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DEPLETION AND ENRICHMENT ZONES IN THE BENDIGO GOLD FIELD: A POSSIBLE SOURCE OF GOLD AND IMPLICATIONS FOR EXPLORATION

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Abstract

A regional lithogeochemical survey in the Bendigo region of central Victoria, Australia, covering an area of 3,750 km² and including the giant Bendigo gold field and other large regional gold fields such as Maldon, Castlemaine, and Fosterville, was completed in 2004 by Ionex Pty Ltd. A total of 142 rock samples were collected and analyzed for gold and associated elements. Extensive areas having an anomalously low gold content (termed "depletion zones") were detected in the vicinity of known gold fields and constitute a large proportion of the surveyed area. The results show that the gold content in the depletion zones is 70 percent below regional background levels.

The Bendigo gold field itself is located within a positive gold anomaly (enrichment zone) with an average value of 14 ppb in all rock types and an extent of approx. 100 km². To the north is a depletion zone on the order of 700 to 800 km², with an average gold content of less than 0.5 ppb in all rock types. In total, the gold enrichment and depletion zones occupy an area of more than 1,000 km² against a regional background of 0.7 to 4.7 ppb Au (avg 1.29 ppb). If this depletion zone extends to a depth of 2 km, the volume of depleted rock would be at least 1,400 km³ and the extent of apparent depletion would be 3,000 to 4,000 tonnes (t) of gold.

The quantum of apparent gold depletion at Bendigo is on the same order of magnitude as the gold enrichment in the Bendigo gold field and associated dispersion haloes (3,000 t Au). Substantial depletion zones are also present adjacent to the other important gold deposits within the survey area. The presence of extensive gold depletion zones adjacent to the major gold deposits of central Victoria raises the possibility that these rocks were a source of gold in the deposits. These findings provide possible new criteria for the appraisal of prospective regions.

Introduction

The model of primary lithogeochemical haloes of ore deposits was established in the 1930s and has not changed. The primary halo of an ore deposit is considered an environment of enrichment of ore-forming and associated elements generated by processes associated with mineralization. However, extensive multi-element geochemical data show that primary lithogeochemical haloes may be quite complex, including both enrichment and depletion zones. In some cases, these appear to be spatially linked to each other and may be seen as a single geochemical system. Where these different zones have been identified, good correlation exists between the physical dimensions of the depletion zone and the abundance of the depleted elements in the corresponding enrichment zone (e.g., Goldberg et al., 2003). In many deposit types, this correlation implies a role for the regional rock mass as a source of metal and that the depletion zones are mobilization environments (after Rose at al., 1979) for the ore-forming elements.

In 2004, Ionex Pty Ltd completed a regional lithogeochemical survey in the Bendigo-Ballarat gold subprovince of Victoria, Australia, covering an area of 3,750 km². This study investigates the existence of genetically related enrichment and depletion zones in the giant turbidite-hosted Bendigo gold field and in the nearby gold fields of Maldon, Castlemaine, and Fosterville.

General Geologic Setting of the Bendigo Area

The Bendigo area is located in the Bendigo-Ballarat gold subprovince in the western part of the Lachlan fold belt. The geologic setting and gold mineralization have been described by Ramsay and Vandenberg (1990), Cox and Wall (1991), Forde and Bell (1994), Phillips and Hughes (1996), Ramsay et al. (1998), and Bierlein et al. (2000). The width of the gold district is some 110 km and is defined by the Heathcote fault zone and the Avoca fault zone. Gold mineralization in the Bendigo-Ballarat zone occurs within north-trending reverse fault systems in a thick (several kilometers) monotonous succession of quartz-rich turbidites of Cambro-Ordovician age. The rocks are mostly flyschoid sedimentary facies, shales, and muds, rhythmically interbedded with sandstone and graywacke. Regional metamorphic grade in sedimentary rocks ranged from prehnite-pumpellyite to lower greenschist conditions during regional deformation. The sedimentary rock is folded, with mostly submeridional axes of folding. The folding normally has a wavelength of between 10 and 15 km and an amplitude of 1 to 2 km. Local folding, spaced 100 to 300 m apart, with amplitudes of 50 to 100 m, in places has a chevron form. The sequence is intruded by laterally extensive late- to

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postorogenic granites and porphyritic dikes, generally of Early to Late Devonian age.

Primary gold mineralization is largely confined to a number of discrete gold fields that are elongated north-south, parallel to the regional fold and fault trend. Gold is the only important commercial element in these deposits. The turbidite-hosted, gold-bearing quartz veins at Bendigo commonly occur as saddle reefs along anticlinal axes.

The Bendigo gold field (Fig. 1) is hosted by the Castlemaine Supergroup (Lower to Middle Ordovician), 2 to 3 km west of the Whitelaw fault. The Maldon and Castlemaine gold fields are located south of the Bendigo gold field, and the Fosterville gold field occurs to the east. At least 29 smaller gold fields and gold reefs are located in the area (Weston and Nott, 1993; Sharpe and MacGeehan, 1990; Ramsay et al., 1998).

The Bendigo gold field is the largest gold producer in the Victorian gold province. In 1997, the total past production from the deposit was estimated to have been 697 tonnes (t) of gold, including 540 t primary and 157 t alluvial gold (Philips and Hughes, 1996); a further 13 Moz (400 t) of gold has been defined by Bendigo Mining Ltd (2004). This deposit is a classic example of a low-sulfide, gold-quartz deposit (sulfide less than 5%) located in a folded sequence of sandstone and shale as saddle reefs and discordant veins, predominantly in anticlinal domes. A minor part of the mineralization occurs in synclinal positions. Mining operations have progressed to a depth of 1,407 m (Sharpe and MacGeehan, 1990; Willman and Wilkinson, 1992), and gold-quartz reefs have been observed over a distance of about 12 km (north-northwest to south-southeast) and a width of 3 km. This corridor contains 12 to 14 north-northwest–trending anticlines, approx. 200 m apart. The average gold content of the quartz reefs is 12 to 27 g/t, and precipitation of gold and associated elements is considered to have occurred during multiple stages (Jia and Kerrich, 2000). Alteration near the ore includes carbonate and white mica, with minor amounts of pyrite and arsenopyrite (Bierlein et al., 2000).

Sampling and Analysis

Samples of both granitoids and sedimentary rocks were collected along roads and tracks to approximate a grid of 5 × 5 km covering 3,750 km^2. Samples were taken from outcrop at sites least affected by weathering; the weight of each sample was about 500 g. A total of 142 samples were selected, 19 from Late Devonian granodiorite of the Harcourt intrusion, and the remainder from sandstone or shale.

The rock samples were analyzed for a wide range of elements at ALS Chemex in Brisbane, Australia. This paper discusses the behavior patterns of only two elements, gold and zinc, as preliminary analysis indicated that zinc is a characteristic element of the enrichment zones (Goldberg et al., 2003). Other elements associated with gold (Ag, As, Sb, Bi) provide additional information but are not considered here. The gold analysis was carried out by fire assay using a Pb bead and an ICP-MS finish (Hall and Pelchat, 1994). The Zn analysis was carried out using the ICP-MS method following lithium metaborate fusion. By prior arrangement with the laboratory, a significantly larger number of blanks were employed to monitor detection limits. We note that, in the case of gold, the sub-part per billion values do not occur at random, but tend to cluster over relatively extensive areas (see below). In the case of zinc, the effects are broadly similar, but the clusters are less extensive. The mean error for Au was 29.6 percent. The mean error for zinc was 1.75 percent. The results of the Au and Zn assays are shown in Figures 2 and 3, respectively, and in Tables 1 and 2.

The sampled rock types in the mapped areas have very similar background concentrations of Au and Zn, corresponding closely to established Clark values for these rock types (e.g., Taylor and McLennan, 1985; Wedepohl, 1995). Background concentrations of gold in average sedimentary rocks are 1 to 5 ppb. Histograms of data from this study indicate similar background ranges for granitic and sedimentary rocks in the Bendigo gold field (Figs. 2, 3). Background concentrations of Zn are 50 to 100 ppm in both granitoids and sedimentary rocks. In this analysis, values less than 0.5 ppb Au and 25 ppm Zn are chosen to indicate depletion of Au and Zn relative to background in both rock types. Enriched rocks are considered to contain >4.7 ppb Au and >110 ppm Zn.

Results

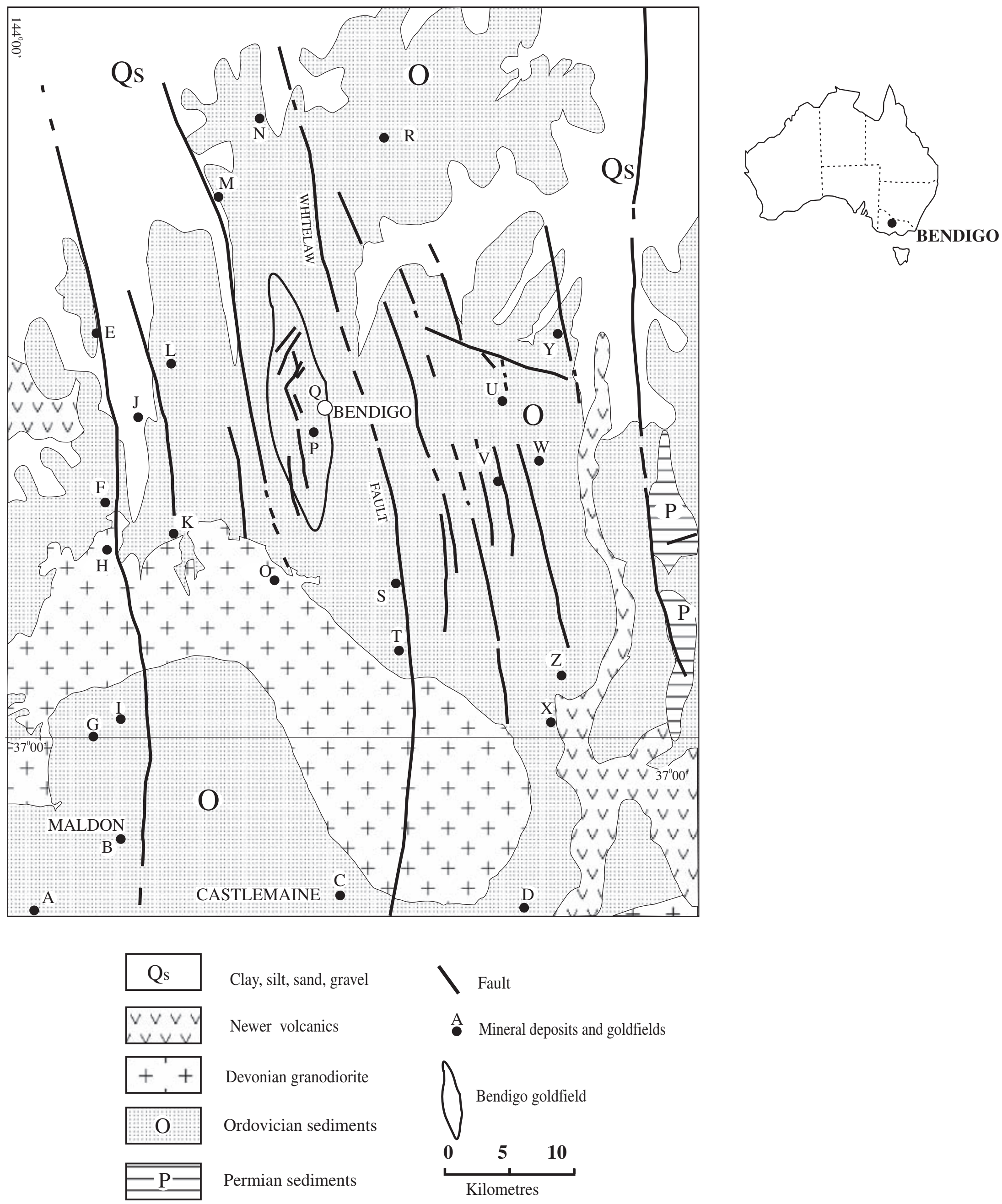
Distribution of gold in regional geochemical samples

The ranges of gold concentrations in samples of granitic and sedimentary rocks are shown in Figure 2; samples with <0.5 ppb Au account for approximately 40 percent of all samples. Gold analyses within the range 0.5 to 4.7 ppb have an average value of 1.29 ppb, close to the Clark value for these rocks. A third smaller group of samples contain > 4.7 ppb Au, up to 70 ppb Au, and is characterized by an almost even distribution throughout this range.

The distribution of gold analyses within the surveyed area is shown in Figure 4. A general characteristic of the map is an apparent spatial connection between the gold enrichment and depletion zones, the gold depletion zones being in close proximity or immediately adjacent to zones of gold enrichment, with paired enrichment and depletion zones separated by the background. Four paired enrichment and depletion zones are identified in the surveyed area.

The Bendigo gold field: The Bendigo gold field had a total production of 697 t. The gold enrichment zone surrounding the Bendigo gold field has an area of approx. 100 km^2 and includes a local anomaly with the highest concentration (59 ppb Au) coinciding with the Deborah ore zone. Adjacent to and west of the Deborah is a local anomaly coinciding with the small Marong gold deposit. To the north is an extensive gold depletion zone that has not been completely outlined, as outcrop at the northern end is concealed by recent sediments. The mapped extent of the depletion zone is 700 to 800 km^2 and is characterized by rocks having uniformly low concentrations of gold to <0.5 ppb. Within the depletion zone there is a local gold enrichment zone that coincides with the Elysian Flat gold deposit (R in Figs. 1, 3). The combined zones occupy an area well in excess of 1,000 km^2.

The Maldon gold field: The Maldon gold field had a total production of 65 t Au, including 56 t primary gold and 9 t alluvial gold. The gold-enriched zones have a combined area of about 300 km^2, coinciding with the location of the gold mineralization, but they have not been fully outlined to the south



MINERAL DEPOSITS AND FIELDS

A Blue mine & Victory mine (Au)
B Daylesford - Maldon goldfields (Au)
C Castlemaine - Malmsbury goldfield (Au)
D Metcalfe (Au)
E Leichhardt (Au)
F Shelbourne goldfield (Au)
G Day Dawn mine Au(Mo,Bi)
H Shelbourne wolfram (W)
I Nuggety reef (Au,Zn, Bi, Cu,W)
J Wilsons Hill goldfield (Au)
K Lockwood goldfield (Au)
L Marong goldfield (Au)
M Sebastian goldfield (Au)
N Raywood goldfield (Au)
O Crusoe goldfield (Au)
P Bonati&Co. Mine (Au,Sb))
Q Bendigo goldfield (Au)
R Elysian Flat Goldfield (Au)
S Mandurang goldfield (Au)
T Sedgwick goldfield (Au)
U Yankee creek (Au)
V Enright reef (Au)
W Axedale goldfield (Au)
X Myrtle Creek goldfield (Au)
Y Fosterville (Ellesmere) goldfield (Au)
Z Lyell goldfield (Au)

FIG. 1. Geologic map of the Bendigo region (after Vandenberg, 1999), indicating the positions of gold fields and mineral deposits (after Weston and Nott, 1993). Major gold fields occur at Bendigo, Maldon, and Castlemaine.

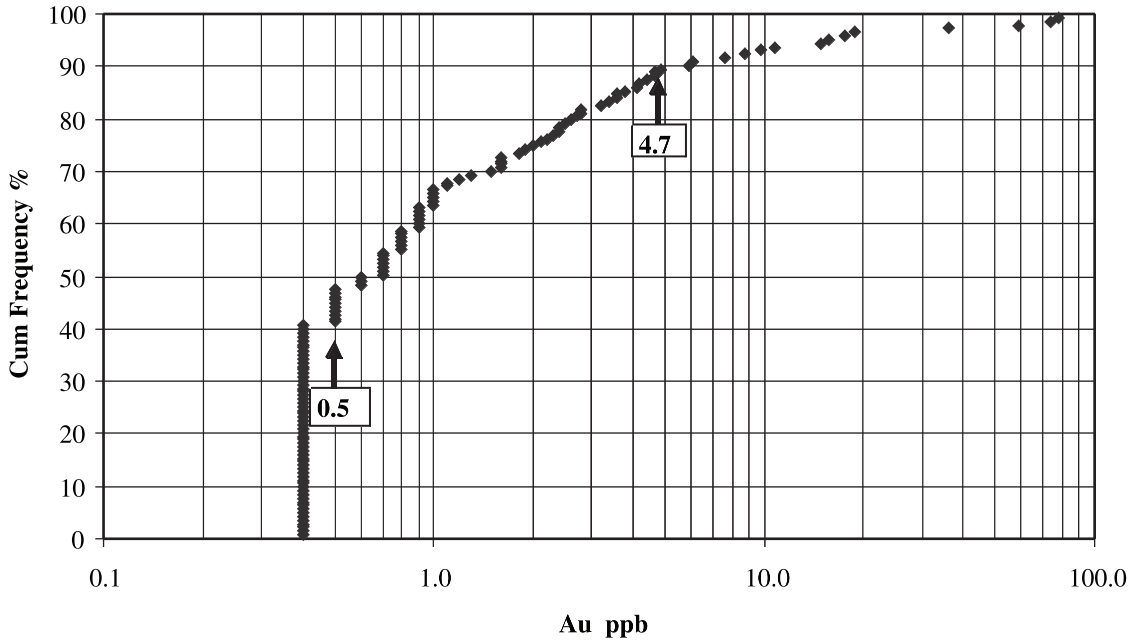


FIG. 2. Cumulative distribution plot of Au in granodiorite and sedimentary rock of the Bendigo region. A total of 142 samples were used. Concentrations of ≤ 0.5 ppb are interpreted to represent gold depletion relative to background values of 0.5 to 4.7 ppb, close to an average crustal abundance for such rocks (Govett, 1983). Values ≥ 4.7 ppb are interpreted to represent gold enrichment.

and west. A gold depletion zone of more then 200 km^2 surrounds and continues to the north of the enriched zones. The depletion zone has been observed both in sedimentary rock and Late Devonian granodiorite (Harcourt intrusion).

The Castlemaine gold field: The Castlemaine deposit is a significantly eroded deposit that has produced 27 t of primary gold and 146 t of alluvial gold. Two zones of gold enrichment are apparent: one in the south, which coincides directly with gold mineralization at Castlemaine, and one in the north, which coincides with four smaller gold fields, from west to east—the Mandurang, Sedgwick, Myrtle Creek, and Lyell deposits (see Fig. 1). Several zones of gold depletion that may be spatially associated with the gold enrichment zones have a combined area of about 300 km^2.

The Fosterville gold field: The Fosterville gold field produced 27 t of primary gold. It occurs within a zone of gold enrichment (30 to 40 km^2) that is surrounded by a zone of gold depletion (150 km^2) subparallel to the Bendigo gold field. Smaller gold fields did not exhibit such as clear pattern, although that may be an expression of sampling density.

Distribution of zinc in regional geochemical samples

The Zn concentrations in granitic and sedimentary rocks range from 3 to 240 ppm. Concentrations between 25 and 110 ppm are considered background (Fig. 3) and are close to the Clark values for these rocks. Concentrations of less than 25 ppm are considered to represent depletion, whereas concentrations of more than 110 ppm are considered to be enriched.

A zone of significant enrichment of Zn surrounds the Bendigo gold field (Fig. 5), with a diameter of about 25 km, although in the center of this zone two of the samples had low Zn concentrations. Other smaller local zinc anomalies correspond to or are near known gold anomalies, including in the areas of the Maldon and Castlemaine gold fields, but many deposits and occurrences are surrounded by rocks with background concentrations of zinc.

A Possible Source of Gold in the Bendigo Region

If the observed zones of gold depletion represent areas from which gold was mobilized, the magnitude of this process can be estimated from the size of the depletion zone. The mean content of gold in surface samples within the depletion zone at Bendigo is 0.4 ppb. The background level in the sampled areas is 1.29 ppb. In this case, the apparent loss of gold from the depletion zone is approximately 70 percent. If the depth extent of the depleted zone is at least 2 km—which seems realistic, as the orebodies at Bendigo have been observed to a depth of 1,400 m—then the volume of depleted rock could be as much as 1,400 km^3 (this figure refers to only the mapped part of the Bendigo gold depletion zone; the zone may extend farther to the north under cover). Mass balance suggests that the loss of gold from a depletion zone of this size could amount from 3,000 to 4,000 t. This analysis does not take into account any effects of shortening or volume loss during deformation, and the extent to which the apparent zones of enrichment and depletion may be controlled by dominant folding pattern is unclear. However, the magnitude of gold depletion corresponds broadly to the past production and remaining resource (identified by drilling) in the Bendigo gold field, plus dispersed mineralization in the enclosing volume of some 100 km^3 (the zone of enrichment), which has an average gold content of 14 ppb. The close correlation between the apparent mass of gold depletion and the mass of

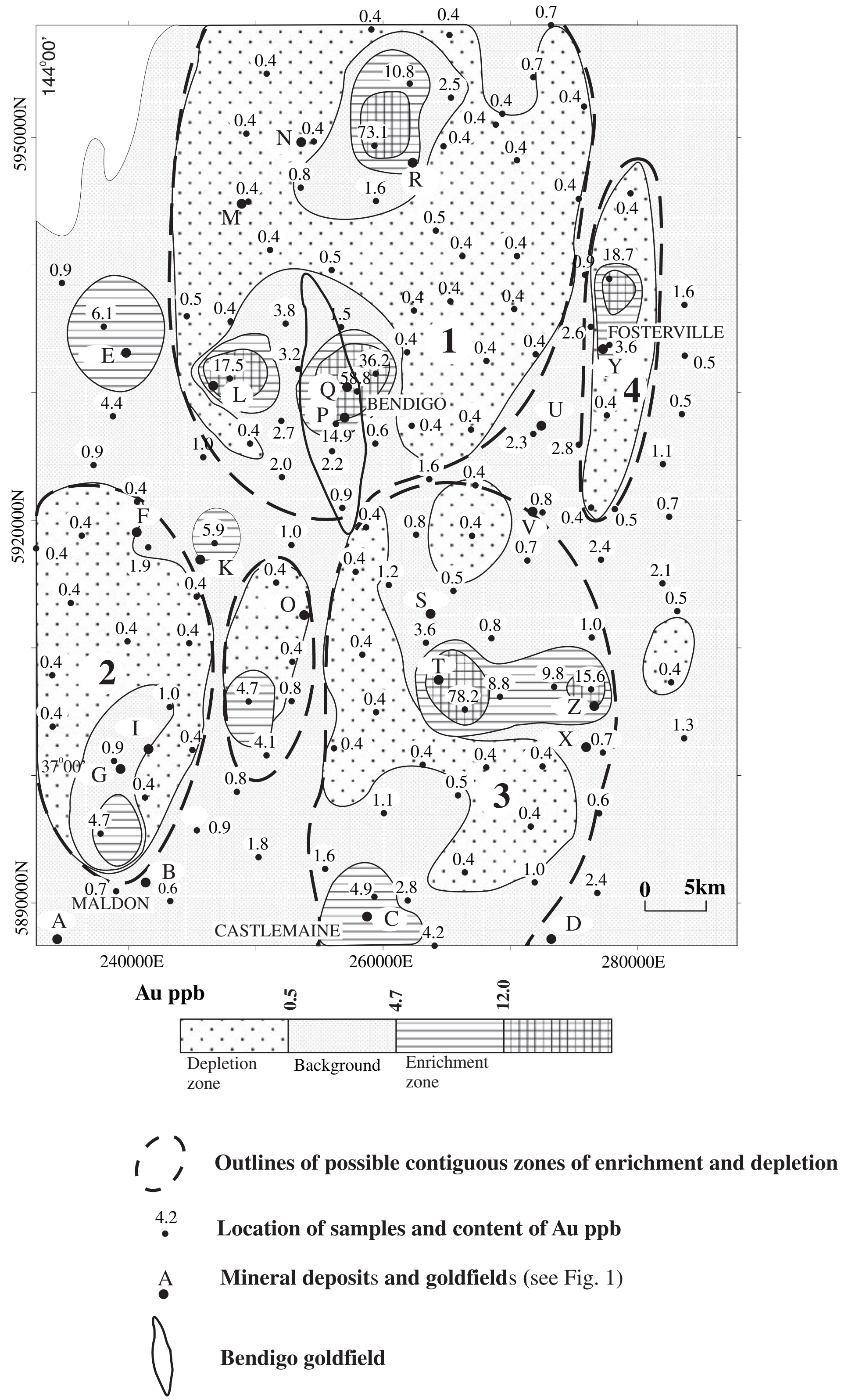


FIG. 3. Distribution of Au in granodiorite and sedimentary rock in the Bendigo (1), Maldon (2), Castlemaine–Myrtle Creek (3), and Fosterville (4) (Bendigo region). The contours of the geochemical anomalies correspond to the levels of concentration in the cumulative distribution plot (cf. Fig. 2). Also shown are the points where rock samples were taken, spaced about 5 km apart, and their gold content. The positions of the gold fields and mineral deposits (after Weston and Nott, 1993) are also shown. Outlines of possible contiguous zones of enrichment and depletion are interpreted to reflect areas in which gold mobilized from one location may have been enriched in an adjacent location (cf. Goldberg et al., 2003).

Table 1. Gold and Zinc Analyses of the Ordovician Sedimentary Rock at the Bendigo Area

Sample no.	X_UTM	Y_UTM	Au (ppb)	Zn (ppm)
1	264056	5886661	4.20	30
2	261938	5890207	2.80	39
3	259321	5890495	4.90	353
4	255448	5892682	1.60	65
5	250212	5893593	1.80	109
6	245354	5895691	0.90	24
7	241273	5898269	<0.5	24
8	237772	5895441	4.70	176
9	238998	5890929	0.70	30
10	243260	5890151	0.60	214
11	276860	5890785	2.40	266
12	277297	5901787	0.70	81
13	277010	5897029	0.60	127
24	266435	5905164	78.20	108
25	269198	5906169	8.80	94
26	273461	5906948	9.80	69
27	268525	5910753	0.80	11
28	265534	5914466	0.50	73
29	263367	5910401	3.60	31
33	259390	5926003	0.60	186
34	262250	5927403	<0.5	3
35	266920	5927101	<0.5	134
36	271826	5926766	2.30	16
37	275390	5925923	2.80	22
38	276373	5920992	<0.5	5
39	272551	5920602	0.80	95
40	267266	5922733	<0.5	26
41	267000	5918785	<0.5	7
42	252806	5905825	0.80	60
43	250828	5901572	4.10	227
44	248503	5898715	0.80	100
45	245000	5902000	<0.5	28
46	238831	5901129	0.90	51
47	249422	5905797	4.70	47
48	243209	5905360	1.00	39
50	246741	5918198	5.90	88
56	235429	5913519	<0.5	32
57	232699	5917789	<0.5	17
58	236302	5918789	<0.5	21
59	240643	5921466	<0.5	119
60	237220	5924327	0.90	78
61	238746	5928142	4.40	31
62	238028	5935166	6.10	252
63	234734	5938588	0.90	35
64	244556	5935979	0.50	29
65	248011	5935579	<0.5	55
66	247948	5931099	17.50	54
67	245860	5924938	1.00	63
68	252795	5918064	1.00	103
69	252042	5923377	2.00	219
70	252004	5927790	2.70	71
71	249534	5926000	<0.5	29
72	253325	5931853	3.20	197
73	252331	5935404	3.80	171
74	251106	5941176	<0.5	9
75	249399	5944967	<0.5	34
76	249241	5950288	<0.5	68
77	254561	5949678	<0.5	14
78	253526	5946060	0.80	144
79	255953	5939608	0.50	309
80	256701	5935131	1.50	51
81	261896	5933160	<0.5	37
82	263636	5923221	1.60	116
83	262600	5918864	0.80	104
84	258667	5919446	<0.5	104
85	256798	5920967	0.90	98
86	257837	5915956	<0.5	40
87	260450	5914924	1.20	110
88	265300	5937150	<0.5	148
89	270320	5936546	<0.5	28
90	268133	5932489	<0.5	122
91	272005	5932997	<0.5	34
92	276346	5935149	2.60	164
93	275882	5939233	0.90	73
94	275391	5945185	<0.5	15
95	275818	5952422	<0.5	62
96	270542	5948209	<0.5	9
97	270537	5940700	<0.5	116
98	266241	5940700	<0.5	84
99	264150	5942693	0.50	270
100	264750	5949300	<0.5	12
101	259323	5949357	73.10	30
102	259441	5945012	1.60	56
103	262436	5936433	<0.5	11
104	259425	5931493	36.20	51
105	255990	5925401	2.20	76
106	256293	5927544	14.90	119
107	257954	5930090	58.80	72
108	277149	5916899	2.40	103
109	271354	5916846	0.70	148
110	276413	5910811	1.00	89
111	276371	5906742	15.60	47
587	250850	5954996	<0.5	34
588	259077	5958457	<0.5	13
589	262100	5954210	10.8	112
590	265229	5958018	<0.5	32
591	265341	5953121	2.5	7
592	269384	5951850	<0.5	16
593	268864	5950998	<0.5	67
594	273213	5958797	0.7	71
595	271830	5954713	0.7	9
596	287010	5941829	<0.5	12
597	287117	5936197	<0.5	278
598	287794	5931381	<0.5	124
599	287830	5926250	<0.5	96
600	287077	5922025	0.5	96
601	283695	5902911	1.3	93
602	282667	5907300	<0.5	92
603	281982	5915057	2.1	197
604	283150	5912877	0.5	59
605	285995	5912406	7.6	96
606	287094	5917958	0.7	34
607	282509	5920265	0.7	69
608	278232	5920867	0.5	15
609	277603	5928215	<0.5	61
610	277810	5933733	3.6	30
611	277794	5938917	18.7	43
612	279466	5945609	<0.5	9
613	283709	5936879	1.6	154
614	283736	5932892	0.5	65
615	283516	5928318	0.5	13
616	282015	5924393	1.1	167
617	287650	5905660	3.4	363

TABLE 2. Gold and Zinc Analyses of the Late Devonian Granodiorite at the Bendigo Area

Sample no.	X_UTM	Y_UTM	Au (ppb)	Zn (ppm)
14	271935	5891622	1.00	71
15	266438	5892400	<0.5	66
16	271625	5896000	<0.5	61
17	272550	5900707	<0.5	61
18	268124	5900624	<0.5	6
19	265895	5898439	0.50	63
20	263118	5900847	<0.5	48
21	260071	5897037	1.10	64
22	256150	5902132	<0.5	67
23	259450	5904950	<0.5	55
30	258373	5909463	<0.5	56
31	252869	5908911	<0.5	95
32	251596	5915115	<0.5	64
49	244746	5910367	<0.5	38
51	245342	5914017	<0.5	43
52	241528	5917876	1.90	12
53	239895	5910512	<0.5	37
54	233997	5903823	<0.5	18
55	233977	5907850	<0.5	9

gold enrichment suggests that depleted sedimentary rock may have participated or contributed to the source of gold in the Bendigo deposits. Similar depletion zones are also present in the other gold fields in the Bendigo region. Figure 6 shows that the size of the depletion zone may provide a first-order indication of the potential of the positive anomaly and the possible scale of the ore metal accumulation.

Although the source of gold in orogenic gold deposits is considered to have been mainly from deeper crustal sources (e.g., Solomon and Groves, 2000), the presence of extensive gold depletion zones adjacent to the major gold deposits of central Victoria suggests that release of gold from adjacent rock types might also have contributed to local gold endowment. This finding may be relevant in the context of metamorphic models for the source of gold in orogenic deposits in which metamorphism of upper crustal sequences is viewed as a source of gold.

Implications for Exploration

This survey has shown that the major ore deposits of the Bendigo region occur within large-scale enrichment zones of the ore elements, in some cases including zinc. In the case of the giant Bendigo gold field, a sampling density of one sample per 25 km^2 identified a clear zone of gold enrichment and depletion, as well as a donut-shaped positive zinc anomaly. The delineation of paired enrichment and depletion zones in regional geochemical surveys may enable an explorer to identify the general location of large and very large deposits at an early stage of exploration. Mapping such geochemical systems is a rapid and low-cost method that provides an important focus for application of other exploration methods.

This paper invites the reader to consider the possibility of a relationship between depletion zones and gold mineralization at the giant Bendigo gold deposit and other large gold deposits nearby. It is presented as a contribution to further discussion on the surface expression of alternative genetic models.

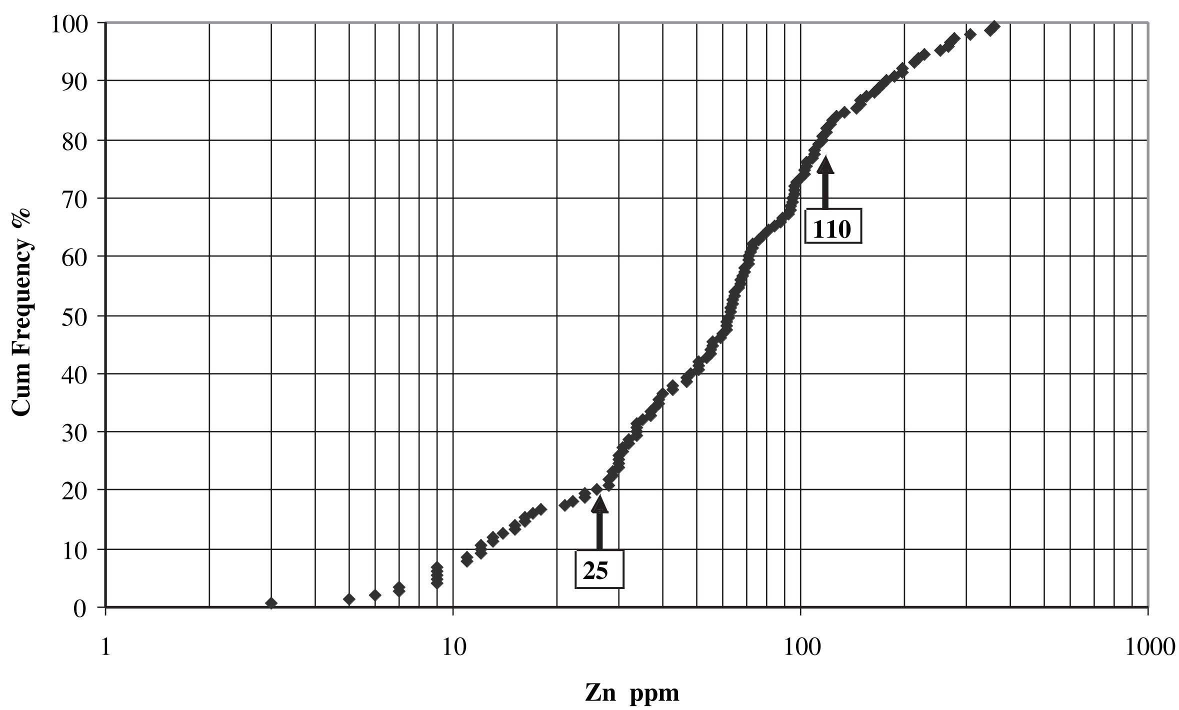


FIG. 4. Cumulative distribution plot of Zn in granodiorite and sedimentary rock of the Bendigo region. A total of 142 samples were used. Concentrations of ≤ 25 ppm are interpreted to represent zinc depletion relative to background values of 25 to 110 ppm, close to an average crustal abundance for such rocks (Govett, 1983). Values ≥ 110 ppm are interpreted to represent zinc enrichment.

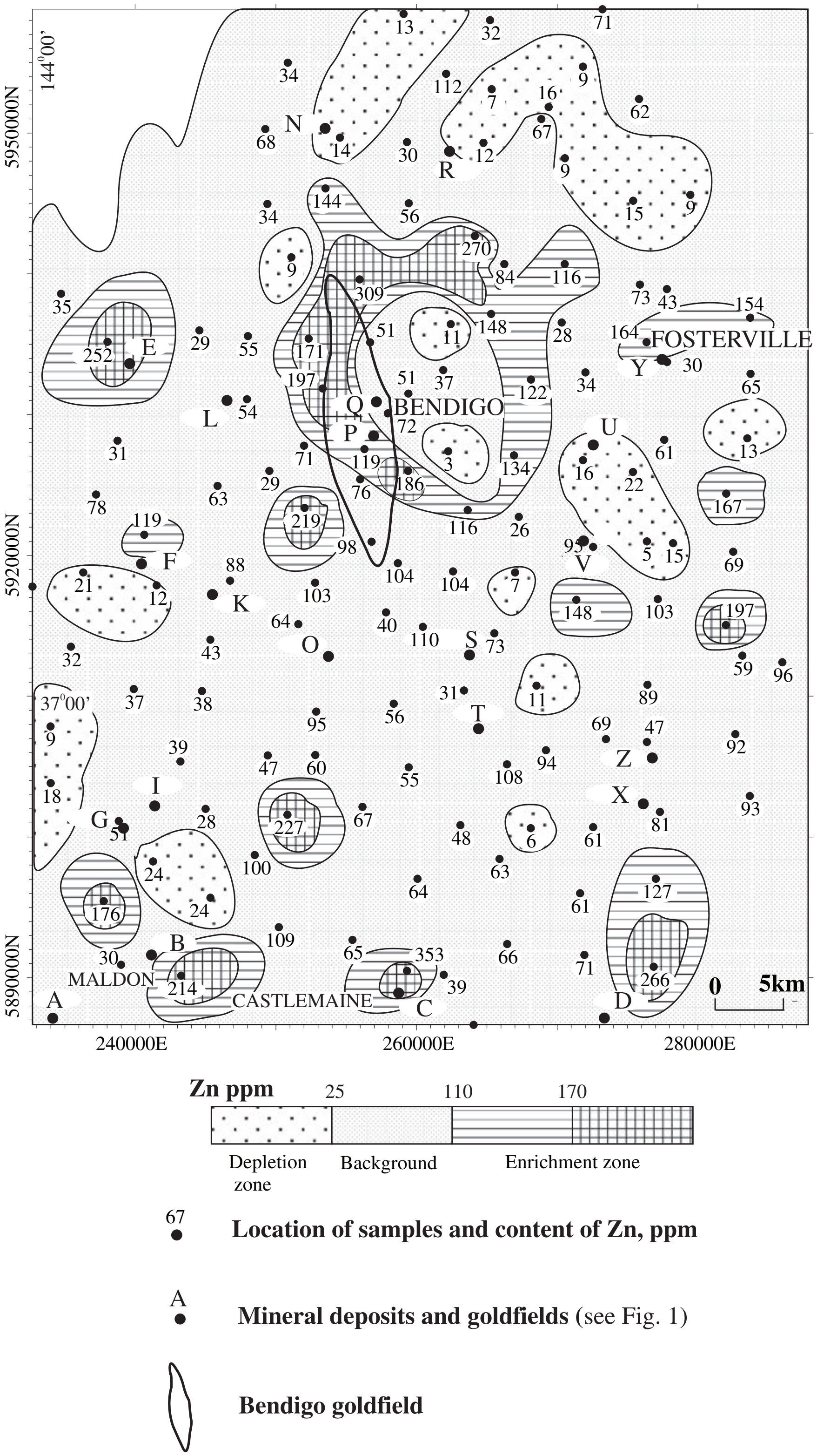


FIG. 5. Distribution of Zn in granodiorite and sedimentary rock in the Bendigo region. Contours of the geochemical anomalies correspond to the levels of concentration in the cumulative distribution plot (cf. Fig. 4). Also shown are the points where samples were taken, spaced about 5 km apart, from host rock, and their zinc content. The positions of gold fields and mineral deposits (after Weston and Nott, 1993) are also shown. Contours show the positions of major gold fields (Bendigo, Maldon and Castlemaine).

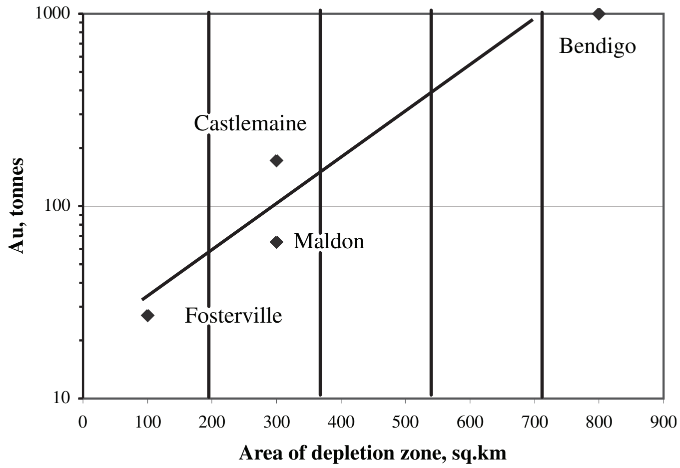


FIG. 6. Correlation between the size of possible gold depletion zones and gold reserves in the gold fields of the Bendigo region (Bendigo, Castlemaine, Maldon, and Fosterville).

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