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Some Aspects of the Tectonics of the Verkhoyansk Fold-and-Thrust Belt (Northeast Asia) and the Structural Setting of the Dyandi Gold Ore Cluster

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THEME 10: Metallogenetic Provinces in the Circum-Arctic Region

Summary: Different types of thrust fronts alternate along strike in the Verkhoyansk fold-and-thrust belt along its boundary to the Siberian platform in northeast Asia. From south to north, strongly emergent fronts are replaced by buried ones with passive roof duplexes which, in turn, are substituted by fold-thrusts and frontal monoclines. This sequence of principal structures is then repeated northward. A relationship can be established between the gold mineralization of the Dyandi gold ore cluster in the north of the belt and dislocations developed in the zone of roof-thrusts of the Kharaulakh blind autochthonous roof duplex.

INTRODUCTION

The Verkhoyansk fold-and-thrust belt extends along the eastern margin of the Siberian platform and belongs to the external zone of the Verkhoyansk-Chersky collisional orogenic belt (Fig.1). The fold-and-thrust belt is subdivided into the West Verkhoyansk and South Verkhoyansk sectors and has a typical miogeoclinal structure (PROKOPIEV 1998). Upper Proterozoic to Mesozoic sediments of the Verkhoyansk belt belong to the Verkhoyansk passive continental margin of the North Asia craton. Along the front of the belt, the Late Jurassic to Cretaceous Priverkhoyansk foredeep is developed.

Folding in the fold belt region resulted from the collision of the North Asia craton with the Kolyma-Omolon superterrane and the Okhotsk terrane which occurred in Late Jurassic to Neocomian times. Two major phases of deformation can be recognized: early collisional and late collisional. In the fold belt area, two groups of gold ore deposits can also be distinguished as early and late collisional. The early collisional mineralization is older than collision-related granitoids in the axial part of the belt which are dated at 120-90 Ma. The early collisional, up to 100 km wide, belt of gold deposits coincides with the axial part of the Verkhoyansk fold-and-thrust belt. Mineralization is concentrated in ore zones and clusters. The late collisional group includes deposits related to the peak of the collision in the Early Cretaceous. In this paper, we present a classification of the frontal structures of the Verkhoyansk fold-and-thrust belt, which may be of economic interest since the region is promising for hydrocarbons. We also discuss the tectonic control of the early collisional gold mineralization pattern, based on the example of the Dyandi ore cluster in the NW-Verkhoyansk sector of the fold belt.

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CLASSIFICATION OF THE FRONTAL ZONE OF THE VERKHOYANSK FOLD-AND-THRUST BELT

The structures of thrust assemblages in the West Verkhoyansk sector differ from those in the South Verkhoyansk sector. In the West Verkhoyansk sector, a frontal, middle, and inner zones are distinguished.

- The frontal zone includes mainly fold-thrusts.
- The middle zone contains a passive roof duplex. Main detachment in these zones occur at the base of the Late Paleozoic-Mesozoic Verkhoyansk clastic complex.
- The inner zone represents a blind autochthonous roof duplex of the Late Precambrian-Middle Paleozoic carbonate complex and imbricate fans and pop-up structures in the Verkhoyansk clastic complex.

The structure of the South Verkhoyansk sector is defined

- by the high-amplitude Kyllakh thrust and
- by an allochthonous roof duplex in its central part (Fig.2).

A frontal zone (front) of a fold-and-thrust belt is an area in the outer part of an orogen, normally at the boundary between belt and foredeep (including, in some cases, the foredeep rocks) or undeformed platform formations. Two classifications of thrust fronts are known, one proposed by VANN et al. (1986) and the other by MORLEY (1986) (Fig.3A); both complement each other. MORLEY (1986) distinguishes two classes of thrust fronts: emergent and buried. Emergent fronts are subdivided into strongly and weakly emergent. In the emergent thrust fronts, the displacement of thrust sheets on the detachment results in the overlapping of submarine or subaerial paleo-erosion surfaces. In the submarine environment, syntectonic deposition may occur on thrust sheets or ahead of the thrust front in foredeep basins. Under subaerial conditions, the front of the moving thrust sheet is likely to undergo syntectonic erosion and to ride over its own debris. Various relations between the rates of sheet motion and those of front destruction were discussed by LEONOV (1970). Strongly emergent thrust fronts are characterized by a deep erosion level and by characteristic klippen and erosional tectonic windows.

Emergent fronts are analogous to thrust fronts of type 1 and 3 from the classification of VANN et al. (Fig.3A). In buried thrust fronts (after MORLEY 1986), the detachment level is not exposed at the erosion surface and displacement on the de-

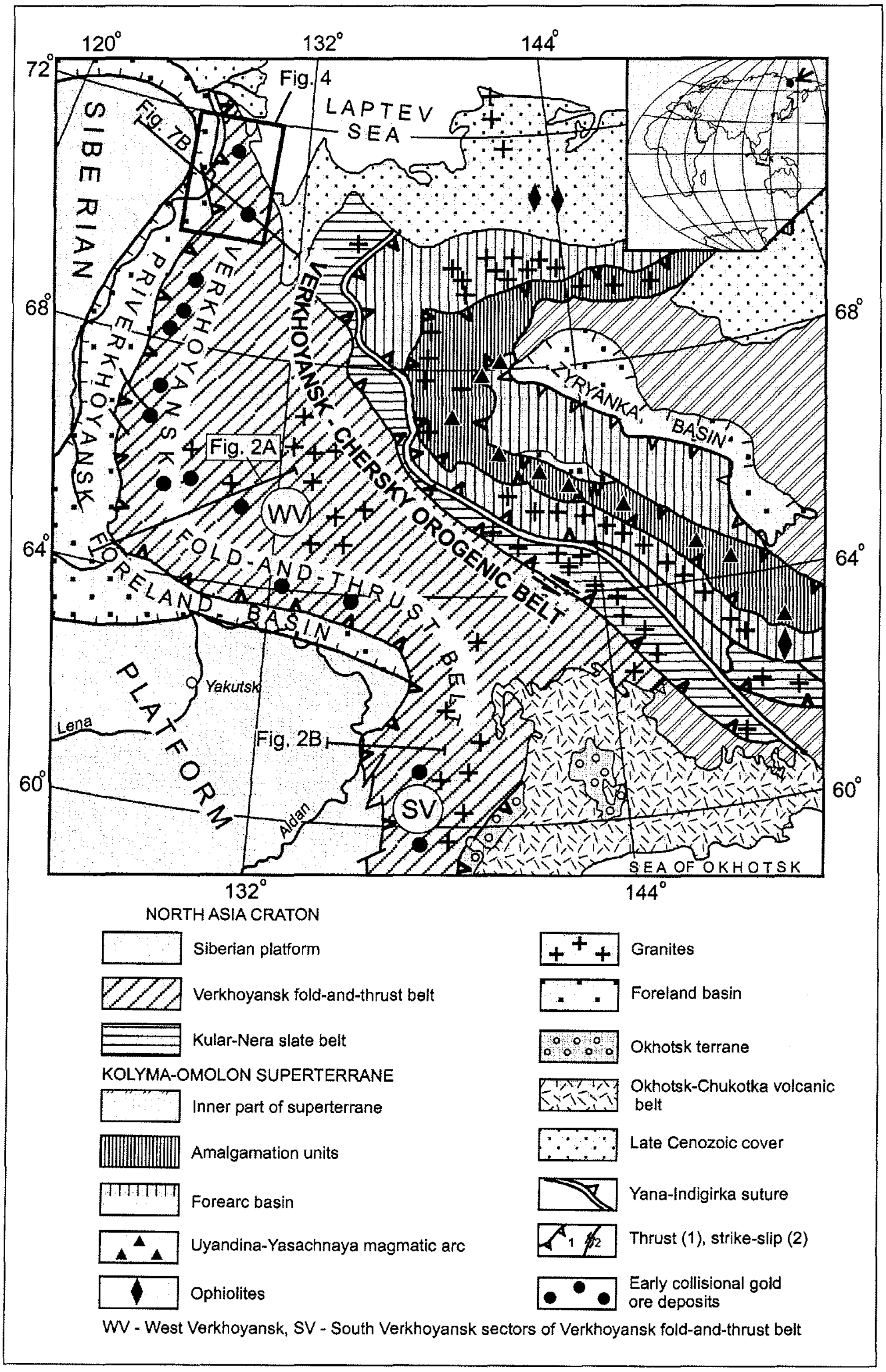

Fig. 1: Tectonic map of the Verkhoyansk-Chersky orogenic belt. The rectangle marks the location of the schematic geological map of the northern part of the West Verkhoyansk sector (see Fig. 4). Straight lines show locations of a geological cross section and gravity profile in the northern part of the West Verkhoyansk sector (see Fig. 7), and structural cross sections in the West Verkhoyansk (see Fig. 2A) and South Verkhoyansk sectors (see Fig. 2B).

tachment horizon dies out towards the foreland and is lost in the tip-line (a limit of the thrust) in which horizontal displacement is zero. Fronts of this type are either passive-roof duplexes (tectonic wedge) or frontal monoclines, or fold-thrusts. Buried fronts correspond to thrust fronts of type 2 and 4 from the classification of VANN et al. (Fig. 3A).

The front of the Verkhoyansk fold-and-thrust belt is one of the largest in Northeast Asia, extending more than 2000 km along the Siberian platform margin. It is divided into a number of branches (Fig. 3B) which, in some cases, coincide with western terminations of previously established segments (PARFENOV et al. 1995).

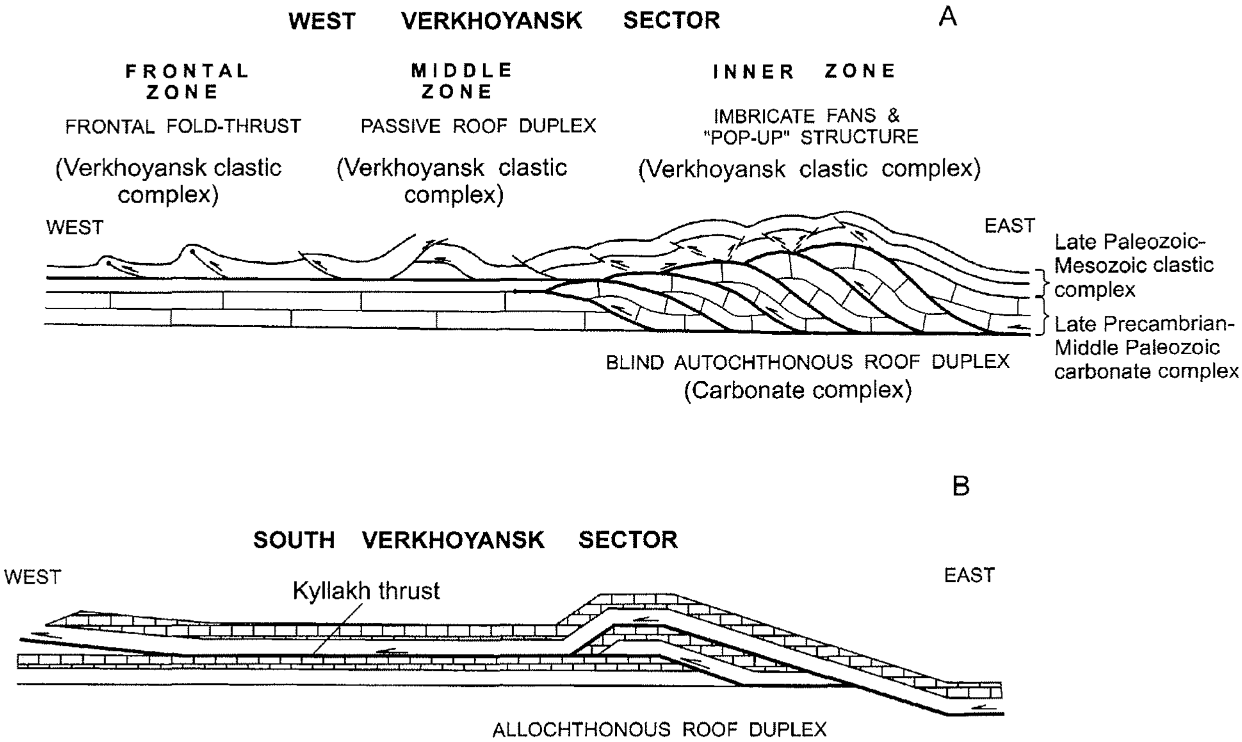

Fig. 2: Schematic structure of the West Verkhoyansk (A) and South Verkhoyansk (B) sectors of the Verkhoyansk fold-and-thrust belt. See Fig. 1 for locations.

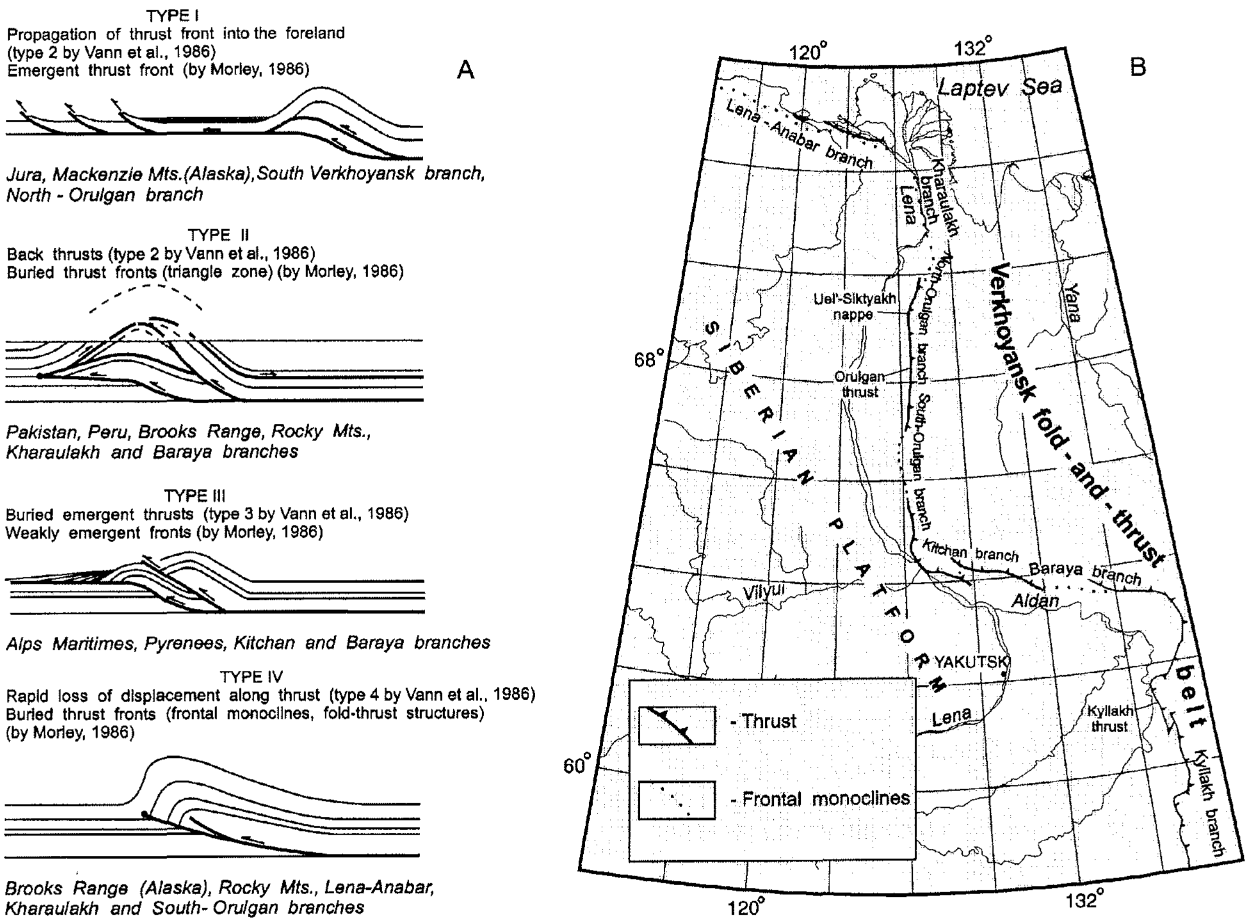

Fig. 3: Classifications of thrust fronts of the Verkhoyansk fold-and-thrust belt. A: main types of thrust fronts (after VANN et al. 1986, MORLEY 1986 with additions and modifications); B: tectonic branches of the Verkhoyansk thrust front.

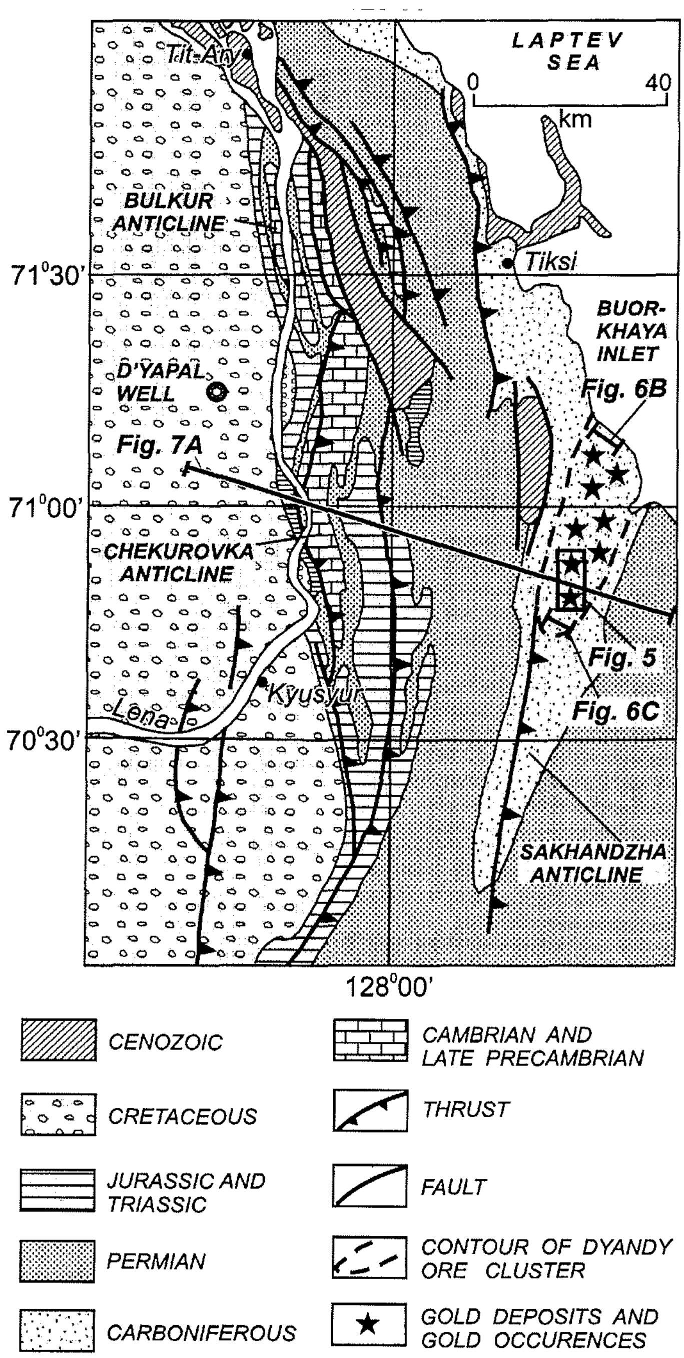

Fig. 4: Schematic geological map of the northern part of the West Verkhoyansk sector. Position of sections 6B and 6C are indicated; see Figure 1 for location.

The northern Lena-Anabar branch includes frontal monoclines and anticlines with steeper southern limbs consisting of Triassic and Jurassic terrigeneous rocks. Drilling revealed underlying Riphean - Lower Paleozoic carbonate rock units and Carboniferous - Permian terrigeneous rocks. From geophysical modelling it was established that the crystalline basement surface gently plunges towards the north. The anticlines are concentric rootless folds which are formed when a detachment is present at their base. Southwards, subhorizontal sediments indicate that the detachment horizon dies out in this direction and becomes zero in the area of the southern bends of marginal monoclines where a tip-line occurs. Detachment occurs along the crystalline basement surface where it either dies out or rises out of sequence to upper stratigraphic horizons. The level on which the displacement is lost is at the boundary between the Riphean – Lower Paleozoic carbonate and the Upper Paleozoic terrigeneous rock units with their different competency. Repetition of the carbonate complex section results in the formation of rootless folds.

The Kharaulakh branch has a similar structure but is characterized by a deeper erosion level. Here, Riphean and Cambrian carbonate deposits are exposed at the surface in the cores of the Bulkur and Chekurovka anticlines (Fig. 4). The detachment first follows the surface of the crystalline basement, then rises to upper levels and dies out in the tip-line, also at the boundary of the carbonate and terrigeneous rock units. In the southern Kharaulakh branch, there are thrusts with a vergence opposite to tectonic transport which compensates the horizontal movement in the wedge-type structures (passive-roof duplexes) or triangle zones. Thus, the Lena-Anabar and Kharaulakh branches combine features of thrust types II and IV: buried thrust fronts or structures with a tip-line (Fig. 3A).

The North Orulgan branch further to the south, is a strongly emergent thrust front belonging to type I. Large horizontal displacement (up to a few tens of kilometers) occurs along the Orulgan thrust (Fig. 3B) in the front area. The Uel'-Siktyakh nappe (Fig. 3B) is composed of Middle or Upper Carboniferous to Lower Permian rock units overlying Cretaceous sediments of the Priverkhoyansk foredeep (PROKOPIEV & OXMAN 1997). The South Orulgan branch is characterized by a frontal monocline in Triassic-Cretaceous rocks, complicated by small thrusts. In the central part of the branch, the main displacement occurred along the Sobolokh-Mayan thrust in the west, the tip-line of which was higher than the present-day erosion level. The detachment is restricted to pelite horizons at the base of the Triassic. According to calculations, the point where displacement on the detachment was lost, is 50 km to the west of the frontal monocline. Thus, the South Orulgan branch belongs to type IV, buried thrust fronts or frontal monoclines and structures with a tip-line. In the central part of the Kitchan branch, there are exposed fold-thrusts for which positions of tip-lines have previously been calculated (PROKOPIEV & GRINENKO 1989). It was found that the formation of frontal thrusts here was accompanied by synsedimentary folds (PARFENOV et al. 1995). In the north and south of the branch, there are blind fold-thrusts overlain by Upper Jurassic and Cretaceous rocks. The Kitchan branch belongs to type III: weakly emergent thrust fronts (after MORLEY 1986) or buried thrusts (after VANN et al. 1986).

The Baraya branch is characterized by back thrusts in the hinterland of the frontal monocline which are roof thrusts in the passive-roof duplex. The formation of the front here was accompanied by the accumulation of a thick series of Cenozoic sediments in the Lower Aldan basin, sealing the early low-angle thrusts. The detachment seems to disappear in Permian clayey horizons. Compensation for shortening is also due to imbricated fans developed ahead of the passive-roof duplex. The Baraya branch combines thrust fronts of types II and III: buried and weakly emergent. The Kyllakh branch is a typical example of a strongly emergent thrust front (type I),

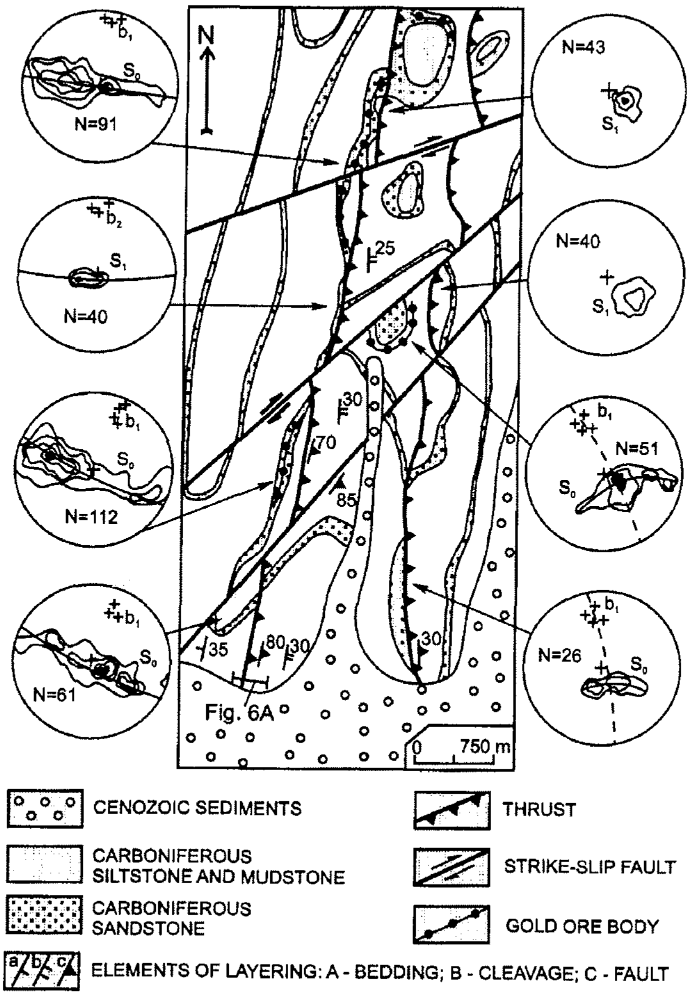

Fig. 5: Geological map of the Dyandi deposit. See Figure 4 for location. Position of section 6A is indicated. Stereograms show bedding poles (S_0) and cleavage poles (S_1).

with a horizontal displacement of the allochthonous sheet of up to 90 km (PROKOPIEV 1998). The detachment is restricted to the bottom of the Lower Riphean.

TECTONIC SETTING AND STRUCTURE OF THE DYANDI GOLD DEPOSIT

The Dyandi gold ore cluster is located in the northern part of the West Verkhoyansk sector of the fold-and-thrust belt. It occurs in the core of the Sakhandzha anticline in the northern part of the Khraulakh anticlinorium, 70 km to the east of the front of the fold belt (Fig. 4). This area is characterized by undifferentiated Middle-Upper Carboniferous siltstones with sandstone intercalations and Lower Permian turbidites consisting of alternating siltstones, sandstones and shales (Fig.5). Gold-quartz mineralization is restricted to three stratigraphic horizons in which ore bodies occur as concordant and crossing veins and stockworks in sandstone strata (ABEL' & SLEZKO 1988).

Figure 6A shows a geological section of the Dyandi deposit, the largest in the ore cluster. Gold-quartz veins occur east of a steeply-dipping brittle shear zone. The western termination of the zone is taken where the intensity of rock deformation diminishes. The shear zone is composed of deformed blocks of terrigeneous rocks with quartz vein embedded in the tectonic breccia. Thin (15-40 cm) sandstone sheets are cleaved into blocks (Figs. 6A, 2). Studies of the slickensides revealed that earlier thrusts are crossed by later strike-slip faults. In the footwall, bedded siltstones and sandstones form a low-angle, west-dipping (10-20°) monocline. The rocks are draped into open concentric folds. Thin sandstone strata (10-15 cm) are segmented into separate blocks as long as 20-70 cm (Figs. 6A, 1). Several, 2-4 m-thick, thrust-bounded tectonic sheets occur east of the main fault. Dislocations of rocks in adjacent sheets differ and significant displacement along the separating thrusts is observed (Figs. 6A, 5). Cleavage and axial surfaces of the folds are oriented parallel to the thrusts (Figs. 6A, 7, 8). They exhibit a low-angle dip to the south-east. Differential movement of the rock matter is observed along the cleavage surfaces. Near the thrusts, compressed and isoclinal folds with hinges gently plunging to the SE are developed. The horizontal amplitude of the fold limbs attains a few tens of meters (Fig. 6). At some distance from the main fault, the intensity of deformation decreases, the folds become open, thickness of tectonic sheets increases to 5-16 m. The analysis of tectonic fractures revealed a thrust tectonic stress field (Figs. 6A, 3, 4).

Siltstones and sandstones are faulted and folded 5 km SE of the Dyandi deposit and form compressed and cleaved isoclinal folds overturned to the west (Fig. 6B). The accompanying crush zone is 2-5 m thick. The stereogram of bedding poles indicates gently SW-dipping cylindric folds with bends. The vergence of the structures indicates a dislocation direction from SE to NW. North of the Dyandi deposit, near the Buor-Khaya inlet, thrust deformations are accompanied by tectonic breccias, tectonic melange, and recumbent folds (Fig. 6C). Cleavage is shallower than bedding. A zone of tectonic melange with an apparent thickness of 9 m is composed of lenticular fragments of sandstones up to 30 cm across, embedded in a matrix of schistose siltstones. Gold-bearing quartz veins are oriented parallel to the cleavage. Thus, N-NE-trending thrusts and related deformations control the distribution of gold-bearing quartz veins.

Figure 7 shows a structural section across the northern part of the West Verkhoyansk sector of the belt compiled from geologic mapping and low-quality seismic data (ABEL'SKY et al. 1968) as well as a geophysical profile constructed from gravimetric data. Two surfaces of a regional detachment have been identified here. The top detachment is at the base of the Upper Paleozoic turbidites, a few meters above the stratigraphic unconformity separating them from the underlying Paleozoic carbonate deposits. The basal detachment is assumed to lie between the Upper Precambrian deposits and the crystalline basement (PARFENOV et al. 1995).

Tectonic styles of the lower carbonate and the upper terrigeneous complexes are rather distinct from each other. The structure of the region is controlled by the Kharaulakh blind autochthonous roof duplex, represented in the west by the Chekurovka anticline exposed on the bank of the Lena river. The roof thrust of the duplex is located at the bottom of Upper Paleozoic to Triassic deposits dislocated by thrust sheets and

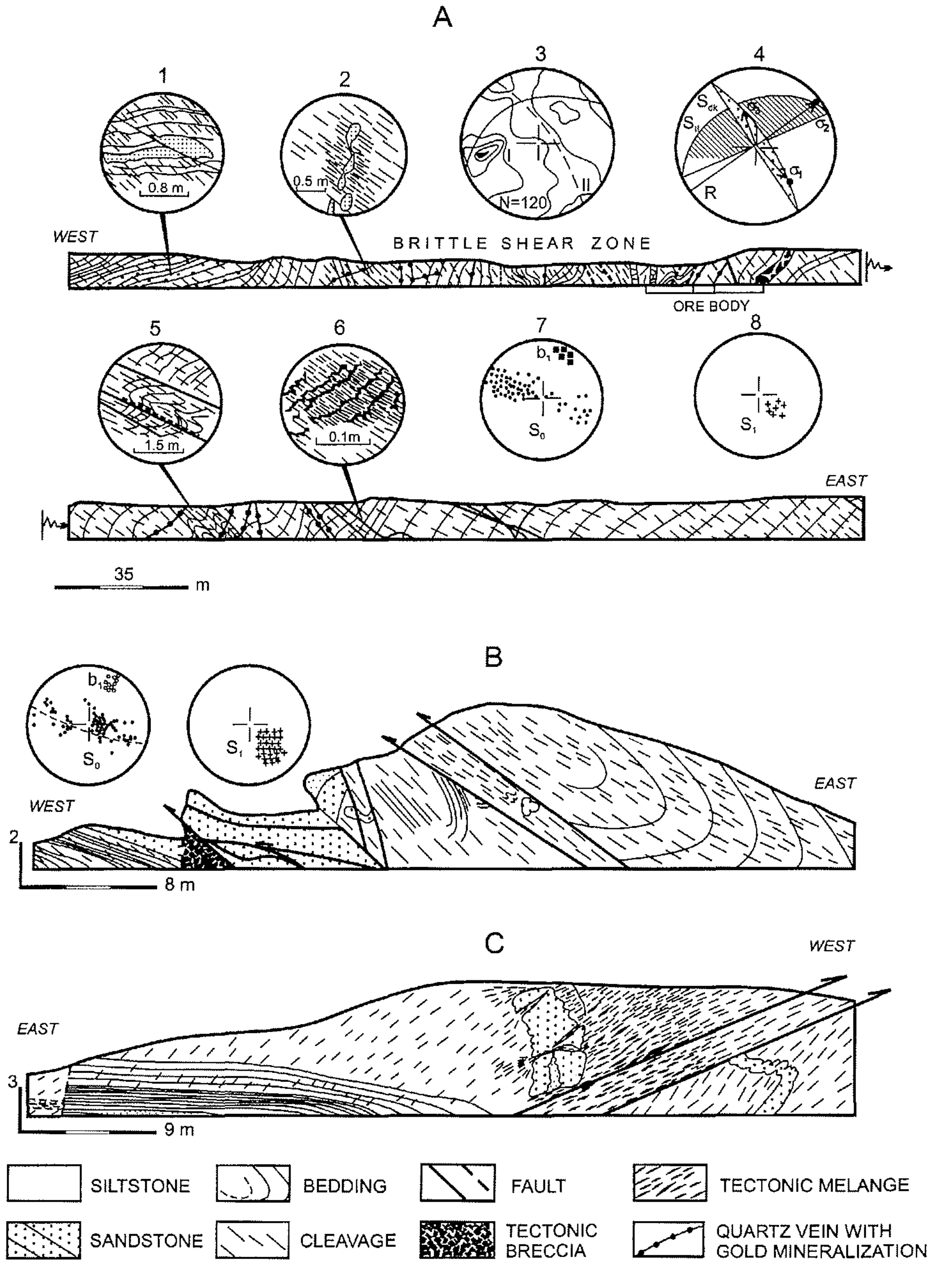

Fig. 6: Structural sections and stereograms of the Dyandi ore cluster. (see Figures 4 and 5 for location).
A1: deformation in the thrust zone, A2: boudinage, A3: stereogram of fracture poles, A4: orientation of stress axes (R: fault, S: fracture, dash line shows a belt of fracture poles, Sdk: dynamo-kinematic plane, σ_1: axis of maximum compressive stresses, σ_3: axis of minimum compressive stresses, σ_2: intermediate axis; A5-6: fold deformation of bedding; A7: stereogram bedding poles (dots) and intersection lines of bedding and cleavage (squares), A8: stereogram cleavage poles.
B-C: Thrusts and related deformations. Stereograms: dots - bedding poles, crosses - intersection lines of bedding and cleavage, open circles - cleavage poles.

pop-up structures. The duplex itself is made up mainly of carbonate rocks of Upper Precambrian and Cambrian age. Anticlines, such as Sakhandzha, in the Verkhoyansk clastic complex above the duplex, correspond to the highest part of horse structures in the duplex, while synclines of the Verkhoyansk complex occur above the junction of horse structures (Fig. 7).

In the core of the Sakhandzha anticline, lower horizons of the terrigeneous complex (Early-Middle Carboniferous deposits) are exposed. They are mostly close to the detachment (roof thrust of the duplex) and, hence, are mostly dislocated. It is here that the Dyandi gold ore cluster is situated. Upper horizons of the terrigeneous complex do not exhibit such a high amount of gold-bearing intercalations. Therefore, the data given above suggest a close relationship of the gold mineralization to the deformation in the zone of the roof thrust of the duplex. Gravimetric profiling conducted in the core of the Sakhandzha anticline suggests an unexposed granitoid massif to which the thermal domes previously established here (Yapaskurt & Andreev 1985, Yapaskurt 1992) might be related. The age of the granitoids and thermal domes is younger than that of the gold mineralization described (Fridovsky 1998). In more southerly regions it was established that the Khobotu-Echiy granitoid massif and a large unexposed granitic pluton in the central part of the West Verkhoyansk sector of the belt are restricted to the culmination of the Kuranakh duplex (Prokopiev 1998), which suggests also a close relationship of granitoid magmatism to duplex structures of the fold-and-thrust belt.

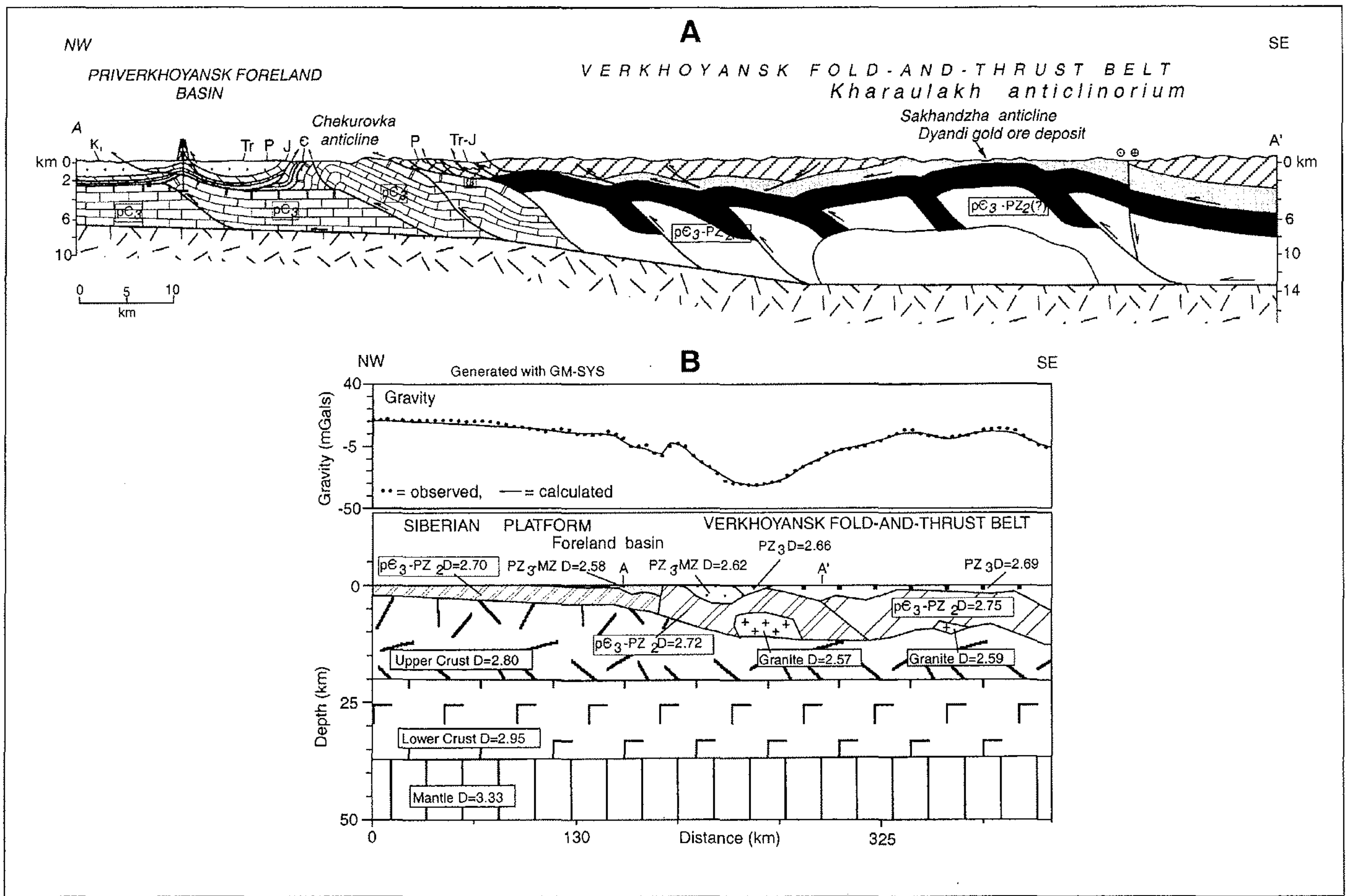

Fig. 7: Geological cross sections (A) and gravity profile (B) across the northern part of the West Verkhoyansk sector. See Figures 1 and 4 for location.

CONCLUSIONS

1) The Verkhoyansk fold-and-thrust belt provides the rare opportunity to observe all classical types of thrust fronts within one mountain range. This can only be explained by the large extension of the belt and different conditions of thrust formation in different segments. An interesting regularity in the occurrence of different front types was found: front types successively change from one to another from S-N along the strike of the belt: strongly emergent fronts change into buried ones with passive duplexes which, in turn, pass into fold-thrusts and frontal monoclines. Further to the N, where the North Orulgan branch begins, the succession is repeated. This classification of fronts of the Verkhoyansk fold-and-thrust belt is a first attempt to summarize data for this complex structure.
2) A relationship exists between gold mineralization and structures developed in the zone of the roof thrust of the Kharaulakh duplex. A chain of early collisional gold occurrences runs along the axial part of the Verkhoyansk fold-and-thrust belt (Fig. 1). They are localized in the centers of the largest anticlinoria of the belt, such as Orulgan, Kuranakh, and Baraya, above the culminations of blind autochthonous roof duplexes of the carbonate complex (PROKOPIEV 1998).

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