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University of the Witwatersrand
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PALAEOHYDROLOGY OF *c.* 2 Ga OLD MISSISSIPPI VALLEY-TYPE Pb-Zn DEPOSITS, SOUTH AFRICA: RADIOGENIC AND STABLE ISOTOPE EVIDENCE

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by

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ABSTRACT

There are a large number of epigenetic Pb-Zn (± Ag, Au, Cu, F) deposits in the cover rocks of the Kaapvaal Craton (South Africa). These include small volcanic and breccia-hosted deposits in the Ventersdorp Supergroup and the better-known Mississippi Valley-type (MVT) deposits in the carbonates of the Ghaap and Chuniespoort Groups.

Two small Pb-Zn deposits within mafic rocks of the Ventersdorp Supergroup in the Douglas area, situated distal to and southwest of the Bushveld Complex, possess an unusual, extremely Rb-rich chlorite associated with the mineralization. This chlorite and the accompanying altered host rocks yielded a Rb-Sr age of 1.98 Ga. Pb-isotope data from associated galena falls on the same array as other Pb-Zn deposits, the Stacey and Kramers (1975) radiogenic intercept of which gives an age of *c.* 2.0 Ga. Furthermore, the 2.7 Ga old tuffaceous Makwassie Quartz Porphyry (MQP) in the Zoetlief area has suffered complete resetting of both the Pb/Pb and Rb/Sr isotopic systems at *c.* 2.0 Ga. We interpret these data to indicate a craton-wide epigenetic fluid event at *c.* 2.0 Ga, which exploited the MQP as the main aquifer and metal source.

MVT mineralization at the Pering Zn-Pb deposit (Northern Cape Province, South Africa) is hosted in fracture-generated north-south-trending breccia bodies of Early Proterozoic age. The fluids carrying the metals were focussed in vertical bodies within the fracture zones, and two of these were sampled in boreholes penetrating similar parts of the succession. Borehole S26 is in the Scheurfontein fracture zone close to Pering Mine, and borehole LB1 is in the Choga Amoet fracture zone some distance to the east.

Sr-isotopic results show highly radiogenic $^{87}Sr/^{86}Sr$ ratios (>0.710) which support earlier models suggesting that the origin of the radiogenic Sr-isotopic compositions in the calcite cements is the MQP felsic tuffs of the Ventersdorp succession occurring at deeper levels within the basin. Relationships between $\delta^{18}O$ and $\delta^{13}C$ performed on carbonate cements within the aquifers are complex: the range in $\delta^{13}C$ for some of the cements represents a mixture from two sources and with a progression from heavy carbon in the host to somewhat lighter carbon in the cements. Similarly, the lighter $\delta^{18}O$ values have a narrow range indicative of high fluid/rock ratios. The fluids were focussed into vertical and horizontal feeder channels composed of sparry dolomite, as well as into vugs filled with sphalerite, galena and hydrocarbons. These fluids are recorded district-wide in cement stratigraphy in the weakly mineralised distal feeders known as “drusestones”.

The *c.* 2 Ga Kheis Belt on the western edge of the Kaapvaal Craton represents an apparently long-lived tectonic event that was part of a larger southern African magmatic arc existing between 2.1 and 1.9 Ga. Textural data, from individual Zn-Pb ore deposits in the Transvaal Basin, suggest that ore-forming fluids were activated before the main Bushveld intrusive event in the Zeerust-Thabazimbi area (i.e., in the western sector of Transvaal Basin) at 2.06 Ga, whereas geochronological data indicates post-Bushveld ages in the Ghaap Plateau area (southwestern sector). The Rb-Sr mica dates obtained from deformed parts of the Bushveld age Molopo Farms Complex (distal and west of the Bushveld Complex) that lie within the Kheis deformational front are also *c.* 2.0 Ga in age. A younger age (1.9-2.0 Ga) is indicated for the overthrust volcanics of the Olifantshoek Supergroup. These diverse results could indicate an early origin for some of the MVT deposits, probably

at the initiation of the magmatic arc which extended from the Northern Cape in Southδ Africa as far as central Africa - the last manifestation of which is the Kheis fold and thrust belt. The carbonate platform sequence on the western side of the Kaapvaal Craton records a long history of deformation and fluid flow. Some episodes of mineralization appear to have been initiated prior to *c*. 2.05 Ga, and ended at *c*. 1.9 Ga - a period of *c*.150 Ma.

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INTRODUCTION

Duane et al. (1991) postulated that carbonate-hosted Pb-Zn deposits in the Northern Cape Province are derived from ore fluids, which acquired metals from sediments and volcanic rocks within and below the Proterozoic Ghaap Group. These metal-charged fluids then migrated through aquifers along a tectonic and gravity gradient, caused by the Kheis tectonism to the west, to the sites of mineralization. In particular, the rocks of the western Kaapvaal Craton (Fig. 1) have been pervasively altered and reset by fluid interaction. The extent of this regional fluid migration is supported by other studies (e.g., Duane et al., 1988; Duane and Kruger, 1991; Sumner and Bowring, 1996), but the nature of the flow pathways and the timing remain unconfirmed.

Given the stratigraphic thickness of the Ghaap and Transvaal carbonate rocks and the underlying Ventersdorp volcanic rocks, and the distribution of Pb-Zn deposits within these formations, the vertical extent of the fluid flow was probably up to 2 km. The lateral extent of the flow appears to have extended up to 500 km from west to east (and along a north-south front of the same extent). Following the suggestion of Duane and Kruger (1991), that a craton-wide hydrothermal event (linked to the Kheis Orogeny at *c.* 2.0 Ga) was responsible for significant mineralization and isotopic overprinting in rocks of the Transvaal Supergroup, the timing of this fluid flow and its link to the age and duration of the Kheis Orogeny as an agent for tectonically driven brine migration, has been vigorously disputed (e.g., Martini et al., 1995; Cornell et al., 1998).

In this work we present geochronological and other supporting evidence from Sr-, O- and C- isotope measurements for at least district-wide fluid-migration event(s). Gangue minerals in Mississippi Valley-type (MVT) deposits have relatively higher $^{87}Sr/^{86}Sr$ ratios than expected by comparison with the country rocks (e.g., Medford et al., 1983), whereas this is not the case in barren drill core, or where mineralization is sparse. Sr-, C- and O-isotopic compositions are useful discriminators between different diagenetic and epigenetic fluids, different mineral-solution reaction mechanisms, and between the varied processes of fluid-rock interaction (e.g., Banner, 1995). The present study investigates carbonate rocks of the Ghaap Group in the vicinity of the Pering Zn-Pb Mine, as well as other smaller, but related deposits in the Transvaal Supergroup carbonate rocks and in the underlying Ventersdorp Supergroup volcanic rocks.

Potential aquifers are very scarce in the carbonate succession other than in the “drusestones” discussed below. Furthermore, the sandstones and shales present are thin and impervious. By contrast, there are a number of potential aquifers within the underlying Ventersdorp Supergroup, the thickest and most widespread of which is the Makwassie Quartz Porphyry (MQP) and its outlier and inlier correlatives present throughout the entire area (Fig. 1). Microscopic examination shows that the MQP is a fragmental tuff that was subsequently indurated and is now a cryptocrystalline “rhyolite”. Geochemically, this rock provides an ideal source for both Zn and Pb, and the tuffaceous nature would have at the time provided a fluid pathway with both a high permeability and porosity. Other potential aquifers in the Ventersdorp Supergroup consist mainly of clastic sediments (arkosic) and

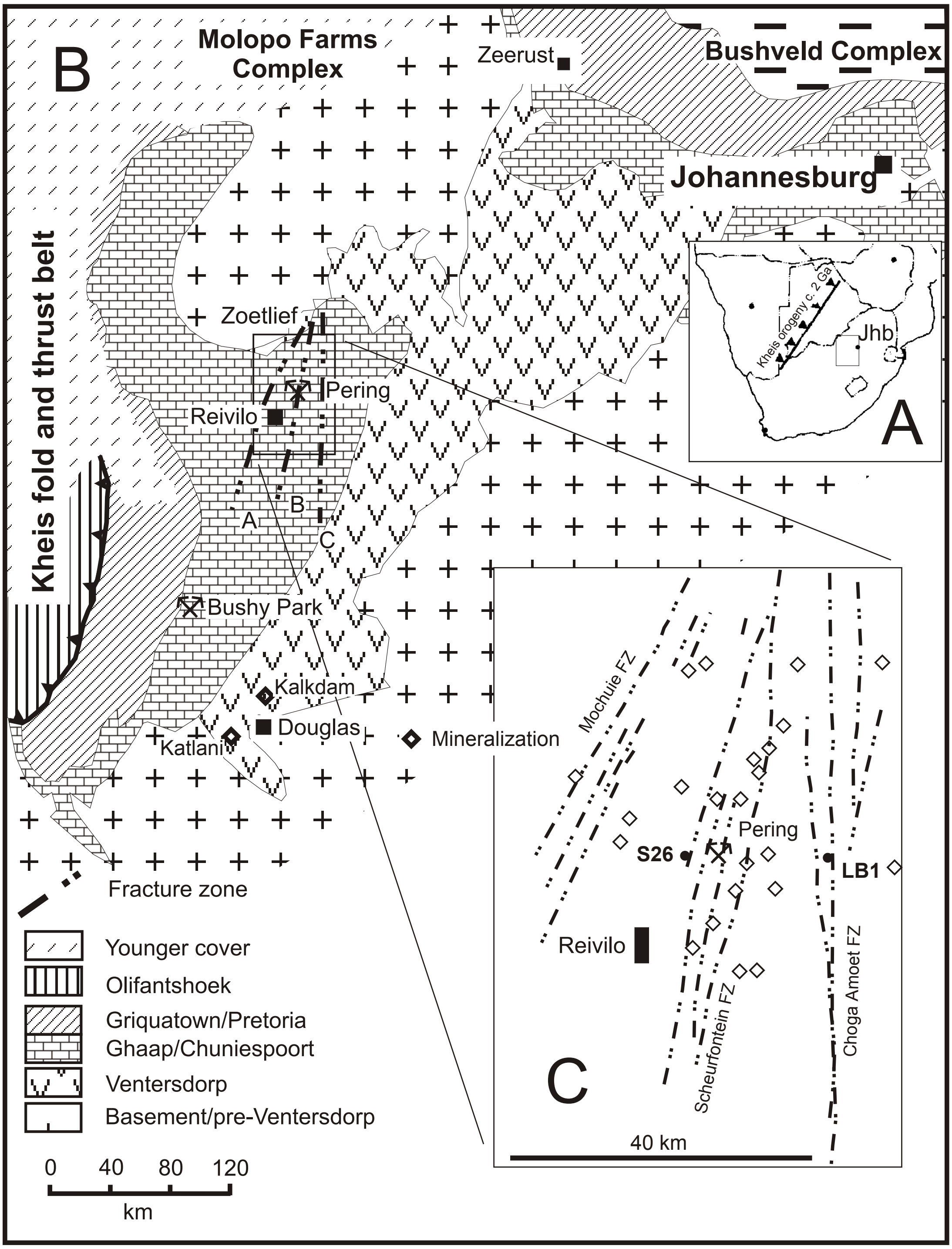

Figure 1: General map of the western Kaapvaal Craton with the main lithologies and ore deposits indicated. Three fracture zones (A = Mochuie; B= Scheurfontein; C = Choga Amoet) are indicated, as well as the location of the Zoetlief Group, the Pering and Bushy Park deposits and the locations of the towns of Reivilo and Douglas.

mafic and felsic fragmental rocks (tuffs and agglomerates) but, unlike the MQP, these are laterally impersistent.

These aquifers, which are sandwiched between relatively impermeable mafic volcanic rocks, would allow lateral fluid transport on a large scale. Furthermore, any deep penetrating fractures and/or faults would focus the fluids into the overlying rocks where mineralization could occur.

GEOLOGICAL SETTING

Geochronology and stratigraphy

The rocks studied are Lower Proterozoic Transvaal Supergroup cyclothems on the Ghaap Plateau and altered and metasomatised units of the Allanridge Formation of the Ventersdorp Supergroup (Fig. 1). The Ghaap Group is dominantly a carbonate sequence, comprising sub-aerially exposed evaporitic horizons, stromatolitic facies, and deeper-water carbonate muds. The sediments were initially preserved as limestones and replacement by pervasive dolomitisation was an early diagenetic event (Beukes, 1987). The rocks sampled in this study include material from the Campbell Rand Subgroup, which form a thick succession of dolomitic shales, carbonaceous shales and stromatolite units (Fig. 2). Below the Reivilo Formation lie the quartzites and shales of the Monteville Formation. Below the Campbell Rand Subgroup lies the Schmidtsdrif Subgroup composed mainly of cryptalgal and clastic dolomites and shales, which are mostly barren of mineralization. The entire carbonate succession overlies different units of the Ventersdorp Supergroup.

Carbonate-hosted mineralization and fracture systems

There are three major fracture systems in the vicinity of the Pering Mine identified from air photographs, TM and field work (Fig. 1C). These are, from west to east, the Mochuie fracture zone trending NNE, the Scheurfontein fracture zone trending north by east, and the Choga Amoet fracture zone trending due north. Pering Mine and borehole S26 are within the Scheurfontein fracture zone, and the LB1 borehole is located in the Choga Amoet fracture zone directly to the east. Surface expressions of mineralisation and that intersected by other boreholes are also largely on the same trends (Fig. 1B,C). In detail, the mineralization in the area around Pering is dispersed in a low-grade halo (<1%) in the dolomites of the Ghaap Group and the highest grades within and outside the pit (3-4% Zn-Pb) are associated with north-south breccia bodies straddling a fault system (Hounsome, 1993).

Mineralization at Pering is hosted largely in the 150m-thick Steekdorings member of the Reivilo Formation (Wheatley et al., 1986), and comprises columnar and domal stromatolitic units alternating with thin carbon-rich shales. The following lithologies mark the sites of mineralization: (1) carbonaceous shale occurs in 0.5m-thick beds and has noticeable pyrite mineralization; (2) finely laminated stromatolitic dolomite with sphalerite occupying the fractures in the laminae is the most abundant in the mine series; (3) massive, laminated dolomite is developed in convex-shaped domes and, in places, above Carbon Shale 2, they exhibit flat-topped topography; (4) ripple dolomite is characterised by distinctive ripple marks with amplitudes up to 1.5 cm; and (5) breccia bodies, with fine

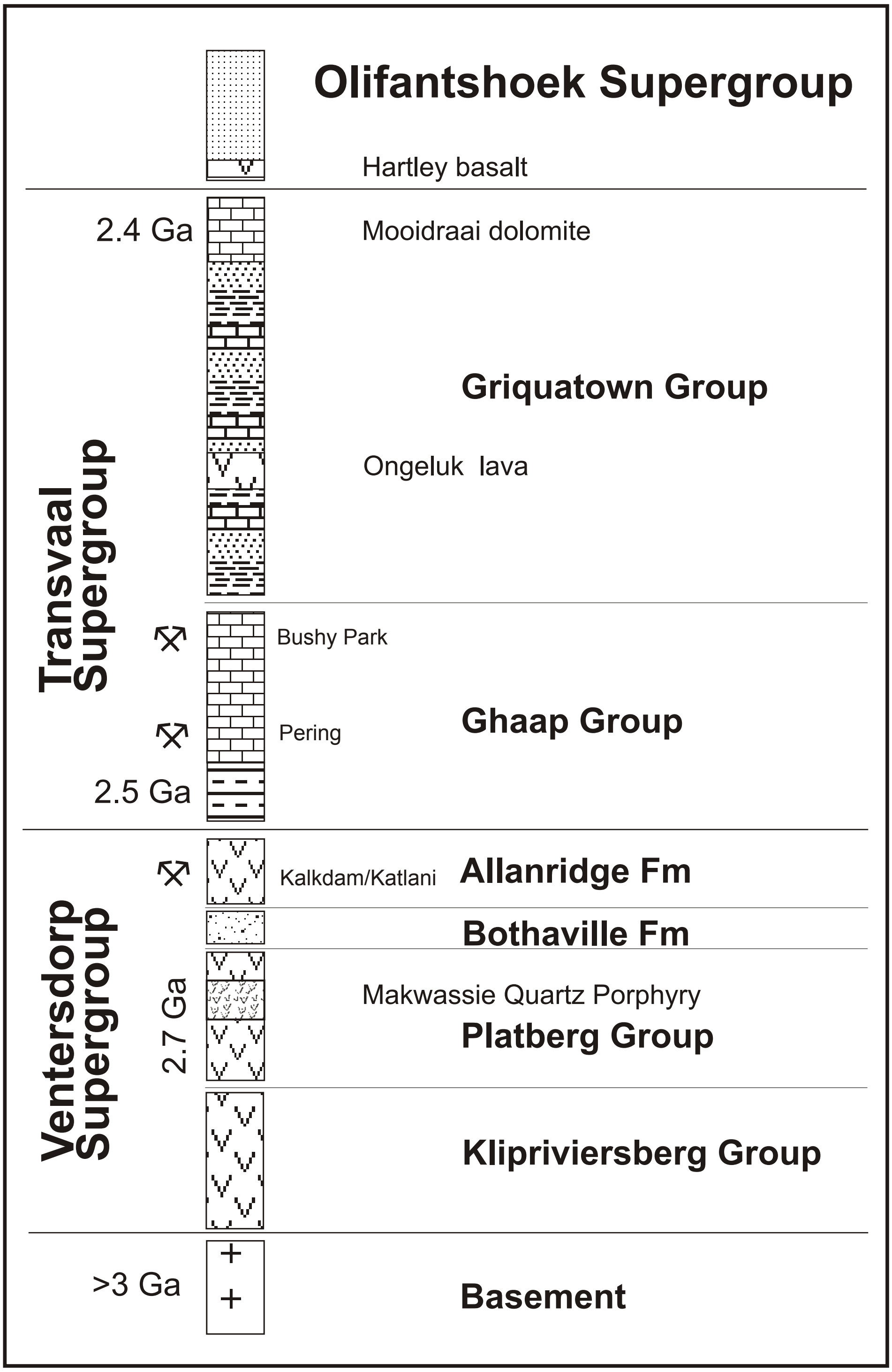

Figure 2: General schematic stratigraphic section (not to scale) showing Basement, Ventersdorp, Ghaap and overlying successions (modified after Clendenin et al., 1988). Location of ore deposits and potential aquifers are indicated.

dolomite matrix, and angular to subrounded blocks of all the above lithologies, occur cemented by late calcite and dolomite cements.

Sphalerite, with subordinate galena is the dominant sulphide and the Zn:Pb ratio is approx 6:1 (Wheatley et al., 1986). The sphalerite has two distinguishing colours, an early light-honey-coloured, coarse-grained form, and a later, brown, disseminated form. Gangue minerals associated with the ore include white sparry dolomite, quartz, and late calcite (± pyrobitumen). A basin-wide hydrocarbon migration event is recorded in residues from stromatolitic dolomites in the Transvaal and Ghaap successions (Roberts et al., 1993), and records one of the earliest hydrocarbon-forming events.

Detailed core logging using a simple Alizarin Red S stain to distinguish carbonate phases, and subsequent core logging identified three phases of carbonate in the vugs. These were numbered from oldest (C1), deposited on dolomite, to youngest (C3), in the centre of the vugs (Turner, 1992). Phase C1 is a relatively un-zoned rim or rind on the host dolomite and represents a distinct pulse of hydrothermal fluid. Phase C2 exhibits fine oscillatory growth zones, indicating varying trace element concentrations and episodic growth. No zoning was evident in phase C3, which staining indicated to be pure calcite, whereas C1 and C2 are highly magnesian calcite or dolomite. Sphalerite is associated with phases C1 and C2 and can be found between the dolomite host and C1, within phase C1, between phases C1 and C2, and within phase C2. Organic matter was deposited with phase C2 and C3 (see Turner, 1992 for further details).

Volcanic-hosted mineralization

Basaltic andesitic lavas of the c. 2.7 Ga Allanridge Formation, the topmost formation of the Ventersdorp Supergroup, crop out near the town of Douglas in the southwest of the basin (Fig. 1B). The lava flows are massive in the middle to highly amygdaloidal at the base and top, providing contrasting permeability and porosity. These permeable zones have acted as channels for subsequent fluid flow, hydrothermal alteration and mineralization. The degree of alteration and mineralization in the flows is directly related to the abundance, size and distribution of the initial vesicles. In the middle of the flows, where amygdales are sparse, the rock matrix is relatively unaltered. Microscopic analysis showed that plagioclase crystals are relatively well preserved, but primary ferromagnesian minerals have been replaced by chlorite. Towards the base and top of the lava flows the alteration becomes more pervasive: primary texture becomes difficult to identify as calcite, followed by micro-crystalline quartz, predominates in the groundmass (Whitelaw, 1998). The amygdales are filled to varying degrees with calcite, chlorite and quartz. Sphalerite is intimately associated with the calcite, and at Kalkdam, the calcite is paragenetically older, and may represent vesicular cavity fills overprinted by later hydrothermal events. This supposition is supported by the available isotope data. The chlorite and quartz appear to be later than the calcite in both the amygdales and the rock matrix. At a similar outcrop (Katlani), about 40km south of Kalkdam, the later alteration is not nearly so pervasive and galena and sphalerite are common.

The mineralised area of the Kalkdam outcrop is localised predominantly at one flow top interface. The mineralization present is galena associated with quartz in the amygdales, together with minor chalcopyrite. Galena is also abundant in crosscutting areas of hydrothermal breccia. These zones are approximately 1m in width and strike obliquely to the flow tops. Clearly, the mineralization has exploited flow top breccias and vesicular areas, but is fed via faults from a potassium-rich source of fluid with a high $^{87}Sr/^{86}Sr$ from lower in the volcanic stratigraphy. This source is the MQP, which is present lower in the succession.

SAMPLE PREPARATION, GEOCHRONOLOGY AND ISOTOPE GEOCHEMISTRY

During this study a number of attempts were made to directly date the fluid event and the Kheis deformation using both the Rb/Sr and Pb/Pb systems. This new data and a large body of previous work, summarised in Walraven et al. (1990), indicate substantial low-grade metamorphism and associated fluid flow through the volcanic rocks over a wide area. The rocks studied include the basement, the Ventersdorp and Transvaal Supergroups, and the Kheis-related volcanic and sedimentary rocks.

Drill core was provided by Shell South Africa and eight cores were logged in detail, but only two were sampled for isotopic analyses. These included borehole S26, close to the Pering Mine and also within the Scheurfontein fracture zone, and borehole LB1, which is approximately 20 km away to the east, associated with the Choga Amoet fracture zone. Additional samples were collected within Pering Mine and from its immediate hinterland. The aim of this procedure was to identify and sample potential conduits for fluids. The most feasible structures in the field appeared to be vugs or druses, which occur above and below thin shale horizons. These shale horizons are exposed in the mine, sandwiched between stromatolite units and brecciated 'druzestone' horizons in the Pering Member. Other potential sites are fractures and brecciated areas.

Methodology

Sample preparation and the results obtained have been described in detail by Turner (1992), and only a summary is provided here. Thin sections of vugs were prepared prior to selection for isotope geochemistry. Individual carbonate phases within the vugs, in particular those associated with sphalerite mineralization, were difficult to identify using transmitted-light microscopy, and a combination of cathodoluminescence, and staining with Alizarin Red S, was used to distinguish carbonate phases.

Approximately 0.1g of each carbonate phase was used for radiogenic isotope analysis and duplicate samples of 0.1-0.2 g were collected for stable isotope analysis. Analytical procedures followed the methods in use at the University of the Witwatersrand, Johannesburg (Hugh Allsopp Laboratory for Sr-isotope data and the Schonland Centre for Nuclear Sciences for stable isotopes), and specific details are reported in Turner (1992) and Whitelaw (1998).

For $^{87}Sr/^{86}Sr$ determinations, replicates of SRM-987 Sr standard were routinely run and an average of 19 duplicates gave an $^{87}Sr/^{86}Sr$ of 0.71022 ± 6. Carbon and oxygen isotopic compositions were obtained by analysing the CO_2 liberated from each sample by H_3PO_4 in a VG Micromass 602C fitted with double-inlet, double-collecting isotope ratio unit. Based on duplicate analyses of most samples, the analytical uncertainty (σ) is no greater than ± 0.059‰ for $\delta^{13}C$, and no greater than ± 0.12‰ for $\delta^{18}O$. All the results are expressed with respect to the PDB carbonate standard.

The results of $^{87}Sr/^{86}Sr$, carbon, and oxygen isotope analyses made on a selection of carbonate samples from the S26 and LB1 boreholes and $^{87}Sr/^{86}Sr$ results from Pering Mine area are listed in Table 1.

Table 1: Rb/Sr, $^{87}Sr/^{86}Sr$, $\delta^{13}C$ ‰ and $\delta^{18}O$ ‰ data for carbonate samples from drill cores S26 and LB1, as well as additional samples from around Pering Mine. Calculated $^{87}Sr/^{86}Sr$ initial to 1930 Ma. Values read from older to younger cements (i.e., DOL-C1-C2-C3). The $\delta^{13}C$ and $\delta^{18}O$ data are relative to PDB

Sample#	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	± 1s	R_{1930}	$\delta^{13}C$	$\delta^{18}O$
Borehole S26								
A-DOL	0.667	16.60	0.1163	0.707794	± 17	0.70461	-0.38	-10.12
A-C1	0.027	14.10	0.0055	0.702406	± 31	0.70226	-0.29	-10.6
AC2	0.024	15.20	0.0046	0.704500	± 18	0.70437	-0.51	-11.51
B-DOL	0.237	12.84	0.0534	0.707052	± 22	0.70559	-0.24	-10.34
B-C2	0.051	45.20	0.0033	0.729615	± 14	0.72953	-0.46	-14.04
B-C3	0.011	46.90	0.0007	0.737165	± 14	0.73715	-1.92	-11.45
Gb-DOL	0.080	10.94	0.2115	0.715791	± 30	0.71521	-0.72	-13.45
Gb-C2	0.072	34.60	0.0060	0.727765	± 18	0.72760	-0.56	-11.85
L-DOL	0.168	10.59	0.0459	0.709974	± 18	0.70870	-0.11	-10.63
L-C2	0.0716	43.34	0.0048	0.752812	± 19	0.75268	0.43	-12.21
M-DOL	0.566	11.20	0.1463	0.714700	± 95	0.71070	-0.31	-10.94
M-C1	No Sr data		0.06	-10.97				
M-C2	0.039	12.80	0.0089	0.717596	± 21	0.71735	-0.45	-12.46
M-C3	0.011	84.70	0.0004	0.749424	± 23	0.74941	-1.62	-10.72
N1-DOL	0.120	11.40	0.0305	0.712794	± 17	0.71196	-0.24	-11.25
N1-C1	0.066	39.00	0.0049	0.749631	± 16	0.74950	-0.26	-11.25
N1-C2	0.046	62.40	0.0021	0.761621	± 16	0.76156	-0.56	-12.45
N2-DOL	0.165	14.00	0.0341	0.713439	± 14	0.71251	-0.36	-10.28
N2-C1	0.076	30.14	0.0073	0.736918	± 18	0.73672	-0.16	-10.78
N2-C2	0.057	73.10	0.0023	0.750837	± 14	0.75078	-0.84	-11.72
X-DOL	0.097	10.70	0.0263	0.712873	± 42	0.71216	0.43	-11.05
X-C2	0.070	42.80	0.0047	0.726489	± 11	0.72636	0.49	-13.24
X-C3	0.004	30.60	0.0003	0.715046	± 18	0.71504	-6.46	-8.93
Borehole LB1								
N-DOL	0.036	16.20	0.0065	0.719923	± 17	0.71975	1.00	-10.37
N-C2	0.038	47.80	0.0023	0.730361	± 18	0.73030	0.64	-12.52
N-C3	0.019	194.40	0.0003	0.723773	± 16	0.72377	-0.06	-15.97
P-DOL	0.035	10.70	0.0095	0.711365	± 20	0.71111	1.09	-10.42
P-C2	0.032	29.40	0.0031	0.730677	± 12	0.73059	0.83	-10.99
R-DOL	0.046	10.68	0.0124	0.725119	± 10	0.72478	1.64	-11.09
R-C2	0.061	31.10	0.0057	0.742042	± 14	0.74187	1.13	-11.36
S-DOL	0.060	23.40	0.0074	0.727787	± 23	0.72759	1.39	-9.81
S-C2	0.030	76.20	0.0011	0.741038	± 13	0.74101	0.7	-11.13
S-C3	0.012	27.00	0.0013	0.747696	± 13	0.74766	-0.48	-12.69
Pering Mine samples								
HS1	0.118	94.23	0.0036	0.777516	± 13	0.77742		
HS2	0.064	147.10	0.0013	0.747580	± 12	0.74755		
ZZ1/1A	14.300	11.97	3.5	0.833196	± 21	-		
ZZ1/1B	17.100	12.10	4.2	0.833517	± 11	-		
K1/2A	2.700	12.50	0.6149	0.714981	± 14	0.699		
K1/2B	2.500	12.19	0.5917	0.715856	± 28	0.698		
K1/3A	0.251	13.70	0.0531	0.716830	± 12	0.71536		
K1/3B	0.274	13.60	0.0583	0.717052	± 12	0.71543		
ZZ1/4A	73.000	106.30	1.9989	0.769362	± 12	0.71382		
ZZ1/4B	70.500	107.10	1.92	0.768863	± 13	0.71563		

Rb-Sr geochronology

Volcanic-hosted deposits

The Katlani and Kalkdam deposits within the Allanridge Formation have yielded a K- and Rb-rich chlorite, which is associated with the mineralization. The Rb-Sr data from altered whole rocks and chlorite indicate an age of 1977 ± 43 Ma with a MSWD of 20 (Fig. 3). The initial ratio is 0.7114, and differs strongly from some calcite amygdales, which imply an initial ratio of *c.* 0.701 a value consistent with the original nature of these 2.7 Ga old mafic-to-intermediate volcanics. For further discussion of these rocks and the data the reader is referred to Whitelaw (1998).

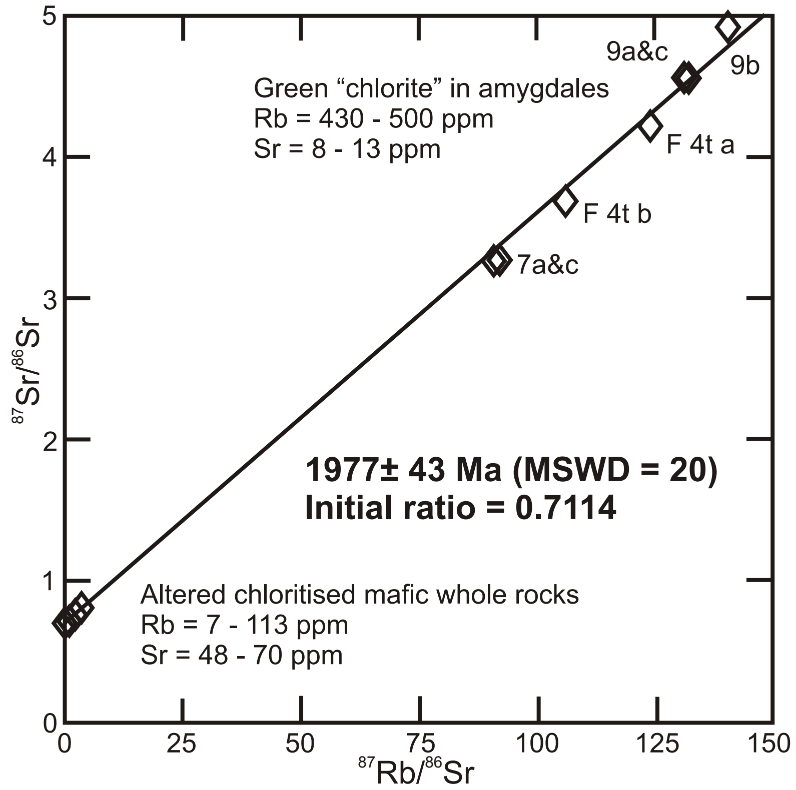

Figure 3: Rb/Sr isochron diagram of Rb-rich "chlorite" from the Katlani and Kalkdam deposits in the Ventersdorp lavas. These data give the clearest indication of a c. 2.0 Ga age for the fluid flow and mineralising event in the Ghaap area.

Carbonate-hosted deposits

Some late phases from Pering Mine are anomalously enriched in Rb relative to Sr and have extremely high present-day $^{87}Sr/^{86}Sr$ ratios (Table 1), which may be geochronologically significant. Preliminary data from the Pering samples, when plotted on an Rb/Sr isochron diagram (Fig. 4), conform to an apparent *c.* 1.9 Ga age, which is identical within error of the Rb/Sr and Pb/Pb ages obtained for the alteration event of the felsic Zoetlief phase of the Ventersdorp felsic volcanics (Walraven et al., 1991). Duane et al. (1991) considered this alteration event coeval with the mineralization in the overlying Ghaap carbonates, and this age is therefore used to calculate the initial ratios. Nevertheless, since the Rb/Sr ratio is very low for most samples, the initial ratio differs little from the present day $^{87}Sr/^{86}Sr$ ratio. This approximate age is also supported by work on the late tectonic Hartley Basalt Formation, which indicates an age of 1928 Ma (Cornell et al., 1998).

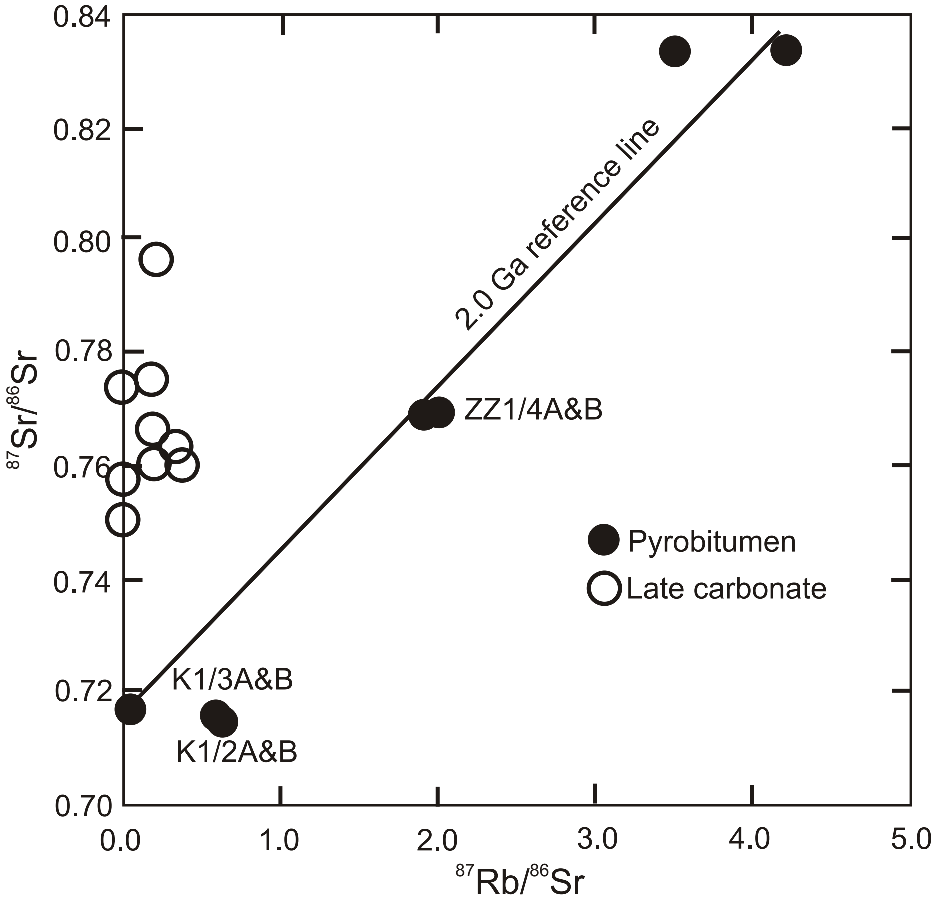

Figure 4: Rb/Sr diagram of the available data from the Pering deposit. Note that the "pyrobitumen" is enriched in Rb and contains age information. However, the initial ratio is very variable and cannot be fixed unambiguously. The Pering data are, nevertheless, consistent with a c. 2 Ga age.

Carbonate-hosted mineralization

Most carbonate cements have very low Rb/Sr values (e.g., Smalley et al., 1987; Schultz et al., 1989). Mineralizing fluids can acquire Sr, with a high ^{87}Sr/^{86}Sr, as a result of interaction with a high Rb/Sr lithology of broadly "granitic" composition. Carbonate minerals deposited with ore minerals may therefore be enriched in ^{87}Sr relative to pre-existing carbonate minerals (Kesler et al., 1988; Brannon et al., 1991).

In the following discussion two C3 samples are quite exotic with respect to the other samples. One, from borehole S26, has low ^{87}Sr/^{86}Sr, unusually light carbon and unusually heavy oxygen, and the other, from borehole LB1, has relatively low ^{87}Sr/^{86}Sr, but very high Sr content and light oxygen. These samples may be unrelated to the other samples and suggest some additional fluids may have interacted with other source rocks such as the mafic lavas of the Ventersdorp Supergroup.

The vug-filling carbonates in the drill-core samples around Pering Mine have high $^{87}Sr/^{86}Sr$ values like the ore-zone carbonates at Pering Mine reported previously by Duane et al. (1991). The plot of $^{87}Sr/^{86}Sr$ versus Sr (Fig. 5), indicates that there is a general trend from dolomites with a low $^{87}Sr/^{86}Sr$ and low Sr content to cements with a higher $^{87}Sr/^{86}Sr$ and Sr content. This positive relationship holds for both the proximal S26 and distal LB1 drill cores as well as for samples from the Pering Mine itself and samples from the surrounding area. This suggests that the differences in the $^{87}Sr/^{86}Sr$ compositions and Sr contents of the cements were influenced largely by the interaction of an exotic epigenetic mineralising fluid (with a high $^{87}Sr/^{86}Sr$ ratio and a relatively high Sr content) with the local dolomite (low $^{87}Sr/^{86}Sr$ and low Sr content), as the latter form one end of the array. This is likely to have been a complex infiltration and mixing process with significant dissolution and reprecipitation. It should be noted that, without exception, samples taken within breccias associated with high-grade mineralization contain radiogenic Sr. The values are also higher than the average Sr-isotopic composition of Proterozoic seawater (*c*. 0.703; Veizer et al., 1992). The ^{87}Sr enrichment of the minerals suggests that at least some of the Sr in the mineralizating fluids was derived from an evolved Rb-rich source. This contention is supported by analyses of some late organic residues from Pering Mine, which contain substantial Rb and have a high Rb/Sr ratio, indicating a Rb-rich fluid.

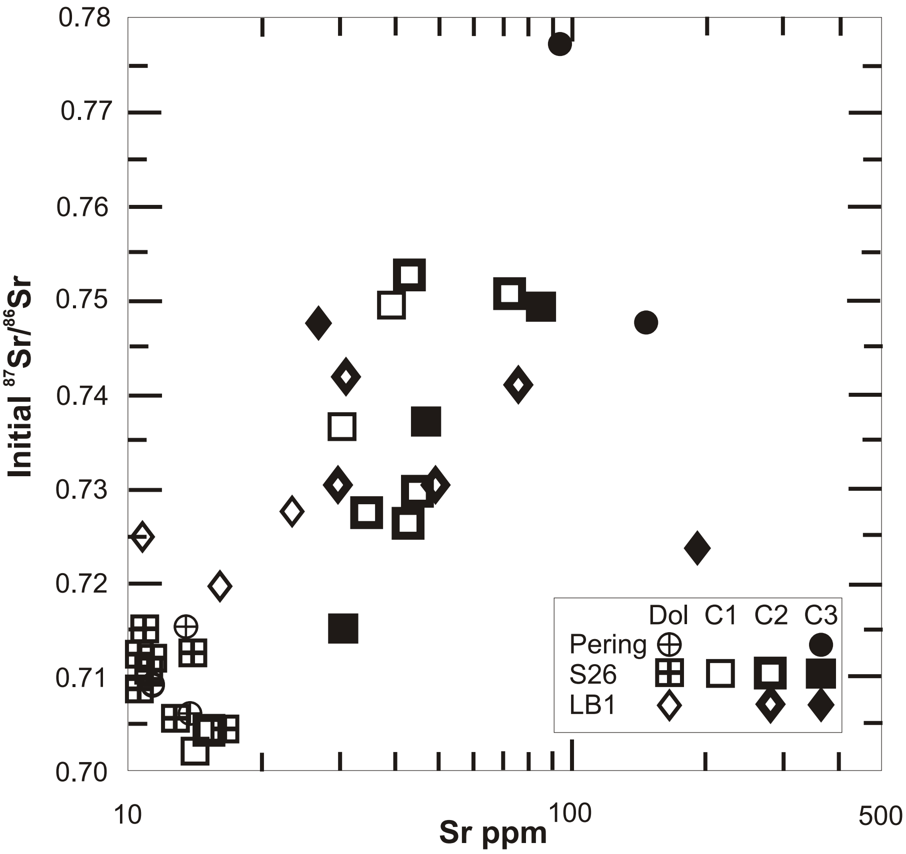

Figure 5: Correlation diagram between Sr concentration and initial $^{87}Sr/^{86}Sr$ of the host dolomite and vug-filling carbonate phases in the proximal S26 drill core (square symbols) and the distal LB1 drill core (diamond symbols). The host dolomite is represented by light symbols with a cross. The progressive filling of fractures is indicated by progressively more closed symbols. Samples from Pering Mine include those from Duane et al. (1991).

The mean initial $^{87}Sr/^{86}Sr$ (at *c*. 2 Ga) of the dolomite wall rock is lower for S26 (0.7104) than that for LB1 (0.7208). In drill core S26 there is a trend towards more radiogenic values from dolomite host (mean = 0.7104) towards C1 cement (mean = 0.7295), to C2 cement (mean = 0.7311) and on to C3 (mean = 0.7339). For LB1 a similar trend is evident beginning with C2 (mean= 0.7359) being less radiogenic in composition than C3 cement (mean = 0.7477). In detail, the data for drill core S26 indicates a fluid, which has a low initial ratio (0.70-0.71) and precipitated dolomite with a low Sr concentration (10ppm) similar to the host dolomites. This fluid mixed with a radiogenic fluid (0.75-0.76) with a higher Sr concentration (100 ppm Sr in precipitated carbonate). In the case of the more distal LB1 drill core, a more diffuse mixing process appears to have taken place, and even the host dolomite has been significantly affected, having a higher $^{87}Sr/^{86}Sr$ ratio (0.7208) than that of S26 (0.7104). Thus the fluids may not be well focussed in LB1 dolomites and formed a rather more diffuse "front" compared to those in S26 dolomites.

There is no strong relationship between either $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values (Fig. 6a) or between $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ (Fig. 6b), indicating that these systems were largely decoupled. The Sr largely reflects the interaction of the extra-basinal fluid with the local host rocks, whereas the $\delta^{18}O$ of the cements was also influenced by temperature of precipitation, and kinetic factors such as the degree of dissolution in the vicinity of cement precipitation (probably not significant) and contrasting pore-water residence times. The $\delta^{13}C$ appears to essentially reflect the composition of the local host rocks as shown by the differences between samples from S26 (around 0‰) and LB1 (around 1.28‰). The samples of S26 are mainly from the Reivilo Formation, which contains abundant layers of organic-rich stromatolites, in contrast to LB1, which intersects the Monteville and Lokammona Formations. The light carbon in some samples is commonly attributed to the mixing of light carbon from organic matter with heavier carbon from marine calcite close to 0‰ in composition (e.g., Irwin et al., 1977). However, since the majority of the samples are close to the host dolomite in composition, it is suggested here that the local dolomite is the dominant source of carbon.

In detail, the relationship between $\delta^{18}O$ and $\delta^{13}C$ (Fig. 6c) is quite complex. The range in $\delta^{13}C$ for some of the cements represents a mixing of carbon from two sources in each of the two localities. In both drill cores there is a progression from heavy carbon in the host to somewhat lighter carbon in the cements. Similarly, the ^{18}O values are moderately depleted and the range is narrow, except for the C3 phase, which indicates more marked proximal to distal differences. In the distal LB1 drill core there is a slight positive relationship between carbon and oxygen, indicating that in the progression Dol, C2 and C3 both carbon and oxygen become lighter as would be expected with an evolving fluid at progressively higher temperature. This is not the case in the S26 drill core where $\delta^{18}O$ shows the progressive decrease Dol, C1 and C2, but C3 has a heavier oxygen, and $\delta^{13}C$ shows no evolution, except for C3, which tends towards lighter carbon.

Resetting of rocks and minerals and the chronology of "Kheis"- related events

The primary ages of the Ghaap dolomites and the overlying Griquatown Group are between 2.5 and 2.4 Ga (see Barton et al., 1994; Sumner and Bowring, 1996; Bau et al., 1999). A number of studies of rocks within this succession indicate substantially lower whole rock Rb/Sr, U/Pb and Pb/Pb ages between 2.4 Ga and 1.9 Ga (Armstrong, 1987; Duane and Kruger, 1991; Walraven et al., 1991; Cornell et al., 1996; Bau et al., 1999). This clearly indicates disturbance of the isotopic systems by an event close to 2.0 Ga.

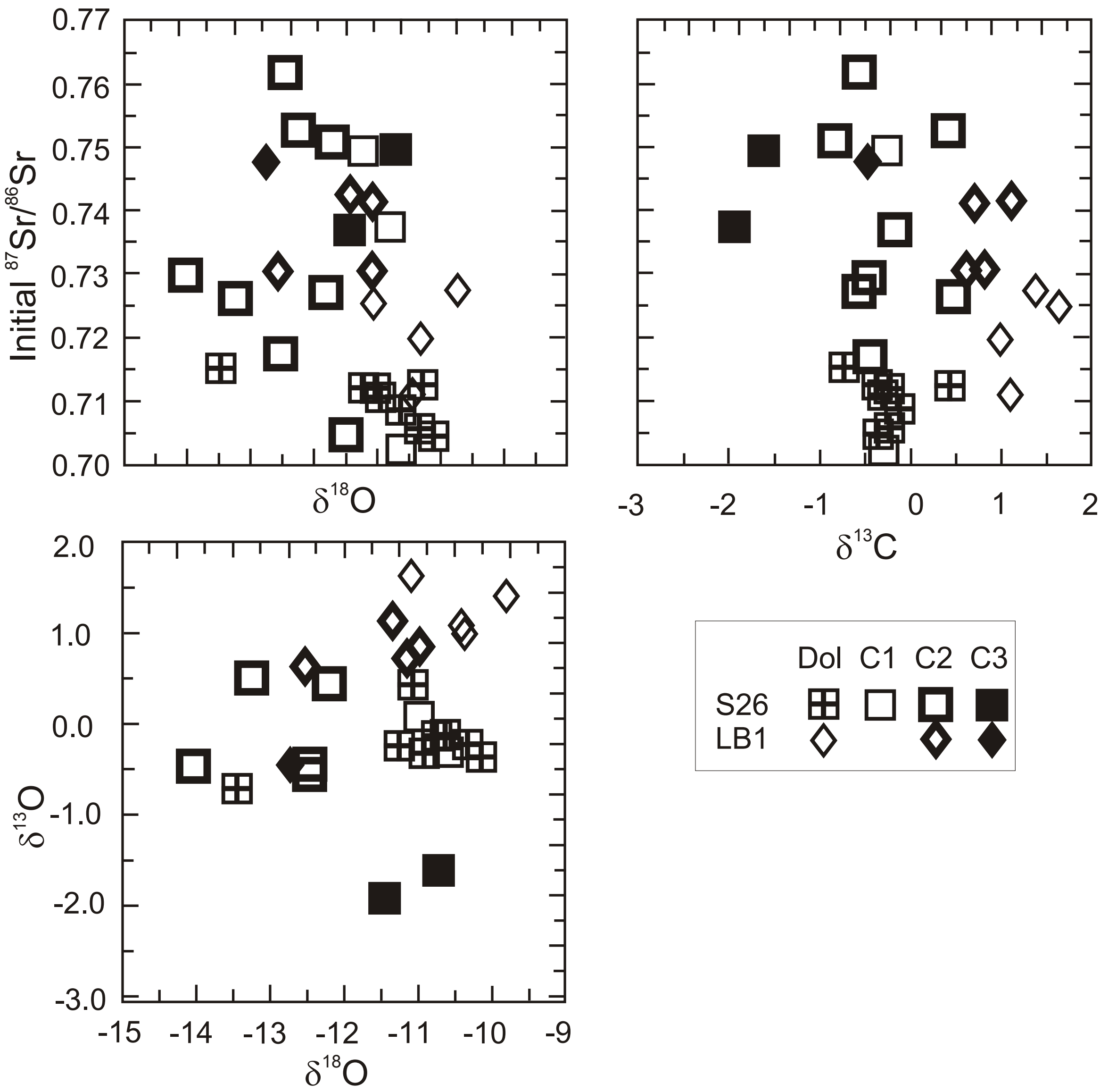

Figure 6: Correlations of $^{87}Sr/^{86}Sr$, $\delta^{18}O$ and $\delta^{13}C$ for host dolomite and vug-filling carbonate phases in the Scheurfontein fracture zone (S26) drill core (square symbols) and the Chocha Amoet fracture zone (LB1) drill core (diamond symbol). The host dolomite is represented by light symbols with a cross. The progressive filling of fractures is indicated by progressively more closed symbols. (a) plot of $\delta^{18}O$ vs $^{87}Sr/^{86}Sr$, (b) plot of $\delta^{13}C$ vs $^{87}Sr/^{86}Sr$, and (c) plot of $\delta^{18}O$ vs. $\delta^{13}C$.

The best-constrained study of this resetting is the data of Walraven et al. (1991) on the Zoetlief (Ventersdorp) volcanics (Fig. 1). A well-constrained Pb/Pb evaporation age on zircons from the felsic volcanics of this unit indicates an extrusion age of 2714 Ma, which is indistinguishable from that of the Makwassie Quartz Porphyry (Armstrong et al., 1991) on geochronological and lithostratigraphic considerations. Rb/Sr and Pb/Pb dates on resetting are 1901± 83 and 1982 +169/ -191 Ma, respectively).

Collectively, these data indicate substantial low-grade metamorphism, alteration and associated fluid flow through these rocks over a wide area between *c*. 1.9 and 2.0 Ga, and coeval with the early stages of the Kheis tectonism.

Pb-isotope evolution of the Kaapvaal epigenetic J-type ores

The evolution of ore Pb-isotopes derived from different sources at a particular time can be interpreted using the inverse $^{207}Pb/^{206}Pb$ versus $^{204}Pb/^{206}Pb$ ratio diagram (Fig. 7). On this projection, the pure radiogenic end-member plots as the intercept and the "initial" or common Pb plots close to a growth curve such as that of Stacey and Kramers (1975). Any mixture of the radiogenic and common Pb end-member plots on an isochron line. If the array is linear (isochron) a single "common" Pb source and the age can be inferred. However, if there is more than one source rock of the same age, but different common component, then the radiogenic intercept remains the same, but there is a spread towards different initial ratios. However, if the source contains components of widely differing ages and initial ratios, the data becomes less uniquely interpretable.

The Pb/Pb array for all available galena data from the deposits on the Kaapvaal Craton (Fig. 7) indicates that the source rocks were of the order of 2.7 Ga old, and that this source was stripped of metals at *c*. 1.9 to 2.1 Ga as originally suggested by Duane et al., (1991). A source rock interpreted to be dominantly the MQP erupted at 2.7 Ga and, having an average crustal "Stacey and Kramers (1975)-type" Pb-isotope character at that time, comprises a mixture of glass shards and minerals such as zircon and potassic feldspar. In such a rock U and Pb are held in somewhat different sites. U is enriched in the labile glassy mesostasis and in stable zircon and is depleted in the feldspar. In contrast, Pb is strongly held in the feldspar and is also present in the glass. Similarly, in any arkosic rock of similar age, the feldspar is the main host for Pb, and any clays would be relatively enriched in U.

During any subsequent epigenetic event (*c*. 700 Ma later in this case), which passes a reactive fluid through such an aquifer, the fluid first reacts with the labile constituents, which are enriched in U. Therefore, the first Pb stripped from such a rock is enriched in radiogenic Pb derived from the labile components. Subsequent fluids strip progressively more common Pb as the more resistant U-poor components (potassic feldspar) are attacked. Any reactive fluid that passes through the rocks would, at the same time, reset the entire isotopic system to the time of fluid flow. Large-scale stripping would result in a total reset to the original common component, whereas less stripping would result in some of the derived isotopic variability being retained. Any subsequent isotopic evolution would result in "older" ages in the "live" system. Furthermore, the Pb carried away in the reactive fluid would itself exchange with any other rocks, which the fluid intersects. The influence of this metal-rich fluid can be pervasive, even if only small amounts interact with the host rocks.

Contrasting arrays of "live" Pb-isotope data from the MQP and other supracrustal rocks, and the "dead" galena Pb-isotope line are shown in Figure 7. The live (Zoetlief) MQP line indicates a mixture of present day radiogenic Pb accumulated since the system was reset. The reset initial Pb (the intercept indicates the pure radiogenic part of the $^{207}Pb/^{206}Pb$ accumulated, and hence the age), and the common end of the line, intersects the Stacey and Kramers (1975) curve close to the intercept of the primitive end of the galena line, which is also the most primitive Pering galena. The dead galena array indicates an array at the time of Pb stripping from the source rock; thus the intercept indicates the radiogenic part of the source accumulated since eruption at *c*. 2.7 Ga, until stripping, which reset the live system at *c*. 2.0 Ga. The linear array of galena data indicates a common source of both common and radiogenic components in the fluid, and this is consistent with the data on the MQP.

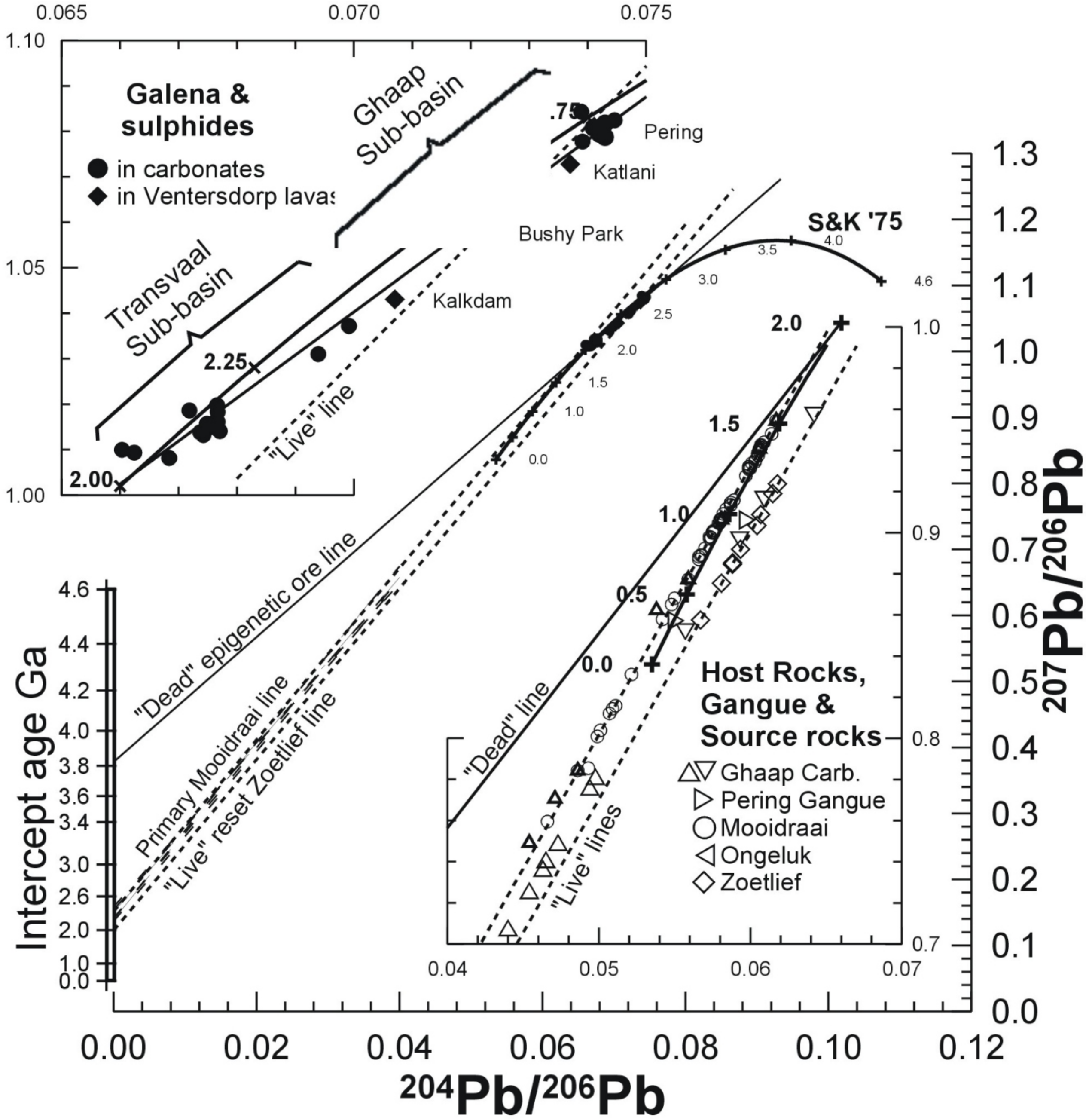

Figure 7: A $^{207}Pb/^{206}Pb$ vs $^{204}Pb/^{206}Pb$ diagram showing the main elements of reset "live" MQP Pb-isotope data and the "dead" galena Pb-isotope line. This projection was chosen to enable both radiogenic and galena Pb's to be shown at appropriate scales on the same diagram. Other reset live lines from the Ventersdorp, Ghaap and Griquatown rocks older than the primary 2.4 Ga Mooidraai dolomite of Bau et al. (1999) are also shown. The "live" lines intersect the "dead" galena array, which may indicate the source of the resetting fluids. The "dead" galena array indicates that a source rock (close to the Stacey and Kramers, 1975 composition) that evolved from c. 2.7 Ga was stripped of radiogenic and old common Pb at c. 2.0 Ga. This indicates a single source for the MVT- type deposits of the Kaapvaal Craton - inferred to be the MQP.

Since the fluid evolves with respect to Pb (and Sr) isotopes as it moves through the rocks, the more distal parts will be the most radiogenic and the more proximal parts less so. This would be reflected in the Pb-rich "dead" ore deposits precipitated from such fluids and is observed as such. In general, the more proximal deposits (close to the Kheis Belt) are more primitive, and the distal ones radiogenic. Furthermore, since a progression of fluids may encounter a focussing fracture into the overlying carbonates, the ore deposits themselves may show a progression from early radiogenic to later unradiogenic Pb. This latter idea is not yet proven, as all the Pb analysed from Pering Mine is of the later variety, which is most abundant. However, the more abundant Sr data indicate a large isotopic variation, which may indicate that similar variations in Pb could be expected.

DISCUSSION AND TECTONIC MODEL

A considerable database exists for Sr, Pb, C, O isotopes and petrographic observations for the carbonates of the Transvaal Supergroup. The Sr and Pb isotope data from the calcite and galena at Pering, Zeerust and Douglas, and other areas, shows that all the mineralization is derived from the same or a similar source as the Pering array of Duane et al. (1991). This source is interpreted as being the Makwassie Quartz Porphyry, a fragmental felsic tuff layer of very wide extent on the Kaapvaal Craton and found within the Ventersdorp lavas. This is strongly supported by the potassium-rich nature of the chlorites, at Kalkdam and Katlani (close to Douglas), which indicated a particularly potassium-rich fluid and hence source rock. The very high $^{87}Sr/^{86}Sr$ initial ratios of gangue calcite found throughout the region also indicates a very high time integrated $^{87}Rb/^{86}Sr$ ratio. The Makwassie Quartz Porphyry fits this description well.

The chronology and duration of events that led to migrating mineralising fluids and the associated deformation of the Kheis tectonism is not yet well understood. However, a larger picture of a southern African magmatic arc, active at *c*. 2.00 ± 5 Ga, is emerging (Holzer et al., 1998). Deformation associated with this crustal event, and the subsequent closure of the arc, is recorded in the Magondi Orogeny in Zimbabwe, in the Limpopo Belt (e.g., Kamber et al., 1995), as well as in the Zambian Copper Belt area (Rainaud et al., 1999). Its extension to the south is the age equivalent Kheis Orogeny (Duane and Kruger, 1991).

At Pering, breccia bodies are conspicuous sites of high-grade mineralization. The breccia bodies are subparallel, are cemented with late calcite and are associated with north-south trending faults and fractures of indeterminate age (Hounsome, 1993). The faults were primary conduits for the Zn-Pb fluids and the breccias allowed fluids to spread laterally along porous stromatolite zones. Erosion of the north breccia pipe exposes a deeper and more fractured orebody, hence the spectacular grades developed (> 20% Zn+Pb). The fluids appear not to have mixed with local meteoric fluids as suggested in Duane et al. (1991), since the $\delta^{13}C$ and $\delta^{18}O$ values are much higher than expected for meteoric waters.

Thus, the provenance of the fluids must be derived from sources below the Reivilo Formation with a radiogenic Sr composition unchanged since deposition. Duane et al. (1991) and Turner (1992) proposed that the radiogenic Sr-isotopic composition of carbonates was acquired by interaction with Ventersdorp lavas underlying the dolomites. The Makwassie Quartz Porphyry is a felsic volcanoclastic unit, which was shown to have anomalously radiogenic $^{87}Sr/^{86}Sr$ compositions by Walraven et al. (1991). Duane and Kruger (1991) have shown that the regional "disturbed" isotopic ages for the whole of the western part of the Kaapvaal Craton are indicative of a regional flushing of fluids in response to orogeny. A case in point is the dispute over the age significance for the base of the Transvaal Basin (e.g., Jahn et al., 1990; Sumner and Bowring, 1996). Clearly, the pervasive nature of the fluid event is underlined by the paucity of reliable whole-rock ages for both the Ventersdorp and Transvaal successions, which are otherwise only attainable by high-precision zircon work (e.g., Cornell et al., 1996; 1998).

The data presented here clearly show a district-wide fluid event, recognisable within a sedimentary succession, which can be correlated between widely spaced drill cores and is consistent with epigentic fracture-controlled mineralization. In general, cementation mechanisms are not clearly understood (Wood and Boles, 1991), but those involved in emplacement mechanisms for deep-seated fluids have clearly shown that seismic pumping is a viable mechanism for moving hot reactive fluids in faults (Sibson, 1987). It is becoming increasingly clear that dolomitization accompanies widespread regional fluid flow and that MVT deposits occur where fracture permeability is enhanced to the maximum by faulting (Clendenin and Duane, 1991; Vearncombe et al., 1995). Similar observations have been made elsewhere (e.g., the Polaris MVT deposit, Arctic Canada - Savard et al., 2000).

A tectonic model of widespread Pb-Zn (± F, Cu, Ag, Au) epigenesis on the Kaapvaal Craton

The temporal history of the Transvaal Supergroup MVT and other epigenetic Cu-Pb-Zn-Ag deposits around the margins of the Bushveld Complex needs to be addressed. Already it appears that whole-rock ages are not generally viable on Kaapvaal volcanic basement rocks and a long history of alteration by regional brine migrations is considered the causative agent (Duane and Kruger, 1991; Duane et al., 1991), as is implicit in the model of Oliver (1986).

Present models for tectonic fluid-flow-coupled mineralization on the western edge of the Kaapvaal Craton (Duane and Kruger, 1991; Duane et al., 1991) place wide limits on the age of fluid flow and mineralization during the Kheis Orogeny (2.1 - 1.9 Ga). Although this hypothesis is accommodated by all the available chronological data, precise dating of the fluid migration is proving elusive, and is clearly episodic. However, more recent work has narrowed this age to between 2.06 and 1.90 Ga and there appears to be more than one mineralising event in the long history of the Kheis foreland fold and thrust belt.

In view of the above the authors propose the following temporal and tectonic model for epigenesis on the Kaapvaal Craton derived/modified from the model of Oliver (1986) and that of Duane and Kruger (1991) and Duane et al. (1991). This model also incorporates the recent work on the Limpopo Belt (summarised in the tectonic model of Holtzer et al., 1998) which emphasizes convergent tectonism at 2.0 Ga.

It is suggested that early fluids were expelled from the craton margin by basin collapse toward the end of the accumulation of the Griqualand and Pretoria Groups. This early phase dominated the northern basin and was terminated by the intrusion of the Bushveld Complex.

Continued closure and dextral movement along the northern margin of the Kaapvaal Craton (Palala shear zone) until 2.0 Ga (Holtzer et al., 1998) was accompanied by the initiation of thrusting and fluid expulsion along the eastern Kheis margin. This margin subsequently became a major fold and thrust belt on the continental side of an "Andean-type" belt now located in the interior of Botswana. Debris and volcanic rocks from this belt formed the Olifantshoek (and associated volcanics), Waterberg and Zoutpansberg basins situated to the north.

Further compression involving Kheis tectonism forced fluids out of the belt and onto the craton margin (Fig. 8) where they exploited suitable aquifers such as the widespread MQP tuffs and any available fractures, which focussed the fluids to form ore deposits in suitable hosts. These deep-seated, hot and reactive fluids were the chief agents of epigenetic mineralization and the pervasive alteration of the supracrustal rocks on the Kaapvaal Craton. Their effects are very widespread and are seen throughout the Kaapvaal Craton.

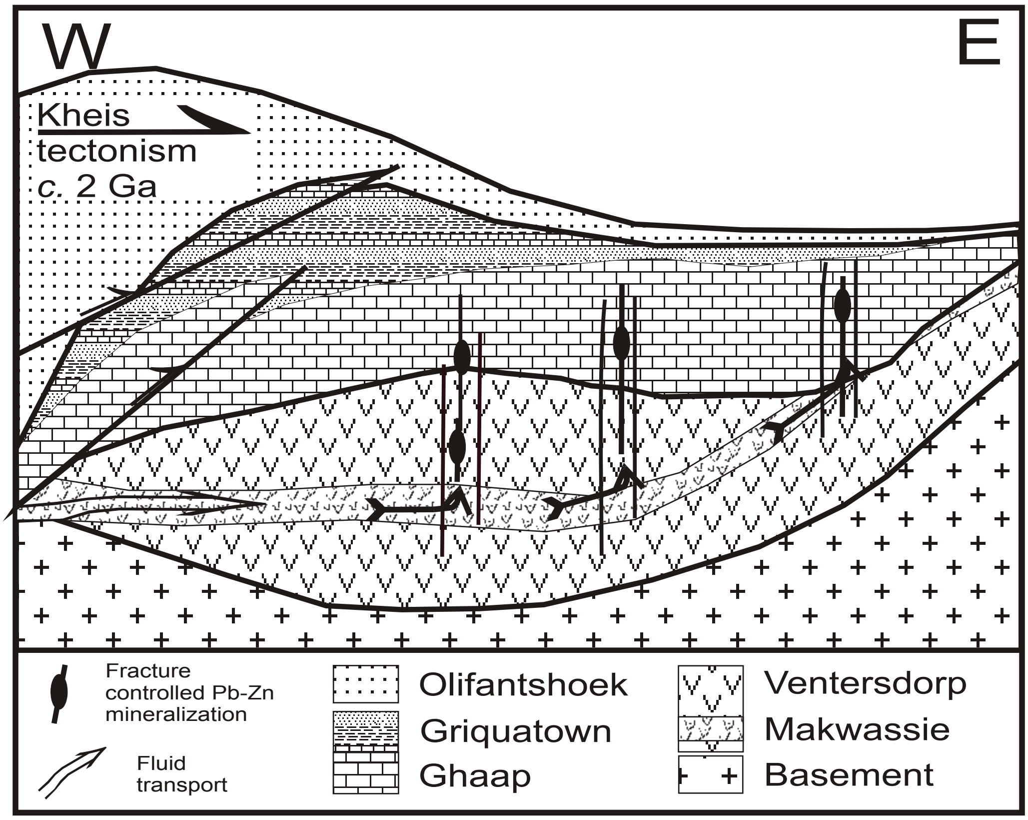

Figure 8: Expulsion of fluids from the collapse of the Ghaap, Griqua and Olifantshoek basins onto the Kaapvaal Craton margin at c. 2.0 G. These events are nearly coeval with the closure of the Limpopo Belt and the intrusion of the Bushveld Complex. Continued closure and dextral movement along the northern margin of the Kaapvaal Craton (Palala shear zone) until 2.0 Ga was accompanied by the initiation of thrusting and fluid expulsion along the eastern Kheis margin. This margin became a major fold and thrust belt on the continental side of an "Andean-type" belt and is located in the interior of Botswana. The debris and volcanics from this belt formed the Olifantshoek sediments (and associated volcanics). Collapse and compression of the basin expelled fluids onto the craton margin and exploited aquifers such as the MQP, which also served as a source of Pb and Zn. These fluids were focussed via fractures into the overlying Ghaap dolomites and Ventersdorp volcanic rocks to form MVT- and volcanic-hosted epigenetic deposits.

CONCLUSIONS

The geology of the western Kaapvaal and Ghaap MVT deposits has been interpreted in various ways. Models have been proposed ranging from expulsion of syn-sedimentary basinal brines into stratabound karst-like features (Wheatley et al., 1986) to pre-Bushveld Complex hydrothermal cells in a rifted (extentional) environment (Martini et al., 1995, Cornell et al., 1999). By contrast, Duane et al. (1991- and this work), in taking a wider view, require compressive expulsion of fluids from the Kheis fold and thrust belt to the west. A close analogy and resemblance of the Pering and related deposits (Fig. 8) exists with some North American deposits (e.g., Clendenin and Duane, 1990). The evidence for a compressive expulsion of fluids hypothesis includes:

1) structurally controlled mineralization in north-south fracture systems roughly aligned with the Kheis fold and thrust belt;

2) steeply dipping fractures extending through the full stratigraphic section, which focussed eastward moving fluids;

3) stable isotope evidence for hot ascending brines, confined to brecciated fracture zones;

4) Pb-isotope evidence for Pb extracted at *c*. 2.0 Ga from a primitive (2.7-3.0 Ga) crustal source below the Ghaap Plateau;

5) district-wide variation in the Pb- and Sr-isotopic composition, which cannot be accounted for by extraction from an intra-basinal source;

6) evidence for resetting of most lithologies on the craton by penetrating fluids with exotic Sr and Pb signatures derived from old crustal sources and interpreted to be the Ventersdorp felsic volcanics - specifically the Makwassie Quartz Porphyry; and

7) the Pb- and Sr-chronological evidence from both reset rocks, and the ore deposits, indicates an age of between 1.9 and 2.0 Ga for the mineralization.

The models proposed by various workers may be partly reconciled if the more northerly (Zeerust) deposits are pre-Bushveld in age (Martini et al., 1995), and those of the Ghaap Plateau are post-Bushveld in age, as suggested by the data presented here and by Duane et al. (1991). This suggests a long-lived episodic hydrothermal system that may span up to 150 Ma. This hydrothermal system may be related to different episodes in the development of the southern Kheis Belt fringing the eastern margin of the Kaapvaal Craton, the northern Magondi fold and thrust belt fringing the northeastern margin of the Zimbabwe Craton, the associated Bushveld magmatic province (Coetzee and Kruger, 1989), and the events in the Limpopo Belt.

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