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The Adola Goldfield, Ethiopia

Geology and Genetic Hypothesis

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The Adola goldfield area is built up of erosional remnants of Upper Precambrian rocks. Its tectonic setting, on a regional scale, is that of a mobile belt and can be interpreted by plate convergence. The source of gold, in this context, is believed to be ultramafic rocks of an ophiolitic suite which originated as flows extruded in the Upper Precambrian sea basin. It formed, together with the argillaceous-arenaceous sediments, the oceanic crust.

A tentative genetic interpretation of mineralization envisages the concentration of gold as a hydrothermal process extending over a considerable period of time. The solutions can be best explained as connate brines derived from trapped sea water. The saline fluids are believed to have been activated by burial when serpentinization and diagenetic sulfide mineralization have probably taken place. The onset of tectonism and anatectic granitic plutonism initiated the period of epigenetic hydrothermal events. An extensive hydrothermal system, involving reconstituted fluids, was set in motion, the main stage of metal mobilization probably having taken place during talc hydration metamorphism, the early epigenetic gold carrying sulfides precipitated by biogenically derived sulphur in permeable arenitic beds. Closing of the basin led to extensive physical deformation, continued plutonism, metamorphism and hydrothermal mobilization and remobilization, resulting in hypothermal precipitation of sulfides in structural dilatant sites, probably in a series of events, with gold incorporated in sulfides.

Some later rejuvenating plutonic and hydrothermal episodes may have followed, possibly associated with the Mozambiquan orogeny, which left a metamorphic imprint of 550 ± 100 Myr in the region.

Etiopska zlatonosna pokrajina Adola sestoji iz erozijskih ostankov zgornjega dela predkambrijskih kamenin. Njeno zapleteno geološko zgradbo in metalogenezo je možno razložiti s konvergentnim razvojem po teoriji plošč. Izvor zlata bi v tem kontekstu mogli iskati v ultramafičnih kameninah ofiolitnega zaporedja, nastalega s podvodnimi izlivi lav različne sestave ter iz vmesnih glinastih in peščenih sedimentov, ki so skupno sestavljali oceansko skorjo. Te kamenine so danes na območju Adole ohranjene v dveh meridionalnih pasovih z vložki granitov.

V Adoli gre za zlatonosne sulfide, nastale na različne načine, v raznih časovnih obdobjih in v več generacijah. Primarna nahajališča zlata so vezana izključno na zgornji del predkambrijskih kamenin. Hipoteza o mineralizaciji temelji na predpostavki, da je prvotni izvor zlata iskati v ultrabazičnih kameninah, ki izhajajo iz zemeljskega plašča. Koncentracija zlata pa je bila večfazni proces, ki se je pričel z metamorfozo kamenin. Metasomatoza — najprej serpentinizacija in nato steatitizacija z nastankom lojevca — je iz magmatskih silikatov in oksidov sprostila vrsto kovin, vključno zlato, ki so migrirale v raztopinah. Izvor raztopin je verjetno treba iskati v morski vodi, ujeti v porah sedimentov.

Pričetek tektonizma in anatektičnega magmatizma je uvedel hidrotermalne procese, pri katerih so raztopine, spremenjene z dodatkom CO_2, prepojile in izluževale kamenine. Proces steatitizacije je sprostil kovine, ki so migrirale — verjetno kot kloridi — in v pelitsko-arenitskih sedimentih med učinkovanjem žveplovega vodika precipitirale v obliki sulfidov.

Med orogenezo in plutonizmom so nastale epigenetske kremenove žile s sulfidi in hipotermalna rudišča. Zlatonosni sulfidi železa in barvnih kovin so kristalizirali predvsem v prepustnih conah zaradi znižanja pritiska in temperature. Zlato se nahaja v sulfidih v trdni raztopini. V površinski coni se zaradi preperevanja sprosti iz oksidiranih sulfidov ter se v obliki lusk in tudi večjih skupkov zbira v koluviju in aluviju.

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Introduction

The alluvial and colluvial gold placers in the Adola area of Sidamo Province in southern Ethiopia — an subject of lively mining activity during the past four decades — originated from as yet little-known primary sources. The placers' characteristics indicated that the primary gold sources are very near and evidently scattered over a large area. Quartz reefs and veins have been occasionally visually examined for specks of gold, but proved disappointingly barren, prompting the notion that the primary deposits are not profitable to work. Since there is rich alluvium available in the valleys, no systematic attempt to trace the source of detrital gold upslope was ever undertaken.

The area is poorly exposed, deeply weathered and partly covered by rain forest. Nevertheless, considerable geological information has been gradually gathered during the last decade. Primary gold was recently found (1975) by chance at two localities, and excavations resulted in appreciable gold recovery. It is becoming increasingly clear that proper attention must be given also to primary gold sources and their colluvial derivatives in future development of the Adola goldfield.

This paper is an attempt to summarize the known information on the geology of the Adola mine area and to elaborate on its metallogeny. Little geochemistry work has been done. Quantitative abundance data on gold are extremely meagre, and those on rocks are practically non-existent. Because of the complexity of the geology, poor exposure, insufficient evidence and limited possibility for systematic research, the conclusions necessarily involve speculation. Considerably more geochemical and field information will be required before the origin, and the eventual economic importance of the primary sources, can be known.

Geological research

When the goldfield became known in 1936 it was alluvial gold that attracted attention, and exploration has been directed only to placers since then. Visible gold has been found in quartz pebbles in the alluvial gravel, and occasionally in scattered quartz float, prompting the view that auriferous quartz occurs in veins linked with certain lithologies. N. H. Van Dornick (1950) was the first to suggest, on field evidence, to test primary sources by deep drilling, and he recorded detailed geological sections along some larger placers west of Shakisso.

D. Jelenc (1966) recognized that gold was associated with the group of rocks which he named Adola series. He produced a rough geological sketchmap of the goldfield, and suggested a genetic link between gold and amphibolitic rocks.

Hunting Geology and Geophysics Ltd. (1969) carried out a photogeological survey of the Sidamo area and provided valuable regional information.

C. F. Gilboy (1970) and A. M. Chater (1971) produced geological maps of the southern parts of the Adola area at 1 : 50 000 scale, and established the first lithostratigraphic subdivision of the Precambrian there. Their work provided fundamental data for the understanding of the regional geology of the area.

The U N — E t h i o p i a Mineral Survey (1971) studied the regional geology of the Sidamo Province and that of parts of the mine field. Regional reconnaissance geochemical drainage survey and some soil sampling and geophysical traverses were carried out. A provisional geological map at 1 : 50 000 scale was produced for the central part of the mine field. V. K a z m i n (1970) reconnoitered the Shakisso-Reggi area for the gold-quartz veins. Local geology and mineralization in the Chambi area was briefly dealt with by G. K o c h e m a s o v (1971).

The Agere Maryam area west of the Adola area, where gold placers are known to exist (D. J e l e n c , 1966), was photogeologically studied by V. K a z m i n (1971).

Working on a primary gold project, S. M o r e t e (1971, 1972, 1973) mapped and examined the Tula-Kajemiti-Demi Denissa area south of Hayudima. Deep drilling and surface excavations revealed many details, making this area the best understood part of the Adola goldfield.

Useful lithological data were provided by various groups exploring the placers, and reported mainly by B i a z e n B o g a l e (1972, 1973, 1974). M e l k a Y e w h a l a w o r k (1966) contributed some data on the Maleka-Monissa area.

V. K a z m i n (1975) studied the Sidamo Precambrian in the framework of differentiation, subdivision and correlation of the Precambrian of Ethiopia, and he examined the role of ophiolites in the Ethiopian basement in the regional context of the development of the Red Sea belt and the Mozambique belt (1976).

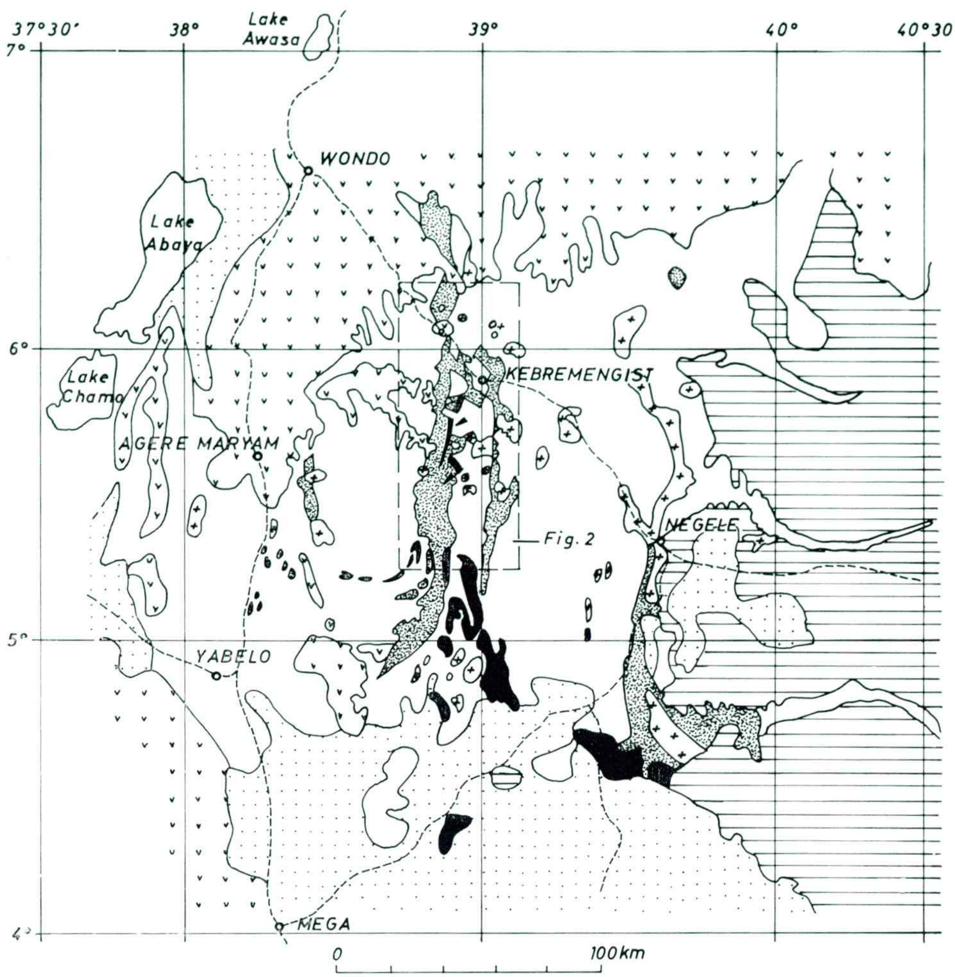
The eastern marginal part of the Adola area has been recently mapped by T e l a h u n B a l c h a in the course of regional mapping of Sheet NB 37-11 (Negele) at 1 : 250 000 scale.

A photogeological map of the Adola goldfield at 1 : 50 000 scale has been completed by M. H a m r l a (1977) as a compilation of his own and other field data.

The majority of the available chemical data has been produced by the Chemical Laboratory of the Ministry of Mines in Addis Ababa. A number of core samples from Adola drilling have been recently reanalyzed for gold, applying absorption spectrophotometry with a detection limit of 0.2 ppm.

Regional geology

The Ethiopian Precambrian can be divided in three complexes (V. K a z m i n and A. J. W a r d e n , 1975). The Lower Complex of high grade gneisses, migmatites and metamorphic granites is apparently of Archean age. The Middle Complex is prevailingly psammitic and pelitic and has been recognized in southern Ethiopia only, its local designation being the Zembaba Group (formerly Wadera Group). The Upper Complex consists of geosynclinal volcanic, volcanoclastic and sedimentary assemblages. According to V. K a z m i n (1976) an Upper Precambrian geosyncline extended from the present-day Red Sea region in northern Ethiopia southwards in two meridionally trending zones. The Adola area belongs to the Eastern Zone which extends across the Kenyan border at Moyale (south-east of Mega) (J. W a l s h , 1972) whereas the Western Zone runs in the west of Ethiopia and partly in the Sudan.



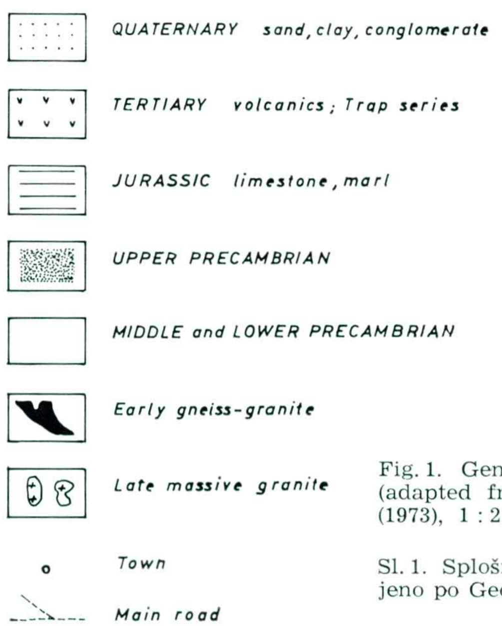


Fig. 1. General geology of the Sidamo region (adapted from the Geological map of Ethiopia (1973), 1 : 2 000 000 and some of the cited references)

Sl. 1. Splošna geologija območja Sidamo (prirejeno po Geološki karti Etiopije (1973), 1 : 2 000 000 in drugih navedenih virih)

In southern Ethiopia all three complexes are developed. The Upper Precambrian has been subdivided into a lower part named the Adola Group, and an upper part the Mormora Group, unconformably overlying the former. Similar rocks, correlated with the Adola Group, have been recorded in the Bul-Bul basin south of Negele and near Agere Maryam (V. Kazmin and A. J. Warden, 1975); these scattered patches are remnants of the original Eastern Zone, which was tectonically displaced and erosionally reduced (Figure 1). Tectonism was apparently accompanied by metamorphism and plutonism, which produced numerous bodies of granitic rocks. Some were affected by metamorphism and exhibit foliated gneissose texture, others postdated metamorphism and appear as massive »younger« granites, differing from the earlier ones in texture, mineralogy and structural position. Whereas the early granites are mostly confined to the Lower Complex and seem to be part of it, the later massive granites are usually fracture-bound bodies. No detailed petrological examinations of granitoids have yet been done. Further generations are likely to exist, with associated pegmatites and aplites.

The youngest magmatism in Sidamo is manifest in flood basalts spread over the peneplaned Upper Tertiary surface. They are associated with Tertiary and Quaternary rift valley volcanism.

Geology of the Adola area

The Upper Complex in the wider Adola area is confined to two parallel meridionally aligned zones, the Western or Adola Belt, and the Eastern or Kenticha Belt. They are separated by gneisses of the Lower Complex, and unconformably overlie older rocks in complicated structural relationship. A simplified geological map of the area is shown in Figure 2.

Lithology

The rocks of the Lower (Archean) Complex consist of various gneisses and migmatites, the prevailing rock type being biotite-amphibole gneiss. Feldspathic sandstones, locally granitized and with schistose interbeds, are the essential rock type of the Middle Complex Zembaba Group. The latter are preserved in open synclines and both are overlain by the Adola Group (V. Kazmin and A. J. Warden, 1975).

Adola Group. The Adola Group assemblage consists of an original alternation of magmatic extrusive rocks and shallow-water sediments. The mafic-ultramafic extrusives were metamorphosed to amphibolites, talc rocks, schistose amphibole rocks and serpentinites. They form an ophiolitic suite, the bulk of which is confined to the lower part of the assemblage. The members of the suite form layered sheet-like bodies from one to several hundred meters wide.

The amphibolites are texturally fine- to coarse-grained rocks, massive or foliated. They are composed mainly of actinolite-hornblende and some pyroxene as well with variable amounts of plagioclase apparently of sodic variety, usually micaceous, quartz being very subordinate or absent. They display all gradations from amphibolitized rocks to amphibolites.

The massive amphibolites were derived from subaqueous basaltic flows, with relict pillow structures still discernible in places (A. M. Chater, 1971).

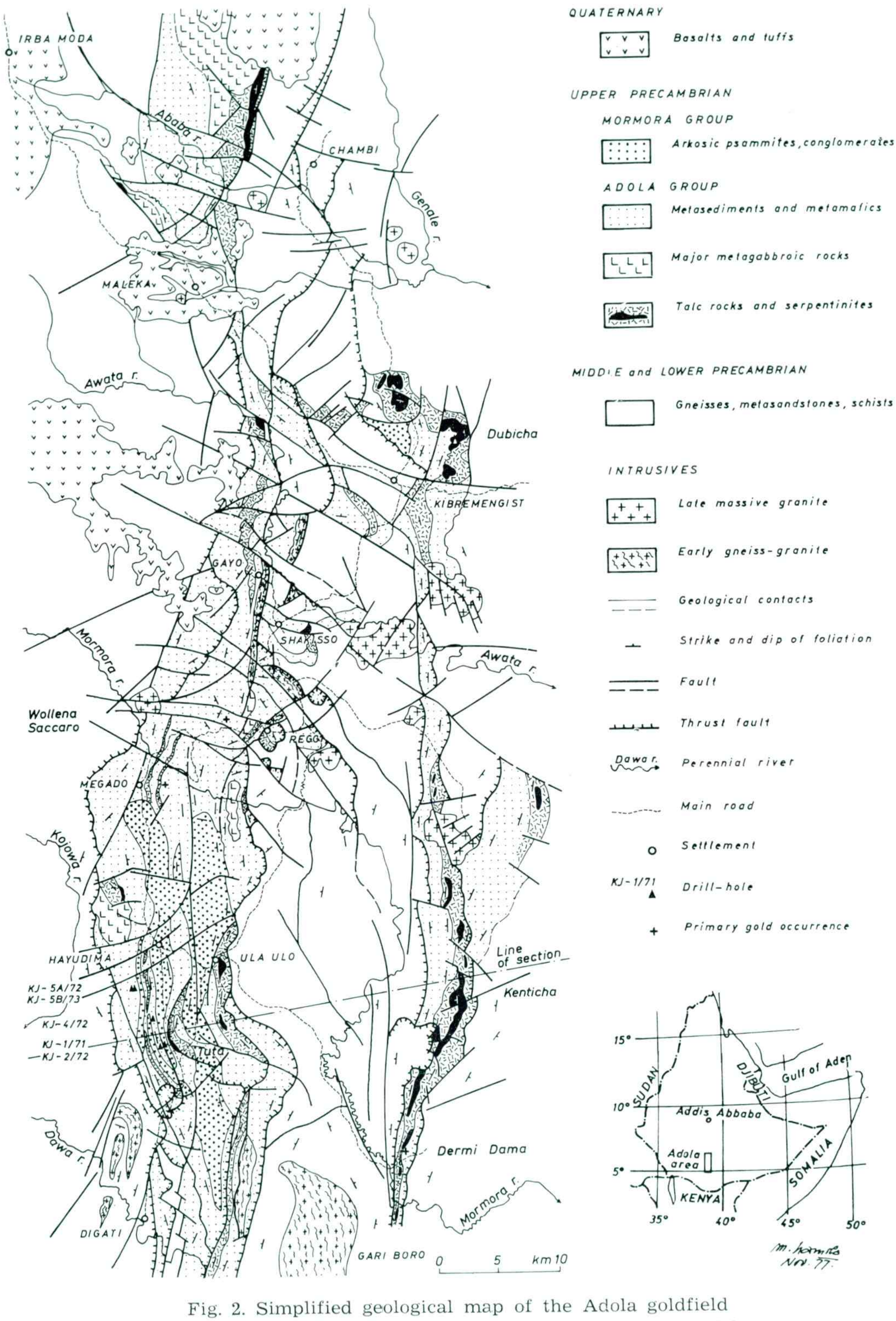


Fig. 2. Simplified geological map of the Adola goldfield

Sl. 2. Poenostavljena geološka karta nahajališča zlata Adola

Where in contact with the sediments, baking can be observed (S. Morete, 1972). On the other hand, the foliated or schistose amphibolites are intimately interbedded with sedimentary rocks, indicating a possible derivation from original calcareous mudstones or tuffaceous products. The presence of calcareous para-amphibolites in the younger Kajemiti beds, derived from arenaceous sediments, supports this assumption.

Talc rocks are on the surface foliated, flaky and fibrous, consisting of talc with minor amounts of other hydrous silicates such as chlorite and amphiboles. In depth, drilling revealed massive greenish grey soapstone, or rather a crystalline talc-dolomite layered rock, at the margins foliated and grading into chlorite-biotite schist, and in the central part looking serpentinitic with markedly increased nickel and arsenic contents. Dolomite occurs in crystals, and there is possible siderite in small veinlets as well (S. Morete, 1973). Disseminated chromite is omnipresent and magnetite can be seen in places.

Serpentinites occur as separate lenslike, tabular bodies, arranged as a rule in meridional lineaments along the margins of both belts, and grading laterally and vertically into talc rocks. There are more than 30 such bodies, easily recognisable since they are remarkably devoid of vegetation. The massive green-grey rocks consist of the serpentine minerals lizardite and antigorite (K. Ogasawara, 1965; D. Jelenc, 1966). Relics of original olivine and pyroxene can be recognized in less altered rocks (C. F. Gilboy, 1970). Patches and veinlets of asbestos are frequent. Opaque matter consists of magnetite and chromite. Magnetite occurs as crystal impregnations and minute amorphous veinlets (D. Jelenc, 1966). Chromite is generally disseminated, but occurs also as minor lens-like segregations. Scattered boulders of massive chromite originated from such concentrations.

The origin and control of serpentinites has been controversial. Drilling revealed that they originated from ultramafic rocks forming part of the layered assemblage of various metamorphosed extrusives, constituting the ophiolite suite. Their composition is discussed in a later section of this paper.

The metasediments are represented by pelitic-psammitic varieties such as phyllites, shales, chlorite schists, sericite and mica schists and quartzites, derived from original shallow-water sediments, frequently dark and graphitic. Closely alternating and grading into each other, these rocks are intercalated with extrusives. The thickness of individual beds is variable from a few metres to several hundreds of metres, the thickest beds being in the upper part of the sequence. Quartz-sericite schists may have been derived from tuffaceous volcanoclastic rocks, and phyllitic chlorite schists possibly from argillaceous muds. Quartzites are micaceous, compact or foliated fine-grained rocks. When weathered they are loose and friable. Gradations to phyllitic schists are common. The presence of graphitic matter is a characteristic feature. Its amount is variable, the colour consequently varying from white to dark grey. As a rule, graphitic quartzites and phyllitic shales are interbedded.

Quartzites appear frequently silicified and recrystallized, exhibiting saccharoidal texture. They contain sulfides as disseminated grains and stringers. Such rocks, when weathered, appear dark and ferruginous. According to S. Morete (1972) all quartzites are saccharoidal and contain varying amounts of ferruginous admixtures. At places he observed hard reddish brown jaspero-

Table 1

General tentative lithostratigraphic sequence of the Adola area in southern Ethiopia

Tabela 1

Poskusni prikaz litostratigrafskega zaporedja na območju Adole v južni Etiopiji

	Marmora Group	Kajemiti Beds	Arkosic psammites with basal and intraformational conglomerates; phyllitic chlorite schists
	Unconformity		
UPPER COMPLEX	Adola Group		Quartzites, often graphitic and ferruginous, with intercalations of schists and para-amphibolites
			Amphibolites, massive and foliated; talc schists with metasedimentary intercalations
			Chlorite schists, slates, mica schists, phyllites, frequently graphitic, with quartzitic and amphibolitic interbeds
		Ophiolitic suite	Amphibolites; tremolite-actinolite-talc-chlorite schists, with pelitic-psammitic interbeds
			Talc rocks, massive and foliated, talc-chlorite schists; serpentinites and less altered ultramafics
			Phyllites and quartz-mica-chlorite-amphibole schists
			Massive gabbroic-amphibolitic rocks, foliated hornblende rocks
	Unconformity		
MIDDLE COMPLEX	Zembaba (Wadera) Group		According to G. Kochemasov (1971):
			Gneissose feldspathic mica-quartz-amphibole psammites with kyanite at places; locally granitized, with schistose interbeds
	Unconformity		
LOWER COMPLEX	Archean		According to C.F. Gilboy (1970):
			Biotite gneiss and biotite-hornblende gneiss
			Quartzo-feldspathic gneiss
			Banded biotite-muscovite gneiss
			Plagioclase-amphibole gneisses and migmatites

idal quartzites with common magnetite crystalloblasts and felted black tourmaline crystals.

Mormora Group. The younger metasedimentary rocks overlie the Adola Group with marked depositional unconformity. They are mainly represented by arkosic psammitic metasediments with intercalations of polymict conglomerates, which are localy designated the Kajemiti Beds. This unit is extensive south of the Mormora river but has not yet been recognized further to the north. Graphitic phyllites along the western margin of the Kenticha Belt have been mapped (on Sheet NB 37-11, Negele) as belonging to the Mormora Group, and micaceous-chloritic schists in the Kibremengist area may be a facies variation of the Kajemiti Beds. However, these relationships are far from certain. The indicated southerly provenance of the Kajemiti psammites would nevertheless support the assumption of a facies change (S. Morete, 1973).

The arkosic psammites of the Kajemiti Beds have been derived from feldspathic arenites. Their thickness appear to be in the order of several hundreds of metres. The foliation and bedding are well expressed and cross-bedding is well preserved. The rocks are prevailingly fine- to medium-grained, always calcareous, with biotite as the main mafic mineral. With increasing hornblende the rock grades to amphibolitic arkose and even to amphibolite, similar to amphibolites in the Adola Group. These rocks have been derived from sedimentary calcareous products. According to N. Hinza (1971) the para-amphibolites comprise 30 to 40 per cent quartz and the same amount of amphibole, about 10 per cent biotite, 6 to 15 per cent calcite and 2 to 12 per cent of opaques, mainly pyrrhotite. Feldspar amounts 10 to 25 per cent; it is altered albite, apparently detrital and derived from siliceous igneous rocks.

Conglomerates prevail at the base and appear also as intraformational lenses. The composition of the pebbles and large boulders is that of pre-Adola rocks: granite-gneisses, quartzites, amphibolites and quartz. They indicate a break in sedimentation, probably reflecting the terminal stage of geosynclinal deposition.

The rocks of the Upper Complex exhibit generally low-grade metamorphism of greenschist facies. In places, minerals such as garnet, kyanite and staurolite point to a higher-grade metamorphism of amphibolite facies.

A general tentative lithostratigraphic sequence for the Adola area is shown in Table 1. Details are obscure due to poor exposure, structural deformation and original depositional facies variations.

Igneous activity in the area is manifest by granitoid plutonic rocks which may be divided, on field evidence only, into two types. The early granites of syntectonic or rather pretectonic origin are medium-grained, leucocratic, strongly foliated granit-gneisses. They appear in antiform cores at Gari Boro and northwest of Digati, surrounded by and grading into gneisses. They occur also within the Adola Group rocks outcropping along prominent fractures, and were dislocated together with the Group.

The later type is represented by non-foliated pink or grey biotite granites, many of them porphyritic, showing sharp contacts with older rocks and appearing in more or less round bodies. The intrusions took place seemingly along zones of weakness marked by faults and high-angle thrusts, probably also as small diapiric plutons. They form mainly areas of high rugged relief but also small roughly circular areas without relief (e.g. Chambi area). There were probably more phases of igneous activity resulting in several generations of late granites.

Several larger masses of amphibolitic gabbroic rocks, and reportedly also dioritic rocks, occur in the marginal parts of the Adola Belt (A. M. Chater, 1970; V. Kazmin-A. J. Warden, 1975). An intrusive origin attributed to them is questionable though not impossible. They appear closely associated with the extrusive assemblage, pointing rather to a common origin. If intrusive at all, they should be coeval with tectonism but not comagmatic with granites.

Pegmatites and aplites are common in pre-Adola rocks and seem to be associated with granitoids. Simple pegmatites contain albite, micas and abundant haematite and magnetite, occasionally amazonite, beryl and minor iron and copper sulfides. Albitized amazonite pegmatites seem to be associated with young granites, whereas pegmatized granite dykes and aplites are associated with the early granites (G. Kochemasov, 1971).

Quartz veins intersect all kinds of rocks from gneisses to metaconglomerates. Swarms of veinlets are common in fractured and sheared rocks. Whether or not they are more frequent in certain rock types is uncertain. The veins rarely exceed several tens of metres in length and more than one metre in width, their orientation and dip being variable, not infrequently following the foliation. Vein quartz may contain sulfides or other minerals or be completely barren, as elaborated later.

Quartz forms the bulk of the alluvial gold-bearing gravel. Float of saccharoidal quartz is ubiquitous, forming persistent layers within soil residuum.

The remnants of late Quaternary flood basalts cap higher ground of the goldfield. The rocks are olivine basalts prevailingly with occasional tuffs. Their very young age is proved by the fact that no volcanic material is found in the placer gravels.

Structure

A number of dislocations displace and intersect the two meridionally aligned belts of the Adola rocks, including the basement. The contacts with older rocks are structural and dip generally west. The deformations resulted from generally east-west directed stress.

The western boundary of the Adola belt is a thrust fault, probably quite complicated in places. The eastern margin is another complicated overthrust fault, involving early granites in narrow strips. This prominent fracture zone was first recognized by C. F. Gilboy (1970) and A. M. Chater (1971) in the Gari Boro area as the Ujima discontinuity. It can be followed northwards to the Ganale river and beyond. The complicated fault line could mark a plane of décollement along which granites have been mechanically introduced, with phyllitic-chloritic shales as the slide surface.

The Adola belt seems to be internally tightly isoclinally folded, the beds possibly overturned and overthrust, the foliation dipping steeply east and west accordingly. Steeply plunging isoclinal folding was revealed in the Kajemiti-Tula area, the serpentinites there outcropping along an easterly dipping thrust fault of more local nature. The Kajemiti Beds were tightly folded and dislocated together with the older rocks.

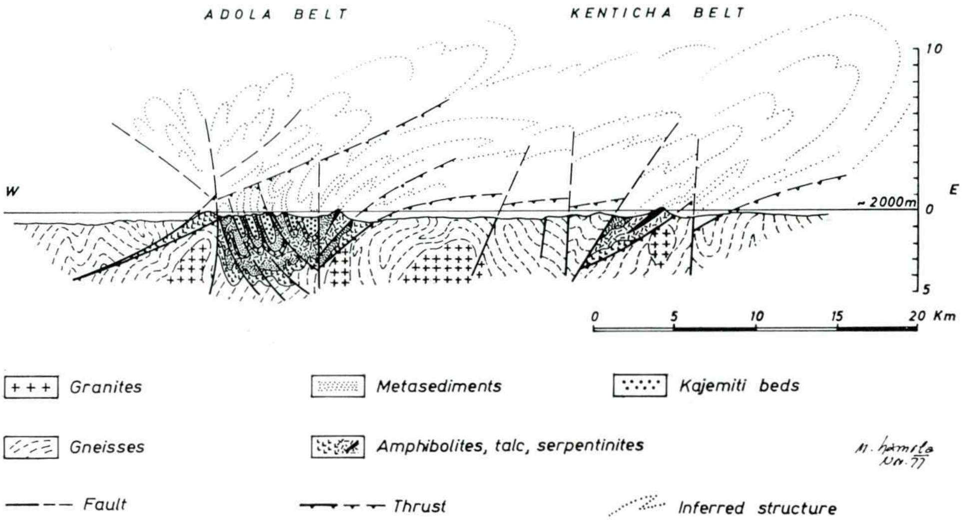


Fig. 3. Idealized geological section Tula-Kenticha
Sl. 3. Idealiziran geološki profil Tula-Kenticha

The eastern or Kenticha belt, with its lower portion of the Adola suite of rocks preserved only, shows similar contact relations. Strong shearing faulting and overthrusting has been noted by V. Kazmin (1976) who recognized three or more tectonic scales overthrust upon each other in an easterly direction. The northern part of the belt around Kibremengist is structurally as well as lithologically problematic, since contact relations here are quite obscure. The eastern belt can be interpreted as the remnant of a large eastward overturned fold, subsequently overthrust under continuous tangential pressure, and in turn disintegrated by deep faulting. An idealized structural interpretation is shown in Figure 3.

Strong strike-slip or tear faulting is evident. A number of tear faults, running at oblique angles to the east-west direction of the stress, are believed to be of an early origin; the deep nature of some of them has been revealed by aerial magnetometry (Geoterex, 1970). Longitudinal faults and related features such as bedding slipages and shearing are apparently obscured by folded structure and well hidden in the forest- and soil-covered terrain.

Some of the oblique dislocations are probably younger and apparently associated with the Tertiary and Quaternary rift tectonics, predating basaltic volcanism.

Origin

The Adola assemblage with interbedded ophiolites and metasediments reflects deposition in a marine environment. The remnants of the Upper Precambrian rocks are scattered from Agere Maryam to Negele in a zone about 150 kilometres wide at present, roughly indicating the extent of the Eastern Upper Precambrian Zone (V. Kazmin, 1976). The assemblage is comparable to volcanic »greenschists« and »greenstones« which, in various parts of the world, constitute the geological environment of a number of important gold deposits.

The idea of plate tectonics seems best suited as the causative mechanism to explain the complexities of the Adola area. It is generally accepted today that a plate tectonic model of the present type might be reasonably applicable to problems of pre-Mesozoic time, and some even view it as the key to understanding Precambrian geology. Concerning mineral genesis, theories have been advanced linking the formation and control of ore deposits with plate tectonic regimes. Specifically, gold mineralizations worldwide seem to be linked with the processes operative at convergent plate boundaries (F. J. Sawkins, 1972).

Structural interpretation of the Ethiopian Precambrian in terms of plate tectonics was attempted by V. Kazmin (1976). In this context the Adola ophiolites emerge as a continental geosuture of ancient cratonic blocks, marking the presence of a fossil subduction zone. The Adola Group assemblage would, then, have originated as oceanic crust in an ancient marine basin formed by crustal spreading, its extrusives derived from underlying mantle. By convergence of the land masses, with the oceanic crust caught between them, a »mountain range« formed. The collision culminated in intense folding deformation, and the impact produced overthrusting of fan-like folds in an easterly direction. Since thrusting towards the consumed plate is typical in collision-type mountain building (A. Hallam, 1973), the presumed fossil subduction zone might have been inclined to the west.

At the destructive margins magmatism was generated via subduction, consumption and anatexis of the oceanic lithosphere. As in present-day tectonic setting, the primary sites of granitic plutonism must have overlain the subduction zones. Consequently the generation of early granitoids could have predated the orogeny or at least its paroxysm. It is conceivable that the anatectic destruction of oceanic crust and dynamic stress accounted for formation and mobilization of the agents involved in metasomatism, mineralization and magmatic phenomena.

Since the descending plate, near the continental margin, was tensionally severed and fractured, mafic magma from the mantle could have been tapped by deep faulting and introduced into the oceanic crust where, in turn, it was subjected to changes. An alternative intrusive origin for some massive gabbroid rocks within the ophiolite suite could be explained in this way.

The onset of tectonic deformation was probably gradual, resulting in a temporary emergence and erosion of the oceanic crust. The discordant Kajemiti Beds, with psephites at their base, do indicate such a break; the arkosic arenites apparently derived from early formed volcanic or more probably plutonic bodies.

Erosion has been operative since Precambrian times, with short periods of subsidence in the Mesozoic (Jurassic) and the Tertiary only. The extremely long periods of peneplanation must have reduced the Precambrian folded belt to a bare remnant of the original mass. What has remained are virtually the roots of the original mountain range.

Horst-graben uplift movements associated with late rift faulting started an erosion cycle to which the formation of the gold-bearing placers in Adola area is apparently linked (M. Hamrla, 1971).

Timing of events

The ages of units and events can be deduced from a limited number of radiometric measurements and regional studies. Accordingly, V. Kazmin (1975, 1976) thought that the Adola Group possibly should be positioned at the very base of the Upper Precambrian, somewhere between 1400 and 1600 Myr, and the orogenetic activity terminating the Red Sea geosynclinal development, at approximately 700 to 750 Myr or even earlier.

Age determinations on foliated gneissose granites gave values between 480 and 680 Myr (6 analyses), and those for massive granites 495 and 515 Myr (2 analyses) (cf. V. Kazmin, 1975). The chronometric data do not give true ages since they reflect the 550 ± 100 Myr thermal imprinting of the »Pan-African tectono-structural phase« (C. R. Neary et al., 1976), corresponding to the Mozambiquan orogeny in East Africa (A. S. Rogers et al., 1965). In addition, for slow cooling plutons, the K/Ar values might be too low. However, the highest age 680 Myr for a composite sample of the early gneissose granite was obtained by the Rb/Sr method (C. F. Gilboy, 1970).

Considering the K/Ar ages around 1400 Myr (2 analyses) for granitic rocks cutting through the Upper Precambrian of western Welega (Metal Mining Agency of J., 1974), and ages 600 to 700 Myr for granitoid rocks near Asmara in Eritrea (cf. V. Kazmin, 1975), as well as the values around 700 Myr for granitic rocks of northeastern Sudan (C. R. Neary et al., 1976), it is evident that an exact dating of the early granites is impossible at this stage.

It could be envisaged, then, that the development of the Upper Precambrian oceanic basin possibly predated the 1000 Myr time limit. The closing of the basin and the orogeny may have roughly encompassed the time-span 1000 to 800 Myr since this was the period of major worldwide orogenetic events (M. H. P. Bott, 1971). The early granitic intrusions would, then, be coeval with or predate the orogeny.

Younger plutonism would, accordingly, encompass the period 800 to 500 Myr. The intrusions seem to have been controlled by the early tectonic, and there is a compositional similarity with the early granites. These factors, supported by the highest as yet obtained K/Ar age 794 ± 100 Myr for a »younger« granite in western Welega (Metal Mining Agency of J., 1974), rather point to early plutonic events, probably corresponding to the waning stages of orogenic silicic magmatism.

That this is not necessarily so is indicated by a 286 Myr age for a pegmatite dyke related to the late granites in the Chambi area (G. Kochemasov, 1971). Minor intrusive episodes could have taken place also later, provided the above datum is correct. Similarly, in northwestern Sudan (C. R. Neary et al., 1976) some granites occur as small, nearly circular masses, and with ages of 500 Myr and 100 Myr represent the younger plutonic episodes.

Field and geochemical evidence of mineralization

Regarding the origin of primary gold in Adola, D. Jelenc (1966) speculated on syngenetic gold occurring in amphibolites and chlorite schists, the UN — Ethiopia Mineral Survey (1971) advocated the detrital origin of gold in conglomerates of the Kajemiti Beds, and M. Hamrla (1971) (cf. S. Morete, 1973) favoured a hydrothermal origin of the auriferous deposits.

The idea of a detrital origin of gold from the Kajemiti Beds is a remote possibility due to the fact that gold-bearing placers are totally unrelated to the areal extent of the Kajemiti Beds. The evidence available at present, direct and indirect, though still scarce, supports the hydrothermal hypothesis.

Regional reconnaissance geochemical drainage survey undertaken by the UN — Ethiopia Mineral Survey (1971) showed the background values of copper, nickel, zinc and arsenic to be appreciably higher in the Adola area than in the Sidamo region as a whole. Very limited soil sampling produced weak local base metal anomalies, which were not followed up.

Tula-Kajemiti—Demi Denissa area

An attempt to explore for primary gold started in 1971 in the Tula-Kajemiti-Demi Denissa area, covering nearly 15 square kilometres. Rich placers occur in this area which is built of meridionally aligned strips of different rocks of the Adola suite. Panning of the surface layer for detrital gold, soil geochemistry, excavating and deep drilling were involved. About 1400 soil samples and 330 drill-core samples were assayed for Cr, Ni, Co, Cu, Zn, Pb, Ag and As. Five inclined drill-holes totalling 559 metres were drilled, a large number of pits and some trenches were excavated and sampled, and the terrain was mapped in detail (S. Morete, 1973). The exploration started on the working hypothesis that gold was associated with base metal sulfides. Although the project was halted before completion, valuable data were gathered.

Soil sampling revealed the lithological control of the metal values. Copper conforms with the quartzitic beds, the highest values being in the ferruginous silicified quartzites, and nickel, chromium and arsenic with the amphibolite and talc layers.

Detrital gold in scree and soil could have originated from ferruginous quartzites as well. Its provenance was not proved because the gold occurrences were too scattered and too few.

Lithological and geochemical characteristics have been established on drill-cores. The drill-hole KJ-4/72 is shown in Figure 4, and the drill-holes KJ-5 A/72 and KJ-5 B/73 in Figure 5.

Amphibolites contain disseminated sulfides such as pyrite, pyrrhotite and chalcopyrite. Though common they are not abundant. Similar sulfide disseminations in amphibolites have been reported from elsewhere.

Graphitic quartzites encountered in drill-holes contain pyrite in disseminated grains and stringers following the foliation. Pyritized joints, small fractures and fault breccias are common. Veinlets of calcite were revealed as well.

Rare, small scattered pyrite crystalloblasts occur in talc rocks, together with chromite and magnetite. Some fractures were seen to be pyritized, and a small veinlet near the contact with quartzite contained pyrrhotite, chalcopyrite and

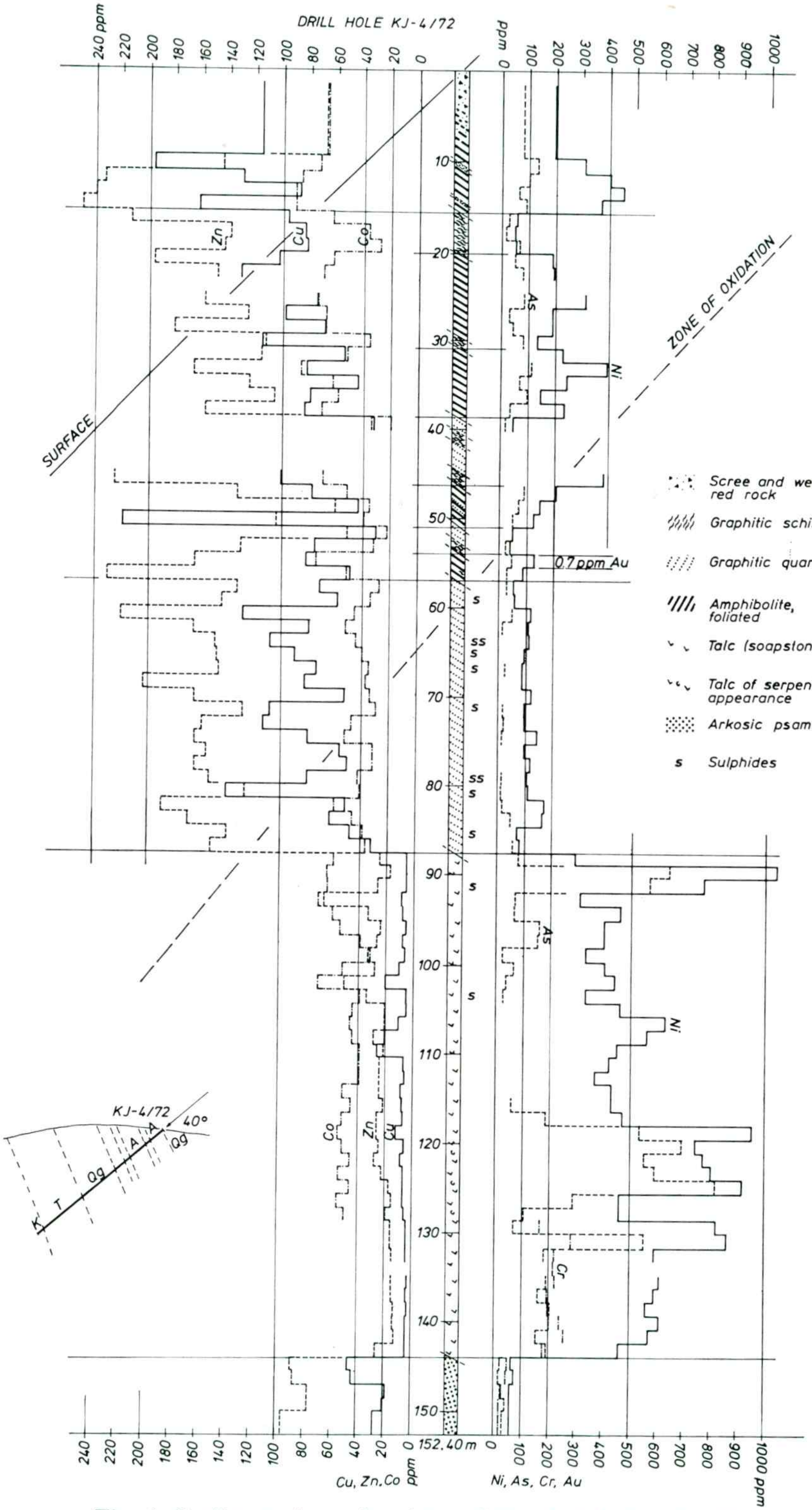


Fig. 4. Section and geochemistry of the drill-hole KJ-4/72
Sl. 4. Profil in geokemija vrtine KJ-4/72

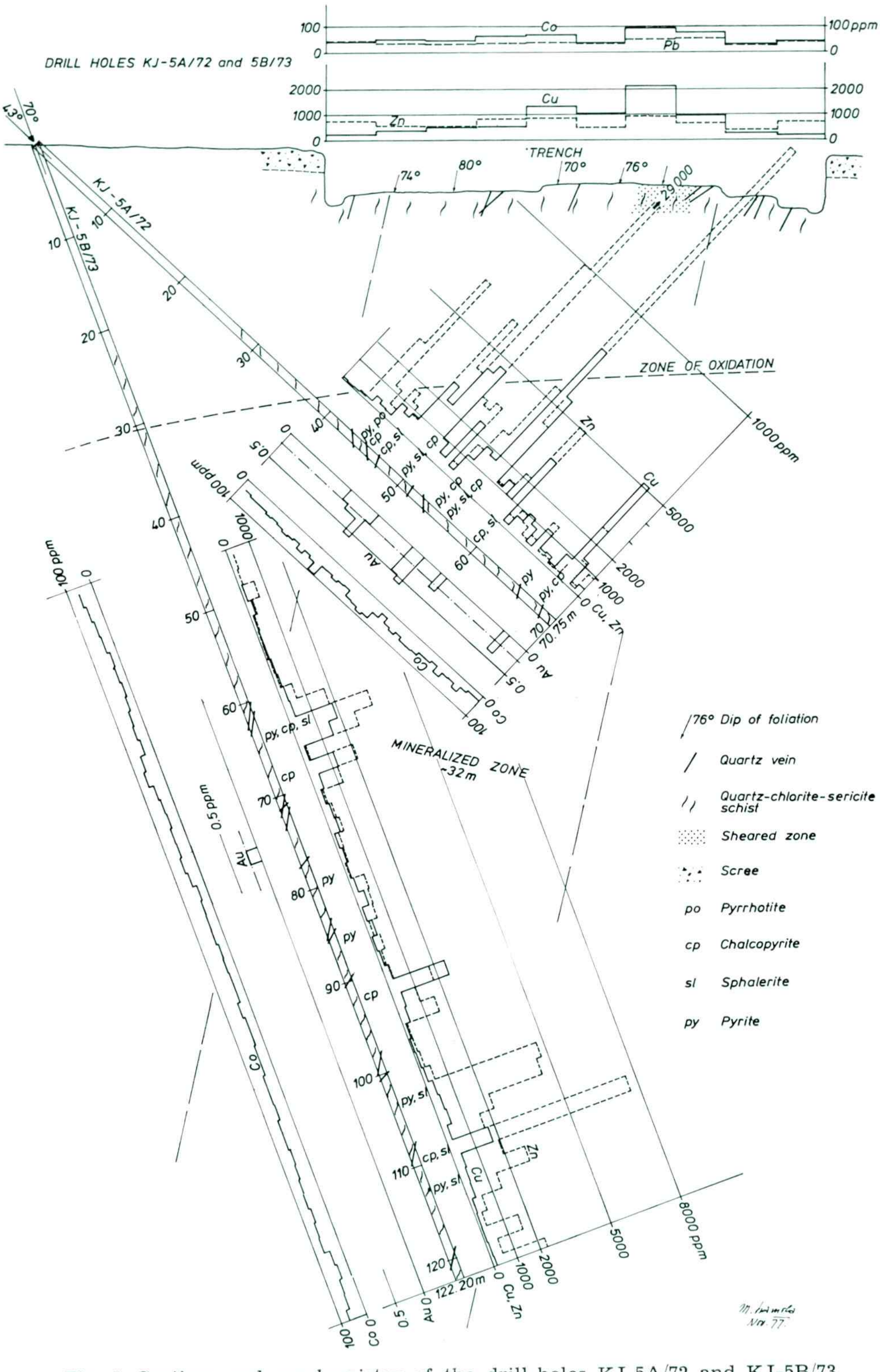


Fig. 5. Sections and geochemistry of the drill-holes KJ-5A/72 and KJ-5B/73

Sl. 5. Profila in geokemija vrtin KJ-5A/72 in KJ-5B/73

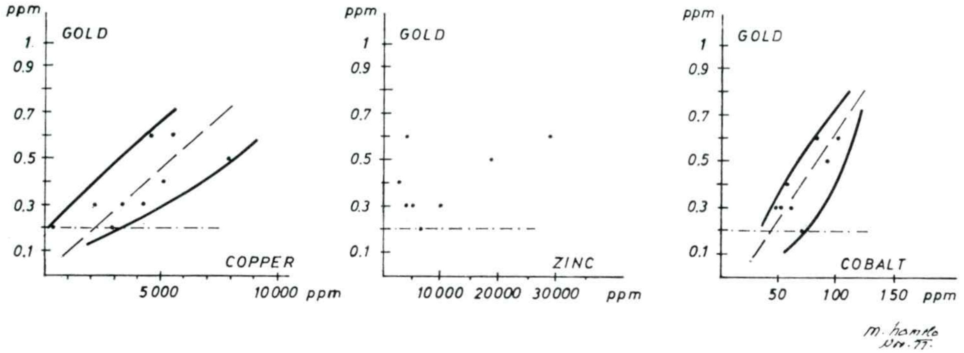


Fig. 6. Graphs of gold versus copper, zinc and cobalt (drill-holes KJ-5A/72 and KJ-5B/73)

Sl. 6. Razmerje zlata proti bakru, cinku in kobaltu (vrtini KJ-5A/72 in KJ-5B/73

arsenopyrite (?) (S. Morete, 1973), the minerals apparently introduced epigenetically.

Arkosic psammites are variable in grain size, the primary sedimentary features being well discernible. Finely dispersed pyrrhotite is ubiquitous, its amount ranging from 1 to 8 per cent (N. Hinza, 1971).

Of several weak though well expressed Cu-Zn anomalies in the Demi Denissa area, the most conspicuous features about 700 metres in lenght and 150 metres in width, assaying up to 510 ppm copper and above 200 ppm zinc. The faulted area is built of phyllitic sericite-chlorite schists occasionally with quartz, biotite and amphibole. This rock unit extends southwards in a long belt beyond the Dawa river. Trenching and drilling revealed a sheared zone mineralized with chalcopyrite, sphalerite, pyrrhotite and pyrite, about 30 metres wide and dipping 75^0 west. Sulfides occur disseminated and in small veinlets following the foliation. Quartz, garnet, tourmaline and amphibole are associated. Limonite, tenorite and malachite appear in the oxidized zone, reaching to 30 metres below the surface.

In drill-hole KJ-5A/72 gold was detected in samples assaying higher than about 2800 ppm copper (at the detection limit of 0.2 ppm). In drill-hole KJ-5 B/73, which intersected the mineralized zone about 50 metres deeper, gold was detected in one core sample only, assaying 0.2 ppm and 310 ppm copper. Although gold was proved in 10 samples only, its positive correlation with copper is evident, possibly with cobalt as well, but none with zinc (Figure 6). This is the first direct proof of the positive relationship of gold with copper. The metal assay values in both drill-holes are shown in Figure 5. Gold might be preferentially linked with chalcopyrite. Silver, unfortunately has not been determined; it might parallel the gold.

The distribution of nine elements in the drilled rock units is shown in Figure 7, as the average values from the available assay data. The available corresponding data for serpentinites and vein quartz are shown as well. The number of samples and their representativeness are variable, and the backgrounds are not known; the values therefore indicate orders of magnitude of relative significance only.

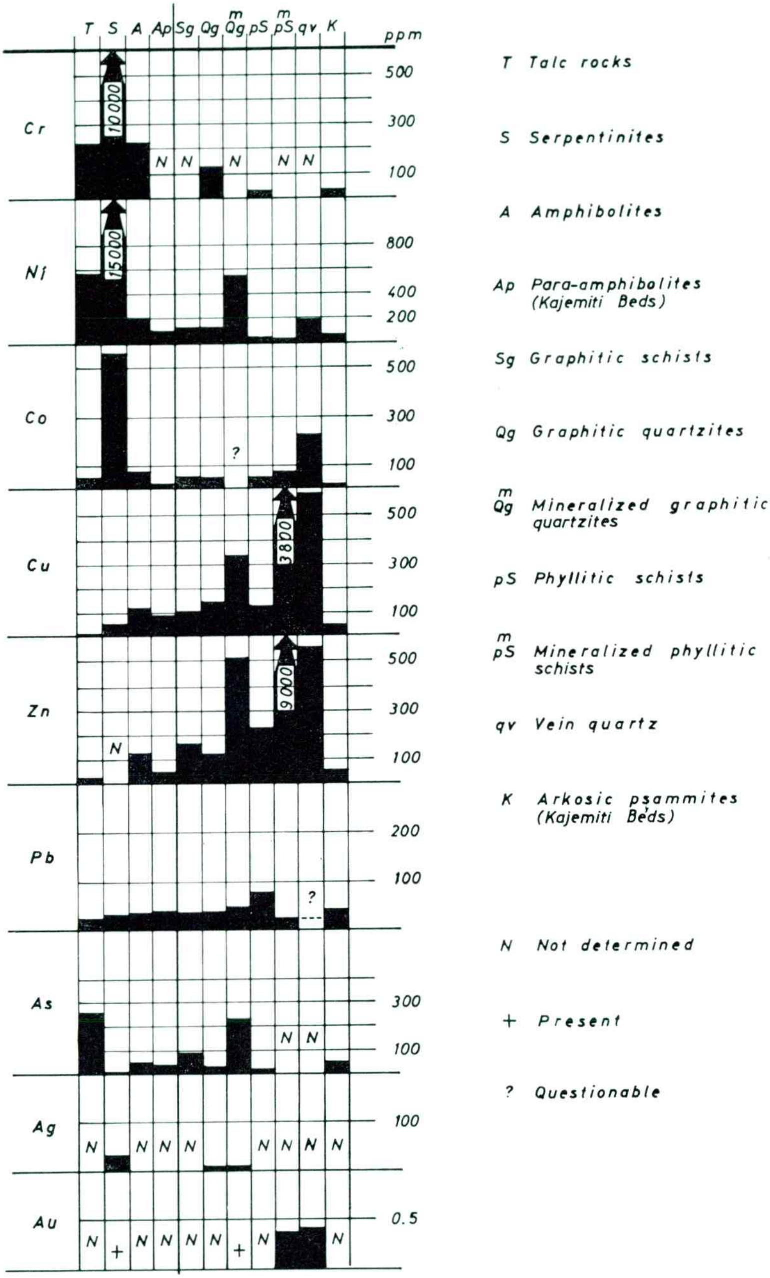


Fig. 7. Distribution of some elements (as rough average values) in different Upper Precambrian rocks

Sl. 7. Porazdelitev nekaterih elementov (kot grobe povprečne vrednosti) v raznih kameninah zgornjega predkambrija

Wollena Saccaro-Megado area

At Wollena Saccaro near Reggi village, specks of native gold were found in situ in an outcrop of dense pinkish white quartzitic rock. There are few outcrops in this poorly exposed area. Greenish schists can be seen in pits, and float of graphitic phyllites and quartzites on the sloping ground. Massive amphibolites occupy hilltops nearby.

The quartzitic rock is foliated, the parting planes marked by graphite and dispersed mica. Unclear dips of about 70° northwest are conformable with the general submeridional trend in this area. Numerous box-works after original sulfides occur in the rocks, commonly filled with ochre. The shapes are square, the size rarely above 10 millimetres but averaging much less. Sulfides have been completely oxidized and gold has been freed in the process, leaving visible specks in the cavities. Limonitic stainings and incrustations are common, but there is no evidence of copper.

The banded quartzitic rock was evidently silicified and metamorphosed under stress. The graphitic admixture supports the conclusion that the rock originated as an arenaceous sediment. The mineralization is apparently premetamorphic.

Gold in colluvial placers which formed on the slopes, is prevailingly coarse and dendritic, probably due to supergene hydrothermal aggregation.

Similar yellowish saccharoidal quartz, occurring as float on thickly soil-covered forested ground about 1.5 kilometres east of Megado, when ground and washed, yielded fine gold. The weathered and friable rock is quite similar to that from Wollena Saccaro. Quartzitic and schistose beds supposedly build this part of the goldfield which excels in rich placers.

Dermi Dama area

In the southern part of the Kenticha Belt, at the locality called Dermi Dama, gold occurs richly dispersed in quartz slope talus. The valley alluvium nearby proved exceptionally rich too. No gold was detected in this area before 1975.

A narrow belt of Adola rocks occupies a meridionally trending ridge, consisting of deep green tremolite-actinolite-chlorite schists and foliated talc rocks dipping generally 55° west, with serpentinites included as discontinuous elongate bodies. A weathered grayish quartzo-feldspathic rock, probably an original arkosic arenite or an altered felsic flow, was exposed in pits. It is intimately interspersed with swarms of yellowish quartz veinlets.

The vitreous quartz is stained with ochreous limonitic matter, revealing the presence of sulfides. Associated gold was freed by weathering. It is uncertain whether the mineralization is controlled structurally or lithologically. Detrital gold is coarse-grained.

Quartz veins, skarns, pegmatites

Quartz veins in the Gayo area appear in schists and along the contacts with gneiss-granite (V. Kazmin, 1970). P. Antolini (1958) reported 26 grams per ton gold from a quartz vein in this area. Pyrite and chalcopyrite may be associated.

Drilling in the Tula-Kajemiti area revealed a number of quartz veins. Usually less than 5 centimetres thick they follow a system of joints with submeridional tendencies, the dips being very variable. Vitreous bluish quartz contains some mica, occasional rutile and irregularly shaped grains of pyrite up to 6 millimetres in size. Sulfide also fills very fine cracks in quartz. Gold could not be detected in analyzed core samples. Sulfide was isolated and tested for nickel, cobalt and arsenic but unfortunately not for gold. It proved to be iron pyrite.

Black tourmaline is quite common in quartz pebbles of alluvial placers, the provenance of which is believed to be quartz veins. Gold dispersions have been occasionally seen in quartz pebbles.

Quartz veins in the Chambi area carry pyrite, tourmaline, rutile, occasionally molybdenite, apatite and iron oxides, ilmenite and chalcopyrite (G. Kochemasov, 1971). One such sample with box-works after sulfides assayed:

Cu	580 ppm	W	10 000 ppm	Au	0.4 ppm
Zn	555	Sn	200	Ag	1.3
Co	215	Bi	500		
Mo	100	Ni	184		

Another quartz-tourmaline vein with pyrite, rutile and apatite assayed:

Mo	20—100 ppm
Sn	20—100
Bi	20—500
Be	10—100

In the same area Biazen Bogale (1974) reported quartz veins with malachite and sulfides occuring in amphibolites. Several chip samples assayed up to 3400 ppm copper but only 30 to 50 ppm zinc and 20 ppm lead. Tourmalinized sulfide quartz breccias were reported to exist as well.

Skarn-type quartz-epidote rocks occur in the area too, with amphibole and carbonates, apatite, tourmaline, molybdenite and sulfides in places. Spectrographic analysis of a sample of such rock yielded, according to G. Kochemasov (1971):

Bi	500 ppm
Be	20
Mo	20
Ag	20

Elements present: As, Pb, V and B

Pegmatitic dykes in the Chambi area carry, according to G. Kochemasov (1971), albitized amazonite, micas, garnet, cassiterite, beryl, iron- and copper sulfides. Tourmaline occurs in quartz veins cutting the dykes but not in pegmatite itself. Certain pegmatites show high values of lead in potassium feldspars, assaying 134 to 536 ppm.

The mineralization in the Chambi area seems to be associated with granites; vein quartz and auriferous sulfides are known to appear in such environment, and gold may appear as exsolutions. However, ore microscopic examinations (on Leitz Panphot) of pyrite from quartz veins did not reveal any gold even at highest magnifications.

The UN-Ethiopia Mineral Survey (1971) reported that gold flakes had been observed in float of limonitic quartz breccia, but the locality was not given.

Awata sulfide belt

Heavy pyritization in argillitic-quartzitic graphitic beds was reported by the UN-Ethiopia Mineral Survey (1971) near the Awata river south of Kibremengist. The ferruginous rocks are limonitized and show infrequent quartz laminations. The sulfidation was considered a "fahlband" and the possibility of it being auriferous prompted a magnetometer and geochemical soil survey. Low base metal values were obtained, but a fairly continuous trend of higher than average copper and zinc values was indicated for a 4-kilometre zone of heavily pyritized rocks (G. Kent, 1970).

Whether or not any gold is associated with the sulfides has not been established. The fact that minor alluvial gold was detected in the lower reaches of the Teppa placer south of Kibremengist (Biazen Bogale, 1974) would make its provenance from pyritized beds probable.

Serpentinites

The Adola serpentinites have been described by many authors since they represent potential nickel ore deposits (D. Jelenc, 1966; Y. K. Bentor, 1963, 1967; K. Ogasawara, 1965; Z. C. Vlaicu and A. W. Ruffael, 1967; D. Levitte and G. Kent, 1968; S. C. Artena, 1974). Nickel green occurs in the residue of serpentinites as coating and veinlets, the ore grading 1 to 3 per cent nickel, 0.02 to 0.05 per cent cobalt and 0.5 to 1.6 per cent chromium. The nickel mineral is a member of the pimelite series belonging to garnierite group (Y. K. Bentor, 1967; D. Jelenc, 1966).

A drill-hole 289 metres deep was sunk in 1966 at Big Dubicha serpentinite body and another one 79,6 metres deep in 1963 at the Tula body. No reliable logs were produced. »Peridotite« reportedly occurs in the first hole below 143 metres, and disseminated chalcopyrite, calcite veins, garnierite and azurite (?) were seen on the whole lenght of the core. »Fresh rock« was encountered in depth in the shorter drill-hole.

The drilling proved that serpentinites are layered bodies interbedded with metasediments and other mafic types, with portions of original rock unserpentinized. Serpentinization seems to be most complete toward the upper parts of the bodies, which prompted the view that it took place in situ due to weathering (D. Levitte and G. Kent, 1968). K. Ogasawara (1965) determined a specimen from the Tula body to be chromite-bearing peridotite. Whatever the original rock, chromiferous, nickeliferous ferromagnesian silicates were its essential components.

According to K. Rankama und Th. G. Sahama (1950), the average primary content of some elements in ultrabasic rocks is in the following ranges:

Ni	0.08 to 0.3 per cent
Co	0.02 to 0.04
Cr	0.2 to 0.34
Cu	0.015 to (0.08)

According to D. Jelenc (1966), the unaltered serpentinites in Adola assayed less than 0.5 per cent nickel, less than 0.05 per cent cobalt, and the sulphur content is less than 0.01 per cent. With the exception of alleged chalcopyrite in the Dubicha drill-hole — a highly problematic datum not confirmed at all — and problematic box-works after sulfides reported by S. Morete (1973) in Tula serpentinite, there is no firm evidence of primary sulfides in Adola serpentinites. The conclusion is that the original magma was very low in sulphur.

The contents of metals and other constituents in fresh serpentinites from various localities in Adola have been given by S. C. Artena, (1974) as follows:

Constituent	Approximate range (per cent)
Cr	up to 1
Co	0.01 to 0.1
Cu	0.005
Pb	0.001 to 0.005
Mn	0.04
Ba	0.01
V	less than 0.01
Ag	0.0003—0,003 (= 0.1 to 1 oz/ton)
CaO	0.05 to less than 1
Na_2O	0.1 to 2
Al_2O_3	0.1 to 0.3
Elements not detected:	As, B, Bi, Cd, Sb
Elements not sought:	Au, F, Cl

Analyses of soil covering serpentinites at two localities showed the consistent presence of gold in amounts between 0.66 and 1 ppm. A sample of chromite assayed less than 0.15 ppm gold.

Traces of platinum group metals have been found in Adola as well. No platinum has been noted to date but the osmiridium mineral sisserskite occurs together with detrital gold in placers of the lower Demi Denissa area (J. Hagos, 1972). Precious minerals are genetically associated with and derived from mafic or ultramafic rocks.

Summary

Summarizing the above evidence, the following modes of sulfide mineralization are recognisable, either as proved or implicit sources of primary gold in the Adola area:

(a) Silicification and mineralization in metasedimentary, usually graphitic quartzitic beds with pyrite and base metal sulfides, appearing as disseminations, stringers, pyritized joints and breccias. Gold is definitely associated with sulfides.

(b) Mineralization in graphitic argillitic-quartzitic beds with disseminated pyrite and minor base metal sulfides, apparently of early origin.

(c) Dissemination of pyrrhotite in arkosic psammites (Kajemiti Beds), apparently of early origin.

(d) Mineralization in structural sites with pyrite, pyrrhotite and base metal sulfides carrying gold, associated with the high-temperature gangue minerals. Gold is positively correlative with copper and possibly cobalt too.

(e) Mineralization in quartz veins with pyrite, occasional and minor base metal sulfides and molybdenite, rutile and tourmaline. Several generations of veins are evident, some auriferous and others barren.

(f) Mineralization in skarn-type rocks and pegmatites with minor iron and copper sulfides, molybdenite and gangue paragenesis typically associated with granites.

(g) Weak random dissemination of pyrite, chalcopyrite and pyrrhotite (?) in metamafic rocks, apparently originating by blastic growth.

(h) Mineralization in altered ultramafics with trace amounts of gold and other elements in unknown mineralogical form.

Discussion

The metallogenetic considerations take into account that gold has been released by weathering of sulfides, resulting from several modes and stages of sulfide mineralization. Their origin is interpreted in the framework of sedimentary, structural, metamorphic and magmatic phenomena associated with a convergent plate boundary regime, the ultimate source of the metal being the mantle.

A genetic hypothesis must therefore provide for the presence of the source rocks, for a hydrothermal system with fluid agents involved in mobilization and transport of metals, for the generation of sulphur, energy and for suitable precipitation environment. The concentration of gold in the Adola goldfield can be reconstructed as a multi-stage process, the details of which are as yet little known, let alone documented.

Possible source and mode of occurrence of gold

In the absence of evidence to the contrary, the postulate that gold in Adola originated from mafic-ultramafic magmas — the likely source for other metals as well — is based on the following:

(a) Gold has been found to pertain to soil over the serpentinites, and in the chromite derived from ultramafites (S. C. Artena, 1974).

(b) Gold tends, because of its siderophile character, to concentrate in the iron phase of meteorites — compositionally analogous to mantle (M. H. P. Bott, 1971), in native iron of basalts, and has been detected in chromites and magnetites of mafic-ultramafic rocks (K. Rankama and Th. G. Sahama, 1950; V. M. Goldschmidt, 1958; R. I. Tilling et al., 1973).

In magmatic differentiation gold either concentrates in the sulfide phase together with copper, silver and nickel, or it may be carried over to the silicate phase (K. Rankama and Th. G. Sahama, 1950); gold in association with olivine is well known (V. M. Goldschmidt, 1958). In sulphurdeficient systems, as apparently was the case in Adola ultramafic magmas, gold ions would also concentrate in oxide phase magnetite and chromite, which crystallized directly from the melt along with olivine.

R. I. Tilling et al. (1973) have shown that the relatively highest gold contents pertain to volcanic mafic rocks; specifically it is the highest in early crystallizing mafic silicates and oxides. The average gold content in ultrabasic rocks is 5 to 6 ppb (0.005 to 0.006 ppm) and in basalts 4 ppb (R. P. Viljoen et al., 1969). Basalts from the mid-Atlantic ridge assay 10 ppb, and tholeiitic basalts from Hawaii are relatively high in gold too (D. Gottfried and L. P. Greenland, 1972). V. G. Moisenko and I. I. Fatyanov (1972) found 21.3 ppb gold in dunitic-harzburgitic rocks and 2 to 4 ppb in gabbroic rocks, to quote a few examples.

(c) Since a number of gold deposits of older geological periods occur in analogous geologic-tectonic settings associated with »greenrocks« of extrusive origin, it is only logical to relate the origin of gold to the specific geological environment. Greenstones of South Africa's Barberton region contain 5 to 20 ppb gold (R. P. Viljoen et al., 1969), and metagabbros and metadiabases of the Canadian Shield about 18 ppb (J. F. Stephenson and Ehman, 1971; Weber and Stephenson, 1973). Higher than average gold values in greenstones have been confirmed by R. I. Tilling et al. (1973). Despite the latter's argument that no particular rock is a more favourable gold source than another, the fact that many gold deposits are related to »greenrock« sequences must have a definite bearing on its source.

It is therefore believed that during the crystallization of maficultramafic magmas, gold has been incorporated in the crystal structure of the early igneous minerals. The original partition of gold, and other precious metals as well, between the silicate and oxide phases in a melt is unknown (J. H. Crocket and L. L. Chyi, 1972). In magnesium-rich olivines nickel, cobalt and chromium are usually present. Nickel and cobalt occur either in early sulfides or — if sulphur is absent — incorporated in the structure of silicate minerals. Widespread substitution of metals occurs in silicates. Nickel, cobalt and copper substitute iron and magnesium, their atomic radii being very close. Nickel especially has a great tendency to enter the olivine composition though it may also form the Fe-Ni alloys awaruite and josephinite and the nickel spinel trevorite (R. Rankama and Th. G. Sahama, 1950). Gold might have entered the silicate structure by some way of substitution as well, occupying either fixed positions in crystal structure or related to its defects. D. Gottfried and L. P. Greenland (1972) thought gold to be associated with trace elements of large ionic radii, and R. P. Viljoen et al. (1969) suspected electronegativity of gold to make it likely to enter the lattice of silicates. It appears however that, according to the available reference, the linkage of gold with ferromagnesian silicates has been little studied.

Alternatively, gold might be taken up in solid solution in oxides. Because of great dissimilarities of atomic radii of iron, chromium and gold, a direct diadochic replacement is unlikely. Gold might be trapped as minute inclusions in native form. According to W. A. Deer et al. (1967) oriented inclusions are particularly common in magnetite; oxides of Al_2O_3, Fe_2O_3 and SiO_2 can enter the magnetite structure. The similarity of the crystal structures of magnetite, chromite and gold supports this possibility.

Gold is released by the breakdown of host minerals during metamorphic destruction. Details of its migration are not known; J. H. Crocket and L. L. Chyi (1972) reported that serpentinization concentrates gold by a factor of two or three. If this is so, gold will concentrate either in secondary hydrosilicates or oxides such as amorphous magnetite — an oxidation product of olivine alteration.

Speculation concerning composition of mafic-ultramafic rocks

The ophiolitic suite in the Adola area consists of mineralogically and texturally variable rock units appearing in layers, the lithologies changing mainly in the vertical sense. Petrologically the rocks have been little studied. The relatively higher base metal and cobalt contents in amphibolites might be due to secondary epigenetic introduction, especially in para-amphibolites. On the other hand, the discontinuous bodies of serpentinites are characterized by strong concentration of nickel and cobalt, a feature not observed in any other rock type. It is believed that both differences in original magma and specific metamorphic processes were critically involved in the formation of various lithologies.

It might be speculated that massive amphibolites originated as layered pillow lavas and volcanic flows derived from more feldspathic and calcium rich, less magnesian basaltic magmas, probably similar to those producing rocks of tholeiitic composition.

Serpentinites normally originate from peridotitic rocks consisting essentially of magnesian olivine, orthorhombic pyroxene (enstatite) and possibly some augite as well, with opaque accessories. Adola serpentinites must have originated from similar rocks, though probably not from dunite, harzburgite or lherzolite Alpine ultramafic types, which are of plutonic origin.

Originally subaqueous volcanic flows, these rocks were probably peridotitic equivalents such as picritic basalts, possibly comparable to oceanites from Hawaii. Similar rocks have been considered by R. P. Viljoen et al. (1969) as the principal source of gold in South Africa's Barberton region. Significant differences in chemistry of mafic-ultramafic rocks have been found in this region, which shows surprising similarity to the Adola area.

The foliated amphibole-chlorite-talc rocks originated probably from similar ultramafic rocks, apparently richer in calcium incorporated in monoclinic pyroxenes and plagioclases. These rocks, however, could also represent intermediate stages in the development of talc directly from unserpentinized ultrabasic rocks (W. A. Deer et al., 1967).

It is generally believed that, beneath oceans, magma is produced by partial fusion of primary mantle material which is thought to be peridotitic. There is still much controversy about the generation of various basaltic magmas. Chemical inhomogeneities of the mantle, fractional crystallization, gravitational settling, selective fusion and depths of formation have been considered probable mechanisms generating different facies of basaltic magmas (M. H. P. Bott, 1971).

Hydrothermal alteration

Serpentinites and talc rocks originate by hydrothermal alteration of magnesian silicates in original ultramafites. Serpentinization — the commonest type of alteration — is a complex low-temperature reaction involving water with a low CO_2 content, which may be supplied from variable external sources. The process cannot be explained by a single unique reaction, and its details are not yet completely understood (I. S. Carmichael et al. 1974; J. B. Moody, 1976).

On the other hand, talc usually originates by successive alteration of serpentine. Although considered a product of more advanced metamorphism, and according to A. Harker (1950) more of a stress mineral than serpentine, there is a considerable overlap of the stability fields of the two minerals (W. A. Deer et al., 1967). In altered rocks a distinct zonal pattern — with a relict core of partially serpentinized rock, and a marginal zone of talc-carbonate facies — is very commonly observed. Talc can form also directly from unserpentinized rocks. If such rocks are calcium-rich, or by involving of calcium-rich solutions, talc may originate through intermediate stages of development of tremolite and chlorite rocks (W. A. Deer et al., 1967).

In Adola, both rocks are closely associated spatially. The possibility that serpentinites originated from specific rocks rich in nickel, cobalt and chromium, formed by any selective process of segregation, and brought to the surface as »pockets« within basaltic flows subsequently altered to talc, is unlikely. Serpentinites and talc rocks originated by progressive alteration from one original rock type. Accepting this interpretation, the talc alteration would have progressed so far as to be nearly complete, leaving only minor lens-shaped portions of serpentinite embedded in talc rocks. The differences in chemism would, then, have resulted from leaching and removal of metals during talc alteration.

The conversion of olivine to serpentine by addition of water is expressed by the known equation:

$$\underset{\text{Forsterite}}{2\,Mg_2SiO_4} + 3\,H_2O \rightarrow \underset{\text{Serpentine}}{Mg_3Si_2O_5\,(OH)_4} + \underset{\text{Brucite}}{Mg\,(OH)_2}$$

Correspondingly, fayalite would yield serpentine and magnetite, the ferrous ion from olivine oxidized to ferric ion in magnetite, the necessary oxygen being obtained from decomposition of water. In the reducing environment native iron can occur as well (O. K. Eckstrand, 1975). Chromite can be replaced by secondary magnetite or spinel (J. B. Moody, 1976). Cobalt is located in magnetite, and nickel and copper from olivine are partly converted to opaque minerals and partly enter into serpentine. Gold is reportedly enriched, probably in oxides and spinels (J. H. Crocket and L. L. Chyi, 1972). Magnesia goes into solution but silica remains relatively constant.

Talc usually forms from serpentine by the addition of CO_2:

$$\underset{\text{Serpentine}}{2\,Mg_3Si_2O_5\,(OH)_4} + 3\,CO_2 \rightarrow \underset{\text{Talc}}{Mg_3Si_4O_{10}\,(OH)_2} + \underset{\text{Magnesite}}{3\,MgCO_3} + 3\,H_2O$$

Similarly tremolite, chlorite or diopside may be converted to talc by the addition of CO_2, with dolomite and silica removed in solution.

Magnetite in serpentinite, both primary and secondary, is attacked by CO_2 as well. According to O. K. Eckstrand (1975) ferric ion is changed to ferrous, oxygen is released and an oxidising environment is produced:

$$\underset{\text{Magnetite}}{Fe_3O_4} + 3\,CO_2 = \underset{\text{Siderite}}{3\,FeCO_3} + \tfrac{1}{2}\,O_2$$

In successive alteration two reaction fronts form; the advanced serpentinization front is marked by a reducing environment, and the following talc alteration front by and oxidizing environment.

In talc-carbonate alteration magnesia is largely removed, and oxidic minerals are decomposed. The chemical changes are intensified if acids or other agents are introduced from any sources. Iron, nickel, cobalt are set free and go into solution; nickel is very stable in aqueous solutions and can migrate to considerable distances. Cobalt is readily oxidized, together with ferrous iron, into the trivalent state and they accumulate in situ. However a part of ferrous iron and divalent cobalt remain in solution and can be transported as carbonate. Both metals can be transported also as colloidal hydroxides. Copper gets into solution as well, probably as cupric sulphate if the SO_4^- ion is available, whereas ferrous sulphate would be rapidly oxidized to form sulphuric acid and ferric hydroxide (K. Rankama and Th. G. Sahama, 1950). Gold apparently passes into solution as well, in one or another form. Silica tends to form colloidal solutions and is enriched in talc relative to serpentine.

The decomposition of silicates and the movement of elements is still a subject of research, the composition of the participating solutions having a decisive bearing on the possible chemical variables. According to J. B. Moody (1967) the pH of aqueous solutions, the presence of chlorine and p/T conditions determine the elements which may be leached as well as the mobilities of the solutions.

In the weathering of nickeliferous serpentinites, as has been the case in Adola, nickel, together with ferric iron and cobalt, concentrates in the residual soil in the form of hydrosilicates. There is no such concentration in residuals derived from talc and other rocks since these elements have been removed prior to exposure to weathering.

Solutions: a review of possible media of transport

The breakdown of the primary host minerals released the gold, which passed into solution and, together with other metals, migrated to the next or final localization.

There is sufficient information to the effect that gold is transported in thermal waters and concentrated at a wide range of p/T conditions. Gold is soluble in various forms in both acid and near-alkaline aqueous solutions. In natural hot springs that deposit gold, slightly alkaline solutions seem to prevail (B. G. Weissberg, 1969). K. B. Krauskopf (1967) advanced the hypothesis that metals are carried in solutions as chloride complexes and precipitate as sulfides in the presence of hydrogen sulfide, usually as colloidal particles; aurous and auric chloride complexes are highly soluble and mobile. H. L. Barnes (1962, 1972) advocated the transport of gold by means of bisulfidic complexes in neutral to weakly alkaline solutions. D. E. White (1965, 1968) favoured sodium-calcium-chlorine brine as »a potent solvent for many metals«. and R. W. Boyle (1968) thought antimony, arsenic and tellurium complexes to be intimately involved in the transport of gold. H. C. Helgeson and R. N. Garrels (1968) demonstrated the solubility of gold in acid chloride-rich aqueous solutions. B. G. Weissberg (1970) suggested that gold-sulfide complexes in near-neutral solutions are particularly effective in the formation of gold deposits. V. G. Moisenko and I. I. Fatyanov (1972) stated categorically that gold is transported in solutions as sodium chloride and as a thiosulphate complex, the temperature of formation of hydrothermal gold deposits ranging from 30 °C to 430 °C.

Gold can be also transported in organic complexes (A. S. Radtke and B. J. Scheiner, 1970). Upon oxidation of the organic component, metallic gold is formed. Certain components of organic carbon are believed to be capable of adsorbing gold complexes since gold is often found in carbonaceous rocks. Gold can be dissolved and reprecipitated in weathering environments at relatively low temperatures (C. F. Park and R. A. MacDiarmid, 1970), as proved by the aggregation of fine particles to nuggets in placers.

Chemical systems involved in solubility of gold are evidently complex. R. W. Boyle (1968) rightly stated that no single complex can be regarded as the responsible agent in the formation of gold deposits.

Silica — amply participating in gold deposition — is soluble and can be concentrated in a wide range of pH conditions. It is thought to be derived from alteration of the country rocks. The importance of colloidal solutions in silica deposition is well known. Sols can serve also as means of transporting the metals; the colloidal hypothesis might be applicable for gold as well.

Regarding the possible origin and nature of liquid agents in the formation of the Adola gold deposits, in line with the available evidence and postulated ability of saline chloride brines to serve as agents of metal transportation, the most likely seems to be the derivation from sea water trapped in sediments. Connate waters are rich in elements and salts usually found in sea water, chlorides being most abundant. Silica concentration is variable but, as in sea water, generally low (D. E. White, 1965). According to J. H. Taylor (1965) all mineralizing solutions contain a substantial percentage of connate waters.

Sea water has been recognized as a possible fluid for serpentinization (J. B. Moody, 1976), and oceanic water was apparently the agent of alteration of serpentine blocks dredged from the mid-oceanic ridges (I. S. Carmichael et al., 1974). Boron and chlorine are usually found in serpentinites (J. Turner and J. Verhoogen, 1960; J. Rucklidge, 1972). Since their amount in ultramafic rocks is insignificant, but they attain high concentrations in sea water, they are introduced by the serpentinizing fluid which, by implication, is a sea water derived brine.

The abundances of halogens in the Adola serpentinites have not been determined. The presence of tourmaline and possibly apatite could be alleged to relate to the content of halogens in connate fluids. The solution might have been initially a sodium-chloride brine, probably near-neutral; the pH value of present-day sea water is 8.1 to 8.4. In the long process of reactions in the changing geological environment, the composition of solutions was subject to constant changes. According to J. B. Moody (1976), the fluids involved in serpentinization become strongly alkaline. Regarding the migration of the metals in connate solutions carrying chlorides, J. Rucklidge (1972) characterized it as »a matter of uncertainty and speculation«.

Possible stages of mineralization

R. I. Tilling et al. (1973) emphasized that the concentration of gold from its disseminated original position in the parts per billion range to economic levels, the content of gold in transporting solutions equally being extremely low, requires favourable configuration and nature of the hydrothermal system, especially in terms of dilatancies, duration and intensity of events R. W. Boyle (1959, 1968) too stressed the overwhelming importance of dilatancy as sites where deposits can form. B. G. Weissberg (1969) and others have shown that gold deposits can be easily formed even at very low concentrations of ore-forming solutions during geological times.

The mineralizations recognized in the Adola area apparently differ in relation to the time of formation. It is conceivable that the hydrothermal system was activated already during diagenesis, when the compaction from the weight of the accumulated material set the saline waters entrapped in pore spaces of sediments, in motion. Serpentinization may have been initiated already in the burial stage, the waters percolating the rocks, with various anions and cations passing into solutions.

The sedimentary suite of the Adola Group rocks generally contains graphitic matter, apparently derived from water organisms such as blue-green algae. In stagnant waters under anaerobic conditions, sulphur was formed biogenically either through bacterial decomposition of organic matter or reduction of sea-water sulphate. It seems that the euxinic environment was conspicuously important in Adola sulfide mineralizations as the source of hydrogen sulfide, since hypogene sulphur was apparently low or even absent.

(1) The sulfide disseminations in argillaceous-arenaceous sediments point to an early **diagenetic** origin. The metal components dissolved in solutions, from whatever source their provenance may have been, readily precipitated in the sulphurized environment at a relatively low temperature. The silica content in solutions was apparently low. Though some gold could have been concentrated via adsorption from sea water by organic matter, it seems that the early generation of sulfides does not contain much or any gold.

The iron sulfides usually disseminated in sedimentary rocks are authigenic pyrite and pyrrhotite, the former precipitating in strongly reducing environments with weakly acid to alkaline waters and abundant hydrogen sulfide, and the latter in shallow less reducing environments.

The metals can be also introduced epigenetically in solutions, the paragenetic sequence similar to that of ore veins in this case. A way to discriminate between the sulfides of authigenous or »sedimentary« and »hydrothermal« origin might be found in the Ni/Co ratio. In authigenous origin nickel predominates over cobalt and vice versa (K. Rankama and Th. G. Sahama, 1950).

The average whole-rock ratios from the data available for some rock units in the Tula-Kajemiti area are given in Table 2.

Table 2.
Ni/Co ratio found in some rock units from the Tula-Kajemiti area

Tabela 2.
Razmerje Ni/Co v nekaterih kameninskih enotah območja Tula-Kajemiti

Rock type	Average Ni/Co ratio	Remark
Graphitic quartzite	$\frac{540}{42} = 13$	
Graphitic schist	$\frac{118}{45} = 3$	
Kajemiti psammites	$\frac{65}{18} = 3$	
Demi Denissa schist	$\frac{42}{44} = 1$	
Mineralized Demi Denissa schist	$\frac{28}{70} = 0.4$	Schist with abundant auriferous sulfides; nine core samples from drill-hole KJ-5A/72

Accordingly, with the exception of Demi Denissa sulfides in sheared schists, an early authigenic precipitation by autochthonous sulphur is indicated in schists and quartzites. Pyrrhotite in the Kajemiti Beds originated apparently in an agitated low-sulphur environment. It is unlikely that original pyrite was altered to pyrrhotite by regional metamorphism; the released sulphur should, in this case, have produced a new generation of pyrite crystalloblasts, which are not to be seen. There is no carbonaceous matter associated, and there is also no indication of detrital gold being derived from the pyrrhotite.

The presence of graphitic metasedimentary beds is a characteristic feature of gold deposits of this type. In the Barberton region of South Africa (R. P. Viljoen et al., 1969), in the Ramagiri area of Andra Pradesh in India (D. B. Ghosh et al., 1970) and in the Morro Velho mine of Brasil (R. Fleischer and P. Routhier, 1973), black graphitic sediments are important lithological units of the gold-bearing suites. The specific environment might have been somehow involved not only as the source of biogenic sulphur and compounds acting as agents in redox reactions, but possibly also in the formation of organic complexes instrumental in migration and deposition of gold.

(2) The onset of orogenesis changed the hydrodynamic regime and introduced a new phase of epigenetic hydrothermal processes, controlled by dilatancy, initially depositional and gradually also structural, and the ready presence of autochthonous sulphur. The phases were overlapping as the environment was changing. The new physico-chemical environment was marked by increased p/T conditions, by a compositional change of the original saline brines due to the influx of meteoric or magmatic waters carrying carbon dioxide and other agencies, and by fracturing of the rocks, increasing so the accessibility of fluids and reactive surfaces. The fluids were expelled under pressure, permeating and leaching the rocks. It is believed that talc alteration reactions took place in the early stages of diastrophism.

The solutions, apparently at not very high, though elevated temperatures, carried dissolved metals and other components and moved towards lowpressure sites. It is likely that sulfide mineralization and silicification of the graphitic arenites and associated sediments took place at this stage. Visible sulfides seem to be pyrites prevailingly, and they contain gold. Quartz, mica, graphite and occasional tourmaline are the associated minerals. The sediments underwent metamorphism and recrystallyzation with crystalloblastic growth of sulfides, proving the **early epigenetic** age of the mineralization.

If chloride was the complexing ion in the oxidizing solutions, then gold could have been dissolved and transported as the stable complex $AuCl_4^-$ (C. F. Park and R. R. MacDiarmid, 1970). Gold was incorporated in sulfides which precipitated in an reducing environment in contact with hydrogen sulfide. Such environment, according to H. L. Barnes (1972) would be indicative of the presence of chloride complexes.

(3) The next stages of **epigenetic** auriferous quartz-sulfide mineralizations could be related to granitic plutonism and orogenesis. Structural deformations produced features of increased permeability — fractures, faults and shears — which readily served as communication conduits and loci of precipitation. The solutions moved following the pressure and temperature gradients; at low-pressure and in cooler zones the minerals precipitated. Gold occurs in copper sulfides and possibly iron sulfides as well. Typical high-pressure high-temperature minerals rutile, garnet and tourmaline, and inconspicuous wall-rock alteration characterize the mineralization as hypothermal. Gold was probably in solid solution, incorporated in the defective lattice of sulfides at elevated temperatures, and exsolved when temperature dropped.

The plutonic activity in the Adola area would, as argued before, broadly coincide with the orogeny. Since the silicic melts would have formed by partial fusion of the upper mantle and the oceanic crust, metals contained in the consumed crustal rocks would be incorporated in the palingenic magma, and volatiles mobilized through dehydration and decarbonation of the crustal material. Some juvenile fluids and metals originating from the mantle could have been added, and additional components mobilized from the cooling magma and adjacent rocks. A remobilization of the early precipitated sulfides, gold included, is conceivable. The fluids migrated and behaved as though they originated from magma in the classical sense of interpretation.

The solutions were probably chemically reconstituted original saline brines. Boron and chlorine appear to have been derived from them, as evidenced in the occurrence of tourmaline and apatite which formed by high-temperature reactions with other constituents. Heated solutions could have removed and carried also large amounts of silica, its solubility and mobility in direct relationship to temperature. Falling temperature gives a likely explanation of silica precipitation. The conclusion that structurally controlled precipitation occurred by both pressure and temperature decrease would, according to H. L. Barnes (1972), speak again for the presence of chloride complexes.

There are more than one generation of quartz, and there were apparently several episodes of hydrothermal activity. To be distinguished, at least, are bluish yellowish high-temperature quartz with gold-bearing sulfides and greasy, milky, barren, probably later introduced lower-temperature quartz, usually forming larger reefs with distinct boundaries.

It is not possible as yet to say if — and to what extent — the youngest massive pegmatoid granites were involved in some later-stage remobilization and reprecipitation of the ore material. The Chambi area, for one, bears strong evidence of hydrothermal activity but it is not known how strong a bearing these events had on the migration of gold.

Primary gold deposits in the Adola area, according to present information, are nearly exclusively confined to Adola Group rocks. A plausible explanation why the Adola sequence was the receptive assemblage is at hand: it was the source of gold and other metals, the source of solutions and the generator of agents of reduction and of biogenic sulphur — probably the main source of the available sulphur, and it presented convenient permeable ground for the movement of fluids and the precipitation of minerals.

Conclusion

An attempt has been made to interpret the obviously complex geological structure of the Adola goldfield and its metallogeny in terms of a convergent plate tectonic regime. In doing so, and because of lacking evidence — field work being impossible at this time — assumptions have necessarily been made. The emerging genetical hypothesis is based on the postulate that the ultimate source of gold is the ultramafic portion of the ophiolitic suite of the Adola Group assemblage, formed as part of an ancient oceanic crust. Through processes of hydration alteration gold was liberated from host minerals and, together with other metals, passed into solutions, which origin can be best explained by affiliation with oceanic water.

It is conceivable that the process of mobilization and migration commenced in diagenesis, the saline fluids activated by compaction. During orogenesis the reconstituted fluids, activated by dynamism and anatectic magmatism, permeated and leached the rocks, mobilizing and remobilizing the constituents, which migrated possibly as chloride complexes and precipitated as metal sulfides, with gold incorporated. The euxinic sedimentary environment, generating biogenic sulphur, is believed to be of crucial importance for sulfide formation at least in the diagenetic and early epigenetic phases. More hydrothermal episodes were probably involved, silicic plutonism influencing the fluids chemically and physically. Both depositional and structural permeable sites acted as conduits for metal-bearing solutions and as loci of precipitation, its mechanism controlled by both physical and chemical factors.

There is a good structural-lithological similarity of the Adola gold-field with some other goldfields of this type and, consequently, an analogy in concentration mechanism might be likely.

The genetic hypothesis presented is a tentative one, seemingly reasonable but clearly not indisputable. The mineralization events extended over a long period of time, and in ancient rocks with such a complex history the details are obscured. Further study will doubtless be a demanding though satisfying exercise, possibly also a rewarding one if economic primary gold concentrations will be located.

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