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ORIGINAL PAPER

Structure of the Muruntau gold ore region in the Kyzyl-Kum desert (Central Asia)

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Abstract

The giant gold deposit Muruntau in most works belongs to the "orogenic type". However, in the description of the geology of the deposit, there is usually no information about the stages (deformation, metamorphism) and the role of regional processes in the formation of host and mineralized rocks of the deposit. Our fieldwork provides unique geological evidence and previously unpublished data that are not reported in any other publications to date. This article presents the results of a detailed structural study of the terrane hosting the Muruntau gold deposit on the example of four sites and the results of deep drilling of two wells. The conducted studies confirm that the lowest Muruntau megaterrane consists of multi-stage metamorphosed Neoproterozoic–Early Paleozoic sedimentary-volcanic rocks and Late Paleozoic carbonate sediments overlain by Late Carboniferous flysch and olistostrome in the top. Two main stages (D1 and D2) of rock deformation in the lower part of the megaterrane associated with the Early Paleozoic accretion and two subsequent stages (D3 and D4) associated with the Late Paleozoic accretion and orogeny are described. Thrust processes D2 and D3 caused the formation of recumbent folds of different orientation and vergence. The normal antiform (D4) extending W–E is an orogenic fold. The Muruntau gold deposit is located in a regional synmetamorphic thrust zone called the Main Muruntau Thrust (MMT), which formed during the Early Paleozoic D2 stage. The MMT is responsible for the formation of secondary rock anisotropy along the cleavage of the D2 recumbent folds and conformal lens-like body of mineralized rocks and gently sloping veins with an area of 7.0 × 2.6 km. The internal structure of the deposit retains fragments of deformed gold quartz veins into recumbent folds. These structural data make it possible to link low-grade gold mineralized zones with Early Paleozoic deformations. We suggest that rock anisotropy within the MMT controlled mineralization twice: in the Early Paleozoic as a synmetamorphic flat high-permeable zone and in the Late Paleozoic as a relatively low-permeable zone for post-magmatic fluids.

Keywords Central Asia · Uzbekistan · Kyzyl-Kum · Terrane structure · Tamdytau · Muruntau gold deposit

Introduction

The Kyzyl-Kum part of the Tien Shan is moderately uplifted part of Paleozoic Laurasia platform that appeared at the Central Asian Orogenic Belt (CAOB) acting in Paleozoic. The platform cover consists mostly of continental clastic sediments alternating with lake and shallow marine deposits.

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The Muruntau gold field and gold ore region are hosted in the Paleozoic rock uplifted at the centre of the Kyzyl-Kum desert (Tamdytau Mountains). As well as whole Tien Shan, the Tamdytau Mountains arose in the Oligocene after the collision of the Laurasia southern rim with the Indian plate (Fig. 1). The ongoing uplift of Tien Shan Mountains and overthrusts related to the plate collisions led to the folding and overthrusting with a horizontal reduction of the Laurasia platform territory in Central Tien Shan area of more than 100 km (Burtman 2000).

The Alpine collision is also accompanied by arcuate overthrusts, moderate vertical and horizontal movements of blocks inside the Paleozoic basement in the Kyzyl-Kum area (Sitdikov 1985). Tectonic block of Tamdytau Mountains have an arcuate-scaly shape with uplifted NW and lowered SE rims (Fig. 2). According to drilling data, obtained during

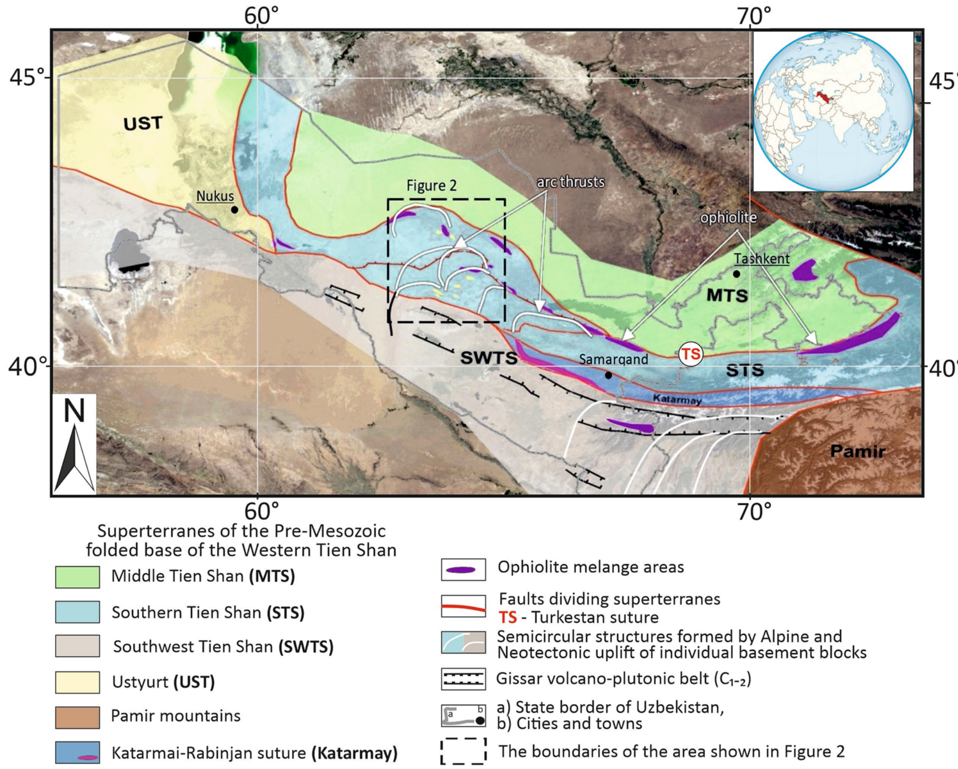

Fig. 1 Paleozoic and Alpine tectonic patterns of Laurasia and India collision in Kyzyl-Kum sector

gold and uranium exploration, alpine deformations of the Paleozoic basement rocks appear as left-shear steep faults and thrust-type arc faults (Shultz 1973).

Due to Alpine deformations, uplifting followed with erosion, the Paleozoic basement of the Kyzyl-Kum is available for study. It consists of multi-stage highly deformed and metamorphosed rock terrane (Fig. 3). They have been accreted during the Late Paleozoic closure of Turkestan Paleo-Ocean (TPO) existing in the CAOB area. TPO was located between the Kazakhstan and Tarim-Kara-Kum (TKM) microcontinents and actively developed since Late Proterozoic to Late Palaeozoic (Burtman 1976; Mukhin 1977; Mukhin et al. 1991).

The accretion complex in Kyzyl-Kum was formed during three Paleozoic events. The first one appeared in the Early Paleozoic (pre-Devonian time, probably in Silurian). Rocks with footprints of Early Paleozoic deformation and metamorphism widely developed at the whole territory of the Kyzyl-Kum Uplands. The sediments are fine-detrital rocks (sandstones and clayey siltstones) deposited in the deep-water parts of the TPO (Mukhin et al. 1991). They are undergone to metamorphism and intensive deformation at Early Paleozoic in the south part of TPO close to TKM (Mukhin et al. 1988; Mukhin 1997). Accretion led to a partial increase of the TKM area in the north with the subsequent formation of a gentle shelf on the accretionary wedge. The shelf was a zone of stable accumulation of carbonate rocks since Early Devonian to Early Carboniferous. This terrane of metamorphic rocks covered with thick carbonate unit, exposed mainly in the southern part of the Tamdytau Mountains, is known as the Murun Terrane (Mukhin et al. 1991).

The second stage of accretion and collision occurred during the final closure of the Turkestan Paleo-Ocean in the Late Carboniferous (Sabdyushev and Usmanov 1971; Burtman 1973, 1976). At this stage, fragments of the marginal and central parts of the TPO crust (Bukan, Kulkuduk, and Tamdy terranes) were obducted onto the shelf deposits of the Murun terrane. Packages of these plates compose the northern part of Tamdytau Mountains (Burtman 1976; Mukhin et al. 1991).

The orogenic deformation appeared as normal latitudinal folds and faults. Granite intrusions and batholith-like bodies appeared already in the Late Carboniferous and Permian, as evidenced by the age and composition of the Late Paleozoic molasses (Sabdyushev and Usmanov 1971). Granite rocks pebbles found in molasses indicate that most of the granite batholiths were already exposed by erosion at that time (Burtman 1976).

Thus, the formation of modern continental crust at the territory of Kyzyl-Kum maybe divided in four main stages: Early and Late Paleozoic stages that happened in partial and final closure of the TPO, and late Paleozoic–Mesozoic and Alpine ones, inside the Laurasia platform.

Most of the existing structural models of Muruntau deposit are based on very limited data obtained from 1: 200,000 scale maps or cosmic images (see for example, Yakubchuk et al. 2002; Seltmann et al. 2020), whereas the

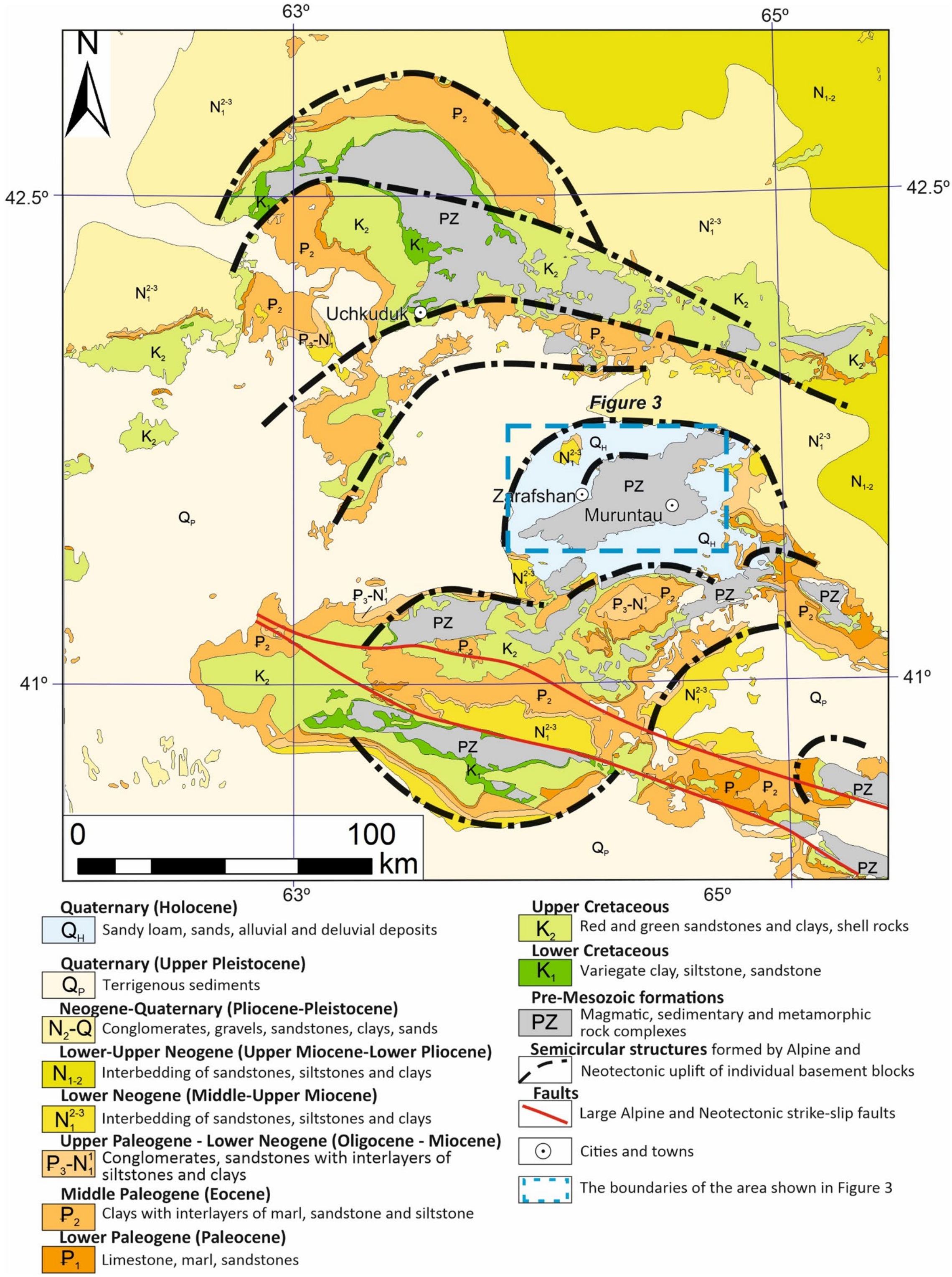

Fig. 2 Alpine tectonic pattern in the Kyzyl-Kum desert (Geological Map of Central Asia 1:1,500,000 with additions)

structural study by Wall et al. (2004) focused on the immediate Muruntau ore field.

During 1986–1991, the Tamdytau area has been detail surveyed at 1:10,000 scale, followed by deep structure drilling program. The research results and methodology were described in a special report (Savchuk 1994). Only very limited volume of the obtained data has been published (Muruntau gold deposit, 1998) due to the USSR collapse.

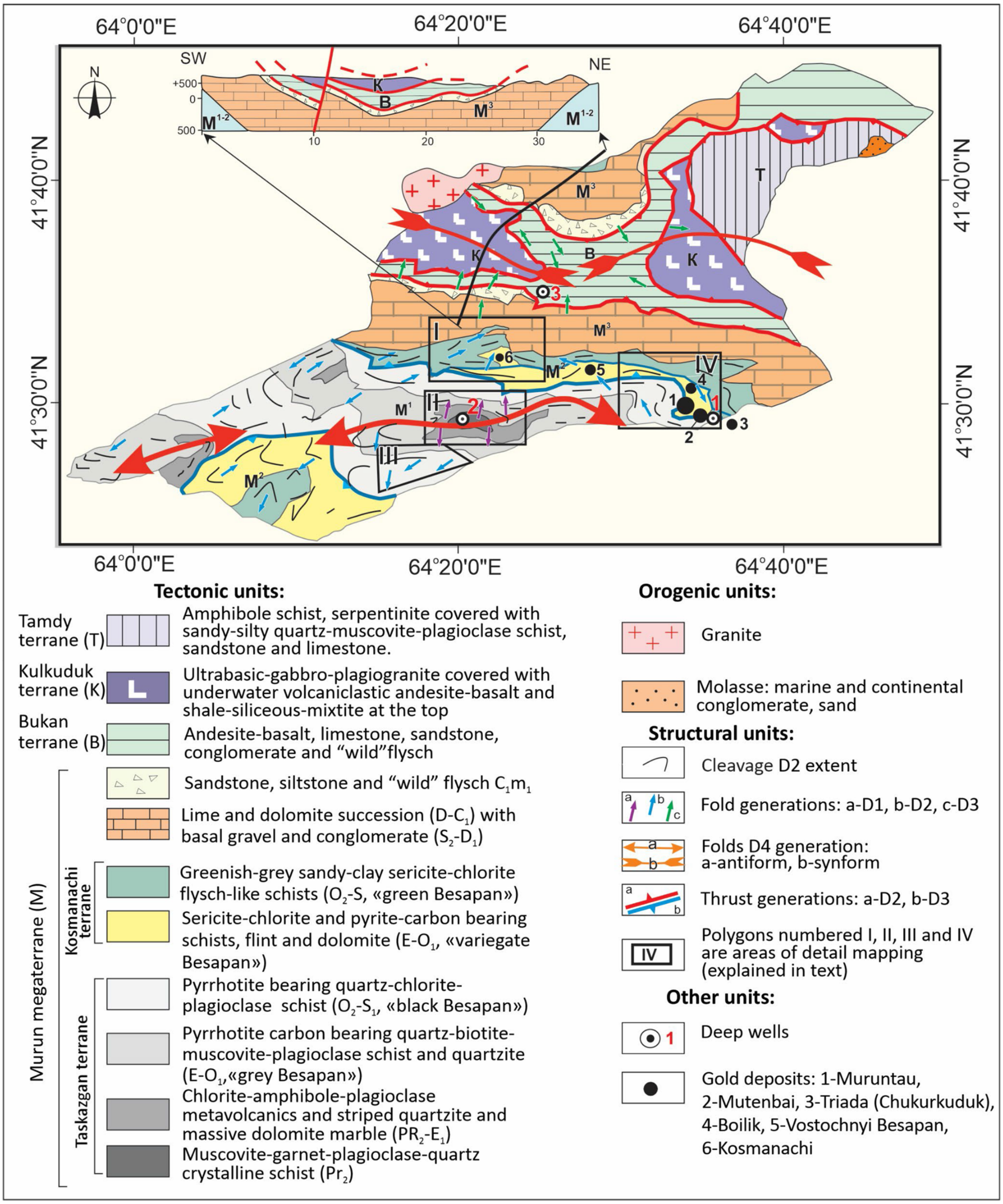

Fig. 3 The Paleozoic terranes of Tamdytau Mountains and location of the areas studied (white circles are deep wells). Cross-section is from V.S. Burtman (1973)

Just 10 years later, some western geologists accessed the limited data for re-interpretation (Heubeck 2001a, b).

Palaeozoic terranes of Tamdytau

There are four Palaeozoic terranes that have been recognized in the Tamdytau area. They successively overlay each other creating Paleozoic folded basement of Kyzyl-Kum (Burtman 1973, 1976, 2008; Mukhin et al. 1991; Mukhin 1997).

Megaterrane Murun (M) is predominantly developed in the southern part of the Tamdytau Mountains. It consists of Early Paleozoic terranes: Taskazgan (M_1) and Kosmanachi (M_2). Both terranes are unconformably overplayed with carbonate unit (M_3^1) and olistostrome (M_3^2). The Taskazgan and Kosmanachi terranes are metamorphosed Neoproterozoic-Early Paleozoic rocks of more than 6 km thick and upper cover is `Early Devonian—Late Carboniferous sediment sequence with a thickness of about 2 km (Figs. 3 and 4).

Lithology. The bottom part of the Murun megaterrane is composed of two terranes (Stratigraphic Dictionary … 2001). The lowest four units (Taskazgan terrane) start from muscovite–garnet–plagioclase–quartz crystalline schists (M_1^1) alternating with carbonaceous and metal-bearing (Au, U, Co, Cr, Ir, Sm, Eu—Kryazhev 2017) quartzite, marble and meta-basalt (M_1^2). Microscopic and chemical elements composition indicate rock sedimentation during Neoproterozoic—Early Cambrian (Stratigraphic Dictionary … 2001; Mirkamalov et al. 2012) in volcanic deep-water environment (Mukhin et al. 1985). Both units are covered with clastic rock named "grey Besapan" unit (M_1^3), which consists of thin-layered muscovite–biotite–albite schist and flintstone, dolomite and calcite marbles of about 1–2 km thick. The "grey Besapan" is overlaid by "black Besapan" (M_1^4) containing dark colored fine clastic chlorite–muscovite–quartz–albite schists of about 0.5–1.0 km thick. Both "grey Besapan" and "black Besapan" rock successions are permanently enriched with carbon, Co–Ni-bearing leucoxene, magnetite and pyrrhotite (Shayakubov 1998; Protsenko 2008). The rocks are mainly deposited in Ordovician (Stratigraphic Dictionary … 2001), probably, including also Cambrian and Early Silurian sediments at the bottom and top.

The upper Kosmanachi terrane (M_2) is composed of "variegate Besapan" and "green Besapan". The "variegate Besapan" (M_2^1) rock succession starts with grey and dark grey fine sand and silt covered with pyrite-carbon bearing schists, sometimes carbonaceous and tuffaceous, and lens-like flint and dolomite bodies. The lower part of "variegate Besapan", consisted of grey sandy siltstone, was dated at the Muruntau gold deposit as Neoproterozoic—Early Cambrian (Mirkamalov et al. 2012), and the upper, consist of metalliferous (pyrite-bearing) schists, carbonaceous and tuffaceous in the area of Kosmanachi dry river—Upper Cambrian to Middle-Upper Ordovician (Puchkov 1989). The "green Besapan" (M_2^2),—greenish-grey sandy-clay sericite-chlorite schists of the flysch-like type. The age of the "green Besapan" is assumed to be Middle Ordovician-Early Silurian (Stratigraphic Dictionary … 2001).

Metamorphism. The Taskazgan terrane (M_1) is metamorphosed in two stages: first progressive stage—to garnet–muscovite–biotite–albite level (250–400 °C),

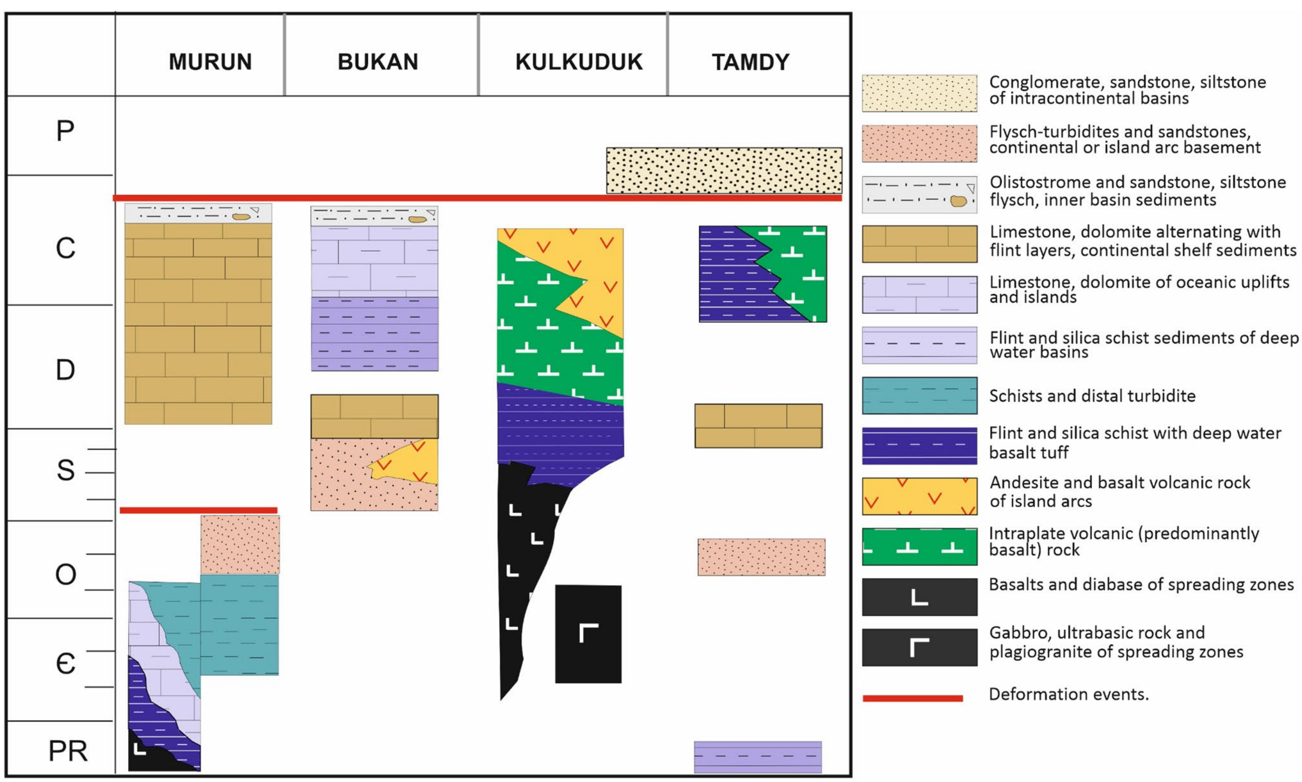

Fig. 4 Stratigraphic columns of the Tamdytau Mountains Paleozoic terranes

second regressive stage—to sericite–muscovite level (180–250 °C, (Khoreva 1971; Khokhlov 1977) of greenschist regional metamorphism. The rock succession contains primary pyrite and marcasite (non-magnetic) that were metamorphosed into pyrrhotite (magnetic), and the organic carbon was transformed into shungite (Protsenko 2008).

The Kosmanachi terrane (M_2) succession is metamorphosed in one stage. Both "variegate" and «green Besapan» rocks are metamorphosed only to the level of sericite-chlorite (180–280 °C). Sedimentary-diagenetic pyrite is recrystallized, but in many cases relics of the primary globular structure are preserved.

Rocks of "grey Besapan" and "black Besapan" overlay tectonically "variegate Besapan" and "green Besapan". The contact is represented by sericite–chlorite mylonites with fragments of meter-scale isocline recumbent folds. The mylonites thickness is tens to few hundreds of meters. This zone of intensive schistosity and mylonitization contains relict lens-like bodies of underlying and overlapping rocks. Mylonite and sericite-chlorite schistosity orientation in the zone are subparallel to sericite-chlorite schistosity developed in Kosmanachi and Taskazgan terranes. It indicates the zone origin as ductile synmetamorphic fault. The fault extends in the latitudinal direction from the Muruntau open pit to the Besapan gold recovery plant area, Kosmanachi and Sugraly spring areas totally of about 40 km length. The zone dips to E, NE and N, respectively. This fault is quite gentle from 30° to 60° and named as a Muruntau thrust zone or MMT (Mukhin et al. 1991). The thrust mylonites and relict blocks are hosted rock for gold ore of the Muruntau ore field (Fig. 3). The upper lithological-stratigraphic unit of Muruntau terrane is composed of Devonian-Early Carboniferous carbonate rock succession of about 2 km thick, which are overlain by the Tournaisian flysch and Early Moscovian olistostrome. The unit starts from the Early Devonian conglomerate horizon of tens meters thick and overlays the lower unit with angle unconformity at the bottom (Sabdyushev and Usmanov 1971; Burtman 1976).

Terrane Bukan (Figs. 3 and 4) tectonically overlays the early Moscovian olistostrome on top of the megaterrane Murun (Sabdyushev and Usmanov 1971). The Bukan terrane (B) succession consists of Lower Silurian clayish shales, sometimes carbonaceous and siliceous. They are covered with tuff sandstones alternating with polymictic sandstones, siltstones, clay shales, basalts, diabase and andesite porphyrite of Late Silurian. Devonian—Early Carboniferous detrital limestones and limestone breccias alternating with horizons of thin-layered plate flints and limestone conglomerate are transgressively cover the Silurian deposits (Burtman 1976; Mukhin et al. 1991). The continental source of the Bukan clastic sediment allows to reconstruct the Bukan terrane environment as a moderately deep-water transition zone of material deposition coming from volcanic uplifts (Silurian) and the continent (Devonian—Early Carboniferous).

Metamorphism of the terrane rocks is almost absent. Normally, the terrane rocks look like diagenetically altered sediments, sometimes containing sericite and chlorite in cement. Nevertheless, isoclinal recumbent folds may be found at the terrane rock.

Tectonic relationship between Bukan terrane and Muruntau terrane has been documented in SG-1 deep hole (Fig. 5). Melange zone is typically developed at the top of the Murun terrane and bottom of the Bukan terrane. The zone is represented as foliated schists containing rock lenses and blocks from upper terranes. Bukan terrane succession (B) overlaying the Murun terrane consists of greenish-grey clastic and carbonate sediments of about 230 m thickness. The underlying Murun terrane is represented with two units, dark carbonaceous quartz-feldspar sand alternating with "wild flysch" at the top of about 240 m thickness (M_3^2) and a more than 300 m thick carbonate rock succession (M_3^1). This rock succession has a robust palaeontology dating (Stratigraphic dictionary… 2001).

Terrane Kulkuduk (Fig. 4) consists of ophiolite rock and deep-water sediment succession. It composes of isolated massifs at the eastern (Bassumar massif) and at the western (Teskuduk massif) parts of the Tamdytau Mountains area. The terrane consists of pyroxenite–dunite–gabbro–plagiogranite at the bottom, underwater volcaniclastic andesite-basalt at the middle and shale–siliceous–mixtite at the top (Burtman 1976; Mukhin et al. 1991).

The age of gabbro-diorite from the Teskuduk massif is 438 ± 6 Ma (Dolgopolova et al. 2017) i.e. Early Silurian and indicates the time of solidification of the magmatic chambers. Hemipelagic sediments began to deposit already in Late Cambrian and low carbonaceous pelagic are of the Ordovician age according to conodonts dating (Mukhin et al. 1991) and, apparently, changed to clastic sediments at the end of Devonian. The mixtite sediments are accumulated during the Early Carboniferous (Sabdyushev and Usmanov 1971).

Metamorphism of the terrane rocks is predominantly greenschist facies or less. It clear appears in sub-horizontal shear zones and thrusts as serpentinization and mylonitization of dunite and harzburgite and are typical for the terrane bottom (Burtman 1976).

Tamdy terrane (Fig. 4) is the topmost unit and represented by metamorphosed sedimentary and volcanic rocks from Precambrian to Devonian (Burtman 1976). The succession is overlaid with unmetamorphosed marine and continental molasse deposits of the Late Carboniferous (Sabdyushev and Usmanov 1971).

The major part of the Paleozoic terrane section is coarse clastic rocks and mixtite. The unstable depositional environment in certain stratigraphic levels and permanent

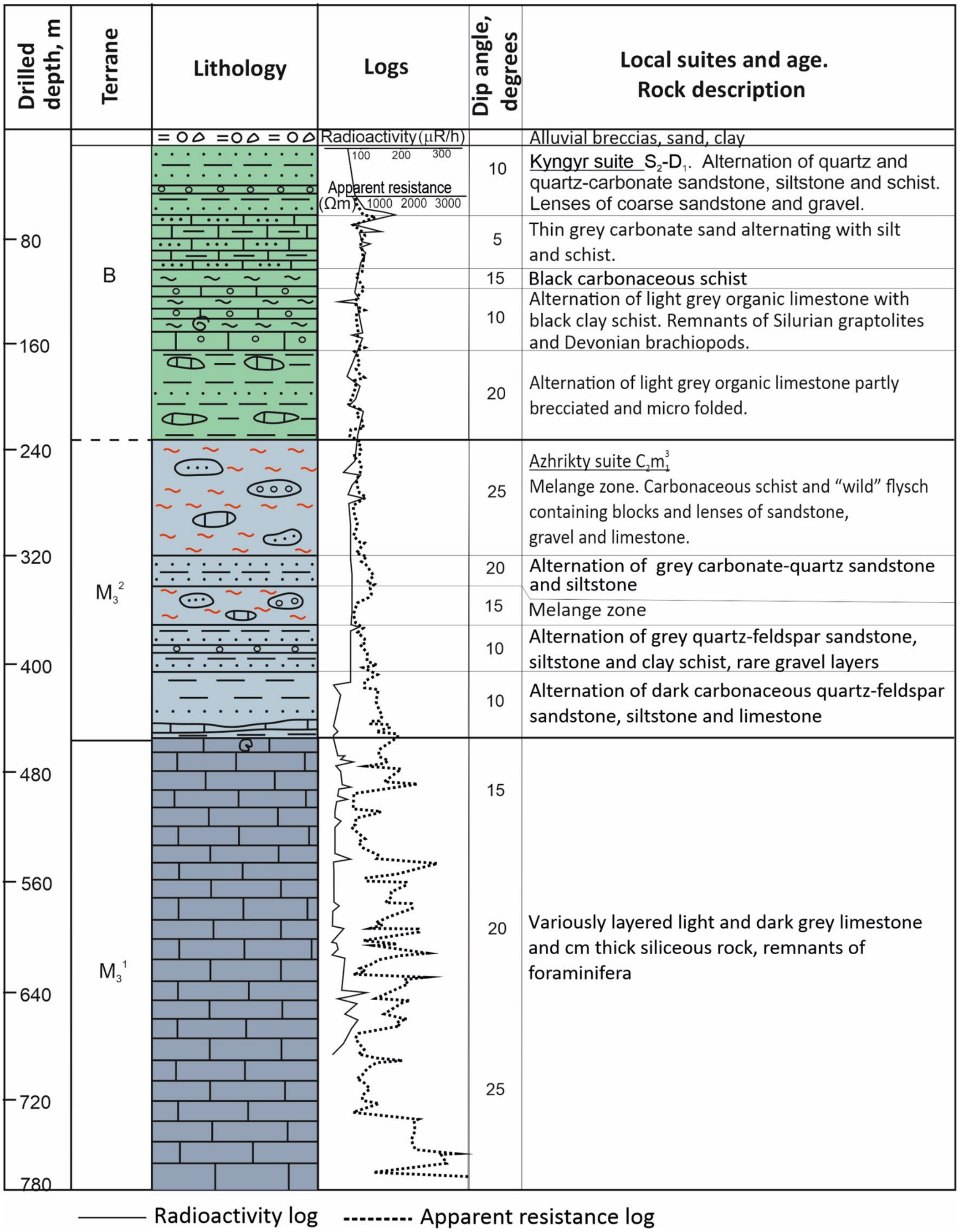

Fig. 5 Lithology succession, radioactivity and apparent resistivity logs recovered in SG-1 deep hole (Sabdyushev and Voronov 1992; Savchuk 1994)

appearance of tectonic contacts indicate an intensive tectonic activity as the frontal part of the active margin (Mukhin et al. 1991).

The Muruntau gold ore field hosts in metamorphosed rocks exposed in the southern part of the Tamdytau Mountains. The ore field host rock is strongly foliated mylonites at the border of the Taskazgan and Kosmanachi terranes. Muruntau ore field (also named "Giant Muruntau") is an area of high concentration of gold mineralization (Seltmann et al. 2020), extending from the center to the eastern end of the Tamdytau Mountains. The gold mineralization develops inside hydrothermally altered rocks of the "variegate Besapan". "Giant Muruntau" also includes the Mutenbai, Triada, Boilik and East Besapantau gold deposits, each is of hundred tons of gold (Shayakubov 1998; Fig. 3).

Stages and styles of the Tamdytau rock deformation

The Tamdytau area has developed in the following geodynamic stages: rock deposition (within Turkestan Paleo-ocean), rock accretions and collision at Kazakhstan and Tarim microcontinents (closure of Turkestan Paleo-ocean), and Tien Shan orogeny in the Central Asian Orogenic Belt (CAOB). Every geodynamic event was accompanied by deformation and metamorphism of the rocks with a specific orientation of compressive forces and P-T environments.

Currently, five structural parageneses are regionally developed in the Tamdytau area, some of which has accompanied with metamorphism (Table 1).

The earliest Paleozoic deformation (D1, Table 1, Fig. 4) in Tamdytau is represented with tight isocline folds. They are most often observed in quartzites and dolomite marbles and, less commonly, in amphibolite and crystalline schists of Neoproterozoic-Early Paleozoic (Mirkamalov et al. 2012). The hinges of the folds and mineral lineation in the rocks are oriented sub-meridional in the Taskazgan polygon (Mukhin et al. 1991).

The cleavage (S_1) of D1 deformation is also observed in the younger rocks of the Taskazgan terrane, referred to as "grey" and "black" Besapan. The cleavage is always represented as a plane-oriented aggregate of muscovite, biotite and chlorite. The cleavage is very often accompanied by streakiness and thin quartz and albite-quartz veinlets. Intersections of the primary bedding by cleavage S_1 in the clastic rocks of the "grey" and «black Besapan» were not observed, which allows to assume both parallel extend.

Indications of deformation D2 (Fig. 3, Table 1) are widely developed in the Taskazgan and Kosmanachi terranes. They are appeared in the Tamdytau Mountains area as isoclinal folds with amplitudes from cm to hundreds of meters, which follows with axial plane cleavage. The largest folds were described in Muruntau open pit (Shayakubov 1998; Babarina 1999). Isoclinal folds look like recumbent, dipping plain and steeply (areas of Yasvay creek, Muruntau quarry, Kosmanachi creek and Karashoho hills). Those folds are everywhere accompanied by axial plane cleavage, usually underlined by sericite and chlorite.

Hinges and axial plains of the isoclinal folds are oriented parallel in both terranes. Under the bottom of the Devonian carbonate sediments, axial plain of isoclinal folds and cleavage in the "variegate" and «green Besapan» rocks (Kosmanachi terrane) plunges north at angles of 45°–60°, gradually curving eastward and flattening up to 20°–40° in the area of the Muruntau deposit. In addition, an eastward curve is accompanied by a change in the orientation of the fold hinges of about 90°–110° clockwise, from 250° to 270° (Kosmanachi creek area) to 300°–330° (Besapan draw-well) and 330°–350° (Muruntau open pit).

The age of deformations D1 and D2 is the Pre-Devonian. This is proved by overlapping Early Devonian basal conglomerate on the folded "green Besapan". Clear visible angular disconformity has been described many times (Mukhin et al. 1991; Shayakubov 1998). The Early Paleozoic age of regional metamorphism is also confirmed by Rb-Sr dating of the "black" and «green Besapan» units which showed the metamorphism occurred not later than 401 + 11 Ma (the border of the Silurian and Devonian, Kostitsyn 1996).

The Late Paleozoic deformations (D3, Table 1) is established according to the internal structure of the Bukan, Kulkuduk and Tamdy terranes. Geology survey (Sabdyushev and Usmanov 1971; Burtman 1973, 2008) have described structure of the Kulkuduk and Tamdy terranes as nappes, with a large number of sub-concordant of thrusts and melange zones almost avoided recumbent folds. In contrast, the rocks that make up the Bukan terrane are deformed into the recumbent folds of D3 quite often (Fig. 3 and 4). The D3 folds are typically not followed with synkinematic metamorphism. The axial plane cleavage is mostly diagenetic sericite and appears selectively in fine rock succession.

The Late Paleozoic deformations D4, (Table 1) presents by North Tamdytau synform and South Tamdytau antiform, extend for about 35–40 km (Fig. 3). The South Tamdytau antiform hinge gently plunges to SW than to W and SE clear showing arc-like extend from East to West. The antiform wings quite gently dip to south (Karashoho areas) and to north-northeast (Kosmanachi and Muruntau areas) with angles 40º–70º and 30º–50º, respectively. The wing geometry may assume the folds vertical amplitude of 5–8 km totally.

The Oligocene deformations D5 (Table 1) are present as system of arc-like faults faced to NW combined with NE extending shift faults. Almost all of them dip to SE with 30°–80° clear show shift with tens and hundred meters.

Structure of studied polygons

The mostly intensive deep structure study of the Tamdytau came at the end of 1980 and the beginning of 1990, while the super-deep SG-10 well (4294 m of depth) and a number of smaller satellite wells directly at the Muruntau gold field (MS-1.2.3 with a depth of 1800–2200 m) were drilled. Important role for understanding the Paleozoic regional

Table 1 Regional stages of the Tamdytau area deformations

Regional deformation events	D1	D2	D3	D4	D5
Terrane	Basement of Murun megaterrane (Taskazgan terrane, especially in quartzite, marble and crystalline schist)	Basement of Murun terrane (both Taskazgan and Kosmanachi terranes)	Top of Murun terrane, Bukan, Kulkuduk and Tamdy terranes	All Paleozoic basement rocks. Main folds are South Tamdytau antiform and North Tamdytau synform	All Paleozoic basement and Cenozoic platform cover rock. Tamdytau arc and antiform
Fold hinges and plane axes extend, vergency	North–South (F_1), not studied	East–West (F_2), north faced	North East–South West, south and northwest faced	East–West, Upright, top faced	North East–South West, northwest faced
Fold shape, amplitude and geometry	Isoclinal, amplitude from cm to tens meters, predominantly microfolds	Isoclinal, primarily recumbent folds. Very often observed from cm to kilometers scale	Primarily isoclinal recumbent and gently dipping folds. Visible amplitude is from tens cm to tens meters	Open subvertical folds, with steeply dipping (40°–60°) wings, vertical amplitude up to 5–8 km	Locally developed, not typical
Axial plane cleavage	Penetrative, permanently appear as schistosity in all type rocks (S_1)	Penetrative cleavage in all rock, axial plane cleavage (S_2) of recumbent folds	Cleavage is penetrative in fine rock. Follows to axial plane of recumbent folds	Cleavage is not typical and represented as fractures	Absent
Lineation	Penetrative, mineral orientation of albite, amphibole and biotite (L_1)	Penetrative mineral lineation (L_2). of sericite, carbon stretches and pebbles	Lineation is not well developed and can be observed inside shear and thrust zones	Absent	Absent
Boudinage and mylonitization	Typical tectonic lenses elongated along cleavage and lineation	Boudinage and disintegrated tectonic lens of appears very often	Mostly typical for flysch-like lithology of Bukan terrane	Inside faults only	Inside faults only
Faults	Ductile zones of synmetamorphic mylonitization along S_1	Ductile mylonitization zones along lithology and stratigraphy contacts	Ductile and brittle zones of mylonitization at the terrane borders	Steep faults, accompanied with dikes and "core" quartz veins containing high grade gold mineralization Brittle deformation	Steep faults, dipping to southeast Fragile deformation
Metamorphism and gold mineralization	Greenschist facies, upper level (T = 350–450 °C, P = 4–6 kb). Diagenetic pyrite replaced with pyrrhotite	Greenschist facies, lower level (T = 200–280 °C, P = 0.5–3 kb. Diagenetic pyrite and carbon matter. Quartz and low-grade gold veinlets are developed very often	Lowermost level greenschist facies transiting to diagenesis. Locally developed quartz veins inside thrust zones	Local contact metamorphism at the periphery of granite intrusions (North Tamdytau and Muruntau)	absent
Dating	Late Ordovician -Early Silurian (?)	Late Silurian (?). Evidence of Early Devonian unconformity at the Muruntau carbonate unit bottom. 401 + 11 Ma Rb–Sr	Moscovian, Late Carboniferous. Youngest sediments at the top Muruntau terrane	Late Carboniferous—Early Permian. Granite pebbles bearing molasse	Oligocene (?)—present. Western end of Tien Shan orogenic belt

structure of Muruntau gold region played the deep wells SG-1 (1a and 1b), SG-2 (up to 1600 m depth).

To study the megastructure of the Muruntau ore region, we selected four key areas: Taskazgan, Karashoho, Kosmanachi and Muruntau ore gold field, located in the core, southern, northern and east rims of the South Tamdytau antiform (D4). Within the polygons, the deformational structures of the rocks were studied at mega (satellite images), macro (outcrops) and microlevels (thin sections). The sites are arranged in such a way that the results obtained characterize a strip with a width of 3–5 km and a length of 15–20 km and covered the areas of all known gold-bearing tectonic complexes of the Murun terrane in Tamdytau.

Taskazgan polygon

Deformation structures of the *first stage* are found in rocks exposed in the core of the South Tamdytau antiform D4. They are represented by numerous tight isoclinal folds and are developed in all types of rocks of the Taskazgan subterrane. Axial plane surfaces are oriented parallel to the boundaries of lithological bodies.

Axial plane axial cleavage (K1) and intersection lineation (L1) are intensively developed in all rock types. They are easily observed both in outcrops (Fig. 6) and in thin sections. Cleavage appears selectively, depending on the rock composition. In hard rocks, such as quartzite and dolomite, the cleavage observes in outcrops every 3–5 mm. Crystalline schists containing quartz, feldspar, amphibole, biotite, muscovite and chlorite, show cleavage of 1 or less mm thick. The cleavage accompanied by metamorphic recrystallization: in quartzite with quartz grain orientation, and in schists, like parallel-oriented biotite and muscovite flakes, and linearly oriented amphibole (actinolite and hornblende). In summary, metamorphism during D_1 deformation appears as schistosity of biotite-muscovite-amphibole facies, $P = 1–3$ kb, and $T = 280–450$ °C (Khokhlov 1977).

All isoclinal folds following the cleavage show wings cut by minor shear zones, which indicates ductile style of the deformation D1. Thus, subparallel alternation of lithology looking as “bedding” represents a metamorphic melange of sediment rock. The observed amplitude of the isoclinal folds in the outcrops is a few meters, rare tens of meters. The folds are accompanied by of S- and Z-types microfolds, visible under a microscope. The hinges of the folds are oriented

Fig. 6 Isoclinal folds D1 in banded quartzite (outcrop photographs faced to south). For location see Fig. 7

predominantly in the N–S direction (Fig. 7). Dips of the hinges and axial surfaces vary depending on the position in the South Tamdytau antiform: in the antiform wings they plunge steeply (60°–80°) to the north and south, being smoothly dipping (10°–20°) in the antiform hinge.

The main structure of the second stage is the recumbent isocline fold F2 named Dzhurgantau antiform (Mukhin et al. 1991; Figs. 7, 8 and 9). The fold is clearly revealed during the boundary mapping between the quartzite, marble and crystalline schist on the one hand and the metaclastic rocks of the «grey Besapan» on another. The contact between the units extends for about 8 km dipping to the south with angles of 40°–60° (Fig. 7). At the western end of the antiform, the rocks smoothly change their extend plunging to the west with angles 30°–40°. Further north, the western gentle decend is replaced by a steep northwest. Over almost the entire extend of the northern wing F4, the rocks dips either south or north, with subvertical rock dip on average. Further east, the rocks dips to south at angles of 50°–60° and the contact becomes overturned. The overturned contact position remains in the eastern pericline of the antiform F4, where rocks gently dips to the southwest and west (Fig. 7). The overturned contact have been outcropped with trenches and observed at a distance of more than a 1.0–1.5 km. Along the contact, quartzites and dolomites are heavily brecciated, and the underlying younger rocks of the "grey Besapan" are transformed into fine-grained schistose carbon mylonites of several to ten meters thick.

Series of cross-sections compiled during the 10 K scale mapping in 1975 and 1979 (Mukhin et al. 1991) allows reconstruct the shape and amplitude of the polygon structure. In the restored form, the structure represents a recumbent fold, faced to the north. The inner part (core) of the fold is composed of quartzites, dolomites, crystalline schists and

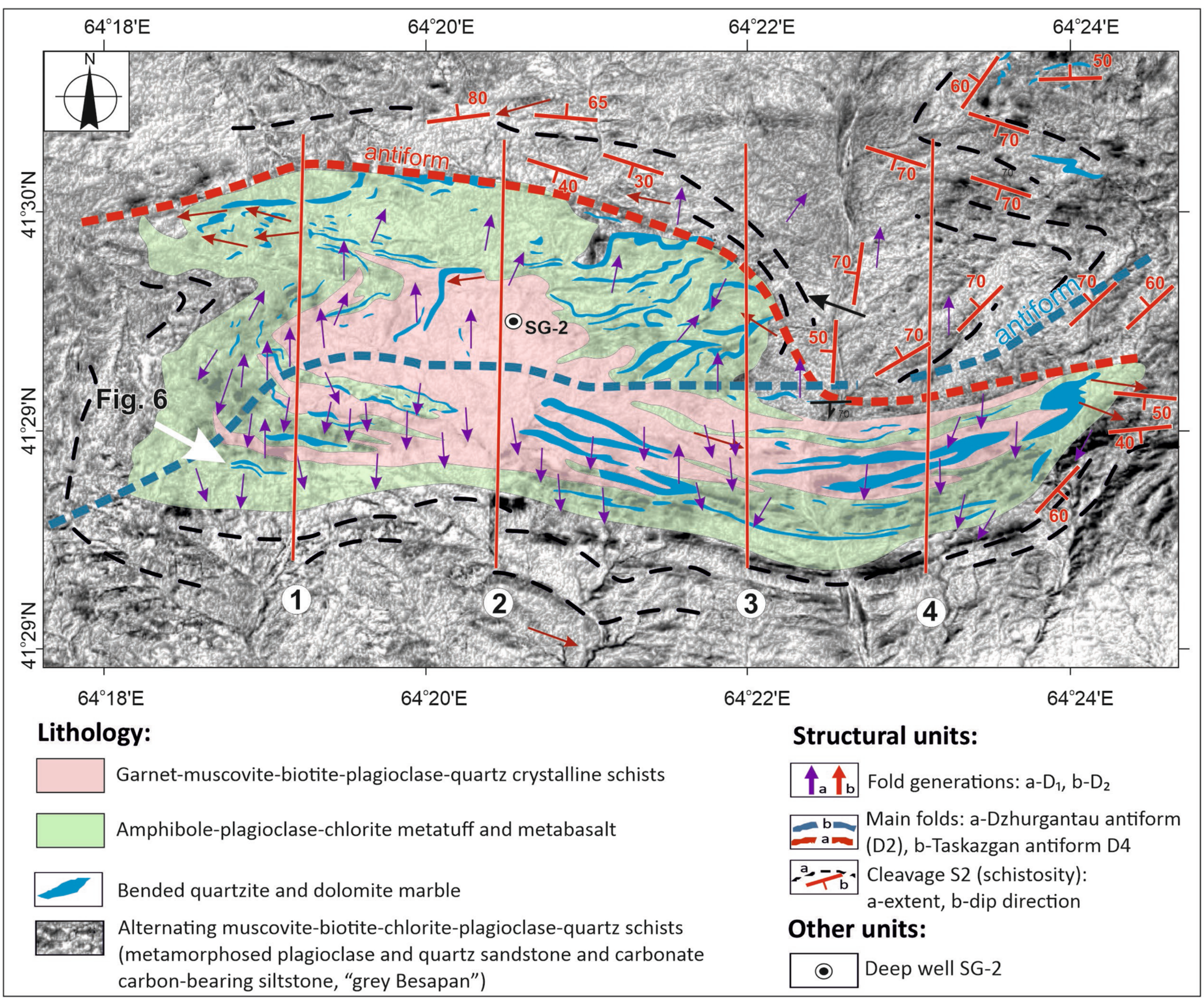

Fig. 7 Air photograph and 1:10,000 geological map of the Taskazgan polygon. Numbered black lines are individual cross-sections (see also Figs. 8 and 9)

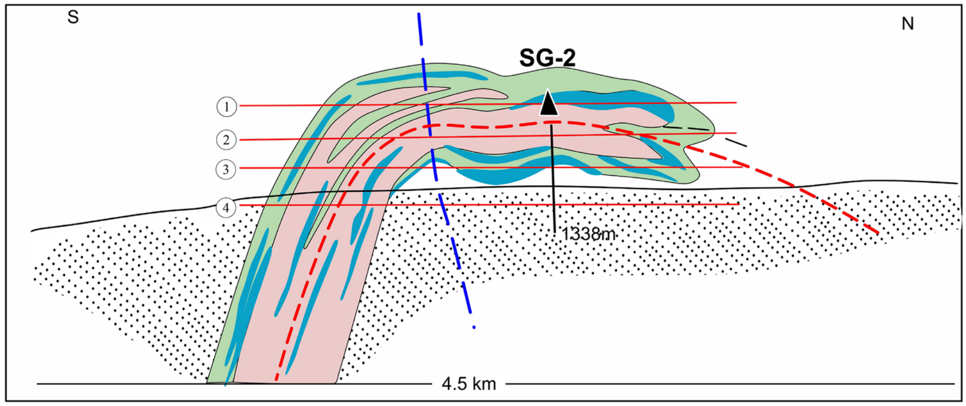

Fig. 8 Rebuilt lithology cross-section through recumbent face-to north Dzhurgantau antiform in the Taskazgan polygon based on four individual cross-sections shown above. For Legends see Fig. 7

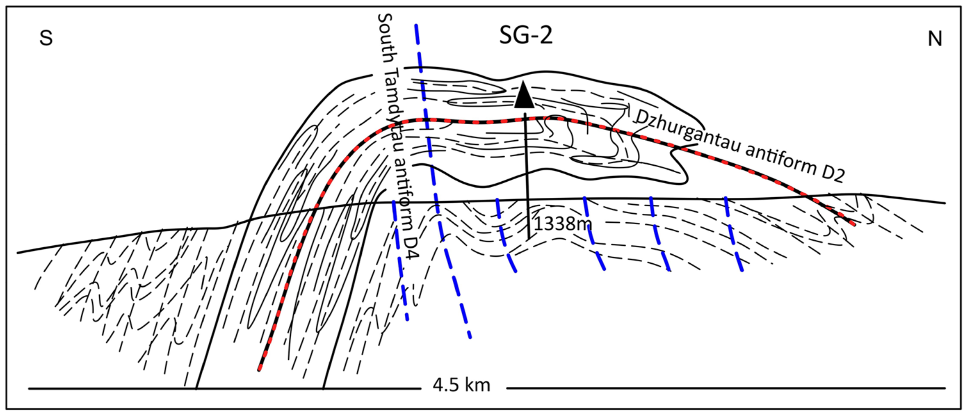

Fig. 9 Same cross-section as Fig. 8 and rebuilt structure and deformation events in the Taskazgan polygon area based on four individual cross-sections. Cleavage (schistosity) S1 shows curved, Cleavage (schistosity) S2 dashed, Cleavage S4 fat blue lines. For other symbols see Fig. 7

metavolcanites, and the outer part is composed of metaterrigenous rocks of the "grey Besapan" (Fig. 8).

The hinge of the recumbent fold is in the northern wing of the South Tamdytau antiform. The hinge extends W–E (270°–90°) direction and descends to west and east under angles of 20°–40°. The recumbent antiform F2 has a visible amplitude of at least 5–6 km and named Dzhurgantau antiform.

The presence of an overturned wing with an amplitude of several kilometers was confirmed while drilling well SG-2 at the core of the South Tamdytau antiform (Fig. 8). The well, with a measured depth of 1538 m drilled (true vertical depth 1338 m), revealed the following overturned sequence of metamorphosed rocks (Fig. 10):

Upper part consists of alternating, low radioactive, grey crystalline garnet–mica–quartz–feldspar schists and dark thin siliceous rock of about 375 m thickness totally (M_1^1). Underlying unit, of about 400 m thick, consists of black–white striped quartzite and massive dark dolomite marble alternating with metabasic volcanic rock tens of meters thick (M_1^2). Rock is quite resistive 100–200 Ωm (Ohm meter) with some peaks up to 1000 Ωm. Carbon contents vary from 0.2 to 0.5 wt% on average. However extremely large carbon contents up to 83.0 wt% are also found. These rocks have light isotopic composition $\delta^{13}C_{opr}$, = − 25.5‰ and exhibit contrasting radioactivity from 0.0–10 to 360 /mR/h (Kryazhev 2017). The lowest part of about 650 m thickness (M_1^3) comprises grey carbonaceous mica–chlorite–quartz–feldspar pyrrhotite-bearing schist with irregular quartzite and marble lenses. Carbon content is 0.1–0.3 wt% on average. Some lenses of organic matter have been also found: C_{opr} = 5.5‰, $\delta^{13}C_{opr}$, = − 24.2‰ (Kryazhev 2017).

The next stage of rock deformations in the area is observed by the deformation of the Dzhurgantau recumbent antiform into the South Tamdytau antiform D4. The South Tamdytau is a fold with a subvertical axial surface oriented in the latitudinal direction. The axis can be traced at more than 40 km from the draw-well Yasvay and Jamantau areas in the west to the longitude of the Besapan Recovery Plant. The northern wing is composed of variously metamorphosed rocks of all four sub-formations of the Besapan Formation, as well as non-metamorphosed sedimentary rocks of the Devonian and Carboniferous (Figs. 4 and 9). Both metamorphic (cleavage of the previous second stage) and non-metamorphic rock successions (bedding) dip at angles of 40°–80°, remaining flat up to horizontal in the core and hinge parts. In cross-section, the South Tamdytau antiform morphology is moderately compressed. The antiform has a slightly asymmetric structure (Fig. 9), and southern wing is significantly steeper (60°–80°) than the north (40°–60°). The

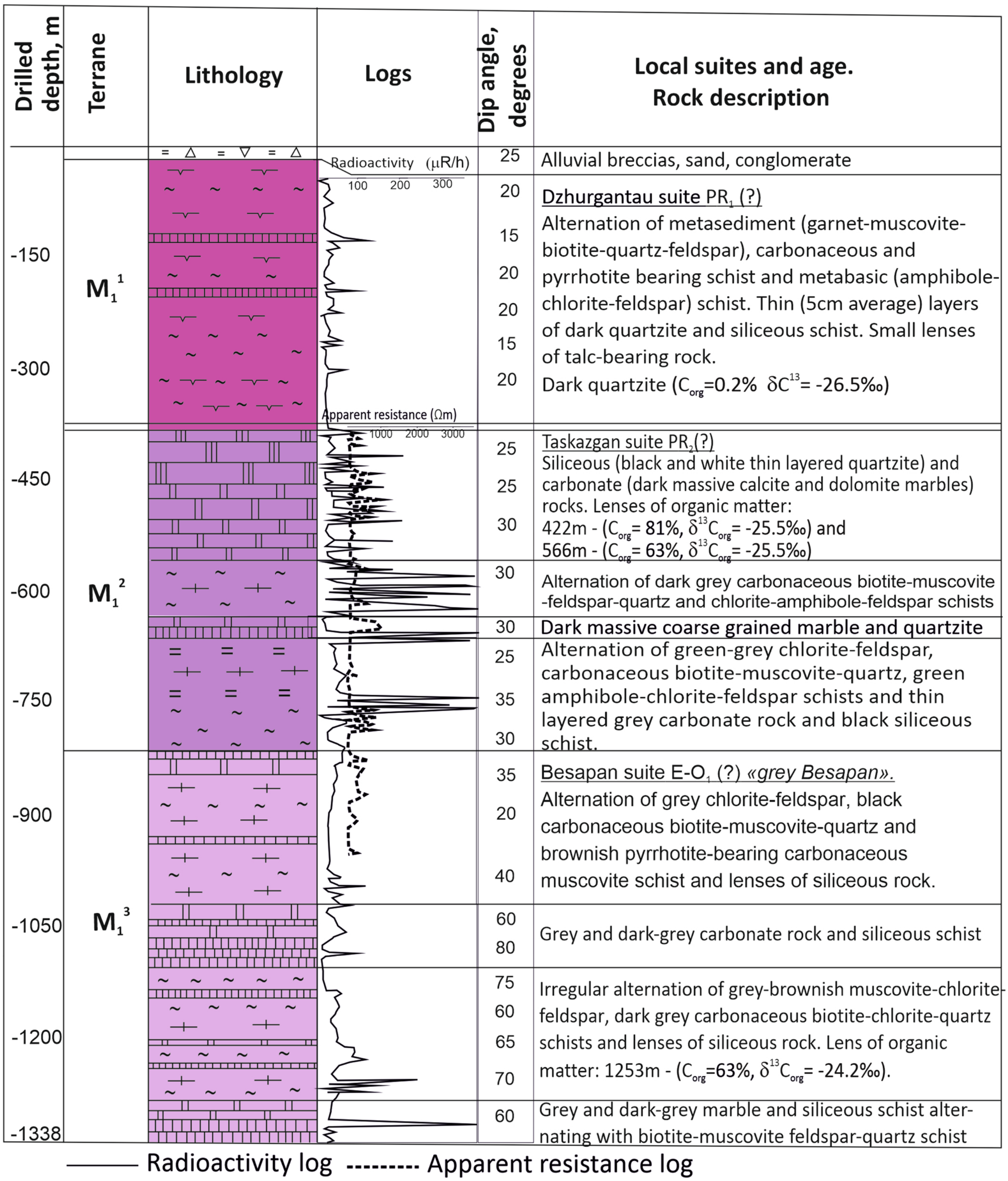

Fig. 10 Lithology succession, radioactivity and apparent resistivity logs recovered in SG-2 deep hole (Sabdyushev and Voronov 1992; Savchuk 1994)

core of the South Tamdytau is located east of the Taskazgan Formation rocks area, which form the western pericline. The eastern pericline is located to the east, about 3–5 km from the Taskazgan polygon gradually plunging to the Muruntau gold field.

Faults following this stage D4 are easily recognizable from the faults of the previous stage D2 due to normal position of fracturing, brecciation, and usually intruded by quartz veins or basic and acidic dykes. The faults are also developed in the Muruntau quarry, studied and dated by many geologists as Late Carboniferous-Permian (Sabdyushev and Usmanov 1971; Savchuk et al. 1991; Kostitsyn 1996; Shayakubov 1998; Kryazhev 2017).

The Mesozoic and Cenozoic rocks unconformably cover all rocks (metamorphic, non-metamorphic and magmatic) involved in the structure of the South Tamdytau, indicating pre-Mesozoic, or more accurate, Late Paleozoic age.

Drilling of the GD-2 deep well showed that the South Tamdytau structure, described earlier as the "Late Paleozoic thermal anticline" as well as the "core of the crystalline basement", (Khoreva 1971; Shayakubov 1998), is much more complicated and represents a combination of two tectonic elements appeared: (1) during the formation of tightly compressed meridional folds and metamorphic melange in biotite–muscovite–chlorite subfacies (F1 and S1), (2) deformation into recumbent face-to-north Dzhurgantau antiform followed with regressive metamorphism in sericite–muscovite–chlorite subfacies (F2 and S2) and (3) Late Paleozoic deformation of multi-metamorphosed rocks into asymmetric South Tamdytau antiform (F4).

Karashoho polygon

The polygon of about 14 km^2 area is located in the southern part of the traverse and belongs to the southern wing of the South Tamdytau (Fig. 3). According to 10 K geological mapping, the site is composed of "grey and black Besapan" rock succession. "Grey Besapan" is represented by a frequent alternation of shale, shale-silt and silt-sandy sediments metamorphosed into Mu-Bi, Mu-Bi-Q, Mu-Bi-Q-Pl schists. They coloured in grey and yellowish (limonite, due to the presence of oxidized pyrrhotite). Relicts of bedding in the rocks show that the rocks were primarily thin- and medium-layered (0.1–50 cm, rarely up to 1–3 m) quartz and quartz-feldspar greywackes with carbonaceous clay cement and interlayers of black flints and dolomites, transformed to quartzite and marble. "Black Besapan" consists of a homogenous sequence of grey and dark grey quartz silty-sand greywackes, poorly layered. There is an admixture of angular flint grains up to 1–3 mm in size in sandy varieties. The composition of the cement is primarily clay-carbonate-montmorillonite, due to the Mu-Chl composition of the matrix.

Two latitudinal ridges are distinguished in remote images of the polygon (Fig. 11). They are 4–5 km length and up to 1 km width. The lens-like ridges are predominantly composed of hard quartz meta-sandstones of the "Black Besapan". The latitude oriented dry valleys are developed inside of the relatively soft shale successions of the "Grey Besapan". The orientation of the isoclinal fold hinges and axial plane cleavage and mineral lineation in the rocks were described, measured and mapped. The overturned and normal rock succession was determined by the relationship of the angle between cleavage and metamorphosed bedding (Fig. 12).

The metaclastic rocks of the "grey Besapan" and "black Besapan" are deformed into isoclinal folds, followed by axial plane cleavage and metamorphic bending (schistosity) visible in the outcrops and thin sections (Figs. 12 and 13). The axial surfaces of the isoclinal folds are always dip to the south at angles of 30°–60° (Fig. 14).

The mapped isoclinal folds hinges D2 have a uniform orientation. They extend strictly along the azimuth of 70°–250°, deviating within ± 20°. Hinges plunge at angles of 20°–40° (Fig. 12).

The rock anisotropy caused with the axial plane cleavage accompanying the isocline folds D2 is stronger than bedding anisotropy. It merges deformed bedding and gives a false impression of a monoclinal rock structure dipping to the south (Figs. 12 and 13). The pseudo-monoclinal appearance of the rock deformed is also enhanced by the orientation of metamorphic minerals along the cleavage planes. The majority of thin sections studied under microscope shows the cleavage S2 as flat-oriented small sericite flakes together with greenish-brown biotite, muscovite and chlorite. However, in thin sections made from the hinge parts of the folds, it is clearly seen that biotite, chlorite, and muscovite is associated with an earlier process of rock metamorphism preceding isocline folding D2 with sericite along the cleavage S2 (Figs. 12 and 13).

The big scale structure D2 of the site consists of two tightly compressed isocline synclines separated with an anticline. The synclines have axial surfaces dipping to the south and extending to E–W as well as small scale folds observed. Folds are of 4 and 6 km length. Synclines have black Besapan rock in their cores, indicating north directed vergency (Fig. 15).

Kosmanachi polygon

The polygon is in the northern wing of the South Tamdytau (Fig. 3). Rock of "black", "variegate" and "green" Besapan formations are developed in the area. The "variegate" Besapan is a host rock for Kosmanachi ore field and Kosmanachi gold-silver deposit. The Main Muruntau Thrust (MMT) is underlain by rocks of "black" Besapan and overlapped with "variegate" and "green Besapan" (Fig. 16).

MMT is a zone of intensive cleavage and schistose mylonitic rocks, mainly of siliceous clay-siltstone and carbonate

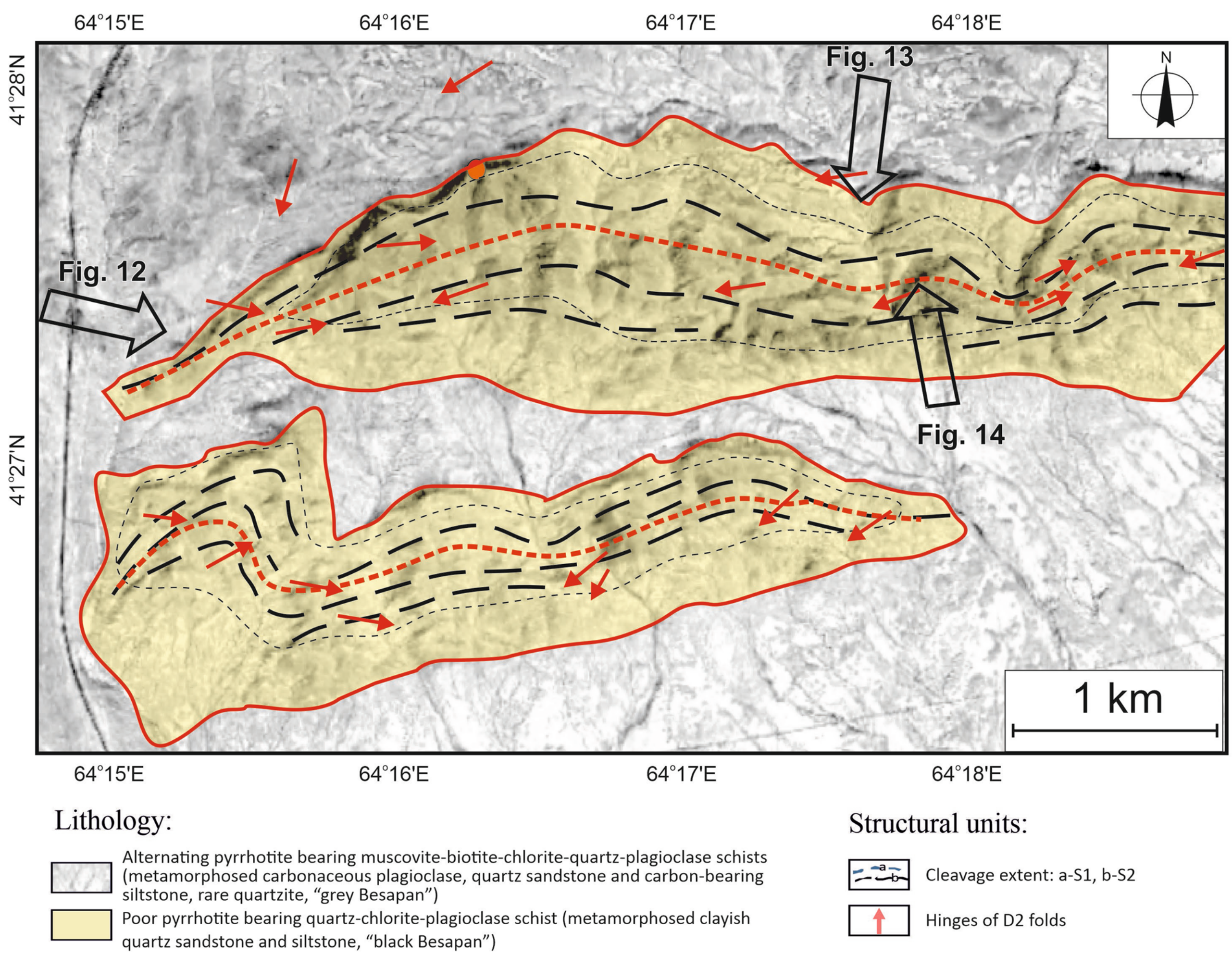

Fig. 11 Geological map of the Karashoho polygon

(flint and dolomitic marble) rocks of "variegate Besapan". The transition from the MMT zone to the host rocks is gradual and has no recognizable rims at outcrop scale. Tectonic lenses, meter and ten meters thick, inside the zone consist predominantly of dark biotite-bearing schists («black Besapan») and sandstone ("green" Besapan). The flint and dolomite rocks are usually deformed into isoclinal recumbent folds (Figs. 17 and 18). The thickness of the MMT zone is 120–1100 m at the Kosmanachi section, however, along the strike, the thrust shears into several zones and then the thickness of the MMT may reach 800–1500 m and up to 3000 m (the Muruntau gold field).

Isoclinal folds and sericite-chlorite axial plane cleavage are developed at hanging and lying walls of MMT. The rocks of the "variegate Besapan" form two extended bodies above MMT at the polygon. The first one is a narrow linear body of 10 × 1.1 km size. It includes the rock lens of «green Besapan». The second body like "amoeba-shape" of 4.6 × 1.6 km size belongs to the Kosmanachi ore field and located to the north from the first. Central part of the "amoeba-shape" area consists of the homogeneous alteration of carbonate-bearing dark grey shale, silt and fine sandstone (Kosmanachi deposit host rock) and outer part of the area is predominantly of pyrite-bearing and siliceous shale with lenticular bodies of dark quartzite and dolomite. The Kosmanachi ore district is surrounded by "green" Besapan rock succession (Fig. 18).

Isoclinal folds are widely developed in the polygon area, the axial surfaces of which are parallel and dip to the north. The fold hinges dip to NEE (50°–70°) in the western part of the polygon and to NNW (310°–340°) in the eastern part, towards each other (Fig. 18). Such hinge orientation allows to assume the Kosmanachi deposit area as a core of asymmetric synform.

Axial plane cleavage is developed in all rock varieties, including hard siliceous and dolomite rocks (Fig. 19). Cleavage is appeared more intensely than the bedding anisotropy of the rocks, which causes visible monocline such as in the Karashoho polygon.

Axial plane cleavage in the Kosmanachi ore district appears much less (Fig. 18) relatively linear zone MMT

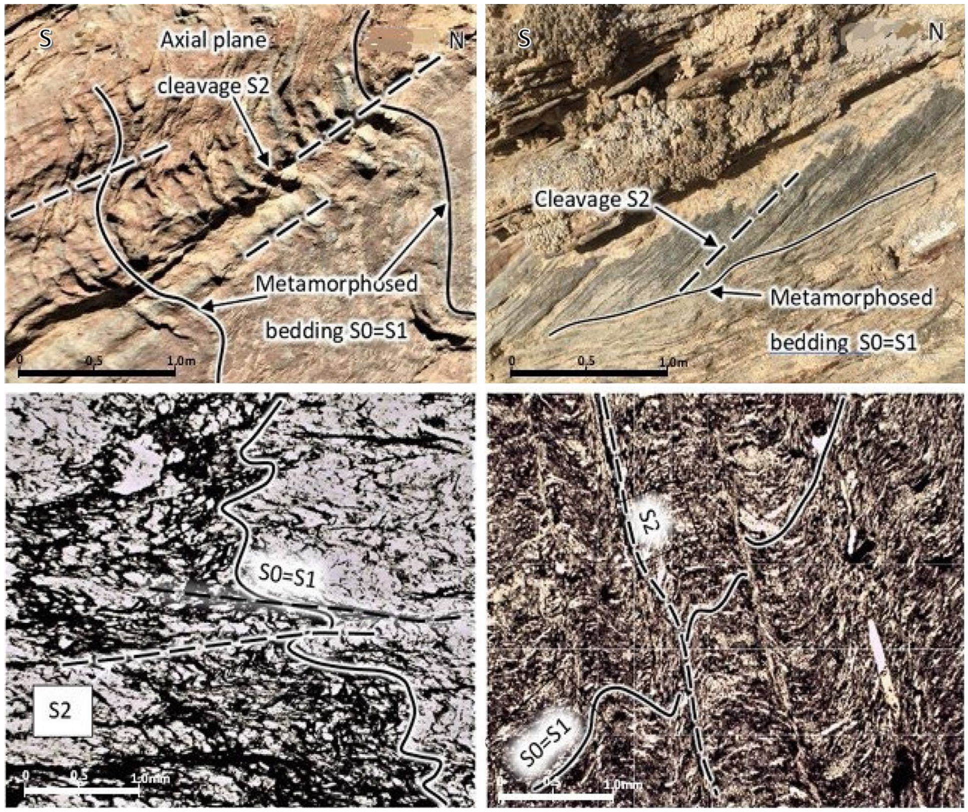

Fig. 12 Meter-scale isoclinal folds in «grey Besapan» rock outcrops showing two stages of dynamic metamorphism. Fold hinge outcrops and thin sections (Nichols parallel): metamorphosed bedding S0 = S1 (biotite-chlorite-albite-quartz schistosity) crossed by sericite-chlorite axial cleavage S2 under various angles

Fig. 13 Fold hinges and axial plane cleavage in «black Besapan» rock outcrops and thin sections (Nichols crossed). Bedding S1 and axial plane cleavage are almost perpendicular to each other (normal rock succession)

(Fig. 17). Correspondingly, primary rhythmic succession of the sedimentary "variegate Besapan" may much easier recognized in the Kosmanachi ore district. The succession consists of 1–20 cm alternating beds of fine chlorite–sericite–quartz–feldspar sandy siltstone and carbon pyrite-bearing shale with siliceous and poor carbonate cement. Pyrite is typical of fine nodules distributed along the bedding (Fig. 18). Large siliceous-dolomite bodies of

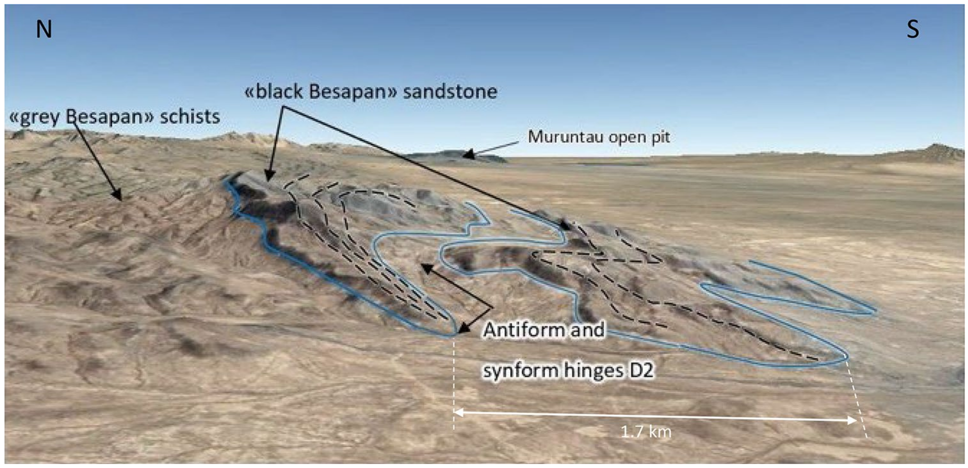

Fig. 14 Perspective view of isoclinal folds D2 in the Karashoho polygon. Legends see Fig. 11

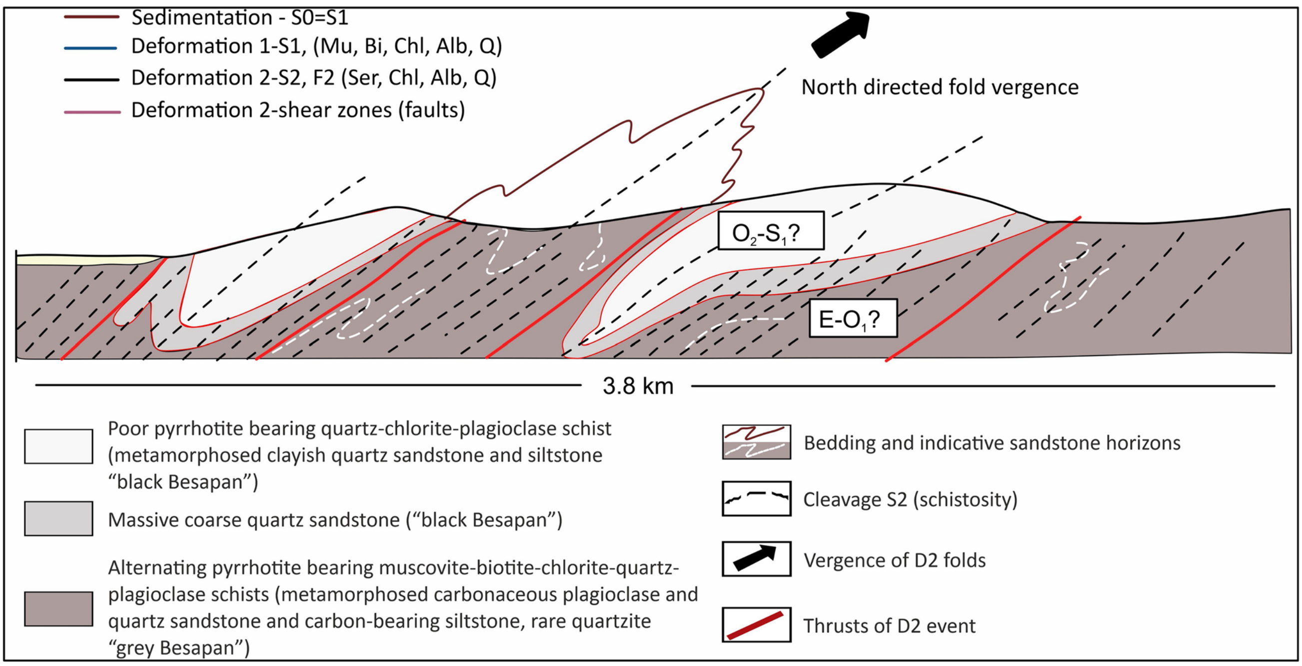

Fig. 15 Geological section across Karashoho polygon. *Mu* muscovite, *bi* biotite, *Chl* chlorite, *Alb* albite, *Q* quartz, *Ser* sericite

several tens of meters thick and few hundred of meters length are also conformably deformed with the shale-silt-sandstone host rocks (Fig. 19).

The shale–silt–sandstone section of the "variegate Besapan" rocks transforms into the relatively coarse flysch of the "green Besapan" gradually at about 200–300 m indicating conformable stratigraphic contact. The lithology and stratigraphic succession of the transitional part are best seen along the northern boundary of the Kosmanachi ore district, where the axial cleavage S2 is perpendicular to bedding very often (Fig. 20).

It is also clear visible, based on the stratigraphic succession, that the isoclinal folds in the Kosmanachi polygon have northern faced vergence with anticline hinges dipping down. The assume is confirmed by grade bedding in the sandstones from transition zone (Fig. 20) and flysch of "green Besapan" hundred meters upper from the transition part (Fig. 21).

The conclusion based on outcrop observation supports with detailed scale mapping of the isocline fold hinges in the Kosmanachi ore district (Fig. 16). Comparison of the fold hinges direction dip show important feature of the structure at the Kosmanachi polygon. The hinges in the western edge of the area dip to NE and ENE with angles 5°–45° and in the eastern area to W and NNW with angles 15°–40° indicating that the Kosmanachi ore district is a geometrical synform. This means, that rocks of the "green Besapan", surrounding

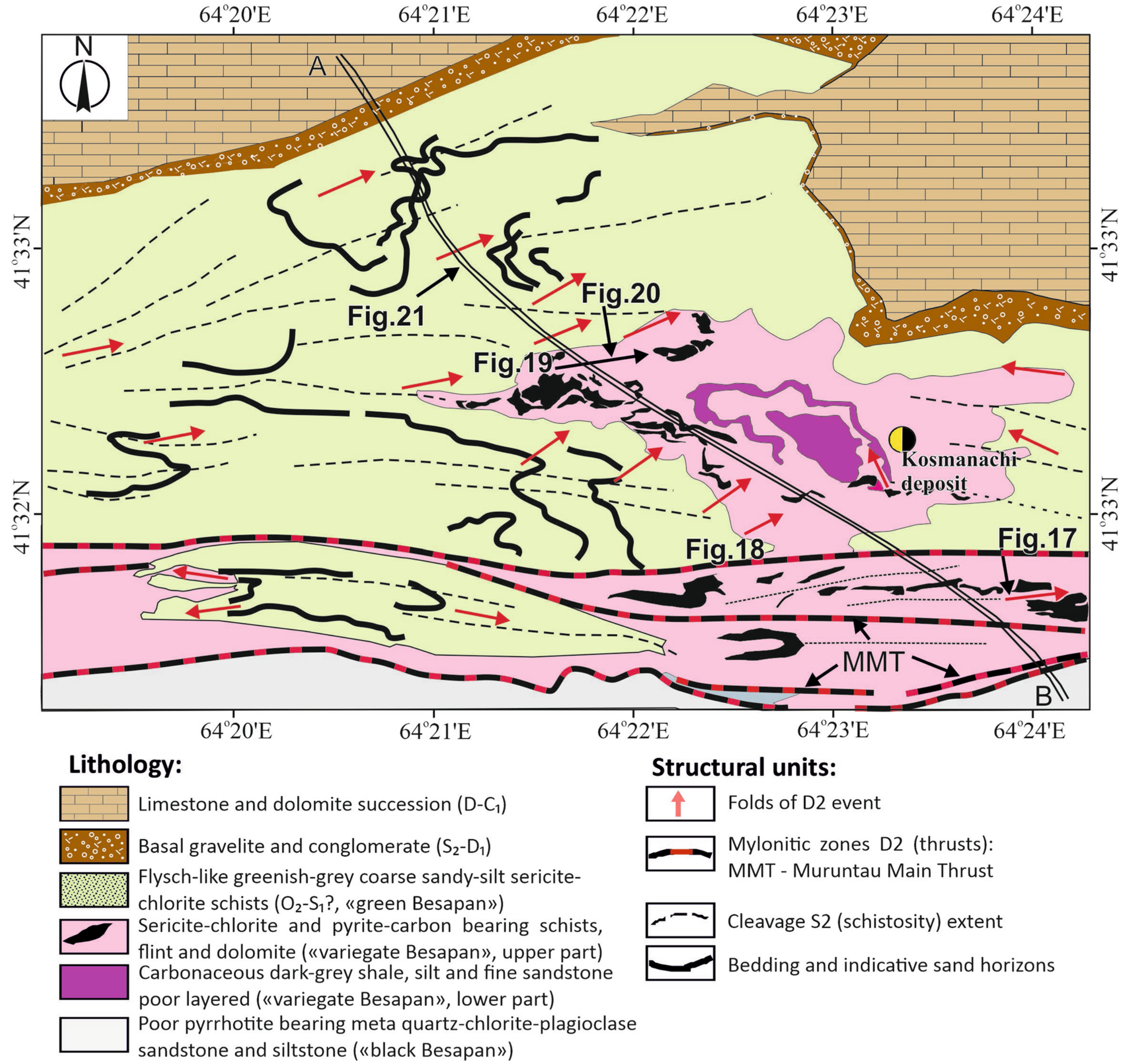

Fig. 16 Geological map of the Karashoho polygon (after Mukhin et al. 1991, with additions from Babarina 1999)

the "variegate Besapan" underlay them. Thus, the whole lithologic sequence is in the overturned position in Kosmanachi polygon. The fold in the Kosmanachi ore district should be identified as geometrical synform having oldest rock in the core and younger in the wings, i.e. an overturned anticline, where rock succession starts at the fold core.

The general structure of the Kosmanachi polygon is presented in the cross-section along the NW–SE line (Fig. 18). The structure is a package of three recumbent synclines and two anticlines cut with MMT at the south and printed with Early Devonian basal conglomerate and carbonate sediments. At the cross-section, due to the northern vergence of the folded structure, the hinges of the anticlines are faced to the north and down, and of the synclines to the south and up (Fig. 22).

Muruntau gold ore polygon

Muruntau gold polygon (Muruntau ore field, "Giant Muruntau") is located at eastern part of the South Tamdytau antiform D4 (Figs. 3, 4, 6 and 23). The upper part ("black Besapan") of Taskazgan sub-terrane rock outcrops at western, lower and upper ("variegate Besapan" and "green Besapan")

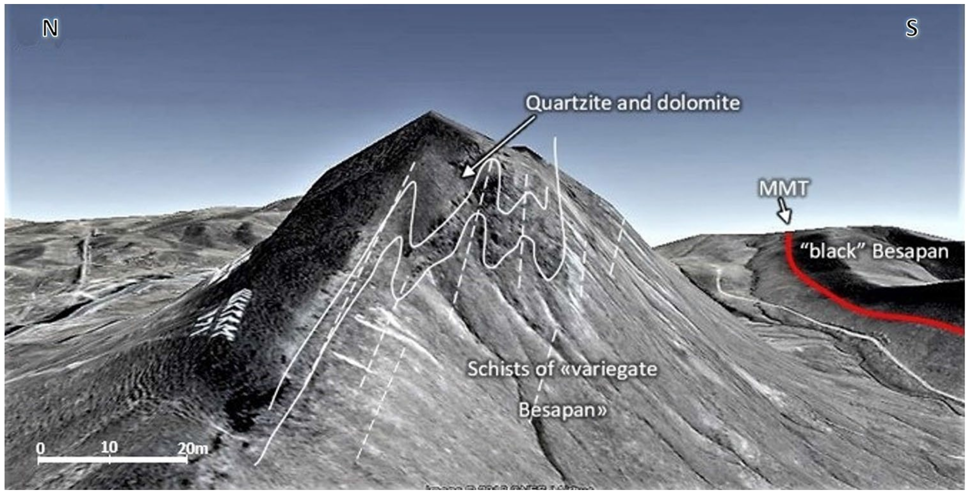

Fig. 17 Quartzite and dolomite within silty carbonaceous schists deformed in isoclinal folds (Kosmanachi polygon, view from west to east)

Fig. 18 Metalliferous (pyrite-bearing) silty shales ("variegate Besapan") deformed in isoclinal folds. Outcrop inside the Kosmanachi ore field

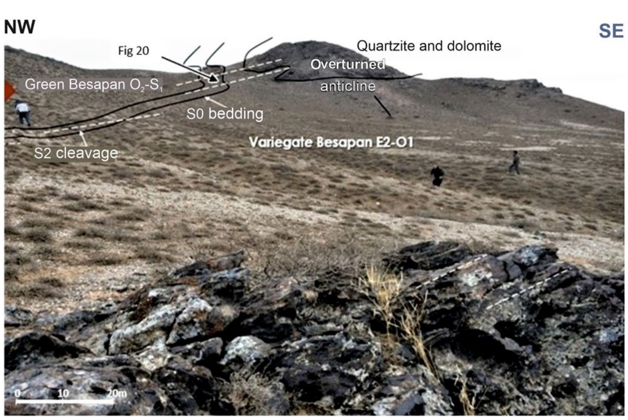

Fig. 19 Stratigraphic contact between upper sub-suite of "variegate" and «green Besapan» deformed into recumbent folds, S style of folds

parts of Kosmanachi sub-terrane outcrop at eastern part of the ore field. Overlapping carbonate succession of Devonian and Early Carboniferous rocks are developed at northern and far eastern part of the area. Cleavage S2 in both sub-terranes dips to east and north under 20°–60°, creating Z-form sigmoid of about 11 km length and extends after of about 15 km west to the Kosmanachi polygon.

«Varigate» Besapan succession creates giant lens maximum of about 5 km wide. The Muruntau lens rock consists predominantly of shale and silt-sandstone, which comparing with Kosmanachi polygon, represents lower and oldest part. Metasomatically reworked rock containing gold mineralisation (Muruntau Lens, Mukhin et al. 1988) composes about of 60–65% the "variegate Besapan" area. The mineralised rock lens represents stockwork-like load, which limited by MMT at the bottom and also dips to west and north conformably to axial plane cleavage D2. Abnormal thickness of the "variegate Besapan" succession (3000 m in average) relative other areas (1000 m in average) caused by a thrust piling of a few rock packages (Mukhin et al. 1988).

Small recumbent folds are found everywhere in Muruntau gold field area at outcrop (from tens cm to a few meters) scale (Babarina 1999). As reported by S. Sabdyushev (oral communication), who mapped the Giant Muruntau at 1:10 K scale in 1987–1991, most intensive isoclinal folds D2 are developed at the "variegate" Besapan bottom close to MMT (Sabdyushev 1989; Kryazhev 2017). Y. Savchuk (Savchuk et al. 2018) has also reported about synmetamorphic folding in the Mutenbai gold deposit. The recumbent folds mapped are presented at Fig. 23. They extend predominantly NW–SE direction at the northern part and change to N–S direction at the center and southern parts following after the Z-sigmoid.

Z-sigmoid cut across by NE oriented normal faults. Most of the faults show brittle-style deformation. The

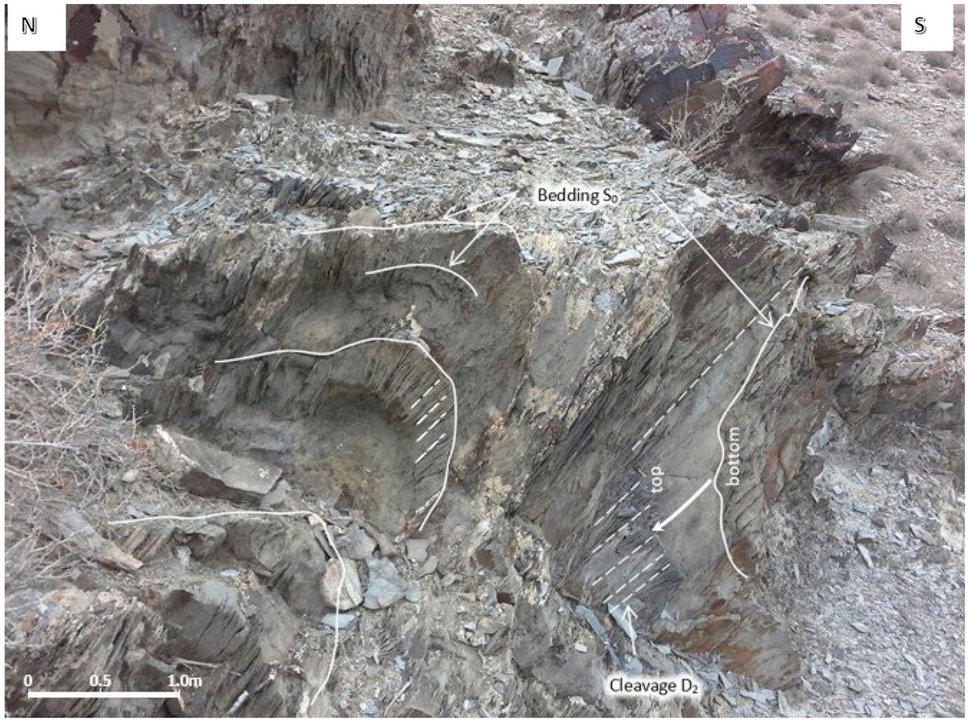

Fig. 20 Hinge of isoclinal fold. Transition sediments from “variegate” to “green Besapan”. Arrow shows bottom to top direction. Turbidite sandstone layers of “green Besapan” appears inside overturned recumbent fold core

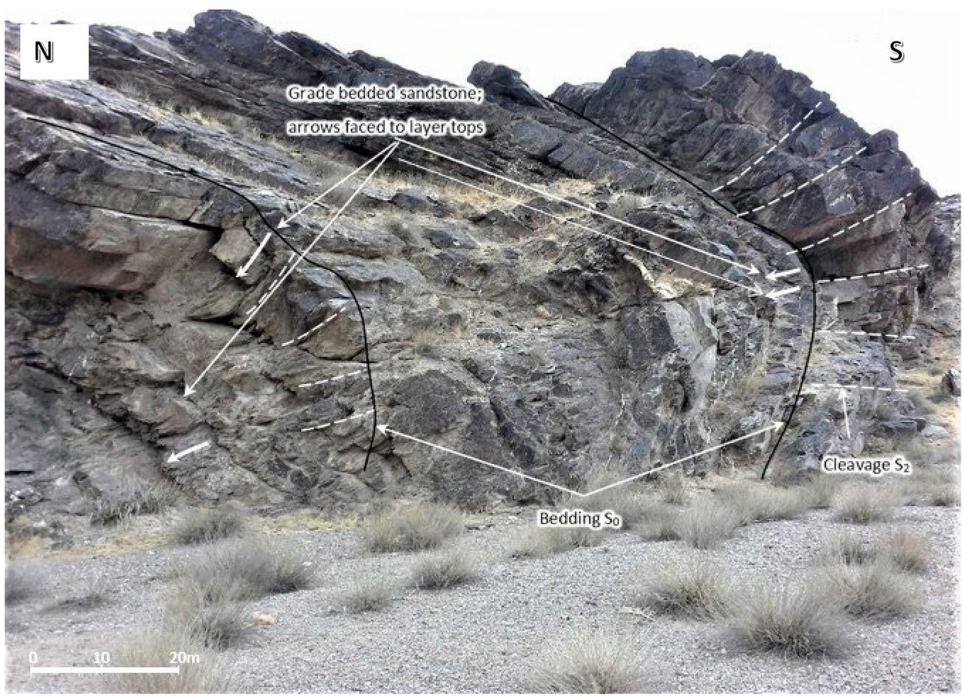

Fig. 21 Hinge of isoclinal fold inside of «green Besapan». Grade bedded meter-thick sandstone layers show normal stratigraphic succession to core of the recumbent fold. Overturned recumbent syncline

faults have clear left-shear movement of about hundreds of meters (Shayakubov 1998). The main faults named Yujnyi, Severo-Vostochnyi and Structurnyi, cut metamorphic cleavage S2 and Devonian—Carboniferous sediments on one hand and almost not appears in Quaternary sediments, which indicates their post metamorphic deformation of Late Palaeozoic—Mesozoic, probably, Oligocene age. We assume these faults belong to D5 stage (Figs. 23, 24 and 25).

“Variegate Besapan” rock is exposed at the surface around 13 km^2 in area. Appearance of gold mineralised rock to north (Besapan East and Boilik) and to south-east (Novoe,

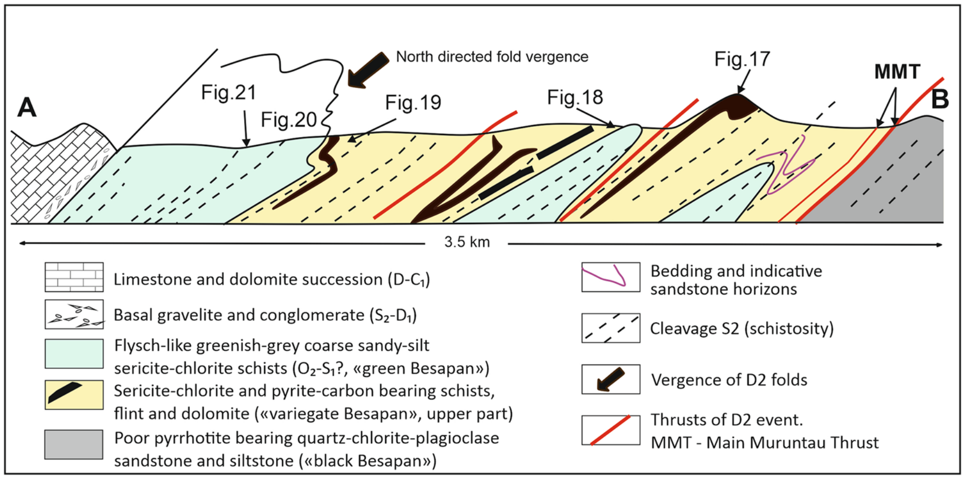

Fig. 22 Geologic section through the structure of "variegate" and "green Besapan" in the Kosmanachi polygon area. Black arrow is vergence direction. For other legends, see Fig. 16

Muruntau, Mutenbai and Triada) from the Muruntau lens contour has been proved by numerous exploration wells up to depth of 1 km. The MS-1, MS-2 and MS-3 have shown appearance of gold mineralised rock hundred meters thick up to depth of 1.5–1.8 km (Shayakubov 1998; Figs. 24 and 25). Explored volume of mineralized lode should be approximately 42 km^3 based on area and depth (Shayakubov 1998).

Four flat and four subvertical commercial ore bodies are distinguished within Muruntau mineralised lens-like load (Shayakubov 1998; Savchuk et al. 2018). Bodies are grouped within the mylonitic rocks created by "ductile" thrusts (Shayakubov 1998; Savchuk et al. 2018). They contain banded biotite–feldspar–quartz metasomatites developing inside highly schistose D2 silty-sandstones. Often, veinlets of quartz are observed inside the metasomatites, oriented parallel to schistosity or deformed into recumbent folds.

The main subvertical bodies are four quartz veins oriented north-east-east and sub-latitudinal direction and dipping to the south with angles 30^o–75^o (Shayakubov 1998). The thickness of the veins varies from 0.5 to 14.0 m. The structure of the veins is complex, there are both simple ones with clear rims, and complex with apophyses. The host rocks experienced brittle deformations during the formation of the veins. Part of the veins is inside of the northeast faults.

Flat ore bodies consist of group of close lenticular bodies that plunge east and northeast according to the host rock schistosity (Shayakubov 1998). Mineralogically gold ore is banded biotite-quartz-feldspar rock developing along primary siltstone and calcareous silts. Approximately 40% of the metasomatically reworked rock volume are commercial gold-bearing ore (above 0.6 g/t content). Inside this metasomatic halo, ores with an average Au content of 3 g/t are deposited, plunging to the east with a metamorphosed cleavage. The extremely high gold content ore (more 5 g/t) are grouped into steeply falling quartz-vein ore columns within faults D5, which join with the zone of the Yuzhnyi fault at a depth.

Gold reserves related to the zones of flat banded metasomatites is about 48%. Together with steeply dipping zones reserves make up about 85% of the deposit. Others 15% are small separate veins with various amounts of sulphides, scheelite and tourmaline. Thus, main gold resources are localized only inside the metasomatic halos.

The abovementioned geometry of ore deposits, following the geometry of the MMT zone and the cleavage planes of the ductile flow, may indicate the relationship of synmetamorphic ductile flow and ore-forming processes. Relationship with metamorphic process may be genetic, and in this case, hypothetical source of a huge amount of fluid should be the host rocks dehydration in the Early Paleozoic. However, this assumption is contradicted by the Late Paleozoic K–Ar and Rb–Sr dating of minerals from sub-concordant lodes of metasomatites, steeply dipping veins and dikes, as well as U–Pb ages of accessories (zircon, monazite in granitoids of the Muruntau ore field) and Re–Os geochronology (molybdenite and arsenopyrite in the main ore body) that all favour a narrow age bracket (295–287 My) of magmatism and mineralization, see Seltmann et al. (2020) and literature therein.

The conformity of the lodes majority to ductile cleavage planes can be also explained, taking into account the anisotropy of metamorphosed host rocks for fluid penetration. If we accept as a hypothesis that the fluid came from subvertical faults from an external source, for example, a granite intrusion located below at 4–5 km depth (Shayakubov 1998), then the low permeability of the rocks in the vertical direction will contribute to the spread of fluid along the cleavage planes and thrusts zones and form subparallel lodes around the faults. This explanation, however, implies the existence of huge masses of fluid in the magma, since the host rocks were previously regionally metamorphosed and practically "dry". This fluid should be moved up a few kilometers up and through the supply channels, the traces of which should have been recorded in the form of steep zones filled by metasomatic rock. Over 60 years of study and exploration,

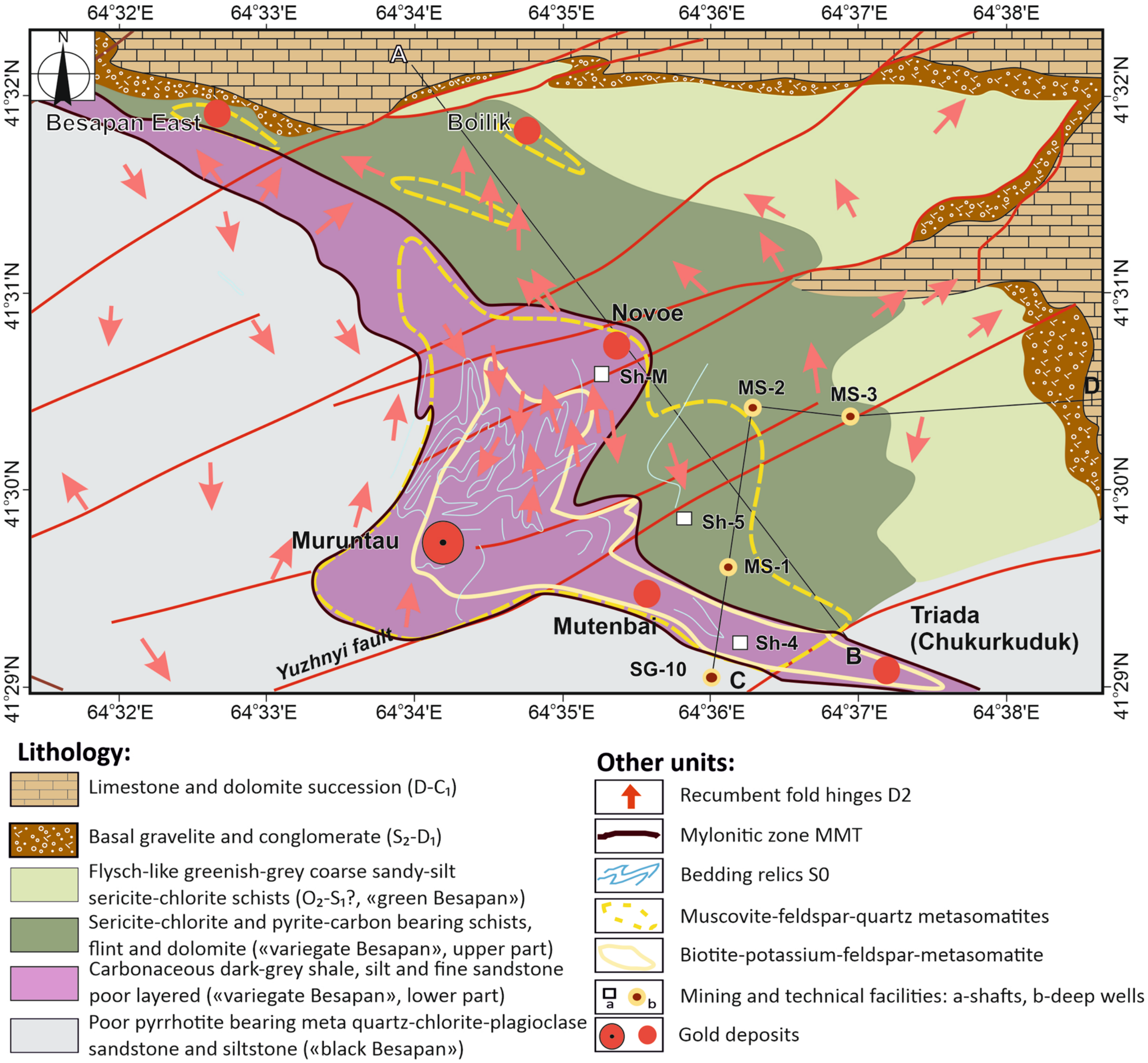

Fig. 23 Muruntau ore field (Shayakubov 1998, with additions). Orientation of recumbent folds hinges (according to Sabdyushev 1989; Babarina 1999)

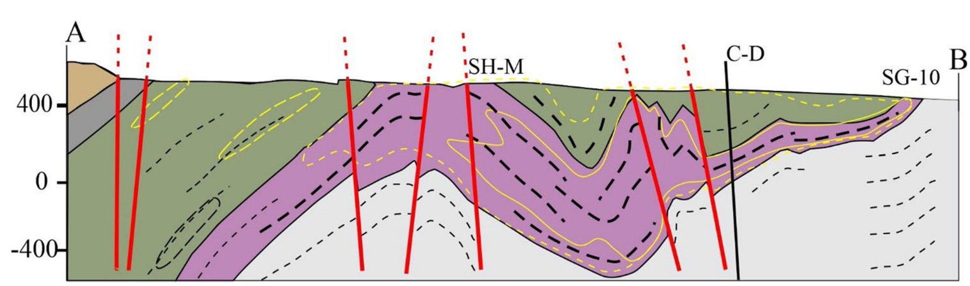

Fig. 24 Muruntau gold field structure through exploration line 127 (A–B cross-section). For legend, see Fig. 23

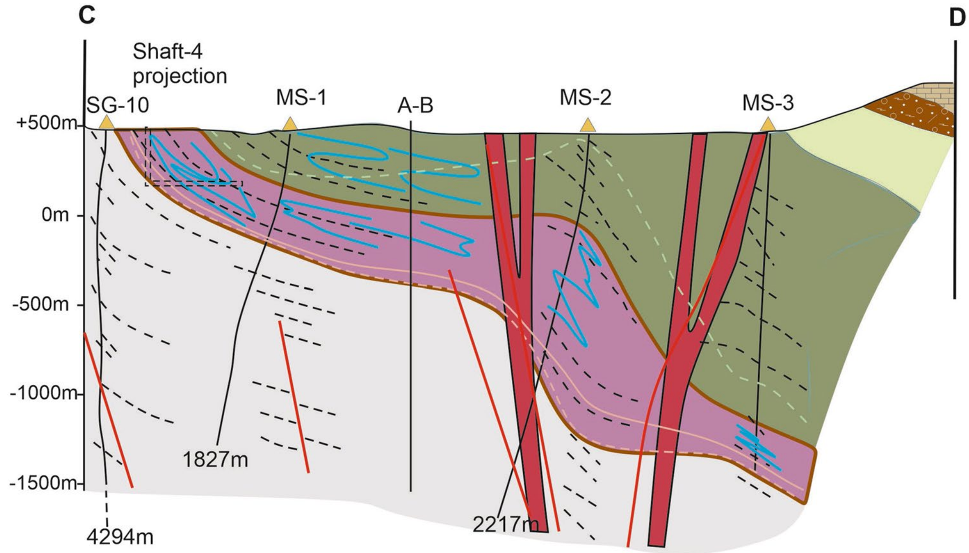

Fig. 25 Muruntau gold field structure along SG-10, MS-1, MS-2, MS-3 deep holes. South-east flank of Muruntau gold deposit (Shayakubov 1998 with authors additions). For legend see Fig. 23

zones that meet these requirements have not been found. The Muruntau stockwork mineralization that precipitated within the host metasomatic rock (dominantly ascribed as "hornfels") after brittle failure cannot be linked with any fluid degassing from the underlying granite intrusions.

An alternative explanation has been stressed by Seltmann et al. (2020) to link the significant Moho upwelling beneath Kyzylkum with block uplift, triggering decompression that drove metamorphic fluid movement causing the massive auriferous mineralized hornfels zone and the generation of vast volume of granitoid melts intruding within the boundaries of the regional scale uplift block that is extending from Kokpatas to Muruntau. This model offers an alternative explanation for the lack of gold mineralization in the Murun granite and the barren magmatic dikes intersecting the deposit.

Discussion and conclusion

The structure of the Muruntau ore region is shown in Fig. 26 as an integrated section of South Tamdytau with a total length of about 16 km.

The folded structure consists of the Taskazgan antiform with a vertical amplitude above 6 km. The antiform is the Late Palaeozoic, probably, simultaneous with main stage of orogenic process. In the general timescale of the of deformations sequence, this antiform is classified as the structure of stage D4.

Before orogenic deformation, Muruntau gold hosted rocks have been deformed and metamorphosed in stages D1 and D2 and represented a metamorphosed accretion prism. Due to D2 deformations, a folded package of two terranes, Taskazgan and Kosmanachi, was formed in the Muruntau ore region. As detailed studies in the areas show, a characteristic feature of the packages is their isoclinic-folded internal structure, which arose during the ductile metamorphic flow of rocks with sericite-chlorite paragenesis of the green schist facies. Rock deformation D2 into W-E oriented folds and metamorphic cleavage flow occurred in a sub-horizontal plane with northern fold vergence.

The geological history of accreted terranes before the appearance of deformation D2 was different. The rocks of the Kosmanachi terrane, before deformation D2, were a stratigraphic sequence of two lithological units: "variegate" (Cambrian-Middle Ordovician) and "green" (late Ordovician–Silurian?) Besapan. The "variegate Besapan" rock have been accumulated in deep-water environment like metal-bearing silts and shale, probably, in the presence of active hydrothermal sources that supplied silica and carbon dioxide (bodies of flints and dolomites) to the basin. The accumulation of «green Besapan» occurred under influence of the distal turbidite flows transporting acid volcaniclastic material. This material may be originated from the uplifted volcanic island arc.

The rocks of the Taskazgan terrane before deformation D2 were a stratigraphic sequence of three lithological units: the Taskazgan suite (Neoproterozoic–Early Cambrian), "grey" (Cambrian–Ordovician), and "black" (Ordovician–Silurian?) Besapan.

Unlike the Kosmanachi terrane, the rocks of the Taskazgan terrane were already metamorphosed before the D2 deformations appearance. The previous dynamic metamorphism D1 occurred under P–T of biotite–muscovite–chlorite green schist facies, transitional to the epidote–amphibolite.

The D1 metamorphism and structural dilatancy of rocks were accompanied by tight folds mainly in the lowest part of the Taskazgan terrane. D1 folds in paragenesis with

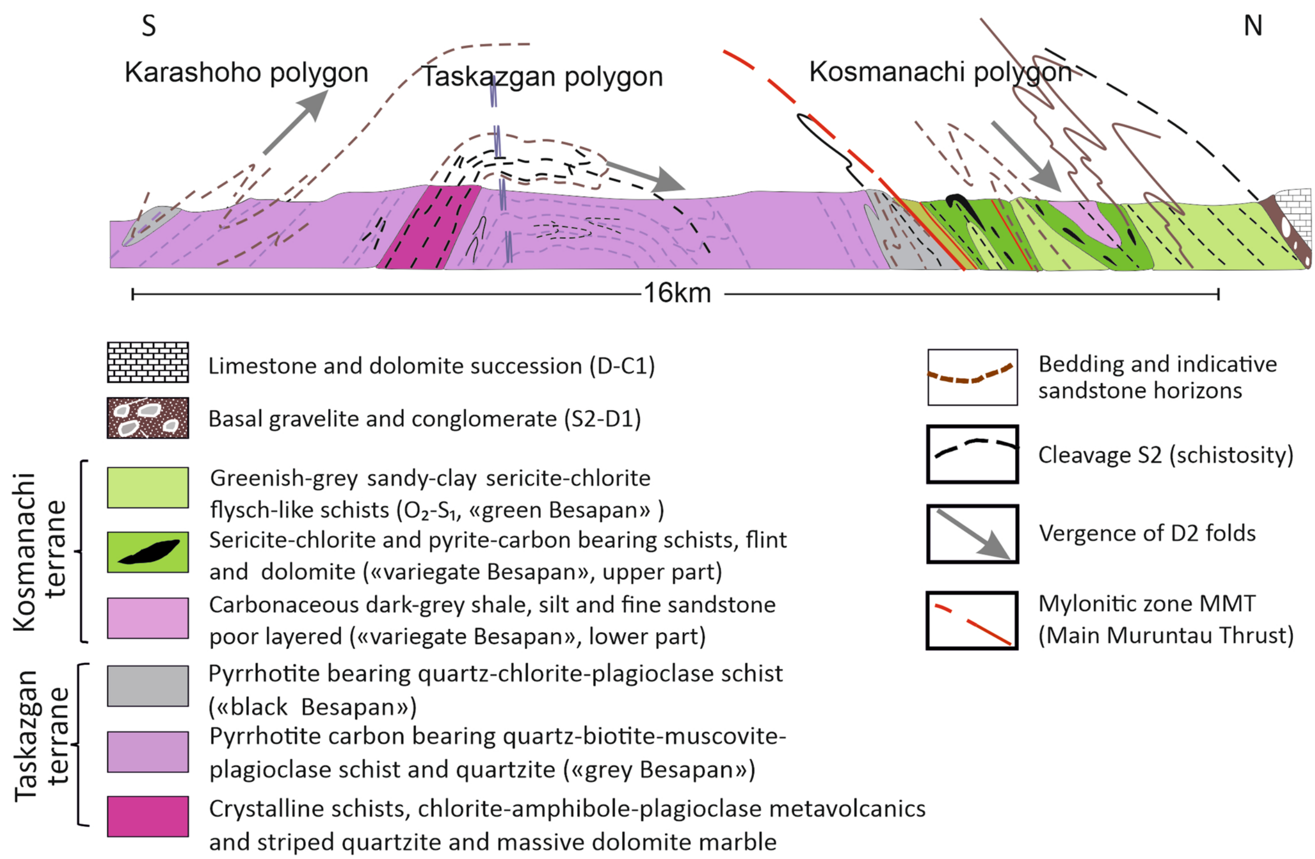

Fig. 26 Geology cross-section along Karashoho–Taskazgan–Kosmanachi polygons

mineralized cleavage are abundantly observed in quartzite, dolomites, crystalline schists and amphibolite. In younger metaclastic rocks, mineralized cleavage D1 is also widely appeared, however, folds related to the cleavage are extremely rare. We assume that the planes of structural dilatancy during the D1 metamorphism were parallel to the rock bedding, that is, probably horizontal.

The orientation of the hinges of the folds D1 on the Taskazgan polygon is sub-meridional and almost perpendicular to the hinges of the recumbent folds D2. The level of temperature and pressure of the relic metamorphism D1 differs significantly, changing regressively from stage D1 to stage D2. We assume the Taskazgan terrane metamorphism took place at the Early Paleozoic basin bottom under heat flow influence from depth. We do not know so much about the D1 event due to high level rock reworking after D2 event.

Very important peculiarity of the Kosmanachi terrane is rock dehydration (Khokhlov 1977) during synmetamorphic accretionary process and thrusting (Mukhin et al. 1988). Rock heating up to 180–250 °C (event D2) removed free water from porous sediments and crystal-related water, that could produce huge (4–10% of the whole Kosmanachi terrane) mass of hot fluid. The hot hydrothermal fluid moved through rock cleavage and mylonitisation zones surfaces triggering quartz veinlet production described very well in Muruntau (Savchuk et al. 2018; Kempe et al. 2016).

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