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THE ORIGIN OF GOLD MINERALIZATION IN THE PILGRIM'S REST GOLDFIELD, EASTERN TRANSVAAL

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by

N. TYLER

(Bureau of Economic Geology, University of Texas, Austin, Texas, U.S.A.)

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ABSTRACT

More than 155 metric tonnes (five million ounces) of gold and a significant amount of silver have been won from ore-deposits in the Pilgrim's Rest Goldfield over more than a century of mining. The principal ore-bodies in the district are found in the Malmani Dolomite, where they occur as peneconcordant, tabular bodies restricted to three stratigraphic zones. These correspond to three, discrete, mineralized areas, separated by expanses of dolomite devoid of mineralization. In the Sabie area, ore-bodies are found in the Black Reef and in the overlying transition-zone with the main mass of dolomite. The prolific Pilgrim's Rest mines exploited gold-silver veins located in the top portion of the dolomite column and in the Pretoria shales that rest on the Bevets conglomerate. To the north, ores in the Vaalhoek Mine are found in the lower dolomite-and-chert zone.

Sedimentological analysis of the host-dolomites indicates that they were deposited under supratidal-to-deep-subtidal (midshelf) conditions on a broad platform. Two transgressive cycles, from supratidal/lagoonal to subtidal carbonates (the transition and lower dolomite-and-chert zones) and from intertidal to midshelf carbonates (chert-poor zone), respectively, are capped by a third phase of carbonate sedimentation, characterized by short-lived and rapid shoaling and deepening events, rather than by overall transgression and regression (the upper dolomite-and-chert zone). A strong relation between ore-body location and environment of deposition of the host-sediment has emerged. Mineralization is restricted to sediments deposited in shallow water (intertidal-to-shallow-subtidal zones); deeper-water carbonates are barren. More specifically, the ores appear to be closely related to carbonaceous, terrigenous sediments.

Fluid-inclusion analysis of quartz gangue in the quartz-pyrite-gold-silver veins indicates that the mineralizing solutions were saline and rich in CO_2. The inclusions were trapped under a temperature-of-formation gradient of 100°C/km. Preliminary geobarometry suggests depths of formation of 5,5-7,0 km. A range of homogenization- and decrepitation-temperatures in each sample indicates that mineralization was a multiphase event. Tightly-clustered sulphur-isotope data ($\delta^{34}S$ of +0,5 - +4,0 per mil). obtained from pyrite are non-diagnostic. Oxygen-isotopic compositions of the mineralizing fluids, recalculated from $\delta^{18}O$ quartz (+12,1 - +19,5), point to a magmatic source and subsequent mixing with saline, evolved formation-water. A magmatic origin is supported by the high, homogenization-temperature-gradient displayed by the fluid inclusions. Reconnaissance fluid-inclusion barometry suggests that the ores were emplaced during late-Transvaal volcanism.

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THE ORIGIN OF GOLD MINERALIZATION IN THE PILGRIM'S REST GOLDFIELD, EASTERN TRANSVAAL

INTRODUCTION

Gold was discovered in the Sabie-Pilgrim's Rest area, on the farms Spitzkop and Hendriksdal, in 1872. The following year was marked by additional discoveries on Geelhoutboom (now MacMac) and in Pilgrim's Creek (Reinecke and Stein, 1929). More than a century and 155 metric tonnes (five million ounces) of gold later, this metal continues to be won from alluvial workings and, more importantly, from strata-bound, "bedded" ore-bodies in the Malmani Dolomite. Strata-bound ore-bodies were first detected in the late-1870's and soon were producing more gold than the alluvial diggings. Although the diggings composed the largest alluvial goldfield in South Africa, they soon faded in importance, as the gold in the rivers and creeks around Pilgrim's Rest and Sabie was worked out.

The golden years of the Pilgrim's Rest Goldfield have passed. Yet, even after 100 years of exploitation, understanding of the genesis of these gold-silver ore-bodies is poor. With the exception of smaller deposits elsewhere in the Malmani Dolomite, such as the Malmani Goldfield in the Marico distinct, western Transvaal, the age and nature of the mineralization at Pilgrim's Rest are unique. No comparable analogues have been reported from elsewhere in the World. Clearly, the Pilgrim's Rest Goldfield warrants detailed investigation of the stratigraphic and structural controls on the localization of the ores, the nature of the mineralizing fluids, and the age of mineralization. This paper describes the results of analyses of the stratigraphic controls on ore-genesis in the Pilgrim's Rest district, of the isotopic composition of the accompanying gangue minerals, and of fluid-inclusions in vein-quartz in the vein-deposits.

Geological Framework

The Sabie-Pilgrim's Rest-Vaalhoek Goldfield, referred to as the Pilgrim's Rest Goldfield in this paper, covers an area of 600 sq. km., centred on Pilgrim's Rest in the eastern Transvaal (Fig. 1). Principal ore-bodies lie within the Malmani Dolomite Subgroup of the early-Proterozoic Transvaal Supergroup. Mineralized vein-systems also crosscut the granitoid basement and occur as bedded, tabular deposits in the protobasinal phase of the Transvaal Supergroup (the Wolkberg Group), in the Black Reef Quartzite, and in the basal part of the Pretoria Group (Fig. 2).

The Transvaal Supergroup is the product of sedimentation in a stable, intracratonic basin that covered at least 500 000 sq. km. Twelve thousand metres of sediment were deposited in this basin, largely under conditions of shallow-marine sedimentation in an epeiric sea. Initial basin-infilling took place in two local sub-basins, named the Wolkberg and the Buffalo Springs basins, in the northeastern and west-central Transvaal, respectively (Button, 1973; Tyler, 1978). Fluvial and deltaic sedimentation predominated during this early phase of clastic sedimentation that was periodically interrupted by volcanism. Crustal instability, indicated by igneous activity, subsequently manifested itself as a broad, crustal downwarp

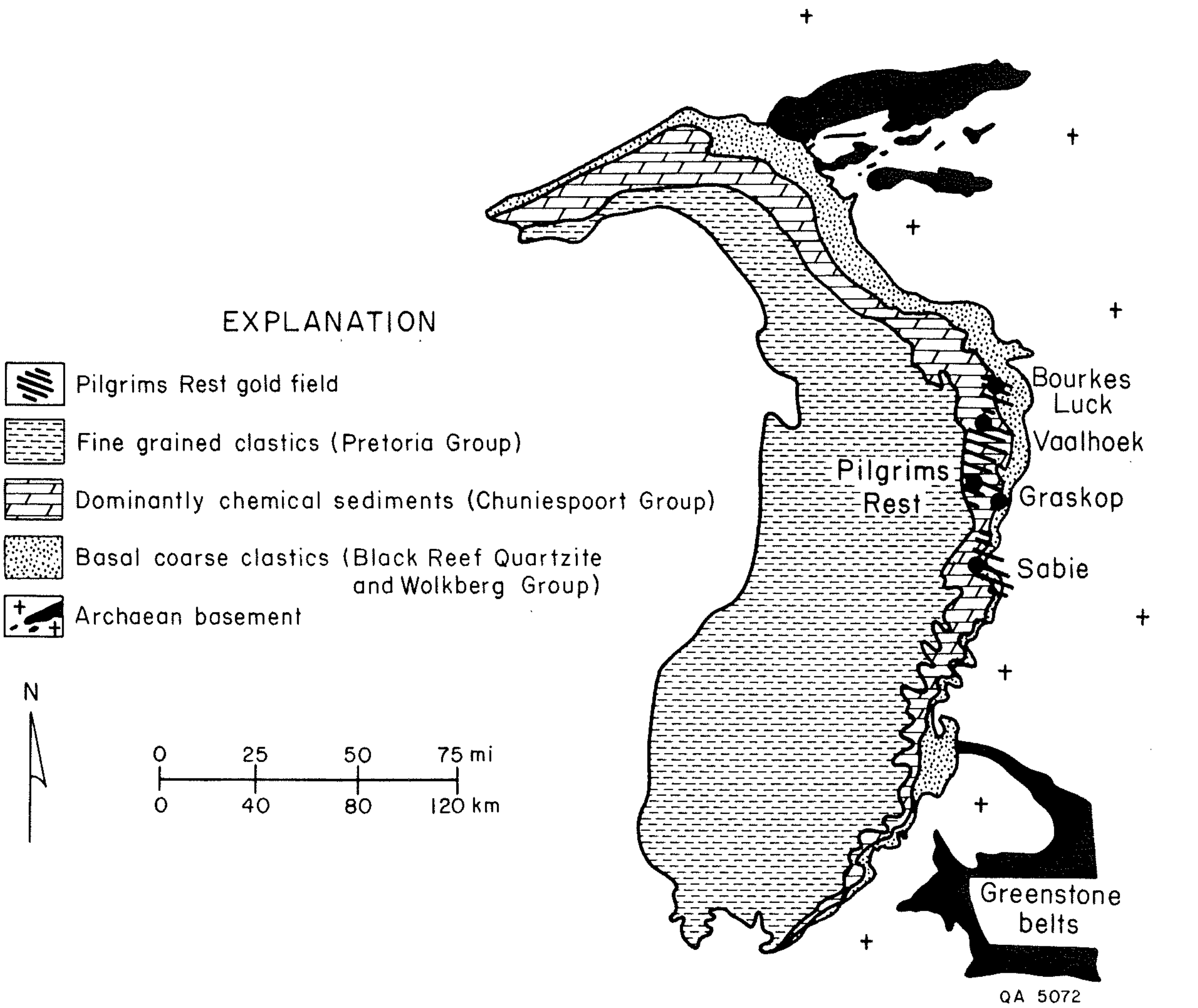
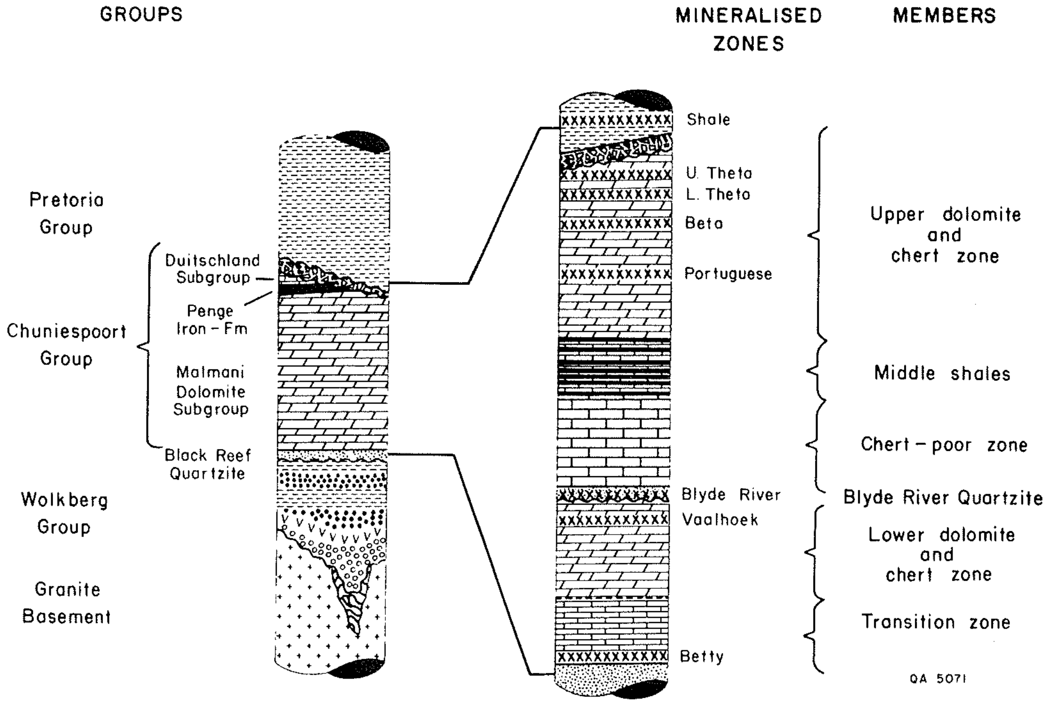


Figure 1 : *Location and simplified geology of the Pilgrim's Rest area.*

that was filled by high-energy, shore-zone clastics (Black Reef Quartzite), by supratidal-to-shelf-edge carbonates (the Chuniespoort Group), and by cyclic, shore-zone and shelf, clastic sediments (Pretoria Group). More-detailed descriptions of the depositional history of this early-Proterozoic, epeiric basin are presented in Button (1973b), Tyler (1979), and Tankard and others (1982).

Distribution of Ore-Deposits

The strata-bound, tabular ore-bodies of the Pilgrim's Rest Goldfield display well-defined areal and stratigraphic distributions. Areally, they occur in three groups : around Sabie, around Pilgrim's Rest, and between Vaalhoek and Bourke's Luck (Fig. 1). Intervening areas to date have proved to be devoid of significant mineralization. A fourth group of mines, which produced from strata-bound ore-deposits in the Pretoria Group in the Mount Anderson area, were not included in the present study. The stratigraphic



<u>*Figure 2*</u> : *Simplified stratigraphic column of the lower Transvaal Supergroup and stratigraphic relations in the Malmani Dolomite, with locations of the principal ore-zones.*

concentration of ore-bodies in the Malmani Dolomite has been mentioned previously. These are further localized into three principal zones. At the base of the Malmani Dolomite is a transition-zone with the underlying Black Reef Quartzite (Fig. 2). This cyclic sequence of thinly-bedded dolomites and calcareous, carbonaceous shales contains significant mineralization. A lower dolomite-and-chert zone, that is gradational with the transition-zone, is the second zone of mineralization. Ore-bodies lie within, and just below, the Blyde River Quartzite. Finally, several auriferous horizons occur in the upper dolomite-and-chert zone (Fig. 2). Mineralization of lesser importance is also contained in the Wolkberg Group, in the Black Reef proper, and in the shales directly overlying the unconformity that separates the Chuniespoort Group from the overlying Pretoria Group (Fig. 2).

Nowhere in the Pilgrim's Rest field is the entire dolomite succession mineralized. To the south, in the Sabie area, the Black Reef and overlying transition-zone are mineralized; in the Pilgrim's Rest area, the upper dolomites are mineralized; and, in the northern parts of the goldfield, ores are contained in the lower dolomite-and-chert zone.

Reasons for the well-defined areal and stratigraphic distribution of ore remain problematic. Zietsman (1967) suggested that mineralized areas were located over broad, regional anticlines; however, exploratory drilling to test this concept was unsuccessful.

Objectives and Methodology

The objectives of this study were : (i) to establish the role played by stratigraphy in defining the stratigraphic and areal distribution of ore-zones in the Pilgrim's Rest Goldfield; and (ii) to determine the nature and origin of the mineralizing fluids.

The first phase of this ongoing study was devoted primarily to a field-examination and sample-collection programme. Subsequent investigation was then confined to fluid-inclusion and isotope analysis. A total of seventeen sections was measured, using the top of the Black Reef Quartzite and the base of the Pretoria shales (Fig. 2) as datums. Measured sections were concentrated north of Graskop and Pilgrim's Rest (Fig. 1), because of poor exposure (largely due to afforestation) south of these towns. During the field programme, outcrops of bedded and vertical ore-bodies were examined and samples collected, mainly from mine-dumps. As most of the mine-entrances have collapsed, observation of the ore-zones was restricted to poorly-exposed and oxidized outcrops and to several intersections in borehole-cores made available by companies active in the goldfield. In addition to dump samples of ore, 50 ore-samples were taken from the 2 000 m of core that were logged. A selection of these was submitted for sulphur- and oxygen-isotope analysis and fluid-inclusion studies.

CARBONATE DEPOSITIONAL ENVIRONMENTS

The understanding and knowledge of carbonate depositional-environments have been greatly expanded over the past twenty years, with the proliferation of studies of modern, carbonate depositional-settings by the research organizations of oil companies and, to a lesser extent, by academic institutions (for excellent reviews of carbonate environments, see Scholle and others, 1983; Wilson, 1975). These studies were in response to the perception that models of modern environments could be used as exploration tools, to locate the oil-pools that lie in carbonate reservoirs. Models developed by these researchers can be usefully applied to the study of ancient carbonate rocks, using the principles of uniformitarianism. However, further back in geological time, these models require modification, as the myriads of species of flora and fauna that played an integral part in carbonate-formation during the Phanerozoic had not evolved in the Precambrian. Early-Proterozoic carbonate deposition was dominated by the biological activity of the cyano-bacteria (single-celled prokaryotes). This was coupled, in many environments, with a significant contribution by mechanical sedimentation. Thus, deciphering the genetic stratigraphy of Proterozoic carbonates becomes an exercise in describing the dimensions and morphology of stromatolites (the physical structures built by the entrapment of sediment by algae) and of mapping their distribution in space and time. The vertical and lateral association of these structures leads to the recognition of depositional facies and the interpretation of their environments of deposition. Modern, stromatolitic, depositional systems occur mainly in the shallow, subtidal-to-intertidal zones. Probably, the best-known environment of this type is Shark Bay in Western Australia (Logan and others, 1964). While the bulk of the flora and fauna of Phanerozoic carbonates cannot be directly equated with Proterozoic deposits, the physiography of their depositional systems is comparable. Figure 3 diagrammatically illustrates the principal carbonate-systems observed in

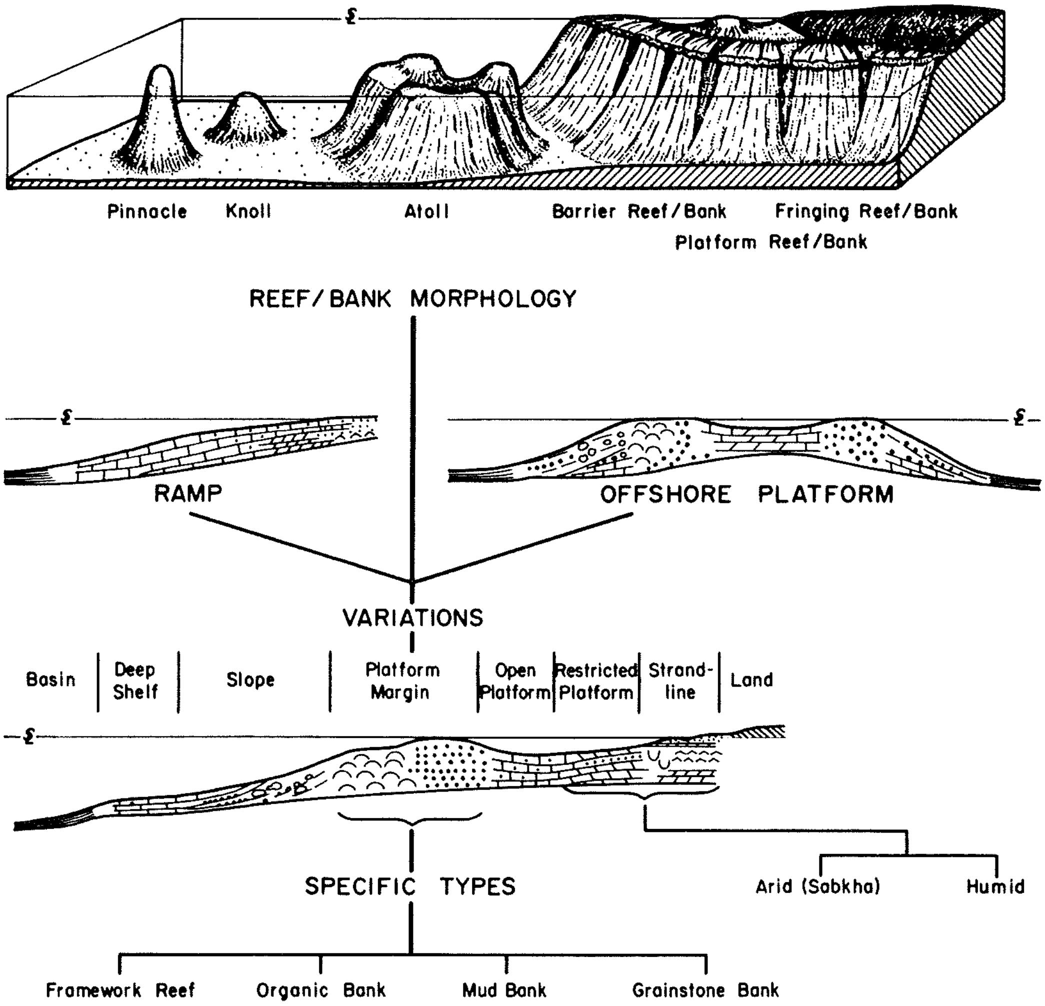


Figure 3 : *Carbonate depositional-systems (from Galloway and others, 1983; after Wilson, 1975).*

modern settings. Environments of interest in this study are the restricted platform (in which fresh-marine circulation is restricted by a shoal or, simply, by the areal extent of the platform) which includes supra-to-subtidal deposits, the open platform and/or ramp, and the platform margin.

THE MALMANI DOLOMITE : AN EARLY-PROTEROZOIC PLATFORM CARBONATE

The Malmani Dolomite has been the subject of several studies during the past 20 years. Papers by Eriksson (1977) and Eriksson and Truswell (1974) reported on aspects of the dolomites on the Transvaal Highveld; Zietsman (1964,

1967) mapped the Malmani stratigraphy in the Pilgrim's Rest area; and Button (1972, 1973b) published the most-extensive description of the Chuniespoort Group, which includes the Malmani Dolomite Subgroup, the Penge Iron Formation, and the Duitschland Subgroup, to date. Yet, a definitive synthesis of the genetic history of the Malmani Dolomite has not been forthcoming.

The Malmani Dolomite Subgroup in the eastern Transvaal is subdivided into five members, principally based on chert-content. Pre-Pretoria uplift and subsequent erosion resulted in the progressive removal (from north to south) of the upper subgroups of the Chuniespoort Group and the stripping-off of the mixed-zone of the Malmani Dolomite Subgroup in Pilgrim's Rest area (Button, 1973b). The four remaining dolomite zones are referred to, in ascending order, as the transition-zone, the lower dolomite-and-chert zone, the chert-poor zone, and the upper dolomite-and-chert zone. The Blyde River Quartzite and the middle shales are important marker-units on either side of the chert-poor zone (Fig. 2). Additional marker-units were used to trace the ore-zones in outcrops of the upper dolomite-and-chert zone; the "bread-and-butter dolomite" and the "bee-hive chert" are, perhaps, the most reliable of these important "flag-units".

The Transition-Zone

The transition-zone, as its name implies, is gradational between the underlying Black Reef Quartzite and the lower dolomite-and-chert zone, above. It is characterized by dark-coloured dolomite, abundant, black, carbonaceous shale, thin, quartzite layers, which are more common at the base of the sequence, and a paucity of chert. The dark-grey-coloured dolomites weather chocolate-brown, due to high iron- and manganese-contents (Button, 1972). Residual manganese wad, which is currently being excavated from the modern, karsted substratum developed around Graskop, for use in the fertilizer industry, is a product of weathering. The carbonates are frequently thinly-interbedded, with black carbonaceous-to-graphitic, pyritic mudstones. Shale-deposition was cyclic. Thin shale-partings occur regularly throughout the zone. Local, thicker and more-abundant partings occur at 120-140 m and 190-200 m above the base of the transition-zone. The black shales are dominantly horizontally-laminated and mudcracked; local siltstones are ripple-laminated. They also contain horizontal and vertical tubular structures thought to represent burrows (Tyler and Tyler, in press). Cross-bedded, thin (generally less than 1 m) quartzites occur as isolated, elongate units in the lower half of the transition-zone. Compositional varieties include pure ortho-quartzites, immature calc-litharenites, and calc-lithic-quartz-wackes. Primary sedimentary structures present are trough and planar crossbeds and interference ripples. The argillaceous sandstones and siltstones may have been preferentially silicified, as they often are associated with dark, ripple-marked cherts.

Diagnostic, biogenic and mechanical, sedimentary structures abound in the zone. Stromatolites are exclusively small-scale, commonly less than 30 cm and rarely attaining thicknesses of up to 1 m. Cryptalgal crinkle-lamination and small, isolated and lateral-linked domes are the dominant biogenic structures. Associated with the stromatolites are ripped-up algal mats, oolite beds, and intraformational, algal breccias, all indicating significant current (tidal ?) activity. More important to the interpretation of the unit was the recognition of salt-casts, which are abundant in several units that are widely developed throughout the area. Salt-casts indicate that the basinal waters were periodically highly saline, suggesting a restricted environment of deposition. Mudcracks are common.

Sediments of the transition-zone are interpreted as having been deposited in an intertidal-to-restricted, possibly partly-lagoonal environment. The small scale of the stromatolites suggests consistently shallow-water deposition and periodic, substantial current-activity. These currents ripped up dried, algal mats and deposited the debris as lags, now recognized as intraformational, flat-pebble breccias. Another indication of regular exposure is the abundant mudcracking of the interbedded shales.

Basin-waters were at times highly saline, as indicated by the ubiquitous development of salt-cast-bearing layers (Gornitz and Schreiber, 1981). The saline brines were probably confined to lagoons formed landward of oolite-shoals. Alternatively, a wide and gently-dipping shelf, coupled with high rates of evaporation, might have resulted in saline depositional-waters. However, the preponderance of wave-and-current-derived structures (ripple-marks, breccias, and oolites) points towards sedimentation in a composite, intertidal-shore-zone/lagoonal setting.

Abundant, fine-grained, terrigenous clastics in the transition-zone represent the products of the erosion of a denuded provenance. The shales of the Pilgrim's Rest area are fine-grained, lateral equivalents of thicker and coarser, deltaic sequences deposited in the Selati-trough depo-axis, 100 km north of Pilgrim's Rest, where sandstone-thicknesses of up to 50 m were attained (Button, 1972). The cyclicity of the shales was a response to delta-progradation and -abandonment, rather than to epeiric, sea-level change.

The Lower Dolomite-and-Chert Zone

The contact of the lower dolomite-and-chert zone with the transition-zone is poorly defined, being marked by an increase in chert-content and in the size of stromatolites and by a decrease in carbonaceous shale-content. Dolomite in this zone is light-grey-coloured. Chertification ranges from massive, total replacement of thick, dolomite beds to delicate silicification of individual, cryptalgal laminae that are only millimetres thick. Impersistent and podlike replacement-bodies are locally present. Chert-content may range from 0 to 100 per cent, but, typically, is between 10 and 40 per cent and averages 25 per cent.

Stromatolites characteristic of the zone are simple, moderately-convex, algal domes that display both linked and unlinked habits. Amplitudes are commonly less than 0,75 m. Parasitic domes frequently are developed on the crests of larger host-domes, and larger domes may overlap smaller ancestors, resulting in a variety of composite, algal structures. Cryptalgal crinkle-lamination is ubiquitous. Larger domes (1 m amplitude) are locally present throughout the Pilgrim's Rest area. In the northwestern parts of the study-area, large (4 m wide by 3 m high to 10 m by 4 m), elongate domes, with long axes perpendicular to the basin-margin, occur. Internally, the domes are crinkle-laminated. Button (1972) inferred strong, tidal activity from similar, algal-mound orientations elsewhere in the basin. The lateral variation in the size of structures leads to the postulate of increasing water-depth to the north and west.

Although algal structures dominate in the lower dolomite-and-chert zone, several units display evidence for traction-sedimentation. Oolite beds and ripple-marked units are developed throughout the zone. Local, thin-pebble, edgewise breccias rest on domed, chert-free dolomite. Grainstones that display ripple-marks, flaser-bedding, hummocky bedding, and broad, shallow troughs are also present and encase thin zones of small domes. Broad, lenticular bedsets are associated with the traction-deposits. Accessory structures and lithologies that are occasionally observed are salt-casts and -tepees and cyclicly-developed, thin, carbonaceous mud-drapes.

The lower dolomite-and-chert zone was deposited in an intertidal-to-shallow-subtidal setting. The larger size of the stromatolites in this zone and the relative paucity of desiccation-structures and halite-casts suggest that sedimentation mostly took place in deeper water than the underlying transition-zone. With the exception of the large domes in the northwest part of the area, most of the structures are comparable in size to the intertidal-to-subtidal, algal colonies of Shark Bay (Playford and Cockbain, 1976). Oolitic beds were deposited in the wave-agitated zone of the upper shore-face, as bars. In places, chertification of these oolite-zones is discontinuous. Silicified oolites display pristine spherical shapes; the unreplaced oolites were flattened, by burial, to pancake-like morphologies, indicating that chertification occurred early in the burial history of the carbonate. This observation lends support to the conclusion reached by Eriksson and Warren (1983) that intense diagenesis, resulting in the dolomitization and silicification of the Malmani carbonates, took place in a shallow-subsurface mixing-zone, between resurging, continental groundwaters and marine-derived, phreatic waters.

The basinward-elongation of giant bioherms and the lenticularly-bedded units, probably deposited in meandering, tidal creeks that transected the foreshore, both indicate the presence of strong tides. Storm-surge currents also created traction-sedimentation structures, such as wave-ripples and hummocky crossbeds on the shore-face.

The Blyde River Quartzite

The Blyde River Quartzite consists of two or three, coarse-grained sheet-sands that rest abruptly on the lower dolomite-and-chert zone in the Pilgrim's Rest-Vaalhoek area. The unit shales out to the south, in the Sabie area. This cross-bedded quartzite attains a maximum thickness of approximately 40 m. At its thickest development, the composite quartzite is interbedded with chert-rich dolomite and black, carbonaceous shale. Three distinct sub-units are present in this area : a lower, small-pebble, conglomeratic and cross-bedded sandstone, typical of the quartzite elsewhere in the area, passes upward into interbedded dolomite and sandstone; a middle zone of contorted, quartzite lenses in black, organic-rich shale; and an upper (12-15 m thick) unit, similar to the lower sandstone, being a medium-grained quartzite, with scattered, detrital feldspars and limonite after pyrite.

In addition to the lateral shale-out of this unit, it thins away from the escarpment and into the basin, where it commonly rests on, and merges with, a thin shale. Paleocurrent directions are weakly bimodal, with a dominant trend to the southwest. Button (1972) noted that the stratigraphic interval containing the quartzite is marked elsewhere in the basin by an unconformity represented by a chert-in-shale breccia, so it is probable that this unit was deposited during, or following, a period of emergence and erosion.

The lateral continuity and basinward thinning of the Blyde River Quartzite suggest deposition in a clastic, shore-zone system. Based on paleocurrent analysis, the sediment-source was the Precambrian granitic terrane to the northeast. The coarse grain-size and the two-fold depo-axes (one parallel to strike, the other dip-oriented) indicate that the Blyde River Quartzite was deposited as a composite, cuspate, wave-dominated, delta/strandplain-system. Progradation of the delta-system towards the west, in the area of thickest development, facilitated the superimposition of the distributary-system over pro-delta muds and laterally-extensive, delta-front sheet-sands. Subsequent transgression reworked the prograded distributary-sands into the upper of two sheet-sands.

The Chert-Poor Zone

Dark-coloured dolomites of the chert-poor zone comprise a well-defined and laterally-extensive marker-unit that is developed over the entire strike-length of the Chuniespoort Group, from Ngodwana to Potgietersrus (Button, 1972). Sections through this zone document a transgressive sequence, from shallow, sub-tidal deposits at the base to deep-water dolomites (indicated by the scale of the algal bioherms) at the top. A rapidly-upward-shoaling (regressive) cycle caps the succession which is overlain by the middle-shale-marker unit.

Organo-sedimentary structures at the base of the chert-poor zone are small, moderately-convex domes, associated with cryptalgal, horizontal lamination, crinkle-lamination, and broad, gently-convex domes, with dimensions of 1,2 m x 0,3 m. Traction-sedimentation units are limited to wave- and interference-rippled grainstone. Locally, isolated mega-domes are developed.

Dome-dimensions increase with height in the succession. Mega-domes, with typical dimensions of 4 m wide by 2-3 m high, predominate midway up the zone. These are associated with smaller domes, crinkle-lamination, and columnar stromatolites. The largest domes are of giant proportions and are observed near the top of the successions. Spectacular exposures of the giant domes are present on Maragise Hill (on the farm London), where strike-parallel cliff-faces display domes 20-30 m high x 40 m wide. At this locality, the zone is intruded by a thin sill, which follows the paleo-topography of the mounds, undulating across the cliff-face. Smaller, parasitic domes and crinkle-lamination define individual beds of the giant domes. The scale of the host-structures is so large that the minor structures disguise the true nature of the upper part of the succession, making recognition of the bioherms difficult, except where they are displayed on the cliff-faces. The giant domes provide a vital clue to the origin of the chert-poor, dark-coloured dolomites of the Chuniespoort Group. A second cliff-face exposure of the giant bioherms occurs on Ledovine, at the fourth bridge across the Blyde River, north of Pilgrim's Rest.

The giant bioherms are capped by a 10-15 m-thick zone of mega- and smaller domes which grade upwards into shaly dolomite and, subsequently, into interbedded shales and dolomite of the overlying middle-shale-zone.

The vertical change in the scale of organo-sedimentary structures, from small domes at the base to giant bioherms near the top of the zone, indicates deposition under conditions of increasing water-depths. The amplitude of the giant structures (30 m+) provides a good minimum estimate of water-depths. These giant bioherms represent the largest structures present in the Malmani Dolomite and, probably, deposition under relatively deep-water conditions. Thus, shallow, subtidal deposits at the base give way to shelf-assemblages at the top of the succession in this transgressive sequence. Similar, large domal structures have been described from Precambrian carbonates in Canada where they are interpreted as outer-shelf deposits (Ricketts, 1983).

The dark colour and paucity of chert in the dolomites is consistent with a deep-water origin. Deep-water carbonates in the Permian Basin of West Texas, and elsewhere, are frequently dark in colour. Furthermore, silicification of Malmani dolomites is considered to be related to mixing of continental water and basinal water in the shallow subsurface (Eriksson and Warren, 1983). It is speculated that the deeper-water dolomites remained in the zone of marine-derived, phreatic waters basinward of the zone of mixing of the two water-masses, and, for this reason, were not subjected to intense silica-diagenesis in the shallow subsurface. In contrast, shallow, subtidal-to-intertidal carbonates of the lower and upper dolomite-and-chert zones were silicified.

The Middle Shales

The middle-shale-marker is a locally-developed assemblage of very fine-grained sandstones, siltstones, and shales, thickly interbedded with domed, generally chert-poor dolomite. Regional mapping by Button (1972, 1973b) showed that the terrigenous clastics have a restricted distribution, being localized in the Pilgrim's Rest area. The entire middle-shale-assemblage (of clastics and carbonates) averages 50 m thick.

The terrigenous clastics commonly compose thin, fining-upward cycles, from rippled, very fine-grained sandstones to horizontally-bedded, black, organic mudstones, with isolated, starved ripples, flaser-bedded units, and lenticular-bedded units. Pyrite is commonly present. Contacts with underlying carbonates are abrupt, with thin mud-layers being draped over domes, or gradational, where the carbonates display increasingly-abundant and thicker, wispy shale-drapes. The shales are locally mud-cracked and burrowed (Tyler and Tyler, in press). Thin, rippled, dolomitic grainstones are frequently interbedded in the shales. Associated dolomites are characterized by such structures as rare mega-domes, dominant small-scale domes, crinkle-lamination, columnar stromatolites, and ripple-laminated zones. Wispy shale-laminae are ubiquitous.

The mud-cracked, middle-shale-assemblage rests on an abrupt, shoaling sequence. It is developed over a restricted area. Interbedded dolomites characteristically display small-scale domes of probable inter-tidal origin. The shales, therefore, were deposited in an intertidal-to-nearshore-subtidal setting. The localized distribution of the shales suggests that they were preserved near to the source of sediment-influx into the basin, which was probably a small, high-constructive, mud-rich delta. The cyclicity of the shales implies rapid lobe-progradation, with subsequent over-extension and foundering of the delta-system. This autocyclicity is characteristic of modern, high-constructive deltas.

The Upper Dolomite-and-Chert Zone

The upper dolomite-and-chert zone displays the greatest variability in scale and morphology of the associated algal structures of all the Malmani Dolomite zones in the Pilgrim's Rest area. Domes range in scale from cm-sized, digitate stromatolities to the mega-domes of the "bread-and-butter" dolomite-marker. Morphologies are diverse and include simple, gently-convex-to-highly-convex domes, crenulated domes, isolated and linked, columnar stromatolites, cryptalgal crinkle-laminates, and algal mounds, with poorly-developed, internal lamination, known as thrombolites. Both scale and morphology of the structures vary rapidly, indicating that, during deposition of the upper dolomite-and-chert zone, the receiving-basin was subjected to numerous transgressions and regressions. Tepee-structures and intra-formational breccias, composed of ripped-up, desiccated, algal mat are evidence for periodic, subaerial exposure. Positions of the migrating shore-line are marked by oolite-beds and beach-rosettes, which are composed of sub-vertical intraclast platelets in a dolomitic groundmass, that are formed by reworking of indurated and desiccated,algal mat in the zone of breaking waves (Ricketts and Donaldson, 1979).

Alternating units of chert-rich and chert-poor dolomite result in a characteristic,step-like outcrop-belt consisting of ledges and slopes, respectively. Chert-content in this zone varies from zero to total replacement, but averages 20-30 per cent on the typical outcrop. Replacement-bodies result in three, distinctive marker-units : (i) the "bread-and-butter" dolomite which is a zone of broad mega-domes in which silicified bands, 3-10 cm thick, are separated by 15-20 cm-thick bands of dolomite; (ii) the "beehive" chert, consisting of laterally-linked, conical mounds 1 m wide by 2 m high; and (iii) a metre-thick bar of chert,220 metres above the base of the zone. All of these marker-units have been used by prospectors to locate and trace approximate positions of the ore-zones. They are continuous throughout the field-area, and one of then, the "bread-and-butter" dolomite, which is conspicuously-exposed at Lone Creek Falls, near Sabie, was traced from Pilgrim's Rest to Potgietersrus by Button (1972).

Physical, sedimentary structures, such as wave-, current-, and interference-ripples, are common throughout the zone. Terrigenous, clastic sediments, such as the slate-marker that directly overlies the "bread-and-butter" dolomite, are only locally developed, although the dolomites occasionally contain thin, impersistent, wispy shale-laminae.

An amygdaloidal basalt is poorly exposed at the top of the zone, where it lies directly below the Bevets conglomerate. Angular clasts of the basalt are contained within the overlying breccia. The lava has been traced over a 10-km strike-length, from van der Merwe's Reef (5 km north of Pilgrim's Rest) to Frankfort. It varies in thickness from 1-2 m, in outcrop, to 20 m, in core-intersections. The basalt rests directly on a thick (20-30 m) sill that intrudes the uppermost part of the zone. Alternatively, this poorly-exposed unit may represent the upper, vesiculated part of the underlying sill, but, since clasts of the igneous rock are contained in the Bevets conglomerate, sill-intrusion would have had to have occurred during Malmani time.

The upper dolomite-and-chert zone is considered to have been deposited in an intertidal-to-shallow-subtidal environment, similar to that in which the lower dolomite-and-chert zone was deposited. The mega-domes of the "bread-and-butter" dolomite probably represent the deepest-water deposits of the zone. Rapid and frequent shoaling and transgressive cycles indicate considerable instability in the receiving-basin, a trait that continued during deposition of the younger mixed-zone of the Malmani Dolomite. The mixed-zone was removed in the Pilgrim's Rest area during the pre-Pretoria, erosional event. A further indication of crustal instability during upper-Malmani times is the basalt lava-flow.

Depositional History of the Malmani Dolomite

Three depositional cycles have been recognized in the Malmani Dolomite in the Pilgrim's Rest area (Fig. 4). Cycle 1, which includes the transition- and lower dolomite-and-chert zones, represents a transgressive sequence from lagoonal and shallow, intertidal sediments to shallow, subtidal deposits. The cycle of increasingly-deeper-water sediment is abruptly terminated at the top of the lower dolomite-and-chert zone. The Blyde River Quartzite, a composite, wave-dominated, coastline deposit, lies at the top of Cycle 1; however, elsewhere in the basin, this stratigraphic position is marked by a chert-in-shale breccia, considered by Button (1972) to represent an unconformity. Transgressive Cycle 2 consists of intertidal, dark-coloured dolomites which grade upward into deep-water shelf-deposits, represented by giant, algal bioherms. This cycle is contained entirely in the chert-poor zone (Fig. 4). An abrupt, shoaling sequence caps the transgressive phase and is associated with carbonaceous mudstones of probable high-constructive, but mud-rich, deltaic origin (the middle shales). The upper Cycle 3 is neither transgressive nor regressive, but, rather, was subjected to numerous fluctuations in water-depth. Dolomites of the upper dolomite-and-chert zone were deposited dominantly in the intertidal-to-subtidal zone, although local areas were probably subaerially exposed, at times. This cycle is also capped by a regional unconformity, marked by a chert-in-shale breccia.

Numerous, second-order cycles were superimposed on the principal cycles. These were of too-small a magnitude to be mapped with accuracy during this project, and it is uncertain if they represent basin-wide events, or local, possibly structurally-influenced features.

The overall environment of deposition of the Malmani Dolomite was a broad platform. Members traced around the outcrop in the eastern Transvaal are correlative with equivalent members in the Potchefstroom synclinorium (Button, 1972) and with the Campbellrand Subgroup in the northeastern Cape Province. Only in the northeastern Cape are possibly- deep-water equivalents recognized (Beukes, 1978; Tankard and others, 1982). Individual marker-units, such as the "bread-and-butter" dolomite, also display considerable, lateral continuity. This implies that the conditions that prompted the formation of marker- and other units were similar over great distances. The landward limit of the basin during Cycle 1 was probably near to the current outcrop-

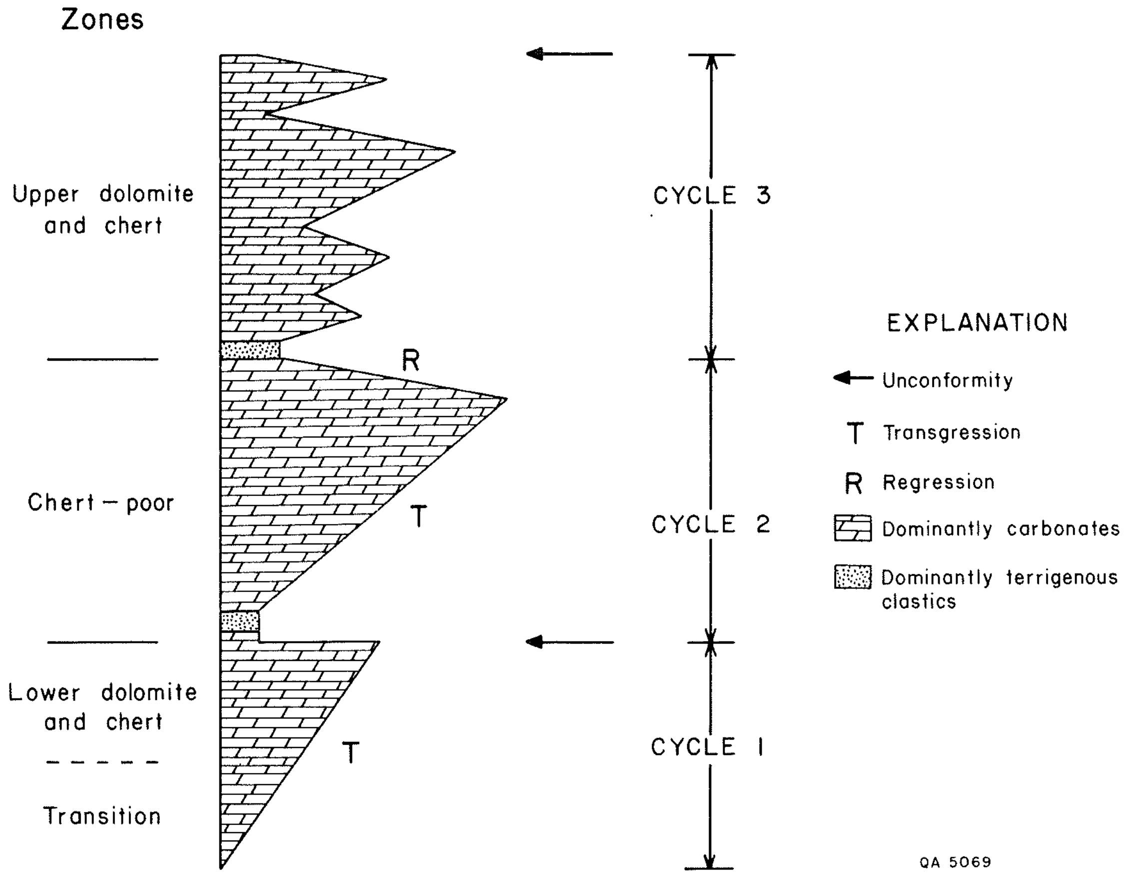


Figure 4 : *Cyclicity in the Malmani Dolomite.*

belt, but, during Cycle 2, it was certainly many tens, and perhaps hundreds, of kilometres to the north and east. The sea shrank during the deposition of Cycle 3. The only evidence of a seaward margin of the platform is found in the northern Cape where platform-edge carbonates merge with basinal limestones, between Postmasburg and Koegas (Beukes, 1978). The platform, therefore, was at least 800 km long; the width, however, is indeterminant.

The inferred, depositional settings of the mappable units of the Malmani Dolomite in the Pilgrim's Rest area are shown in Figure 5. Supratidal and shore-zone sequences merge with deeper, subtidal, middle-shelf assemblages, typified in the Pilgrim's Rest area by giant, algal bioherms. A composite, transgressive cycle of this type would include Cycles 1 and 2 above, i.e. a gradation from the lower dolomite-and-chert zone to the chert-poor zone. Subsequent regression facilitated the basinward migration of intertidal deposits, with consequent superposition of the upper dolomite-and-chert zone over deeper-water deposits. In contrast, the transition-zone was probably barred with back-barrier deposits, consisting of saline, lagoonal and intertidal, algal sediment. It is in these sediments, which are frequently burrowed in Phanerozoic and modern, depositional systems, that most of the possible burrows were observed. A southerly, longshore drift was responsible for introducing fine-grained, terrigenous, clastic material from the deltaic depo-centre in the Selati trough.

STRATA-BOUND GOLD-SILVER DEPOSITS IN THE PILGRIM'S REST GOLDFIELD

This section discusses observations made in the field and inferences drawn from a review of previous work in the area. Almost all of the ore-bodies are now worked out or inaccessible, making the detailed descriptions of Hall (1910), Wybergh (1925), Reinecke and Stein (1929), Swiegers (1949), and, more recently, Fowler (1968), invaluable. The auriferous deposits are classified into strata-bound (flat) lodes, vertical lodes, strata-bound leaders, and blows (Hammerbeck, 1976).

Ore-Deposits

Strata-bound ore-bodies, consisting of quartz, pyrite, and a variety of ore-minerals, were the principal producers in the district. They are tabular in geometry and are mostly conformable with bedding, but, locally, transect bedding-planes. As noted by early authors, they occur in groups, e.g. the Sandstone, Betty, Rietvallei, Elandsdrift, and Glynn's ore-bodies in the Black Reef and transition-zone, and the Portuguese, Beta, and Theta ore-bodies in the upper dolomite-and-chert zone. The lodes thin and gold-values decline both along strike and downdip, where calcite becomes a dominant gangue-mineral. Ore-bodies are said to "calcite-out" (A.R.C. Fowler, personal communication, 1983), which is synonymous with their becoming uneconomic, downdip. Other gangue-components are chlorite and black, carbonaceous, and frequently-graphitic shale.

Reinecke and Stein (1929) provided an overview of the typical characteristics of strata-bound ore-bodies at Pilgrim's Rest. These authors described the ore-zones (referred to as "reefs" by early miners) as being very-thin sheets, usually less than a metre thick, but ranging up to three metres thick. The composite reefs usually consist of upper and lower quartz-zones which mantle a central, pyrite-rich zone. Gold is consistently found in the pyrite-rich zone and in either the upper or the lower quartz-band, the other quartz-band remaining virtually barren. Quartz, according to Reinecke and Stein (1929), frequently replaces wallrock-shale, and, where shale is absent, adjacent dolomites and cherts are replaced, to a depth of 30 cm, by pyrite. In this circumstance, gold is also contained in the altered wallrocks. An example of mineralization of this type is the lower Theta Reef. Quartz may have been introduced in only minor amounts (such as in the Portuguese Reef), and, here, only pyritization of wallrocks occurred.

Wallrock-alteration is not pronounced. Pyritization is the dominant form of alteration, and adjacent host-rocks commonly contain pyrite cubes.

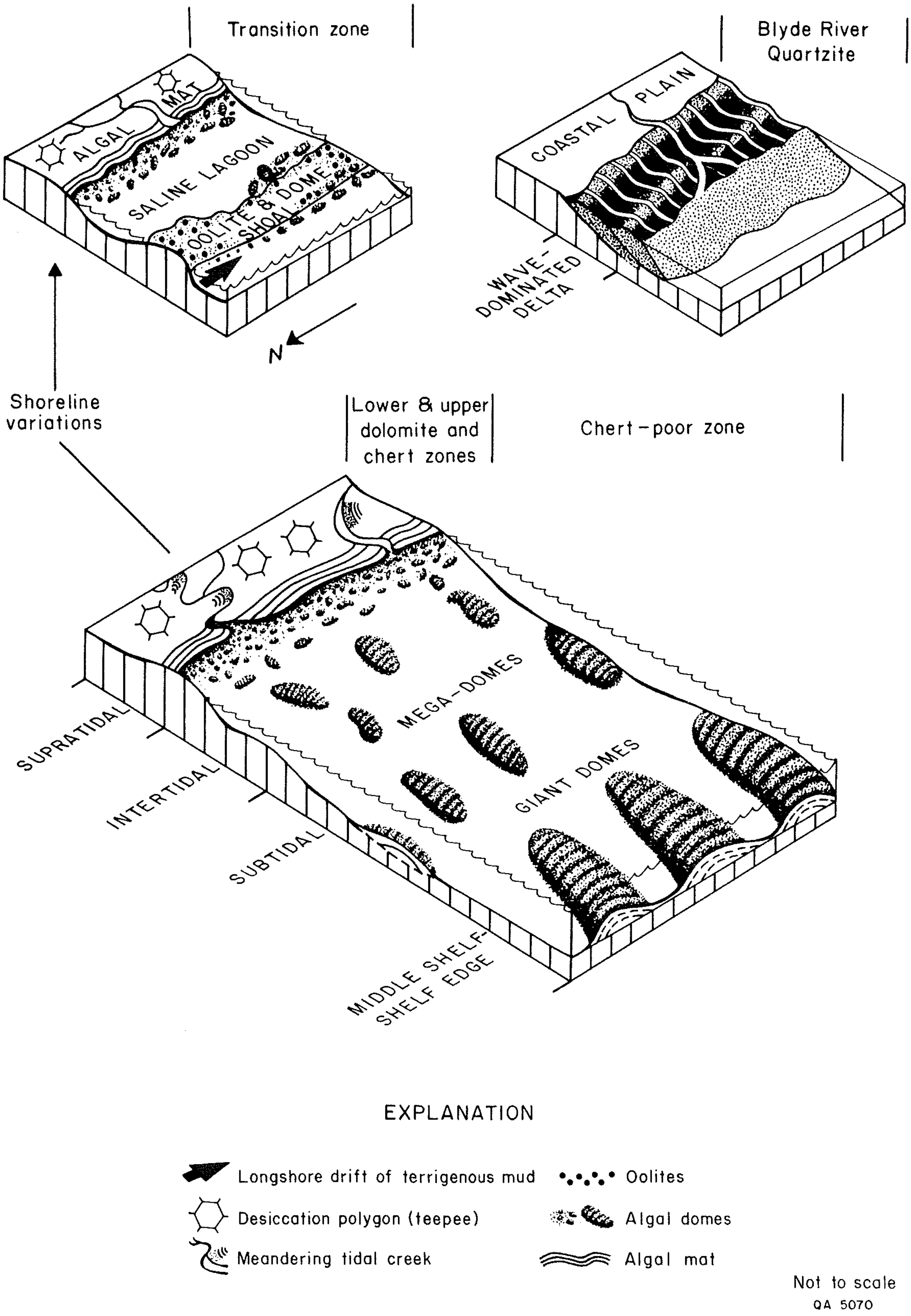


Figure 5 : *Depositional model of the Malmani Dolomite in the Pilgrim's Rest area. The facies-tract is compressed. Based on the great lateral continuity of marker-units, the depositional system was a broad platform.*

Pyrite crystals gradually die out less than 30 cm away from the reef proper. Silicification of the wallrocks is moderate in the carbonates and takes the form of finely-crystalline aggregates or veinlets of silica (Swiegers, 1949). Silicification of the terrigenous clastics is minimal. Clastic rocks have, however, suffered chloritization, sericitization, and carbonatization (Swiegers, 1949). In the Pretoria Group, as well as in shaly host-rocks in the dolomite, rafted shale-fragments in the reefs are almost completely replaced by the chlorite mineral penninite. Shale wallrocks contain blebs of chlorite, separated by felted, sericitic masses. Where sericitization is pronounced, the adjacent, clastic wallrocks are often discoloured to a bright shade of green. Intensity of sericitization may vary considerably along the strike of the ore-body, so that areas of unaltered wallrocks may be adjacent to pyritized and intensely-sericitized shale, as at Columbia Hill Mine. Carbonatization is best developed in the shales, often giving rise to "spotted" shales (Swiegers, 1949). This form of alteration consists of scattered aggregates of euhedral dolomite, averaging 2 mm in diameter. Carbonate hosts are locally recrystallized to depths of 50 cm from the ore-zone and elsewhere, such as in the Beta Mine, are bleached from the typical, dark-bluish-grey to a pale-pinkish-grey or cream colour.

The mineralogy of the ore-zones has been described by Swiegers (1949) and Zietsman (1967). Principal ore-minerals are arsenopyrite, chalcopyrite, tetrahedrite, electrum, and bismuthinite; associated minerals are pyrrhotite, native bismuth, galeno-bismuthinite, scheelite, galena, bornite, and sphalerite. Visible gold was observed in a few of the workings. Apart from the economically-important gold and silver, elements which fingerprint the origin of the deposits are As, Sb, and Bi. The Bevets Reef contains appreciable concentrations of Hg (A. Berlein, personal communication, 1983). Analyses of selected ore-samples indicate the presence of B (10^1-10^2 ppm range) and F (10^1-10^3 ppm range). The elemental-suite Au, Ag, As, Sb, Hg, B, together with Cd, Se, Te, and Ti, suggests that the Pilgrim's Rest ores are related to deep-seated, hydrothermal activity.

Vertical lodes, typified by the Rietfontein Reef, display mineralogies similar to the flat lodes. The vertical lodes are localized along north-striking shear-zones, faults, and dykes in basement granite. The Gregory Reef, which is located east of the Rietfontein Reef, displays a change in dip from vertical to inclined, as it penetrates the base of the Wolkberg Group. The reef bends into the plane of the bedding of the host-sediment.

Leaders and stockworks are strata-bound zones of thin, transgressive veins that are commonly associated with "bedded" ore-zones. They display sub-vertical, sub-parallel distributions (leaders) or random, cross-cutting distributions (stockworks). The veins are commonly thin (5 cm), consisting of pyrite and quartz, and generally extend over 12-15 m (Hammerbeck, 1976). In one of the borehole cores, the stockworks occur as stacked zones, several metres thick, separated by bleached dolomite.

Blows are elongate quartz-bodies, lenticular in cross-section, protruding above or below the associated strata-bound, tabular ore-bodies (Hammerbeck, 1976). Values are irregular, but blows are frequently extremely rich, containing "jewel boxes" of bright-yellow crystals and veins of gold in pure, white quartz (Fowler, 1968).

Sedimentary Controls of Mineralization

A strong relation between mineralization and environment of deposition of the host-sediment has emerged as a consequence of the present study. Ore-deposits are preferentially developed in the transition-zone, in the upper dolomite-and-chert zone, and, to a lesser extent, in the lower dolomite-and-chert zone. Dolomites and associated lithologies of all three of these zones originated in supra-tidal-to-shallow-subtidal sub-environments. Deeper-water carbonates, such as the chert-poor zone, are devoid of mineralization. Clearly, the auriferous zones are associated with shallow-water carbonates. This is further confirmed by the fact that all of the mineralized zones are associated with small-scale stromatolites.

Possibly, equally important is the ubiquitous occurrence of carbonaceous material within the strata-bound ore-bodies. Pyritized, black shales occur in the wallrocks in contact with mineralization, as folded partings within massive ore, and as rafted fragments in the ore-zone. The rafting-off of fragments into the ore-zone and the graphitic nature of the carbonaceous debris led Zietsman (1967) to conclude that the shales facilitated thrust- and dipslip-faulting along bedding, with the accompanying creation of open spaces suitable for fissure-fill mineralization. Zietsman's (1967) proposed structural control of mineralization has not yet been confirmed.

The carbonaceous shales may have had the additional role of being a reductant of mineralizing solutions that carried the gold, silver, and other metals into the dolomite column. The ability of carbonaceous material to remove metals from mineralizing solutions has been well documented in Mesozoic uranium terranes. Experiments have shown that, in very acidic solutions, where gold is soluble as a chloride-complex, organic matter causes the reduction of positively-charged gold and colloidal, metallic gold is precipitated (Ong and Swanson, 1969). However, based on the preferential association of mineralization with shale, rather than with carbonate, it is unlikely that the auriferous fluids were highly acidic, since they would then have reacted with the host-carbonates. An alternative suggestion is that at least part of the organic material associated with the ores may have been introduced during mineralization. Ong and Swanson (1969) have shown that, in slightly-acidic-to-basic waters, gold is transported as a stable, organic-protected colloid. These colloids are precipitated when the fluids enter a different chemical environment. Although it is premature to draw any conclusions on the specific role played by the organic detritus, the evidence suggests that it assisted in either the transportation or in the precipitation of gold-ores.

The question of a primary, sedimentary control on the areal distribution of mineralization can be answered only in a negative sense. Based on the detailed, measured sections in the northern half of the district and on the examination of more-widely-distributed borehole cores, there does not appear to be a sedimentary control for the localization of mineralization in the Sabie, Pilgrim's Rest, and Vaalhoek areas. On a regional scale, the only difference between the stratigraphy in the Pilgrim's Rest Goldfield and the remaining Malmani Dolomite outcrop is the middle-shales assemblage, which is restricted to the Pilgrim's Rest area. It is unlikely that these shales, which are unmineralized, played a major role in the genesis of the Pilgrim's Rest ores.

Fluid-Inclusion Characteristics

During a preliminary investigation of the nature of fluid-inclusions in Pilgrim's Rest gold deposits, Ash and Tyler (in press) selected samples of vein-quartz from six ore-bodies. The samples were purposely selected to provide information on as wide a range of ore-body-types as possible and on mineralized zones found at different levels in the section (Fig. 2). Two samples were from vertical lodes, one from the Rietfontein Reef and one from the Gregory Reef, both of which cut across basement granites. Two samples were obtained from tabular, strata-bound ore-bodies, one from the Blyde Reef at the top of the lower dolomite-and-chert zone and one from the Theta Reef in the upper dolomite-and-chert zone. The remaining two samples were taken from irregular bodies. One sample was obtained from the Trixie Leader in the Wolkberg Group and the second sample from the Vaalhoek stockwork which is associated with the Vaalhoek Reef in the lower dolomite-and-chert zone.

Ash and Tyler (in press) found the Pilgrim's Rest fluid-inclusions to be complex. They recognized four principal types (Fig. 6). Type-1 inclusions are essentially aqueous, 2-phase inclusions. Type-2 inclusions are 2-phase inclusions containing two of the following : $Co_2 \pm H_2O \pm CH_4$. Type-3 inclusions are characterized by the presence of variable quantities of daughter-minerals halite, sylvite, and anhydrite, in addition to liquid- and vapour-phases. Type-4 inclusions are nearly-pure CO_2. In addition to compositional variability, the fluid-inclusions exhibited a range of CO_2-densities (Table I). The denser fluid-inclusions (>0,85 g/cm^3 CO_2) contained trace amounts of methane. Salinites determined in aqueous fluid-inclusions proved to be moderate-to-high, ranging from 2 to greater than 25 weight-per-cent and averaging 15 weight-per-cent. The samples also displayed a range of homogenization- and decrepitation-temperatures that relate directly to the stratigraphic interval separating the ore-bodies. Samples from stratigraphically-deeper deposits homogenized at 300-400°C, whereas the shallower deposits displayed average homogenization-temperatures of 200°C.

Despite the great variability of the Pilgrim's Rest fluid-inclusions, Ash and Tyler (in press) recognized several, unifying characteristics that suggest a common genesis. The temperature-of-formation gradient, the high-density, CO_2-rich character of inclusions from all stratigraphic levels, and the characteristic, moderate-to-high salinity of the inclusions suggest that the mineralization at Pilgrim's Rest was the product of vertically-migrating CO_2-rich, metal-bearing, saline brines that moved upward along planes of weakness, such as shear-zones (Rietfontein Reef), tectonic fractures, and dyke-filled fractures (Gregory Reef). On encountering accessible, permeable, clastic and carbonate beds, that may or may not have been sites of bedding-plane slip, in the sedimentary succession, the fluids spread laterally, forming the strata-bound, tabular ore-bodies characteristic of the goldfield.

Synthesis of homogenization-temperatures of pure-CO_2 inclusions with homogenization-temperatures of the remaining inclusions and utilization of CO_2-isochore data of Hollister and Burruss (1976) allowed the estimation of pressures and depths of formation of the Pilgrim's Rest ores (Fig. 7). Recognizing that mineralization was probably a multiphase event, Ash and Tyler (in press) suggested that the minimum, average, entrapment-pressure of the strata-bound ore-bodies was approximately 1,4-1,5 kbars. The stratigraphically-deeper, vertical lodes display an entrapment-pressure of

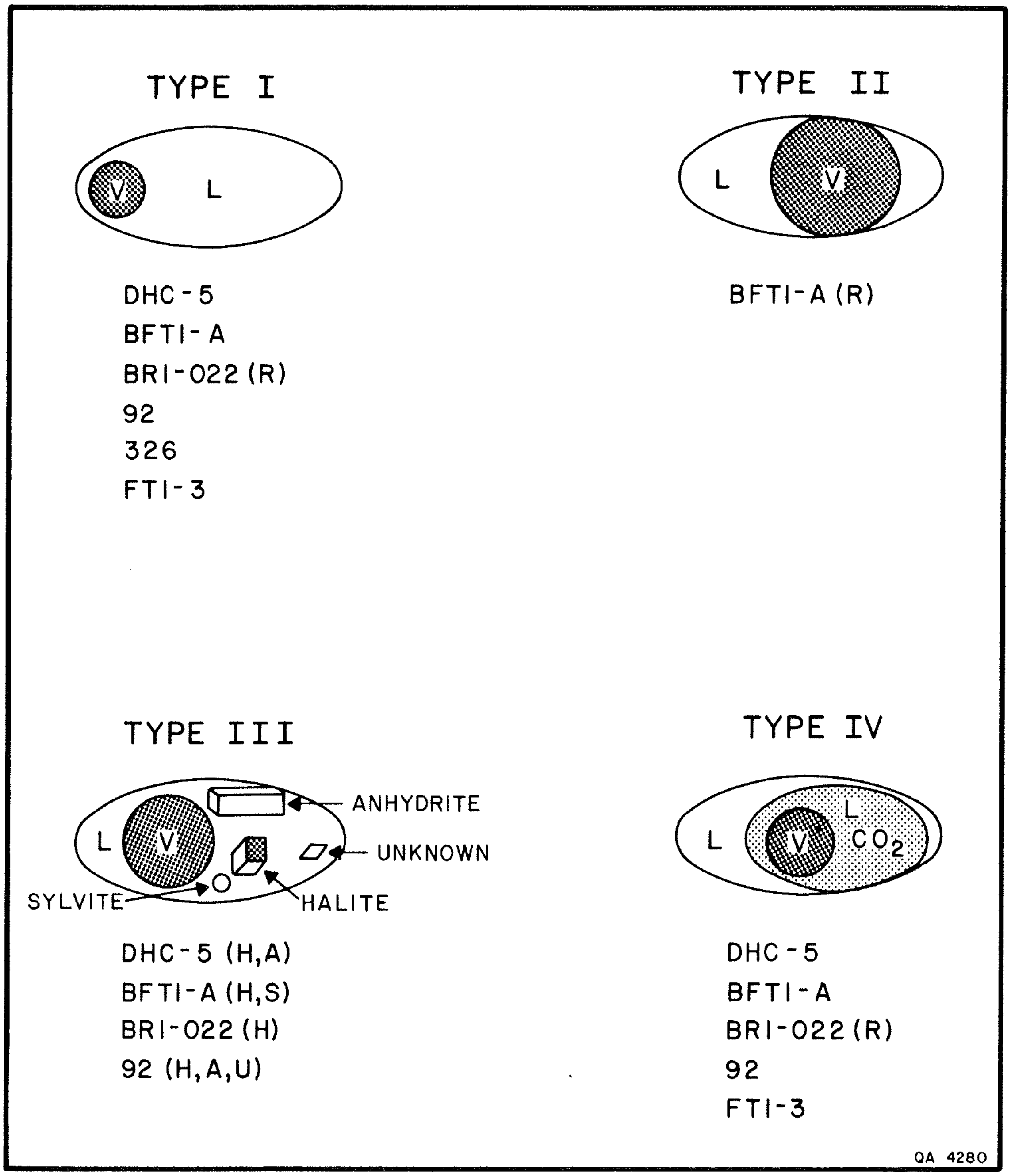


Figure 6 : *Schematic illustration of fluid-inclusion types observed in the Pilgrim's Rest veins. (R) occurs in trace-amounts; (H) halite daughter-mineral; (A) anhydrite; (S) sylvite; (U) unknown daughter-mineral. Samples are : DHC-S : Theta Reef; BRI-022 : Blyde Reef; BFT.1A : Trixie Leader; FTI-3 : Vaalhoek stockwork; 92 : Gregory Reef; and 326 : Rietfontein Reef. After Ash and Tyler (in press).*

TABLE I

Summary of Physical and Chemical Characteristics of Pilgrim's Rest Fluid-Inclusions. From Ash and Tyler (in press)

Deposit	T_h (°C)	$T_{decrep.}$ (°C)	Density of CO_2 (g/cm^3)	CO_2 (Mole %)	Salinity (Wt % NaCl equivalent)	Comments
Theta Reef	185 - 325	200	>,85	25 - 60	9 - >25	halite, anhydrite (?)
Blyde Reef	max. 275 decrep. domin.	200	,87 - ,92	10 - >60	locally >25	halite rare
Vaalhoek stockwork	190 - 200	200	,65 - ,93	<5 - 85		no daughters
Trixie Leader	>400	175 - 200	,65 - ,80	0 - 30	2-12 plus sylvite	halite rare
Gregory Reef	335 - 375	300 - 350	,87 - ,95	15 - 35	high, 23	abundant daughters T_h daughters >450° CO_2 less dominant

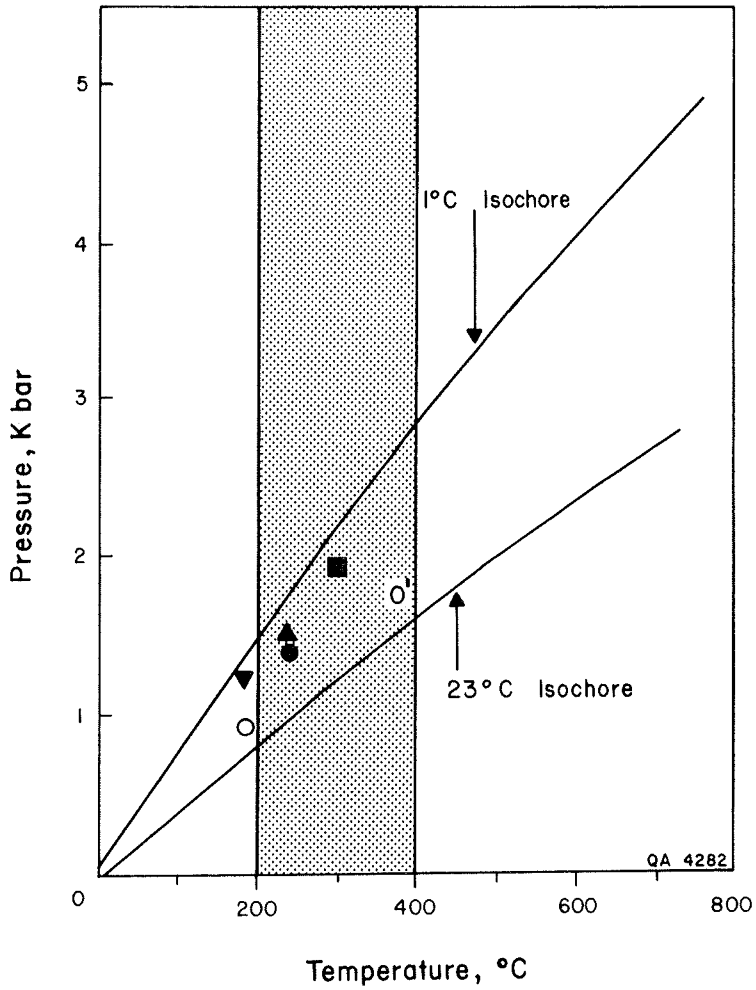
1,9 kbars (Fig. 7). These pressures translate to depths-of-entrapment of 5,5 km for the upper, strata-bound bodies and 7 km for the vertical reefs, respectively. Between 1 000 and 1 200 m of sediment separate the ore-bodies; thus, the calculated depths-of-formation are in reasonable agreement with, and are supported by, the stratigraphic interval separating the ore-bodies.

The stockworks appear to have formed under abnormally-low pressure-conditions. The Vaalhoek stockwork displays formation-pressures and -depths of 1,25 kbars and 4,6 km, respectively. This apparent depth-of-formation is consistent with pressure/depth data obtained from the other ore-bodies, being too shallow for its stratigraphic setting. The stockwork sample displayed a tight grouping of well-defined homogenization- and decrepitation-temperatures, in consequence of which Ash and Tyler (in press) considered the fluid-inclusion data valid. One possible reason for the abnormally-low pressures-of-formation is the structural setting of the stockwork. The Vaalhoek stockwork is a fracture-fill ore-body that lies in close proximity to a major dyke (the Vaalhoek dyke), which was clearly intruded under tensional conditions. Ash and Tyler (in press) suggested that remobilization of ore may have occurred during the emplacement of the dyke. The remobilized ores were reprecipitated in fractures at sub-normal pressures in an extensional-tectonic regime. The dyke-filled fractures may have been open to the surface, allowing reprecipitation of ore under hydrostatic, rather than lithostatic, pressures. The tight grouping of homogenization- and decrepitation-temperatures of this sample suggests that the fluid-inclusion geobarometer was reset during remobilization.

Comparison of Pilgrim's Rest fluid-inclusion characteristics with other major precious-metal deposit-types (Table II) yields interesting similarities. When compared to other deposit-types, the Pilgrim's Rest fluid-inclusions are anomalously saline. No apparent relation between sample-location and salinity was found in the Pilgrim's Rest ore-bodies. Homogenization-temperatures are comparable with Archean, lode-gold deposits (200-400°C). Both deposit-types formed under lithostatic pressures; both contain ubiquitous, high-density CO_2-inclusions. Furthermore, lode-gold and the Pilgrim's Rest fluid-inclusions contain accessory methane. These data suggest the Pilgrim's Rest vein-gold deposits to be comparable with Archean lode-gold deposits and to have originated, possibly, under broadly-similar conditions. The genesis of Archean lode-gold deposits has been the topic of heated debate. Recently, the post-kinematic or syn-metamorphic school, fortified by isotopic data, has gained acceptance over the previously-widely-held belief of a syngenetic origin. Colvine and others (1984) concluded that the mineralizing fluids in lode-gold systems are derived from a magmatic or metamorphic source. A fundamental difference between the two classes of deposits is that lode-gold deposits, as well as epithermal gold deposits (such as Creede, Carlin, and Cortez) were formed from dilute solutions. By contrast, data from Pilgrim's Rest suggest that the mineralizing fluids were moderately-to-highly saline.

Stable-Isotope Geochemistry

To supplement field and fluid-inclusion studies of quartz-pyrite-precious-metal veins at Pilgrim's Rest, eight pyrite samples and nine quartz samples were analyzed to determine the sulphur- and oxygen-isotope properties of the gold-bearing veins. Sulphur-isotope analysis was undertaken by



HOMOGENIZATION TEMPERATURES

Sample and symbol			Median $T_h(CO_2)$ °C	T_h Range °C	T_h Median °C	Description
DHC	Theta reef	●	10	200 - 300	240	Stratiform reefs
BRI	Blyde reef	▲	6	200 - 280	240	
FT1-3	Vaalhoek stockwork	▼	3	170 - 210	190	Stockworks
BFT-1A	Trixie leader	O O'	18	160 - 270* max >400	190	
92	Gregory reef	■	4	270 - 400	300	Vertical reef

*All decrepitation temperatures

Figure 7 : Data tabulation and P-T-CO_2 isochore-plot of Pilgrim's Rest fluid-inclusion data. The shaded area brackets estimated minimum temperatures of formation, as deduced from available total-homogenization data. Modified from Hollister and Burruss (1976) and Ash and Tyler (in press).

TABLE II

Diagnostic Fluid-Inclusion Characteristics of Principal Ore-Deposit Types

From Ash and Tyler (in press), after Colvine and others (1984)

Deposit-Type	Fluid-Composition	Salinity (wt. % NaCl equivalent)	T_h (°C)	Remarks
Pilgrim's Rest	CO_2, H_2O ± CH_4	Saline: range 2 - >25 (av. 15)	200 - 400	CO_2-rich; daughter-minerals (KCl, NaCl, $CaSO_4$ common); high-density CO_2
Massive Sulphide	H_2O	Dilute: 1 - 8	200 - 370	no boiling
Mississippi Valley	H_2O, hydrocarbons	Saline: >15	100 - 150	no boiling
Porphyry Cu	H_2O, CO_2 (rare)	Saline: up to 75	up to 750	boiling common
Porphyry Mo	H_2O, CO_2 (minor)	Moderate: <15	up to 500	CO_2-phase separation
Epithermal Au-Ag	H_2O, CO_2 (minor)	Dilute: <5	<350	boiling common
Sn-W Skarns	H_2O, CO_2 (minor)	10 - 45	600 - 650	local boiling
U-veins	H_2O, CO_2 hydrocarbons	Dilute: 1 - 5	<400	CO_2-phase separation
Lode Gold	H_2O, CO_2, CH_4	Dilute: <5	200 - 400	CO_2-rich inclusions ubiquitous; high-density CO_2

Coastal Studies Laboratory, a commercial analytical laboratory in Austin, Texas; oxygen-isotope analysis was kindly provided by Professor Lynton Land of the Department of Geological Sciences, University of Texas at Austin.

Nine samples of vein-quartz were obtained from two reefs in the basement granite and at different stratigraphic levels in the overlying Transvaal Supergroup (Fig. 8). Four samples were from strata-bound, "bedded" ore-bodies in the Malmani Dolomite, two from the Peppersteak Reef in the Pretoria Group (also a strata-bound vein), and two samples from the vertical feeder-reefs in the basement granite. A single sample was obtained from the Trixie Leader, a stockwork developed in the Wolkberg Group below the Black Reef Quartzite.

All of the quartz samples fall in the range $\delta^{18}O$ + 12,1 to +19,5°/∘∘ (Fig. 8). The strata-bound bodies in the Malmani Dolomite (Vaalhoek, Portuguese, Beta, and Theta reefs) display $\delta^{18}O$-values tightly clustered between 17 and 18°/∘∘. The vertical feeder-bodies in the basement granites are characterized by slightly-lower, isotopic compositions (14,1-15,2°/∘∘). Strata-bound ore-bodies in Pretoria-Group shales exhibit the lowest, isotopic compositions (12,1-14,4°/∘∘). In contrast, $\delta^{18}O$-values are highest in the Trixie Leader. Although the samples display a relatively narrow range of oxygen-isotope compositions, there is a systematic variation in the isotopic make-up of the quartz. The vein-quartz is isotopically heaviest in dolomite, intermediate in granite, and lightest in shale host-rocks.

The sulphur-isotopic composition of pyrite from five strata-bound veins and single samples from the Trixie Leader and the Vaalhoek stockwork all fall in the narrow range of $\delta^{34}S$ + 0,5 to + 4,0°/∘∘. Unlike oxygen-isotopes, where the Trixie Leader sample was isotopically heaviest, the Trixie Leader falls within the range displayed by the strata-bound ore-bodies (Fig. 8).

The isotopic composition of the mineralizing fluids can be estimated, using $\delta^{18}O$-quartz data, fluid-inclusion homogenization-temperatures, and oxygen-isotope separation-factors for the system quartz-water, and using Friedman's and O'Neil's (1977) modified fractionation-curves of Clayton and others (1972). Calculated $\delta^{18}O$-fluid-values are a function of the estimated fluid-temperature. At elevated temperatures (400°C), variations in temperature result in only minor differences in the estimated oxygen-isotopic composition of the mineralizing fluid. At low temperatures (less than 300°C), small differences in temperature result in large changes in the calculated, isotopic composition of the fluid. Hence, homogenization-temperatures are a critical parameter in the calculation. Fluid-inclusion data from Pilgrim's Rest are complex, with samples displaying a range of homogenization-temperatures. This temperature-variation reflects multiple phases of mineralization and results in a spread of possible, isotopic compositions of the mineralizing fluid (Table III). The deeper ore-deposits (Rietfontein, Gregory, and Trixie), that are characterized by higher homogenization-temperatures, display $\delta^{18}O$-fluid-compositions averaging +10,4°/∘∘. The fluids that precipitated the shallower, strata-bound ore-bodies were characterized by slightly-lower $\delta^{18}O$-fluid-values, averaging +9,7°/∘∘ at temperatures of 300°C. Using lower homogenization-temperatures (less than 240°C), the compositional difference between the fluids at depth and the shallower fluids is more pronounced (Table III). Better definition of the vertical variation in the fluid-composition will require more-solidly-defined, fluid-inclusion information.

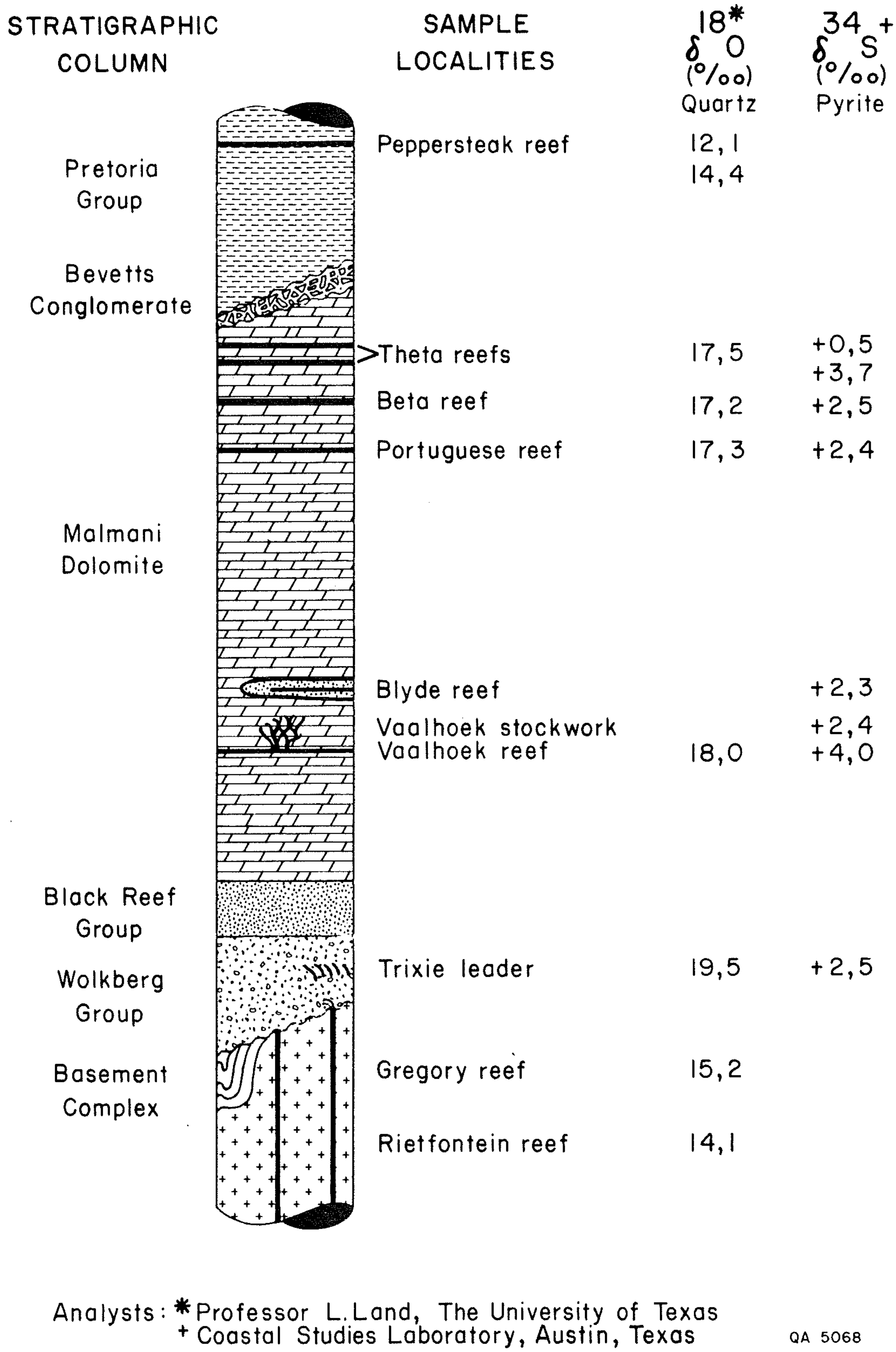


Figure 8 : *Sample-locality column and isotopic compositions of selected ore-bodies.*

TABLE III

Calculated Oxygen-Isotope Composition of Mineralizing Solutions at Pilgrim's Rest, Based on Fluid-Inclusion Data of Ash and Tyler (in press) and Oxygen-Isotope Separation-Factors (Friedman and O'Neil, 1977; modified from Clayton and Others, 1972). Temperature-Values Represent Clusterings of Data

	$\delta^{18}O$ Quartz (°/oo)	Fluid-Inclusion Homogenization-Temperatures (°C)	$\delta^{18}O$ Fluid (°/oo)
Upper dolomite-and-chert zone (Theta, Beta, and Portuguese reefs)	17,3	300+ 240 200	9,9 7,3 5,1
Lower dolomite-and-chert zone (Blyde, Vaalhoek reefs)	18,0	260-280	9,4
Trixie Leader	19,5	270*	10,9
Vertical reefs in granite (Rietfontein, Gregory)	15,2 14,1	400+ 300	10,7 9,6 8,0 6,9

\+ Pronounced cluster of homogenization-temperatures

* Based on highest temperature of decrepitation

Neither the sulphur- nor the oxygen-isotope data fall entirely within unique, compositional fields. Pilgrim's Rest $\delta^{34}S$-pyrite-values are comparable with igneous rocks, volcanics, evaporites, and sedimentary sulphides (Kaplan, 1981) and are similar to isotopic compositions of pyrites in epigenetic vein-deposits and Archean massive-sulphide deposits (Fig. 9). The total range of possible $\delta^{18}O$-fluid-compositions falls in an area common to metamorphic water, magmatic water, and evolved, meteoric and formation-water (Fig. 9). At higher homogenization-temperatures, the deeper ore-bodies display the signature of a magmatic- or metamorphic-fluid source, as these values lie outside the range of compositions of evolved, meteoric and formation-waters. At shallower levels and at lower temperatures-of-formation, the data are non-diagnostic. When considered in the context of the composition of the solutions at deeper levels, the shift towards oxygen-depletion at shallower levels suggests that the upwelling fluids may have mixed with evolved formation-waters in the sedimentary succession.

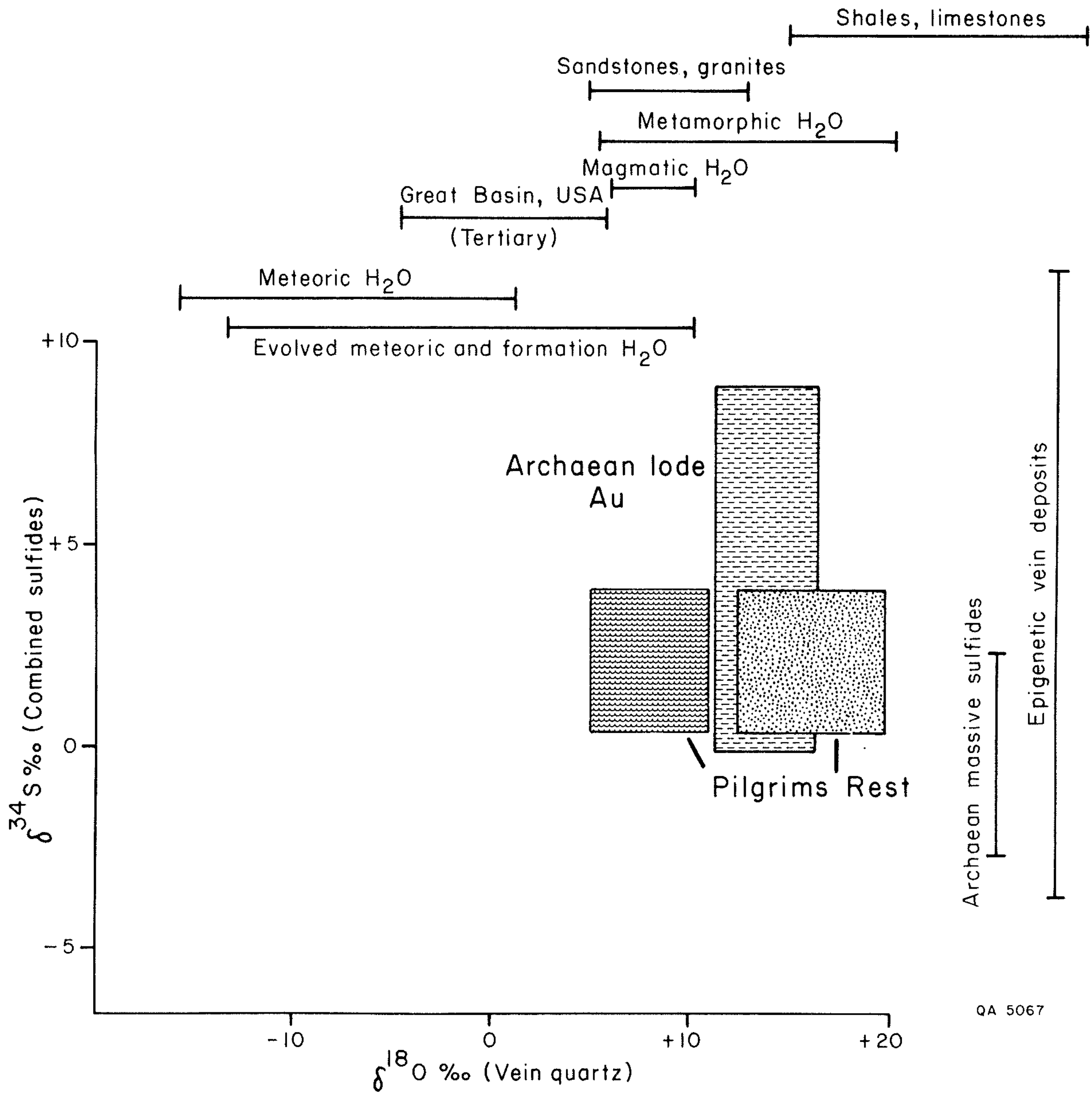


Figure 9 : *Isotopic composition of quartz and pyrite from Pilgrim's Rest, with comparative values. Stippled pattern represents the range of $\delta^{18}O$-quartz values; wave-pattern shows the field of possible $\delta^{18}O$-fluid values. Adapted from Colvine and others (1984) and Taylor (1979).*

CONCLUSIONS

The Malmani Dolomite is the principal host of gold mineralization in the Pilgrim's Rest Goldfield. The dolomite was deposited on a wide, laterally-extensive platform. Sedimentation was cyclic and was periodically interrupted by subaerial erosion. Most of the sediment was deposited in shallow, subtidal environments, with the exceptions of the giant bioherms of the chert-poor zone and the supra-tidal-to-lagoonal clastics and carbonates of the transition-zone. Gold-silver mineralization is confined to the shallow-water deposits of the Malmani Dolomite. Deeper-water shelf-carbonates are devoid of mineralization. The intimate association of strata-bound ore-bodies with carbonaceous or graphitic shales suggests that these fine-grained, terrigeneous clastics may play a critical role (perhaps as a reductant) in the genesis of the strata-bound ores.

Field-relations and fluid-inclusion and isotope information indicate that the vertical lodes in the basement granites and the strata-bound bodies, stockworks, and leaders in the Transvaal Supergroup were all part of an integrated, but multiple-generation, mineralization-system. Reconnaissance, fluid-inclusion homogenization-temperatures suggest that there was a temperature-of-entrapment gradient of at least 100°C over the 1 000-1 200 m of sediment that separate the deeper from the shallower ore-bodies. Inclusions from quartz-veins cutting basement granites homogenize at between 300 and 400°C; inclusions from the shallower, strata-bound reefs homogenize at 200°C. Each sample displays a range of homogenization- and decrepitation-temperatures, supporting Swiegers's (1949) conclusion that mineralization was a multiphase event.

Mineralizing solutions appear to have been derived from more than one source. Reefs cutting the basement display a magmatic or metamorphic, isotopic signature. The fluid-inclusion-derived, temperature-of-entrapment gradient of approximately 100°C/km strongly supports a magmatic origin of the mineralizing fluids. At shallower levels, the data are less diagnostic. However, the vertical evolution in fluid-chemistry suggests that the upwelling brines mixed with evolved formation-waters in the sedimentary assemblage. Fluid-inclusion evidence shows that the fluids were saline, rich in CO_2, and contained trace-amounts of methane at all stratigraphic levels. Evidence for evolution of the fluids, as they migrated upward, is strong. Deeper deposits, such as the Gregory Reef, contain fluid-inclusions rich in daughter-minerals, suggesting that, at deeper levels, the fluids were high in total dissolved solids. At shallower levels, fewer daughter-minerals are found in the inclusions, indicating a decrease in the dissolved-solids content and a change in the chemistry of the brines.

Based on current information, the following emplacement-model is proposed for the origin of the Pilgrim's Rest Goldfield (Fig. 10). It is emphasized that this is a working-model that will probably be modified as additional information becomes available. Fluids, derived, in part, from a deep-seated, magmatic source, were conveyed upward along regional north-trending fault-zones and shear-zones. Metals were acquired, not only from the provenance, but also, possibly, from greenstone remnants through which they passed. As the upward-migrating solutions entered the supra-crustal, hydrochemical regime, decreases in pressure and temperature, probably accompanied by mixing with minor volumes of evolved formation-waters, facilitated precipitation of gold, silver, pyrite, and quartz on the walls of fractures forming the vertical lodes. Most of the evolving fluid continued to migrate upward into the sedimentary column, where it encountered greater volumes of evolved formation-water and zones that favoured lateral penetration and migration. Mixing of the invading waters with ambient waters was more thorough in the sediments; hence, the original, isotopic composition of the fluids is masked.

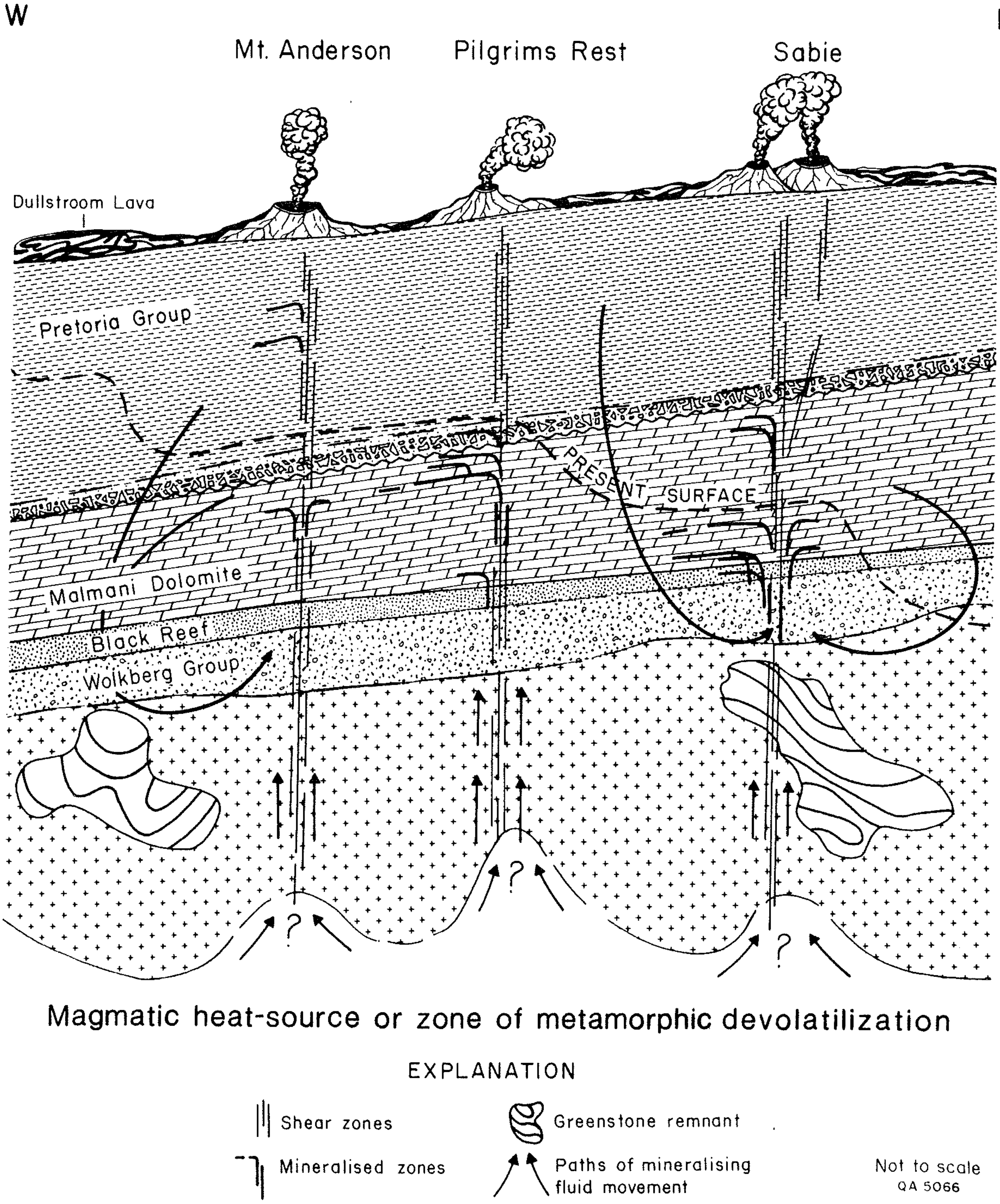


Figure 10 : *Emplacement-model of strata-bound gold-silver ore-bodies of the Pilgrim's Rest Goldfield.*

Mingling of magmatic waters with evolved formation-brines may explain the anomalously-saline nature of the mineralizing solutions at Pilgrim's Rest. As noted earlier, the Pilgrim's Rest fluids display higher salinities than the mineralizing solutions of Archean lode-gold deposits or of epithermal deposits of the western United States. There is strong evidence that the Malmani Dolomite may have contained intervals that were partly evaporitic in origin. Ubiquitous salt-cast-bearing layers in the transition-zone point to lagoons that periodically contained highly-saline waters, landward of which were probably-extensive sabkhas or salt-flats. Salt and sulphates are readily dissolved in the subsurface, removing evidence for their existence and increasing the salinity of formation-waters. It is postulated that a process of this nature provided saline formation-waters that, via mixing with the invading magmatic brines in the sediments and, to a lesser extent, deeper in the section, resulted in the high salinities of the mineralizing fluids at Pilgrim's Rest.

Clastic sediments, deposited under intertidal-to-shallow-subtidal conditions, acted as conduits for the lateral migration of brines. These may have been zones of preferential dip-slip- and thrust-faulting, as Zietsman (1967) has proposed. The precipitation-mechanism of the strata-bound deposits in the Malmani Dolomite was probably different from that in the basement granites. As the fluids spread laterally, they encountered highly-reducing conditions, as a result of the presence of organic material in the shales. The abrupt change in the ambient, chemical environment resulted in the precipitation of gold from solution, possibly, initially, as gold-organic compounds, as well as the precipitation of pyrite and other metallic compounds. A similar mechanism of gold-organic complexing has been inferred by Radtke and Scheiner (1970) for the origin of the Carlin gold deposits in Nevada. In the ore-zones, quartz, which commonly forms a central, barren core, was the last mineral to precipitate. As the solutions cooled, they continued to spread out laterally and parallel to dip, where the final stages of mineralization were marked by the precipitation of quartz, pyrite, and calcite.

Pressure-data from fluid-inclusions indicate that precipitation of the ores took place at depths of between 5,5 and 7,0 km. Approximately 8 km of Pretoria Group sediments and volcanics overlie the Malmani Dolomite in the eastern Transvaal (Button, 1973b). Thus, if the depth calculations are correct, as they appear to be, based on stratigraphic relations, then the veins possibly were injected into the basement granites and into the overlying sediment during late-Pretoria time. This was a period of great crustal instability and was marked by the extrusion of up to 1 400 m of basaltic-to-intermediate volcanics, known as the Dullstroom Lava. Subsequent differentiation of the magmatic source resulted in the outpouring of an additional 3 000 m of acid lavas (the Rooiberg Felsites). These early-Proterozoic, magmatic events could have been the heat-source that drove the hydrothermal solutions at Pilgrim's Rest. Alternatively, the Bushveld Complex may have provided the requisite, thermal energy. However, if this were the case, then depths-of-formation, based on the thickness of the overlying stratigraphic column, would have been closer to 10 and 12 km.

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