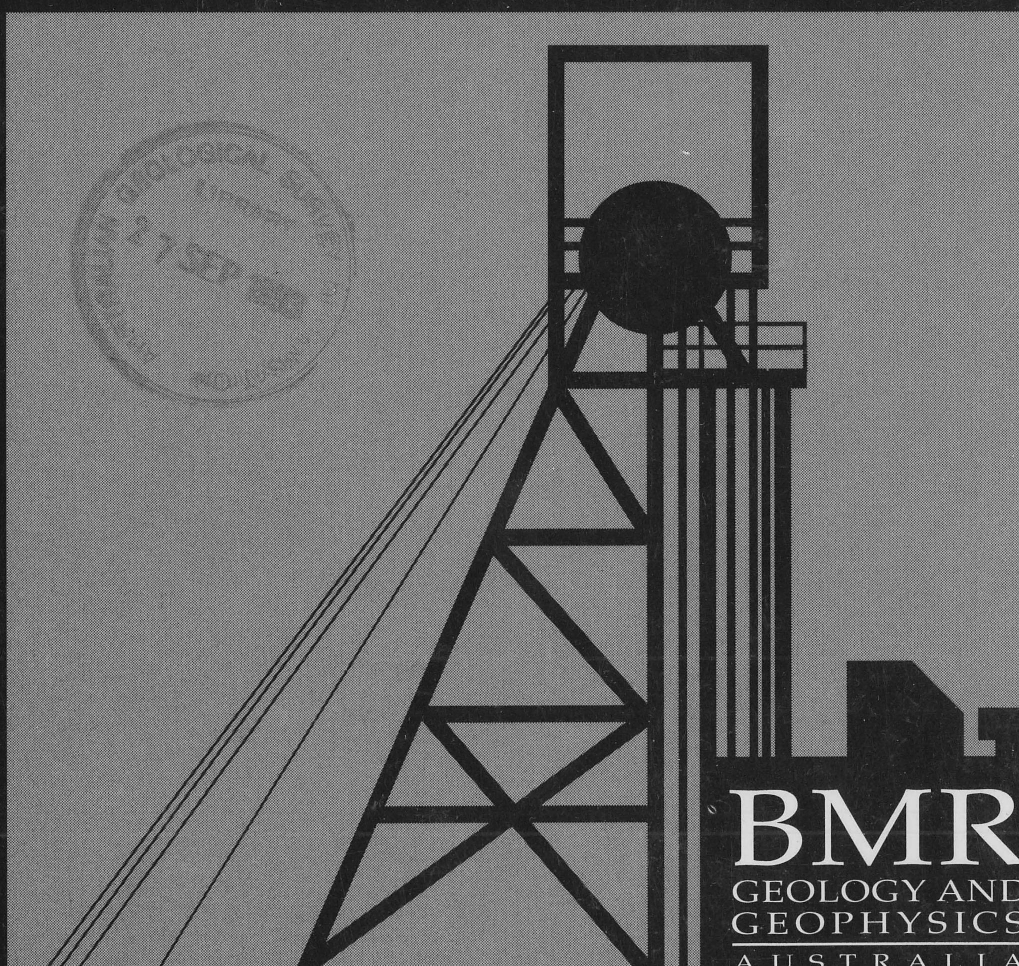
Mineral Provinces

Epithermal Gold Mineralisation in the northern Drummond Basin, Queensland
Record 1992/72

AUSTRALIA



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GEOLOGY AND GEOPHYSICS
AUSTRALIA

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ERALS AND LAND USE PROGRAM
EAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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AUSTRALIAN GEOLOGICAL
SURVEY ORGANISATION

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ABSTRACT

Epithermal gold mineralisation in the northern Drummond Basin exhibits many of the classic features of the adularia-sericite or low-sulphidation type of deposit. The mineralisation is characteristically low in sulphur (generally <2% sulphides, mainly pyrite); has pervasive silicification of variable intensity and quartz veining which is typically banded and chalcedonic; and has argillic/phyllic (mainly sericite and mixed layer clays) and propylitic alteration. Some deposits contain adularia, and include preserved siliceous sinters. Hydraulic fracturing and breccias are common.

All of the significant known gold mineralisation in the northern Drummond Basin, with the possible exception of the main lode at Mount Coolon and the Ukalunda deposit, is believed to be hosted by units at the base of the Drummond Basin sequence, and recent AGSO/GSQ mapping has suggested that these rocks are more extensive than previously recognised, thereby enhancing the prospectivity of the area. Typically, gold mineralisation occurs in an acid to intermediate volcanic environment, and is hosted mainly by volcaniclastic rocks which may be associated with lavas. The sequence may have been a source of gold and, perhaps more significantly, sulphur for the transport of gold: however, this has not been demonstrated and the basement rocks to the volcanic units equally could be considered as a possible source for metals and/or sulphur. K-Ar dating suggests that multiple hydrothermal events resulted from episodic magmatic activity, and that the base of the Drummond Basin sequence acted not only as a host for mineralisation, but that volcanic units (which are well developed at the base) could have been a heat source for at least some of these hydrothermal systems.

The Drummond Basin sequence is cut by predominantly north and northeast trending structures which could have focussed and channelled fluids and control the alignment of prospects and deposits on a regional scale. Several deposits and prospects appear to correlate with magnetic linears (e.g. Yandan, Wirralie, Bimurra, and Pajingo), and Mount Coolon, Bimurra, and BHP prospects such as Conway, Bluegum, and Battery Hill have a N-S alignment which closely corresponds to a magnetic corridor apparent on regional-scale aeromagnetic data. These regional structural trends can be reflected at a prospect and deposit scale (e.g Pajingo and Conway).

Siliceous sinters have been recognised at a number of BHP prospects (Conway, Durah Creek, Hill 273, and possibly Bimurra) and reported widely from deposits and prospects throughout the northern Drummond Basin. The importance of sinters to exploration for epithermal ore deposits is that they provide tangible and unambiguous evidence of a palaeosurface, and they indicate the possible presence of a significant mineralising system within 1000 metres of the earth's surface. Oxygen isotope data indicate that sinters are isotopically heavy relative to associated quartz veins and this may provide an additional tool for characterising ancient sinters.

Whole-rock oxygen isotope analyses of slightly altered volcanic and intrusive rocks from throughout the northern Drummond Basin and distant from epithermal systems have led to the identification of an area of ^{18}O depletion of at least 1500 km^2. The full extent of this depleted area and the mechanism responsible for it are not clear, due mainly to the structural complexity, poor age control, and generally poor outcrop over most of the region. However, it coincides closely with the present outcrop distribution of volcanic and intrusive rocks, and is consistent with field observations that suggest the source region for the Late Carboniferous volcanic units (predominantly ignimbrite) was in the northeastern sector of the mapped area. The data appear to be most consistent with large-scale interaction of meteoric water with cooling intrusive and extrusive rocks, and calculations indicate that water:rock ratios close to unity would have been capable of producing the observed whole-rock ^{18}O depletion.

Many Tertiary epithermal deposits in the USA occur within areas that have undergone regional oxygen isotope depletion, and the association of extensive whole-rock ^{18}O depletion in the northern Drummond Basin with an area recently recognised as being highly prospective for epithermal gold mineralisation provides further evidence of this relationship. It suggests that regional patterns of whole-rock oxygen isotope depletion may be particularly useful in discriminating those areas which could be prospective for epithermal mineralisation.

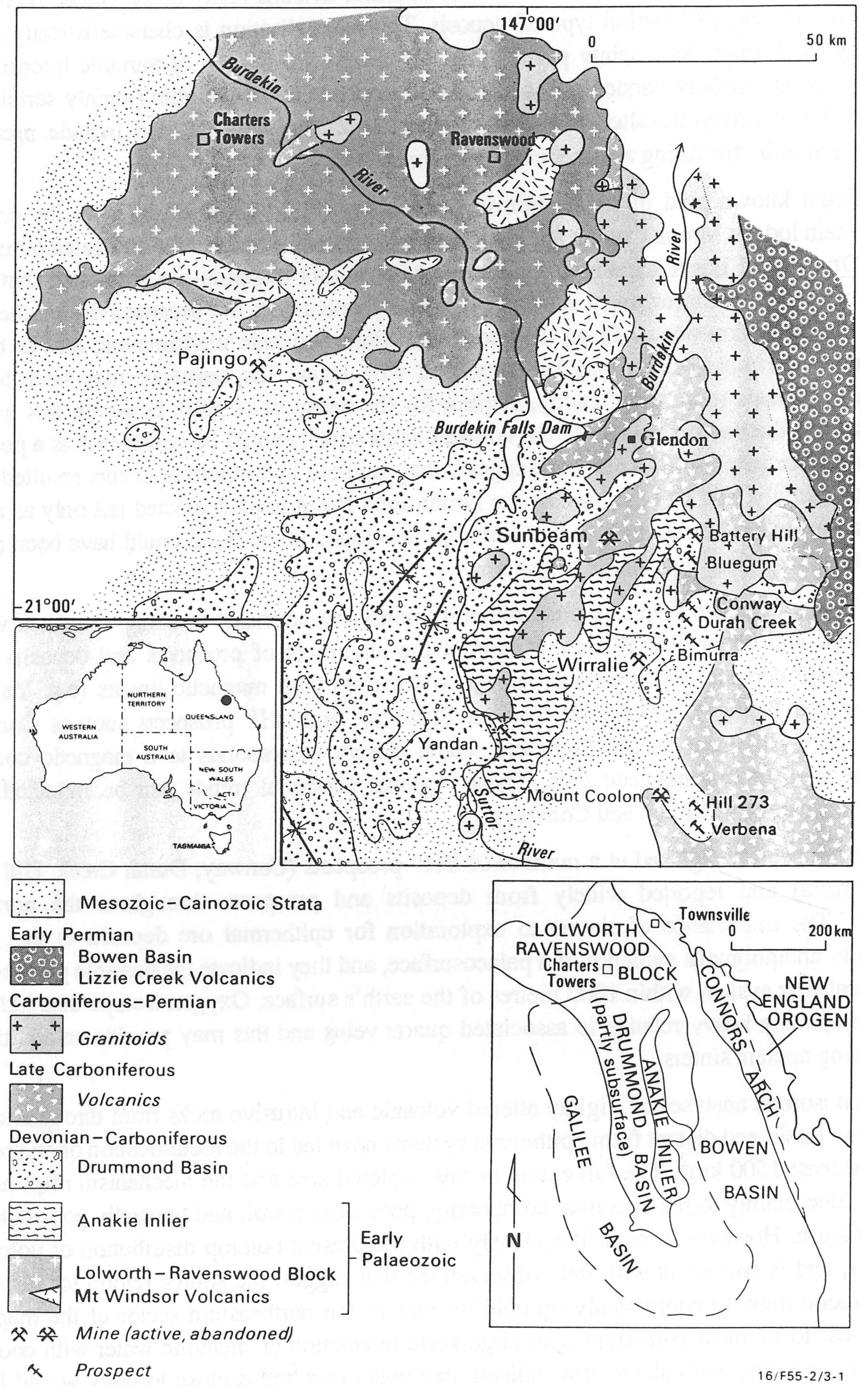

Figure 1. Simplified geological setting of the northern Drummond Basin, with the localities of epithermal propects and its relationship to regional structural subdivisions (inset) (modified from McPhie & others, 1990).

INTRODUCTION

Before 1984, mineral output from the Drummond Basin had been restricted mainly to black coal from Blair Athol in the Clermont district. Numerous gold and copper prospects had been identified and the region had produced some copper, minor gold, silver, bismuth, and gemstones.

In the northern Drummond Basin, the Mount Wyatt goldfield, about 50 km north of Mount Coolon was one of the earliest fields to be recognised (Daintree, 1870), but production was minor. The discovery of gold at Mount Coolon in 1913 (Fig. 1) led to production of slightly less than 6200 kg of gold between 1914 and 1939, and the recovery of 1850 kg of silver from 1930 to the cessation of mining in 1939 (Morton, 1935; Olgers, 1972). Production was from a quartz lode now regarded as being of epithermal origin, but modified by a later intrusive event (Wells & others, 1989). In 1928 prospectors from the Mount Coolon goldfield discovered gold at Bimurra, initiating a small gold rush which lead to the recovery of an unspecified but small amount of alluvial and hard rock gold.

Although gold had been produced from deposits now recognised as epithermal, the potential for significant epithermal gold mineralisation throughout the region was not realised until the greenfield discovery of the Pajingo deposit in 1984 (Porter, 1988). Since that time, the northern Drummond Basin has become the principal focus for gold exploration in northeast Queensland (Wood & others, 1990). That exploration activity has been assisted by the refinement of the bulk leach extractable gold (BLEG) technique, and has culminated in the discovery of the Wirralie (Fellows and Hammond, 1988) and Yandan (Wood & others, 1990) deposits, a re-evaluation of the Mount Coolon mine, and the recognition of numerous epithermal prospects.

REGIONAL GEOLOGIC SETTING

The Drummond Basin is a large intracratonic basin which developed in northeast Queensland between the Late Devonian and Early Carboniferous, and crops out over an area of 25000 km^2 (Fig. 1; Olgers, 1972). It is believed to have formed as an intracontinental basin west of a continental margin volcanic arc (Connors-Auburn Arch) active during the same period (Murray & others, 1987).

It consists of thick units of predominantly terrestrial volcaniclastic sandstone and mudstone, and intermediate to felsic lavas and pyroclastic rocks. Olgers (1972) described the geology of the basin in terms of three tectono-sedimentary cycles separated by disconformities: the base comprises a thick sequence of intermediate to felsic volcanics and volcaniclastic rocks (cycle 1), followed by dominantly fluvial sedimentation during broad basin-wide subsidence (cycle 2) and finally, the re-emergence of active volcanism during a period of more mature fluviatile and lacustrine sedimentation (cycle 3).

The Anakie Inlier, which is of Early Palaeozoic or possibly Proterozoic age, is the only exposed basement and crops out in the eastern part of the basin: it is composed mainly of metasedimentary rocks, and lesser extrusive and intrusive rocks and sediments. Deformed Middle Devonian sedimentary rocks (Ukalunda Beds) unconformably overlie the northern part of the Anakie Inlier, and are exposed in the northern Drummond Basin. Mesozoic and Cainozoic sediments obscure much of the Drummond Basin sequence, both east and west of the Anakie Inlier. In general, outcrop is good in the far northern areas of the exposed Drummond Basin, but rapidly deteriorates and becomes very poor southwards.

Primary volcanic rocks (such as the Bimurra Volcanics, the laterally equivalent Stones Creek Volcanics, and Star of Hope Formation), comprising porphyritic two-pyroxene andesitic lava, minor dacitic ignimbrite and rhyolitic lava, are widespread, particularly in the lowermost units (cycle 1) of the Drummond Basin (Oversby & others, in prep.). On the northern and eastern margins of the Anakie Inlier, the Drummond Basin sequence includes folded, partly marine, sedimentary strata containing Late

Devonian fossils. Although the sequence has been subdivided, the stratigraphy is complicated by numerous facies changes, internal disconformities, and poor age control (McPhie & others, 1990).

Widespread Late Carboniferous igneous activity between 290 Ma and 305 Ma (Black, in prep.) resulted in a lower, more deformed, compositionally diverse sequence of ignimbrites, lavas and conglomerates, overlain by generally less-deformed rhyolitic ignimbrite sheets (McPhie & others, 1990). These rocks are regarded as belonging to the Bulgonunna Volcanic Group (Oversby & others, in prep.).

Both the volcanic rocks at the base of the Drummond Basin sequence and those related to Late Carboniferous magmatic activity are largely the products of subaerial eruption and reflect a proximity to eruptive sources. The Late Carboniferous volcanic sequence is deeply eroded, and co-magmatic high-level plutons are widely exposed, particularly in the northeastern sector of the basin.

Granitoid intrusions in the area are I-type, with one group older than and non-conformably overlain by the Late Carboniferous volcanic rocks, and the other probably comagmatic with the Late Carboniferous sequence. The older group comprises predominantly high-K granitoids that are zoned from quartz-monzodiorite through granodiorite and monzogranite to alkali-feldspar granite: minor tholeiitic gabbros, probably of several different ages are also present. The younger granitoids are mainly felsic monzogranite, with subordinate granodiorite. Chemically the two groups are similar. They have uniformly low Sr/Y ratios, but there is a tendency for the Carboniferous granitoids to become slightly more enriched in large ion lithophile elements (e.g. Pb, Rb, Ba, Th, U, K) and slightly more depleted in high field strength elements (e.g. Nd, P, Zr, Y) from north to south. This suggests slightly different physico-chemical environments of magma generation within the continental crust, not directly related to subduction zone melting. If a subduction zone was involved, then the chemical polarity would indicate that the continental margin was to the north (McPhie & others, 1990; Silver and Chappell, 1988).

BHP EPITHERMAL PROSPECTS

In late 1984, following a regional geological and metallogenic study of eastern Australia, BHP selected areas in the northern Drummond Basin for systematic gold search under Authority to Prospect holdings initially centred on the Bimurra mineralisation. Ultimately, BHP tenements extended along a 120 km north-south strip to the east of Mount Coolon and Wirralie, covering an area of about 2500 km^2 (Fig. 2).

Although initial interest was focussed on Bimurra, the success of an orientation stream sediment survey in that area using the BLEG technique led to the application of this method by BHP to a gradually expanding area of exploration title. It contributed to the discovery of the Conway, Battery Hill, Isabella, Bluegum, Bobby Dazzler, Durah Creek, and Eaglefield prospects.

As a result of regional mapping (McPhie & others, 1990; Oversby & others, in prep.), these and several other prospects, and major deposits in the area (with the possible exception of the Mount Coolon and Ukalunda deposits) are now believed to be hosted by Devonian-Carboniferous volcanic rocks within the Drummond Basin. A brief description of each of the more extensively explored BHP prospects (beginning with the northernmost) follows.

Battery Hill

This prospect is confined to an area less than 0.25 km^2 and contains low-grade gold mineralisation within short, narrow zones of quartz-veined, hydrothermal breccia in altered rhyolitic to dacitic volcaniclastic rocks. Six continuously cored drill holes (totalling 740 m) and 55 shallow percussion holes were drilled to investigate the mineralisation, and test resistivity and soil anomalies. Hydrothermal alteration is marked

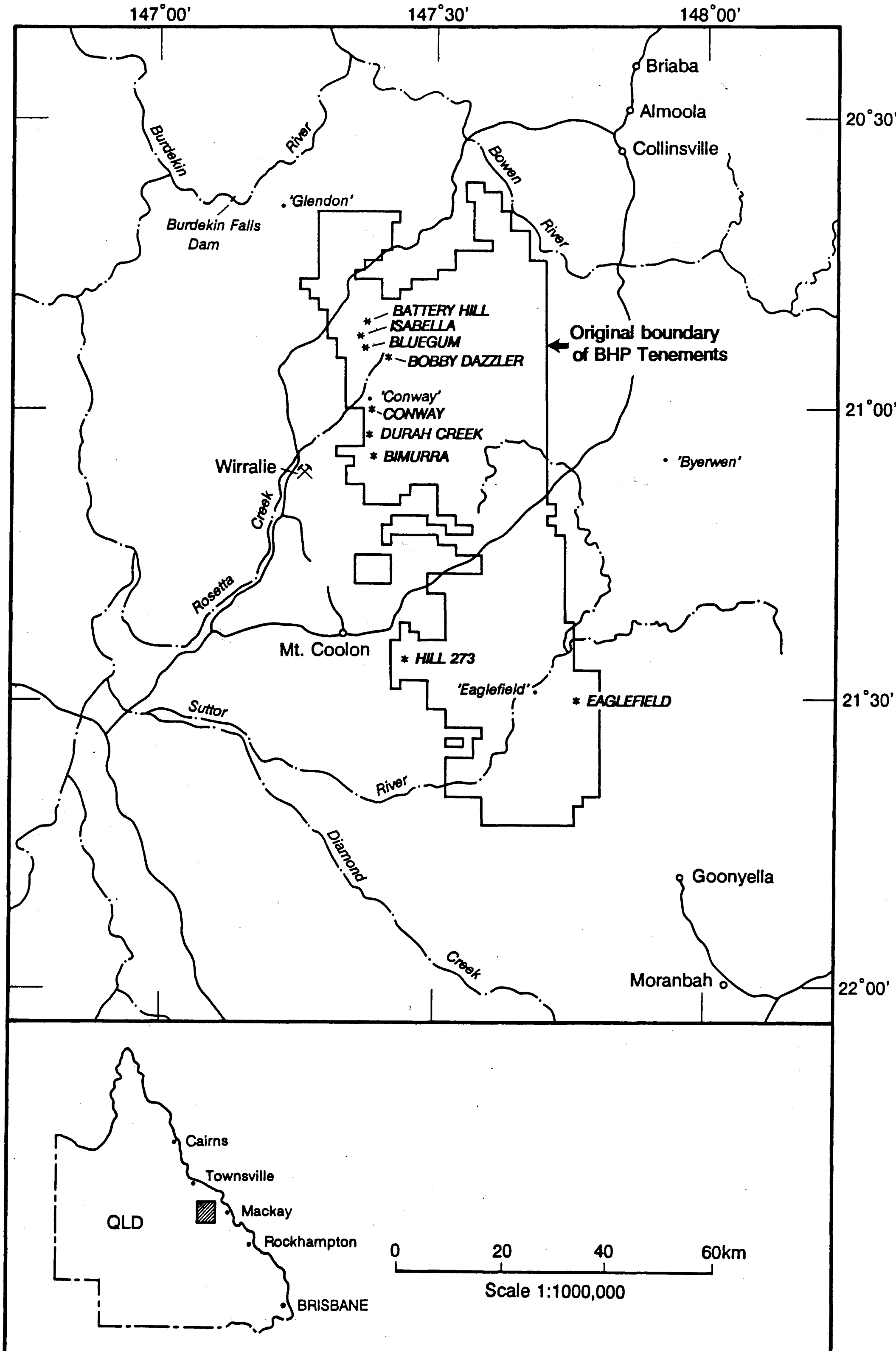

Figure 2. Original BHP tenement boundaries with prospects identified.

by weak to intense, pervasive silicification (essentially fine-grained quartz after chalcedony) that is fracture controlled. Sericite-rich assemblages are weakly to moderately well developed in the wall rocks, and appear to be superimposed on weak and pervasive propylitic alteration which could be a regional feature. Trace disseminated pyrite ± rare pyrrhotite (partially replaced by marcasite), chalcopyrite, sphalerite, and arsenopyrite are present. A siliceous volcanic mudstone (8750 0036, Table 1) containing Late Devonian-Early Carboniferous *Lepidodendron sp.* fossil plant fragments and a completely silicified, finely laminated epiclastic mudstone (8750 0037, Table 1) crop out on the southwest margin of the prospect.

Isabella

The Isabella prospect lies about 2.5 km south-southwest of Battery Hill, directly east of the junction between Isabella Creek and the Sellheim River. The prospect was discovered by geological traversing to field check a north-trending photo-linear which marks the contact between massive rhyolitic ignimbrite to the west and a rhyodacitic crystal- and ash-rich tuff unit to the east. A soil colour anomaly also reflects the contact, with reddish coloured soils (rhyodacitic) occurring to the east and fawn-brown coloured soils (rhyolitic) to the west. This colour contrast extends for several kilometres and is easily identified on colour aerial photographs of the area. Further to the east, near the Sellheim River, fossiliferous fine- to medium-grained sandstone and finely laminated siltstone crop out and are possibly volcanically derived. They have a shallow, generally southerly dip. In the prospect area the contact between the ignimbrite and tuff is probably faulted. Two sub-parallel zones of silicified quartz vein breccia crop out immediately to the east of the contact and extend discontinuously north for at least 500 m. The western of the two zones comprises strongly silicified quartz vein breccia up to 5 m wide. The eastern zone occurs 5-10 m to the east of this and is similarly up to 5 m wide, but differs in being hematitic and, in places, contains grey coloured, colloform-banded chalcedony. Low grade gold mineralisation occurs in the eastern hematitic breccia zone but has not been recorded from the western zone. The prospect was investigated with one continuously cored drill hole (100 m) and nine shallow percussion holes. Poor drilling results and the small areal extent of the alteration system deterred any further exploration. The drill holes intersected a sequence of rhyolitic to dacitic volcaniclastic rocks which, in outcrop, are pervasively silicified (thin chalcedony veins are also present) and variably altered to argillic/phyllic mineral assemblages. In drill core the western breccia zone is expressed as a stockwork of fine white hair-width quartz veins. The eastern breccia comprises several cross-cutting quartz veins with grey colloform banded chalcedony and quartz-infilled vugs. Disseminated pyrite, and thin veinlets of pyrite and chalcopyrite are rare, generally accounting for less than one percent by volume of the rock.

Bluegum

Bluegum occurs between 4 and 5 km due south of Battery Hill, and about 2 km north of a Pb-Zn skarn prospect (Mount David) which was held by CRA in the early 1980s. Hydrothermal alteration at Bluegum has been recognised over an area of several square kilometres, but is most strongly developed along two steep ridges over an area of less than 1 km^2. Twelve continuously cored drill holes (totalling 1347 m) and 32 shallow percussion holes have been drilled to investigate geochemical anomalies, siliceous zones, and areas of high resistivity. Bluegum is hosted within a sequence of shallowly-dipping rhyolitic to andesitic volcaniclastic rocks, lavas, and breccias. A pronounced vegetation anomaly related to the dominant variety of eucalypt, extends over and beyond the Bluegum prospect; it appears to reflect differences in the composition of soils derived from different rock-types and is unrelated to the mineralisation. Relatively fresh rhyolitic ignimbrite (8750 0082 to 0086, Table 1) crops out in the bed of the Sellheim River, about 300 m due west of Bluegum.

TABLE 1 WHOLE ROCK CHEMICAL ANALYSES FROM BHP PROSPECT AREAS

BMR No	8750 0036	8750 0037	8750 0082	8750 0083	8750 0084	8750 0086	8750 0106	8750 0107
SiO_2	85.38	99.20	75.32	73.46	75.17	74.73	73.02	76.12
TiO_2	0.11	0.01	0.12	0.13	0.15	0.26	0.28	0.29
Al_2O_3	8.98	0.40	13.47	14.06	13.16	13.45	11.71	13.21
Fe_2O_3	0.34	<0.01	0.87	1.08	0.70	0.89	1.56	1.52
FeO	0.09	0.08	0.27	0.55	0.74	0.55	0.12	0.25
MnO	0.05	<0.01	0.09	0.13	0.17	0.09	0.16	0.02
MgO	0.29	0.01	0.20	0.44	0.42	0.44	0.47	0.27
CaO	0.02	0.01	0.68	1.04	0.91	1.70	2.24	0.14
Na_2O	0.04	<0.01	3.70	2.62	2.66	2.40	3.77	0.61
K_2O	3.07	0.05	4.28	4.78	4.05	3.13	3.10	4.46
P_2O_5	0.01	<0.01	0.03	0.04	0.04	0.04	0.06	0.02
F	0.01	0.01	0.01	0.01	<0.01	0.02	<0.01	0.03
L.O.I.	1.87	0.27	1.08	1.89	2.08	2.54	3.45	3.37
TOTAL	100.26	100.04	100.12	100.23	100.25	100.24	99.94	100.31
ppm								
As	32	6.5	5.5	1.5	3	1.5	0.5	30
Ba	310	23	660	710	700	370	3720	610
Be	1	<1	3	3	3	2	3	2
Bi	<1	1	1	1	<1	<1	<1	1
Ce	22	<2	34	39	44	53	61	53
Co	2	<1	2	2	2	2	4	2
Cr	<2	<2	<2	<2	2	2	2	4
Cs	11	<3	10	10	7	8	7	14
Cu	3	1	1	2	<1	34	4	3
Ga	11	1	15	19	14	15	8	13
Ge	2.5	2	1	1.5	1.5	1	0.5	1
La	17	<2	19	21	21	31	38	36
Li	10	15	8	8	12	15	17	18
Mo	<2	<2	<2	<2	2	<2	<2	<2
Nb	6	1	11	12	10	7	8	10
Nd	5	<2	15	17	17	26	26	22
Ni	1	1	<1	1	1	1	1	1
Pb	16	15	23	31	120	26	14	12
Pr	<2	<2	3	4	5	6	7	7
Rb	200	4	180	240	180	190	110	190
S	240	24	7	17	26	77	730	47
Sc	3	<3	4	4	5	8	9	7
Se	0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Sn	<2	<2	4	4	3	5	<2	3
Sr	27	4	88	140	120	130	180	64
Th	17	1	17	18	18	17	15	14
U	2.5	0.5	3.5	6.5	4	3.5	2	3
V	24	4	6	8	10	18	20	23
Y	6	1	27	28	29	34	36	17
Zn	6	1	36	68	180	47	45	35
Zr	68	3	85	96	100	150	150	170

8750 0036 siliceous volcanic mudstone, Battery Hill prospect
8750 0037 silicified finely laminated epiclastic mudstone, Battery Hill prospect
8750 0082 rhyolitic ignimbrite, Sellheim River, ~300 m west of the Bluegum prospect
8750 0083 rhyolitic ignimbrite, Sellheim River, ~300 m west of the Bluegum prospect
8750 0084 rhyolitic ignimbrite, Sellheim River, ~300 m west of the Bluegum prospect
8750 0086 rhyolitic ignimbrite, Sellheim River, ~300 m west of the Bluegum prospect
8750 0106 altered flow banded rhyolite, near the Durah Creek propect
8750 0107 altered flow banded rhyolite, near the Durah Creek propect

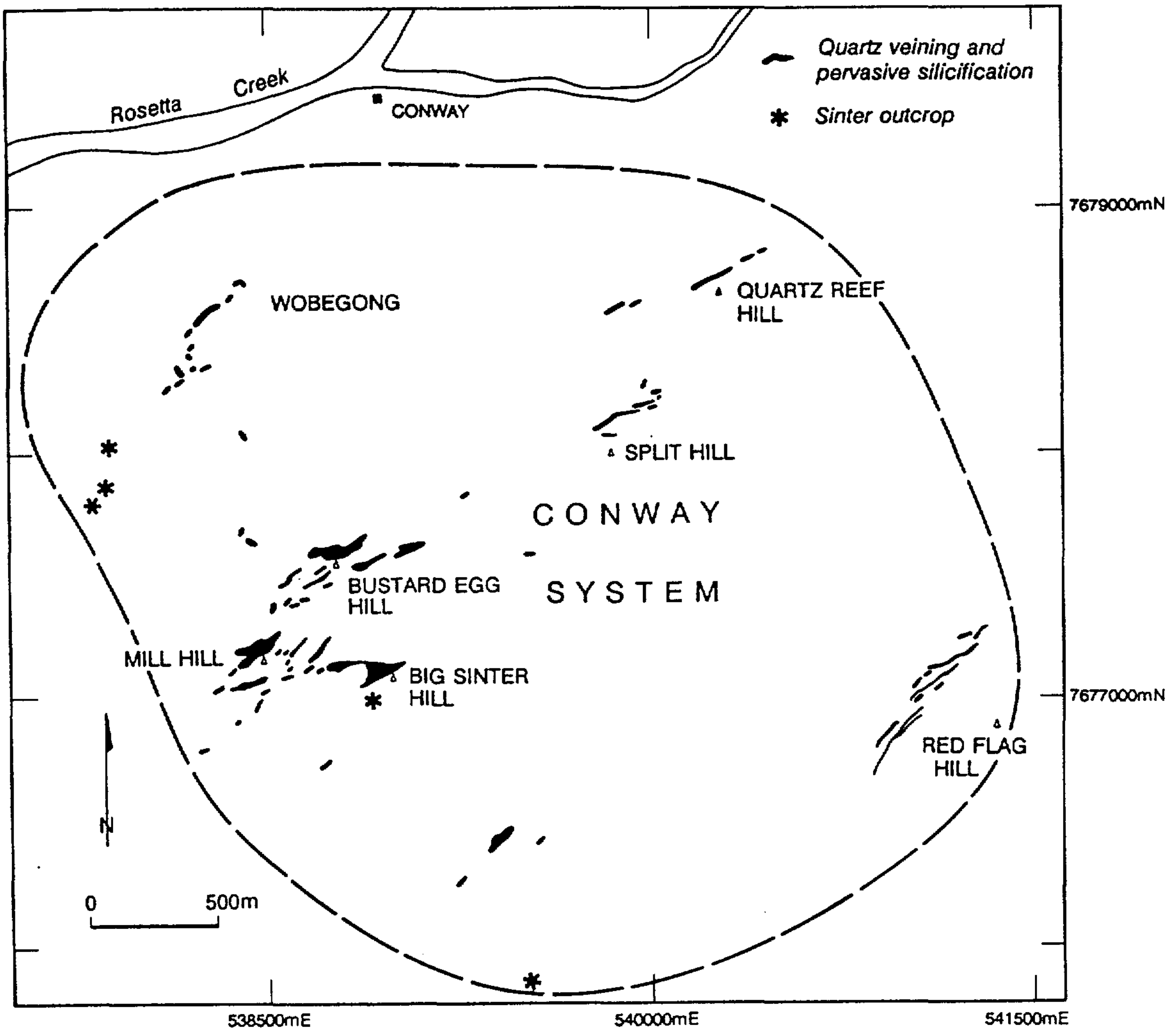

Figure 3. Areas of pervasive silicification and quartz veining, and the distribution of sinters throughout the Conway prospect.

Hydrothermal alteration is fracture-controlled and is characterised by surface quartz veins on topographic highs, pervasive weak to intense silicification, and weak to moderate argillic/phyllic alteration. Where alteration is intense, original rock textures have been obliterated, except where quartz grains survive. Quartz veining associated with the silicification has been followed by at least two generations of calcite ± zeolite (identified mainly as laumontite, with lesser gmelinite), chlorite, epidote, prehnite, and opaque mineral veining. In places, this late vein mineralogy has a patchy distribution in the host rocks, and has the appearance of a retrograde skarn assemblage. Although not intersected by drilling, skarns may occur at depth in the Bluegum prospect, given its proximity to skarn mineralisation at the Mount David prospect. Disruption to individual calcite grains indicates continued deformation after the latest veining. Sulphides are minor with an irregular distribution and generally do not exceed 5 percent of the core; they consist mainly of disseminated, anhedral to euhedral pyrite (individual grains are typically <100 microns but up to 4 mm across), lesser irregular grains of sphalerite, arsenopyrite, chalcopyrite, galena, and rare chalcocite, bornite, and pyrrhotite. Other opaque mineral phases include hematite and jarosite, commonly along late fractures. Native gold (<200 micron grain size) was identified in outcropping quartz veins.

Bobby Dazzler

The Bobby Dazzler prospect is located 800 m to the east of Rosetta Creek and 6 km southeast of the Bluegum prospect. Low grade gold mineralisation occurs in several discontinuous quartz veins and quartz-cemented breccias within variably clay-altered and silicified, pale-coloured quartz crystal tuff. Nineteen shallow percussion holes, totalling 455 m, were drilled to investigate a soil gold anomaly which coincided with outcrop of quartz-cemented breccia and vein quartz, and float consisting of chalcedony, quartz-cemented breccia, and vein quartz. The drilling failed to intersect any economically significant gold mineralisation. The better gold grades appear to be confined to a narrow, west-northwest-striking, south-dipping zone, with a weakly mineralized footwall envelope up to 50 m in width. The dominant mineralized rock type is a moderately to strongly silicified quartz crystal tuff.

Conway

This prospect lies immediately to the south of Conway homestead and occupies an area of about 15 km^2 (Fig. 3). Within the prospect, there are a number of anomalies (Wobegong, Mill Hill, Bustard Egg Hill, Big Sinter Hill, Split Hill, Quartz Reef Hill, and Red Flag Hill) which correspond with topographic highs and areas of intense silicification. The extent and indicated potential of the Conway system have made it a prime exploration target, resulting in the drilling of 26 continuously cored holes (totalling 2375 m) and 143 shallow percussion holes (each between 30 and 100 m deep). Drill holes were sited primarily to test geological and geochemical targets.

Conway is hosted predominantly by a sequence of massive trachyte, rhyolitic to andesitic lavas and volcaniclastic rocks which belong to the Bimurra Volcanics at the base of the Drummond Basin sequence (Hutton & others, 1991; Oversby & others, in prep.). Recent BHP mapping (Fig. 4, Table 2) has inferred the presence of an unconformity between the basal andesitic unit and overlying units, and has confirmed the existence of an angular unconformity above a massive flow-banded trachyte higher in the sequence. Intrusive quartz trachyte, syenite, and rhyolite dykes have cut the sequence and appear to have become extrusive in places; these intrusive rocks appear to have been associated with quartz veining throughout the prospect and with siliceous sinters deposited within an epiclastic unit to the southwest of Wobegong at the top of the Drummond Basin sequence. Plant fossils (Fig. 5) occur throughout the prospect area and are part of a well preserved Late Devonian to Early Carboniferous Lepidodendron flora recognised in the Drummond Basin (Olgers, 1972).

Exposure throughout the Conway system is generally poor, and typically consists of low ridges of rubbly outcrop and scree. Weathering of the hydrothermally altered host rocks, combined with cover by remnants of the overlying Tertiary Suttor Formation (fluvial sediments consisting mainly of sandstone, siltstone, and conglomerate) and later alluvium restrict surface observations.

Four major fault zones are interpreted to cross the Conway grid, all with a general northeasterly trend (Fig. 6). One fault zone cuts north of Bustard Egg Hill across to Quartz Reef Hill. It can be traced by the disruption to bedding in the epiclastic unit to the west of Bustard Egg Hill and, in the Quartz Reef Hill area, by a 350 m long by 2 m wide quartz-veined breccia. The emplacement of a rhyolite dyke immediately north of Quartz Reef Hill could also be controlled by this fault zone. A second fault zone, which incorporates Mill Hill, Bustard Egg Hill, and Split Hill, has been defined by the orientation of fracture-controlled siliceous zones. A third fault zone containing siliceous alteration between Mill Hill and Big Sinter Hill represents a small offshoot of the second fault zone. The fourth fault zone extends through the Red Flag Hill area: aerial photo interpretation suggests that this zone has been cut by younger, unmineralised faults.

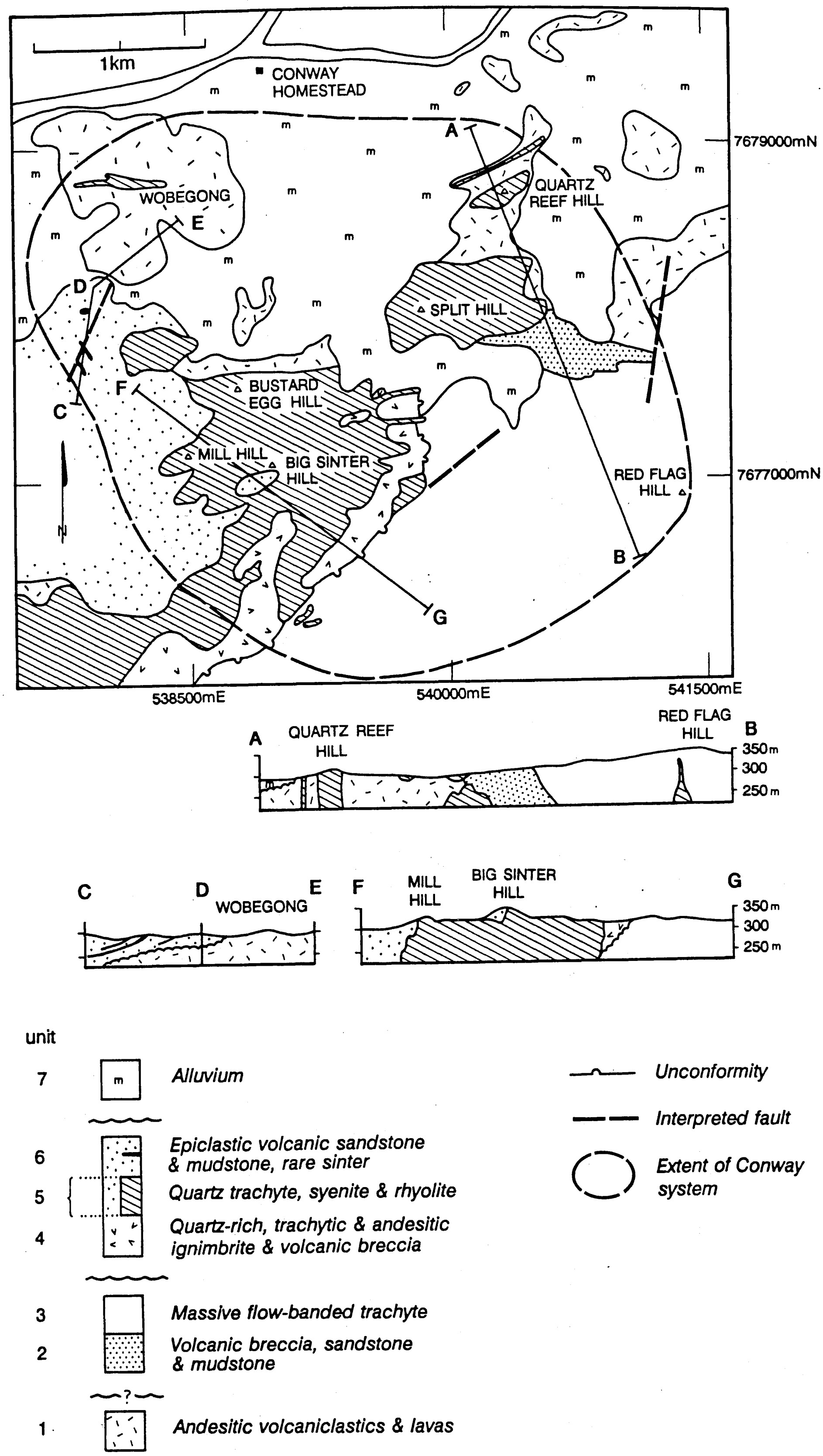

Figure 4. Geology of the Conway prospect.

TABLE 2 LITHOLOGICAL UNITS FROM THE CONWAY PROSPECT

UNIT	LITHOLOGICAL DESCRIPTION	THICKNESS	REMARKS
7	Alluvium	>350 metres	-
~~			
6	Epiclastic volcaniic sandstone & mudstone with rare sinter	Variable	Partly sourced from lower units, contains interbedded siliceous sinters with combined thickness up to 3 metres
5	Quartz trachyte, syenite & rhyolite	Variable	Mineralisation related to emplacement of this unit
4	Quartz-rich trachytic & andesitic ignimbrite and volcanic breccia	>130 metres	Several undifferentiated facies, pumice-rich in places; angular unconformity with unit 3
~~			
3	Massive flow-banded trachyte	>1200 metres	Very minor volcaniclastic rocks
2	Volcanic breccia, sandstone & mudstone	~230 metres	Minor flow-banded trachyte, lapilli-rich ignimbrite, disconformably overlies unit 1
~~?~~~~~~~~~~~?~~~~~~~~~~~?~~~~~~~~~~~?~~~~~~~~~~~?~~~~~~~~~~~?~~~~~~~~~~~?~~			
1	Andesitic volcaniclastic rocks & lavas	>1000 metres	-

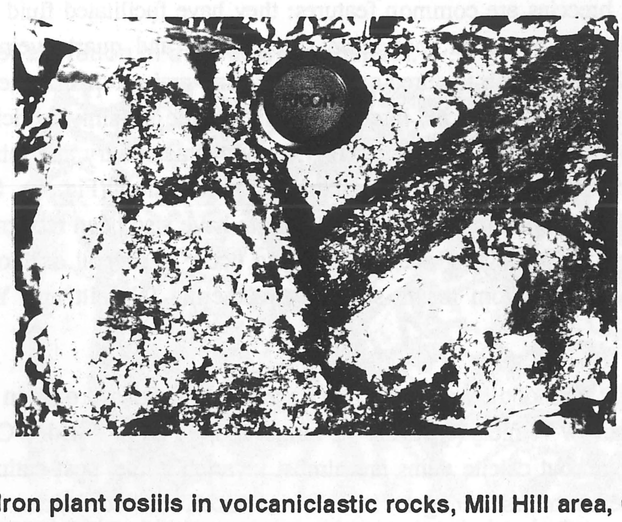

Figure 5. Lepidodendron plant fosiils in volcaniclastic rocks, Mill Hill area, Conway (lens cap 60 mm in diameter).

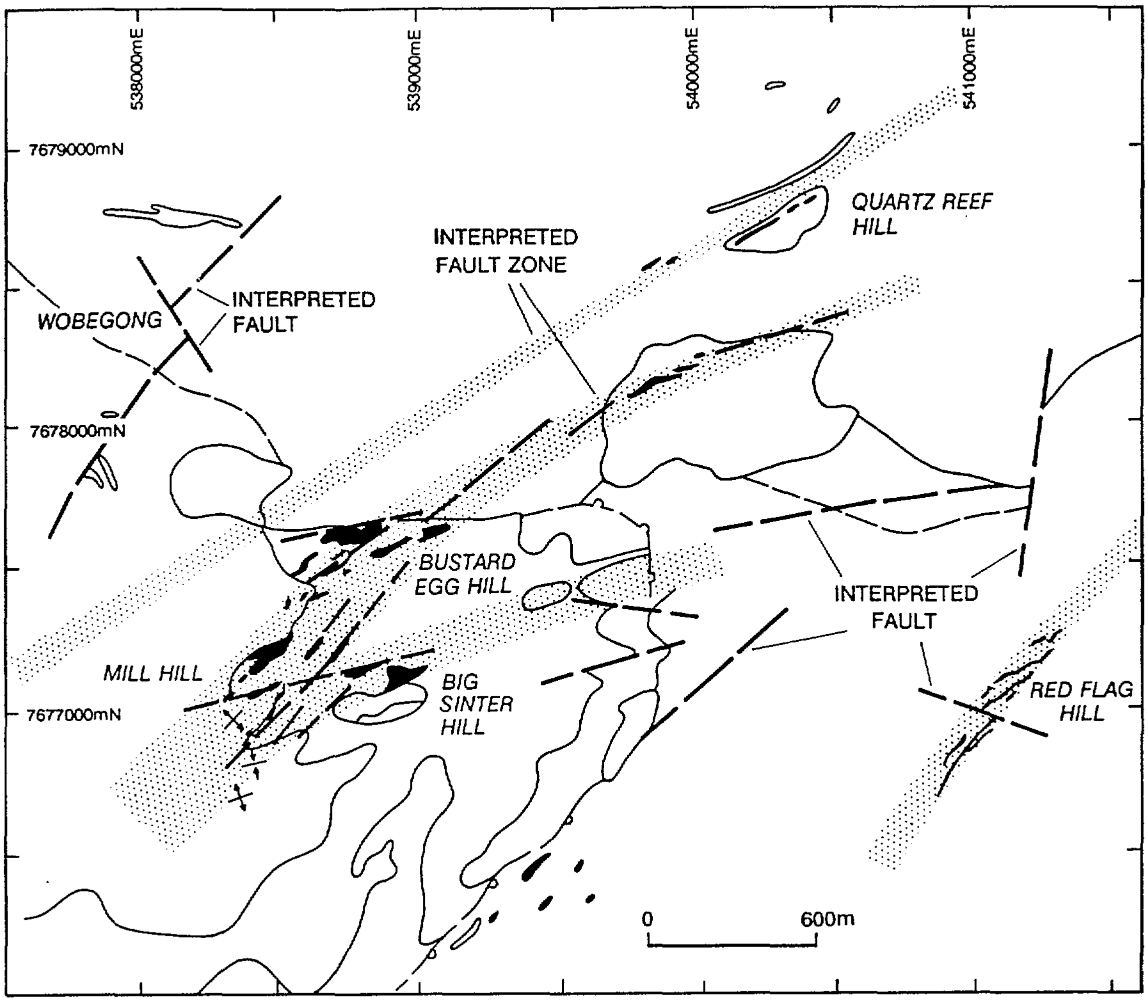

Figure 6. Structural interpretation of the Conway prospect with areas of silicification (solid black) and selected geological boundaries overlaid.

Hydraulic fractures and breccias are common features: they have facilitated fluid flow and affected the distribution of alteration—in particular, pervasive silicification and quartz veining. Silicic alteration includes colloform-banded and comb-textured quartz veins, fine-grained quartz after chalcedony in veins, and silica-cemented breccias. Weak to intense argillic/phyllic (mainly sericite and mixed layer illite/smectite) and propylitic alteration are common; X-ray diffractometry and thin section examination of outcrop samples have outlined areas of argillic/phyllic alteration (Fig. 7). Secondary K-feldspar alteration, minor kaolinite, alunite, pyrophyllite, and jarosite have also been recognised. Pyrophyllite has been identified in outcrop at Wobegong and is thought to occur in several drillholes at Conway. Some clay alteration probably results from recent surficial weathering (Nesbitt and Young, 1989; Camuti, 1989).

Calcite ± zeolites (mainly laumontite and analcime) have been recognised only in core; they fill tension fractures and occur as narrow veinlets (typically <2 mm, but up to 20 mm wide). Offsetting relationships between vein sets are rare, but calcite veins are almost invariably late, post-dating the brecciation and crosscutting earlier alteration assemblages. In rare instances, bladed calcite has been completely pseudomorphed by quartz (Fig. 8).

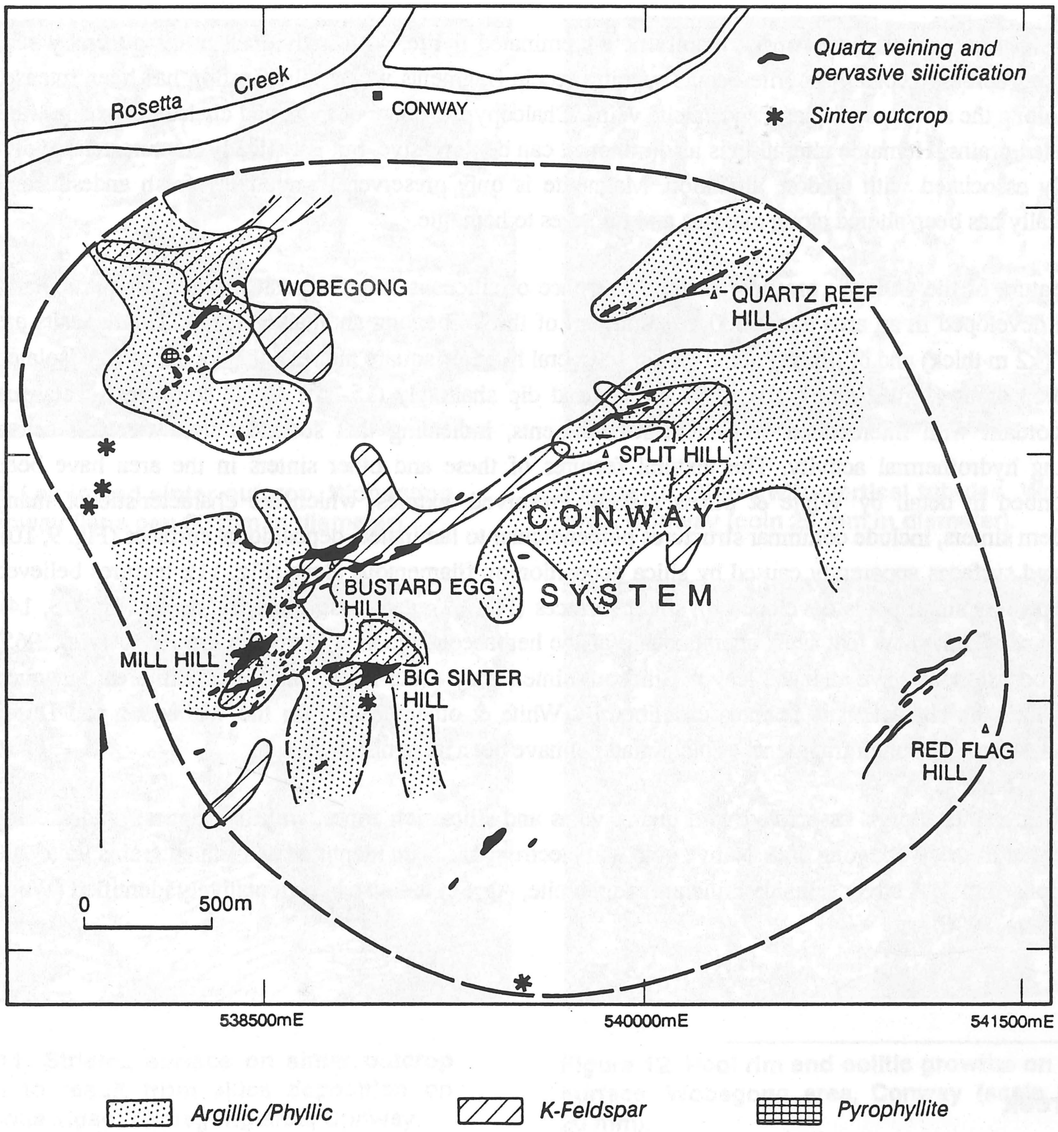

Figure 7. Distribution of alteration in the Conway prospect.

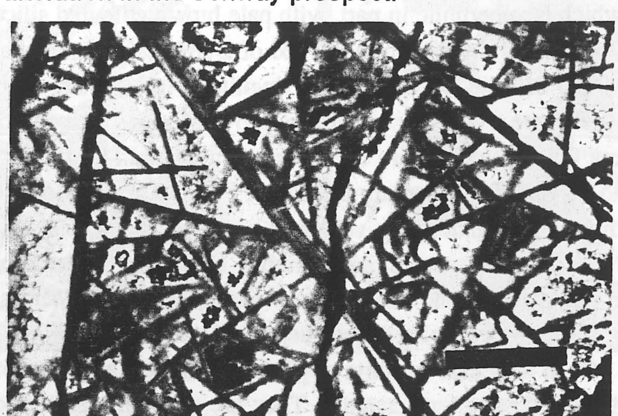

Figure 8. Quartz pseudomorphing bladed calcite, Conway (scale bar is 2 mm).

Sulphides are minor: they consist mainly of disseminated pyrite, with individual grains generally <30 microns across. Typically, pyrite occurs within breccia fragments where silicification has been intense, and along the selvages of quartz and calcite veins. Chalcopyrite, lesser bornite, and chalcocite exist as rare isolated grains. Hematite alteration is also minor: it can be pervasive, but is typically fracture-related and rarely associated with epidote alteration. Magnetite is only preserved in relatively fresh andesite and typically has been altered along margins and fractures to hematite.

A feature of the Conway prospect is the occurrence of siliceous sinter deposits, which are particularly well developed in an area about 500 m southwest of the Wobegong anomaly (Fig. 3). The deposits are thin (<2 m thick) and of limited aerial extent (<several hundred square metres); they occur as five isolated outcrop areas aligned along a northeast trend, and dip shallowly (15-25°) to the southwest. They are concordant with interbedded volcaniclastic sediments, indicating that sedimentation was still active during hydrothermal activity. The textural features of these and other sinters in the area have been described in detail by White & others (1989). Preserved textures, which are characteristic of many modern sinters, include columnar structures perpendicular to laminated, depositional surfaces (Fig. 9, 10); striated surfaces apparently caused by silica deposition on filamentous algae (Fig. 11); textures believed to represent small pools developed on sinter surfaces (Fig. 12); and fossil plant fragments (Fig. 13, 14), many of which show leaf scars characteristic of the herbaceous lycopod Oxroadia gracilis (Alvin, 1965) and, occasionally have attached leaves. Siliceous sinters may occur in the Big Sinter Hill area; however, they lack the characteristic features described by White & others (1989) for the Wobegong and Durah Creek sinters, although fragments of plant material have been recognised.

Gold mineralisation is associated with quartz veins and silica-rich zones, with the highest grades being recorded in the Wobegong area. Native gold and electrum has been identified as isolated grains up to 200 microns across. A silver selenide mineral (naumannite, Ag_2Se) has also been tentatively identified (Wood & others, 1990).

Durah Creek

The Durah Creek prospect is located about 6 km south of the Conway prospect and was discovered through stream sediment sampling which recorded a subdued gold anomaly from the general vicinity. Outcrop in the area is poor, except in creeks where exposure is good. The dominant rock unit is a flow-banded rhyolite which is spherulitic in part, with pale brown coloured siliceous bands and nodules. Analyses for altered flow-banded rhyolite from the bed of Durah Creek immediately NW of the prospect are given in Table 1 (8750 0106, 8750 0107). The rhyolite is interbedded with laminated fine-grained tuffs and lithic tuffs, which have a westerly to northwesterly strike and a steep, southerly to southwesterly dip. In the prospect area these volcanics are unconformably overlain by flatlying arenaceous sediments which are interpreted to be part of the Tertiary age Suttor Formation. They occur as flat-topped residuals on local topographic highs. The underlying volcanics are bleached where these sediments have been recently eroded. The volcanics in places are variably altered to a predominantly argillic mineral assemblage, with local silicification and chalcedonic veining. On the western side of the prospect four outcrops of sinter occur which appear to have been deposited unconformably on the underlying rocks, and are well exposed on a 300 m long east trending ridge. Unlike sinters at Wobegong (Conway), the Durah Creek sinters appear to lack fossil plant material. They are generally laminated, however, and contain columnar structures perpendicular to the laminations and locally, they have well developed surface textures similar to those seen at Conway (see Figs. 10, 11, 12) and in modern sinters (White et al, 1989).

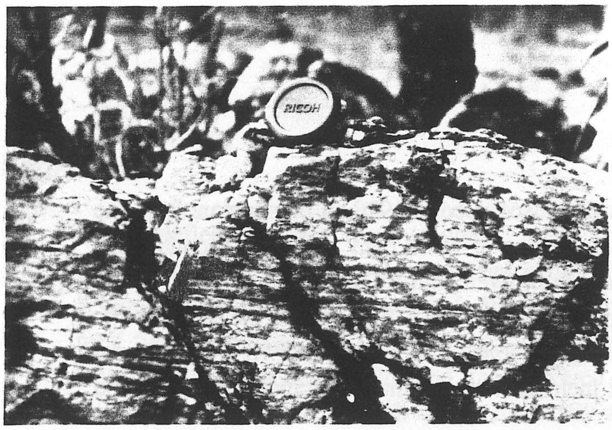

Figure 9. Laminated sinter outcrop, Wobegong area, Conway (lens cap 60 mm in diameter).

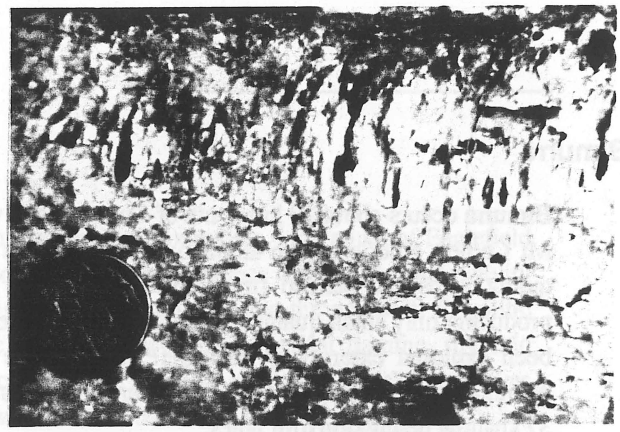

Figure 10. Sinter with vertical tubules, Wobegong area, Conway (coin 25 mm in diameter).

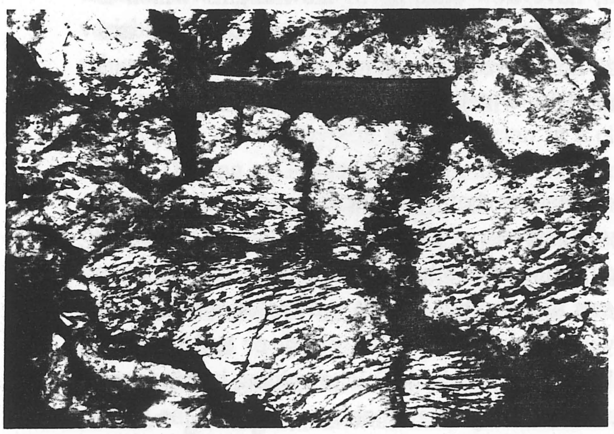

Figure 11. Striated surface on sinter outcrop believed to result from silica deposition on filamentous algae, Wobegong area, Conway.

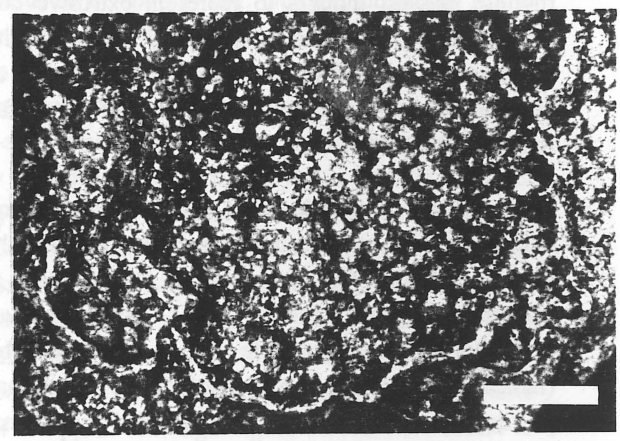

Figure 12. Pool rim and oolitic growths on sinter surface, Wobegong area, Conway (scale bar is 20 mm).

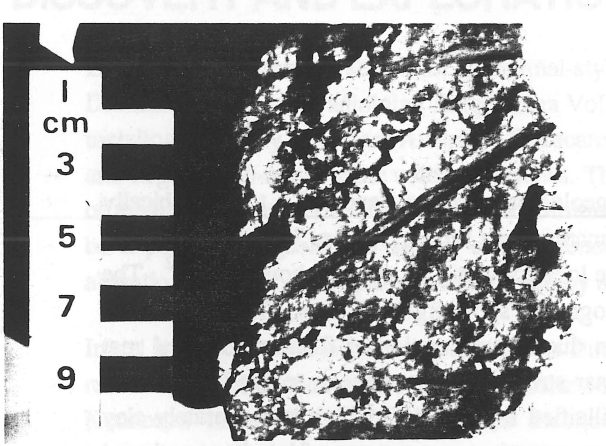

Figure 13. Sinter containing tubular plant stems (Oxroadia gracilis), Wobegong area, Conway.

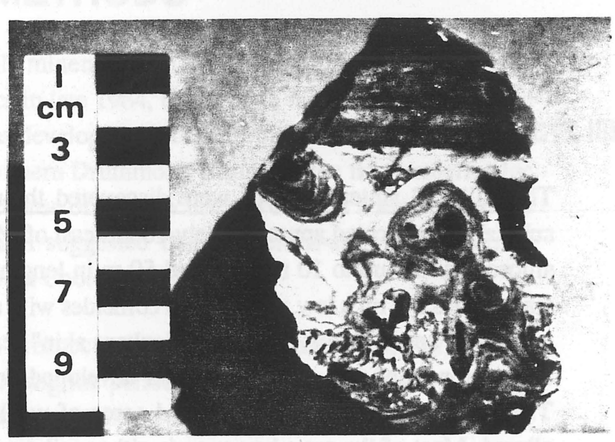

Figure 14. Laminated sinter in which tubular plant stems have acted as loci for concentric accretionary silica deposition, Wobegong area, Conway.

Bimurra

Bimurra occurs about 10 km south of Conway, and was first discovered in 1928 by prospectors from the Mt Coolon goldfield. The alteration system occurs over an area of more than 10 km^2. Discontinuous quartz veins and banded fine-grained quartz after chalcedony were mined intermittently until 1935, producing only small quantities of gold from ore averaging about 11 g/t Au. Since 1980, the prospect has been explored extensively, and BHP at one time held about one third of the known hydrothermal alteration system. Exploration in this part of the system included two continuously cored drill holes and 37 shallow percussion drill holes.

Rhyolitic volcaniclastic rocks and flows are the dominant rock types in the area, and are in part overlain by sandstone, pebble conglomerate, claystone and siltstone of the Tertiary Suttor Formation. Several large rhyolite masses, thought to represent extrusive domes, have flow-banding at the margins which is discordant with the nearly flat-lying volcanic units. Vesiculated and spherulitic rhyolite lavas, and rhyolitic ash-flow tuffs and rhyodacitic lithic crystal airfall tuffs have also been recognised. Proximity to a volcanic source is suggested by some of the airfall material which consists of coarse fragments of moderately welded tuff.

Hydrothermal brecciation and alteration are prominent features both in outcrop and drillcore, and siliceous sinters have been tentatively identified in the northeast part of the Bimurra system. Moderate to intense argillic/phyllic and propylitic alteration and silicification are both pervasive and related to veins and fractures (from 1 mm to 1.5 m). Crosscutting vein sets are rare, but at least two episodes of banded chalcedonic silica ± sulphide veining have been observed. Massive crystalline, platey or lattice quartz (indicative of silica replacement of bladed calcite) has also been recognised. Calcite veining is minor and postdates the silicification. Disseminated pyrite and rare isolated grains of chalcopyrite are the main sulphides present, although early work by Kennecott reported the presence of marcasite, galena, and an unspecified silver sulphide. Magnetite is only preserved in relatively fresh volcanic rocks.

Finely disseminated gold has been identified in association with pyrite, and is essentially confined to quartz-filled breccias and silica-rich zones of limited dimensions.

Hill 273

The Hill 273 sinter outcrops were discovered through geological reconnaissance of a topographically subdued area located approximately 10 km east of Mt Manaman near Mount Coolon. Several outcrops of siliceous sinter up to 10 m wide and 50 m in length were located within an area of about 0.2 km^2. The sinter crops out on a low ridge which coincides with a topographic spot height of 273 m. The sinter is well laminated and exhibits excellent "elephant skin" textures due to preservation of filamentous algal mat impressions, and has moderately well developed columnar structures perpendicular to the laminations. The sinter is flanked by outcrop and scree of weakly silicified rhyolitic tuff which is moderately clay altered. Most of the area, however, is either soil covered or comprises rare outcrop of laterite, weathered rhyolite or, rarely, ignimbrite. Trace gold values up to 0.1 ppm, with 2 ppm Ag were recorded from weakly altered rhyolitic tuff. Weakly detectable gold occurs in the sinter. Shallow percussion drilling failed to intersect any mineralisation.

Eaglefield

The Eaglefield prospect covers an area of about 50 km^2, centred approximately 4 km south of Eaglefield Station homestead. The prospect area has extremely poor outcrop and evidence of hydrothermal activity is restricted to a number of isolated, albeit aerially significant, locations within the prospect. Rhyolitic rock types dominate and include rhyolitic ignimbrite with prominent and abundant fiamme, rhyolitic lapilli tuff, flow banded rhyolite and finely-layered epiclastic tuffs. Evidence of hydrothermal activity was initially discovered on a small hill immediately adjacent to Goondooloo Dam, located about 4.5 km southeast of Eaglefield homestead, where float of altered volcanics and quartz exhibiting lattice textures (after bladed calcite) was observed. Poorly exposed sediments of probable Tertiary age flank the hill. About 3.5 km northeast of Goondooloo Dam, volcanic units penetrate the Tertiary and more recent cover to form a low undulating rise, which extends for a distance of about 4 km. Outcrop along this rise is variably altered to a predominantly phyllic assemblage and records low level gold and silver values with minor, but detectable, mercury. Pervasive silicification and sericitization is locally evident, accompanied by crustiform banded microcrystalline quartz veining and lattice quartz textures. Clasts of weakly clay/sericite altered rhyolite and tuff occur in a clast-supported breccia with a very fine-grained quartz matrix. Drilling at Goondooloo Dam intersected finely laminated flow-banded rhyolite, rhyolite and fine- to medium-grained rhyolitic tuff which was weakly to strongly silicified, sericitized or chloritized. Silicification is generally pervasive in nature but includes microcrystalline quartz and chalcedony veining. Sericitically altered rock types usually comprise an assemblage of pale green and white illite/mica, and chloritic alteration is only recognised where it replaces biotite in rhyolite. Pyrite is the only sulfide observed, but rarely exceeds 1% by volume. Shallow percussion drilling along the ridge of hydrothermally altered volcanics to the northeast of Goondooloo Dam intersected variably altered rhyolite with low grade gold mineralisation to a maximum of 1.3 ppm. The higher gold values were found to invariably correlate with increased pyrite content, up to an estimated 5% by volume. The investigations at Eaglefield resulted in the discovery of barren and weakly gold mineralized hydrothermal alteration systems which may be exposed at relatively shallow depth.

DISCOVERY AND EXPLORATION METHODS

BHP began a systematic search for epithermal-style gold mineralisation along the northeastern edge of the Drummond Basin and adjoining Bulgonunna Volcanics in late 1984, following a regional geological and metallogenic study of eastern Australia. The search was developed on a hot spring adularia-sericite model and targeted sub-aerial felsic volcanic terranes. The northern Drummond Basin and the northeastern edge of the basin in particular, became a focus of interest because of the concurrence of what was perceived to be a permissive geological setting and evidence which suggested that epithermal-style hydrothermal alteration and gold mineralisation existed nearby at Mount Coolon and Bimurra.

Initial interest centred on the area around the Bimurra prospect where small quantities of gold had been recovered from banded chalcedony and quartz veins during the period from 1928 to 1935, and work by Kennecott in 1980 had identified and described features which were indicative of an epithermal environment. The approach followed by BHP was based on an appreciation and understanding of modern hot spring hydrothermal systems and the anticipation that other palaeo hot spring systems were likely to be present in the Bimurra district, and possibly might be preserved at an economically productive level of erosion.

A simple exploration strategy was developed by BHP which sought to locate large paleo hot spring alteration systems and to determine their level of preservation. Because of the abundant siliceous products of hot spring systems, examination of stream float was considered to offer a simple but effective way to rapidly screen large areas of potentially prospective geology. To assist this and enable alteration systems to be prioritized for subsequent exploration, low density stream sediment sampling using BLEG (bulk-leach extractable gold, also known as BCL (bulk cyanide leaching)) analysis was employed.

The decision to use the BLEG analytical technique followed from a judgement at the outset of the exploration programme that conventional minus 80-mesh stream sediment sampling and/or panned concentrate sampling and analysis of these fractions for gold were not the most effective geochemical techniques to apply to the exploration for hot spring epithermal gold mineralisation. It was considered that the minus 80-mesh and panned concentrate stream sediment techniques were unreliable in their ability to detect weakly gold-anomalous alteration systems and the very fine-grained gold commonly deposited by hot spring hydrothermal fluids. The development of the BLEG analytical technique in the early 1980s was timely in that it provided a means by which fine-grained gold and very low-level gold anomalies could be detected.

To confirm the suitability of the BLEG technique an orientation stream sediment survey was conducted by BHP. Fourteen sample sites were selected in streams draining the northern and eastern parts of the Bimurra prospect and unmineralized geology to the southeast. Five of the sites were located in Conway Creek, a third-order drainage; five sites were in second-order tributaries which flowed into Conway Creek; and four sites were within first-order streams which similarly, ultimately drained into Conway Creek. At each of the fourteen sites a nominal 50 gm sample of panned concentrate was collected along with 10 kg of stream sediment which was subsequently dry-screened into -2 mm + 850 micron, -850 + 425 micron, -425 + 180 micron and -180 micron (minus 80-mesh) fractions, respectively. At six of the sites a 6 kg sample of the stream sediment was collected for BLEG analysis.

At the time that the samples were collected it was considered important to select good trap sites for stream sediment samples, including samples for BLEG analysis, and as a result all of the sample sites were chosen on the basis of their trap site characteristics. A Garrett Gravity Trap pan was used to produce the nominal 50 gm sample of panned concentrate from approximately 10 kg of -2 mm size stream sediment.

The panned concentrate samples were dried, weighed, pulverized to minus 200-mesh and analyzed for gold by fire assay followed by AAS analysis. The analytical precision of this technique was considered to be ± 15%, with a detection limit of 5 ppb. The four screened sample fractions were analyzed for gold using the same fire assay technique.

Copper, lead, and zinc were analysed by digestion in perchloric/nitric acid followed by an AAS finish; arsenic was analysed by hydride generation followed by AAS; and mercury was analysed by the Jerome gold film method. The precision of the methods used for copper, lead, zinc, arsenic and mercury was ±10% in each case. Detection limits were 2 ppm for copper, zinc and arsenic, respectively; 5 ppm for lead; and 1 ppb for mercury.

The BLEG analysis was performed using a 24 hour static leach, gold precipitation onto zinc dust with subsequent dissolution in aqua regia and gold extraction into MIBK. Gold concentrations were determined by direct-spray AAS, with detection limits for this method at 0.05 ppb. The BLEG analyses were carried out by Tetchem Laboratories in Brisbane, with all other analyses being completed by Pilbara Laboratories in Townsville.

The fourteen sample sites are shown on Figure 15 along with the gold values recorded for the BLEG, panned concentrate and the minus 180 micron size screened sediment fraction. The gold results for each of the samples and sample types are listed in Table 3. Results for copper, lead, zinc, arsenic and mercury

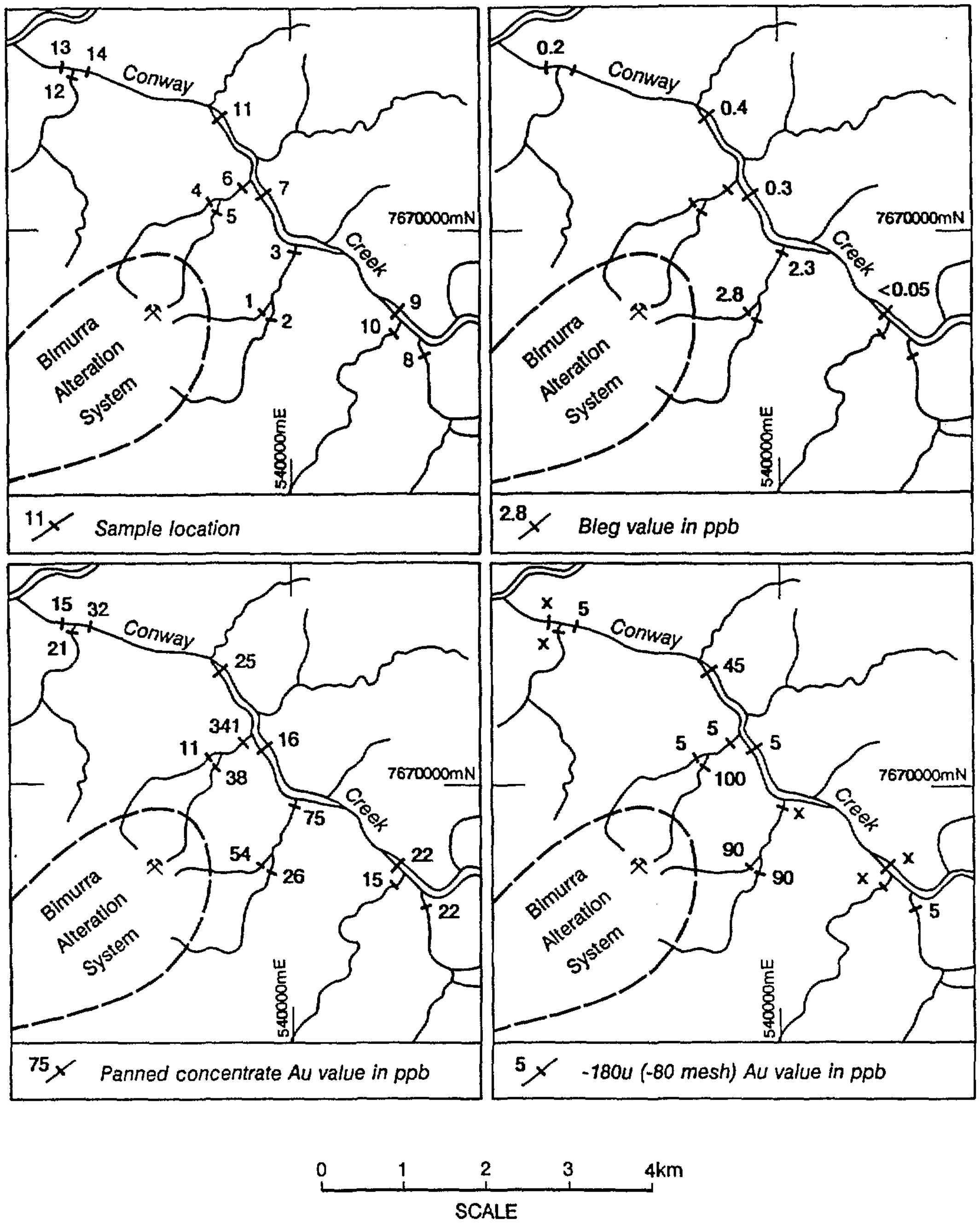

Figure 15. Gold values from an orientation stream sediment survey of the Bimurra area.

for each of the four screened sediment size fractions are listed in Table 4. Gold results from BLEG, panned concentrate and the four screened fractions are listed in Table 5 which also indicates the approximate distance downstream from the mineralisation source of each sample site.

From Table 5 and Figure 15 it is obvious that the dispersion train of gold in the panned concentrate and the minus 180 micron size screened fraction sample is short, and in the case of the screened fraction is at best restricted to first and second order streams. The BLEG technique on the other hand is capable of detecting weakly anomalous gold values several kilometres downstream in the third-order Conway Creek. The sixth BLEG sample, which was collected at site 9, and outside the influence of the Bimurra

TABLE 3 BIMURRA ORIENTATION STUDY - GOLD RESULTS

SAMPLE SITE	BLEG (ppb)	PAN CONC. (ppb)	F1 (ppb)	F2 (ppb)	F3 (ppb)	F4 (ppb)
1	2.80	54	15	10	80	90
2	-	26	120	X	X	90
3	2.37	75	10	X	X	X
4	-	11	35	5	X	5
5	-	38	5	5	X	100
6	-	341	5	5	5	5
7	0.32	16	X	5	X	5
8	-	22	X	5	5	5
9	<0.05	22	5	5	X	X
10	-	15	X	X	X	X
11	0.41	25	X	X	X	X
12	-	21	X	X	5	45
13	0.24	15	X	X	X	X
14	-	32	X	X	5	5
Detection limit	0.05	5	5	5	5	5

X = below detection limit

Sample fraction:
- F1 -2 mm to +850μ
- F2 -850μ to +425μ
- F3 -425μ to +180μ
- F4 -180μ

mineralisation, did not contain detectable gold. Subsequent experience in the BHP tenements showed that the regional background level of gold using the BLEG technique was less than 0.1 ppb.

Table 6 compares the minus 180 micron (minus 80-mesh) results for copper, lead, zinc, arsenic and mercury with the BLEG result from the same sample site. The copper, lead, zinc, arsenic and mercury values are weakly anomalous at sites close to the Bimurra mineralisation but decay erratically away from the source.

The results of the Bimurra stream sediment orientation study were taken to confirm the viability of the BLEG technique for first-pass reconnaissance sampling, and as a result an area of approximately 2500 km^2 held under exploration title by BHP was subjected to widely-spaced stream sediment sampling and float examination. The sampling interval used in the streams was derived from the orientation work at Bimurra and was set nominally at a maximum of 10 km of cumulative drainage, measured downstream from the headwaters of the stream system.

The results of this sampling are shown on Figure 16. The ability of the BLEG technique to identify weakly gold mineralised hot spring alteration systems is clearly shown. Battery Hill, Bluegum, Conway, Bimurra, and a number of smaller occurrences such as Isabella and Bobby Dazzler correspond with a well defined pattern of anomalous BLEG values. First-pass reconnaissance sampling in each instance located the alteration system with BLEG values of plus 0.5 ppb, and in many instances of plus 1.0 ppb. The existence of the north-trending corridor of alteration systems extending from the Bimurra to Battery Hill prospects is readily apparent.

TABLE 4 BIMURRA ORIENTATION STUDY
COPPER, LEAD, ZINC, ARSENIC, & MERCURY RESULTS

SAMPLE SITE		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Element															
Cu (ppm)	F1	4	6	5	5	5	3	8	5	4	2	3	6	4	5
	F2	6	5	4	4	3	3	3	3	4	3	1	5	5	4
	F3	7	5	4	3	4	4	3	4	3	3	2	8	4	5
	F4	45	12	10	10	8	6	5	12	12	6	6	33	37	20
Pb (ppm)	F1	5	X	X	X	7	X	X	12	8	X	X	11	X	11
	F2	13	X	X	15	X	X	X	X	X	X	10	14	X	5
	F3	X	X	X	16	X	19	X	X	X	X	8	X	X	X
	F4	36	X	8	10	13	15	X	X	X	X	9	35	X	X
Zn (ppm)	F1	18	26	16	5	16	16	18	31	33	25	23	23	28	27
	F2	23	20	16	15	18	12	24	19	25	26	21	35	29	28
	F3	27	18	24	25	18	22	24	29	30	23	31	42	30	29
	F4	52	25	23	38	30	28	29	35	47	28	31	80	45	36
As (ppm)	F1	8	41	20	54	38	32	5	X	8	12	5	18	8	12
	F2	18	31	12	26	20	19	4	5	X	X	5	12	3	3
	F3	10	32	12	16	9	16	7	X	X	X	5	11	7	3
	F4	15	28	4	16	15	18	X	IS	X	3	X	20	5	X
Hg (ppb)	F1	4	X	X	18	14	24	3	3	3	3	18	17	8	8
	F2	6	1	X	15	4	10	X	X	X	1	17	6	X	X
	F3	5	X	29	15	5	7	3	9	5	X	22	2	8	17
	F4	7	4	11	10	6	X	2	9	65	6	4	X	X	6

X = below detection limit (for Cu 2 ppm, Pb 5 ppm, Zn 2 ppm, As 2 ppm, Hg 1 ppb)
IS = insufficient sample
Sample fraction:
F1 -2 mm to +850μ
F2 -850μ to +425μ
F3 -425μ to +180μ
F4 -180μ

TABLE 5 BIMURRA ORIENTATION STUDY
COMPARISON OF GOLD RESULTS FOR BLEG, PANNED CONCENTRATE AND FINER SEDIMENT FRACTIONS

SAMPLE SITE	DISTANCE FROM SOURCE (km)	BLEG (ppb)	PAN CONC (ppb)	F1 (ppb)	F2 (ppb)	F3 (ppb)	F4 (ppb)
1	1	2.8	54	15	10	80	90
3	2	2.3	75	10	X	X	90
7	3	0.3	16	X	5	X	5
11	4	0.4	25	X	X	X	X
13	6	0.2	15	X	X	X	X

X = below detection limit
Sample fraction:
F1 -2 mm to +850μ
F2 -850μ to +425μ
F3 -425μ to +180μ
F4 -180μ

REGIONAL STREAM SEDIMENT BLEG GEOCHEMISTRY, BULGONUNNA PROJECT AREA

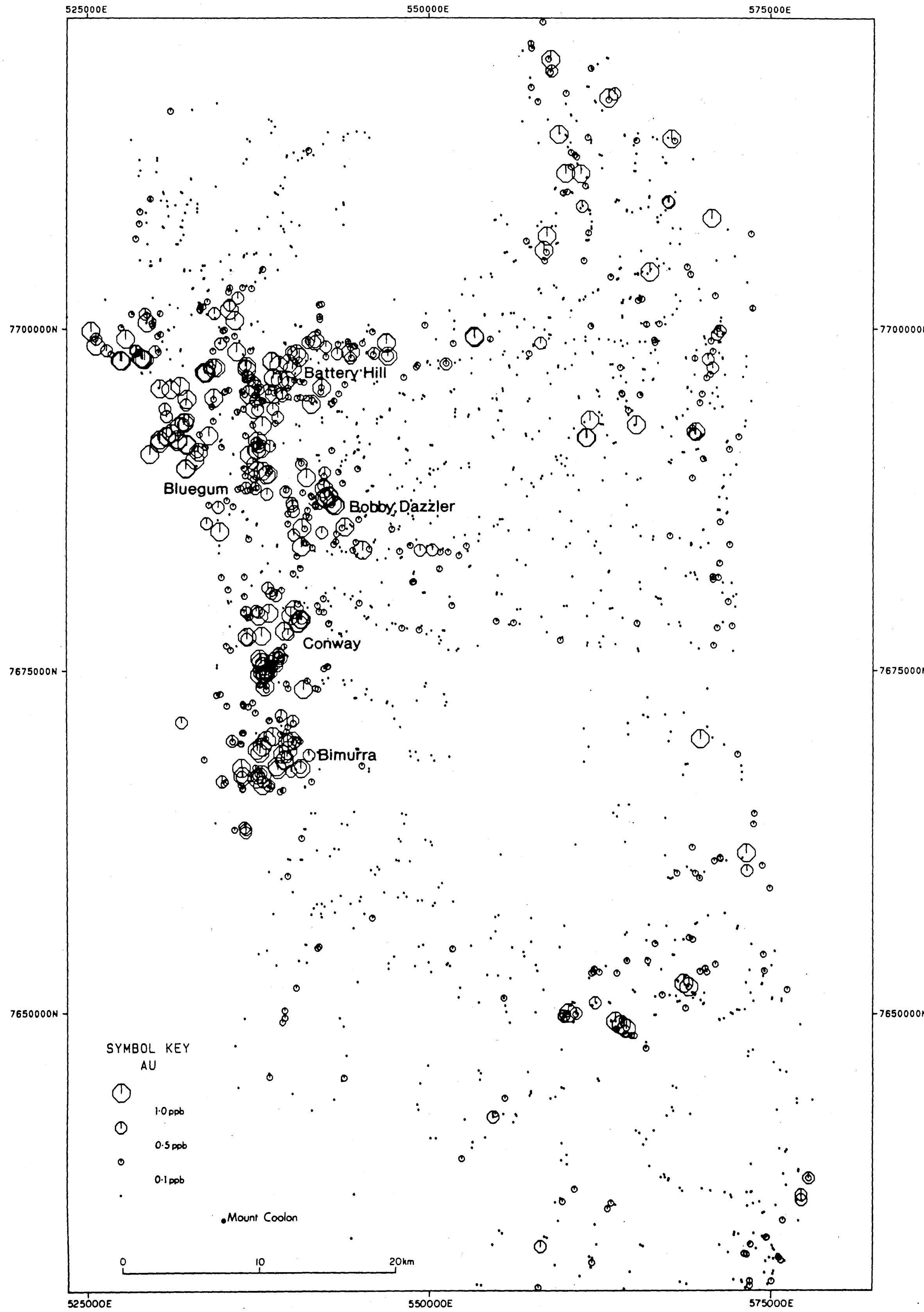

Figure 16. Regional stream sediment BLEG geochemistry for BHP prospects.

TABLE 6 BIMURRA ORIENTATION STUDY
COMPARISON OF BLEG AND MINUS 180µ COPPER, LEAD, ZINC, ARSENIC, AND MERCURY RESULTS

SAMPLE SITE	DISTANCE FROM SOURCE (km)	BLEG (ppb)	Cu (ppm)	Pb (ppm)	Zn (ppm)	As (ppm)	Hg (ppm)
1	1	2.8	45	36	52	15	7
3	2	2.3	10	8	23	4	11
7	3	0.3	5	X	29	X	2
11	4	0.4	5	9	31	X	4
13	6	0.2	37	X	45	5	X

X = below detection limit

GEOPHYSICAL TECHNIQUES

The geophysical information in this section has been drawn from Irvine and Smith (1990) and is based on an airborne magnetic and radiometric survey conducted by BHP over their prospects in April, 1985. The survey was flown over a north-south strip extending from immediately north of Bluegum to about 10 km south of Bimurra. Flight lines were oriented east-west with a line spacing of 250 m and a flying height of 80 m.

The data are presented as a series of images. Figure 17A is a total magnetic intensity (TMI) image in which the more magnetic units in the geology are depicted as white-red and those with the lowest magnetic response are in blue. In Figure 17B an east-west horizontal gradient filter has been applied to the magnetic data to enhance subtle structural features, and in Figure 17C an "alteration" filter has been used to highlight areas with relatively flat magnetic response which result from the destruction of magnetite in areas of hydrothermal alteration. This "alteration" filter has been produced by reduction to the pole of the TMI data, removal of low frequency components arising from deep sources and the application of a sawtooth filter (Pratt, 1978). Figure 17D is a potassium/thorium ratio image derived from the radiometric data with high ratios in white-red and low ratios shown in blue.

Figure 18 is reproduced from Irvine and Smith (1990). It summarises and interprets the main features in the images (Figure 17) in relation to the Bluegum, Conway, and Bimurra prospects. The most significant attribute is a north-south corridor about 5 km wide which is characterised by a series of magnetically quiet areas and contains all of the above prospects. The edges of the corridors are not precisely defined by the magnetics, but this region of relatively flat magnetic response can be seen on the published regional and unpublished detailed aeromagnetic maps. Conway and Bimurra appear to lie at the intersections of this corridor with similar east-northeast trending magnetic corridors that may contain other prospects and deposits (e.g. Wirralie). The magnetic data show no clear evidence for structural control, though Irvine and Smith (1990) have suggested that several lineaments pass close to Conway. It should be added that other areas of low magnetic response occur on the regional aeromagnetic maps; however, these areas do not necessarily relate to regions of hydrothermal alteration as other explanations are possible.

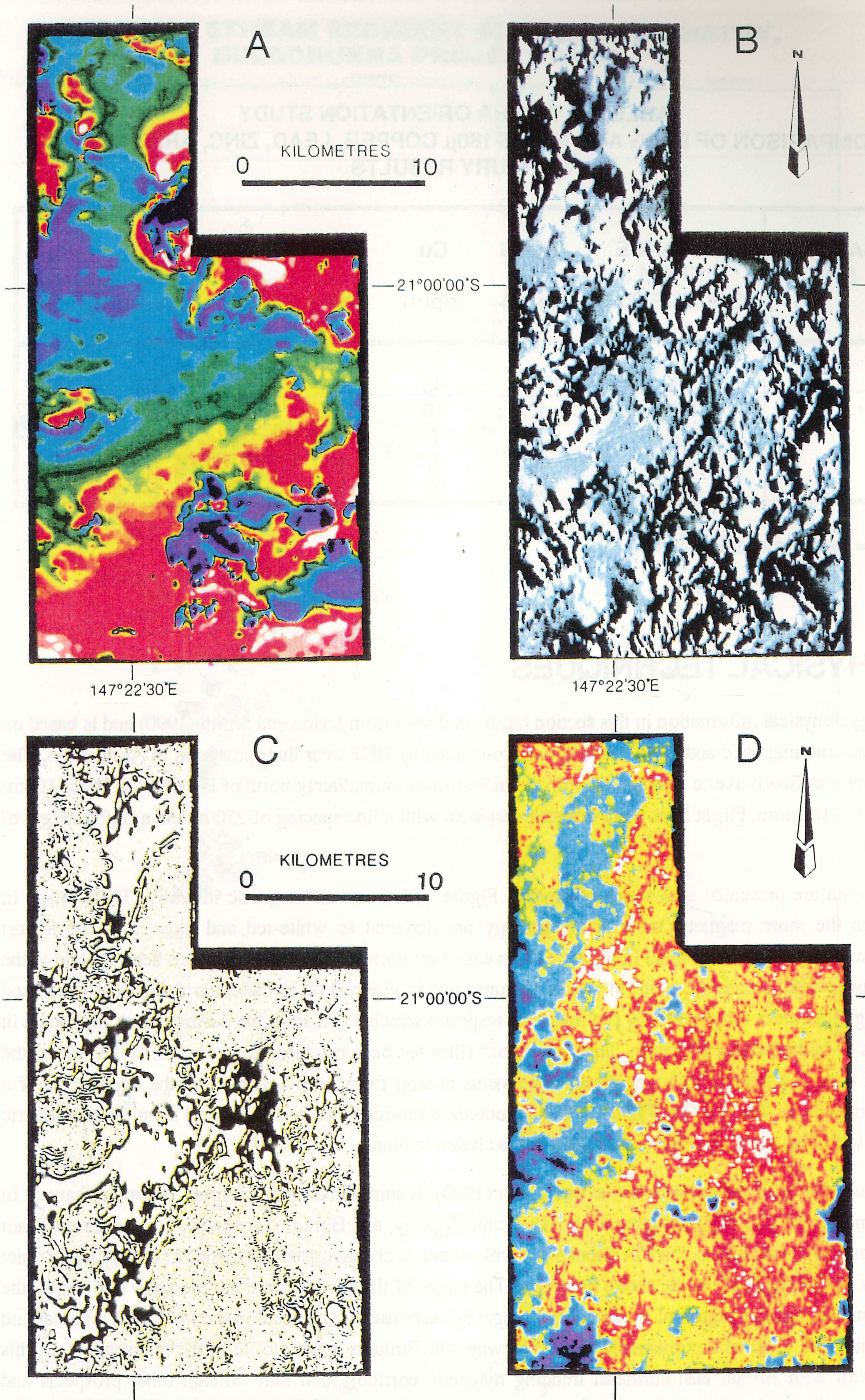

Figure 17A–D. Geophysical images for the Bluegum-Conway-Bimurra area (reproduced with permission from Irvine and Smith, 1990). A—Total magnetic intensity. B—East-west horizontal gradient of total magnetic intensity. C—Aeromagnetics – "alteration" filter image. D—Potassium/thorium ratio image derived from the radiometric data.

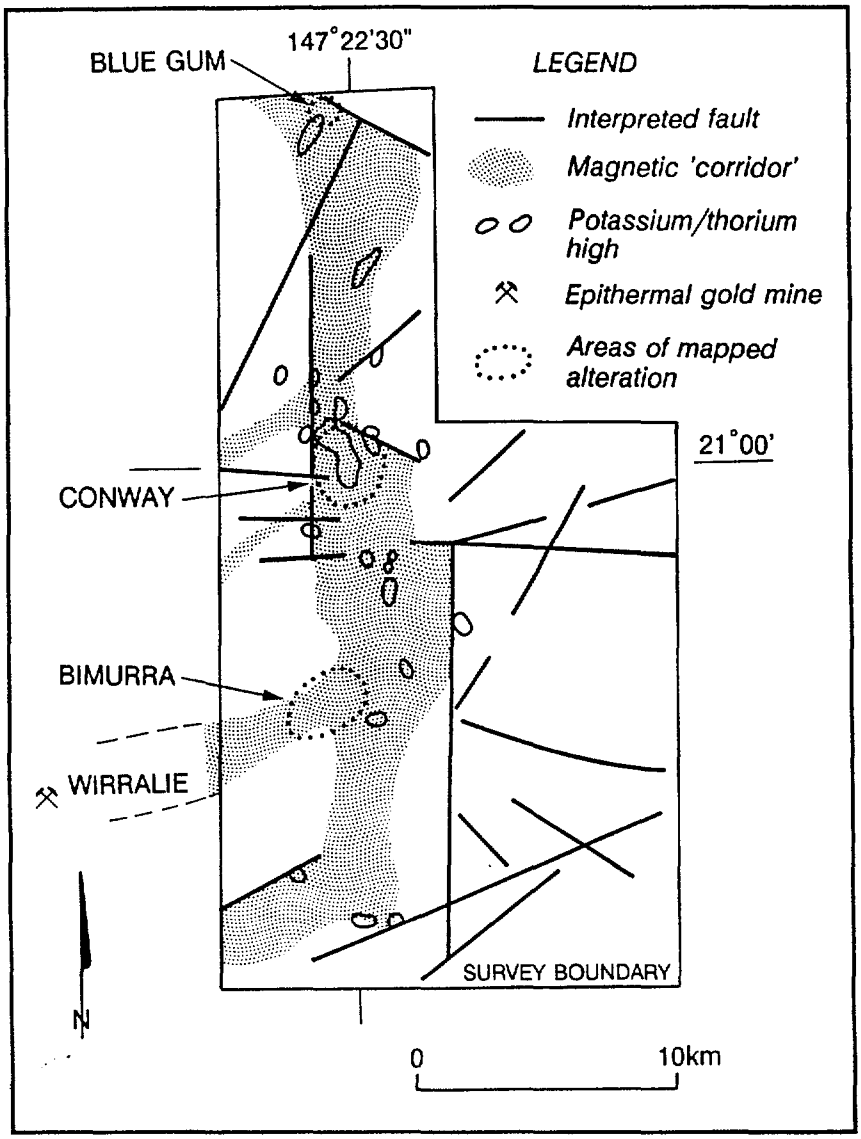

Figure 18. Summary interpretation of airborne magnetics and radiometrics for the Bluegum-Conway-Bimurra area (reproduced with permission from Irvine and Smith, 1990).

The potassium/thorium ratio image (Figure 17D) indicates that although discrete highs correlate reasonably well with the Conway and Bluegum prospects, they do not correlate well with the Bimurra prospect. These potassium-rich areas could correspond to areas of intense hydrothermal alteration in which sericite is the dominant K-rich mineral phase.

RELATIONSHIP OF EPITHERMAL GOLD MINERALISATION TO REGIONAL FEATURES

The Drummond Basin is believed to have formed as an intracratonic basin west of a continental margin volcanic arc (Connors-Auburn Arch), active during the Late Devonian to Early Carboniferous (Murray & others, 1987). All of the significant proven gold mineralisation in the northern Drummond Basin, with the possible exception of the main lode at Mount Coolon and the Ukalunda deposit, is believed to be hosted by units at the base of the Drummond Basin sequence (Hutton, 1989; Law & others, 1989). In the area studied, these units are represented by the Bimurra Volcanics (Hutton & others, 1991) in the south and laterally equivalent Stones Creek Volcanics (Oversby & others, in prep.) to the north. Early mapping (Law & others, 1989; Ewers & others, 1989) suggested that these rocks were much more extensive than previously recognised, thereby enhancing the prospectivity of the region. Recent mapping, constrained by U-Pb ion microprobe single zircon dating of critical units, has confirmed this observation, although the outcrop extent of the Drummond Basin sequence is not as great as was first thought. The BHP prospects of Battery Hill and Bluegum occur near outcropping basement (i.e. Ukalunda Beds) to the Drummond Basin sequence: skarn mineralisation at the Mount David prospect, 2 km south of Bluegum, is hosted by the Ukalunda Beds.

In the northern Drummond Basin, gold mineralisation occurs in an acid to intermediate volcanic environment, and is hosted mainly by volcaniclastic rocks which can be associated with lavas. These rocks appear to represent a favourable host sequence to mineralisation because they are cut by structures which could have focussed and channelled fluids on a regional scale. They may have acted as a possible source of gold and, perhaps more significantly, sulphur for the transport of gold (Seward, 1973): however, this has not been demonstrated and the basement rocks to the volcanic units equally could be considered as possible source material for metals and sulphur.

Predominantly north and northeast trending structures in the northern Drummond Basin appear to control the alignment of prospects and deposits on a regional scale; however, as already noted, direct evidence for these structures is generally lacking. Many deposits and prospects appear to correlate with magnetic linears. Mount Coolon, Bimurra, Conway, Bluegum, and Battery Hill have a north-south alignment which closely corresponds to a magnetic corridor apparent on regional-scale aeromagnetic data (Figure 19; Wood & others, 1990). Yandan, Wirralie, Bimurra, and Pajingo appear to fall close to magnetic linears which trend in either an east-northeasterly or northwesterly direction and conform in general with one or other of the two shear directions deduced by Olgers (1972). These regional structural trends may also be evident at a prospect and deposit scale. For example, the four major fault zones interpreted to cross the Conway prospect all have a northeasterly trend and, as a consequence, intrusive rhyolite dykes and quartz veins have a similar orientation (Figs 3 &4), and the Scott Lode at Pajingo strikes in an east to northeast direction (Porter, 1988).

AGE OF MINERALISATION

Sericite alteration at Pajingo has been dated by the K-Ar method at 330 ± 10 Ma (Etminan, 1989), and Cunneen and Sillitoe (1989), on the basis of field criteria, consider the epithermal system at Verbena to be Late Devonian. In this study, K-Ar dating obtained through the Australian Mineral Development Laboratories (AMDEL) for sericite from the BHP prospects yielded ages of 298 to 334 Ma, 321 Ma, and 283 to 301 Ma (Late Carboniferous to Early Permian) for Conway, Bimurra, and Bluegum, respectively (Table 7). This sericite was gouged from fractures and separated from those volcanic rocks with intense sericitic alteration. Samples were selected for dating once cleared of contamination by X-ray diffraction. Recent analysis of a further sericite sample from Conway (DDH C-131, 78m) has yielded a K-Ar age of 342 ± 15 Ma (Perkins and Walshe, in prep.)

The spread of ages for prospects and deposits in the northern Drummond Basin suggests that multiple igneous episodes rather than a single event were responsible for the epithermal activity, and that in some cases, hydrothermal events may have overprinted one another along reactivated structural features.

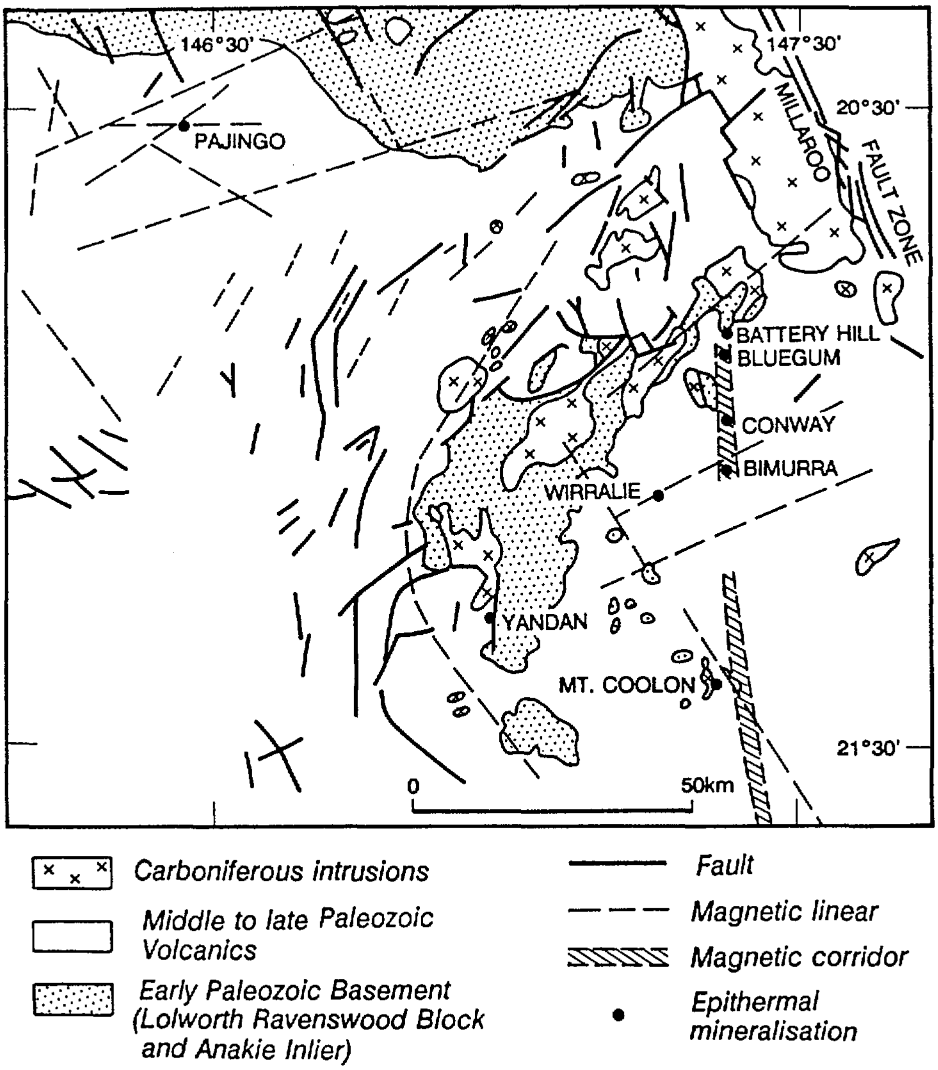

Figure 19. Structural setting of epithermal gold deposits in the Drummond Basin (from Wood & others, 1990).

The timing of regional magmatic events in relation to mineralising events remains poorly constrained and in need of further work. Recent U-Pb single zircon dating and field investigations have indicated a major period of felsic to intermediate magmatic activity between about 290 Ma and 305 Ma which relates to the extrusion of the Bulgonunna Volcanic Group and associated intrusive rocks, and an earlier, poorly defined period of intermediate volcanism at about 356 Ma (Black, in prep.). Earlier work recorded a Rb-Sr whole rock isochron age of 297 ± 12 Ma for the Bulgonnuna Volcanics (Webb and McDougall, 1968 if the decay constants recommended by Steiger and Jager (1977) are used). Granites intruding these volcanics yielded similar Rb-Sr ages of 308 ± 25 Ma and a range of K-Ar biotite and hornblende ages from 288 Ma to 303 Ma (Webb and McDougall, 1968). This major period of igneous activity between about 290 Ma and 305 Ma correlates with the K-Ar ages obtained for Bluegum, and some K-Ar ages at Conway.

The older ages for prospects and deposits in the northern Drummond Basin (including the Late Devonian –Early Carboniferous age of plant material caught up in the Wobegong sinters) cannot be correlated with confidence to known regional igneous events. K-Ar ages are usually considered to provide minimum

TABLE 7 K-Ar AGES FOR SERICITE FROM BHP PROSPECTS

BMR SAMPLE	%K	$^{40}Ar^*$ ($\times 10^{-10}$moles/g)	$^{40}Ar^*/^{40}Ar_{Total}$	AGE+
Conway				
8750 0005	7.13	42.767	0.993	317±2 Ma
	7.07			
8750 0026	7.29	41.210	0.994	297±2 Ma
	7.41	41.405	0.980	299±3 Ma
8750 0067	8.25	48.942	0.995	312±3 Ma
	8.31			
8750 0071	6.93	43.527	0.993	330±3 Ma
	6.91			
8850 0016	7.75	46.772	0.989	318±5 Ma
8850 0035	7.93	50.551	0.993	334±5 Ma
Bimurra				
8750 0080	5.72	34.995	0.988	321±3 Ma
	5.75			
8750 0091	7.31	38.680	0.991	283±3 Ma
	7.23			
Bluegum				
8850 0054	6.71	37.839	0.981	299±4 Ma
8850 0062	6.47	36.767	0.993	301±4 Ma

* denotes radiogenic ^{40}Ar

+ error limits in age given for the analytical uncertainty at one standard deviation

Constants: ^{40}K = 0.01167 atom percent

$\lambda_\beta = 4.962 \times 10^{-10}$ per year

$\lambda_\varepsilon = 0.581 \times 10^{-10}$ per year ages; hydrothermal systems at Conway and Bimurra could relate to the 356 Ma igneous activity but may appear younger as a result of Ar loss caused by heating during the extensive magmatic event at about 300 Ma. If this is the case, then the base of the Drummond Basin sequence not only acted as a host for mineralisation, but volcanic units (also at the base) could have been a heat source for some of these hydrothermal systems.

DETAILED STUDIES ON BHP PROSPECTS

Of the BHP prospects, Conway provided the greatest scope for detailed fluid inclusion and stable isotope studies because of its large area (about 15 km^2) and the extent of quartz veining and drilling on the prospect. There was the added advantage that the interpretation of these studies was not complicated by a complex tenement situation, since BHP holdings covered the entire outcrop area of the Conway prospect. Some data are presented here for the Bluegum and Bimurra prospects: however, these and other prospects are smaller and generally lack suitable material either in drillcore (where available) or outcrop. In the case of Bimurra, a number of companies shared coverage of that prospect and the hydrothermal system is partially obscured by Tertiary rocks.

Outcropping quartz veins were sampled across the Conway prospect (Fig. 3) and rare quartz and calcite veins intersected in core were sampled also. Sampling of the Bluegum prospect was more restricted for the reasons outlined above.

In general, low sulphidation epithermal systems are characterised by fluid temperatures below 300°C, low salinities (normally <5wt. % NaCl equivalent), possible evidence of boiling, and evidence that meteoric water has been the major fluid source (Bodnar & others, 1985; White and Hedenquist, 1990). Epithermal deposits of this type typically form within 1000 m of the surface. Provided the effects of salinity and dissolved CO_2 can be taken into account, an estimate of the depth of formation (below the palaeowater table), and hence the level of erosion, can be gauged from fluid inclusion data, if there is clear evidence of boiling. Where boiling cannot be demonstrated, fluid inclusion data can be used to infer a minimum depth of cover (Roedder, 1984). Combined stable isotope and fluid inclusion studies can be used to assess fluid/wall rock ratios and to indicate the extent of fluid/wall rock interaction, thereby gauging the mineralising potential of a system.

Fluid Inclusions

Early formed chalcedonic silica, which has recrystallised to fine-grained quartz is unsuitable for microthermometry, but such chalcedony is suspected to have formed at temperatures <200 °C (Bodnar & others, 1985). Later euhedral quartz in veins and vugs tends to be clear and inclusion-free. However, some crystals exhibit growth zones which are defined by dark bands of small primary fluid inclusions (Fig. 20). In some samples, microfractures (presumably developed during either diagenesis or low grade regional metamorphism) crosscut euhedral quartz crystals and are defined by inclusion trails (Fig. 21).

Techniques Fluid inclusion microthermometric measurements were made with a Chaixmeca heating/freezing stage using standard fluid inclusion techniques (Roedder, 1984). Temperature measurements were accurate to ± 0.2°C at subzero temperatures and were within 2 percent of the measurement above 100°C. A Dilor Microdil 28 laser Raman microprobe was used to identify daughter mineral phases and gaseous species in fluid inclusions.

For mass spectrometry (GC-MS), quartz samples were coarsely crushed and a 100 mg portion was taken for analysis. This portion was crushed in a mortar and pestle, sieved to 30-100 mesh, washed with water,

Figure 20. Euhedral quartz with growth zones marked by fluid inclusions, Conway (scale bar is 2 mm).

Figure 21. Growth zoned euhedral quartz cut by microfractures defined by inclusions (scale bar is 0.5 mm).

acetone, and dichloromethane, and dried at room temperature. Approximately 30-40 mg was placed in a quartz sample holder and introduced into the source of the mass spectrometer. Typically, the sample was heated up to 550°C at a rate of 0.5°C per second, and was maintained at 550°C for 15 minutes or until such time as decrepitations had stopped. During analysis, the mass spectrometer was scanning a mass range of m/z 10-300 at a rate of 1 scan per second with an electron energy of 70 eV.

Results and discussion At Conway, fluid inclusion measurements were made on 24 outcropping quartz vein samples from across the prospect, and 2 quartz and 3 calcite samples from drillcore. About 1000 heating and freezing measurements were made. A further 300 measurements on 4 outcropping quartz vein samples and 6 quartz samples from drillcore were made on samples collected from Bluegum. The raw data for individual samples and histograms for homogenisation temperatures are contained in Ewers and Hoffman (1992).

Typically, fluid inclusions in Conway material contain a liquid and vapour phase at room temperature, with the vapour phase occupying about 10 volume percent of the inclusion. The inclusion size rarely exceeds 20 microns, and useable inclusions are commonly in the 3-10 micron range.

Bodnar & others (1985) have been able to predict homogenisation temperatures for fluid inclusions hosted by quartz in epithermal environments on the basis of the shapes of inclusions and their liquid:vapour ratios. This observation holds for Conway, where fluid inclusions with consistent liquid:vapour ratios and homogenisation temperatures around 200-230°C are irregularly shaped, and appear to become smooth-surfaced and equant to negative crystal-shaped at homogenisation temperatures above about 260°C. However, there is abundant evidence in most samples for necking and/or leakage. The presence of one phase, liquid-filled inclusions is widespread and indicates that the healing of inclusions has continued to low temperatures (100°C). Groups of fluid inclusions exhibiting inconsistent liquid:vapour ratios are commonly associated with these liquid-filled inclusions and therefore are more likely to be the products of healing processes rather than the inhomogeneous entrapment of liquid- and vapour-rich phases during boiling (Bodnar & others, 1985). Definitive evidence for boiling based on fluid inclusion studies has not been observed at Conway, but continued necking after nucleation of another phase would mask such evidence.

Bodnar & others (1985) conclude that homogenisation temperatures and salinity data should not be collected from groups of apparently contemporaneous fluid inclusions with variable liquid:vapour ratios since they will be erroneous and therefore misleading. As a consequence, only isolated planes or areas within growth zones, where inclusions exhibit consistent liquid:vapour ratios have been measured.

Decrepitation mass spectrometry of fluid inclusions from Conway has indicated that they are water-dominant. Mass spectrometry and laser Raman microprobe results for surface vein quartz indicate that CO_2 is either absent (<0.1 mole percent in the Bustard Egg Hill, Split Hill, and Big Sinter Hill areas) or very low (between 0.1 and 0.2 mole percent in the Wobegong and Quartz Reef Hill areas). Trace methane and light hydrocarbons are suspected in some samples, but gases such as hydrogen sulphide and nitrogen were not detected.

The data from Conway indicate that vein and vug quartz predominantly formed in the temperature range 200-300°C, with the highest homogenisation temperatures (up to 338°C) recorded in the Red Flag Hill area (Figs. 22A-F, 23). Freezing point depressions of ice are commonly above -1°C and not below -3.7°C, corresponding to salinities which are below 1.5 wt % NaCl equivalent, and rarely approach 6 wt % NaCl equivalent (Fig. 24).

Although the fluid inclusion data do not provide unequivocal evidence of boiling conditions, boiling point-depth relations (Haas, 1971) can be applied to estimate the minimum depth of formation for outcropping quartz veins at Conway. Assuming hydrostatic pressures and allowing for up to 10% overpressuring for a liquid-dominated system, minimum pressures are in the range 16-129 bars, corresponding to minimum depths of formation between about 150-1700 m. The effect of increasing fluid salinity would be to decrease pressures (Cunningham, 1978), and increases in the CO_2 content of the fluid would increase pressures significantly (Hedenquist and Henley, 1985a); however, the data for Conway indicate that the low salinity and CO_2 levels do not warrant consideration.

Fluid inclusions in samples from Bluegum, are more complex. Regular, liquid-rich inclusions containing 10 volume percent vapour (similar to those at Conway) are dominant; they occur along growth zones and are commonly from <3 to 10 microns. Data indicate consistently higher homogenisation temperatures (Fig. 25). Rare inclusions contain up to 5 solid phases which appear to have been trapped accidentally; halite and possibly anhydrite were identified with the laser Raman microprobe.

At Bluegum, regular to irregular CO_2-rich inclusions (generally in the 5-10 micron range) with a variable vapour phase (from 10 to 75 volume percent) and <5 volume percent liquid CO_2 are also observed. The presence of CO_2 in vapour and liquid phases was recognised from direct observation, microthermometric measurements (i.e. T_h for CO_2 and $T_{m\text{-clathrate}}$), laser Raman microprobe analysis, and decrepitation mass spectrometry. Measurements of the $T_{m\text{-clathrate}}$ and homogenisation temperatures for liquid CO_2 (V) are shown in Figure 26. The average clathrate melting temperature is +9.2°C, close to the +10°C $T_{m\text{-clathrate}}$ for the CO_2-H_2O system, and homogenisation temperatures for liquid CO_2 approach the critical point for pure CO_2.

The formation of clathrate ($CO_2 \cdot 5.75\ H_2O$) in an inclusion causes a considerable increase in the apparent salinity of the residual solution (Collins, 1979; Hedenquist and Henley, 1985a); therefore, $T_{m\text{-ice}}$ measurements on these inclusions will be in error by showing an enhanced salinity because of clathration. Nevertheless, $T_{m\text{-ice}}$ measurements are a useful measure of the presence of CO_2 in an inclusion. A plot of homogenisation temperature versus salinity data illustrates this point. Apparent higher salinities in fluid inclusions from Bluegum (Fig. 27) relative to those from Conway (Fig. 28) may be a reflection of the presence of CO_2, although minor concentrations of salts other than NaCl can depress freezing point measurements significantly. For Conway (Fig. 28), there are no clear distinctions between different anomalies in the prospect area in terms of salinity. Fluid inclusions containing liquid CO_2 are rare in epithermal systems; their presence at Bluegum probably reflects a proximity to skarn mineralisation at the nearby Mt David prospect.

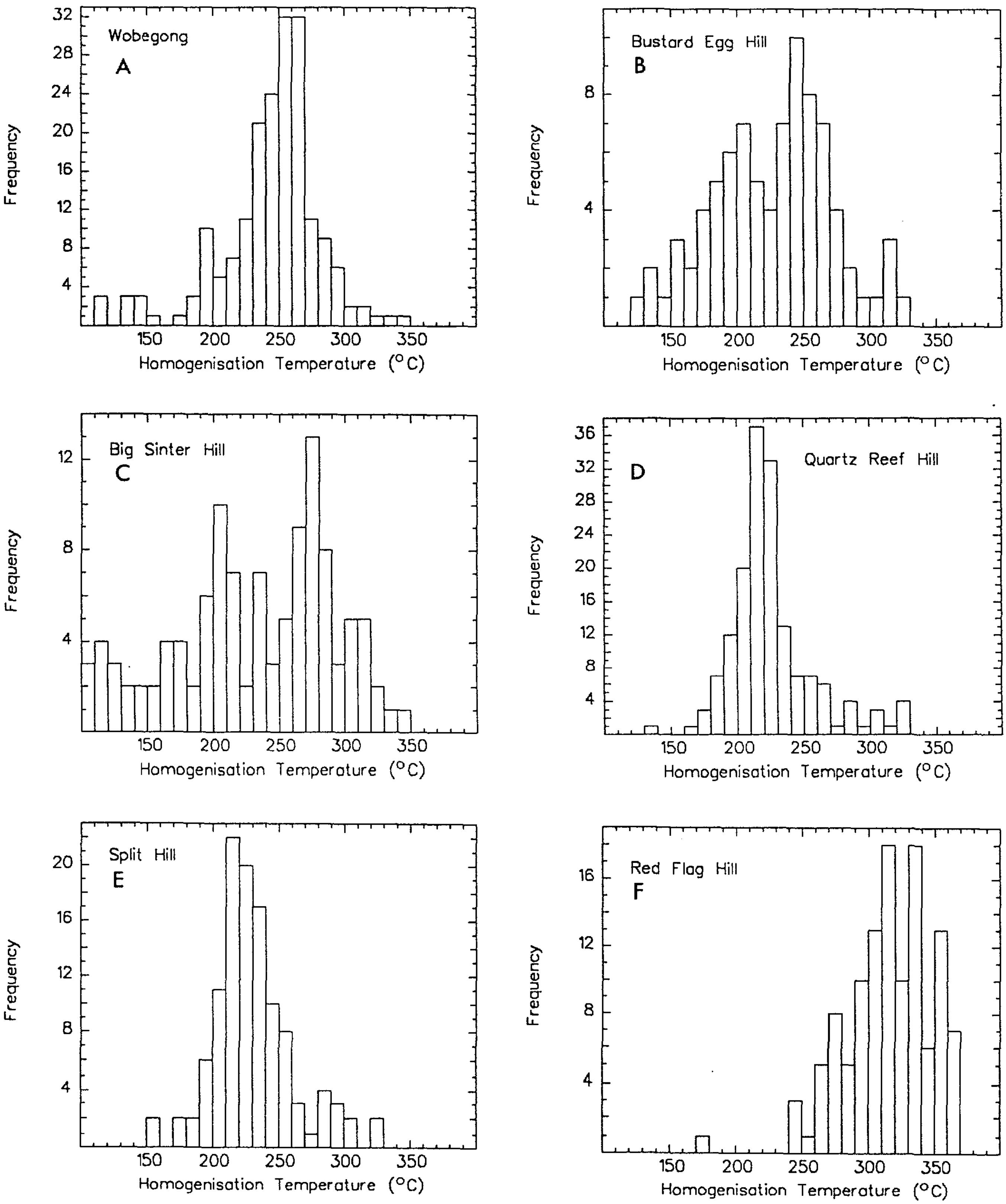

Figure 22A–F. Homogenisation temperatures (°C) for fluid inclusions in quartz veins from different areas of the Conway prospect.

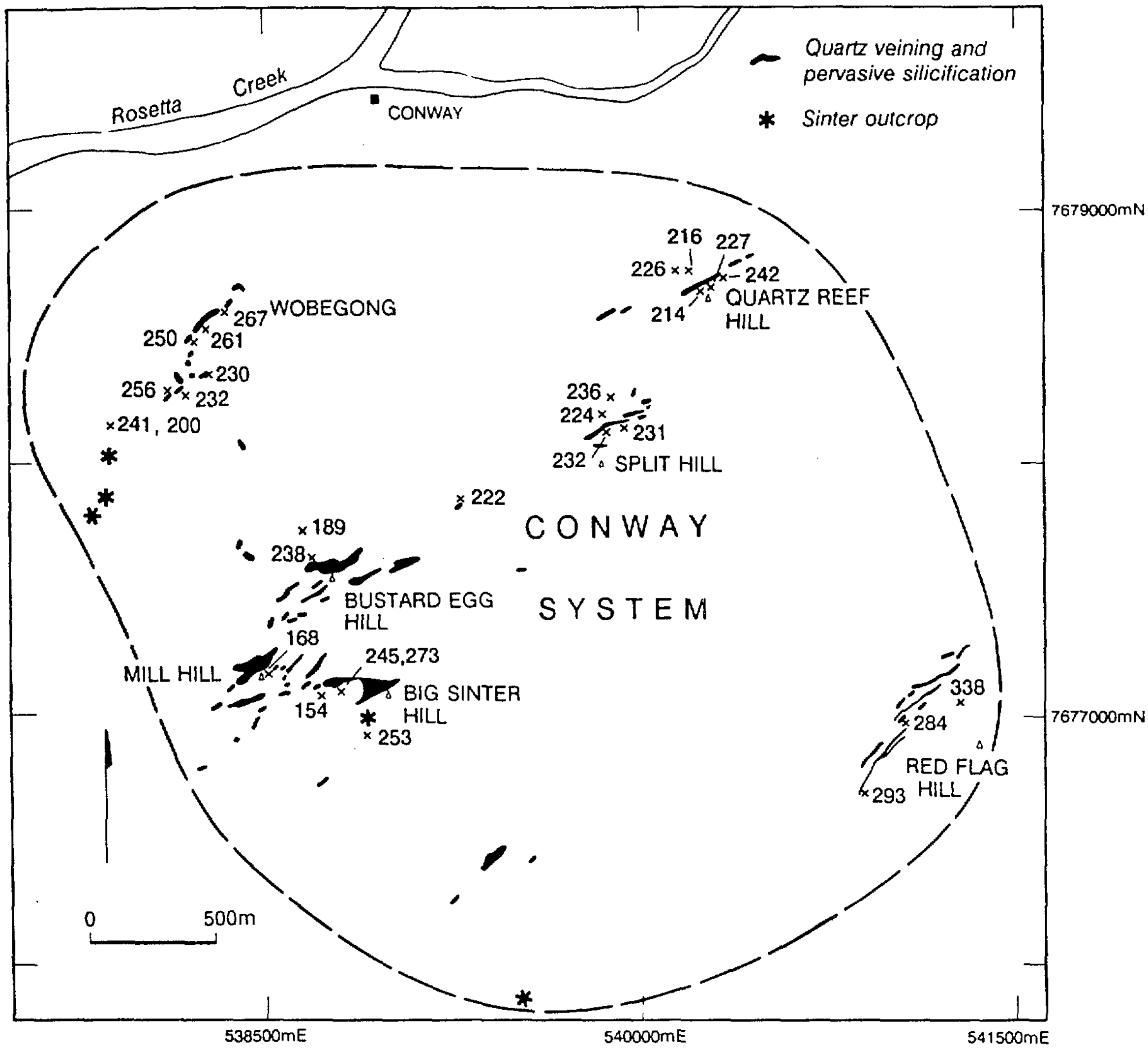

Figure 23. Mean homogenisation temperatures (°C) for fluid inclusions in quartz veins sampled from outcrop and drillcore across the Conway propect.

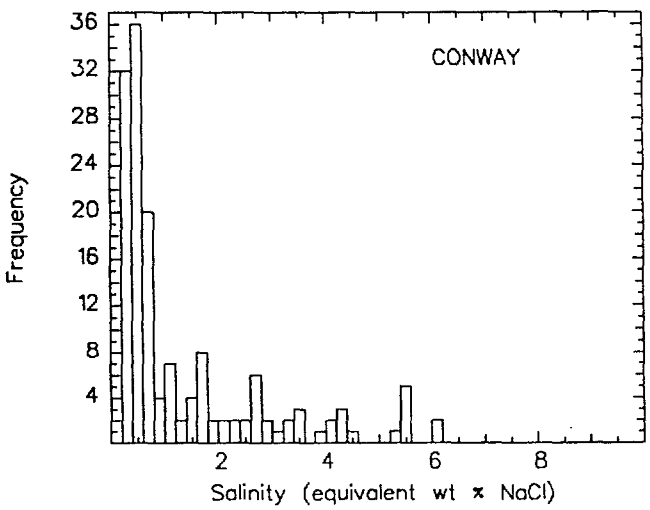

Figure 24. Salinities for fluid inclusions from the Conway prospect.

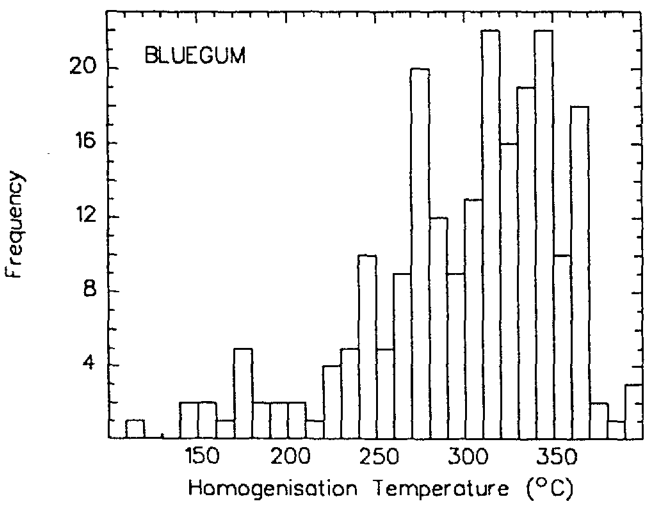

Figure 25. Homogenisation temperatures (°C) for fluid inclusions in quartz veins from the Bluegum prospect.

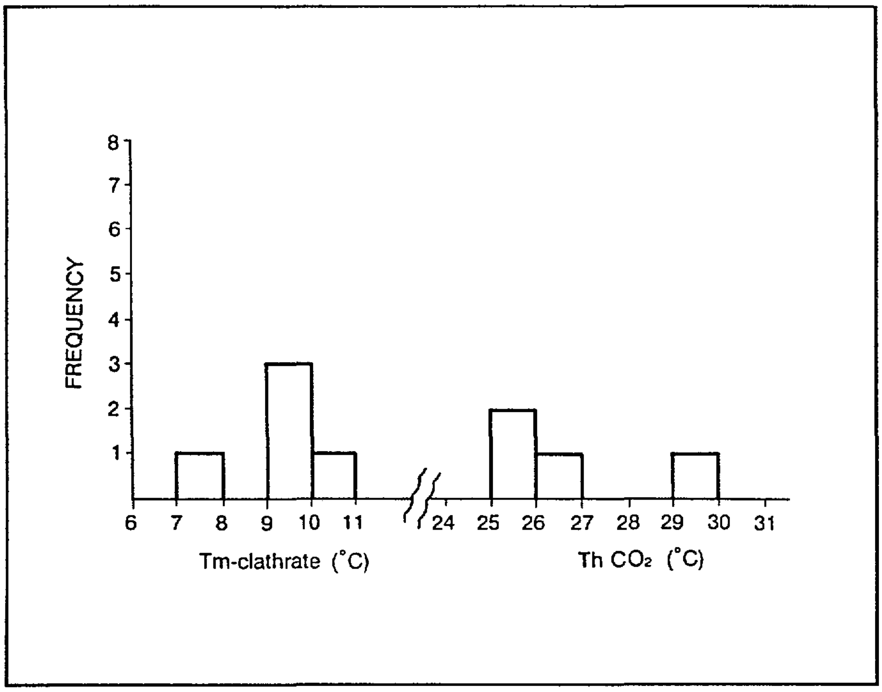

Figure 26. Microthermometric measurements (°C) of clathrate melting and the homogenisation behaviour of CO_2, Bluegum prospect.

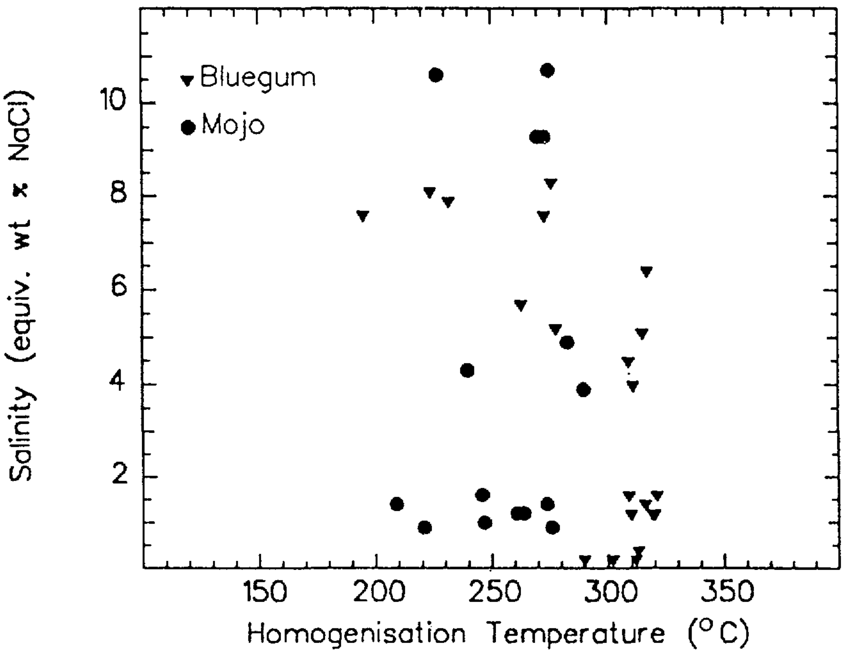

Figure 27. Salinity versus homogenisation temperatures for fluid inclusions from Bluegum.

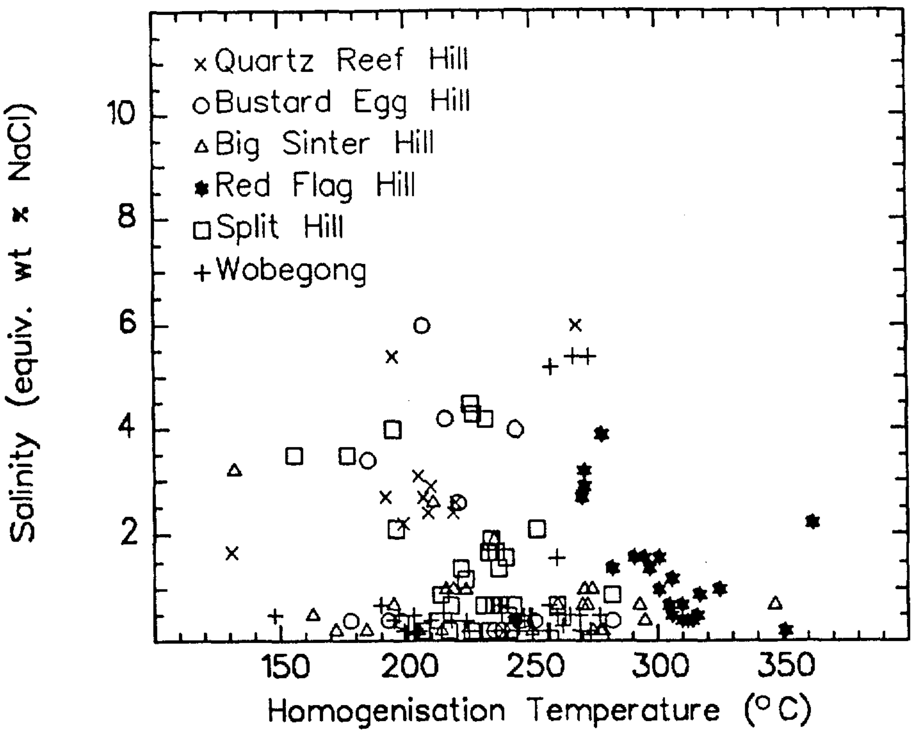

Figure 28. Salinity versus homogenisation temperatures for fluid inclusions from Conway.

Stable Isotopes

Information regarding the source of the epithermal fluids, the source of sulphur present in minor sulphide phases, and the extent of water-rock interaction can be derived from isotopic analysis of silicates, carbonates, and sulphides.

Techniques Stable isotope data (S,C,O) were obtained for sulphides and carbonates with a VG Isogas Sira 12 stable isotope analyser following standard preparation procedures (McCrea, 1950; Robinson and Kusakabe, 1975). The oxygen isotope composition of silicate mineral and whole-rock samples was measured with a Micromass 602D mass spectrometer after preparation of samples by methods outlined by Clayton and Mayeda (1963), and Taylor and Epstein (1962). $\delta^{34}S$-, $\delta^{13}C$-, and $\delta^{18}O$- values have a reproducibility of ± 0.2 per mil and are reported relative to CDT for sulphur, PDB for carbon, and SMOW for oxygen.

Results and discussion $\delta^{18}O_{SMOW}$ values for quartz veins in drillcore and outcrop samples are given in Table 8 and plotted in Figure 29. $\delta^{18}O$ values for the Conway, Bluegum, and Isabella prospects fall within the range +2.2 to + 9.4 per mil, with values for the Conway system between +2.8 and +9.4 per mil. Oxygen isotope data for known (based on field and textural criteria) and suspected siliceous sinters are presented in Table 9. $\delta^{18}O$ values for sinters described from Wobegong (Conway), and the Durah Creek and Hill 273 prospects are also plotted in Figure 29. They range from +10.9 to +14.4 per mil, and are consistently more ^{18}O-enriched than the quartz veins.

The ^{18}O composition of hydrothermal minerals formed by mineral-water exchange reactions are determined by the temperature of deposition (which controls the extent of isotopic fractionation) and by fluid compositions (which are controlled in turn by the source of the fluids, the types of host rock, and water-host rock reactions). For quartz, if the temperature of deposition and the isotopic composition are

TABLE 8 OXYGEN ISOTOPE DATA FOR QUARTZ VEINS FROM BHP PROSPECTS

AREA/Sample No.	$\delta^{18}O_{SMOW}$
Wobegong (Conway)	
8750 0014	+8.8 (2)
8750 0040	+8.7 (2)
8750 0043	+6.0 (2)
8750 0044	+3.6 (2)
8750 0045	+6.8 (2)
Bustard Egg Hill (Conway)	
8750 0101	+8.0 (2)
Big Sinter Hill - Mill Hill (Conway)	
8750 0058	+4.4 (2)
8850 0007	+2.8
8850 0023	+3.8
8850 0037	+7.2
Quartz Reef Hill (Conway)	
8750 0047	+5.0 (2)
8750 0048	+5.5
8750 0049	+5.6 (2)
8750 0050	+7.7
8750 0051	+6.5
Split Hill (Conway)	
8750 0054	+5.6 (2)
8750 0055	+5.1
Red Flag Hill (Conway)	
8750 0103	+9.0 (2)
8750 0104	+6.9 (2)
8750 0105	+9.4 (2)
Isabella prospect	
8850 0040	+3.9
8850 0044	+2.2
Bluegum prospect	
8750 0089	+4.9
8750 0090	+5.5

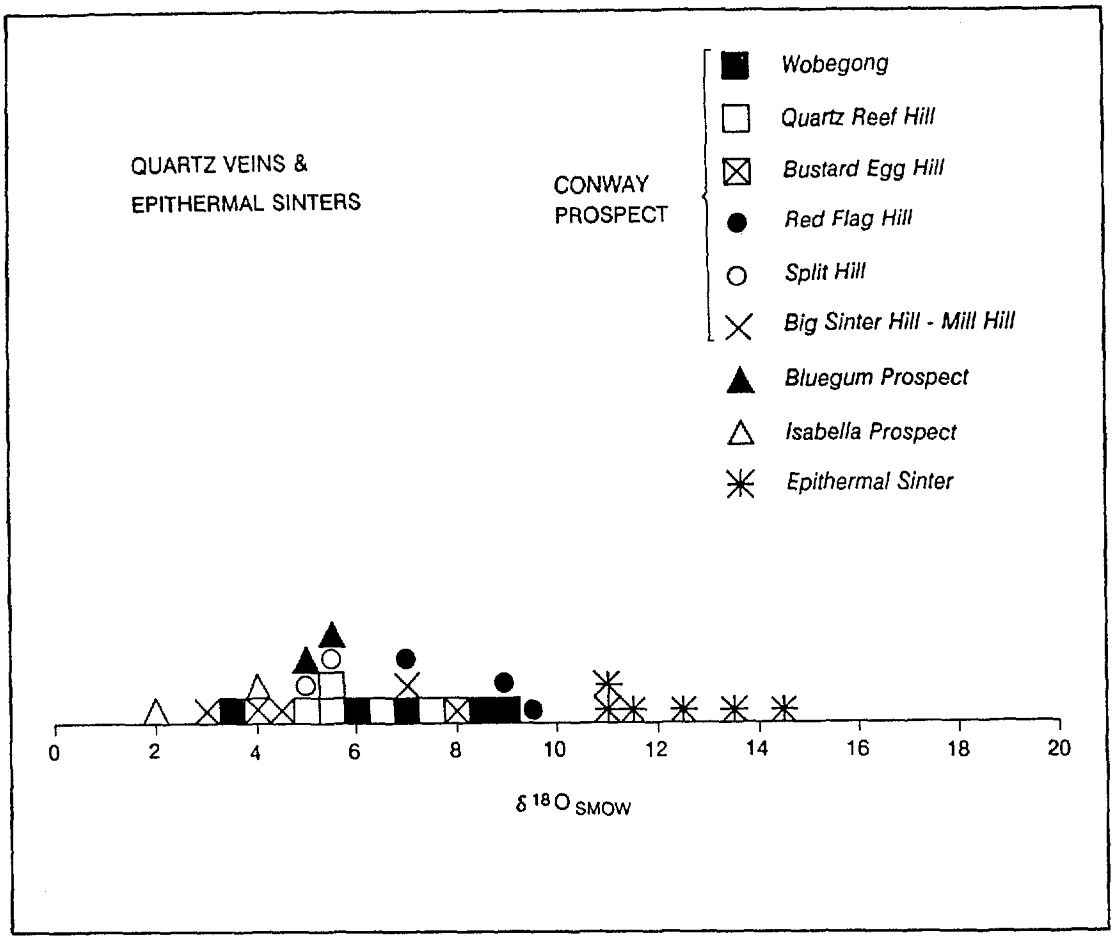

Figure 29. $\delta^{18}O_{SMOW}$ values for quartz veins and siliceous sinters from BHP prospects.

known, then changes in quartz $\delta^{18}O$ values due to temperature can be assessed. Where the range in $\delta^{18}O$ values is greater than can be explained by temperature alone, that spread will be a reflection of varying degrees of water-rock interaction. Areas of low $\delta^{18}O$ values probably mark zones of high fluid flow and therefore should represent good exploration targets; fluids passing through these zones have less opportunity to exchange with the host rocks and this will lead to the deposition of isotopically lighter quartz. If the fluids depositing quartz have exchanged significantly with the wall rocks, then that quartz will be isotopically enriched in $\delta^{18}O$.

The $\delta^{18}O$ values for quartz veins at Conway formed at temperatures of 190-340°C range from 2.8 to 9.4 per mil. Applying oxygen fractionation factors for quartz-water (Matsuhisa & others, 1979) at quartz deposition temperatures based on fluid inclusion measurements (and assuming no salinity effects), calculated $\delta^{18}O$ values are in the range +1.9 to -5.3 per mil (Fig. 30). In the Red Flag Hill area, these values are consistently higher (+1.7 ± 0.3 per mil) than those elsewhere at Conway (-3.5 ± 1.5 per mil). The results indicate a strong involvement of meteoric water, and are therefore consistent with the dominant role that meteoric fluids have in epithermal systems (Field and Fifarek, 1985). In the Red Flag Hill area, either the meteoric fluids were more exchanged with the host rocks, suggesting low water:rock ratios or they contained a significant component of ^{18}O-enriched magmatic water. The former scenario appears to be most likely, and is consistent with the tighter, pervasive silicification in the Red Flag Hill area rather than the more open fracture-related quartz veining elsewhere in the Conway system.

TABLE 9 OXYGEN ISOTOPE DATA FOR SINTERS, SUSPECTED SINTERS, AND RELATED QUARTZ VEINS

AREA/Sample No	**SAMPLE**	$\delta^{18}O_{SMOW}$	
Conway area	quartz veins	+6.3±1.9 (range +2.8 to 9.4) (20 samples)	
Wobegong (Conway)			
8750 0038	sinter	+11.2 (2)	
8750 0108	sinter	+10.9 (2)	+11.5±0.7
8750 0109	sinter	+12.5 (2)	
8850 0001	sinter	+11.5	
Big Sinter Hill - Mill Hill (Conway)			
8850 0005	sinter?	+7.3	
1300m SE of Big Sinter Hill (Conway)			
8850 0047	sinter?	+9.5	
Durah Creek			
8850 0065	sinter	+14.4 (2)	
Bimurra			
8850 0066	sinter?	+7.9	
Battery Hill			
8750 0037	silicified mudstone, sinter?	+8.5	
Hill 273			
8850 0096	sinter?	+13.6 (2)	

Clayton and Steiner (1975) reported large ^{18}O-enrichments (+22.2 and +23.6 per mil) in siliceous sinter deposited at the surface at 55-60°C from water discharged from steam wells at Wairakei in New Zealand. They noted that hydrothermal quartz deposited at depth at 250°C in the same system had a $\delta^{18}O$ value of +3.9 per mil. At the nearby Broadlands system, Blattner (1975) observed that the $\delta^{18}O$ value of vein quartz was generally in the range +3.9 to +12.3 per mil and decreased with both depth and increasing temperature. Such marked ^{18}O-enrichment for sinters relative to higher temperature vein quartz can be explained by the rapid increase in fractionation which occurs in the quartz-water system with decreasing

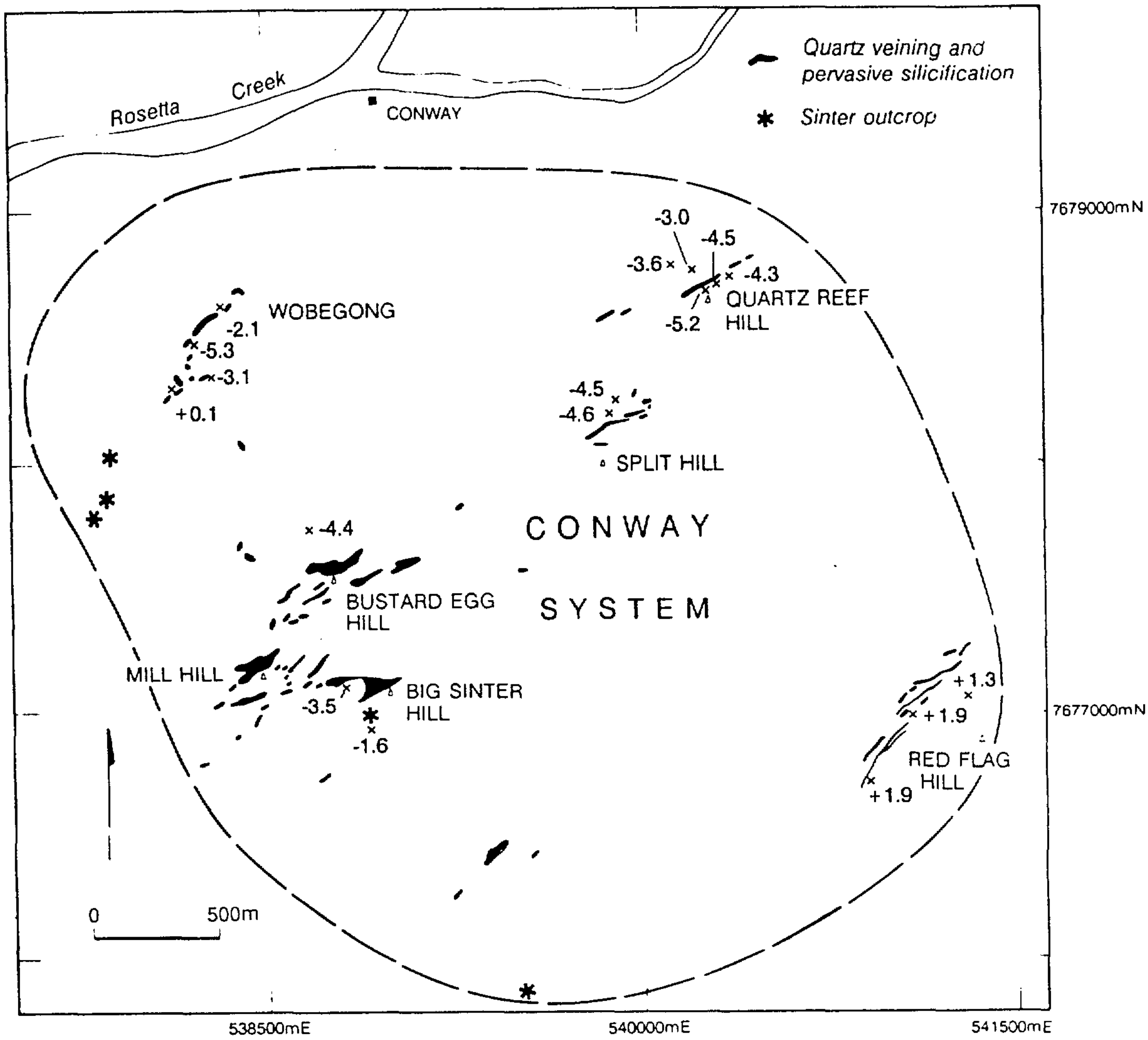

Figure 30. Calculated fluid $\delta^{18}O$ $_{SMOW}$ values from oxygen isotope compositions and fluid inclusion homogenisation temperatures for quartz.

temperature, particularly below 100°C (Friedman and O'Neil, 1977). Although temperature differences alone may account for the observed trend in vein quartz $\delta^{18}O$ values as a function of depth, other factors such as an influx of lighter meteoric water at a given depth along a permeable horizon, and zones of high fluid flow where the fluid has not significantly exchanged with the host rocks, could locally affect the isotopic composition of quartz deposited from solution.

Studies of fluid-mineral isotopic equilibria in geothermal systems by Clayton & others (1968), Blattner (1975), and Clayton and Steiner (1975) have shown that quartz is very resistant to isotopic exchange. Provided that there is no significant exchange when the amorphous opaline sinter recrystallises to chalcedonic sinter, the original isotopic signature should be preserved.

Data for the Wobegong sinters and related, high temperature vein quartz (Table 9) confirm the trends observed in modern geothermal systems; the Wobegong sinter (+11.5 ± 0.7 per mil) is consistently and significantly more ^{18}O-enriched than the nearby vein quartz (+6.3 ± 1.9 per mil). This sinter value is consistent with deposition from a fluid at 90-100°C having a value of around -9 to -8 per mil—a value indicative of a meteoric water source, and conforming with meteoric water values of -10 per mil suggested at the nearby Pajingo epithermal gold deposit, which appears to be of similar age (Etminan & others, 1988). The Durah Creek sinter described by White & others (1989), and a suspected sinter at the

TABLE 10 SULPHUR ISOTOPE DATA FOR PYRITE FROM BHP PROSPECTS

AREA/Sample No.	$\delta^{34}S_{CDT}$
Conway prospect	
8750 0068	-4.9
8750 0069	+6.2
8850 0008	+2.6
8850 0021	+2.2
8850 0030	-1.9
Isabella prospect	
8850 0041	-6.3
Bluegum prospect	
8750 0099	-6.1
8750 0100	+1.5
8850 0051	+0.4
8850 0053	-16.5
8850 0061	+7.5
8850 0069	-0.6
8850 0070	-1.1
8850 0070 (pyrrhotite)	+0.5
8850 0075	-0.8
8850 0077	-0.7
Battery Hill prospect	
8850 0082	+4.5
8850 0086	-3.2
8850 0087	-0.4

Hill 273 prospect also have high $\delta^{18}O$ values, and are therefore indicative of a low-temperature hydrothermal origin. If the $\delta^{18}O$ value of meteoric water in the area was assumed to be between -10 and -8 per mil (based on data from Pajingo and Conway), then the temperature of formation (using the fractionation data of Kawabe, 1979) for the Durah Creek and Hill 273 sinters would have been about 65-80°C and 70-85°C, respectively.

On the basis of the isotope data, suspected sinters which lack diagnostic textural features and occur at Conway (Big Sinter Hill area and about 1300 m to the southeast of Big Sinter Hill), appear to be high temperature rather than surficial, low-temperature deposits. Similarly, a suspected sinter at the Bimurra prospect, and a completely silicified, finely laminated mudstone at the Battery Hill prospect may not be genuine sinters. Applying a meteoric water $\delta^{18}O$ value of -10 to -8 per mil, each of these suspected sinters would have formation temperatures generally well in excess of 100°C (in the range 98-133°C; Kawabe, 1979); these temperatures are inconsistent with the deposition of silica from hydrothermal fluids discharged at the surface. However, it has already been suggested from the K-Ar dating that more than one hydrothermal event may have exploited existing structures at Conway. It is conceivable that suspected sinters in the Big Sinter Hill area and to the southeast of Big Sinter Hill could have been

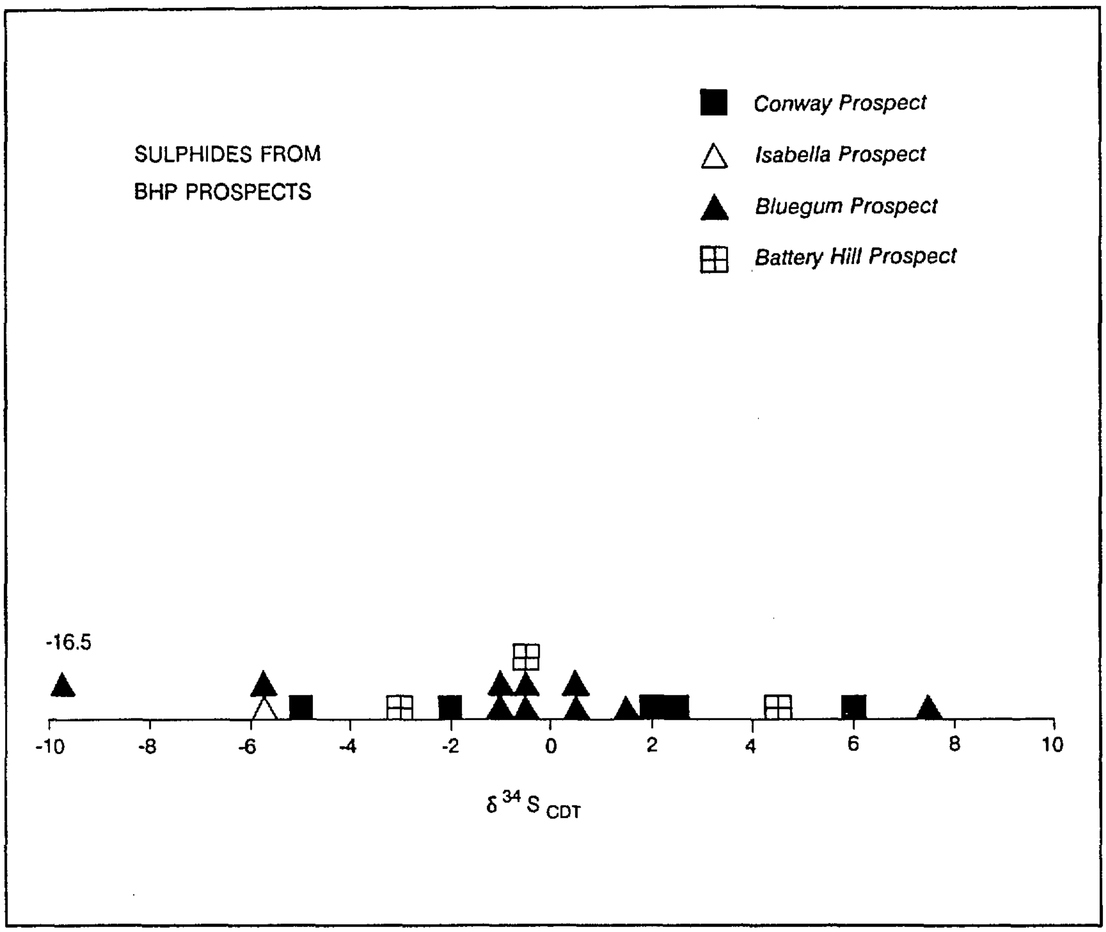

Figure 31. $\delta^{34}S_{CDT}$ values for disseminated and vein pyrite from BHP prospects.

deposited during a second hydrothermal event when the regional meteoric water value for oxygen may have been lighter (i.e. < -14 per mil).

The magnitude of ^{18}O enrichment in a sinter will be variable and difficult to gauge, since the temperature at which the sinter was deposited and the isotopic composition of the fluid involved will influence the degree of fractionation dramatically (Friedman and O'Neil, 1977). Nevertheless, the results indicate that a suspected sinter should be significantly ^{18}O enriched relative to higher temperature vein quartz.

Travertine sinters do not appear to be preserved and may not have formed in the area, but it should be noted that they also would be isotopically heavy relative to associated higher temperature calcite, since ^{18}O fractionation for the calcite-water system is in the same sense as the quartz-water system (Friedman and O'Neil, 1977). However, calcite is more susceptible than quartz to isotopic exchange with later fluids and therefore the isotopic recognition of travertine sinters would be more difficult.

Recognition of an ancient sinter has important exploration implications (Ewers, 1989). Sinters provide tangible evidence of a palaeosurface associated with an extinct geothermal system and indicate the possible presence of an economic epithermal gold deposit beneath and possibly adjacent to the sinter. Failure to recognise them or the incorrect interpretation of a siliceous rock as a sinter could lead to false assumptions in assessing an epithermal prospect, and perhaps to a misdirected exploration program. Some or all of the characteristic features of modem sinters may either be absent or simply not preserved in ancient sinters. The results of this work indicate that the application of oxygen isotopes provides a useful additonal tool for identifying low-temperature sinter deposits in ancient terranes, particularly where field and textural relationships are either lacking or equivocal.

$\delta^{34}S_{CDT}$ values for disseminated and vein pyrite from four BHP prospects are given in Table 10 and illustrated in Figure 31. The data cluster about the 0 per mil value for magmatic sulphur, but exhibit a

TABLE 11 OXYGEN AND CARBON ISOTOPE DATA FOR CALCITE SAMPLES FROM BHP PROSPECTS

AREA/Sample No.	$\delta^{13}C_{PDB}$	$\delta^{18}O_{SMOW}$
Wobegong (Conway)		
8750 0001	-3.7	+7.8
8750 0007	-3.0	+9.3
8750 0008	-4.7	+5.0
8750 0009	-5.4	+5.6
8750 0010	-5.8	+7.2
8750 0011	-6.4	+9.5
8750 0012	-6.9	+9.6
8750 0013	-5.5	+4.4
8750 0014	-4.5	+7.9
8750 0030	-4.9	+4.8
8750 0031	-5.4	+5.0
8750 0032	-4.0	+6.8
8750 0033	-6.1	+4.9
8750 0034	-4.7	+5.5
Bustard Egg Hill (Conway)		
8750 0061	-2.8 (2)	+10.8 (2)
8750 0070	-4.4	+6.0
8750 0074	-3.9	+6.8
Big Sinter Hill - Mill Hill (Conway)		
8850 0024	-3.8	+4.4
8850 0028	-4.2	+3.3
8850 0031	-4.6	+3.7
8850 0032	-5.3	+3.5
8850 0034	-7.5	+11.2
8850 0036	-4.8	+4.9
Bluegum prospect		
8750 0094	-12.5 (2)	+13.6 (2)
8750 0095	-7.8	+2.5
8750 0096	-6.9 (2)	-1.8 (2)
8750 0099	-13.9	+7.7
8850 0072	-7.0	-1.8
8850 0073	-6.1	-3.2
8850 0076	-7.3	-2.0
Durah Creek area		
8750 0106	-6.6	+7.5
Mt David skarn prospect		
8850 0017	-2.9	+2.9
8850 0018	-1.1	+5.1
8850 0019	-2.9	+3.4

range (-16.5 to +7.5 per mil) similar to that found for volcanic-hosted epithermal gold deposits (Field and Fifarek, 1985). This variability could reflect an inhomogeneous or mixed sulphur source, and would result also from ^{34}S fractionation caused by near surface oxidation of hypogene fluids giving rise to more ^{34}S-depleted pyrite. There are no clear distinctions between the prospects, but this may be a function of insufficient data.

The isotopic results for calcite (Table 11) were obtained principally on drillcore samples from the Conway and Bluegum prospects. Some further data were collected from diagenetic nodular calcite in a flow-banded rhyolite from the Durah Creek area, and limestone outcrop at the Mount David Pb-Zn skarn

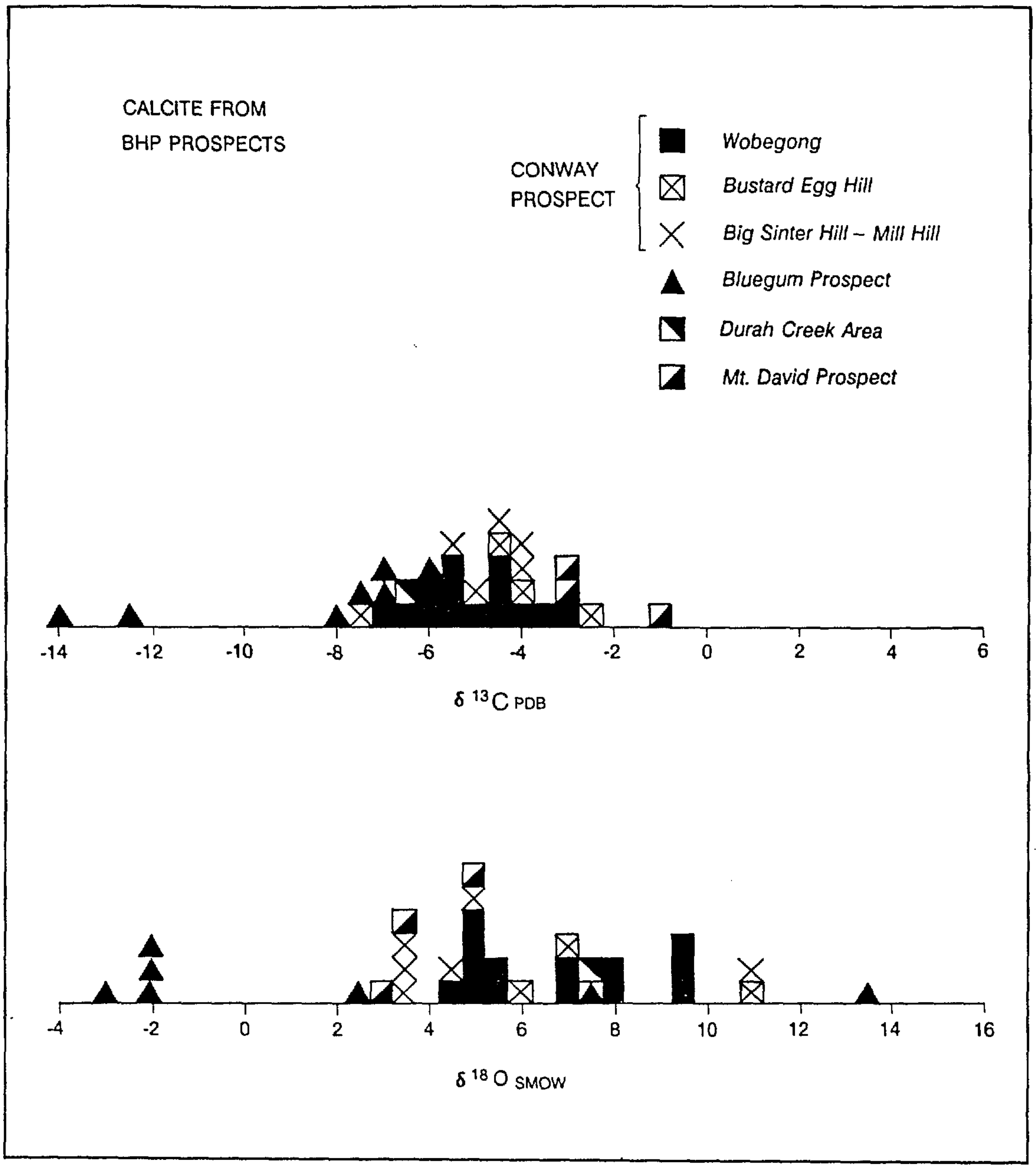

Figure 32. $\delta^{13}C_{PDB}$ and $\delta^{18}O_{SMOW}$ values for calcite from BHP.

prospect about 2 km south of Bluegum. Both the oxygen (-3.2 to +13.6 per mil) and carbon (-3.9 to -1.1 per mil) isotope variations (Fig. 32) are within the range of values commonly expected for carbonates in epithermal systems (Field and Fifarek, 1985). Carbon isotope variations can be influenced by an inhomogeneous source and/or differing proportions of compositionally distinct carbon in the samples. They are also controlled by carbon-bearing species in solution (e.g. H_2CO_3, HCO_3^-, etc), and boiling is capable of producing an increase in $\delta^{13}C$ values for precipitating calcite (up to 2 to 3 per mil) due to increasing pH of the fluid (Matsuhisa, 1986). The very negative $\delta^{13}C$ values for some Bluegum samples may reflect the presence of organic material, although laser Raman studies provide no evidence of hydrocarbons in fluid inclusions, and organic-rich sediments are not known in the area.

Oxygen isotope data for late calcite veins (which generally post-date pervasive silicification and quartz veining and formed during the thermal decline of the hydrothermal system) can be used in conjunction with fluid inclusion measurements on calcite from similar sampling intervals to calculate the isotopic composition of the fluids depositing calcite. For temperatures around 200°-250°C, these fluids varied

TABLE 12 OXYGEN AND HYDROGEN ISOTOPE DATA FOR SERICITE FROM BHP PROSPECTS

AREA/Sample No.	$\delta^{18}O_{SMOW}$	δD
Conway		
8750 0005	+4.2 (2)	-98
8750 0026	+3.4 (2)	-88
8750 0065	+3.4 (2)	-84
8750 0067	+3.1 (2)	--
8750 0071	+2.5 (2)	-90
8850 0016	+0.2	-107
8850 0035	-1.1	-101
Bimurra		
8850 0080	+3.6 (2)	-77
Bluegum		
8850 0054	-3.7	-134
8850 0062	+0.1	-134

between about +4 and -5 per mil. These values suggest that, in the waning stages of hydrothermal activity, the system was not overwhelmed by fluids that were isotopically light. Rather, they appear to indicate that the isotopic composition of the fluids was largely determined by the host rocks and that water:rock ratios were generally low.

Sericite samples suitable for K-Ar dating were also analysed for their δD and $\delta^{18}O$ composition (Table 12). These data can be used to assess the isotopic composition of the epithermal fluids using an estimated temperature for mineral deposition and the fractionation curves published for the muscovite-water pair (Friedman and O'Neil, 1977). Because sericite alteration and quartz veining are temporally related, fluid inclusion data from quartz veins were used to constrain depositional temperatures for sericite; these were set at 230°-300°C for Conway, 250°-330°C for Bluegum, and arbitrarily set at 250°-300°C for Bimurra, where data are lacking. The results have been plotted in Figure 33, and indicate similar trends to those observed in other epithermal deposits. The fluids were dominantly (possibly exclusively) meteoric and experienced an ^{18}O-shift to the right of the meteoric water line because of exchange reactions involving their more ^{18}O-enriched host rocks. Commonly, δD values are not significantly affected by water:rock exchange because the fluid is the principal source of hydrogen and therefore predominates. However, data for Conway and possibly Bluegum suggest that there was some enrichment in deuterium; this trend may be caused by the evaporation of surface waters prior to recharge as at the Salton Sea (Craig, 1966) and by boiling of subsurface waters as at Yellowstone (Truesdell & others, 1978). The results plotted in Figure 33 also suggest that fluids involved at Bluegum were isotopically lighter than those responsible for Conway and possibly Bimurra. Such differences are normally a function of variations in altitude and/or latitude. If Bluegum is younger than Conway as K-Ar dating would suggest, then the dramatic trend to

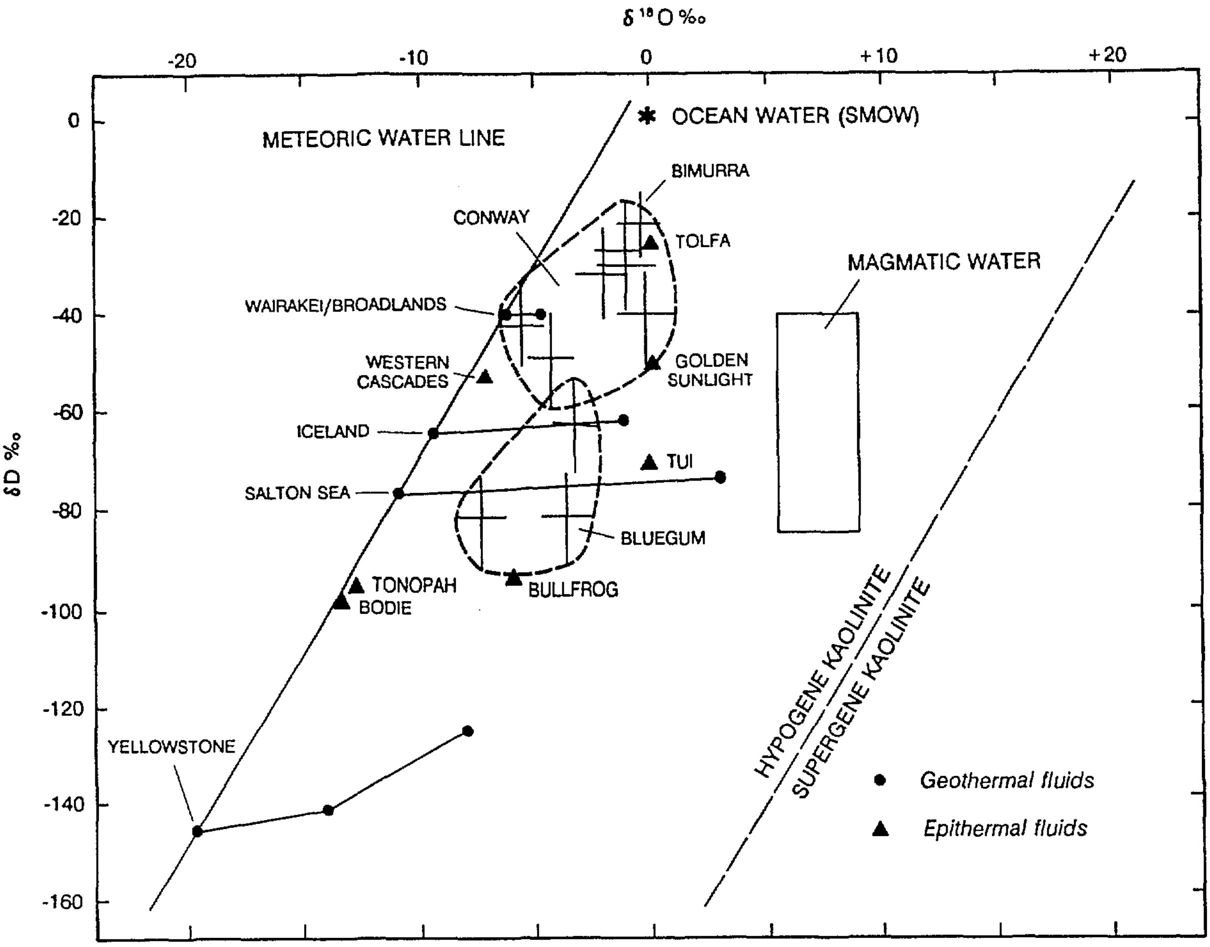

Figure 33. Calculated δD and $\delta^{18}O_{SMOW}$ for epithermal fluids at Bluegum, Conway, and Bimurra in relation to geothermal fluids and fluids involved in epithermal deposits (modifed from Field and Fifarek, 1985).

higher latitudes during the Late Palaeozoic (e.g. according to Veevers (1984) the palaeolatitude from 370 Ma to 240 Ma changed from 28°S to 80°S) could easily account for any shift to lighter δD and $\delta^{18}O$ values.

Water:rock ratios It has been recognised widely that in epithermal systems, altered host rocks, regardless of igneous or sedimentary parentage, are variably depleted relative to their unaltered counterparts because of the interaction between ^{18}O-depleted meteoric water and more ^{18}O-enriched host rocks (e.g. Clayton & others, 1968; Taylor, 1973; Rye & others, 1974; Blattner, 1975; Radke & others, 1980; and Porter and Ripley, 1985). Whole-rock oxygen isotope data for the Conway prospect (Table 13) indicate a marginal depletion in the $\delta^{18}O$ values relative to those normally attributed to igneous whole-rock samples (i.e. +5 to +12 per mil; Taylor, 1974a). The extent of this depletion is difficult to gauge, since equivalent, unaltered rocks do not outcrop and have not been intersected by drilling adjacent to the Conway prospect.

Taylor (1971; 1973; 1977) has shown that if an initial whole-rock oxygen isotope value of +6.5 per mil is assumed, then for a given $\delta^{18}O$ initial value for the meteoric water involved, the effects of varying temperatures and water:rock ratios on the $\delta^{18}O$ of hydrothermally altered igneous rocks can be gauged. Details of the calculation have been given in Taylor (1971), and are based on a simple closed-system model, assuming that $\delta^{18}O_{rock}$ and $\delta^{18}O_{plagioclase}$ are essentially identical at equilibrium, thereby allowing the feldspar-water fractionation of O'Neil and Taylor (1967) to be used (i.e. $\Delta \cong 2.68(10^6/T^2) - 3.53$).

TABLE 13 WHOLE-ROCK OXYGEN ISOTOPE DATA FOR SAMPLES FROM THE CONWAY PROSPECT

AREA/Sample No.	$\delta^{18}O_{SMOW}$
Wobegong	
8750 0006	+5.7
8750 0015	+4.2
8750 0022	+5.0
8750 0027	+4.4
Bustard Egg Hill	
8750 0068	+4.4
8750 0075	+3.1
Red Flag Hill	
8850 0011	+4.0 (2)
8850 0012	+4.9

The results of these calculations are shown in Figure 34 for meteoric water with assumed initial $\delta^{18}O$ values of -4, -10, and -16 per mil and temperatures between 200 and 400°C for each case. Recent studies at the Pajingo deposit (Etminan & others, 1988) and the Conway prospect (Ewers, 1991) in the northern Drummond Basin have suggested that the regional meteoric water value at around 330 Ma was about -10 per mil. Because the palaeolatitude for this region is known to have been highly variable during the Palaeozoic and latitude is known to have a significant effect on meteoric water isotopic values (Taylor, 1974a), a 6 per mil variation either side of the selected -10 per mil regional meteoric water $\delta^{18}O$ value has been illustrated. For Conway, Figure 34 indicates that for measured fluid inclusion temperatures of 200-300°C and an assumed initial $\delta^{18}O$ whole-rock value of 6.5 per mil, water:rock ratios of between about 0.2 and 0.3 would have been capable of producing the whole-rock oxygen isotope values reported in Table 13. If the initial $\delta^{18}O$ whole-rock value is assumed to be higher (e.g. 8 per mil), water:rock ratios would increase marginally at any given temperature and initial meteoric water $\delta^{18}O$ value. However, heavier initial meteoric water $\delta^{18}O$ values (e.g. -4 per mil) would result in much higher water:rock ratios which become unrealistically large at temperatures around 200°C.

Open-system behaviour, in which each increment of fluid makes only a single pass, results in a lower estimate of the water:rock ratio at a given temperature than for closed-system conditions (Taylor, 1977). It should be noted that the calculated water:rock ratios represent minimum values whether closed or open system behaviour is assumed, since the fluid flow would have been largely fracture-controlled leading to incomplete equilibration.

Reconstruction of the Conway Prospect

An analysis of data for Conway suggests that it was tilted to the west and eroded at some stage subsequent to formation exposing a slice through the system. The recognition of a telescoped sequence of siliceous

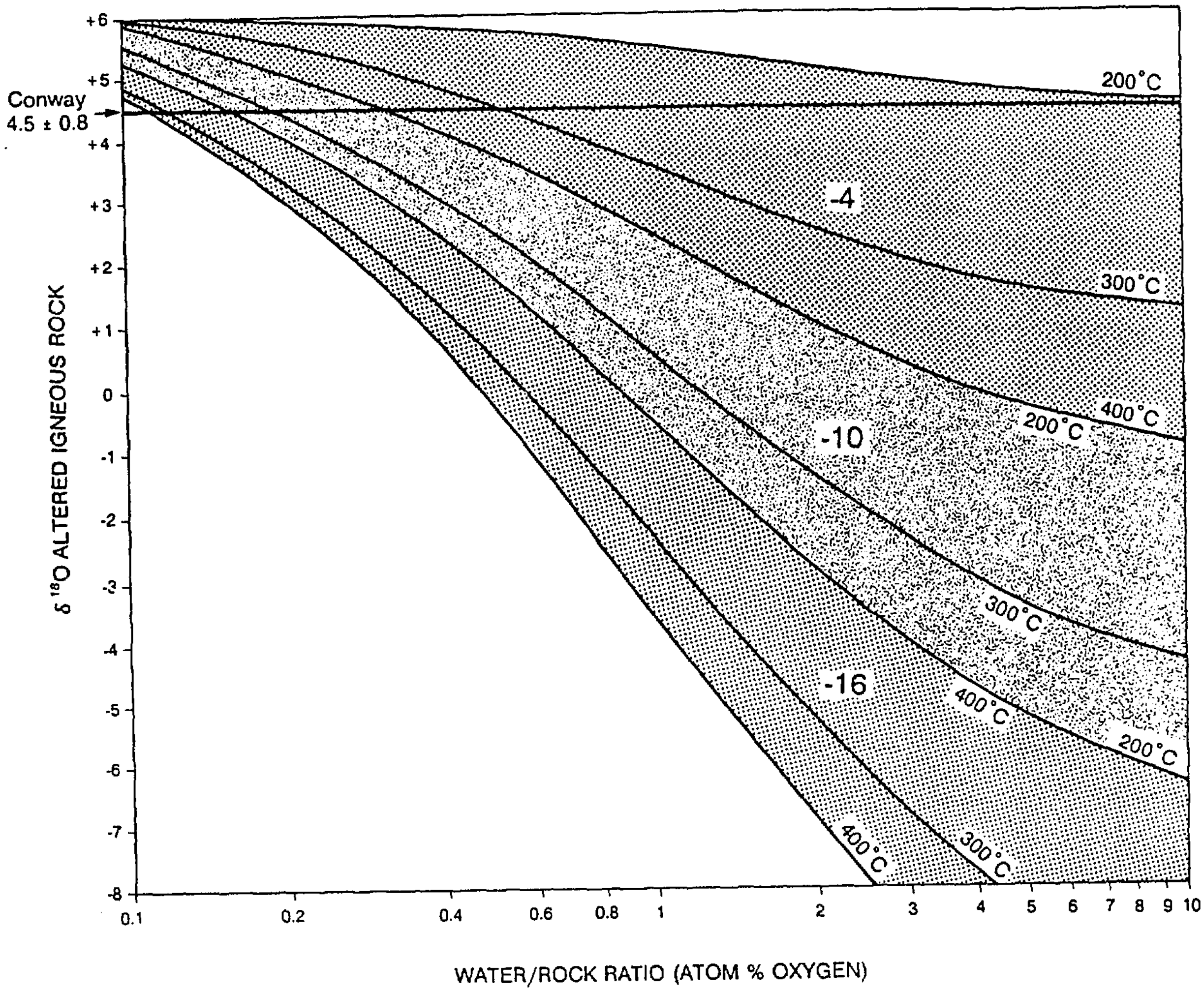

Figure 34. $\delta^{18}O$ **variation at Conway as a function of water:rock ratio, assuming an initial** $\delta^{18}O$ **whole-rock value of +6.5 per mil for a range of initial meteoric water** $\delta^{18}O$ **values (-4, -10, -16 per mil) and temperatures of 200°C, 300°C, and 400°C (see text for details).**

sinters, which dip up to 25° to the southwest, are concordant with interlayered volcaniclastic rocks, and occur up to 600 m to the southwest of the Wobegong anomaly, indicates an original palaeosurface. Fluid inclusion data (Fig. 23) suggest that the Red Flag Hill area was the hottest part of the system with temperatures around 300°C, and that temperatures declined to the north and west at higher elevation in the geothermal system. An I.P. survey over Conway has outlined a large discrete resistivity anomaly to the south and southeast of Big Sinter Hill; this anomaly is thought to be a zone of intense silicification and may have been an upflow zone within the hydrothermal system. Calculated $\delta^{18}O$ values for fluids which deposited quartz (Fig. 30) indicate that meteoric water was the dominant fluid source. Low water:rock ratios and consistently higher fluid $\delta^{18}O$ values at Red Flag Hill relative to other parts of the system, suggest greater isotopic exchange occurred with the host rocks in that area under restricted fluid flow conditions.

The alteration at Conway conforms broadly to these observations and the measured fluid inclusion temperatures. Silicification and sericitic alteration are the dominant style of alteration and are consistent with depositional temperatures from 220°-300°C. Chalcedony was developed locally and is indicative of depositional temperatures below about 190°C. Pyrophyllite, which has been identified in outcrop at Wobegong and is thought to occur in several drillholes, will deposit from fluids between ambient

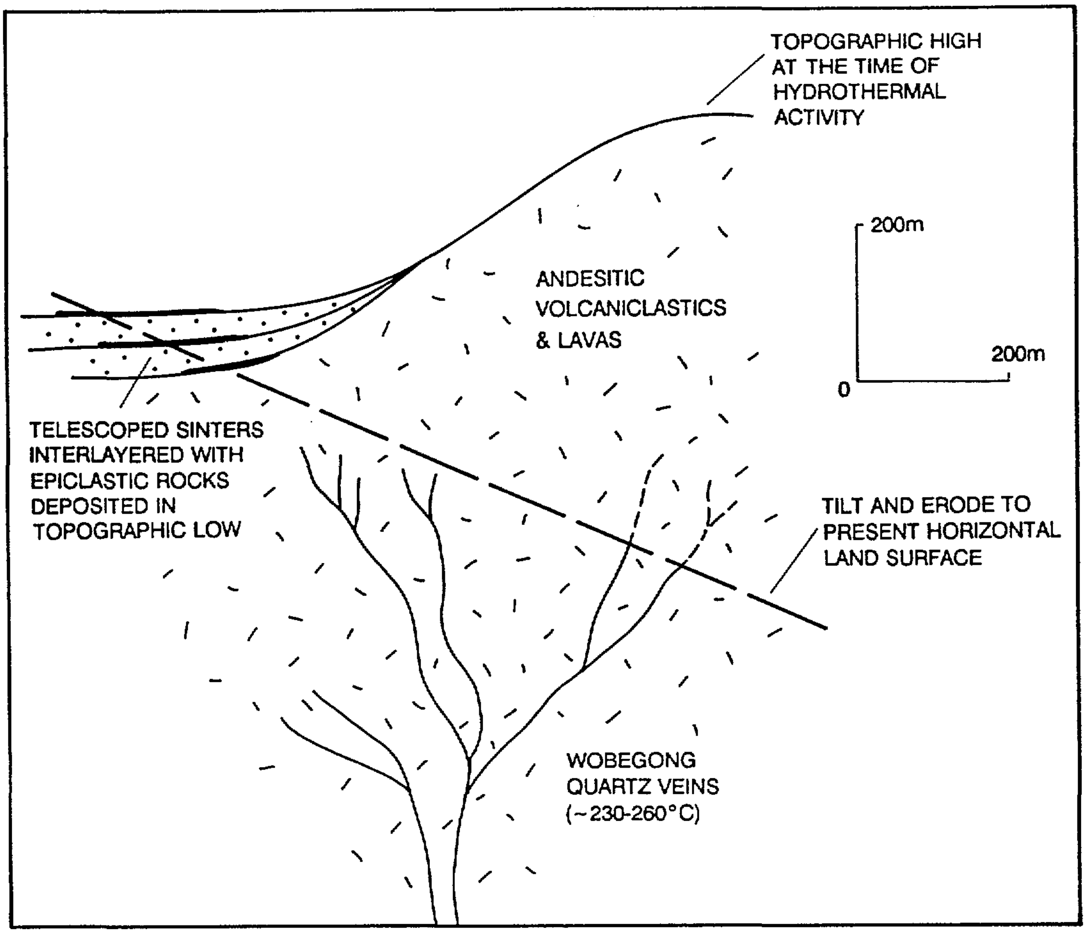

Figure 35. Single system reconstruction of the Conway prospect.

temperatures and about 260°C depending on whether the fluids were saturated or supersaturated with respect to silica (White and Hedenquist, 1990). Zeolites (mainly laumontite and analcime) are late in the paragenesis and are typically deposited from fluids with a low CO_2 content at temperatures below 200°C. Kaolinite and alunite are minor phases; they may be the residual evidence of a weakly developed acid cap formed during the waning stages of hydrothermal activity and/or the products of recent weathering. Similarly, mixed-layer clays may have formed during weathering rather than the waning stages of hydrothermal activity. Since the overwhelming majority of the world's epithermal deposits are relatively young, the effects of diagenesis and deep weathering on hydrothermal mineral assemblages developed in a system as old as Conway are difficult to assess (for example, the Tertiary Suttor Formation at one time covered the Conway prospect).

Boiling is known to be a particularly effective mechanism for causing gold deposition, but is seldom easy to demonstrate. Although there is evidence that boiling occurred at Conway, it appears to have been localised rather than widespread. Hydraulic fracturing of the host rocks at low pressures must have involved boiling. Lattice textures, resulting from the silica replacement of bladed calcite, and adularia are indicative of boiling, but are rarely seen in the vein mineralogy at Conway. Secondary K-feldspar alteration does occur in the wall rocks, but this may have resulted from fluid/wall rock reactions at high K^+/H^+ ratios (Hemley and Jones, 1964) rather than boiling. Fluid inclusion data do not confirm that boiling occurred, but it should be added that widespread necking after nucleation of many inclusions at Conway would tend to mask such evidence. In contrast to Conway, the Bimurra prospect has a large amount of lattice texture developed within it, suggesting that the system was both CO_2-rich and boiling.

Low CO_2 contents for fluids involved at Conway could be unfavorable in generating a significant epithermal gold deposit. Hedenquist and Henley (1985b) have suggested that relatively high gas contents in geothermal systems are important to the formation of epithermal deposits for two reasons. Firstly, the CO_2/H_2S molal ratio in active systems is about 10-100 and a high CO_2 content implies a high H_2S content in the fluid. Since gold is transported in solution predominantly as a bisulphide complex (Seward, 1973), elevated H_2S concentrations in the fluid are essential for gold transport. Secondly, high CO_2 contents promote gas accumulations which could induce hydrothermal eruptions and the formation of highly fractured vents. These vents are important because they provide fluid flow paths along which deposition may occur in response to changes in the fluid (e.g. boiling).

Two possible reconstructions for Conway based on these observations and extending from the time of hydrothermal activity to the present erosional level of the system are outlined in Figure 35 (single system) and Figure 36 (two overprinting systems). For a single system, marked topographic relief when the geothermal system was active could have lead to the deposition of a series of telescoped sinters in valley floors (Fig. 35). Subsequent tilting of the original land surface to the west and uplift in the east followed by erosion could account for the present day relationships observed between the Wobegong sinters, quartz veins and the more deeply eroded quartz veins to the east in the Red Flag Hill area. Alternatively, two (or more) hydrothermal systems may have exploited reactivated structures within the Conway prospect (Fig. 36). The original hydrothermal system may have been eroded (Fig. 36A) and overprinted by a second later system (Fig. 36B). Tilting to the west and further erosion of both systems (Fig. 36C) would lead to the relationships now seen in the local geology at Conway (Fig. 4).

These two reconstructions indicate how the Conway system may have developed, though variations on these themes and further reconstructions may well be possible. For example, the presence of suspected siliceous sinter deposits (based on field observations) in the Big Sinter Hill area, immediately adjacent to high temperature quartz veins formed at about 250°C (Fig. 23) requires explanation, since sinters are surficial deposits and veins formed at 250°C would require at least 450 m of cover. Clearly they could not have formed simultaneously at the same stratigraphic level. The sinters and quartz veins in that area could be parts of different systems separated in time, similar to the scenario presented in Figure 36. This may explain the spread in K-Ar ages of sericitic alteration at Conway, which could result from Ar loss during a later hydrothermal event and is consistent with the suggestion that different igneous events have given rise to prospects of different ages throughout the region. The bimodal distribution of fluid inclusion populations in the Bustard Egg Hill and Big Sinter Hill areas (Figures 22B and 22C) could suggest two distinct hydrothermal events, although the data could equally be explained as two thermal peaks within the same hydrothermal event. The distinction between two overprinted epithermal systems is likely to be difficult to resolve since they will each demonstrate similar alteration and fluid characteristics. A variation on the single system reconstruction (Fig. 35) is that the high temperature veins and sinters were indeed part of the same geothermal system that was active over a long period and was eroded during that time. Rocks in the Conway area are predominantly andesitic to trachytic and, like most andesitic volcanic terranes, there could have been considerable topographic relief initially which could have resulted in significant and rapid erosion. In these circumstances, the early-formed quartz veins may have been deeply eroded and juxtaposed with later sinters within the lifetime of the same hydrothermal system.

REGIONAL OXYGEN ISOTOPES

The compilation by Taylor (1974a) of oxygen isotope data for unaltered primary igneous rocks has shown that they have a typically narrow range between about +5 and +12 per mil relative to SMOW, although more recent data suggest that the upper limit may be as high as +14 per mil (Sheppard, 1986). These data provide a reference against which the effects of processes that drastically alter the $\delta^{18}O$ values of igneous rocks can be assessed.

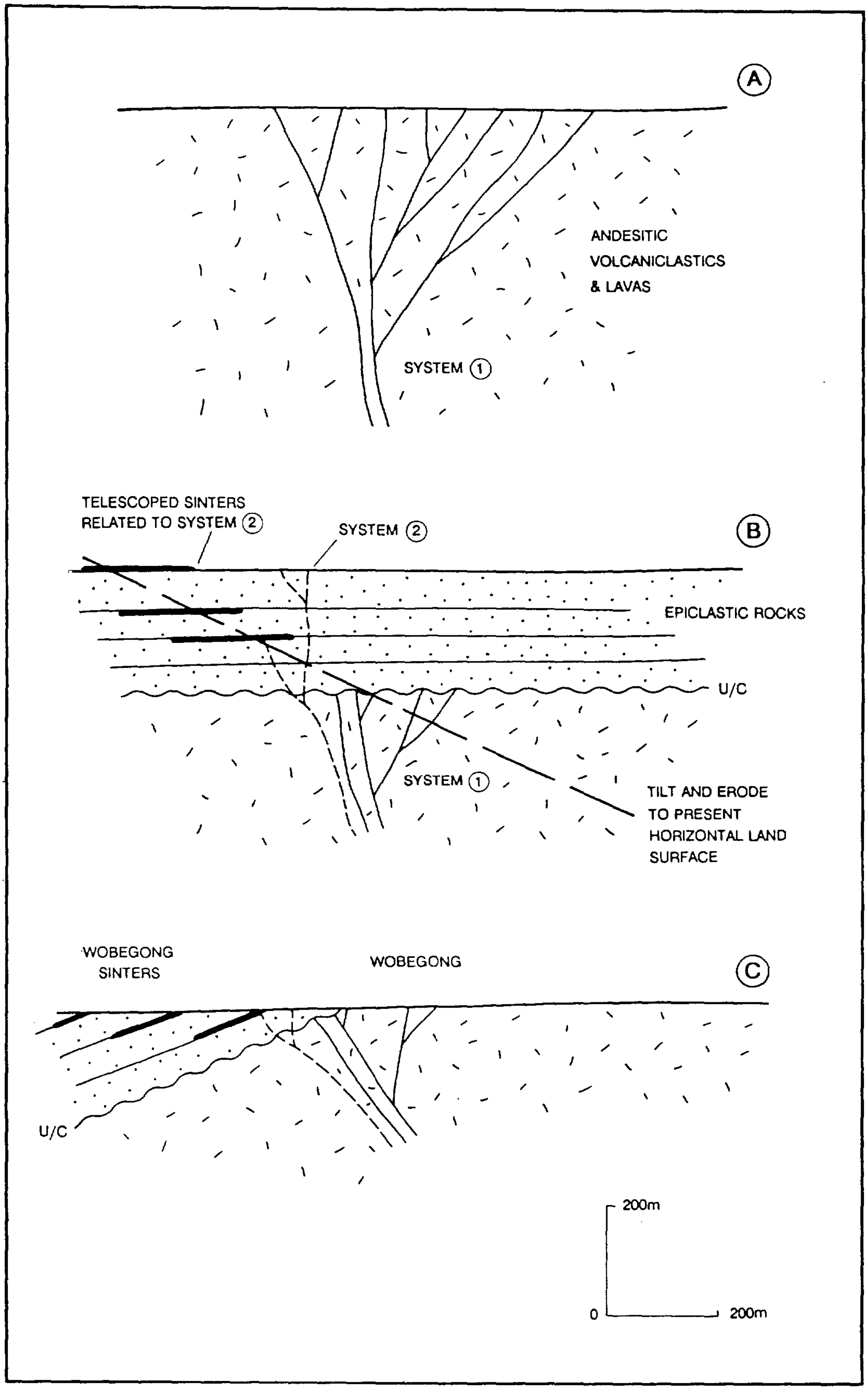

Figure 36. Multiple system reconstruction of the Conway prospect.

As mentioned, whole-rock oxygen isotope data for samples for Conway are slightly depleted relative to normal igneous rock values (Table 13). Because unaltered equivalents of these rocks are neither seen in outcrop nor intersected in drilling outside and immediately adjacent to the Conway prospect, the extent of this depletion was difficult to gauge. Therefore, a suite of regional samples covering both intrusive and extrusive rocks thought to be well removed from epithermal systems were analysed in the expectation that they would exhibit the normal range of igneous values.

The samples were selected to provide a cross section of lithologies and units of differing age from the northern Drummond Basin and overlying volcanic units, and also included intrusive rocks from the region. The material chosen was as fresh as surface outcrop would permit, given that low temperature processes will tend to enrich oxidised and weathered samples in $\delta^{18}O$. Sampling of the volcanic units beyond the area mapped in this study is severely restricted: areas to the north and east are intruded by Early to Late Palaeozoic granitoids, and to the west and south the combined effects of Mesozoic to Cainozoic cover rocks and very poor outcrop limit further collection of material.

Data for 24 volcanic rocks have a wide range of values from -8.2 to +10.4 per mil with a mean value of 0.7 ± 4.9 per mil (Table 14). Sixteen intrusive rocks (which include granites through to gabbros) have a narrower range in isotopic composition (+1.3 to +8.8 per mil with a mean value of 5.8 ± 2.3 per mil); the majority correspond to typical whole rock igneous values, though some show clear evidence of depletion (Table 15).

There are insufficient data to provide a proper analysis for individual rock units; however, the results indicate that isotopically depleted samples occur within both the Bulgonunna Volcanic Group and the base of the Drummond Basin sequence (Fig. 37A). Pyroclastic rocks and lavas are equally depleted, but both are more depleted in general than the intrusive rocks (Figs. 37B and 37C). The distinction between normal and depleted $\delta^{18}O$ values in relation to a simplified geology of the northern Drummond Basin is shown in Figure 38. Although some intrusive rocks within this region are abnormally low, the majority have near normal values. Given the low sample density, the extent of the ^{18}O-depleted area is necessarily approximate; however, it coincides closely with the present outcrop distribution of volcanic and intrusive rocks, and is consistent with field observations that suggest the source region for the Late Carboniferous volcanic units was in the northeastern sector of the mapped area (McPhie & others, 1990).

Over the past 30 years there has been an increasing awareness that regionally, some volcanic and plutonic rocks have primary $\delta^{18}O$ values substantially below the lower limit for "normal" igneous rocks. For example, low-^{18}O igneous rocks have been recognised in the western Cascades (Taylor, 1971), the Skaergaard intrusion (Taylor and Forester, 1979), Iceland (Muehlenbachs & others, 1974), Au-Ag mineralised areas in western Nevada (Taylor, 1973), the Scottish Hebrides (Taylor and Forester, 1971), the San Juan volcanic field in Colorado (Taylor, 1974b; Larson and Taylor, 1986), the Yellowstone volcanic field (Hildreth & others, 1984), and the Lebombo Monocline in southern Africa (Harris and Erlank, 1992).

Models for ^{18}O -depleted igneous rocks

To produce dramatic depletions in whole-rock $\delta^{18}O$ values (by between 5 and 10 per mil), large-scale hydrothermal meteoric water interaction must have occurred at some stage. Low-^{18}O meteoric fluids interacting with rocks at high temperatures are the only plausible means of producing this depletion, because other fluid sources (e.g. magmatic or metamorphic fluids) will either increase or only slightly decrease "normal" igneous $\delta^{18}O$ values. Some volcanic and plutonic rocks are known or suspected to have been derived from low-^{18}O magmas (e.g. Muehlenbachs & others, 1974; Hildreth & others, 1984;

TABLE 14 $\delta^{18}O$ VALUES FOR VOLCANIC ROCKS FROM THE NORTHERN DRUMMOND BASIN

DESCRIPTION OF SAMPLE BMR No.	Rock type	Unit	AMG co-ords	$\delta^{18}O_{SMOW}$
8750 0082	**Rhyolitic ignimbrite**	**Bimurra Volcanics**	8356-370903	+4.3
Strongly welded, moderately lithic-rich & crystal-poor rhyolitic ignimbrite; slight to moderate alteration of feldspar & complete alteration of glass & ferromagnesian minerals to quartz, sericite, chlorite, epidote & hematite; hematite ± quartz in fractures.				
8850 0097	**Dacitic ignimbrite**	**Smedley Dacite***	8356-150165	+1.2
Strongly welded, lithic-poor & moderately crystal-rich.dacitic ignimbrite with minor quartz; slight to moderate alteration of feldspar & moderate to complete alteration of glass, hornblende & biotite to quartz, sericite, chlorite, epidote, & calcite.				
8850 0098	**Andesite**	**Unnamed***	8356-343947	-5.6
Moderately porphyritic augite andesite; moderate propylitic alteration of pyroxene & plagioclase				
8850 0099	**Dacitic Andesite**	**Unnamed***	8356-344943	-0.9
Densely welded, moderately lithic-rich & moderately crystal-rich dacitic andesite; moderate to complete alteration of ferromagnesian minerals & moderate alteration of feldspars to sericite + chlorite + epidote + opaques.				
8850 0200	**Rhyolitic ignimbrite**	**Arundel Rhyolite***	8356-087091	+5.4 (2)
Densely welded, moderately crystal-rich rhyolitic ignimbrite; moderate alteration of feldspars & ferromagnesian minerals to sericite + chlorite + calcite + trace epidote.				
8850 0201	**Rhyolitic ignimbrite**	**Collins Creek Rhyolite***	8356-322067	-0.7 (2)
Densely welded, moderately crystal-rich & very lihic-poor rhyolitic ignimbrite; complete alteration of ferromagnesian minerals & moderate alteration of feldspars to sericite + chlorite + calcite + trace epidote.				
8850 0202	**Rhyolitic ignimbrite**	**Locharwood Rhyolite ***	8356-302004	-1.1
Densely welded, crystal-rich & very lithic-poor rhyolitic ignimbrite; complete alteration of ferromagnesian minerals & moderate alteration of feldspars to sericite + chlorite + calcite + epidote.				
8850 0203	**Rhyolitic ignimbrite**	**Locharwood Rhyolite***	8356-316984	+0.2
Densely welded, moderately crystal-rich rhyolitic ignimbrite; complete alteration of ferromagnesian minerals & moderate alteration of feldspars to sericite + chlorite + calcite + trace epidote.				
8850 0204	**Dacite**	**Locharwood Rhyolite ***	8356-201936	-4.9
Flow-banded, moderately porphyritic dacite with felsic xenoliths; complete alteration of ferromagnesian minerals & moderate alteration of plagioclase to chlorite + sericite + calcite + hematite.				
8850 0205	**Dacitic ignimbrite**	**Stones Creek Volcanics**	8356-403910	+5.1
Densely welded crystal-rich dacitic ignimbrite; slight to moderate alteration of ferromagnesian minerals & feldspars to sericite + chlorite + epidote + calcite.				
8850 0206	**Rhyolitic ignimbrite**	**Pyramid Rhyolite***	8356-107905	+10.4
Densely welded, moderately crystal-rich & very lithic-poor rhyolitic ignimbrite; complete alteration of ferromagnesian minerals & moderate alteration of feldspars to sericite + hematite + trace epidote.				
8850 2501	**Rhyolitic ignimbrite**	**Unnamed***	8356-357318	+1.7 (2)
Densely welded, moderately crystal-rich to crystal-rich & lithic-poor rhyolitic ignimbrite; slight to moderate alteration of feldspar & complete alteration of ferromagnesian minerals to sericite + chlorite + calcite + epidote.				

Harris and Erlank, 1992). A more widely recognised means of producing regionally ^{18}O-depleted igneous rocks involves subsolidus oxygen isotope exchange caused by large quantities of meteoric water being heated and interacting with cooling intrusive and extrusive rocks.

In terms of low-^{18}O magmas, the mechanism for this ^{18}O depletion remains controversial. Broadly, there have been two main hypotheses put forward: the first involves the direct interaction of meteoric water with a magma (Friedman & others, 1974; Hildreth & others, 1984), and the second requires the assimilation or melting of rocks previously depleted in $\delta^{18}O$ through meteoric water interaction (Taylor, 1986; 1987; Grunder, 1987; Bacon & others, 1989).

TABLE 14 (continued)

DESCRIPTION OF SAMPLE				$\delta^{18}O_{SMOW}$
BMR No.	Rock type	Unit	AMG co-ords	
8850 2504	Rhyolitic ignimbrite	Unnamed*	8356-334320	+1.4
Fine-grained, densely welded, very lithic-poor & crystal-poor rhyolitic ignimbrite; moderate alteration of feldspar & complete alteration of glass & minor ferromagnesian minerals to sericite + chlorite + epidote + trace calcite.				
8850 2531	Rhyolitic ignimbrite	Unnamed*	8356-319286	+0.5
Non-welded, very lithic-poor & crystal-poor rhyolitic? ignimbrite; complete alteration of glass & slight to moderate alteration of feldspar to sericite + trace epidote.				
8850 2578	Rhyolitic ignimbrite	Locharwood Rhyolite *	8356-335198	+0.3
Densely welded, very lithic-poor & moderately crystal-rich rhyolitic ignimbrite; almost complete alteration of biotite & slight to moderate alteration of feldspar to sericite + calcite + chlorite + opaques + trace epidote.				-1.3F +5.9Q
8850 2704	Dacitic ignimbrite	Smedley Dacite*	8356-194163	-7.7 (2)
Densely welded, moderately lithic-rich & moderately crystal-rich dacitic ignimbrite; complete alteration of ferromagnesian minerals & slight to moderate alteration of feldspar to sericite + chlorite + epidote + trace calcite.				
8850 2809	Rhyolitic ignimbrite	Collins Creek Rhyolite*	8356-268124	-5.9
Densely welded, crystal-rich & lithic-poor rhyolitic ignimbrite; complete alteration of biotite, partial alteration of hornblende, & slight to moderate alteration of feldspar to sericite + chlorite + epidote + trace calcite.				+5.8Q
8850 3018	Andesite	Stones Creek Volcanics	8356-182329	+2.3
Moderately porphyritic augite andesite; moderate alteration of pyroxene & plagioclase to chlorite + epidote + sericite + calcite.				
8850 3031	Rhyolite	Unnamed*	8256-997319	+3.9 (2)
Sparsely porphyritic rhyolite; moderate alteration of feldspar & complete alteration of biotite (& hornblende?) to sericite + epidote + chlorite + calcite + quartz; epidote ± quartz ± sericite veinlets.				
8850 3039	Rhyodacitic ignimbrite	Unnamed*	8356-031313	+6.4
Strongly welded, lithic-poor, crystal-rich, biotite-hornblende rhyodacitic ignimbrite; finely recrystallised groundmass; biotite & feldspars slightly altered to chlorite + sericite + calcite + epidote.				+9.3Q
8850 3109	Rhyodacitic ignimbrite	Stones Creek Volcanics	8356-212251	-4.5
Fine-grained, moderately lithic-rich (clasts of rhyolite, dacite, andesite) & moderately crystal-poor rhyodacitic ignimbrite; slight to moderate alteration of glass & ferromagnesian minerals (complete), rock fragments & feldspars to chlorite + leucoxene + sericite + clay(?).				
8850 3123	Rhyolitic ignimbrite	Star of Hope Formation	8356-173219	+6.5
Moderately to strongly welded, lithic-rich (clasts of rhyolite, andesite/basalt), moderately crystal-rich to crystal-rich rhyolitic ignimbrite; slight to moderate alteration of glass (complete), rock fragments & feldspars to chlorite + hematite + sericite (?) + clay (?).				
8850 3124	Andesite	Star of Hope Formation	8356-092228	+6.3
Abundantly, finely porphyritic augite basaltic andesite; possible pigeonite & very abundant magnetite; rare plagioclase slightly altered to sericite, trace chloritised glass.				
8850 3154	Rhyolitic ignimbrite	Unnamed*	8357-300365	-8.2
Densely welded, finely recrystallised (matrix), crystal-rich rhyolitic ignimbrite; slight alteration of feldspars, primary ferromagnesian minerals & groundmass to sericite + chlorite; 2-3% recrystallised biotite.				-5.8Q

All $\delta^{18}O$ values are for whole rocks except for Q(quartz) & F(feldspar)   * = Bulgonunna Volcanic Group

Compelling arguments against the incorporation of meteoric water into a magma have been put forward because of the large quantities necessary to produce significant depletions in whole-rock values. Granitic magmas emplaced at shallow levels in the earth's crust can only dissolve at most 2 to 3 weight percent water (Burnham, 1967). Even if this water is entirely of meteoric origin, it is insufficient to lower the $\delta^{18}O$ of a magma significantly. For example, a 1 per mil depletion of a rhyodacite with an initial $\delta^{18}O$ of

TABLE 15 $\delta^{18}O$ VALUES FOR INTRUSIVE ROCKS FROM THE NORTHERN DRUMMOND BASIN

DESCRIPTION OF SAMPLE BMR No.	Rock type	Unit	AMG co-ords	$\delta^{18}O_{SMOW}$
8850 2654	**Microgranite**	**Unnamed**	**8356-348171**	**+7.1**
Fine grained (<0.5 mm), colour index <3, greenish brown biotite & minor green hornblende, minor sericitic alteration of plagioclase. Accessory opaques, zircon, & titanite.				
8830 2104	**Granodiorite**	**Percy Douglas Granodiorite**	**8356-234894**	**+6.9**
Medium grained (1mm) , colour index=23, brownish green hornblende in equal abundance to greenish brown biotite. Pale green hornblende cores after pyroxene. Plagioclase cores to An55.				
8830 2105	**Granodiorite**	**Joe-de-Little Granodiorite**	**8356-212898**	**+5.8**
Medium grained (2mm), colour index=12, subhedral greenish brown biotite more abundant than green hornblende. Plagioclase cores to An50, perthitic orthoclase.				
8830 2136	**Syenogranite**	**Unnamed**	**8357-249414**	**+8.8**
Medium grained (2mm) , colour index=3, reddish brown biotite & minor magnetite. Coarse perthitic orthoclase.				
8830 2138	**Monzogranite**	**Unnamed**	**8357-296432**	**+8.4 (2)**
Medium grained (1-2mm), colour index=7, dark brown biotite, minor pale green hornblende, magnetite & anhedral titanite. Rare plagioclase cores to An50. Perthitic orthoclase.				
8830 2159	**Granodiorite**	**Joe-de-Little Granodiorite**	**8356-210914**	**+7.3**
Medium grained (1-2mm) colour index=7, red brown biotite more abundant than green hornblende, minor opaques, plagioclase cores An50, perthitic orthoclase, accessory subhedral titanite.				
8830 2175	**Quartz Monzodiorite**	**Roscow Granite**	**8356-326831**	**+3.5**
Medium grained (1-2mm) colour index=25, pale green uralite with common clinopyroxene cores more abundant than late brown biotite associated with the uralite, common magnetite, plagioclase cores An60.				
8830 2183	**Porphyritic Microdiorite**	**Unnamed**	**8356-345880**	**+3.4**
Scattered resorbed clinopyroxene phenocrysts to 4mm (5%) & plagioclase (35%) to 2mm, An85, in a groundmass (0.05mm) of plagioclase, actinolite, biotite & opaques.				
8830 2191	**Gabbro**	**Unnamed**	**8356-359992**	**+4.8**
Fine to medium grained (0.5-1mm) two pyroxene gabbro, pale pink orthopyroxene commonly rimmed by clinopyroxene, pyroxenes partly uralitised, minor anhedral biotite associated with uralite. Plagioclase An75 slightly zoned. Rare interstitial quartz to 0.15mm.				
8830 2198	**Syenogranite**	**Unnamed**	**8356-394037**	**+7.2**
Coarse grained (4mm) colour index=4, orthoclase common as anhedral phenocrysts up to 10mm. Plagioclase commonly zoned with some cores to An40. Biotite, magnetite, apatite & zircon form clusters.				
8830 2207	**Granodiorite**	**Unnamed**	**8356-239186**	**+2.3**
Medium grained (1-2mm) colour index=17, brownish green hornblende equal in abundance to dark brown biotite, plagioclase cores to An50, turbid K-feldspar, 0.5% magnetite.				
8830 2211	**Gabbro**	**Unnamed**	**8356-200136**	**+7.8**
Fine grained (0.5mm) colour index=40, two pyroxenes, few patches of irregular opaques + orthopyroxene after olivine, 5% late biotite & opaques, some late pale green hornblende, minor interstitial quartz.				
8830 2215	**Monzogranite**	**Unnamed**	**8357-301382**	**+7.8**
Medium coarse grained (2-4mm), colour index=5, red brown biotite (4%), minor opaques, accessory titanite, plagioclase cores An40, coarse orthoclase perthite				
8830 2229	**Monzogranite**	**Unnamed**	**8356-461139**	**+1.3**
Medium grained (1-2mm), colour index=4, scattered rounded quartz phenocrysts to 5mm, partly chloritised biotite, plagioclase broad cores An40, orthoclase perthite, anhedral opaques.				
8830 2233	**Granodiorite**	**Unnamed**	**8456-548224**	**+6.6**
Medium grained (1-2mm) colour index=20, brownish green hornblende in equal abundance to dark brown biotite, minor opaques mostly within hornblende & biotite clusters, plagioclase broad cores of An55, orthoclase perthite.				
8830 2262	**Monzogranite**	**Unnamed**	**8357-079595**	**+4.3**
Medium coarse grained (1-4mm), colour index=6, red brown biotite more abundant than green hornblende prisms to 5mm long, accessory titanite & allanite, plagioclase cores An35, not strongly zoned, orthoclase perthite.				

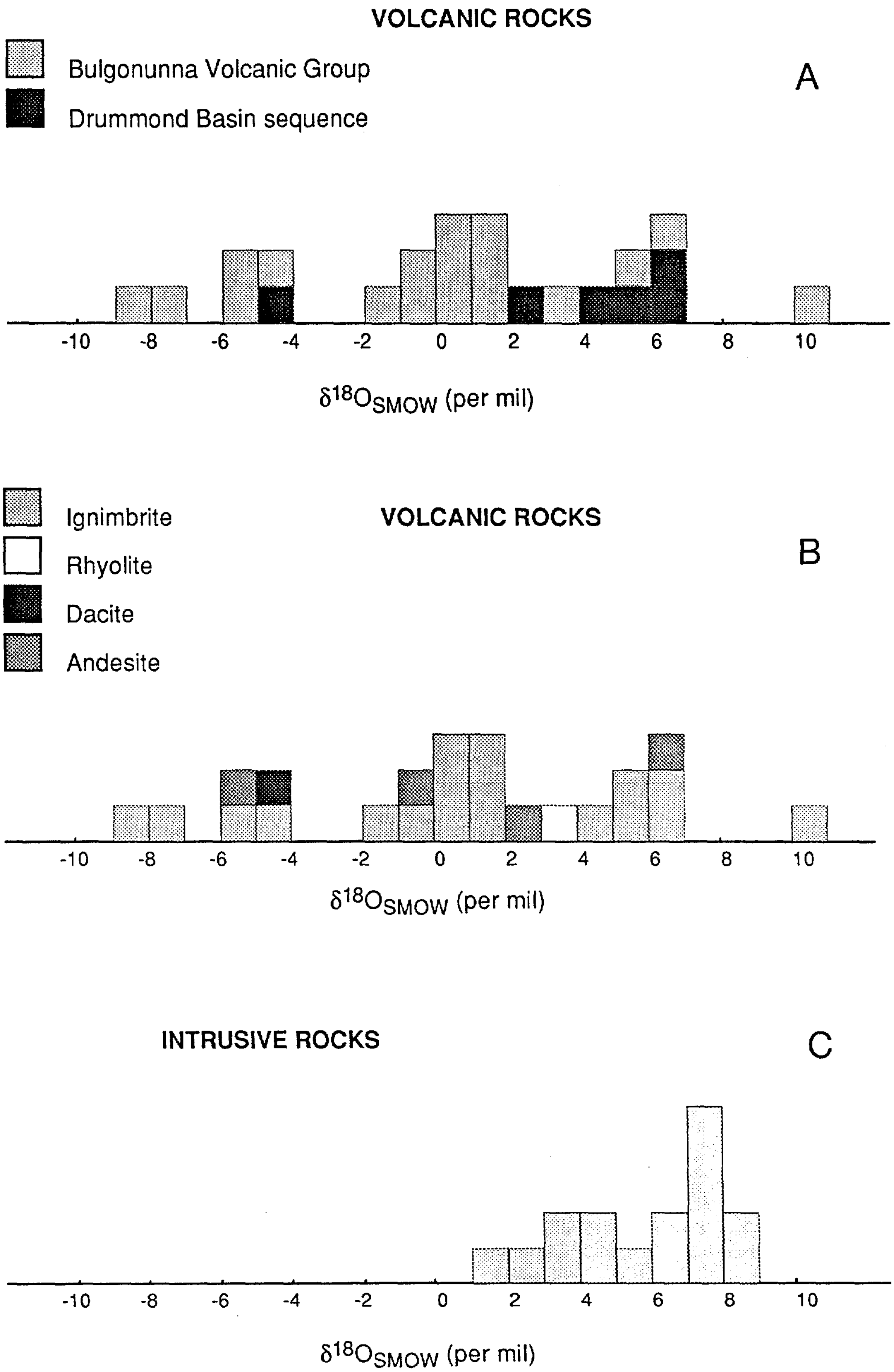

Figure 37. Whole rock $\delta^{18}O_{SMOW}$ values for the northern Drummond Basin. A—Volcanic rocks on the basis of stratigraphy. B—Volcanic rocks on the basis of rock type. C—Intrusive rocks.

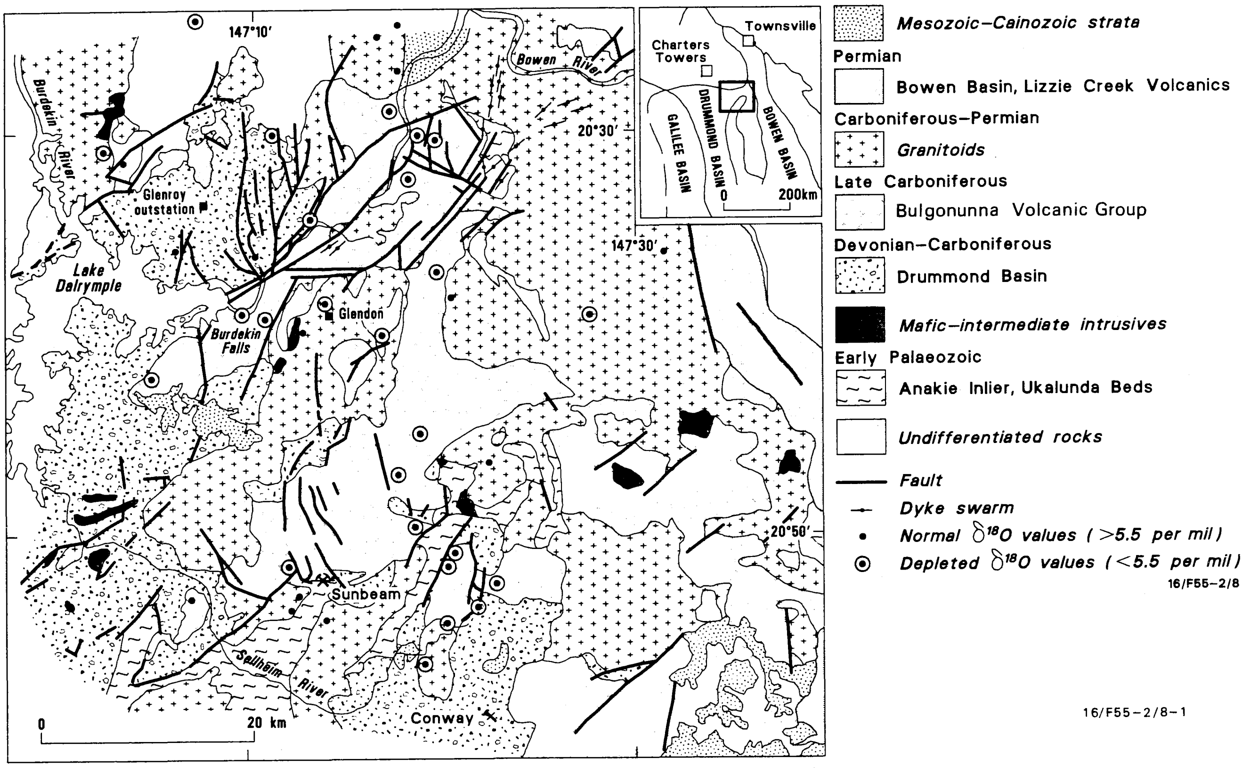

Figure 38. Distribution of $\delta^{18}O$ values for volcanic and intrusive rocks in relation to a simplified geology of the northern Drummond Basin (from Ewers & others, 1991).

6.3 per mil requires the incorporation of 2.9 weight percent meteoric water with a $\delta^{18}O$ of -14 per mil: this is a maximum depletion because it assumes that the meteoric water has not exchanged appreciably with those rocks enveloping the magma (Grunder, 1987).

^{18}O depletion could be caused also by the assimilation into a magma or melting of rocks already low in $\delta^{18}O$ as a result of exchange with meteoric water in a hydrothermal system. There are ^{18}O-depleted volcanic rocks in the Drummond Basin sequence (8850 3018 and 8850 3109 are +2.3 and -4.5 per mil, respectively) which could have resulted from this process and may have acted as source material for later igneous events. However, the age and structural complexity of the area and poor outcrop over much of the region make the reconstruction of a detailed geological history for the region virtually impossible.

The possibility that low-^{18}O magmas were emplaced and erupted in the northern Drummond Basin during the Palaeozoic cannot be discounted. However, the data are more easily explained, and appear to be more consistent with large-scale interaction of meteoric water with cooling intrusive and extrusive rocks. The observation that volcanic units are generally more ^{18}O depleted than the intrusive rocks does not accord with that depletion occurring on a regional scale at the magmatic stage, although locally a comagmatic intrusive and extrusive suite could be isotopically light. Rather it suggests, as Taylor (1971; 1974a) has indicated, that the volcanic rocks have interacted and exchanged isotopically with heated meteoric water to a greater degree than the intrusive rocks because they were more porous and permeable (partly because of their primary, partially fragmental, bedded nature, and partly because they were probably more fractured). Isotopic depletion within some intrusive rocks is more readily explained by high temperature meteoric water interaction along faults and fractures, rather than isotopic differences at the magmatic stage.

It is possible that a strong palaeomagnetic overprint identified by Klootwijk and Giddings (in prep.) in the northern Drummond Basin may relate to subsolidus meteoric water interaction with a cooling volcanic pile. This observation is consistent with their view that the palaeomagnetic overprint is the product of a post-magmatic event rather than the U-Pb single zircon crystallisation ages of 290–305 Ma obtained by Black (in prep.) for the Bulgonunna Volcanic Group. However, if this is the cause, such an overprint would not necessarily extend beyond the northern Drummond Basin in a uniform manner. Recent whole-rock $\delta^{18}O$ data for the Featherbed Volcanics (Ewers and Mackenzie, unpublished data) and the Newcastle Range Volcanics (Bain, unpublished data) do not indicate widespread regional ^{18}O depletion in these volcanic complexes.

Characteristics of ^{18}O-depleted igneous rocks

Taylor (1971; 1974a) noted that igneous complexes abnormally low in $\delta^{18}O$ display characteristic geological, petrological, and isotopic features. These are that:

- the intrusions are emplaced into young, flat-lying and jointed volcanic rocks that are porous an highly permeable to groundwater movement.
- the feldspars are commonly ^{18}O-depleted to a greater degree than other coexisting minerals, and are typically turbid (particularly the alkali feldspars).
- the primary igneous ferromagnesian minerals are partially or completely altered, particularly to chlorite and epidote, and OH-bearing minerals have abnormally low δD values relative to normal igneous rocks.
- granophyric textures and miarolitic cavities are common in intrusive rocks.

If hydrothermal alteration occurs at very high temperatures or, in the case of low-^{18}O magmas, the minerals have directly crystallised from the melt, the characteristic alteration features indicated above may be minor or completely absent. For example, Hemley and Jones (1964) showed that, in the presence of quartz, the stability fields for K-feldspar, sericite, kaolinite, and pyrophyllite are a function of temperature and fluid chemistry (specifically the K^+/H^+ cation ratio). At high temperatures and high K^+/H^+ ratios, K-feldspar will be the stable phase, and therefore will show little evidence of hydrothermal interaction.

Mineralogical data for the volcanic rocks within and overlying the northern Drummond Basin are summarized in Table 14. Partial to complete alteration of ferromagnesian minerals (mainly biotite ± hornblende ± pyroxene) and slight to moderate alteration of feldspar to sericite, chlorite, epidote, and calcite are common, and may reflect subsolidus meteoric-hydrothermal interaction, rather than later low-temperature alteration or weathering of the volcanic rocks. However, there is no clear relationship between the degree of alteration and the extent of ^{18}O depletion. Indeed, some rocks appear to be relatively fresh even though they are heavily ^{18}O-depleted (e.g. 8850 3109, 8850 3154). Intrusive rocks in the area exhibit some of the mineralogical features outlined by Taylor and Forester (1971) for ^{18}O-depleted rocks—for example, pyroxene can be replaced by uralite ± opaques and alkali feldspars are turbid in some samples (Table 15). Although some of these altered samples are ^{18}O-depleted (e.g. 8830 2175, 8830 2207, and 8830 2229), there is (as with the volcanic rocks) no clear relationship between the presence or degree of alteration and the $\delta^{18}O$ whole-rock value.

Larson and Taylor (1986) have systematically mapped $\delta^{18}O$ values for 300 rock and mineral samples from the Tertiary Lake City Caldera in the San Juan Mountains and have related these values to both the type and intensity of mineral alteration. Because of the young age and high state of preservation of this

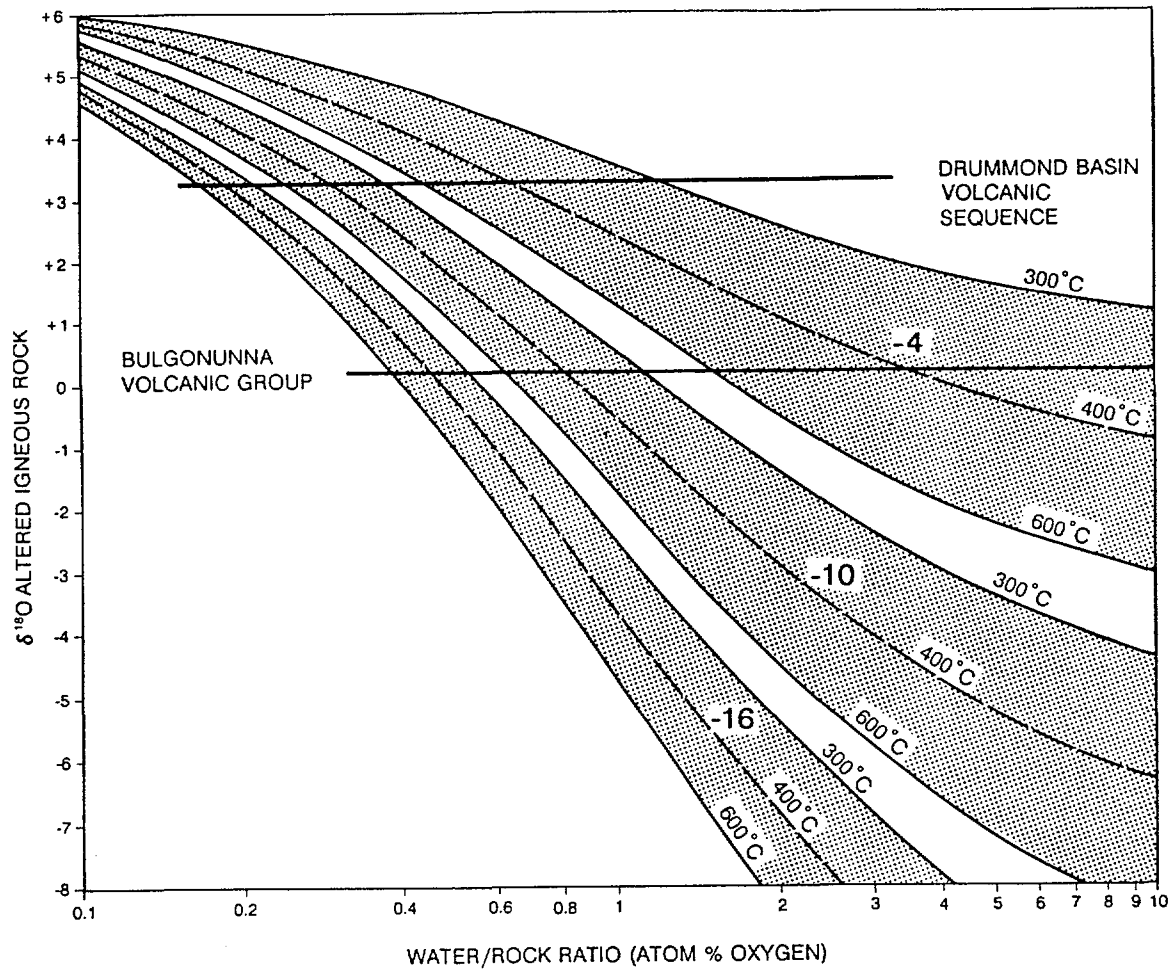

Figure 39. $\delta^{18}O$ variations in volcanic rocks from the northern Drummond Basin, assuming an initial $\delta^{18}O$ whole-rock value of +6.5 per mil for a range of initial meteoric water $\delta^{18}O$ values (-4, -10, -16 per mil) and temperatures of 300°C, 400°C, and 600°C (see text for details).

system, they have been able to model fluid flow within the caldera very precisely. However, the greater age and structural complexity of the northern Drummond Basin and the relatively small number of samples involved in this study preclude such an exercise.

Previous studies have shown that in plutonic granitic rocks unaffected by hydrothermal exchange, the fractionation between quartz and feldspar (Δ_{Q-F}) is normally between about 0.8 and 2.5, depending on feldspar composition (Criss and Taylor, 1983). Low ^{18}O-magmas will tend to follow this fractionation trend even though both quartz and feldspar are ^{18}O-depleted. However, in those rocks affected by meteoric water interaction at high temperatures, the quartz will be resistant to exchange whereas the feldspar exchanges ^{18}O with the fluids rapidly, leading to marked isotopic disequilibrium. Analysis of quartz and feldspar in an ^{18}O-depleted rhyolitic ignimbrite (8850 2578 has a $\delta^{18}O$ whole rock value of +0.3 per mil) indicates a high degree of isotopic disequilibrium with $\Delta_{Q-F} \cong +7.2$ (Table 14): this suggests that subsolidus hydrothermal meteoric water interaction has occurred.

$\delta^{18}O$ values for quartz in an ^{18}O-depleted rhyolitic ignimbrite (8850 2809) and a "normal" rhyodacitic ignimbrite (8850 3039) exhibit essentially normal quartz values (+5.8 and +9.3 per mil respectively, Table

14). However, a rhyolitic ignimbrite (8850 3154) with marked whole-rock ^{18}O depletion (-8.2 per mil) contains quartz with a $\delta^{18}O$ value of -5.8 per mil (Table 14). Taylor and Forrester (1971) have reported similar low $\delta^{18}O$ values for a sample of the Grigadale granophyre from the Scottish Hebrides (-6.3 and -6.0 per mil for the whole rock and associated quartz, respectively). They concluded that this extreme ^{18}O depletion in the Scottish Hebrides was due to the granophyric magma itself being depleted: such low values in the northern Drummond Basin provide evidence that low ^{18}O-magmas could have developed locally.

Water:rock ratios

If subsolidus reactions between meteoric fluids and a cooling volcanic pile are considered largely responsible for the observed isotopic depletion, then some assessment can be made of the necessary water:rock ratios involved. Assuming an initial whole-rock oxygen isotope value of +6.5 per mil, then for a given initial $\delta^{18}O$ value for the meteoric water involved, the effects of varying temperatures and water:rock ratios on the $\delta^{18}O$ of hydrothermally altered igneous rocks can be gauged (Taylor 1971; 1973; 1977). Details of the calculation have been outlined in an earlier section of this report. The results for meteoric water with assumed initial $\delta^{18}O$ values of -4, -10, and -16 per mil and temperatures between 300 and 600°C for each case are shown in Figure 39. As reported earlier, a regional meteoric water $\delta^{18}O$ value of -10 per mil is thought to have applied at the time Conway formed. Since the palaeolatitude for this region is known to have been highly variable during the Palaeozoic, a 6 per mil variation either side of this regional meteoric water $\delta^{18}O$ value has been illustrated. Minimal alteration features for the volcanic rocks suggest that meteoric water interaction took place at high temperatures, probably within the reasonable limits of 300-600°C.

Figure 39 indicates that for mean isotopic values of the Drummond Basin volcanic rocks and the Bulgonunna Volcanic Group, water:rock ratios need not exceed unity for an initial meteoric water $\delta^{18}O$ value of -10 per mil and temperatures above 300°C. It is clear that, for an initial meteoric water $\delta^{18}O$ of -4 per mil, temperatures must be above 400°C to avoid excessive water:rock ratios, particularly for the Late Carboniferous Bulgonunna Volcanic Group (i.e. >5). In those whole-rock samples where $\delta^{18}O$ values are extremely low (< -5 per mil), water:rock ratios must have been very high locally, and meteoric waters must have been isotopically light (i.e. < -10 per mil). In general, the intrusive rocks are less exchanged than the volcanic rocks and have been depleted only where water:rock ratios appear to have been high.

Although the above calculations assume closed-system behaviour, Taylor (1977) has also given an example of an open system in which each increment of fluid makes only a single pass through the heated rocks. This results in a lower estimate of the water:rock ratio than for closed-system conditions at a given temperature. Although calculated water:rock ratios are useful in assessing whether the amount of fluid involved is geologically feasible, they represent minimum values whether closed- or open-system conditions apply, since the fluid flow would have been largely fracture-controlled leading to incomplete equilibration.

Implications for epithermal gold mineralisation

Stable isotope data have demonstrated conclusively that hydrothermal fluids derived from meteoric waters have played a dominant role in the genesis of epithermal gold deposits (e.g. O'Neil & others, 1973; Taylor, 1973; O'Neil and Silberman, 1974; Bethke and Rye, 1979; Criss and Taylor, 1983).

TABLE 16 AREAS OF REGIONAL OXYGEN ISOTOPE DEPLETION IN WHICH EPITHERMAL GOLD MINERALISATION HAS BEEN IDENTIFIED

REGION	SELECTED EPITHERMAL DISTRICT(S)	REFERENCE(S)
Idaho batholith	Yankee Fork	Criss & Taylor (1983),Criss et al. (1985)
Boulder batholith	Virginia City	Sheppard & Taylor (1974),Berger & Henley (1989)
Western Nevada	Tonopah, Comstock Lode, Goldfield, Round Mountain	Taylor (1973); Tingley & Berger (1985)
Western Cascade Range	Bohemia	Taylor (1971); Taylor (1974a)
San Juan Mountains	Creede, Lake City, Silverton	Taylor (1974b): Slack (1980); Larson & Taylor (1986)

Characteristically, host rocks to epithermal deposits are ^{18}O-depleted as a result of isotopic exchange involving these meteoric fluids (Field and Fifarek, 1985).

The association of extensive whole-rock ^{18}O-depletion in the northern Drummond Basin with an area recently recognised as being highly prospective for epithermal gold mineralisation provides further evidence of a relationship seen in younger epithermal districts in the USA. O'Neil and Silberman (1974) first observed that many of the Tertiary epithermal deposits in the USA occur within areas that have undergone regional oxygen isotope depletion. Information summarised in Table 16 suggests that regional patterns of whole-rock oxygen isotope depletion may be particularly useful in discriminating those areas which could be prospective for epithermal mineralisation. This association is not surprising, since hydrothermal systems involving meteoric fluids could be anticipated in high-level volcanic terranes during the waning stages of igneous activity. However, because epithermal deposits typically form near the earth's surface, their preservation will be critically dependent on the level of erosion. Therefore, it is possible that an area which appears favourable on the basis of isotopic data, could be unprospective because the level of erosion has been too great.

The absence of widespread regional whole-rock ^{18}O-depletion in the Featherbed Volcanics (Ewers and Mackenzie, unpublished data) and the lack of success in identifying epithermal gold mineralisation in that area appears to confirm the association noted above. It highlights the likely value in using regional whole-rock oxygen isotope data as an area selection tool to distinguish areas with epithermal potential that could warrant further detailed exploration.

SUMMARY

Epithermal gold mineralisation in the northern Drummond Basin is of the adularia-sericite (Heald & others, 1987) or low-sulphidation type (White and Hedenquist, 1990). All of the significant known gold mineralisation in the area, with the possible exception of the main lode at Mount Coolon and the Ukalunda deposit, is believed to be hosted by units at the base of the Drummond Basin sequence, and recent mapping has suggested that these rocks are more extensive than previously recognised, thereby enhancing the prospectivity of the area. Typically, the gold mineralisation occurs in an acid to intermediate volcanic environment, and is hosted mainly by volcaniclastic rocks which may be associated with lavas.

The Drummond Basin sequence appears to represent a favourable host to mineralisation because it is cut by structures which could have focussed and channelled fluids on a regional scale, and because it contains volcanic units which could have acted as a heat engine for some of these systems. The sequence also may have been a source of gold and, perhaps more significantly, sulphur for the transport of gold (Seward, 1973): however, this has not been demonstrated and the basement rocks to the volcanic units equally could be considered as a possible source for metals and/or sulphur. Predominantly north and northeast trending structures in the northern Drummond Basin appear to control the alignment of prospects and deposits on a regional scale; however, direct evidence for these structures is generally lacking. Several deposits and prospects appear to correlate with magnetic linears (e.g. Yandan, Wirralie, Bimurra, and Pajingo), and Mount Coolon, Bimurra, and BHP prospects such as Conway, Bluegum, and Battery Hill have a N-S alignment which closely corresponds to a magnetic corridor apparent on regional-scale aeromagnetic data. These regional structural trends can be evident at a prospect and deposit scale (e.g Pajingo and Conway).

The timing of regional magmatic events relative to mineralisation remains poorly constrained. K-Ar dating suggests that multiple hydrothermal events resulted from episodic magmatic activity, and that the base of the Drummond Basin sequence acted not only as a host for mineralisation, but that volcanic units (which are well developed at the base) could have been a heat source for some of these hydrothermal systems.

Deposits and prospects throughout the area exhibit many of the classic features of epithermal systems; they are characteristically low in sulphur (generally <2% sulphides, mainly pyrite), and are dominated by pervasive silicification of variable intensity, quartz veining which is typically banded and chalcedonic, and argillic/phyllic (mainly sericite and mixed layer clays) and propylitic alteration. Some also contain adularia, and include preserved siliceous sinters, which are indicative of an original palaeosurface. Hydraulic fracturing and breccias are common.

In general, epithermal fluids are typically of low salinity (normally <5 wt % NaCl equivalent), are characterised by temperatures in the range 200-300°C, and are predominantly of meteoric origin. Detailed fluid inclusion and stable isotope studies for the Conway prospect (which represents the most extensively drilled and best understood of the BHP prospects) confirm these observations. Boiling, which is known to be a particularly effective mechanism for causing gold deposition, cannot be confirmed from fluid inclusion data. However, the alteration provides evidence that boiling occurred on a localised scale at least. Henley and Hedenquist (1985) have highlighted the importance of gas-rich geothermal systems in generating an epithermal deposit. Low CO_2 contents for fluids involved at Conway appear to be unfavourable in this respect. By contrast, fluid inclusions containing liquid CO_2 are rare in epithermal systems; their presence at Bluegum probably reflects a proximity to skarn mineralisation at the nearby Mt David prospect.

Surficial deposits of siliceous sinter are a common feature of present-day hot springs in areas of active volcanism, but they are rarely recognised in older, eroded volcanic terranes because of their low preservation potential. Siliceous sinters have been recognised at a number of BHP prospects (Conway, Durah Creek, Hill 273, and possibly Bimurra) and reported widely from deposits and prospects throughout the northern Drummond Basin. The importance of sinters to exploration for epithermal ore deposits is that they provide tangible and unambiguous evidence of a palaeosurface, and they indicate the possible presence of a significant mineralising system within 1000 metres of the earth's surface. Failure to recognise a sinter, or the incorrect interpretation of a siliceous rock as a sinter could lead to false assumptions in assessing an epithermal prospect, and perhaps to a misdirected exploration program.

White & others (1989) have described features in sinters from the Conway and Durah Creek prospects which are observed in modern sinters deposited in active hot-spring environments: they are conformable with subaerial, hydrothermally altered volcanic rocks, and preserve textures which are characteristic of modern sinters. Oxygen isotope data indicate that sinters are isotopically heavy relative to associated quartz veins and may provide an additional tool for characterising ancient sinters. For example, at the Conway prospect, sinters are consistently and significantly more ^{18}O-enriched (+11.5 ± 0.7 per mil) than nearby vein quartz (+6.3 ± .9 per mil).

Examination of field relations, alteration, fluid inclusion, and stable isotope data suggest that the Conway prospect was tilted to the west and eroded to expose a slice through the hydrothermal system. The Red Flag Hill area represents the deepest and hottest exposed part of that system. For measured fluid inclusion temperatures of 200-300°C, an initial $\delta^{18}O$ whole-rock value of 6.5 per mil, and an initial $\delta^{18}O$ meteoric water value of -10 per mil, water:rock ratios as low as 0.25 would have been capable of producing the whole-rock oxygen isotope values observed at Conway.

Suspected siliceous sinter deposits in the Big Sinter Hill area, immediately adjacent to high-temperature quartz veins formed at about 250°C could be explained either by a single hydrothermal system which has been both long lived and actively eroded throughout its lifetime, or as different systems separated in time which have exploited the same structures. Later overprinting of an earlier hydrothermal system could have occurred at Bimurra (Wood & others, 1990), and other deposits and prospects in the northern Drummond Basin may have been affected similarly.

Whole-rock oxygen isotope analyses of slightly altered volcanic and intrusive rocks from throughout the northern Drummond Basin and distant from epithermal systems have led to the identification of an area of ^{18}O-depletion of at least 1500 km^2. The full extent of this depleted area and the mechanism responsible for it are not clear, due mainly to the structural complexity, poor age control, and generally poor outcrop over most of the region. It coincides closely with the present outcrop distribution of volcanic and intrusive rocks, and is consistent with field observations that suggest the source region for the Late Carboniferous volcanic units (predominantly ignimbrite) was in the northeastern sector of the mapped area (McPhie & others, 1990). The data appear to be most consistent with large-scale interaction of meteoric water with cooling intrusive and extrusive rocks, and calculations indicate that water:rock ratios close to unity would have been capable of producing the observed whole-rock ^{18}O depletion.

O'Neil and Silberman (1974) observed that many Tertiary epithermal deposits in the USA occur within areas that have undergone regional oxygen isotope depletion. The association of extensive whole-rock ^{18}O depletion in the northern Drummond Basin with an area recently recognised as being highly prospective for epithermal gold mineralisation provides further evidence of this relationship. It suggests that regional patterns of whole-rock oxygen isotope depletion may be particularly useful in discriminating those areas which could be prospective for epithermal mineralisation. Because epithermal deposits typically form within 1000 metres of the surface, their preservation will be critically dependent on the level of erosion; therefore, it is still possible that an area which appears favourable on the basis of isotopic data could be unprospective because the level of erosion has been too great.

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