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The Milparinka-Tibooburra district, NW-New South Wales, Australia – a typical example of a mesothermal lode-gold deposit

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Content

Der Milparinka-Tibooburra Distrikt, NW-New South Wales, Australien – ein typisches Beispiel einer mesothermalen, gangförmigen Gold-Lagerstätte

Zusammenfassung

Der Milparinka-Tibooburra Distrikt, in der nordwestlichen Ecke von New South Wales gelegen, besteht aus einer Serie von Grundgebirgskomplexen. Die wichtigsten sind der Warratta, Mount Poole und Tibooburra Inlier. Die Komplexe sind aus niedriggradig metamorphen, stark deformierten Sedimenten, die Easter Monday Beds, zusätzlich mit Einschaltungen von rhyolithischen und basaltischen Gesteinen aufgebaut; innerhalb des Tibooburra Inlier tritt ein granodioritischer Intrusionskörper auf. Die Easter Monday Beds zeigen eine multiple Deformationsgeschichte, bestehend aus zwei Deformationsakten (D_1 und D_2). Der granodioritische Pluton intrudierte während D_1.

Die Easter Monday Beds, vorallem im Warratta und Mount Poole Inlier, sind Träger von typischen mesothermalen, gangförmigen Goldlagerstätten. Drei Generationen von Quarzgängen können auf der Basis ihrer Strukturgebundenheit unterschieden werden. Gänge der zweiten Generation, die syntektonisch während der Entwicklung der Schieferung S_{1a} gebildet worden sind, sind mit freiem Gold, Pyrit und untergeordnet Arsenopyrit, Chalcopyrit, Zinkblende und Bleiglanz, als assoziierte Sulfide, vererzt. Diese vererzten Gänge stellen typische crack-seal Gänge dar und sind von Alterationszonen, die einen Au-S-K Hof zeigen, begleitet. Die Gänge wurden von nahezu neutralen, schwach salinaren $CO_2(CH_4)$-H_2O-Fluids bei Temperaturen zwischen 300 und 340 °C gebildet. Gold wurde höchst wahrscheinlich als $Au(HS)_2$-Komplexe transportiert und im Zuge komplexer Interaktion von Fluidum-Gangnebengestein ausgefällt. K-Ar, Pb-Pb und S-Isotopenresultate weisen auf eine tiefkrustale Herkunft des Goldes, der assoziierten Metalle und des Schwefels hin. Als Alter und Dauer für die Bildung der synmetamorphen, vererzten Gänge kann < 500 bis 420 Millionen Jahre angenommen werden. Der granodioritische Pluton ist nicht direkt für die Mineralisation verantwortlich, hat jedoch möglicherweise eine Rolle als Motor für das hydrothermale System gespielt.

Abstract

The Milparinka-Tibooburra district, located in the northwestern corner of New South Wales, consists of a series of basement complexes, the most important of which are the Warratta, Mount Poole and Tibooburra Inlier. The complexes are composed of low-grade metamorphosed, strongly deformed sediments, the Easter Monday Beds, with subordinate intercalations of rhyolitic to basaltic rocks; the Tibooburra Inlier hosts

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a granodioritic intrusive pluton. The Easter Monday Beds show a multiple deformational history defined by two deformational events (D_1 and D_2). The granodioritic pluton intruded during D_1.

The Easter Monday Beds, particularly in the Warratta and Mount Poole Inlier, host typical mesothermal lode-gold deposits. On the basis of the structural control, three generations of quartz veins can be distinguished. Veins of the second generation, that were formed syn-tectonically during the formation of cleavage S_{1a}, are mineralised with native gold, pyrite and minor arsenopyrite, chalcopyrite, sphalerite and galena as associated sulfides. These mineralised veins are typical crack-seal veins, accompanied by alteration zones, defined by a Au-S-K halo. They were formed by near neutral, low-saline $CO_2(CH_4)$-H_2O-fluids at temperatures between 300 and 340 °C. Gold was transported most likely as $Au(HS)_2$- complexes and precipitated during complex fluid-wall rock interaction. K-Ar, Pb-Pb and S-isotopic results indicate a deep crustal source for gold, associated metals and sulfur. An age and duration of < 500 and 420 Ma is assumed for the formation of syn-metamorphic, mineralised veins. The granodioritic pluton is not directly involved in the mineralisation, but may have played a role as driving mechanism for the hydrothermal system.

Preface

This paper is dedicated to em. Univ. Prof. Dr. H. W. FLÜGEL on the occasion of his 70th birthday. Prof. FLÜGEL has opened to me the gate to geosciences starting at the time when I joined the Department of Geology and Paleontology at the University of Graz in 1974. In the following years I greatly benefitted of Prof. FLÜGEL'S vast competence and knowledge in the various subjects of geoscience, that culminated in his supervision of my PhD project during the years 1978 to 1982. I also would not like to miss the opportunity to express my sincere thanks to the great amount of time he spent to educate us to critical thinking young scientists. This contribution is meant to show that an economic geologist, what I became since I left the University of Graz after graduation in 1982, one is obliged to be a master in various fields of geoscience and to integrate geology, mineralogy, petrology, and geochemistry.

1. Introduction

Gold has attracted man for more than 6000 years, because of its occurrence as a native metal, its unique properties, beauty and rarity. Although the average gold content of the Earth's crust is 3.5 ppb (parts per billion) only (WEST, 1976), there are a huge number and a great variety of gold deposits known around the world, occurring in various rocks ranging in age from the Archean to the Tertiary. It thus requires certain processes to concentrate gold 2000 times and more above its crustal abundance to form an ore body.

Lode-gold deposits are of minor importance economically, i.e. less than 20% of total gold production (ROBERTS, 1987); the majority of the gold production todays comes from Carlin-type and epithermal gold deposits (e.g. the Golden Mile deposit, Kalgoorlie, Western Australia; the Kolyma River basin, northeast Russia etc.), except the Witwatersrand deposits, South Africa. However, much of the gold produced in Russia, the USA and Australia has come from placer deposits (which account for a third of total world gold production; ROBERTS, 1987), and lode deposits are in most cases considered the source for gold placers. Furthermore, central Victoria (Australia), as one of the type locality for lode-gold deposits, represents one of the most Au-mineralised areas in the world, apart from the Witwatersrand in South Africa (PHILLIPS & HUGHES, 1996). Another fascinating aspect of lode-gold deposits is their genesis, which probably has been the most controversial subject concerning any type of gold deposits. As the price of gold increased dramatically in the late 1970's, the interest in and the understanding of lode-gold deposits increased significantly (ROBERTS et al., 1991; GROVES et al., 1998).

Mesothermal lode-gold deposits, independent of their age, share numerous features in common at a variety of scales:

(1) They occur predominantly in greenschist facies environments and are hosted by metasediments or metavolcano-sedimentary sequences. Subordinately, lode-gold deposits also occur in sub-greenschist facies and upper amphibolite facies terranes (GROVES, 1993; GROVES et al., 1990; RIDLEY et al., 1995). (2) They are structurally controlled, i.e. to the anticlinal (saddle reefs), or synclinal section of folds (trough reef), to the limb region of folds (leg reefs, spurs), related to extension fractures, faults, or shear zones. (3) They are generally restricted to the brittle-ductile transition. (4) The gangue mineralogy is dominated by quartz; carbonate, mica, albite, chlorite occur subordinately. (5) The sulfide mineralogy is simple, comprising dominantly pyrite, arsenopyrite, and minor pyrrhotite, chalcopyrite, sphalerite, and galena; gold is native, subordinately hosted by pyrite and arsenopyrite. (6) Veins have a vertical extend to up to 2 km, with almost lack of zoning. (7) Wall rock alteration is minor, but mostly present (i.e. enrichment of mica and chlorite, some addition of carbonate and sulfur). (8) Fluid inclusion studies reveal a dominance of H_2O-CO_2-(CH_4) fluids with characteristically low salinities (< 5 wt.% aquivalent). (9) All deposits are sited along convergent plate margins and are formed during metamorphism/deformation of host rocks; the mineralisation shows various time-relationships to peak of metamorphism, i.e. pre-metamorphic, syn-, and post-peak of metamorphism (c.f. STÜWE, 1998; STÜWE et al., 1993), and may be related to granitoid intrusions.

In this paper the Milparinka-Tibooburra auriferious district is taken as a typical example for mesothermal gold-lode deposits. Various important aspects, such as the source of gold and associated metals, characteristics of the mineralising fluids, processes of gold transport, gold concentration and precipitation, as well as the relation of the deposit to the deformational and metamorphic history of the host rocks, and a possible link to a granodioritic pluton, are addressed. The area investigated does not represent a gold deposit of significant economic importance, but was used as a case study, that offers at a rather small scale all the required features typical for an environment hosting mesothermal lode-gold deposits.

In the following the term 'mesothermal lode-gold deposit' is used closely to the recent meaning by GROVES et al. (1998), which represents a slightly modified definition of NESBITT et al. (1986), GROVES et al. (1989), and KERRICH (1993). Hence, a mesothermal lode-gold deposit is defined here as formed at depths of 6-12 km and at temperatures of 250-400 °C, irrespective of the type of host rock the mineralisation occurs, but definitely formed during deformational processes at convergent plate margins (i.e. orogenic) including accretionary terranes.

2. The Milparinka-Tibooburra district: location, general geology

The Milparinka-Tibooburra district is located in the north-western corner of New South Wales, Australia, about 350 km north of Broken Hill (Fig.1). The area consists of a discontinuous series of complexes, the most important are the Warratta, Mount Poole and the Tibooburra Inlier. They are part of the NNW trending Wonominta Block (MILLS, 1992), which is separated from the further SSW located, composite Broken Hill-Olary Block by a deep fault-bounded depression (i.e. the Bancannia Trough; MILLS, 1992). The complexes are composed of strongly deformed, low-grade metamorphosed, and generally NNW-dipping sedimentary sequences (the Easter Monday Beds; STEVENS & FANNING unpubl. data; THALHAMMER et al., 1998) with minor intercalations of various rhyolitic to basaltic rocks. The inliers crop out as horst-like exposures of basement rocks through the Upper Jurassic to Quarternary sedimentary cover. The Tibooburra Inlier (Fig.1) is characterized by the occurrence of a granitoid intrusive body, the Tibooburra Granodiorite (THALHAMMER et al., 1998). The Tibooburra Inlier is separated from the Warratta Inlier by the NNW trending Warratta Fault, as part of a major regional lineament (the Olepoloko Fault, CRAWFORD et al., 1997; THALHAMMER et al., 1998). This major fault supposedly represents a block boundary between the Kanmantoo Fold Belt in the west, hosting the Mt. Poole and Warratta Inliers, and the Thompson Fold Belt in the east, hosting the Tibooburra Inlier (Fig.1). The Easter Monday Beds are most likely of Cambrian to Early Ordovician in age (STEVENS & FANNING unpubl. data; THALHAMMER et al., 1998), and probably represent a deltaic shelf depositional environment (STEVENS & ETHERIDGE, 1989; STEVENS & CRAWFORD, 1992). The Tibooburra Granodiorite revealed an age of 410 Ma, based on Rb-Sr isotopic dating (SHAW, 1982; THALHAMMER et al., 1998). Geochemical and isotopic investigations showed that the granodiorite has an I-type character (THALHAMMER et al., 1998). The intrusion of the Tibooburra Granodiorite has produced a contact-metamorphic aureole of up to 1 km away from the granodiorite, with cordierite-K-feldspar-biotite-quartz and cordierite-biotite-quartz assemblages (STEVENS & ETHERIDGE, 1989; THALHAMMER et al., 1998).

Gold was produced in the Milparinka-Tibooburra district from lode reefs and alluvial deposits from 1880 to 1930. During this period approximately 3000 kg of gold have been extracted (BARNES, 1975), although a much higher amount can be assumed (e.g. 5000 kg) due to lack of official reports. Lack of water and increasing difficulties in mining operations was the reason mining activities ceased completely in 1933.

3. Quartz veins and quartz-gold-lodes

Quartz veins with a great variety in shape, thickness, and density occur in the Easter Monday Beds of the Mt. Poole Inlier, particularly of the Warratta Inlier, and minor in the Tibooburra Inlier. All veins exhibit a structural control, on the basis of which at least three different vein generations can be distinguished (THALHAMMER, 1992a):

First generation of quartz veins:

The first generation is represented by predominantly thin, up to a few cm thick, irregular, discontinuous quartz veins, occurring exclusively in rather homogeneous slates. They are purely composed of quartz, mostly formed by quartz fibres oriented subparallel to vein-walls, and clearly overprinted by cleavage which indicates a pre-deformational generation, most likely during progressive diagenesis.

Second generation of quartz veins:

These veins are by far most abundant, reach their highest density in laminated, pelitic lithologies, may reach a thickness of up to 4 m, and are mineralised with gold and associated sulfides. These veins exhibit a definite structural control due to cleavage S_1, and show subsequent deformation, i.e. folding, fracturing, pinch-and-swell structures. The following common primary and secondary textures can be encountered in these quartz veins (THALHAMMER, 1992a).

Primary textures are:

i) veins are filled predominantly by either columnar quartz, or quartz fibres which dominantly show an oblique to perpendicular orientation to the vein-wall. Apart of quartz the veins contain subordinately carbonate (up to 20%), albite, mica, sulfides (pyrite, arsenopyrite, chalcopyrite, galena, pyrrhotite in variable amounts), and native gold,

ii) included sheets and fragment of host rock, and inclusion bands, giving the veins a laminated fabric (i.e. crack-seal veins – RAMSAY, 1980; COX & ETHERIDGE, 1983),

iii) typically concave-convex vein-wall contacts that invariably truncate the foliation (i.e. cleavage S_1, Fig. 2a),

iv) quartz fibre boundaries show frequently a saw-tooth shape,

v) common increase in quartz crystal size from the vein-wall towards the centre, and

vi) inclusion trails formed by white mica and fluid inclusions, crossing quartz fibre boundaries (Fig. 3a).

Secondary textures are:

i) undulose extinction in quartz and dynamic recrystallisation of quartz,

ii) bent quartz fibres or quartz columns, particularly towards the centre of the vein, indicating rotation of fibres during vein growth,

iii) pinch-and-swell structures, and

iv) folding of quartz veins (Fig. 2b) and local appearance of remnant quartz-vein folds.

Third generation of quartz veins

Veins clearly cross-cutting and overprinting the second generation of quartz veins, or even cutting through the entire fabric of the host rock, comprise the third generation. They are either composed of quartz fibres with minor carbonate, or of carbonate with subordinate tabular quartz. They are commonly irregular, or follow joint planes over some distance, their thickness does not exceed four centimetres, and they are barren.

Quartz veins in the Tibooburra Granodiorite

Quartz veins in the Tibooburra pluton occur subordinately related to shear zones and fractures in the granodiorite. They are distinct from those in the Easter Monday Beds, composed of coarse-grained, blocky quartz, albite, and minor mica, are up to a few tens of centimetres in thickness, and unmineralised.

4. Mineralogy of auriferous quartz veins

Auriferous quartz veins are those of the second generation. The gangue minerals are represented by carbonate, mica, and chlorite, apart of predominant quartz. Carbonate components are either calcite or ankerite. Mica are resembled by

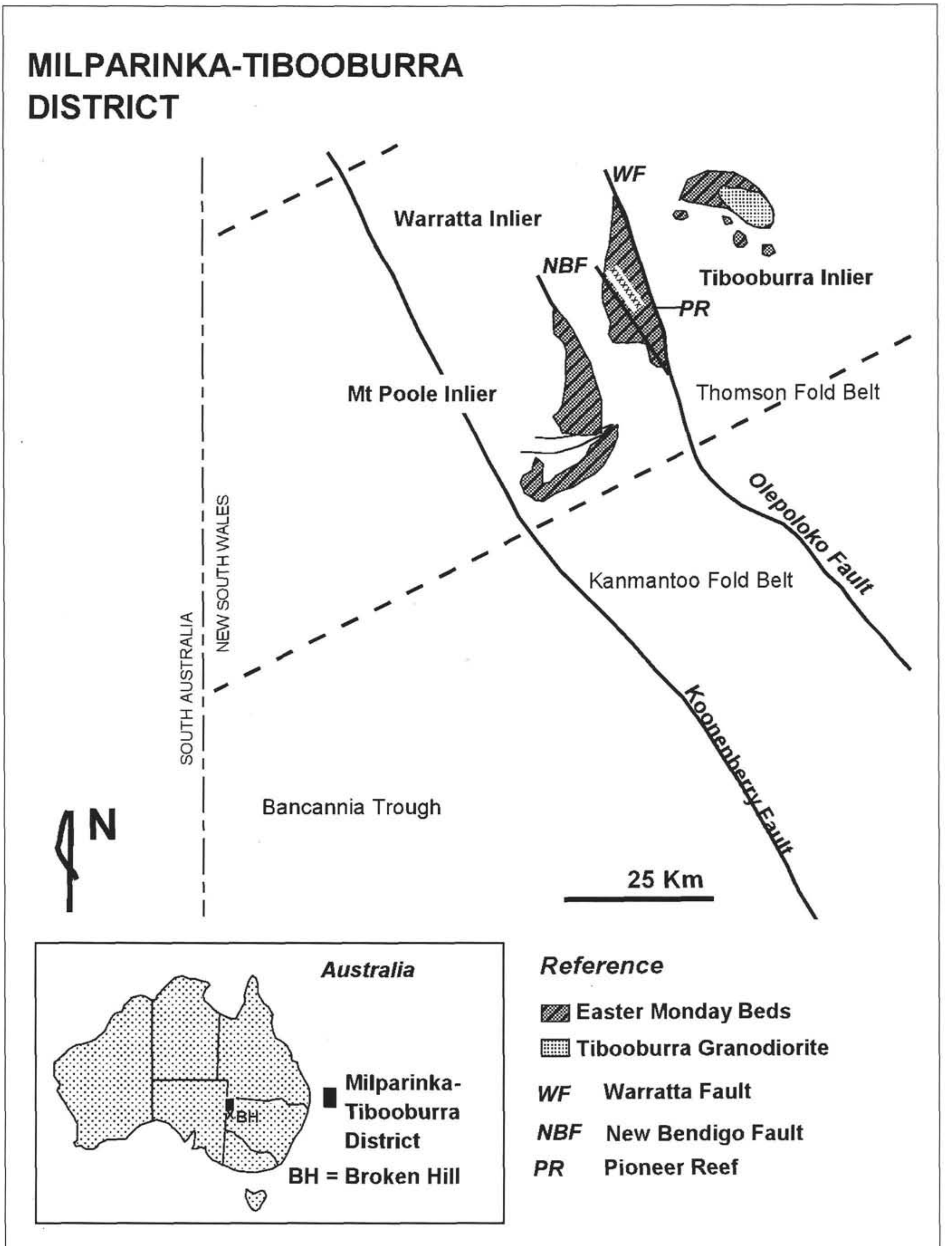
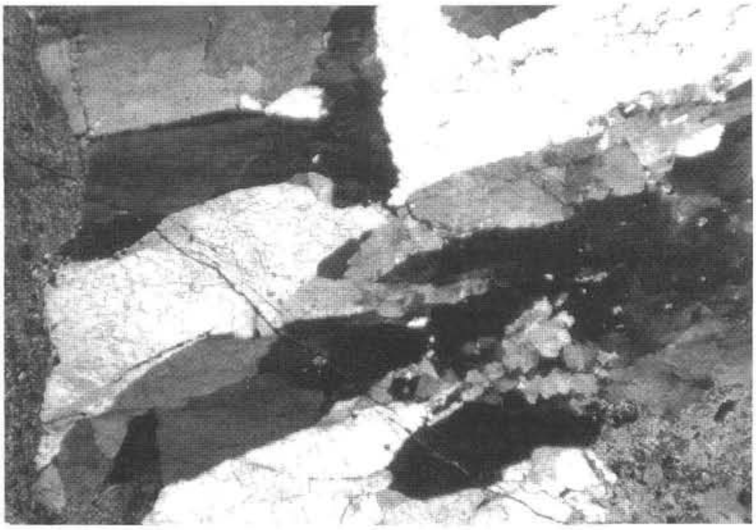
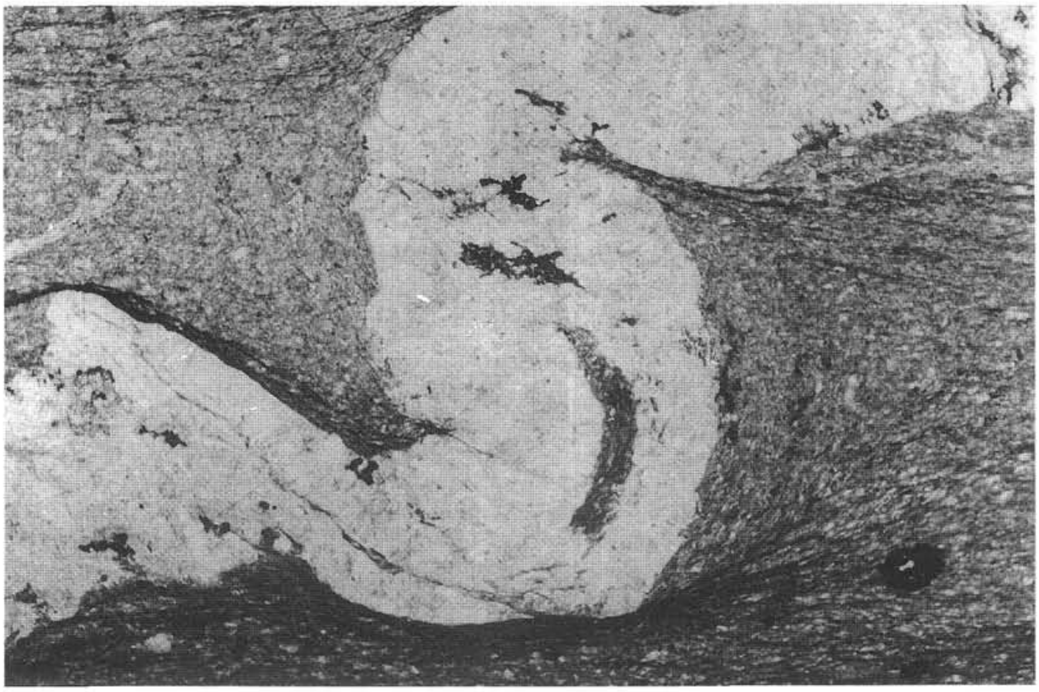


Fig. 1
Geological sketch map of the northern part of the Wonominta Block in NW-New South Wales, Australia, showing the location of the Milparinka-Tibooburra district.



a



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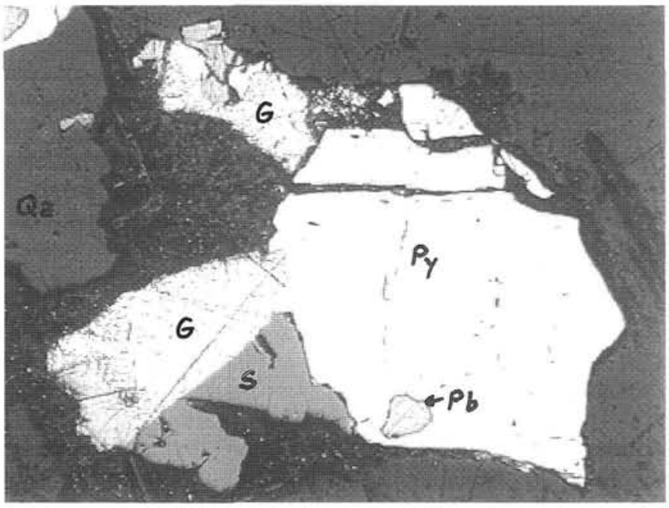


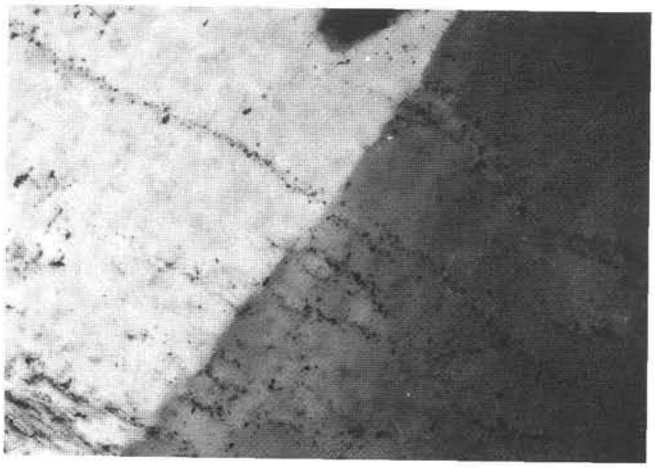
c

Fig. 2

2a – Microphotograph of a quartz vein of the second generation filled with columnar quartz. The typical concave-convex vein-wall contact is visible at the left rim of the photo. Transmitted light under crossed nicols, magnification 40X.

2b – Microphotograph of folded quartz veins, also showing included sheets of host rock (dark patches). Transmitted light under parallel nicols, magnification 2.5X.

2c – Microphotograph of sulfides and native gold from a quartz vein of the Pioneer Reef, Warratta Inlier. Py = pyrite, S = sphalerite, Pb = galena, Qz = quartz. The very soft phase in association with pyrite, galena and sphalerite is gold (G). White inclusions in gold are arsenopyrite. Reflected light under parallel nicols, magnification 125X.



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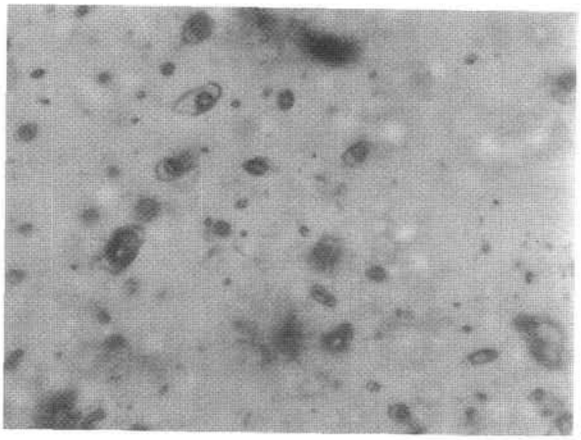

b

Fig. 3
3a – Microphotograph of a quartz vein of the second generation from the Pioneer Reef (Warratta Inlier), showing two quartz fibres with fluid inclusion trails oriented perpendicular to fibre boundaries. The quartz fibres are oriented perpendicular to the vein wall. Transmitted light under crossed nicols, magnification 150X.

3b – Microphotograph of pseudosecondary, CO_2-rich fluid inclusions from a fluid inclusion trail of Figure 3a. Transmitted light under parallel nicols, magnification 625X.

muscovite with varying phengite-component (GUIDOTTI, 1984); chlorites are diabantites according to the classification of FOSTER (1962).

Sulfides are dominated by pyrite (> 90% of total sulfides occurring). Euhedral to subhedral pyrites occur disseminated, whereas anhedral pyrites form irregular aggregates. Pyrite represents a good indicator mineral for gold: veins with abundant, irregular distributed pyrite always revealed gold concentrations above 10 ppm. Pyrite also carries "invisible" gold – an analysed pyrite concentrate from one of the major quartz-gold reefs revealed an Au-content of 390 ppm. Arsenopyrite is the second most common sulfide mineral in the mineralised quartz veins. Arsenopyrite shows commonly euhedral to subhedral shape, and is often closely associated with pyrite. An arsenopyrite concentrate revealed 4 ppm of gold.

Rare sulfides phases are chalcopyrite, sphalerite with Fe-content in the range of 2.2 to 2.6 at.%, galena, which rarely may also form little inclusions in arsenopyrite, and pyrrhotite closely intergrown with chalcopyrite. All sulfides occur generally closely together, e.g. common sulfide assemblages are:

pyrite-arsenopyrite+native gold,
pyrite-arsenopyrite-sphalerite-galena+native gold (Fig. 2c),
chalcopyrite-pyrrhotite+/-pyrite,
arsenopyrite-sphalerite-galena+native gold, and
sphalerite-galena+native gold

Native gold, reaching a size up to 0.3 mm in diameter, is predominantly associated with sulfides; the Ag-content lies in the range of 2 and 8 wt.%. The maximum Au-concentration in mineralised quartz reefs from the area investigated was 460 ppm (KENNY, 1934; BARNES, 1975); this value is most likely due to deep weathering and supergene concentration.

5. Alteration

Alteration along mineralised quartz veins of the second generation is present, although not a very characteristic feature of these mesothermal lode-deposits. Alteration has been studied along several major gold-bearing veins of the Pioneer Reef in the Warratta Inlier (THALHAMMER, 1993; Fig.1). The main quartz vein of the Pioneer Reef ranges in thickness between 0.5 and 3.5 m. A noticable alteration of the host rock, i.e. a bleached appearance and an apparent increase in the sericite/muscovite content (phyllic alteration) in hand specimen, can be detected in an up to 3 m thick alteration halo paralleling the reef margins. Geochemical investigations revealed that major elements such as S, K, and Al (S>K>Al), and trace elements Au, Cu, Rb, Y, Zr, Nd and Ba (Au>Cu>Rb>Y>Zr>Nd>Ba) are enriched compared to unaltered host rock. All other major and trace elements are depleted. Depletion can be explained by dissolution of mineral phases such as quartz, plagioclase, carbonate and chlorite during deformation and metamorphism, because the host rock is more strained in the vicinity of thick quartz reefs. However, enrichment of elements such as S, K, and Au is significant and the result of addition of these chemical components during quartz vein formation. The same characteristics of alteration has been detected in host rock inclusions within the quartz reef.

6. The deformational history of the Easter Monday Beds and their metamorphic evolution.

All quartz vein generations showed a definite structural control. A detailed investigation of the deformational history and metamorphism of the Easter Monday Beds seems crucial, in order to understand the relative timing of quartz vein formation. The deformational architecture of the Easter Monday Beds in the Mt. Poole, Warratta, and Tibooburra Inliers displays two deformational events (D_1 and D_2; THALHAMMER, 1992a; 1993; THALHAMMER et al., 1998). D_1 is characterized by a general WSW-ENE oriented, compressive deformation leading to the development of parallel chevron F_{1a} folds with NNW and SSE plunging fold axes. Associated with the development of F_{1a} folds is an axial plane cleavage S_{1a} with NNW trending cleavage traces. S_{1a} is the most prominent deformational feature in the Milparinka-Tibooburra district and diserves most attention because the mineralised quartz veins of the second generation are related to this feature. The intensity of strain differs depending on the lithology. Psammite-dominated lithologies exhibit mainly folding on the macroscopic scale, and intra-crystalline deformation, e.g. grain shape elongation and parallel alignment of individual detrital components defining the cleavage. Strain analyses in these lithologies indicate a minimum amount of shortening of 40% (THALHAMMER, 1992a).

Megascopic folding is less common in pelite-dominated lithologies, but display higher strain defined by syn-deformational growth of phyllosilicates delineating a well developed slaty cleavage.

With continued shortening, F_{1a} folds became tighter and more inclined with predominant vergence to the NE, resulting in overturned, locally even recumbent F_{1b} folds without changing their axial directions. The appearance of F_{1b} folds can be explained in the course of progressive deformation under homogeneous strain, i.e. passive amplification (SUPPE, 1985; THALHAMMER, 1992a; THALHAMMER et al., 1998). Furthermore, flexural slip along bedding planes led to the development of saddle reefs in hinge regions, and explains why stiffer layers, such as quartz veins, will boudinage, displaying the pinch-and-swell structures which are typical subsequent to deformation of quartz veins of the second generation. Further superimposed deformational structures are crenulation of the S_{1a} fabric, the developement of a discrete crenulation cleavage S_{1b} (Fig. 4), and en-echelon F_{1b} fold patterns. These superimposed structures can be observed particularly in high-strained zones such as those in the vicinity of major faults (i.e. Warratta and New Bendigo Faults, Fig.1) in the Warratta Inlier. Furthermore, two sets of second order faults are present, the first set trending NNE and the second set NE-ENE. Second order faults are particularly common in the Warratta and Tibooburra Inliers. In both inliers second order faults are oriented at high angle to the lineaments (i.e. New Bendigo and Warratta Faults) bounding the Warratta and Tibooburra Inlier, respectively; it is proposed that they resemble Riedel shear faults resulting from strike-slip displacements along the lineaments (HARDING, 1973; SYLVESTER, 1988). It is worth noting that second order faults in the Tibooburra Inlier occur in the Easter Monday Beds as well as in the granodiorite showing the same trend. The Warratta Fault, as part of the interpreted Olepoloko Fault, and the New Bendigo Fault clearly show components of dextural strike-slip movements which are responsible for the developement of superimposed deformational structures. From the Warratta Inlier, where the relationship of structural features is most obvious, it is assumed that the principal deformational regime was dominated by a transpressive deformation during D_1. With subsequent strike-slip movements along the Warratta and New Bendigo Faults the second order faults changed their trends from NNE (first set) to NE-ENE (second set).

Fig. 4
S_{1a}-S_{1b} fabric (crenulation cleavage) in the Easter Monday Beds of the Warratta Inlier. Length of the scale is 16 cm.

Kinkbands and open folds with WSW trending axes, clearly superimposed on F_1 folds and cleavage S_1, display structures of D_2. The WSW-trending axial directions indicate a change in the maximum compressive force during final stage of deformation.

The above delineated deformational evolution of the Easter Monday Beds took place at metamorphic conditions of 300-350 °C temperatures and at a pressure around 4 kb (THALHAMMER, 1993).

7. The relative timing of quartz veins

On the basis of the deformational and metamorphic development within the Easter Monday Beds, it becomes possible to delineate the relative timing of the quartz veins.

The first generation of quartz veins, clearly superimposed by cleavage S_1 is suggested to have formed prior to deformation, possibly during diagenesis.

The second, mineralised generation of quartz veins were formed syn-tectonically. Structures such as i) the intensification of cleavage S_{1a} traces in the host rock as a quartz vein is approached, ii) inclusion seams and included host rock streaks displaying a weakly developed foliated fabric in the vein, and iii) subsequent deformation of quartz veins, clearly indicate a vein origin prior to the development of F_{1b} folds and cleavage S_{1b}. It can be thus concluded that mineralised veins of the second generation have formed after the commencement of cleavage S_{1a}. Syn-tectonic vein formation seems to have continued during the entire stage of the development of cleavage S_{1a} which is recorded by bent quartz fibres, for instance.

Quartz veins of the third generation, cross-cutting the entire folded and cleaved fabric, clearly suggest an origin during the very final stage of deformation.

8. The approximate age of the mineralisation

After having gained information on the relative timing of the quartz veins in the course of the deformational history of the host rocks, K-Ar datings have been carried out in order to obtain an absolute age estimate on the mineralised quartz veins. The alteration zones, as well as host rock slices (i.e. phyllosilicate streaks) included in the veins of the second generation represent obvious signs of the vein formation process (see further below). Three selected samples have been used to determine the age of the syn-metamorphic mica formation during vein growth. The analytical results (THALHAMMER, 1992a) yielded ages between 420 and 441 Ma for the mica formation, and an apparent age of 440 Ma for the generation of mineralised quartz veins can be proposed.

9. The relative timing of the Tibooburra granodiorite emplacement

One substantial question emerging in the context of this mesothermal lode-gold deposit is the role of the Tibooburra Granodiorite. The Tibooburra Granodiorite is represented by a main granodioritic pluton, a number of dacitic dykes and plugs, and some aplite and pegmatite dykes (THALHAMMER et al., 1998), and has an age of 410 Ma based on whole rock and mineral Sr-isotope data (SHAW, 1982; THALHAMMER et al., 1998). In order to clarify a possible link of the granodiorite to the mineralised quartz veins, it is necessary to know at what time the pluton was emplaced relative to the deformational and metamorphic history of the Easter Monday Beds.

An aplite-pegmatitic dyke at the northern edge of the main pluton is folded around F_1 axes. At this location it is not clear whether these are F_{1a} or F_{1b} fold axes. Evidence within the Easter Monday Beds in the contact-metamorphic aureole indicates that a schistosity existed before the cordierite, as part of the contact metamorphism, grew. Minor faults within the Easter Monday Beds and the granodiorite show the same trend and some faults can be traced from the Easter Monday Beds into the pluton. These evidences suggest that the Tibooburra Granodiorite intruded the Easter Monday Beds after the initial development of F_1 folds, pre-dating brittle deformation (THALHAMMER et al., 1998).

10. The ore-forming fluids

The knowledge of the physico-chemical conditions for hydrothermal systems responsible for lode-gold deposits is a fundamental prerequisite in understanding the geochemistry of gold, as well as processes such as transport and precipitation of gold. Therefore, the composition of the mineralising fluids, the T-a_{O2}-a_{S2}-pH-conditions at the time of mineralisation, and the source of sulfur will be delineated, in the following.

Composition of the fluids

Fluid inclusion (FI) studies have been applied in order to estimate ore fluid composition. FI are common in quartz and occur within inclusion bands (Fig. 3a, b) which are oriented parallel to the vein wall and are interpreted to have been formed during the crack-seal process. The FI were included in the quartz host during incremental growth of the quartz fibres and/or columns and hence are considered representative of the ore fluid conditions at the time of mineralisation. These primary (?) or pseudosecondary inclusions exhibit a size of $< 2\ \mu m$ up to $10\ \mu m$, the average lies around $4\ \mu m$. Minor FI occur in planes cross-cutting the inclusion bands and are classified secondary. Two groups of primary/pseudosecondary FI can be distinguished based on their composition (Fig. 3b):

a) H_2O-rich inclusions

These are H_2O-dominated, CO_2-poor inclusions within inclusion bands. Microthermometrical investigations revealed freezing points between 0.9 and 3.04 °C, corresponding to 1-5 wt.% NaCl aquivalent (POTTER et al., 1987). Melting experiments showed homogenization into the liquid state and homogenization temperatures (T_h) in the range of 284 to 352 °C, where 73% of FI homogenize at temperatures between 310 and 340 °C (Fig. 5).

b) CO_2-rich inclusions

These inclusions occur also within inclusion bands and exhibit at room temperatures liquid H_2O (L_1), liquid CO_2 (L_2), and CO_2 vapour (V_2). Microthermometrical investigations on 30 inclusions revealed final CO_2 melting temperatures (T_{mCO2}) of -56.8 to -58.2 °C. This indicates the presence of < 5 mol % CH_4 and/or N_2 (HOLLISTER & BURRUS, 1976; TOURET, 1982). Melting temperatures of clathrate (T_{mCLATH}) range from +9.5 to +10.7 °C, which also indicates presence of other gases (CH_4, N_2) apart of CO_2. Temperatures of homogenization range from 294 to 365 °C, 62% homogenize at temperatures between 310 and 340 °C (Fig. 5).

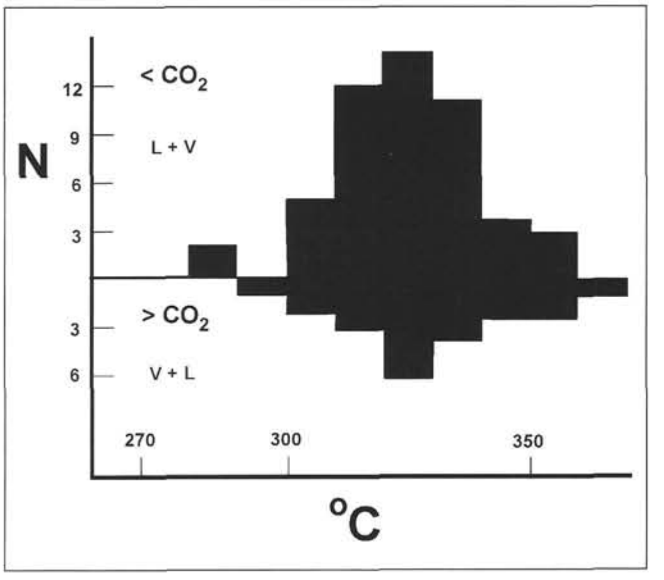

Fig. 5
Histogram of temperatures of homogenization (Th) from H_2O-rich (upper part) and CO_2-rich inclusions.

As a consequence, the ore fluids are of a CO_2 (CH_4)-H_2O-hydrothermal system of low salinity. It can be further concluded that two unmixed fluids, a H_2O-rich and a CO_2-rich, existed at the time of entrapment. Additional compositional characteristics are high K and S contents which are indicated from the geochemical significance of the alteration zone (see above).

T-a_{O2}-a_{S2}-pH conditions of the ore fluids

FI studies and phase equilibria constraints are taken into consideration in order to define the ore fluid conditions in a more detail. The critical point for the pure CO_2-H_2O-system of around 280 °C at metamorphic pressures of 2-4 kb (BOWERS & HELGESON, 1983) rises with the presence of CH_4 and NaCl, and two unmixed fluids may exist up to a temperature of 400 °C. This implies that the fluids were trapped close to the solvus of the CO_2(CH_4)-H_2O(NaCl)-system, and thus homogenization temperatures are close to real temperatures of entrapment without pressure correction (BOWERS & HELGESON, 1983; HO et al., 1990). It can, therefore, be concluded that entrapment of fluids took place at temperatures from 310 to 340 °C, which coincides with syn-deformational vein formation at temperatures of 300 to 350 °C.

The characteristic paragenesis quartz-muscovite/illite in host rock inclusions in the mineralised veins and in the alteration zone gives an indication for the pH-conditions of the fluids. The stability of muscovite/illite coexisting with quartz and lacking kaolinite and K-feldspar is limited to a pH between 4.3 and 5.9 at 300 °C (HEMLEY, 1959; MONTOYA & HEMLEY, 1975; CASADEVALL & OHMOTO, 1977; Fig. 6a). Further indication of pH-conditions derive from the presence of pyrrhotite and the association of pyrite-arsenopyrite which indicate a pH of <6 at temperatures <500 °C, according to OHMOTO (1986). The association of pyrite-arsenopyrite, pyrite+/-pyrrhotite and the absence of hematite and magnetite limits the a_{O2}-conditions of the fluid from log -28.5 to log -36.8, as illustrated in Fig. 6a.

The sulfide mineralogy of the mineralised quartz veins gives indication of the S-activity of the fluids. Accordingly, a log a_{S2} of -7.5 to -9.0 can be assumed, on the basis of the composition of the arsenopyrite in association with pyrite and the FeS-content of sphalerite (SHARP et al., 1985; BARTON, 1969; BARTON & SKINNER, 1979; Fig. 6b).

S-isotope investigations

In this chapter the source of sulfur in the ore fluids will be discussed, based on the sulfide mineralogy of the quartz-lodes and sulfur isotope data.

Sulfur isotopic data ($\delta^{34}S$ values) have been obtained from sulfides (pyrite and arsenopyrite) from the quartz-lodes of the Warratta and Mt. Poole Inliers, from pyrites from altered and unaltered host rocks, and from whole rock samples from the Tibooburra Granodiorite (THALHAMMER, 1991; 1993). The $\delta^{34}S$ values of sulfides from the quartz-lodes lie in the range of +2 and +4‰, pyrites from unaltered host rocks reveal $\delta^{34}S$ values of -0.9 to +1.2‰, those from alteration zones gave $\delta^{34}S$ values of +2.9 to +3.8‰.

In general, three different possibilities can be suggested for the source of sulfur in low-salinity, CO_2-rich, aqueous, mesothermal fluids in the area under investigation:

i) magmatic sulfur, derived from the mantle; the sulfur would be characterized isotopically by $\delta^{34}S$ values of -4 to +4‰, ii) sulfur which has been derived from dissolved sulfides hosted in volcanic or volcano-sedimentary sequences; sulfur isotope data would give $\delta^{34}S$ values in the range of 0 +/-3‰, and iii) sulfur derived from sea water by reduction of SO_4^{2-}; in this case the sulfur isotopes would give $\delta^{34}S$ values of +4 to +12‰.

The sulfur isotopic composition of the fluid is mainly constrained by:

a) the $\delta^{34}S$ value of S_{tot} in the fluid, b) the temperature of the fluid, and c) the a_{O2}- and pH-conditions of the fluid (OHMOTO, 1972; OHMOTO & RYE, 1979; OHMOTO, 1986). The temperature and the a_{O2}- and pH-conditions of the fluid are particularly important because they control the S-isotopic fractionation between S_{tot} of the fluid and the precipitated sulfides. The temperature, a_{O2}- and pH-conditions of the fluid (i.e. 300-330 °C, generally low a_{O2}, and neutral to slightly acid pH-conditions, respectively), as outlined above, clearly indicate that H_2S was the dominating S-species in the mineralising fluids (Fig. 7; OHMOTO, 1972; OHMOTO & RYE, 1979; OHMOTO & LASAGA, 1982). The sulfur isotopic composition of the precipitated sulfides gives a direct indication for the S-isotopic composition of the fluid if one S-species dominates, and if isotopic fractionation between the S-species and the formed sulfides is low (OHMOTO & RYE, 1979). This is in fact the case. Therefore, taking the estimated temperatures of 300-340 °C into account, the $\delta^{34}S$ value of the sulfur in the fluid can be estimated according to the following relation (OHMOTO & RYE, 1979):

$$\delta^{34}S_{\Sigma S\text{-}fl} = \delta^{34}\Sigma H_2S + \Delta SO_4^{2-} \times R(1+R)$$

where R is the mole ratio of $\Sigma SO_4/\Sigma H_2S$ in the fluid, and $\Delta SO_4^{2-} = \delta^{34} S_{SO4}^{2-} - \delta^{34}S_{H2S}$. The presence of SO_4^{2-} as S-species can be neglected under present fluid conditions, and hence, it can be concluded that $\delta^{34}S_{\Sigma S\text{-}fl}$ is simply constrained by $\delta^{34}S_{H2S}$. Under these circumstances, the $\delta^{34}S$ values of pyrite, as the by far dominating sulfide precipitated from the ore fluids, directly give the $\delta^{34}S_{\Sigma S\text{-}fl}$. This implies that $\delta^{34}S$ values of

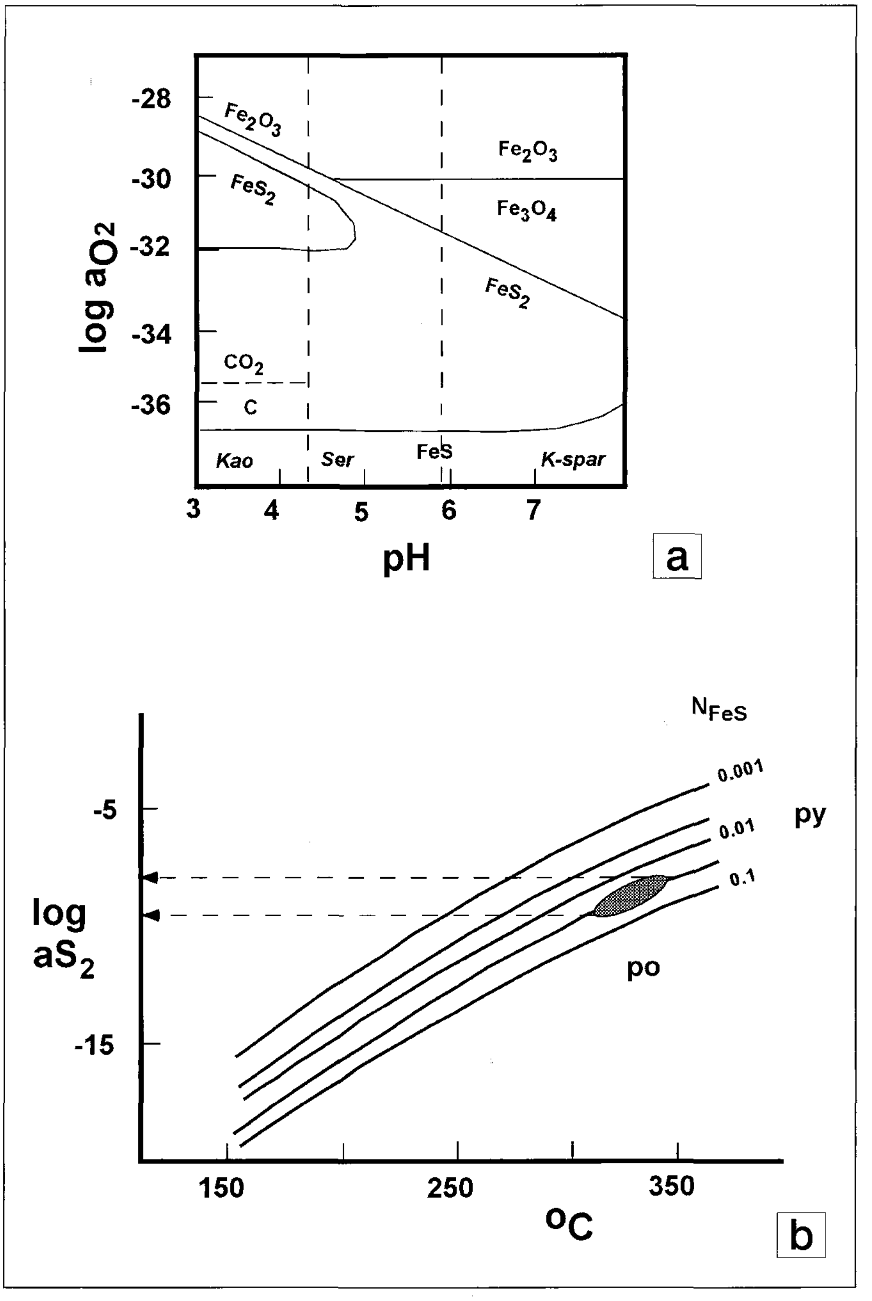

Fig. 6
6a – Log a_{O2}-pH diagram with stability fields for the mineral phases in the system Fe-S-O after CASADEVALL & OHMOTO (1977).
6b – Log a_{S2}-temperature diagram showing the field for arsenopyrites of the Milparinka-Tibooburra district on the basis of FeS contents (contour-lines after BARTON & SKINNER, 1979) at a temperature of 300-350 °C. The stability areas of pyrrhotite (po) and pyrite (py) are indicated.

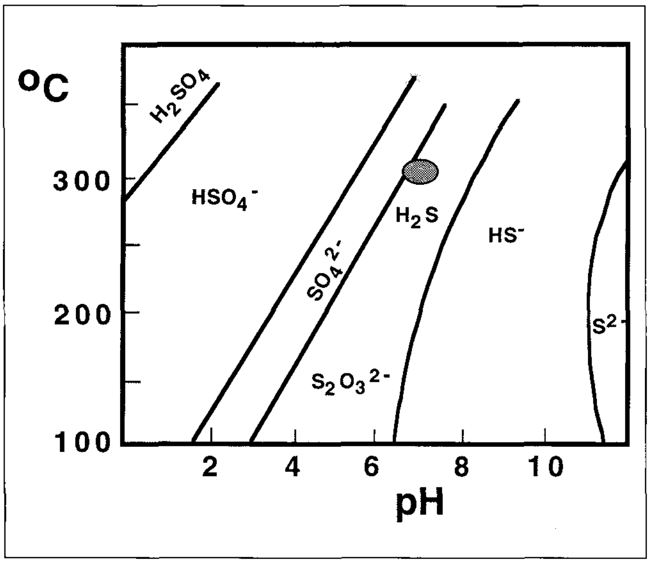

Fig. 7
T-pH diagram with stability fields for various sulfur species after OHMOTO & LASAGA (1982), the approximate T-pH conditions of the mineralising fluids are indicated.

sulfides can be used to obtain indications for the source of sulfur in the fluids. Consequently, a $\delta^{34}S_{\Sigma S\text{-}fl}$ in the range of +2 to +4‰ can be assumed. The $\delta^{34}S$ values further indicate that we are dealing with either a magmatic source of sulfur, or sulfur has been derived from sulfides hosted in a volcano-sedimentary sequence. These two possibilities can not be distinguished clearly on the basis of the present data; a sea water source can be excluded because fluid conditions do not argue for the presence of SO_4^{2}. If assuming that the sulfur derived from sulfides hosted in a volcano-sedimentary sequence underlying the inliers under investigation, the following scenario can be delineated:

Pyrite and pyrrhotite can be assumed to form representative, magmatic sulfide phases within a volcano-sedimentary sequence. During prograde metamorphism the sulfides become decomposed according to the following simplified reactions:

$$FeS_2 + 2H_2O \rightarrow Fe^{2+} + 2H_2S + 2O_2$$
$$FeS + H_2O \rightarrow Fe^{2+} + H_2S + 1/2O_2$$

The result is release of H_2S which would have a $\delta^{34}S$ value very similar to the primary, magmatic sulfides (i.e. around 0‰; OHMOTO & RYE, 1979; OHMOTO, 1986). Experimental studies have shown that H_2S released from primary sulfides during metamorphism in a temperature range of 350 to 650 °C, exhibit an enrichment of the heavy ^{34}S isotope (GRINENKO & GRINENKO, 1976). This implies that ^{34}S fractionates into the fluid phase, with the result that H_2S becomes isotopically heavier, displayed in $\delta^{34}S$ values of up to +5‰, compared to the initial value of 0‰ (CROCKET & LAVIGNE, 1984). This is exactly what we can recognize in the obtained isotopic compositions from sulfides of the quartz-lodes, revealing $\delta^{34}S$ values of +2 to +4‰.

The slightly lighter isotopic composition of pyrites from the alteration zone of quartz-lodes, compared to those from unaltered host rocks could be explained by interaction of fluid with vein-wall rock. During this reaction a limited amount of SO_4^{2-} might be produced resulting in a lower $\delta^{34}S$ value (OHMOTO, 1972; PHILLIPS et al., 1986).

On the basis of mineralogical, geochemical and FI studies outlined so far, the mineralising fluids are slightly acid, slightly oxidising, show low-salinity, are CO_2-, S-, K-rich, with H_2S as the dominating S-species, and in a temperature interval of 300 to 340 °C. They altered the wall rock during vein precipitation, which clearly indicates that ore fluid and host rock was not in equilibrium at the time of vein formation. Therefore, a derivation of fluids from deeper sources, most likely a volcano-sedimentary sequence, but not from the immediate host rocks of the quartz-lodes, is strongly suggested. This conclusion is in agreement with results from many other mesothermal gold-lode deposits (FYFE et al., 1978; PHILLIPS & GROVES, 1983; GROVES et al., 1984; WALL, 1987; GROVES et al., 1988; HO et al., 1990; KERRICH & CASSIDY, 1994; PHILLIPS & HUGHES, 1996; RIDLEY et al., 1996; GROVES et al., 1998; and references cited therein).

11. Formation of mineralized quartz veins

In the following, emphasis is placed on the interaction of fluid circulation, vein formation and deformation processes. The textures of mineralised veins of the second generation give clear evidence for tensile fractures, although they are oriented sub-parallel to the direction of maximum compression (i.e. cleavage S_{1a}; THALHAMMER, 1992a). This implies a local abnormal stress field, for which the main factors responsible are special mechanical properties of the rocks and high fluid pressure. Both factors are present particularly in pelite-dominated lithologies, which represent the preferential hosts for mineralised quartz veins. These lithologies have a very small porosity and permeability under metamorphic conditions and at fluid pressure (P_f) < load pressure (P_l) (FYFE et al., 1978; YARDLEY, 1983; COX et al., 1990) and are folded. It is assumed that migrating fluids pooled beneath low-permeable horizons and were trapped, particularly beneath anticlinal F_{1a} folds (THALHAMMER, 1992a). As a consequence, migration of fluids was impeded, resulting in considerable increase of fluid pressure. As soon as P_f increases to near-lithostatic levels (P_l), and as soon as the developing axial plane cleavage S_{1a} lowered the tensile strength of the rock, a hydraulic fracture is formed sub-parallel to the direction of maximum compression, and filled with fibrous quartz and additional components precipitating from the fluid. As the fracture-fill seals the fracture, the fluid pressure will built up again, and the process will be repeated. This process is known as the 'crack-seal process' according to RAMSAY (1980) and COX & ETHERIDGE (1983). The primary growth features of mineralised veins strongly indicate a complex vein-growth history with hydraulic fracturing and fracture healing in multiple increments. The crack-seal increments are recorded by the appearance of inclusion bands (Fig. 3a) and by included phyllosilicate streaks (Fig. 2b) which give some veins a banded nature. The local truncation of cleavage S_{1a} traces by the vein contacts can be interpreted as occasional jumping of the vein opening from one plane of anisotropy to the other (MAWER, 1987; THALHAMMER, 1992a; 1993). The more columnar-shaped quartz crystals (Fig. 2a) in the veins (as opposed to fibrous quartz) can be explained by more rapid growth occlusion by neighbouring quartz crystals, a process of competition of quartz crystal growth (COX, 1987). The quartz crystal-size increase and common occurrence of quartz columns towards the centre of a vein, is interpreted accordingly. This also indicates that quartz crystals became younger towards the centre of a vein, implying syntaxial vein growth. After incremental precipitation, the successive vein history was dominated by deformation controlled by the regional tectonic regime. This is recorded by the secondary textures of quartz veins of the second generation as outlined above.

The transport paths of the mineralising fluids were apparently constrained by fundamental anisotropies in the host rock. The axial surface cleavage S_{1a} seems to represent the most important plane of weakness in this context.

12. Source of gold and associated metals

Four principle possibilities as a gold source can be stressed:

a) the immediate host rocks to the mineralised quartz veins from which gold would have been liberated during metamorphism, b) gold-derivation from a deep-seated crustal source, c) gold derived from a coeval granitoid, and d) gold derived directly from a mantle source.

In the Tibooburra-Milparinka district all four possibilities of gold derivation are principly present. Starting with possibility c), the Tibooburra Granodiorite can nearly be excluded as a source for gold and associated metals. Although the Tibooburra Granodiorite represents a syn-tectonic pluton that intruded the Easter Monday Beds during D_1, no mineralised quartz veins, no primary quartz-reef deposits, associated with the granodiorite are known (BARNES, 1975; GIBSON, 1989). Also, no elevated increase in the gold contents of the Easter Monday Beds within the contact-metamorphic aureole could be encountered, the Au-contents are in the range of 1 to 3 ppb.

The next possibility to take into consideration are the host rocks to the mineralised quartz veins: the question emerging within this context is, whether 3000 to 5000 kg gold plus associated metals can be dissolved from the Easter Monday Beds during deformation and metamorphism to form the mineralised quartz veins. Evidences such as i) the S-Au-K-enriched alteration zones, ii) no significant gold dissolution in the Easter Monday Beds during deformation and metamorphism, and iii) mass balance calculations on the basis of SiO_2, revealing that the amount of SiO_2 released during deformation and metamorphism in the Easter Monday Beds was by far not sufficient to form the mineralised quartz veins, strongly indicate that the immediate host rocks to the auriferous quartz veins were not the preferential source for gold and associated metals (THALHAMMER, 1991; 1992b; 1993).

Finally, two more possibilities remain: either the gold was derived directly from the mantle, or it came from a deep crustal source. In order to obtain a direct indication for the source of gold and associated metals, the Pb-isotopic composition of pyrites from the mineralised quartz veins, pyrite from the host sediments, gold from veins, and alluvial, naggety gold from a creek at the northeastern edge of the Mt. Brown Inlier (Fig. 1) was determined. Vein pyrites and vein gold revealed consistent $^{206}Pb/^{204}Pb$-, $^{207}Pb/^{204}Pb$-, and $^{208}Pb/^{204}Pb$-ratios, respectively, whereas pyrite from the host rocks is slightly, the alluvial gold significantly more radiogenic (Tab. 1). This is also illustrated in the $^{207/204}Pb$ vs. $^{206/204}Pb$ diagram (Fig. 8). Vein pyrite and vein gold form a cluster very closely beneath the CUMMING & RICHARDS Pb-growth curve (C&R-curve) (CUMMING & RICHARDS, 1975). Calculated μ-values are between 10.72 and 10.73 which coincides with the average μ-value of 10.75 +/-0.03 given for the Pb-growth-curve by CUMMING & RICHARDS (1975). This implies that the lead within the gold and the associated metals of the mineralised quartz veins has a deep crustal source, a source which was formed by a repeated mixture of crustal and mantle components (ZARTMAN & DOE, 1981).

Host rock pyrite plots slightly above the C&R-curve (Fig. 8). The deviation from Pb-Pb ratios of vein pyrite and gold is within the level of precision, and thus it is at present not clear whether the difference is significant. However, the deviation of the alluvial gold is significant (Fig. 8), and suggests that the alluvial gold has recently acquired young, radiogenic lead during nugget-formation. Calculated Pb-Pb model ages for vein pyrite and vein gold yielded 485 to 506 Ma, based on model 3 of CUMMING & RICHARDS (1975) (Tab. 1), commensurate with the K-Ar dating on vein mica.

Table 1
Pb isotopic data from the Warratta Inlier. OT108 = pyrite concentrate from the Easter Monday Beds, PY-1 and PY-2 = pyrite concentrates from auriferous quartz veins of the Pioneer Reef (Warratta Inlier), Au-P = primary gold from the Pioneer Reef, Au-S = "secondary" gold from an alluvial deposit south of the Mt. Poole Inlier.

SAMPLE	OT108	PY-1	PY-2	Au-P	Au-S
$^{206}Pb/^{204}Pb$	18.023+/-0.03	17.958+/-0.03	17.974+/-0.03	17.994+/-0.03	18.235+/-0.03
$^{207}Pb/^{204}Pb$	15.645+/-0.03	15.607+/-0.03	15.607+/-0.03	15.614+/-0.03	15.619+/-0.03
$^{208}Pb/^{204}Pb$	38.160+/-0.15	38.034+/-0.15	38.047+/-0.15	38.075+/-0.15	38.462+/-0.15
$^{207}Pb/^{206}Pb$	0.8681	0.8690	0.8683	0.8677	0.8566
$^{208}Pb/^{206}Pb$	2.1173	2.1180	2.1167	2.1168	2.1093
Pb (ppm)	275	587	349		
t76*	489 Ma	491	480	475	
t6*	469 Ma	506	497	485	
t8*	359 Ma	420	414	400	
μ*	10.79	10.72	10.72	10.73	
$^{232}Th/^{238}U$*	3.94	3.92	3.91	3.92	

* Parameters applied for calculations are those from CUMMING & RICHARDS (1975) Model 3:
μ = 10.75+/-0.03; $^{232}Th/^{238}U$ = 3.84+/-0.02

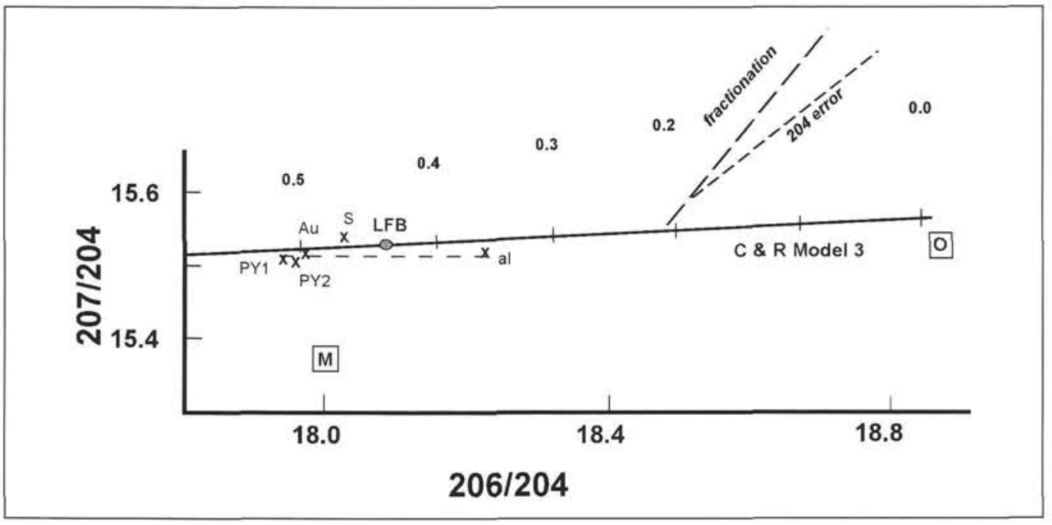

Fig. 8
Composition of Pb isotopes from the Warratta Inlier in the $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram. C & R Model 3 refers to the Pb growth curve after CUMMING & RICHARDS (1975) model 3. M = end of the mantle curve after DOE & ZARTMAN (1979), O = end of the orogene curve after DOE & ZARTMAN (1979), LFB = average of 41 Pb isotopic compositions from the Lachlan Fold Belt, New South Wales (unpubl. data J. Richards), PY1 and PY2 are pyrite samples from gold-bearing quartz veins of the Pioneer Reef (Warratta Inlier), Au is a gold sample from the Warratta Inlier, S refers to a pyrite sample from the Easter Monday Beds (Warratta Inlier), al is an alluvial gold from south of the Mt Poole Inlier (Fig. 1).

13. Transport and precipitation of gold

It is widely accepted now that gold is transported in hydrothermal solutions at mesothermal conditions (i.e. 250 to 400 °C) as a sulfide complex (SEWARD, 1973; 1984; HAYASHI & OHMOTO, 1991). At least three gold bisulfide complexes, $Au(HS)^{\circ}$, $HAu(HS)_2^{\circ}$, $Au(HS)_2^-$ are potentially important in transporting gold. Subsequent work by BENNING & SEWARD (1994; 1996) showed that $Au(HS)_2^-$ is the dominant bisulfide complex in neutral, H_2S-rich solutions.

It has been outlined above that near neutral, $CO_2(CH_4)$-H_2O-fluids, rich in H_2S, of low salinity, and of a deep crustal source were active during formation of mineralised veins in the Milparinka-Tibooburra district. As a consequence, $Au(HS)_2^-$ is suggested the preferential gold-transporting complex, and the solubility of gold can, thus be expressed as:

$$Au(HS)_2^- + H^+ + 1/2H_2 \rightarrow Au + 2H_2S$$

Gold solubility of ore fluids under the proposed T-a_{O2}-a_{S2}-pH conditions with H_2S as the dominant S-species was presumable high (JOHNSON et al., 1992; BENNING & SEWARD, 1996). This could indicate that the ore fluids were probably undersaturated with gold in their deeply seated source regions, as already suggested by PHILLIPS & POWELL (1993). This would imply that deeply sourced fluids remained potential ore fluids over their entire rise from deep up to higher crustal levels without becoming depleted in gold (MICKUKI & RIDLEY, 1993; MICKUKI, 1998).

Precipitation of gold from hydrothermal ore fluids is a response to changes in the physico-chemical conditions of the fluid at the site of deposition, resulting in destabilisation of gold-sulfide complexes. The absolute critical factor is the activity of S ($a_{\Sigma S}$) in the ore fluid. The following parameters seem important for the precipitation of gold in the Warratta and Mt. Poole Inliers:

a) changes of the P-T conditions of the fluid, b) fluid-rock interaction, and c) separation of solid and/or fluid phases.

It is suggested that gold precipitation represents a combination of more than one of these mechanisms. The most important, complex process is the interaction of the ore fluid with the wall rock. Wall rock sulfurisation will result in H_2S loss and precipitation of gold. This is indicated by S-enriched alteration zones. Reaction of the ore fluid with the wallrock, particularly with the dark, finely laminated, pelite-dominated, reducing lithologies of the Easter Monday Beds (i.e. they host the highest density of mineralised quartz veins), will result in reduction of the fluid and destabilisation of gold complexes. A further important mechanism is the separation of sulfide phases (i.e. pyrite, arsenopyrite) caused by a drop in pressure and temperature. A drop in pressure takes place during repeated opening of hydraulic fractures (crack-seal process) resulting in a change of a_{H2S} and hence in precipitation of gold. The presence of both, CO_2-rich and H_2O-rich fluids indicates immiscibility of the initial CO_2-H_2O ore fluid, possibly caused by a drop in temperature and change of the physico-chemistry of the ore fluid. In summary the mechanism of gold and associated sulfide precipitation can be expressed in the following simplified reaction (LAMBERT et al., 1984; THALHAMMER, 1993):

$$Au(HS)_2^- + FeO + 1/2O_2 \rightarrow Au^{\circ} + FeS_2 + 1/2H_2O + OH$$
(in the wall rock)

14. Summary – a comprehensive model of the genesis of mesothermal lode-gold deposits in the Milparinka – Tibooburra District

Auriferous quartz veins in the Milparinka-Tibooburra district occur in low-grade metamorphosed sediments of the Easter Monday Beds in the Warratta and Mt. Poole Inliers. Mineralised veins exhibit the highest density within dark, pelite-dominated lithologies and are structurally controlled due to a penetrative axial plane cleavage S_{1a}. Structural studies and textural characteristics of the mineralised veins strongly suggest a syn-tectonic formation close to the peak of metamorphism. The mineralisation is resembled by free gold, dominating pyrite, subordinate arsenopyrite, pyrrhotite, chalcopyrite, sphalerite and galena. The veins are accompanied by alteration zones at vein margins, which are characterized by an Au-S-K-halo. The Tibooburra Granodiorite, a pluton of I-type character, intruded syn-tectonically the Easter Monday Beds in the Tibooburra Inlier.

The ore-forming fluids are near neutral, slightly oxidising, H_2S-rich, $CO_2(CH_4)$-H_2O-fluids of low salinity. Fluid inclusion studies indicate a temperature of entrapment between 300

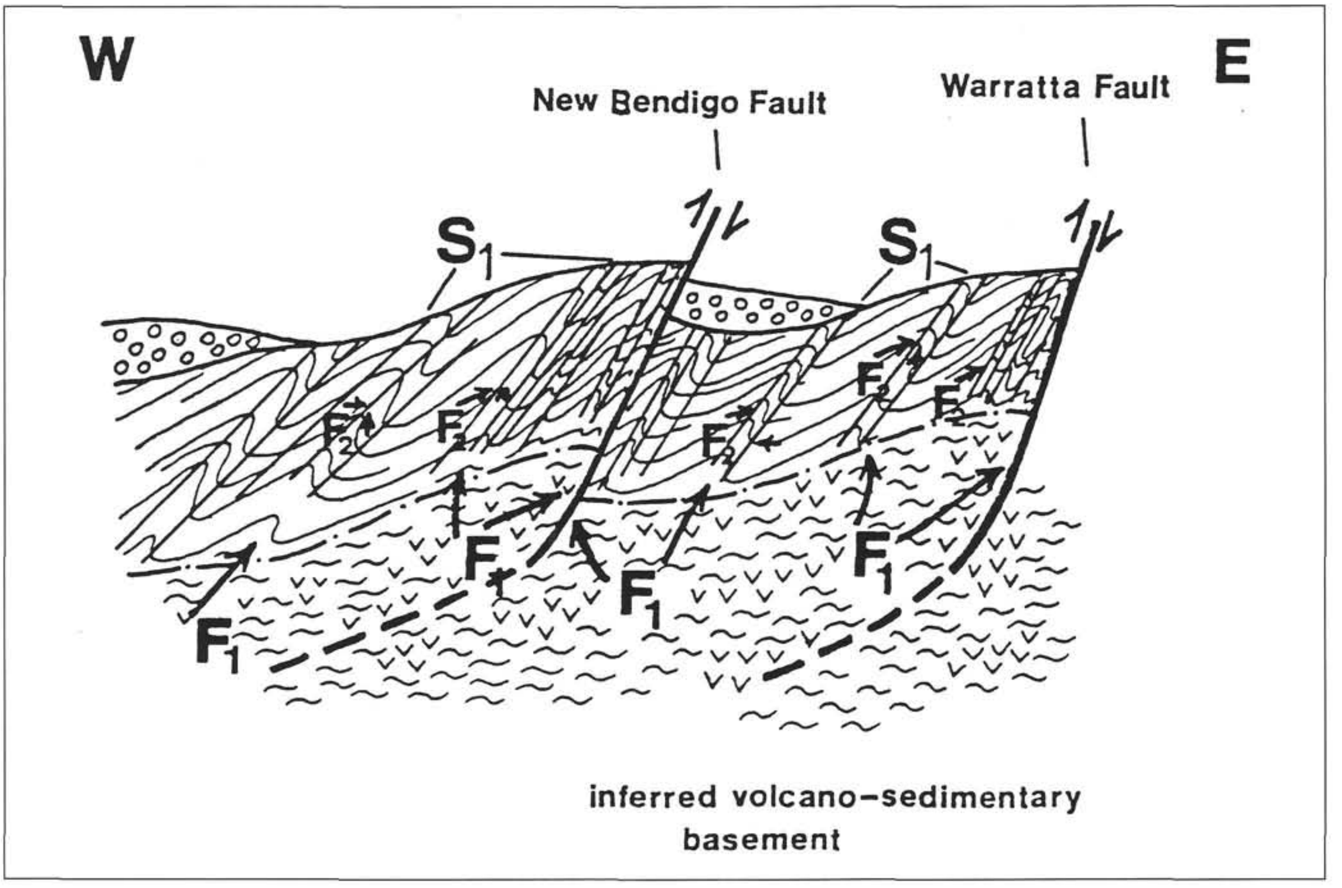

Fig. 9
Schematic section through the Warratta Inlier (not on scale), assuming a volcano-sedimentary basement which is the source for metals and mineralising fluids (F_1). A restricted contribution of local fluids (F_2) can be assumed.

and 340 °C. The existence of alteration zones and sulfur isotope data strongly suggest a deep crustal source of ore fluids. It can be inferred, on the basis of Pb-Pb isotopic data and geochemical results, that this ore fluid source was represented by a volcano-sedimentary sequence (see Fig. 9). The studies further suggest that gold, sulfur, and the associated metals derive from this deep crustal source, initially hosted in primary, magmatic sulfides that became dissolved during metamorphism. Under the outlined hydrothermal fluid conditions, gold was transported as $Au(HS)_2^-$ complex. Ore fluids migrated from deep to lower crustal levels using NE-SW trending lineaments (such as the New Bendigo and Warratta Faults, Fig. 9) and cleavage planes as preferred transport paths. Fluids most likely pooled beneath low permeable pelite-dominated lithologies and were trapped in hinge regions of anticlines. Mineralised quartz veins formed by hydraulic fracturing and fracture sealing in multiple increments, the crack-seal mechanism. The age and duration of metamorphism and mineralised vein-formation, as delineated by K-Ar and Pb-isotopic studies, is presumable between < 500 and 420 Ma. Gold and associated metals were deposited during complex fluid-wallrock interaction and drop of P-T conditions of the fluid leading, most importantly, to a drop in a_{H2S}. This induced destabilisation of gold-bisulfide complexes and leads finally to precipitation of gold.

It has been shown that the Tibooburra Granodiorite, although temporally related to deformation/metamorphism and mineralised quartz vein formation, is not the source of ore fluids, gold and associated metals. However, a contribution of the granodiorite to the ore-forming system as a heat source, and that the I-type parental melt development might represent a driving mechanism for the hydrothermal system, can not be excluded.

15. Acknowledgements

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