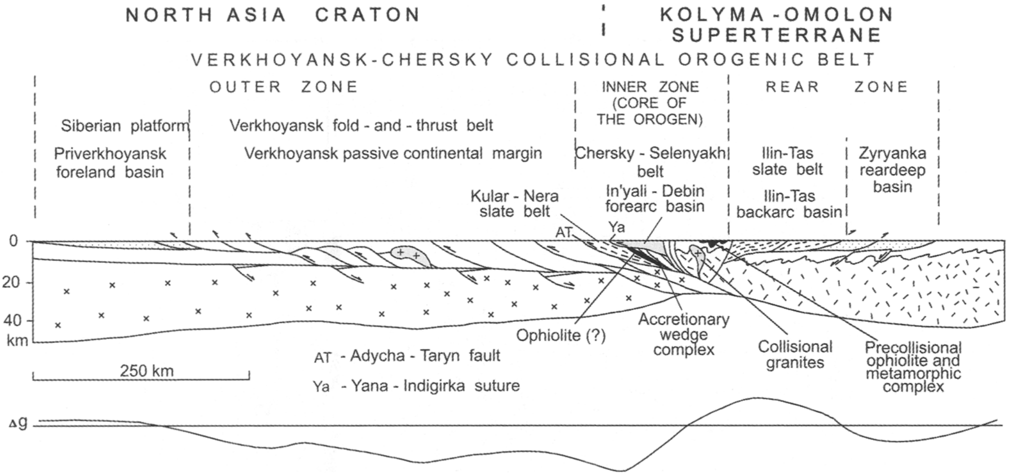

Fig. 3. Geological section through the central part of Verkhoyansk–Chersky collisional orogen. Section line shown in Figure 2.

Outer zone of the orogen

The zone is represented by the Priverkhoyansk foreland basin and the Verkhoyansk fold-and-thrust belt. The Priverkhoyansk foreland basin, consisting of Late Jurassic–Cretaceous sedimentary sequences, stretches for 1100 km at the front of the fold-and-thrust belt. Continental units of Cretaceous age conformably overlie shallow-water marine deposits in the north and continental Upper Jurassic units in the south. Their maximum thickness (3–4 km) is at the front of the fold-and-thrust belt. The Verkhoyansk fold-and-thrust belt has a typical miogeoclinal structure and is subdivided into the West Verkhoyansk and South Verkhoyansk sectors. The sediments of the fold-and-thrust belt were deposited on the Verkhoyansk passive continental margin of the North Asia craton.

Close to the platform, the West Verkhoyansk sector is made up of predominantly Carboniferous and Permian rocks, which to the east are replaced by Triassic and Jurassic units. The sediments make up a thick wedge (up to 15 km) of fragmental coastal-marine, deltaic and shelf rocks of the Verkhoyansk terrigenous complex. To the west, within the Siberian platform, they are replaced by synchronous coastal-marine and alluvial accumulations, and to the east grade into turbidites and deep-sea black shale deposits.

In the frontal zone of the West Verkhoyansk sector fault-propogation folds, back thrusts and intercutenous wedges are mainly developed. The detachment is confined to clay horizons at the base of the Triassic, shifting eastward along the fault onto Permian clay horizons and, apparently, Middle–Upper Devonian gypsum (Parfenov *et al.* 1995). The width of the frontal zone reaches 100 km in the central part of the West Verkhoyansk sector, decreasing both northward and southward. The structure of the central zone is characterized by a blind duplex in a carbonate Late Precambrian–Mid-Palaeozoic complex, and by imbricate fans and back thrusts of the Late Palaeozoic–Mesozoic Verkhoyansk terrigenous complex (Fig. 4a). The detachment there is displaced onto the basement of a sedimentary sequence, is traced by the roof of the crystalline basement, and is the floor thrust of the duplex. The roof thrust of the duplex is a floor thrust for deformation in the Verkhoyansk complex. Duplex development in the carbonate complex determined the formation of the largest anticlinoria of the fold-and-thrust belt. The culminations of the anticlinoria correspond to the most uplifted parts of the duplex structures (Prokopiev 1998). Transverse belts of Cretaceous granite massifs intrude the fold structures of the sector.

The South Verkhoyansk sector along the boundary with the platform is made up of Upper Precambrian, Lower and Middle Palaeozoic terrigenous-carbonate shelf sediments, which are replaced eastward by coeval slope units. In the central part of the sector, Middle–Upper Devonian rift-related rocks are exposed. The Lower Carboniferous–Lower Permian terrigenous deposits on the east of the sector are turbidites typical of deep-sea slope fans. The Upper Permian–Mesozoic sediments, consisting mainly of sandstone units, are of a deltaic nature. In the South Verkhoyansk sector, three tectonic zones of

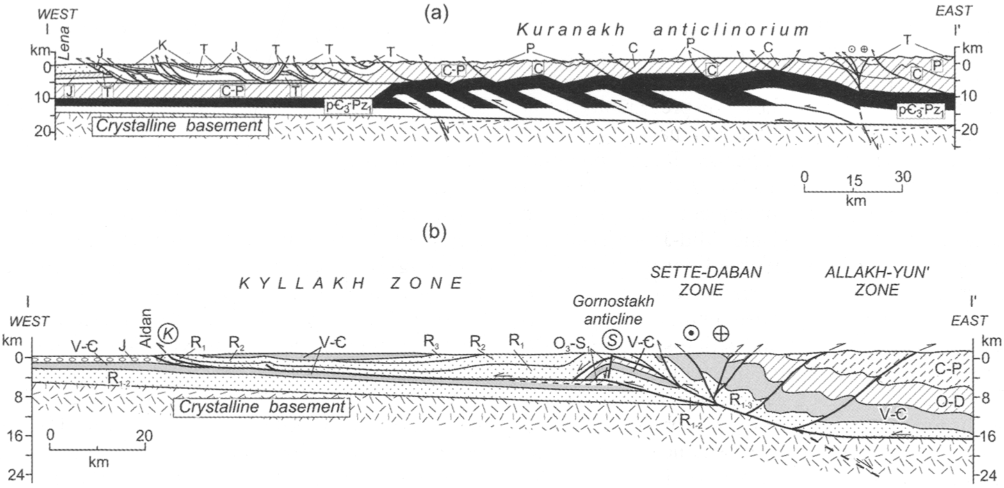

Fig. 4. Geological sections of the central part of the West Verkhoyansk sector (**a**) and of the central South Verkhoyansk sector (**b**), Verkhoyansk fold-and-thrust belt. K, Kyllakh thrust; S, Svetlyi fault (Prokopiev 1998). For locations see Figure 2.

north–south strike are distinguished, differing from each other in the style of deformation (Fig. 4b). Along the boundary with the platform is the Kyllakh zone, which has a fold-and-thrust structure. The structure of the zone is determined by the Kyllakh thrust with an amplitude of horizontal displacement of 90 km, the largest thrust in the fold-and-thrust belt (Parfenov *et al.* 1998). The rear part of the zone is a ramp anticline formed above a large truncated duplex. The Sette–Daban zone, occupying an axial position within the sector, has a 'flower' or a 'palm tree' structure in its transverse section. The formation of a fan-shaped structure and an approximately north–south metamorphic belt is linked to transpressional sinistral displacements along the zone axis. The strike-slip deformations are superimposed on the early thrust structures exposed in the Kyllakh zone. The Allakh–Yun zone is characterized by tight folds with a cleavage of the axial plane of eastern vergence, which are associated with steep thrusts (Prokopiev 1989; Parfenov *et al.* 1995). The inner and the rear zones of the Verkhoyansk–Chersky orogen include rocks of the Kular–Nera slate belt, southwestern and northeastern flanks of the Kolyma–Omolon superterrane.

The inner zone (core) of the orogen

This zone is represented by the Chersky–Selennyakh belt encompassing the Kolyma–Omolon superterrane and the Kular–Nera slate belt (Figs 2 and 3). The Kular–Nera slate belt is made up of intricately and multiply deformed deep-sea black shale units of Permian, Triassic and Lower Jurassic age, which are distal accumulations of the continental slope of the Verkhoyansk passive margin (North Asia craton). The units of the slate belt are separated from the outer shelf deposits of the passive margin by the NW-striking Adycha–Taryn fault zone with indicators of substantial thrust and subsequent sinistral strike-slip displacements. It is presumed that the black shale units are overthrust for 150 km in a westerly direction (Norton *et al.* 1994).

The peripheral assemblages of the Kolyma–Omolon superterrane are represented predominantly by shallow water, dominantly carbonate deposits of Ordovician, Silurian and Devonian age, with, at the base, cherty-clay deep-sea deposits from the Carboniferous, Permian, Triassic and Lower Jurassic. All these strata are intensely deformed by thrusts and strike-slip faults. The Ordovician–Upper Devonian carbonate assemblages of the orogen core are akin to the coeval units of the Sette–Daban zone (southern part of the orogen outer zone) (Bulgakova 1997). In the Early–Mid-Palaeozoic they were located at the margin of the North Asia craton, became separated from it as part of the terranes during Mid-Palaeozoic rifting and were subsequently moved for a distance of 1500–2000 km with respect to the craton during the Carboniferous, Permian and Triassic. This resulted in the formation of the Oimyakon minor ocean basin (Parfenov 1995). Now the tectonic blocks consisting of Lower–Middle Palaeozoic, dominantly carbonate rocks are separated from the Upper Palaeozoic–Mesozoic deposits of the superterrane periphery by systems of gentle thrusts and strike-slip faults.

Within the orogen core, scattered ophiolitic fragments are known. These, of presumably Early Palaeozoic age, make up tectonic nappes and have been described as the Chersky Range ophiolite belt by Oxman *et al.*(1995). The obduction of these ophiolites and subsequent metamorphism occurred at the end of the Mid-Jurassic during amalgamation of terranes and formation of the Kolyma–Omolon superterrane (Parfenov 1995). During the collision, these ophiolites were deformed by late thrusts and strike-slip faults. The Upper Jurassic calc-alkaline volcanites of the Uyandina–Yasachnaya arc, which unconformably overlie Palaeozoic and Early Mesozoic sediments, formed above the subduction zone in which the oceanic crust of the Oimyakon basin moves under the Kolyma–Omolon superterrane during its approach to the North Asia craton. The Polousnyi and In'yali–Debin synclinoria are made up of thick, intricately deformed flysch units of Mid–Late Jurassic age and have been interpreted as assemblages of forearc basins of the Uyandina–Yasachnaya arc (Parfenov 1991). The assemblages of the orogen core are intruded by collisional granites of Late Jurassic–Cretaceous age.

Units of the Kular–Nera slate belt are assigned to the accretionary wedge of the Uyandina–Yasachnaya volcanic arc (Fig. 3; Parfenov 1991, 1995). Deep-sea Lower Carboniferous–Lower Jurassic cherty-clay deposits of the superterrane slope and foot occurring as tectonic sheets and wedges along the periphery of the carbonate unit outcrop in the orogen core. The sediments of the Polousnyi and In'yali–Debin forearc basins were moved during collision in a westerly direction and overthrust on the assemblages of the Kular–Nera slate belt along the Yana–Indigirka suture. They are less deformed than the underlying, more ancient deposits of the accretionary wedge. The Yana–Indigirka suture separates the accretionary wedge and forearc basins, and includes the Chai–Yureinskiy, Charky–Indigirka and Yana faults, recognized earlier (Gusev 1979), which successively replace each other towards the northwest. The Debin outcrops of ophiolites in the SE of the In'yali–Debin synclinorium are, in all likelihood, relics of the oceanic crust of the Oimyakon Basin (Oxman *et al.*1995). Their presence in the middle reaches of the Khroma and Berelyokh Rivers can also be presumed, where they are overlapped by Cenozoic rocks of the Primorsk lowland. Here, they are indicated by intense positive gravity and magnetic anomalies (Spektor & Dudko 1983; Fig. 2). Details of the structure of the accretionary wedge complex remain debatable because it has as yet been poorly studied. The absence of substantial ophiolite outcrops may be evidence that the oceanic crust in the Oimyakon Basin was nearly completely absorbed in the subduction zone. However, the formation of the orogen in the environment of development of an A-subduction zone cannot be excluded (Fujita & Newberry 1982).

An intense gradient in the gravity field corresponds to the accretionary wedge and the orogen core (Fig. 3). The gravitational model (Norton *et al.*1994), computed on the basis of a profile transverse to the strike of the Verkhoyansk–Chersky orogen, shows that rocks of the orogen core are overthrust in its southwestern sector. Examples include units of the Kular–Nera slate belt, which are overthrust by as much as 150 km westwards, overlying the craton margin. This value approximates to the width of the gravity gradient. Northwards, the width of the gradient decreases to 50–70 km, which may give evidence of a smaller-scale overthrust there.

The rear zone of the orogen

The rear zone includes the Ilin–Tas fold-and-thrust belt of northeastern vergence and the Zyryanka reardeep basin (Figs 2 and 3). The Ilin–Tas fold-and-thrust belt is made up of thick (> 6 km) Kimmeridgian–Volgian black shale of the backarc basin of the Uyandina–Yasachnaya magmatic arc (Parfenov 1995). Components of the orogen core are thrust northeastward onto the rocks of the backarc basin, which, in turn, overthrust the Lower Cretaceous–Neogene coal-bearing deposits of the Zyryanka (rear) basin, whose thickness reaches 5.5 km at the front of the fold-and-thrust belt. The detachment of the Zyryanka basin occurs at the bottom of Neocomian units (Gaiduk & Prokopiev 1999). The western and southwestern vergence of folding, characteristic of the outer zone and southwestern flank of the core orogen, is replaced by a northeastern vergence in the northeast of the inner zone and in the rear zone.

Deformation history of the orogen

Folding in the orogen core and in the rear of the outer zone began to form at the end of the Late Jurassic, advancing southwest- and northeastward, and terminated in the formation of systems of frontal thrusts along the boundary with the Siberian platform in the Late Cretaceous and of rear thrusts of the Ilin–Tas fold-and-thrust belt in the Cenozoic (Parfenov *et al.*,1995; Gaiduk & Prokopiev 1999). In the first (early collisional) stage of deformation (Tithonian–Neocomian), thrusts began to form in the orogen core and in the rear of the West Verkhoyansk sector of the Verkhoyansk fold-and-thrust belt, where dislocations are intruded by collisional granites, whose age is given as 150–134 Ma by $^{40}Ar/^{39}Ar$ dating (Layer *et al.* 2001). The Priverkhoyansk foreland basin and syn-sedimentary folding began to form at the front of the orogenic belt outer zone during that time (Parfenov *et al.,* 1995). In the rear zone, sediments accumulated, transported from the orogen core into the Ilin–Tas backarc basin. The Ilin–Tas backarc basin is supposed to have formed as a 'pull-apart basin' structure in the course of development of large strike-slip faults along the northeastern boundary of the orogen core (Prokopiev 1998). Late Mesozoic grabens in the orogen inner zone could have formed similarly. At the beginning of the Neocomian, the Zyryanka rear basin began to form. The stage terminated in the formation of thrusts and strike-slip structures in the South Verkhoyansk sector, which in the east are overlain by Neocomian volcanites of the Uda belt (Fig. 5).

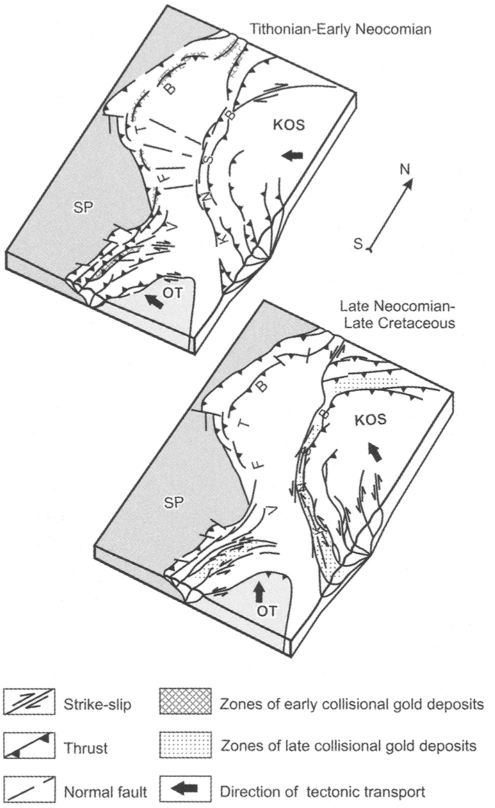

Fig. 5. Geodynamic conditions of collision-related gold ore formation in the Verkhoyansk–Chersky orogen. SP, Siberian platform; KOS, Kolyma–Omolon superterrane; OT, Okhotsk terrane; VFTB, Verkhoyansk fold-and-thrust belt; KNSB, Kular–Nera slate belt.

In the second (late collisional) stage (Barremian–Late Cretaceous), fold-thrust structures and frontal thrusts of the West Verkhoyansk sector of the Verkhoyansk fold-and-thrust belt were formed. A southwestern advance of folding at 132 to 98 Ma, according to $^{40}Ar/^{39}Ar$ dating (Layer *et al.* 2001), is marked by a rejuvenation in the same direction as the trend of intruding granite plutons. At the end of this stage, the thrusts in the orogen core and in the rear of the outer zone are transformed into sinistral strike-slip faults, which is probably linked to the change in the direction of the movement of the Kolyma–Omolon superterrane. The thrusts and strike-slip faults along the southwestern margin of the superterrane are synchronous with them and are intruded by collisional granites ($^{40}Ar/^{39}Ar$ age of 127–120 Ma; Parfenov 1995). In the rear zone, the formation of the Zyryanka basin was by then in progress, and the front of the thrusts of the Ilin–Tas fold-and-thrust belt was shifted northeastwards. The formation of the Ilin–Tas fold-and-thrust belt could occur at the expense of strike-slip displacements along its axial part with the appearance of a transpressional structure of a 'flower' or 'palm tree' pattern, which is indicated by distribution of faults with composite thrust – strike-slip kinematics (Gusev 1979).

Yana–Indigirka metallogenic belt

The 500–600 km wide Yana–Indigirka metallogenic belt extends in a northwest direction for 1200 km, encompassing central and western parts of the Verkhoyansk–Chersky orogen. Its formation was related to a collision between the Kolyma–Omolon superterrane and the North Asia craton, which occurred in the latest Late Jurassic to Early Neocomian.

A metallogenic belt is a basic unit in the zonation of a region. A belt includes all the mineral deposits and occurrences that formed in a particular geodynamic environment. Metallogenic belts are subdivided into metallogenic zones, including mineral deposits and occurrences of common genesis. A zone is characterized by the short time of its formation (within 10 million years) and an irregular distribution of mineral deposits. Metallogenic zones tend to group into ore fields, which combine deposits of similar composition and genesis. Recognition of metallogenic zones and ore districts makes it possible to conduct the zonation of metallogenic belts and to reveal the dynamics of their formation in time and space (Parfenov *et al.* 1999).

Early collisional group of gold fields and deposits

The early collisional group of gold fields and deposits is localized in the the Allakh–Yun, Verkhoyansk, and Kular metallogenic zones within the western part of the Verkhoyansk fold-and-thrust belt and on the northwestern flank of the Kular–Nera slate belt (Fig. 1). The early group consists of gold–quartz deposits, the type of 'Au deposits in shear zonse and quartz veins' (after Nokleberg *et al.* 1996).

The Allakh–Yun metallogenic zone extends north–south for 300 km in the central part of the South Verkhoyansk sector of the Verkhoyansk fold-and-thrust belt (Fig. 1). It is confined to the Minor–Kiderikin zone of highly deformed rocks within the western South Verkhoyansk synclinorium. In the northern part of the South Verkhoyansk synclinorium, the Minor–Kiderikin zone consists of a system of en-echelon tight folds, while in the south there is a high-angle monocline separating compressive folds of Upper Carboniferous rocks on the west and simple open folds of Permian deposits on the east. The Minor–Kiderikin zone makes up an eastern termination of the Sette–Daban transpression shear zone (Fridovsky & Prokopiev 1997). The metamorphogenic gold–quartz veins, characteristic in the zone, are older than large granitic plutons of the South Verkhoyansk synclinorium, which are dated by ^{40}Ar/^{39}Ar at 120–123 Ma (Layer *et al.* 2001) and cut the ore bodies (Silichev & Belozertseva 1980).

The main ore bodies of the metallogenic zone are concordant and cross-cut veins occurring in the hinges and limbs of minor folds. The concordant veins thin out to form concordant stockwork-like bodies. There are also tabular ore bodies confined to tension fractures in sandstone beds. They are oriented sub-perpendicular to the contacts of the beds and parallel to the fold hinges. The concordant veins exhibit a zoned structure. The early thin-banded quartz of grey colour on the periphery of the veins grades towards the centre into the late milk-white massive quartz (Amuzinsky 1975; Silichev & Belozertseva 1980; Konstantinov *et al.* 1988). The early quartz occurs in the areas of bedding-plane slip and bedding-plane slaty cleavage. It replaced schistose rocks and has a thinly banded structure. The veins normally contain angular fragments of the host rocks measuring a few tens of centimetres across. Maximum thickness of the ore bodies is 3–4 m, and length ranges up to a few kilometres.

Principal minerals of the ore bodies are quartz (90–95%) and carbonate (5–8%). Pyrite, arsenopyrite, pyrrhotite, sphalerite, galena, and chalcopyrite constitute 1–2%. The early quartz–pyrite–arsenopyrite assemblage is followed by a quartz assemblage, then by productive quartz–gold–galena–sphalerite assemblage, and a late carbonate–quartz assemblage (Konstantinov *et al.* 1988). Gold from the productive assemblage is pure (830‰ fine) and coarse-grained (0.5–1 mm) (Seminsky *et al.* 1987; Konstantinov *et al.* 1988). Significant gold concentrations (up to several grams per tonne) also occur in pyrite and arsenopyrite of the early mineral assemblage. Maximum Au values (up to 3 kg t^{-1}) are found in galena and sphalerite (Kokin 1994).

The Allakh–Yun metallogenic zone exhibits a characteristic mineralogical, temperature, and geochemical zonality along strike (Kokin 1994). From south to north, the amount of arsenopyrite decreases and that of carbonates increases, decrepitation temperature of productive mineral assemblages goes down, and content of Ag, Sb, and Hg rises to high values. This zonality pattern is attributable to general upwarping of the structures in this direction and to ore formation at higher hypsometric levels. The zone includes the Yursky–Brindakit and the Bular–Onocholokh ore fields (Fig. 1).

The Yursky–Brindakit gold ore field can be traced for 36 km from the Yudoma river in the south to Brindakit creek in the north, within the western limb of the Minor–Kiderekin zone of strongly deformed rocks, Figure 6. The boundaries of the district are defined by the outcrops of Upper Carboniferous and Lower Permian ore-bearing rocks of the Surkechan and Khalyya formations which are subdivided into five units, each up to a few hundred metres thick. Mineralization is confined to the base of the units and occurs in concordant veins. The lower parts of the units are made of sandstones, gritstones, conglomerate, and tuffaceous diamictites, which grade up section into siltstones. Total thickness of the ore-bearing deposits of the Surkechan and Khalyya formations ranges from 1200 m to 2200 m. The fold structure of the ore district is determined by open linear synclines and anticlines. The fold hinges are gently inclined (5–20°) towards the ore field. The largest fold structures up to 1 km wide are traced throughout the ore field. Vergence of the folds changes from western in the north and south of the ore district to eastern in the centre. The anticlines are asymmetric, with short western and longer eastern limbs. Fracture cleavage is developed, oriented parallel to axial surfaces of the concentric folds, and is well seen in aleuropelitic rocks and almost indistinguishable in psephitic and psammitic varieties. There are some localities with more compressive folding, including isoclinal and compressed folds which in plan form lens-

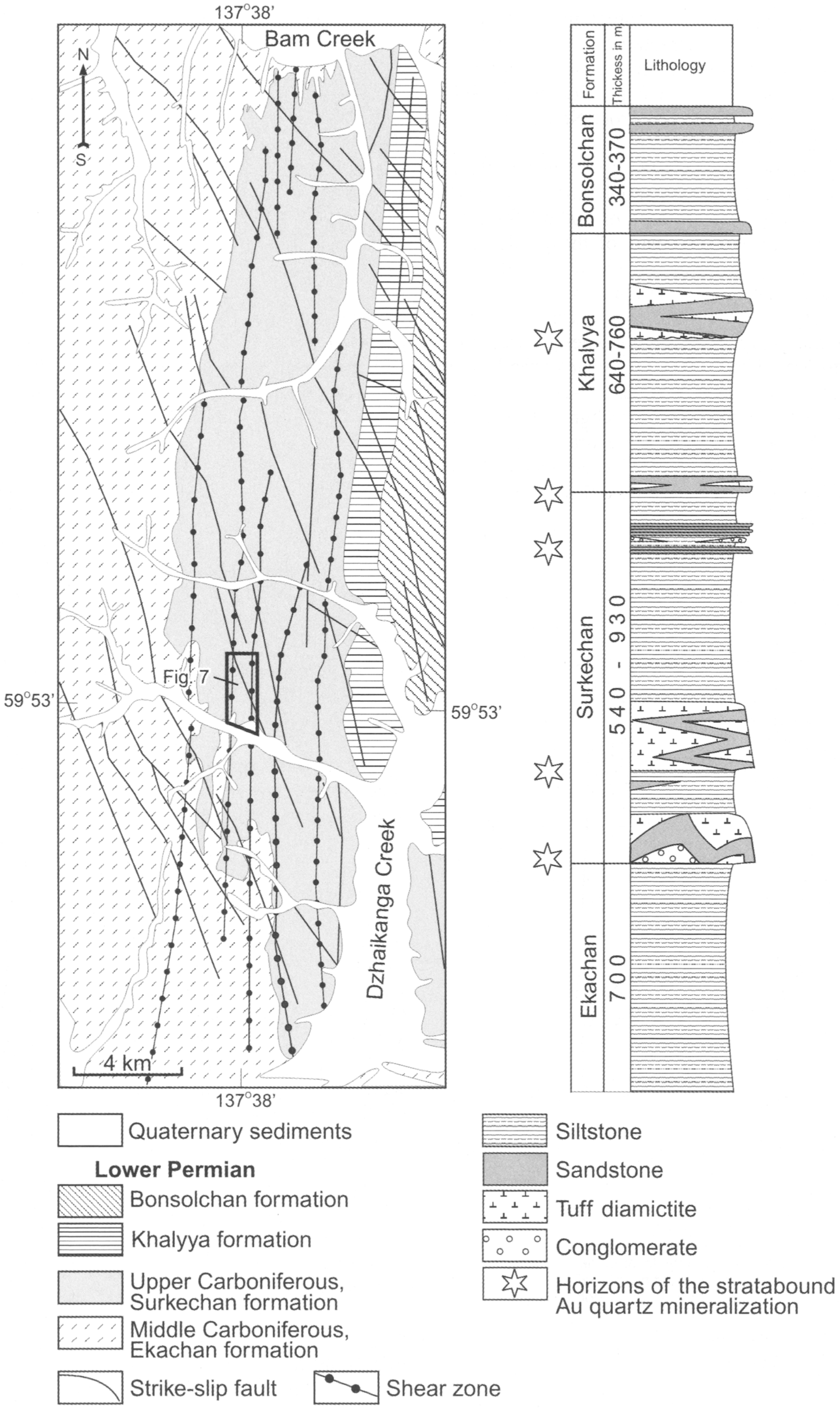

Fig. 6. Schematic geological structure of the Yursky–Brindakit gold ore field.

and-band patterns, non-persistent in width. Compressive folding is characteristic of shear zones which are the main ore-controlling structures of the Yursky–Brindakit ore field (Fridovsky 1998). Within the ore field, the Yurskoe, Nekur, and Duet deposits are known.

The Yurskoe gold–quartz deposit occurs within the limits of a low-angle monocline complicated by minor (with an amplitude of 100 m) folds and the ore bodies make up part of these folds (Fig. 7). Mineralization occurs in the third and fourth horizons of the Upper Carboniferous rocks. The ore bodies are massive in the centre and banded around the periphery. The thickness varies from 0.5 m to 5 m. The ore bodies occur at the base of sandstone units as thick as 1–20 m. Several north–south shear zones are recognized here. The rocks near the shear zones are draped into compressed and isoclinal folds filled with saddle reefs parallel to the cleavage and axial surfaces of the shear folds.

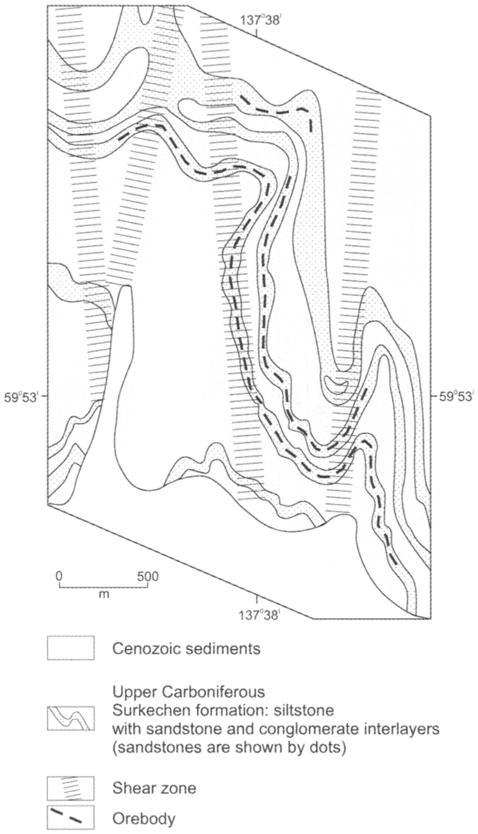

Fig. 7. Geological structure of the Yurskoe gold–quartz deposit, Yursky–Brindakit field.

The Verkhoyansk metallogenic zone extends as a narrow (up to 100 km) band for 1200 km along the western margin of the northern and central sectors of the Verkhoyansk fold-and-thrust belt (Ivensen *et al.* 1975). It is made largely of Carboniferous and Permian terrigenous rocks metamorphosed at greenschist facies. Metamorphism is thought to be related to thrust zones (Arkhipov *et al.* 1981), regional metamorphism (Kossovskaya & Shutov 1955) or to unexposed granitoid plutons (Yapaskurt & Andreev 1985). Early authors proposed the relation of gold mineralization with high-grade metamorphism of greenschist facies (Ivensen *et al.* 1975). Later on it was established that gold content is low in higher-grade rocks of the biotite sub-facies and that best gold values occur in the muscovite–chlorite subfacies (Andreev *et al.* 1990).

The zone consists of several ore fields corresponding to culminations of major anticlinoria (Amuzinsky 1975; Ivensen *et al.* 1975; Fridovsky 1998). From north to south these are the Dyandi–Okhonosoi, Meichan, Dzhardzhan, Balagannakh, Sereginsky, Aialyr, Sudyandalakh, Imtachan, Kygyltas, Sagandzha, Kitin, Barain, and Kharangak gold ore fields (Fig. 1). The main ore bodies of the zone are concordant veins complicated by cross veinlets clustering into stockworks in sandstone beds. Mineral composition of the ore bodies remains unchanged in all of the ore districts of the zone (Amuzinsky 1975). Quartz and carbonates predominate (98–99%). Ore minerals are pyrite, gold, pyrrhotite, galena, arsenopyrite, and chalcopyrite. Hydrothermal alterations include silicification, argillization, carbonatization, and sulphidization.

The Dyandi–Okhonosoi gold ore field is recognized in the north of the Verkhoyansk fold-and-thrust belt. It is made of undifferentiated Middle–Upper Carboniferous siltstones (with sandstone beds) and Lower Permian siltstones, sandstones and slates (Fig. 8). The ore field extends approximately north–south for 90 km and is 10–15 km wide. Gold–quartz mineralization occurs at three stratigraphic horizons. The ore bodies include concordant and cross veins, as well as stockworks in sandstone strata (Abel' & Slezko 1988). The Dyandi gold field and a suite of gold occurrences are known here. The structure of the Dyandi gold–quartz deposit area is determined by linear overturned folds and thrusts. Flow cleavage is clearly defined, following orientation of the thrusts. The deposit consists of stockworks, veins, and mineralized breccias controlled by approximately north–south high-angle faults. The stockworks are up to 900 m long and 100 m wide (avg. 20 m). Concordant and cross-cutting veins are present, ranging up to 80 m in length and 3 m in

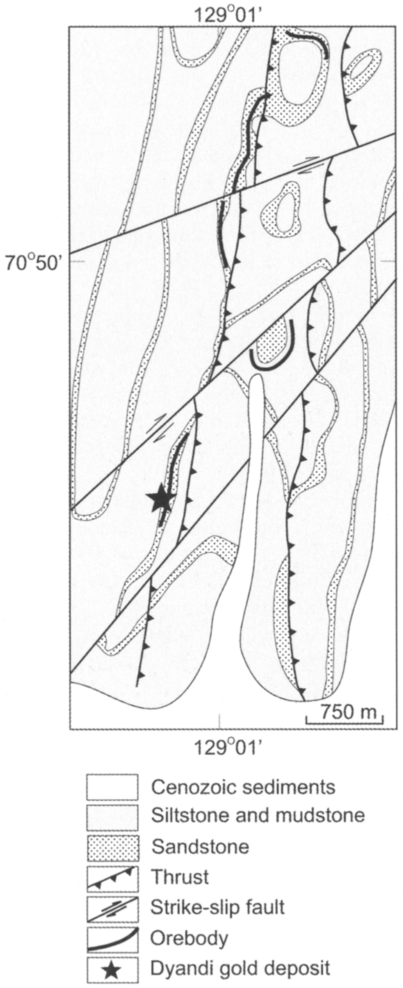

Fig. 8. Schematic geological structure of the southern Dyandi–Okhonosoi gold–quartz ore field.

thickness. The veins and stockworks are accompanied by mineralized breccias. The highest Au values occur in the stockworks—up to 4.3 g t^{-1}. Ag content of the stockworks is up to 1 g t^{-1}. The gold is 700–900‰ fine and occurs as grains up to 2–3 mm in size.

The Kular metallogenic zone is located on the northwestern flank of the Kular–Nera slate belt. It extends northeastward for 150 km and is 30–40 km wide (Fig. 1). The zone is formed from deep-marine black slates of Permian–Triassic age which are intruded by granites dated at 103 Ma by ^{40}Ar/^{39}Ar (Layer *et al.* 2001). Early authors considered the zone to be a fault–fold uplift with simple box and slit-shaped folds (Ivensen *et al.* 1975; Gusev 1979). Detailed structural studies conducted at a later time revealed a complex fold-and-thrust structure of the zone with a wide distribution of refolded recumbent isoclines (Parfenov *et al.*, 1989; Fridovsky & Oxman 1997). The rocks are metamorphosed to greenschist facies (muscovite–chlorite and biotite subfacies).

Metamorphogenic gold–quartz veins form the Kyllakh, Burguat and Dzhuotuk ore fields recognized within the limits of antiforms composed of Permian rocks. The ore bodies consist of quartz, carbonates (ankerite, calcite), chlorite, muscovite and albite. The early pyrite–arsenopyrite assemblage was followed by the later productive Au pyrrhotite–chalcopyrite–sphalerite–galena one (Sustavov 1995). The gold is 750–850‰ fine.

The Kyllakh gold ore field is the most intensively studied (Ivensen *et al.* 1975; Fridovsky & Oxman, 1997). It is delineated in the axial part of the Ulakhan–Sis antiform. The structure of the district is defined by two systems of low-angle thrusts of opposite vergence which control gold mineralization. The ore bodies occur in concordant veins and as mineralized crush zones. The veins are several hundreds of metres long and up to 4 m thick. They contain 1% Pb, 1% Zn, and 0.01% Ag (Ivensen *et al.* 1975). The mineralized crush zones are confined to thrusts or their feathering fractures. Within the ore field, the Emelyanovskoye and Kyllakh deposits are known. The Emelyanovskoye gold–quartz deposit consists of concordant ore bodies. Stratabound saddle, lenticular, and sheet-like veins are typical. Closely spaced veins and veinlets form concordant stockworks. Most of the veins and veinlets follow the orientation of cleavage structures and some of them occupy S-shaped shear fractures. Both up and down dip, the veinlets pass into concordant veins or are truncated by decollement faults. The ore bodies are a few hundreds of metres long and up to 1.5 m thick. They consist mainly of quartz and carbonate, along with subordinate pyrite, galena, sphalerite, gold, pyrrhotite, arsenopyrite, fahlore and chalcopyrite. Gold grains are 3–4 mm in the longest dimension. The Kyllakh gold–quartz deposit consists of three mineralized zones: West, Central and East (Fig. 9). Morphology of the veins is defined by the degree of deformation and metamorphism of the host rocks (Fridovsky & Oxman, 1997). The West zone occurs in an area of highly deformed rocks of greenschist facies (biotite) and is characterized by en-echelon quartz veins of various shape (saddle, beaded and lenticular), ranging in thickness from a few centimetres to 6 m. The Central zone occurs within the less deformed rocks of the stilpnomelane subfacies. Saddle veins here coexist with those developed along the thrust planes ranging up to 1.5 m

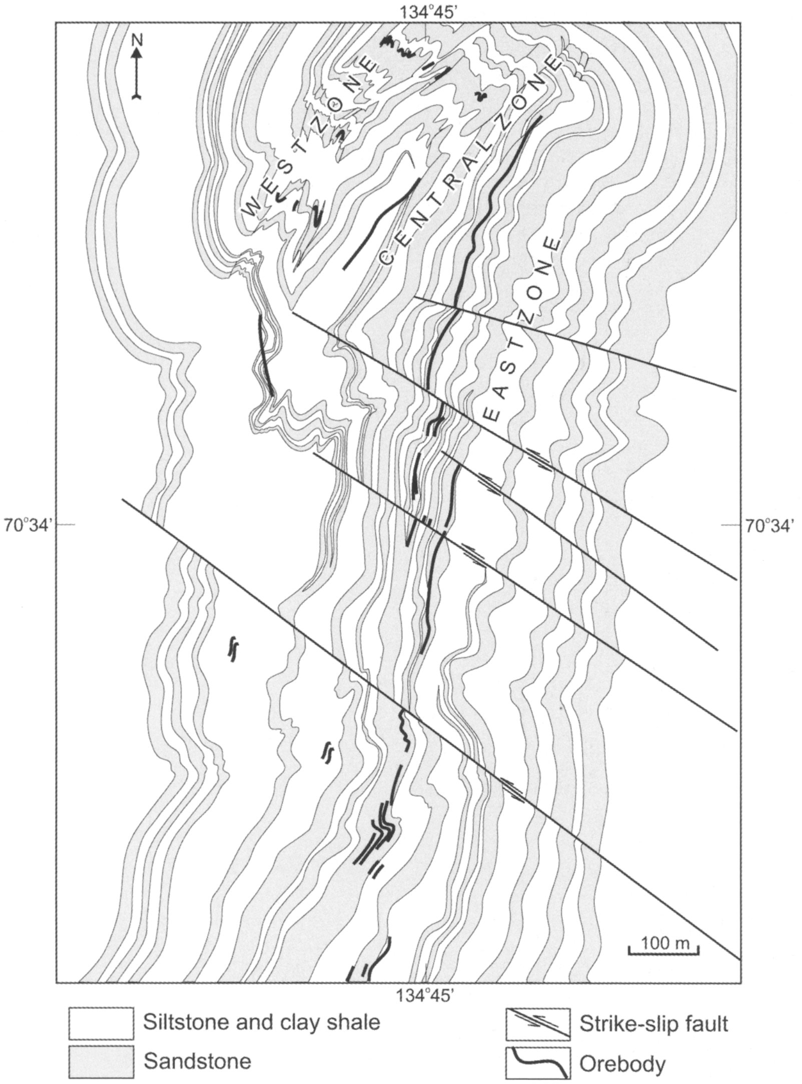

Fig. 9. Schematic geological map of the Kyllakh gold–quartz deposit (modified from Fridovsky & Oxman 1997).

in thickness. The East zone is delineated in monoclinal rocks of the chlorite–muscovite subfacies and consists of tabular ore bodies about 1 m thick. Gold concentration does not exceed a few grams per tonne.

Late collisional gold fields and deposits

The late collisional group of gold fields and deposits is localized in the Adycha–Nera and South Verkhoyansk metallogenic zones within the eastern part of the Verkhoyansk fold-and-thrust belt and at the centre of the Kular–Nera slate belt (Fig. 1). The late group includes deposits of gold–quartz type ('Au deposits in shear zones and quartz veins', after Nokleberg *et al.* 1996).

The Adycha–Nera metallogenic zone extends over the central and southwestern sectors of the Kular–Nera slate belt formed from Permian and Triassic deep-water black slates and the adjacent part of the Verkhoyansk fold-and-thrust belt made of Upper Triassic and, locally, Lower Jurassic shelf deposits. The zone extends northwesterly for 600 km and is 150 km wide (Fig. 1). It includes several hundred gold–quartz vein deposits and occurrences of different morphology. A long history of ore deposition is presumed here, beginning with accumulation of disseminated gold in the Upper Palaeozoic and Lower Mesozoic black slate units in distal parts of the Verkhoyansk passive continental margin and its subsequent mobilization during metamorphism and emplacement of granitoids in the course of Late Jurassic–Early Neocomian collision between the northeastern margin of the North Asia craton and the Kolyma–Omolon superterrane (Fridovsky 1998). The zone includes the Tuora–Tas, Badran, Yakutsky, Saninsky, Kurun–Agalyk, Sokh, Ol'chan, Talalakh, Bazovsky and Zhdaninsky ore fields (Fig. 1).

The Tuora–Tas gold ore field is about 40 km^2 in area, located in the central sector of the Kular–Nera slate belt. The district is composed of Lower Norian and Carnian siltstones and slates with rare sandstone beds. The rocks are metamorphosed at lowest greenschist facies. There are several andesite–basalt dykes up to a few hundred metres long, stiking NE. The dykes exhibit silicification, carbonatization, and chloritization. Small-sized massifs of biotite porphyry granite occur 7 km northwest of the ore district border and hornfels are found at a distance of 3.5 km. The main fold structures of the district trend northeasterly, parallel to the orientation of major north–south faults and cleavage. They seem to be superposed on the earlier isoclinal folds. The ore bodies normally have NE and, more rarely, east–west strike. There are concordant veins (Sokhatinoe deposit, Shyrokoe occurrence), mineralized crush zones, and stockworks (Venera and Sokh–Bar occurrences) (Fig. 10). The concordant veins occur at the contacts of beds with contrasting physico-mechanical properties. They often change into high-angle cross-cutting veins. The veins are up to 100 m long, ranging in thickness from a few tens of centimetres up to 2.5 m. The mineralized crush zones can be traced for a distance of 1.5 km and have a variable thickness. The stockworks are confined to areas of en-echelon mineralizing faults, ranging up to 100 m in thickness. The ore bodies are composed of quartz, carbonates, and ore minerals such as pyrite and arsenopyrite (early assemblage), along with subordinate sphalerite, chalcopyrite, and galena (late assemblage). The gold is free and is 792‰ fine (Rozhkov *et al.* 1971).

The Sokhatinoe gold–quartz deposit consists of concordant quartz veins up to 200 m long and 2 m thick accompanied by cross-cutting veinlets and veins up to 0.5 m thick. Mineralization is confined to a 1.5 km long mineralized crush zone in Carnian sandstones and siltstones (Fig. 10a). Gold content runs to a few tens of grams per tonne. The Venera gold–quartz occurrence is restricted to areas of en-echelon left-lateral strike-slip faults on the southern limb of an approximately east–west-striking fold. The ore body is a stockwork 100 m wide and 200 m long consisting of numerous quartz veinlets and rare master quartz veins up to 2 m thick (Fig. 10b). Gold content ranges from trace amounts to a few grams per tonne.

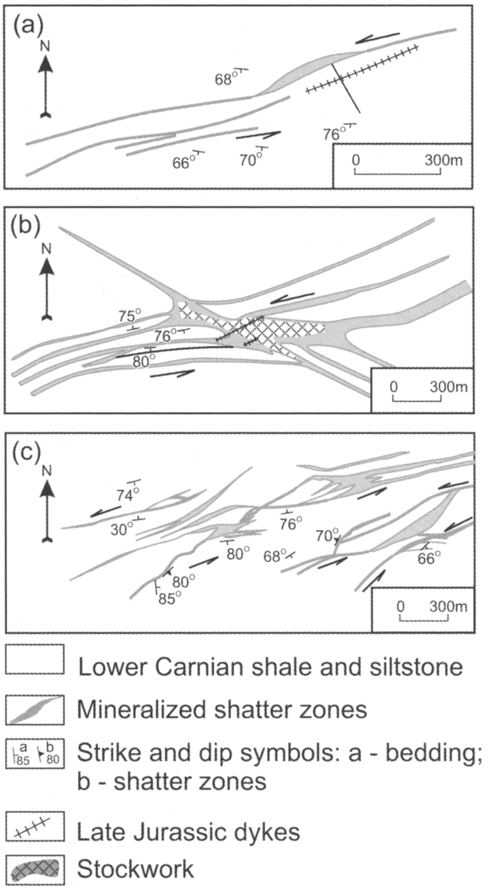

Fig. 10. The structure of ore zones in the Tuora–Tas ore field. (**a**) Sokhatinoe deposit. Ore occurrences: (**b**) Venera, (**c**) Sokh–Bar.

The Badran gold ore field is composed of Upper Triassic sandstones and siltstones deformed into wide low-angle anticlines and narrow slit-like synclines. Gold mineralization is controlled by northwesterly thrusts and strike-slip faults dipping to the NE, which are complicated by east–west- and NE-striking offset faults. The Badran gold–quartz deposit is confined to the plane of the Badran–Egelyakh strike-slip fault with a reverse fault component on which the amount of horizontal displacement is 800 m. The footwall of the fault is formed from Norian clastics, whereas the hanging wall is made of largely Carnian rocks

(Fig. 11). There is no apparent relationship of the deposit to magmatic rocks. The nearest granitoid rocks occur 30 km to the SE of the deposit. Quartz veins and veinlets tend to occur in mineralized crush zones within the Badran–Egelyakh strike-slip fault plane and are traced for a distance of 6 km to a depth of 800 m (Fridovsky 1999). The quartz veins in the fault zone are 200 m long and up to 4.2 m thick in swells. They are accompanied by thin quartz veinlets, most abundant in places where the veins pinch out. Along with the veins and veinlets, disseminated gold is found (mineralized boudins and tectonites). Maximum gold concentrations occur in the massive quartz veins. The ore bodies mainly consist of quartz, calcite, and dolomite. Ore minerals include pyrite, goethite, arsenopyrite, galena, sphalerite, tetrahedrite, along with minor ((1%) chalcopyrite, stibnite, bournonite, and free gold (Amuzinsky *et al.* 1989; Anisimova 1993). Gold is lumpy and interstitial. Fineness varies from 689‰ to 1000‰ (Anisimova 1993).

The South Verkhoyansk metallogenic zone occurs in the South Verkhoyansk sector of the Verkhoyansk fold-and-thrust belt. It is bounded, on the west, by the Minor–Kiderikin fault and, on the east, by the Yudoma fault. The zone is traced in a north–south direction for about 300 km. It is made of Upper Carboniferous to Middle Jurassic terrigenous rocks. Fold structures of the zone are characterized by wide gentle crests with smoothly undulating hinges. Northward, northeast striking strike-slip faults are important, with horizontal displacements of up to 10 km and vertical displacements ranging up to 1 km (Korostelev 1981). Magmatic rocks are represented by large polyphase plutons, as well as stocks, dykes, and

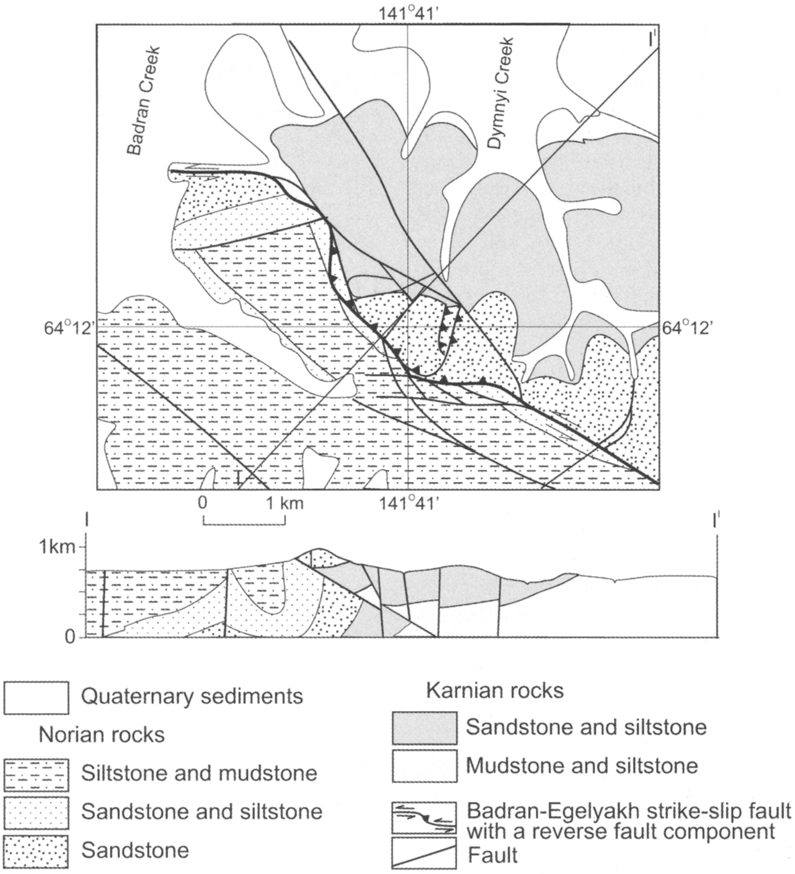

Fig. 11. Schematic geological structure of the Badran gold–quartz deposit.

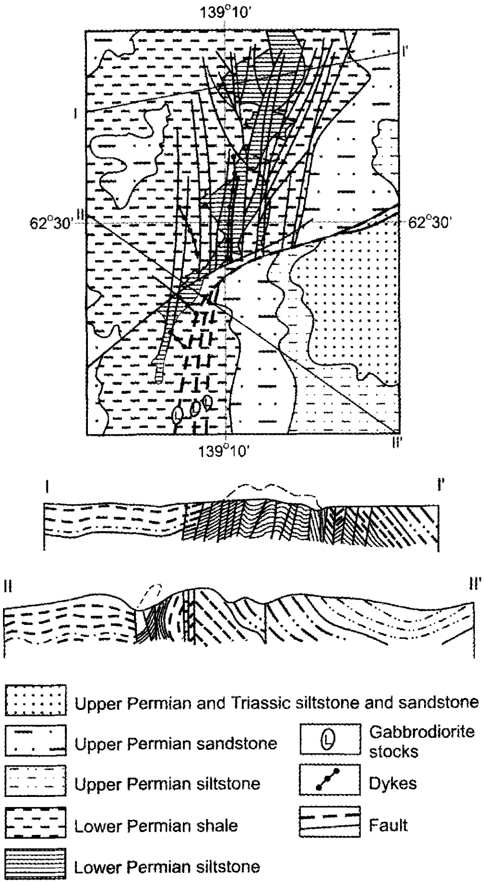

Fig. 12. Geology of the Nezhdaninskoe deposit. Modified after Shour (1985).

subvolcanic bodies. There are gold–quartz veins and crush zones and gold–rare metal deposits within and above the apices of granitoid plutons. The zone includes the Nezhdaninskoe and Zaderzhinsky ore fields (Fig. 1). The Nezhdaniskoe gold ore field occurs in the northern part of the Allakh–Yun tectonic zone and is composed of Permian and Triassic shallow-marine sediments deformed into large linear folds of north–south trend. The major fold is the Dyby anticline about 10 km wide which extends throughout the metallogenic zone for 60 km. It has a gentle crest and rather steep (up to 40°) limbs, with well-defined cleavage of the axial plane. The folds are faulted by diagonal right-lateral northeasterly strike-slips with horizontal displacements of a few hundred metres. Two large (5–7 km^2) granite stocks are known. These are the Dyby stock in the north of the district dated by ^{40}Ar/^{39}Ar at 121 Ma and the Kurumsk stock in the south dated at 92–97 Ma by the same method (Layer *et al.* 2001). Dykes of the district range widely in composition and age. The oldest are NW-trending pre-granitoid dykes of lamprophyre and gabbro-diorite dated at 157–138 Ma (K–Ar) (Indolev 1979). Quartz diorite, granodiorite-porphyry, and plagiogranite-porphyry dykes have younger K–Ar ages (140–110 Ma). The youngest are quartz-porphyry and rhyolite dykes dated at 81–79 Ma which strike NE and approximately north–south for 15 km. The Nezhdaninskoe ore field includes the Nezhdaninka gold–silver–quartz deposit which is the largest in Yakutia. The Nezhdaninka gold–silver–quartz deposit occurs in the crest of the Dyby anticline and is confined to the intersection of four regional fault systems: approximately north–south, northeasterly, northwesterly and approximately east–west. The north–south system hosts the main mineralized crush zones of the deposit. The diagonal fault systems control the location of offset veins (Fig. 12). The deposit consists of mineralized crush zones, rather persistent along strike and down dip, and smaller veins. A total of 117 bodies with ore-bearing potential have been recognized at the deposit, of which only 12 have been thoroughly investigated. The richest is an ore zone in which two thirds of the ore reserves are contained. It is localized in a 15 km long and 1–40 km wide crush zone. The mineralized intervals extend continuously for 1 km along the strike of the zone to a depth of a few hundred metres. The host rocks within the ore field underwent the beresite facies metasomatism and the accompanying synberesite sulphidization. Alteration halos are about 50 m thick around individual zones, while in places where the zones are in close proximity to each other the thickness of the halos ranges up to a few hundred metres. Metasomatic sulphides are highly auriferous: 30–500 g t^{-1} gold in arsenopyrite and 10–150 g t^{-1} gold in pyrite. Gold is 560–900‰ fine, with most values falling into the 780–820‰ category. Mineralization occurs mainly in veinlets and as disseminations. Quartz lenses are no more than 100 × 50 m in size, with the amount of sulphides up to 5%. The feathering quartz veins are traced for 300–400 m along strike and down dip. Their sulphide content does not exceed 3%. Along with quartz, significant carbonate (up to 5–7%) and arsenopyrite (2–3% and in places of intensely sulphidized rocks up to 15–20%) are found. Pyrite is less important. Late sulphides are represented by sphalerite and lesser galena. A range of sulphosalts are present including fahlore, freibergite, geocronite, jamesonite, pyrargyrite, miargyrite and stephanite, but bournanite and boulangerite are prevalent. Some of the ore bodies contain lens-like accumulations of stibnite (Gamyanin *et al.* 2001;Parfenov & Kuz'min 2001).

Discussion

The structure of the Late Jurassic–Cretaceous Verkhoyansk–Cherskiy collisional orogen (orogenic belt) shows virtually all major elements of the idealized model of a collisional orogenic belt, which make it a typical example of this a class of tectonic structure (see Fig. 3). Details of the structure of the accretionary wedge complex remain debatable due to insufficient previous coverage. The absence of substantial ophiolite outcrops may be evidence that the oceanic crust in the Oimyakon basin was nearly completely absorbed in the subduction zone. The direction of movement of the Kolyma–Omolon superterrane in the period of its accretion and collision still remains unclear. Available data (Oxman & Prokopiev 1995) permit us to presume that the collision of the superterrane with the craton occurred in the first stage not frontally but rather at an acute angle during the process of oblique collision. Incidentally, the superterrane, shifting in the northwestern direction, was a rigid indentor analogous to the Indian Plate during its collision with the Asian continent (Tapponnier *et al.* 1982). This is favoured by the fact that deformations are observed along the periphery of the orogen core with composite sinistral strike-slip kinematics, and the age of the collisional granites of the Main Batholith Belt rejuvenates northwestward from 150 to 134 Ma (Layer *et al.* 2001).

We have considered only gold–quartz deposits of the Yana–Indigirka metallogenic belt within the Verkhoyansk fold-and-thrust belt, which are related to two stages of collision between the North Asia craton and Kolyma–Omolon superterrane resultant in the formation of the Verkhoyansk–Chersky orogenic belt. The early collisional Verkhoyansk metallogenic zone is within the West Verkhoyansk sector of the Verkhoyansk fold-and-thrust belt and deposits are confined to axial parts of large anticlinoria in whose cores the oldest Carboniferous rocks of the Verkhoyansk terrigenous complex are exposed. The anticlinoria are located in culminations of large duplex structures with their roof thrusts traced at the base of the Verkhoyansk terrigenous complex. Deposits of the Verkhoyansk zone appear to be related to shear zones representing branches of these faults. It is supposed that deposits of the Allakh–Yun metallogenic zone are located in fan-like thrust zones, while deposits of the Kular metallogenic zone are related to shear zones confined to detachment at the base of the Permian in the Kular–Nera slate belt. The late collisional Adycha–Nera and South Verkhoyansk metallogenic zones are located in the hinterland of the Verkhoyansk fold-and-thrust belt and related to transpressional faults of combined thrust and strike-slip kinematics which originated during the second stage of the collision.

On the eastern margin of the North Asia craton (Verkhoyansk fold-and-thrust belt) there are other deposits assigned to the pre-collisional and post-collisional stages of the development of the territory. Formation of the pre-collisional deposits was related to the development of the passive margin of the Siberian continent. Typical are stratiform lead–zinc deposits of Vendian and Cambrian age (Sardana, Urui). Development of the Verkhoyansk passive continental margin was disturbed by Mid–Late Devonian rifting processes which produced copper mineralization here of the type of cupreous sandstones and schists and native copper in basalts (Kurpandzha), as well as copper–complex metal occurrences and apatite–pyrochlore mineralization in alkali-ultrabasic rocks and carbonatites (Gornoe Ozero). Some authors also include into the belt stratified silver–complex metal (Mangazeika) and gold–silver (Kysyl–Tas) deposits supposing that they formed in the Late Palaeozoic–Early Mesozoic in the course of sedimentation processes on the passive margin of the continent (Parfenov & Kuz'min 2001).

The post-collisional deposits include gold–antimony–mercury, gold–antimony, silver–complex metal, arsenic, antimony, and mercury deposits, among them Kyuchus, Sarylakh, Sentachan, and Prognoz. They were formed in the Late Cretaceous and, possibly, Early Cenozoic, i.e. in general synchronously with the formation of the Okhotsk–Chukotka volcanic–plutonic belt.

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