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DYKE-SHEAR ZONE RELATIONSHIPS IN LATE-PALAEOZOIC GRANITOIDS OF THE PLAST MASSIF AND THEIR SIGNIFICANCE FOR LODE-GOLD MINERALIZATION IN THE KOCHKAR GOLD DISTRICT, SOUTHERN URALS, RUSSIA

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by

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ABSTRACT

The Kochkar gold district in the East Uralian Zone of the southern Urals is located in late-Palaeozoic granite gneisses of the Plast massif. Gold mineralization is associated with tabular quartz lodes that are preferentially developed along the margins of easterly trending mafic dykes. Fabric development indicates that dykes had a profound influence on the development of shear zones in granitoids. ENE- and SE-trending dykes have been reactivated as dextral and sinistral oblique strike-slip shear zones, respectively, forming a set of approximately conjugate shear zones related to the Permian, regional-scale E-W directed shortening. Dyke-shear zone relationships in the Plast massif are the result of strain refraction due to the presence of biotite-rich, incompetent dykes in more competent granite-gneisses. Deformation and the formation of associated gold-quartz lodes occurred close to peak-metamorphic, upper-greenschist to lower-amphibolite facies conditions. Strain refraction has resulted in partitioning of the bulk strain into a component of non-coaxial mainly ductile shear in mafic dykes, and a component of layer-normal pure shear in surrounding granitoids where deformation was brittle-ductile. Brittle fracturing in granitoids has resulted in the formation of fracture permeabilities adjacent to sheared dykes, that together with the layer-normal dilational component promoted the access of mineralizing fluids. Both ore-controlling dykes and gold-quartz lodes were subsequently overprinted by lower greenschist-facies, mainly brittle fault zones and associated hydrothermal alteration that post date gold mineralization.

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INTRODUCTION

In the southern Urals of central Russia, large and very large (> 100 and > 500 to Au) lode-gold deposits are hosted by, or closely related to, voluminous granitoid massifs, smaller intrusive stocks or granitic dykes (Smirnov, 1976; Koroteev et al., 1997). One of the largest of these ore fields, with a production of >300t Au in its over 250 years of mining history, is the Kochkar district, located some 80 km to the SW of the city of Chelyabinsk (Fig. 1).

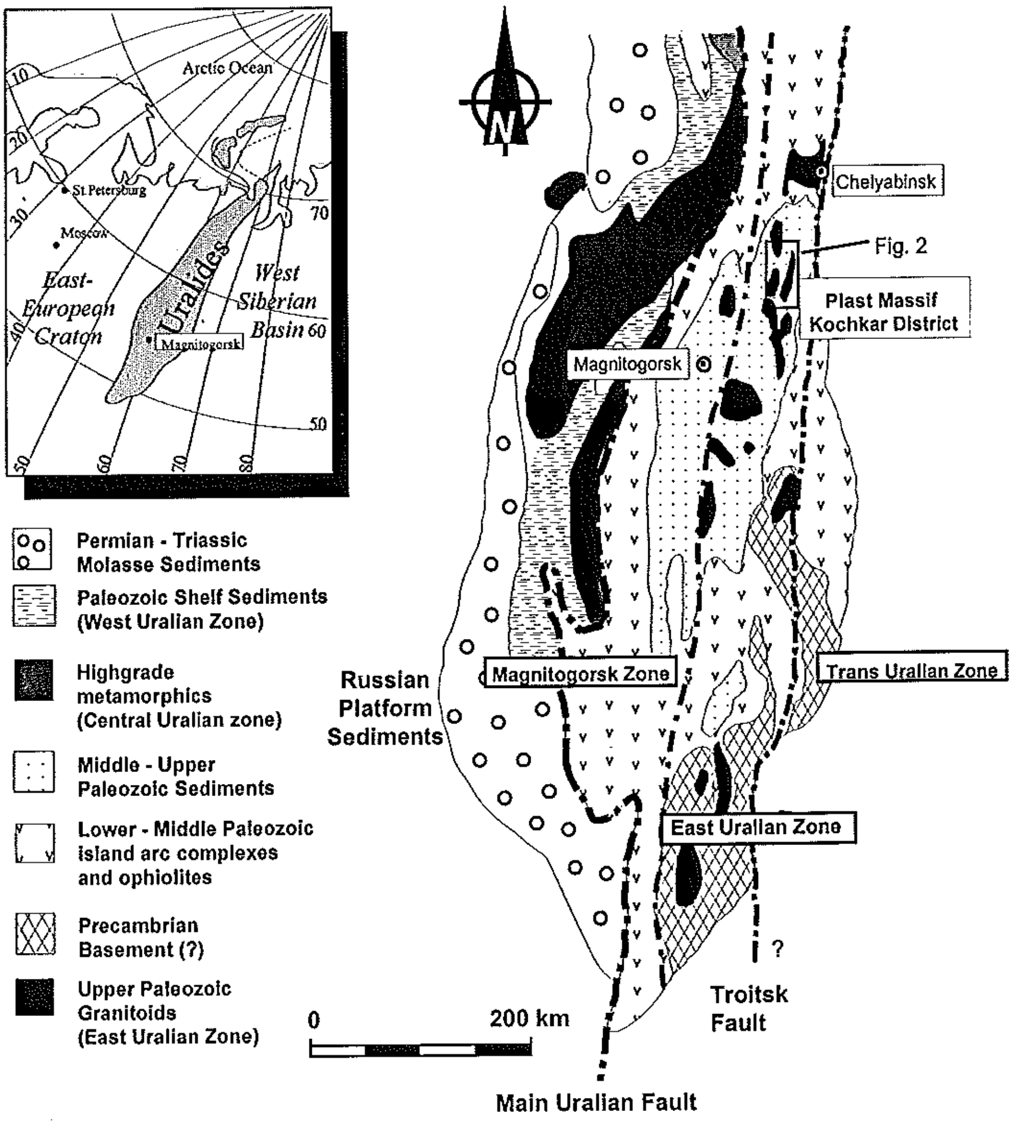

Figure. 1: Inset: Location of the Uralides in central Russia, situated between the East European Platform and rocks of the West Siberian Basin. The simplified geological map of the southern Urals shows the distribution of the main tectonostratigraphic zones and the location of the Plast massif and the Kochkar district in the East Uralian Zone (modified after Puchkov, 1997).

Gold mineralization is confined to granitoids and gneisses of the lower-Carboniferous Plast massif, which forms part of a number of late-Palaeozoic granite-gneiss complexes of the East Uralian Zone in the Urals (Fershtater et al., 1997; Bea et al., 1997). Economic-grade gold mineralization is contained in quartz lodes that are spatially associated with easterly trending mafic dykes, locally termed 'Tabashki'. These dykes describe a crudely radial outcrop pattern along the western margin of the Plast massif (Borodaevsky, 1952; Borodaevsky, 1971; Smirnov, 1976). The genetic relationship between petrographically and texturally complex Tabashki dykes and gold-quartz veins has been a point of controversy amongst Russian workers. The main conjecture hinges on the question of whether gold was introduced with the emplacement of mafic dykes, possibly derived from a mantle source (Sazonov et al., 1992), whether the spatial association between dykes and auriferous quartz lodes is merely fortuitous, or whether mafic dykes have represented structural anisotropies along which gold mineralization was developed (Borodaevsky, 1971). Up to now no generally accepted model for the formation of gold-quartz lodes in the Kochkar district has been presented.

In this contribution we describe the regional geological setting of the Plast massif within the EUZ and the salient geological features of the Kochkar district both of which are poorly documented in the international literature. The main aim of this paper is to describe the relationship between mafic dykes and gold-quartz lodes on a district as well as on an outcrop scale. Fabric development and overprinting structures in mafic dykes, associated quartz lodes, and surrounding alteration zones are used to evaluate the role mafic dykes have played in gold-quartz lode formation.

REGIONAL GEOLOGY

The Urals represent a linear, N-S trending orogen that formed during convergence and final E-W collision of the East European Platform with Asian microplates and intervening island arc complexes during the late-Palaeozoic (Zonenshain et al., 1984, 1990; Echtler et al., 1996; Puchkov, 1997). Most of the large lode-gold deposits of the Urals are hosted by granite-gneiss complexes that are intrusive into mafic-to-intermediate volcanic, volcanoclastic and sedimentary rocks interpreted to represent remnants of mainly mid-to-late Palaeozoic island-arc and subordinate ophiolite complexes (Seravkin et al., 1992). Granite-gneiss complexes and volcanosedimentary rocks constitute the East Uralian Zone (EUZ) also known as the 'main plutonic axis' of the south Urals (e.g. Ivanov et al., 1975) forming the central zone of the internal parts of the orogen (Fig. 1). Supracrustals now strike N-S and are subvertical, parallel to the overall trend of the EUZ as a result of complex deformation during E-W directed shortening during the upper-Palaeozoic assembly of the southern Urals. Based on petrography and radiometric age constraints, two main types of granitoids can be distinguished (Fershtater et al., 1997; Bea et al., 1997): an earlier, upper-Devonian to lower-Carboniferous (360-320 Ma) tonalite-trondhjemite-granodiorite (TTG) suite, and a later Permian (290-265 Ma) suite of two-mica, microcline-bearing granites.

Geology of the Plast massif

Most primary gold deposits of the EUZ consist of auriferous quartz-vein systems hosted by either granite-gneiss massifs and granitic dykes or located in the immediate margins of granite massifs (Koroteev et al., 1997; Kisters et al., 1999). The Plast massif in the central south Urals (Fig. 2) hosts a number of deposits that are collectively referred to as the Kochkar district. This granite-gneiss massif represents one of eight composite plutonic complexes,

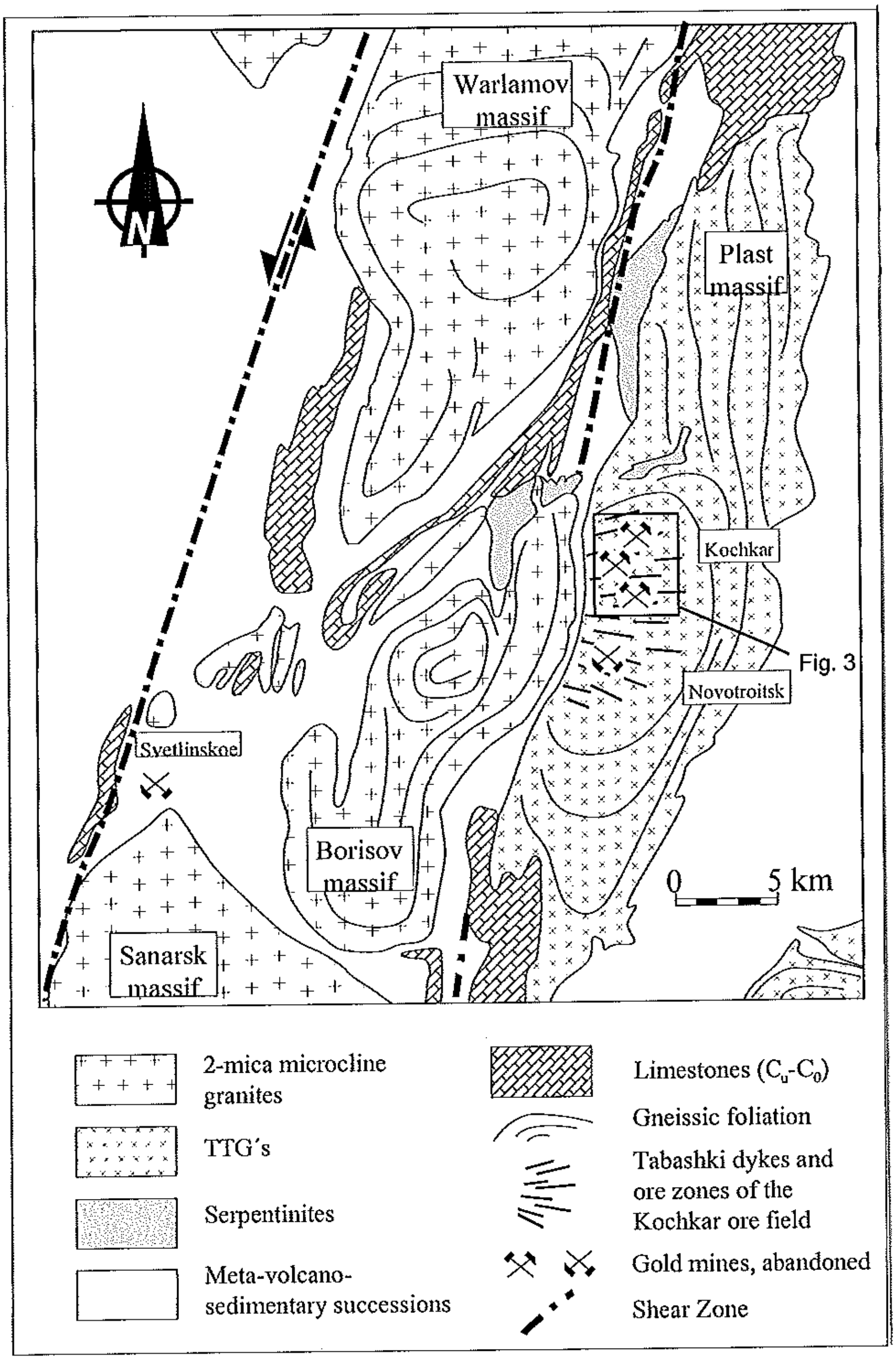

Figure 2: Simplified geological map of the Plast massif and adjacent granite and granite-gneiss complexes in the East Uralian Zone of the central south Urals. Gold mineralization of the Kochkar district is spatially associated with a swarm of easterly, approximately radially trending, mafic dykes that occur along the western contact of the Plast massif bordered by the younger Borisov massif to the west (modified after Borodaevsky, 1952 and Smirnov, 1976). Mining centres include a number of deposits in the northern Kochkar ore field and the Novotroitsk deposit in the southern part of the Kochkar district.

which form a cluster of mainly N-S trending late-Palaeozoic granitoid bodies. The Plast massif belongs to the older suite of lower-Carboniferous TTG complexes (Fershtater et al., 1997) bordered to the west by the Permian two-mica, microcline-bearing granites of the Borisov massif (Fig. 2).

Granite-gneisses of the Plast massif are intrusive into a sequence of N-S trending, steeply inclined, tightly folded and foliated, upper-greenschist to mid-amphibolite facies metavolcanics and less abundant metasediments. Intrusive relationships are indicated by the presence of variably sized xenoliths and rafts of mafic and ultramafic volcanics, volcanoclastics and metasediments in both the granitoids and the granite-gneisses. Contacts between the plutonic rocks and the surrounding supracrustals are sharp, dipping steeply outward from the centre of the massif.

The Plast massif shows a distinctly elongate, N-S trending geometry that measures approximately 50 km along strike with a maximum width of ca. 10 km in its central parts (Fig. 2). Texturally and petrographically it is made up of distinct phases that describe a roughly zonal distribution. The marginal zones of the massif are strongly gneissose, with the gneissosity defined by flattened quartz-feldspar aggregates, aligned micas or a migmatitic (stromatic) banding. The pervasive dynamic recrystallization of all mineral aggregates points to a high-temperature, solid-state origin of the gneissosity, which is concordant to the bedding and foliation of the surrounding supracrustals, thus giving the overall impression of an elongate gneiss dome. Gneisses are mainly of tonalitic and trondhjemitic composition comprising predominantly plagioclase, quartz and biotite, together with minor hornblende, muscovite and alkali feldspar. Towards the core of the Plast massif, gneisses grade into a wide zone of schollen- and raft migmatites together with lesser-deformed or undeformed granitoids. The proportion of gneissose fragments to granite is highly variable, but generally decreases towards the centre of the Plast massif where weakly to undeformed porphyritic granitoids predominate. The latter are mainly of granodioritic and, subordinately, granitic composition and comprise microcline, plagioclase, quartz, biotite and muscovite as their main constituents. Feldspars are almost invariably affected by saussuritization, and mafic minerals are locally affected by chloritization. Fabric development within the Plast massif and cross-cutting relationships between different intrusive phases point to a synkinematic emplacement of the granitoids during regional E-W compression and sinistral transpressive shearing along the regionally developed N-S trending shear belts that bound the EUZ (Fig. 2) (Bankwitz et al., 1997; Kröner et al., 1998).

Numerous types and generations of dykes occur throughout the Plast massif. These can be grouped into early, predominantly felsic dykes including aplites and pegmatites that are variably deformed and several generations of mafic-to-intermediate dykes, which cut the majority of felsic dykes. An easterly trending swarm of mafic dykes is developed around the town of Plast in the central parts of the granite-gneiss massif (Fig. 2). This dyke swarm is of particular significance for gold mineralization in the Kochkar district as will be discussed below.

GEOLOGY THE KOCHKAR ORE FIELD

Economic-grade gold mineralization in granitoids and gneisses of the Plast massif is hosted by steeply-inclined, tabular quartz-sulphide lodes (Fig. 3). The auriferous quartz lodes are spatially associated with mafic dykes, henceforth referred to as ore-controlling dykes that form part of an easterly trending dyke swarm along the western portions of the Plast massif (Figs. 2 and 3). Quartz lodes occur mostly parallel and directly adjacent to mafic dykes. Quartz veins contain, on average, 4-6 g/t Au with locally developed high-grade ore shoots carrying ≥ 30 g/t Au. In contrast, associated dykes and alteration zones surrounding the quartz lodes show only subeconomic gold grades of < 1 g/t Au. The dyke swarm and associated gold quartz lodes are developed along a N-S trending, 15km long and 5km wide corridor around the town of Plast close to the contact of the Plast massif with the Borisov massif in the immediate west (Fig. 2). The main mining centres are the large Kochkar ore field, located in the northern parts of the district, and the smaller Novotroitsk deposit in the south (Figs. 2 and 3). The Kochkar ore field (Fig. 3) that consists of a number of deposits in the northern parts of the district has been studied in detail and will serve to illustrate the salient features of the controls and timing of gold-quartz lodes. Exploration and mining in the Kochkar ore field have identified a continuous down-dip extent of auriferous quartz lodes to depths >1000 m and current mining exploits levels between 400 and 700 m below surface. Mining at Novotroitsk has progressed to 430 m below surface before mine workings were abandoned a number of years ago.

OCCURRENCE AND DISTRIBUTION OF ORE-CONTROLLING DYKES

Over 2000 easterly trending dykes have been mapped within the Plast massif (Borodaevsky, 1952). On a district scale, ore-controlling dykes show systematic variations in trend, describing an overall radial pattern perpendicular to the western margin of the Plast massif. From north to south, dyke trends vary from predominantly ENE at Kochkar (mainly 60-80° and subordinately 45-55°) via easterly trends (80-100°) in the central parts of the ore field to mainly NW-SE trends in the south at Novotroitsk (110-140°). Most dykes show steep-to-subvertical dips with steep southerly dips prevailing in the north and steep northerly dips prevailing in the south. The dykes are most abundant and are widest at the western contact of the Plast massif, which also marks the western limit of the dyke swarm, since most dykes terminate abruptly against this contact. Their abundance and width decreases progressively towards the central and eastern parts of the Plast massif, where they are only sporadically developed. The width of dykes ranges from thin, cm-wide dykelets, to >20m and strike lengths vary from several tens of metres to >1.5 km. At Kochkar, dykes may also occur in closely spaced clusters defining three east-northeasterly trending corridors termed the northern, central and southern zones along which mining is currently concentrated (Fig. 3). Ore-controlling dykes are crosscut by numerous generations of later dykes. While some of the later dykes are subparallel to ore-controlling dykes, the majority of crosscutting dykes shows northerly trends.

Dykes are of mainly mafic to, subordinately, intermediate composition. In underground exposures, they display highly variable textures ranging from fine-grained, massive dykes, to porphyritic or strongly schistose dykes. The mafic dykes are typically black to dark greenish in outcrop and consist predominantly of biotite, amphibole, plagioclase, alkali feldspar, quartz, apatite, zoisite and opaques (mainly sulphides), together with chlorite, actinolite, calcite and sphene. Tectonic fabrics and mineral assemblages clearly indicate that the petrography and textures of the dykes are the result of repeated phases of deformation, alteration and regional

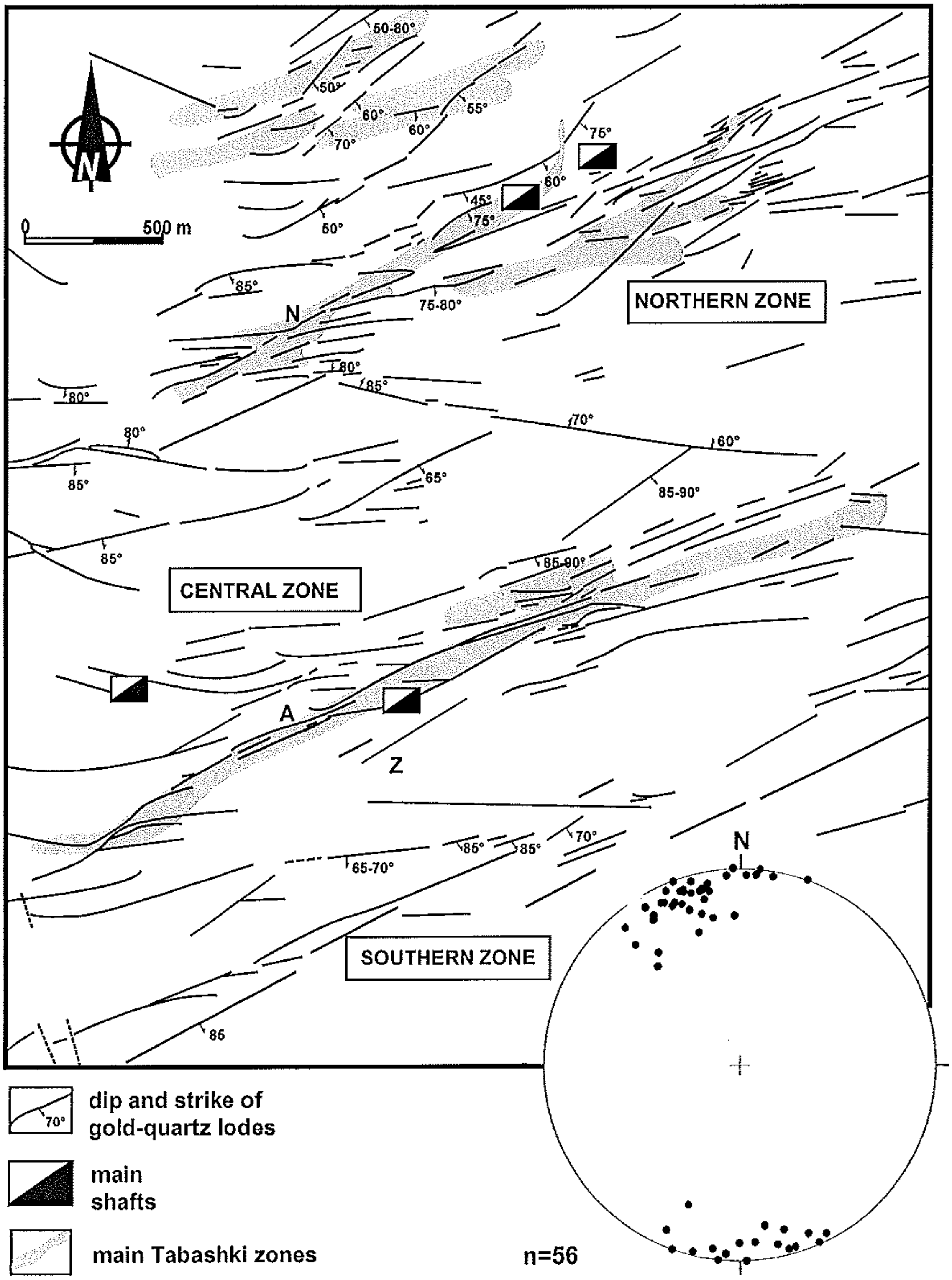

Figure 3: (a) Geological sketch map showing the distribution and orientation of gold-quartz lodes in the northern Kochkar ore field. Gold-quartz lodes show predominantly east-northeasterly trends parallel to the prevailing direction of dyke trends. The dykes are closely clustered in three east-northeasterly trending zones (northern, central and southern zones), which corresponds to a higher abundance of spatially associated auriferous quartz lodes (modified after Borodaevsky and Sher; in Borodaevsky, 1952). Letters indicate location of auriferous veins discussed in the text; N: North Nikolaevskaja; A: North Alexandrovskaja; Z: Zosinskaja. (b) Lower hemisphere equal-area projection of poles to gold-quartz lodes in the Kochkar ore field collected in underground workings and from mine level plans.

metamorphism so that the original composition and petrography of the intrusive dykes is difficult to establish. Based on crosscutting and overprinting relationships of mineral parageneses and tectonic fabrics, the dykes have been affected by at least three events, namely: (1) ductile shearing and the formation of composite mylonitic fabrics in the dykes; (2) late-to-postkinematic growth of metamorphic minerals, notably biotite, hornblende and zoisite; and (3) retrogression of high-grade metamorphic mineral assemblages by greenschist-facies parageneses and associated brittle-ductile deformation (Fig. 4).

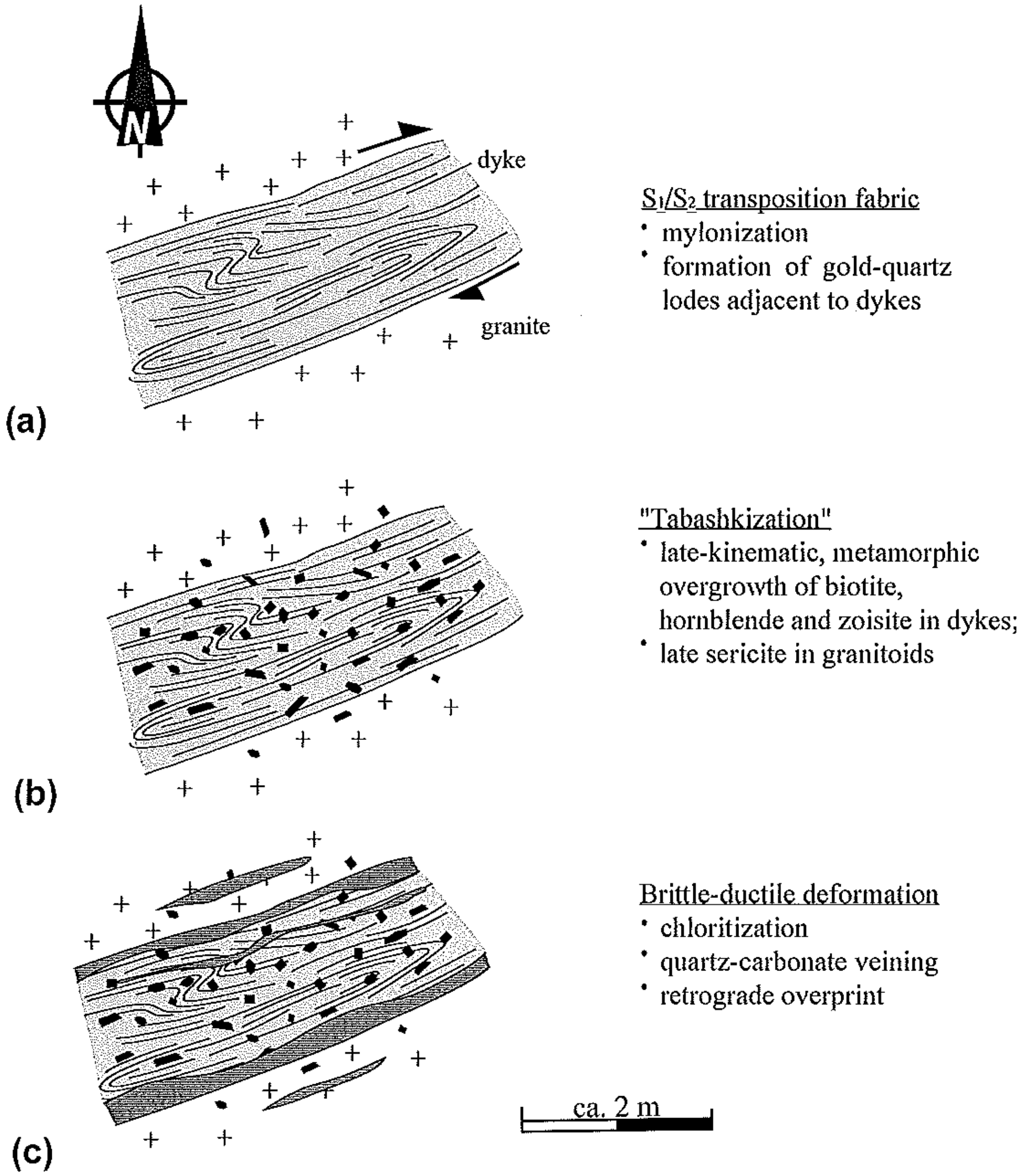

Figure. 4: (a) Synoptic sketch of the development of mylonitic shear fabrics in ore-controlling dykes. The formation of gold-quartz lodes adjacent to the dykes occurred during shearing along dykes.; (b) the overprint of shear fabrics by late- to- postkinematic metamorphic minerals leading to porphyroblastic 'Tabashki' textures; and (c) later chloritization and brittle fabrics as deduced from overprinting relationships of tectonic fabrics and mineral parageneses (see text for further discussion).

Ductile shearing of ore-controlling dykes

Ore-controlling dykes are characterized by a variably developed, dyke-parallel schistosity (S1) defined mainly by biotite and, to a lesser extent, hornblende. Locally, the S1 foliation can be observed to be refolded and transposed into a subparallel S2 foliation. The transposition of fabrics is best observed where quartz veinlets contained in the dykes are isoclinally folded, forming intrafolial folds that become transposed into the S1/S2 fabric. The development of transposition fabrics and recrystallization of mineral textures testify to the high strain, mylonitic origin of the S1/S2 schistosity. This indicates that the dykes most likely behaved heterogeneously during deformation that was activated by shearing. Biotite ± hornblende as the predominant minerals defining the S1/S2 fabric suggest upper-greenschist to lower-amphibolite facies conditions of deformation. High-strain, mylonitic fabrics are mainly confined to the dykes while the adjoining wall-rock granitoids show only subordinate evidence of pervasive ductile fabrics. Progressive overprinting relationships between gold-quartz veins and shear fabrics within and adjacent to ore-controlling dykes suggest that quartz veining occurred synkinematically with the deformation of the dykes. The relationship between deformation and gold-quartz veining will be examined below in detail.

The steeply inclined S1/S2 foliation in the dykes is most intensely developed in ENE- and SE- trending dykes (see also Borodaevsky, 1952). Sheared dykes and adjacent wall-rocks and quartz veins contain a shallow-to-moderately southwesterly plunging mineral stretching lineation defined by stretched quartz and quartz-feldspar aggregates and/or hornblende or biotite/hornblende aggregates. The lineation plunges at shallow-to-moderate angles (10-30°) in a southwesterly direction along ENE-trending dykes (Fig. 5) and towards the northwest along SE-trending dykes. Shear sense indicators such as S-C and S-C' fabric relationships, mica fish, and asymmetrically folded quartz veins point to a predominant component of dextral strike slip movement along ENE-trending dykes that prevail in the Kochkar district, although sinistral strike-slip kinematics were recorded along two E-trending dykes. In contrast, rare southeasterly-trending dykes at Kochkar show a sinistral component of strike-slip. The shallow plunge of the mineral stretching lineation suggests a component of dip-slip movement in addition to the main strike-slip kinematics along ore-controlling dykes. It thus appears that the overall kinematics along mylonitized dykes is best described as oblique strike-slip.

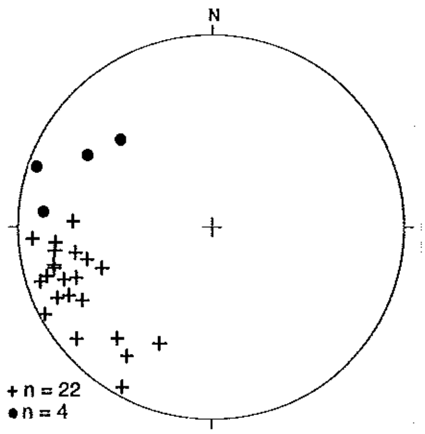

Figure. 5: Lower hemisphere equal area projection of mineral stretching lineations showing shallow-to-moderate plunges to the (west-) southwest and (west-) northwest, respectively. Mineral stretching lineations were measured in ENE-trending, ore controlling dykes and adjoining wall rocks and quartz veins.

Metamorphic textures: 'Tabashki' formation

A characteristic feature of ore-controlling dykes are ubiquitously developed porphyroblastic textures defined by the overgrowth of the S1/S2 fabric by large euhedral, poikiloblastic biotite, green-blue hornblende and, locally, zoisite. The porphyroblastic textures and mineralogy of the dykes are collectively referred to as 'Tabashki' (strictly translated, the Russian term 'Tabashki' refers to the tobacco-like weathering colour of dykes on surface; e.g. Borodaevsky, 1952; Smirnov, 1976). It is important to note that minerals defining the transposition fabrics in the dykes are similar to the later post-kinematic overgrowths, mainly biotite and lesser hornblende. The presence of aligned and recrystallized biotite, together with random and undeformed biotite, indicates that deformation in ore-controlling dykes ceased close to peak metamorphic conditions, but that peak metamorphism outlasted the main phase of deformation. Borodaevsky (1952) related the formation of the poikiloblastic Tabashki textures to the regional Permian metamorphism that has affected the EUZ (Puchkov, 1997).

Late brittle-ductile deformation

The S1/S2 mylonitic fabric and the late-kinematic, peak-metamorphic textures in ore-controlling dykes are locally overprinted by chloritic fault gouges, chlorite-carbonate breccia zones and quartz veins (Fig. 4c). Chlorite defines a S3 foliation that is subparallel to the S1/S2 foliation, but clearly overprints the mylonitic transposition fabric. Chloritic fault gouges are particularly common along the contacts of mafic dykes with surrounding quartz veins and granitoids, but they may also form an interconnected network of brittle-ductile fault and breccia zones that are developed as up to 50 m wide corridors. Sphene is typically enriched in chloritic fault gouges and is likely related to the release of Ti during the breakdown of biotite. On a regional scale, the brittle fault corridors trend NE-SW and NW-SE subparallel to prominent ore-controlling dykes or dyke clusters, showing strike lengths of in excess of 2 km in underground workings at Kochkar. Late quartz veins associated with chloritic fault gouges are barren and easy to distinguish from auriferous quartz veins adjacent to ore-controlling dykes by their white, distinctly milky appearance, commonly lensoid geometry, the absence of sulphides and the presence of chloritic alteration haloes that replace biotite of the Tabashki dykes. Since the chloritic brittle faults invariably overprint ore-controlling dykes and associated gold-quartz lodes, these faults are not considered any further.

GOLD-QUARTZ LODES

Quartz-veining and associated gold-sulphide mineralization occur in mainly three situations relative to ore-controlling dykes, namely (in decreasing order of abundance): (1) along the margins of dykes; (2) within dykes; or (3) in sheared granitoids and gneisses with no direct spatial association to dykes (Fig. 6).

Quartz-sulphide lodes are typically developed along the contact between strongly sheared ore-controlling dykes and enveloping wall-rock granitoids and gneisses (Figs. 6a,b). The massive and/or laminated, greyish-glassy to milky quartz veins are, on average, 0.2 to 1 m (up to 6 m) wide and show distinctly tabular geometries. Contacts between quartz veins and dykes are commonly sharp. Prominent quartz lodes can be traced along strike for over 500 m (Fig. 3) with similar down-dip extents, but an en-echelon segmentation into smaller, lensoid bodies is common. The plunge of individual ore lodes is subvertical. Local widening of quartz lodes is observed in zones of undulations of adjacent dykes along strike, corresponding to

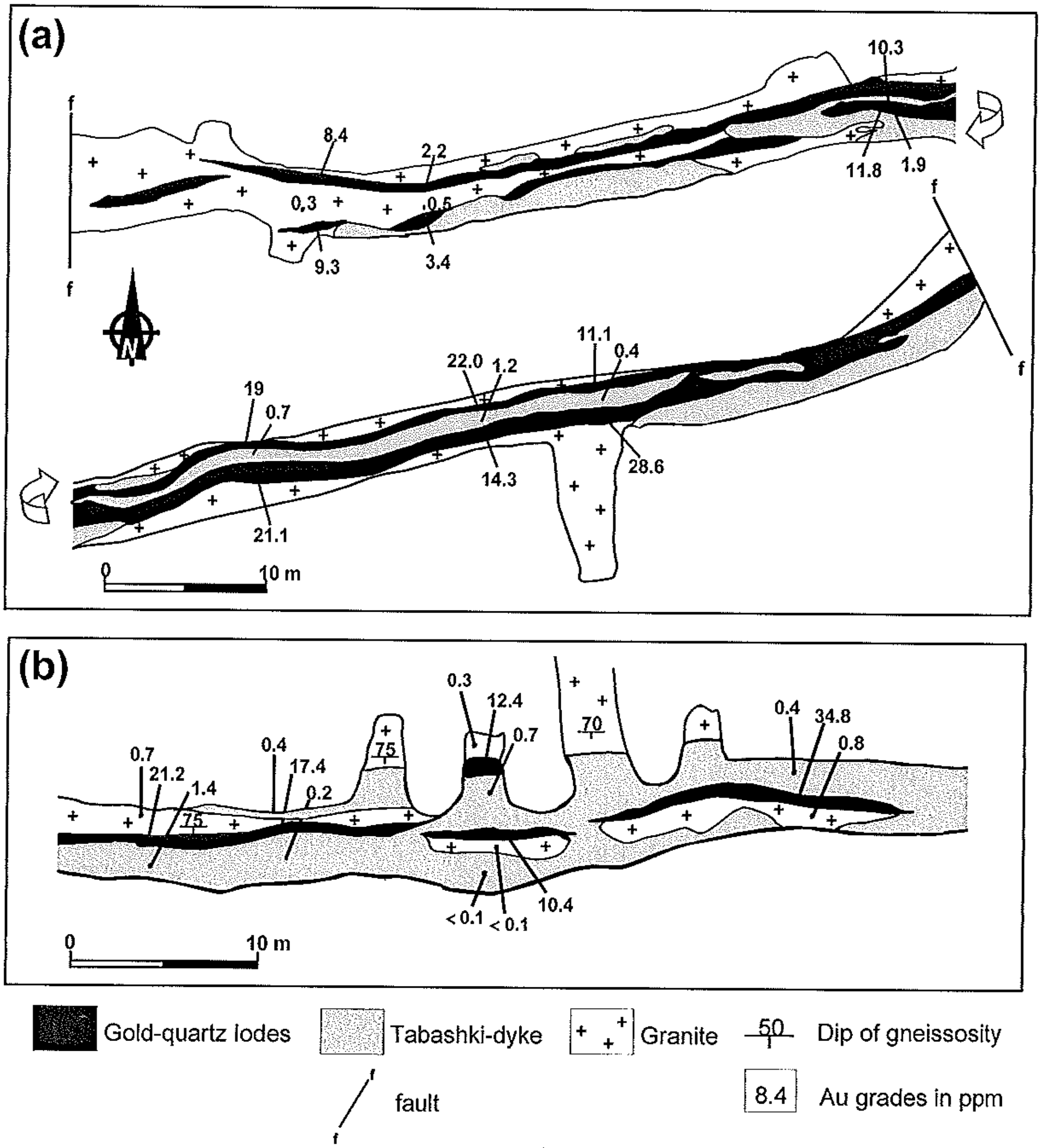

Figure 6 : Detailed maps of underground developments in the Kochkar district, illustrating the spatial association of gold-quartz lodes with mafic dykes. Note that auriferous lodes are preferentially located along the contacts of sheared dykes with surrounding granitoids. In (a), gold-quartz lodes can be observed to overshoot the termination of the ore-controlling dyke by approximately 15m, being hosted entirely by sheared granitoids. Note that quartz lodes in granitoids and adjacent to mafic dykes show similar strikes. The significance of the dyke-wall-rock contact for the development of gold-quartz lodes is particularly well illustrated in (b) where quartz veins are confined to granitic xenoliths in mafic dykes.

releasing bend geometries along ore-controlling dykes. Laminated or ribbon-textured quartz lodes consist of elongate wall-rock septa of foliated dyke material alternating with quartz. Sulphides occur in only subordinate amounts (2-7 vol. %) and mainly parallel to wall-rock laminae, or they form irregular clots within quartz veins. Gold-quartz lodes may occur on both sides or only on one flank of the ore-controlling dykes (Fig. 6a,b). Locally, there is a textural and petrographic zonation from (1) innermost, mylonitic, quartz-veined ore-controlling dykes, via (2) laminated-to-massive quartz-sulphide veins that consist of laminae of dyke material and milky quartz in variable proportions, (3) quartz lodes with subordinate sulfides containing angular, strongly sericitized granitic wall-rock inclusions, (4) altered (sericitized) wall-rock granitoids/gneisses with thin, foliation-parallel quartz veinlets, to (5) outer, unaltered granite gneisses.

Gold-quartz veins occur, to a lesser extent, within the dykes. They consist of either foliation and dyke-parallel quartz veins or numerous cross-cutting generations of variably folded quartz veins that lead progressively into more massive quartz textures. Smaller veinlets can be observed to be folded into asymmetric fold trains that are progressively disrupted and sheared out and ultimately transposed into the S1/S2 fabric of ore-controlling dykes. Larger quartz veins form pinch-and-swell structures or boudins that are aligned parallel to dyke margins. In places, quartz veins show breccia textures made up of angular dyke fragments cemented by massive quartz. In addition to quartz veins hosted entirely by mafic dykes, gold-quartz lodes can be observed to be confined to the contact of wall-rock xenoliths with the engulfing dykes. Although quartz lodes occur within the dykes, ribbons of foliated dyke material in quartz lodes clearly indicate that quartz veining post dates dyke intrusion, underscoring the significance of the contact between ore-controlling dykes and wall-rock granitoids for quartz veining and associated gold mineralization. This aspect will be discussed below (Fig. 6b).

Gold-quartz lodes may also be developed within granodiorites without a close spatial association to dykes. Based on their orientation and structural controls, two types of granitoid-hosted gold-quartz veins can be distinguished. The first type includes ENE trending, steeply dipping, tabular quartz veins or en-echelon quartz-vein arrays at Kochkar that are hosted by up to 5m-wide zones of intensely sheared and altered granitoids. The east-northeasterly trending, subvertical foliation in the granitoids is defined by alteration minerals, mainly sericite and flattened, strongly recrystallized quartz-grain aggregates. Notably, auriferous quartz veins hosted by sheared granitoids frequently occur along the lateral terminations of foliated ore-controlling dykes (Fig. 6a). This style of quartz veining in sheared granitoids contrasts markedly with E-W trending gold-bearing quartz veins that are predominantly found in the central parts of the ore field between the Kochkar district and Novotroitsk. Here, quartz veins are only subordinately associated with foliated granitoids and preferentially developed as shorter (up to 10 - 100 m along strike) quartz lenses and quartz vein arrays hosted by altered, but only weakly deformed granitoids.

Relative timing of dyke emplacement, quartz-lode formation and shearing in dykes

The presence of foliated laminae of dyke material in ribbon-textured quartz veins and dyke fragments in massive quartz lodes indicates that gold-quartz vein formation post-dates dyke emplacement and is largely coeval with shearing in ore-controlling dykes. However, there are rare cases where later dykes crosscut both ore-controlling dykes and associated quartz lodes at low angles implying that either dyke emplacement has locally outlasted shearing along ore-controlling dykes or there have been repeated phases of dyke emplacement.

Mineralization and wall-rock alteration

Auriferous quartz lodes are made up predominantly of quartz with minor amounts of carbonate, sericite, scheelite, biotite together with opaques (mainly sulphides) and later chlorite. Gold is fine grained (commonly < 20 µm) and occurs mainly as specks of free gold in quartz. Sulphides include mainly pyrite and arsenopyrite with subordinate chalcopyrite, sphalerite, fahlores, galena, and bismuthinite (Borodaevsky, 1952; Smirnov, 1976). Approximately 20% of the gold is associated with sulphides and the gold fineness is commonly > 875 (Smirnov, 1976). On a district scale there are considerable variations in the volumetric abundance and relative proportions of sulphide minerals. While gold-quartz veins at Kochkar contain only 2-7 vol.% sulphides (mainly pyrite), mineralization at Novotroitsk is characterized by abundant sulphides (up to 60 vol. %) and a more disseminated type of mineralization with the predominance of arsenopyrite.

Wall-rock alteration assemblages in granitoids adjacent to quartz lodes are simple and commonly consist of quartz and white mica (sericite/muscovite) with subordinate albite, carbonate, and chlorite. In addition, tourmaline is locally present and scheelite may be present along the contacts of quartz veins with wall rocks. Sericite and elongate quartz-grain aggregates may define a vein-parallel foliation in close proximity to gold-quartz lodes, but large euhedral muscovite grains can also be observed to overgrow quartz-veins and the vein-parallel foliation. Chlorite replaces ferromagnesian minerals in the granite. Albite, together with coarse-grained, euhedral muscovite, quartz and relic feldspars from the granitic precursors are present in the more distal alteration zones in the granitoids. The presence of both aligned and randomly orientated alteration minerals, as observed for syn- and postkinematic minerals in Tabashki dykes, suggests that wall-rock alteration and associated mineralization occurred close to peak metamorphism.

DISCUSSION

Relationship between gold-quartz lodes and dykes

The presence of mylonitic fabrics and the deformation of quartz veins within and adjacent to dykes provide compelling evidence that ore-controlling dykes are the loci of intense shear deformation. Shear deformation confined to mafic dykes, compared to relatively unstrained wall-rock granitoids, reflects different rheological properties and, as a result, pronounced strain refraction occurs across competence contrasts between biotite-rich, incompetent dykes and feldspar-dominated, competent granitoids (Fig. 7). A similar development of 'enforced' shear zones on mafic dykes that have represented lithological anisotropies has, for example, been described by Belkabir et al. (1993) and Poulsen and Robert (1989) for dyke-shear zone relationships in the late-Archaean granitoid-hosted Star Lake lode-gold deposit in Canada. Strain refraction (e.g. Treagus, 1983, 1988; Hanmer and Passchier, 1990) involves marked changes of homogeneous strain across layers of different competence during which the bulk strain will be partitioned according to the relative strength of the materials, approaching layer-normal pure shear in the competent material and layer-parallel simple shear in the incompetent material (Fig.7). The direction of maximum finite

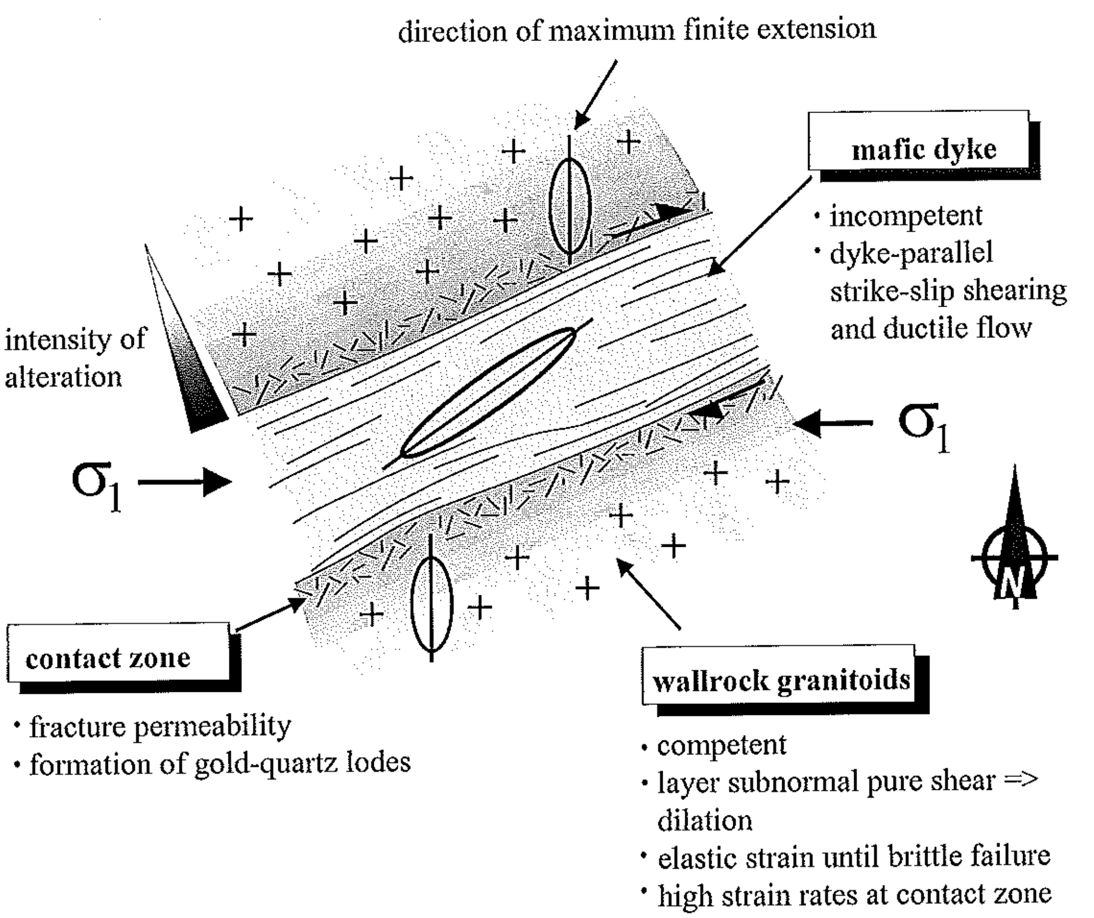

Figure 7: Schematic sketch illustrating the consequences of strain refraction across biotite-rich, incompetent ore-controlling dykes enclosed by competent wall-rock granitoids during regional-scale E-W directed shortening. Strain refraction along ore-controlling dykes results in the resolution of bulk strain into a component of approximately layer-parallel shear in dykes and a component of layer-normal pure shear in surrounding granitoids, as indicated by the strain ellipses. Brittle behaviour of wall rocks and high-strain rates across the interface of incompetent dykes with competent granitoids leads to the formation of fracture permeabilities, which will promote the access of mineralizing fluids along this contact. This relationship explains the commonly observed localization of gold-quartz lodes adjacent to intensely sheared dykes.

extension will be subparallel to the shear zone boundaries in the incompetent material, but subperpendicular to the shear zone boundary in the competent material. The higher the competence contrast between different layers, the higher will be both the strain intensity and the component of layer-parallel simple shear within the incompetent layer (Hanmer and Passchier, 1990). This means that any lithological layer within a heterogeneous rock sequence can effectively become a shear zone depending on competence contrasts, given that the principal strain axes are not exactly layer-parallel and layer-orthogonal (Treagus, 1988).

Given that deformation and associated alteration and mineralization have most likely occurred at upper-greenschist facies conditions (T ca. 400-500°C), strain refraction across the dyke/wall-rock interface has three main consequences (Fig. 7). Firstly, deformation in the feldspar-dominated wall-rock granitoids was likely to be accommodated by combined brittle-ductile deformation rather than ductile flow as in dykes. Secondly, high finite strain confined to sheared dykes indicates large strain gradients perpendicular to dyke walls. Strain gradients will be particularly large across the interface between dykes and enveloping granitoids. Thus, high strain rates will be developed along the margins of sheared dykes with granitoids. Both high strain rates and brittle behaviour of wall-rock granitoids during deformation will promote the formation of fractures and, thus, fracture permeabilities which will greatly enhance the overall permeability of the rocks. The significance of the sharp interface between ore-controlling dykes and competent granitoids for the formation of auriferous quartz lodes is particularly well illustrated where discontinuous and relatively short gold-quartz lodes in dykes are preferentially developed along the margins of wall-rock xenoliths with enclosing dykes (Fig. 6b). Thirdly, the component of pure shear subperpendicular to ore-controlling dykes generates dilation normal to the dyke walls (Fig. 7). Repeated dilation normal to dyke walls readily explains the dyke-parallel laminated or ribbon textures of gold-quartz lodes. Thus, fluid infiltration was promoted particularly along the interface between ductilely deforming dykes and brittle-ductile wall-rocks.

Regional controls on emplacement of ore-controlling dykes

Although the timing of emplacement of ore-controlling dykes is not constrained by radiometric age data, the intrusion of dykes into the lower-to-mid-Carboniferous Plast massif and the overprinting of the dykes by Permian metamorphism constrains the emplacement between the upper-Carboniferous and the lower-Permian. During this time, the far field principal stress direction ($\sigma 1$) in the EUZ was directed E-W (Puchkov, 1997; Echtler et al., 1997), related to the late-Palaeozoic final amalgamation of terranes in the southern Urals. The spatial restriction of dykes to the Plast massif and the abrupt termination of dykes along the contact with surrounding supracrustals suggests that dyke emplacement was controlled by the competent nature of the granite-gneisses. The radial outcrop pattern of dykes around Plast either indicates a systematic and gradual change of the regional stress field on a district scale, or, alternatively, reflects local stress fields being superimposed onto far field stresses. The former seems unlikely, given the relatively limited extent of the dyke swarm. We interpret the dyke swarm to have been emplaced either as a result of the emplacement of the Borisov massif and the associated doming and brittle fracturing of adjacent granitoids of the Plast massif, or during E-W directed regional shortening and indentation of the Borisov massif into the Plast massif. Since the deeper structure and 3-D geometry of the Borisov massif is not known and radiometric ages of Tabashki dykes that could constrain the precise timing of dyke emplacement are not available, this question remains unresolved at present. However, doming readily explains : (1) the spatial restriction of easterly trending dykes to the central parts of the Plast massif; (2) the radial emplacement pattern and systematic changes in the dips of dykes centred around the contact of the Borisov with the Plast massif; and (3) the highest abundance and largest widths of dykes close to the western contact of the Plast massif.

From the development of shear fabrics in ore-controlling dykes and the occurrence of gold-quartz lodes it is particularly the ENE- and SE-trending shear zones/dykes that were amenable to deformation and the development of auriferous quartz-lodes (Fig. 8). Moreover, shear zones and gold-quartz lodes without a direct association to mafic dykes hosted entirely in granitoids are parallel to the prevalent direction of ore-controlling dykes. It thus appears that the orientation and slip direction along sheared dykes roughly correspond to a plane strain,

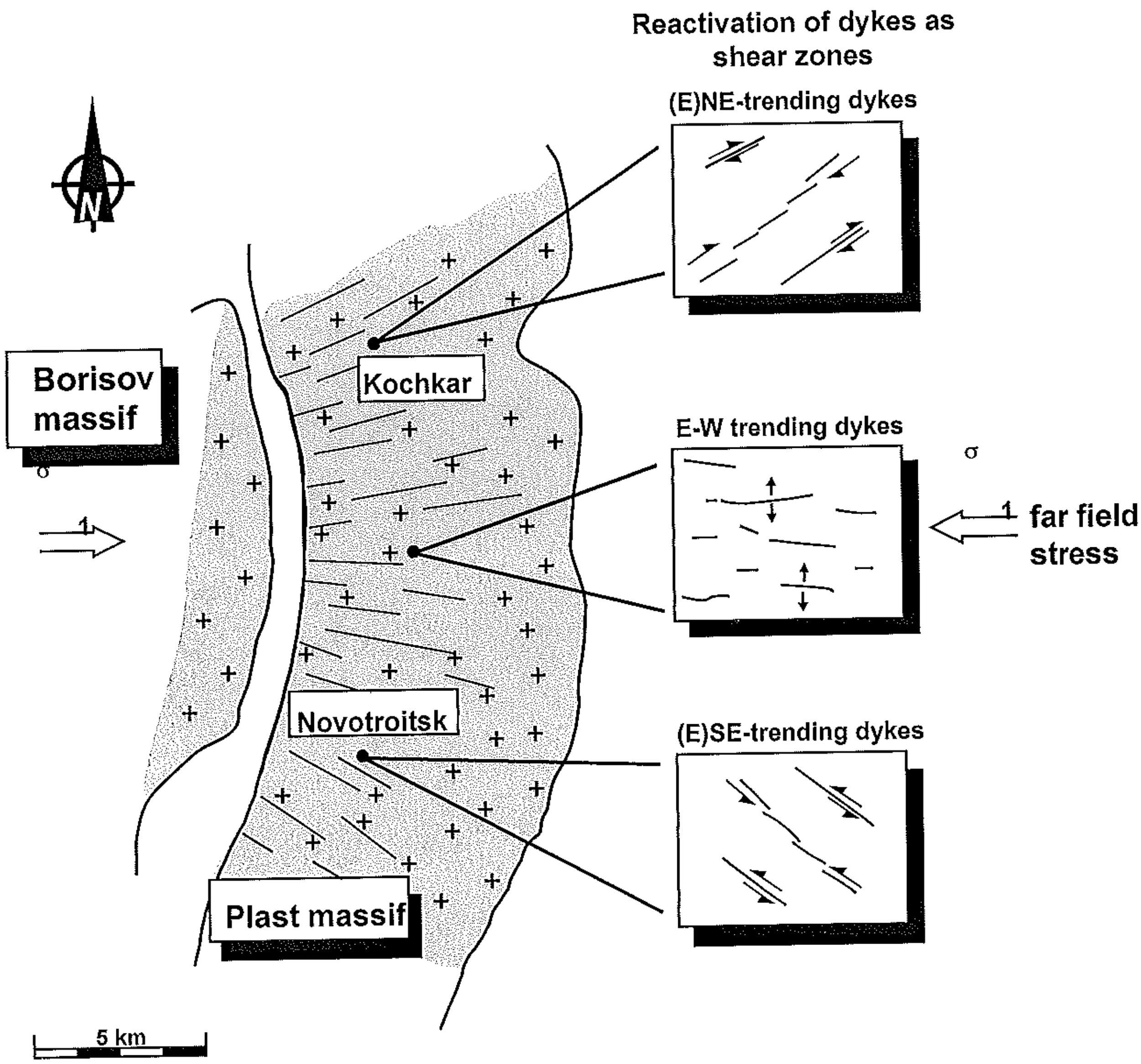

Figure 8: Schematic sketch map of the Borisov and Plast massifs during regional-scale E-W directed horizontal shortening in Permian times. Doming during emplacement of the Borisov pluton is interpreted to account for the occurrence of the radial dyke swarm in the west of the Plast massif and the systematic changes in dip of the dykes. The regional E-W directed far field stress during Permian tectonism was responsible for the reactivation of northeasterly trending dykes as predominantly dextral (oblique) strike-slip shear zones and southeasterly trending dykes as sinistral (oblique) strike-slip shear zones (insets). The orientation and kinematics of 'enforced' shear zones thus correspond to an approximately conjugate shear zone pattern. Dykes trending E-W display only subordinate evidence of shearing and, thus, minor gold-quartz vein development since the principal compressive stress (σ1 far field stress) is subparallel to easterly trending dykes.

conjugate shear zone pattern, although ENE-trending lodes are far more abundant than those of SE trends. The maximum compressive stress (σ_1) would thus be oriented approximately E-W and subhorizontal which corresponds to the regional E-W directed compressional tectonics during the regional-scale Permian deformation (Zonenshain et al., 1990; Puchkov, 1997). The intermediate stress (σ_2) would be subvertical while the least compressive stress (σ_3) is orientated N-S and subhorizontal. In this case, the shorter and lensoid, subvertically inclined, E-W trending gold-quartz veins in the central parts of the ore field correspond to extensional structures. The reactivation of dykes as shear zones thus implies a change in the stress field from earlier vertical tectonics during doming and emplacement of the Borisov massif to later subhorizontal, E-W directed shortening during the Permian regional-scale tectonics in the southern Urals.

CONCLUSIONS

In this study, we have attempted to explain the close spatial relationship between deformed mafic dykes and auriferous quartz lodes of the late-Palaeozoic Plast massif of the southern Urals. The formation of a set of conjugate shear zones in the Plast massif was profoundly influenced by the presence of mafic dykes. The dykes acted as weak layers during regional-scale E-W directed horizontal shortening related to the Permian terrane amalgamation in the Uralides. Dyke-shear zone relationships at Kochkar are a result of strain refraction induced by the presence of incompetent dykes. Strain refraction has resulted in a partitioning of the bulk strain into a component of layer-parallel simple shear in the weak layer and a component of layer-normal pure shear in the surrounding competent material. As a consequence, ENE- and SE-trending dykes have been preferentially activated as oblique dextral and sinistral strike-slip shear zones, respectively.

Fabric development and the predominance of relatively weak phases, such as biotite, indicate that the simple-shear component in incompetent dykes was accommodated by mainly ductile flow. In contrast, deformation in adjacent granitoids was accomplished by a combination of brittle fracture and ductile creep. The brittle-ductile behaviour of competent granites together with the layer-normal dilational component provided fracture permeability and dilatancy which promoted the access of mineralizing fluids. The close spatial association between the development of 'enforced' shear zones in incompetent dykes and gold-quartz lodes preferentially developed along the margins of high-strain zones illustrates the significance of fracture permeability for fluid flow in crystalline rocks at elevated metamorphic grades, as opposed to grain-scale permeabilities during predominantly crystal-plastic creep and ductile deformation.

On a regional scale, the common association of orogenic lode-gold deposits with syn-kinematic granitoids in the East Uralian Zone indicates the role of plutons as competent inhomogeneities within the supracrustal belt. Competent granitoids have represented sites of reduced mean stress during regional deformation which are likely to focus regional-scale fluid flow during deformation and metamorphism (Oliver et al., 1990; Ridley, 1993). Similar relationships between plutonic complexes in metavolcano-sedimentary belts and fluid flow patterns have been described from late-Archaean granite-greenstone terranes (Ridley, 1993; Ojala et al., 1993; Cassidy et al., 1998; Poulsen and Robert, 1989) with which the East Uralian Zone shares numerous structural and lithological similarities.

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