Geochemical characteristics of ca 3.0-Ga Cleaverville greenstones* and later mafic dykes, west Pilbara: implication for Archaean crustal accretion

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Different tectonic settings proposed for greenstones in the Cleaverville area, west Pilbara, include Archaean oceanic crust in an accretionary complex, oceanic island arc, and intraplate rift. The geochemistry of these greenstones and that of later mafic dykes offers insights to the crustal accretion and changes of tectonic environment with time in this area.

In a previous AGSO Research Newsletter (1998: 28, 25–28), we reported new Nd-isotope and chemical data for felsic and mafic igneous rocks from the west Pilbara. Combined with geochronological data, these data support a model in which juvenile crust formed at different times in the east and west Pilbara Craton in response to plate tectonics and terrane accretion.

Stratigraphic synopsis, Cleaverville area

In the Cleaverville area (east of Karratha; Fig. 30), greenstones with mid-ocean-ridge basalt (MORB) affinities (Regal Formation), and ~3020-Ma felsic volcanic rocks (Cleaverville Formation) with young Nd T_{DM} model ages (3110–3210 Ma), apparently represent juvenile crust. According to Hickman (1997: Geological Survey of Western Australia [GSWA], Annual Report, 76–81), these rocks have depositional ages of ≥3020 Ma (Cleaverville Formation) and ≥3050 Ma (Regal Formation). Over much of the west Pilbara, the Regal Formation stratigraphically underlies the Cleaverville Formation (mostly chert–banded iron formation (BIF) and clastic rocks); the contact is conformable and unfaulted in several places. The Regal Formation is generally in tectonic contact with the 3260-Ma Nickol River Formation, Ruth Well Formation, and Karratha Granodiorite. The entire succession is loosely constrained between 3020 and 3260 Ma. One

* The expression 'Cleaverville greenstones' refers to greenstones in the Regal Formation in the Cleaverville area.

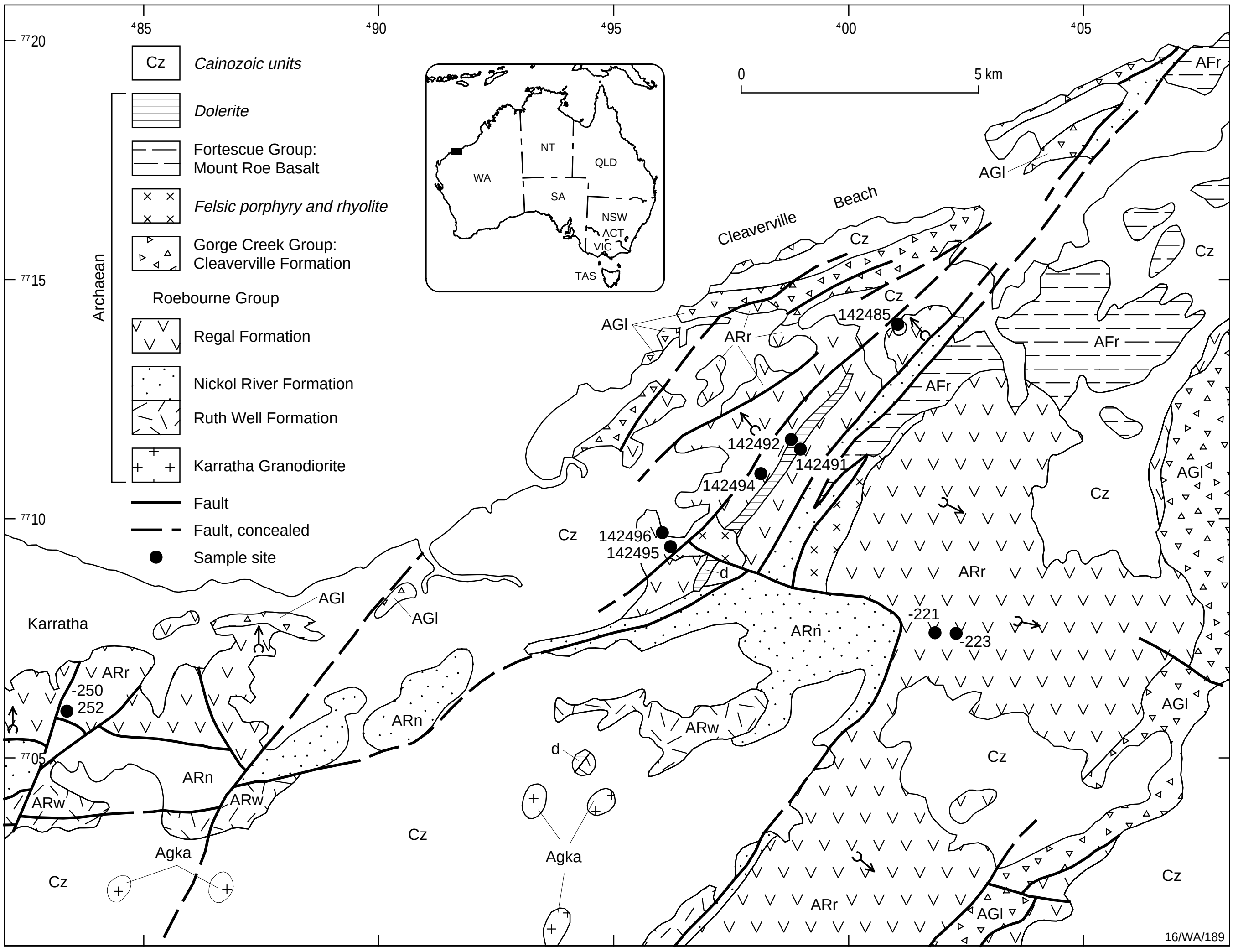

Fig. 30. Simplified geology between Cleaverville and Karratha, west Pilbara, showing Hickman's (1997: op. cit.) revised stratigraphy and sample locations. Note: sample sites annotated '-221', '-223', '-250', and '-252' have the prefix '80040'.

of us (AHH) considers that the Regal Formation (with MORB-like basalts) has been thrust across the 3260-Ma units, apparently from the northeast.

Cleaverville greenstone genesis: conflicting views

Pillow basalts in the Regal Formation greenstone succession were previously interpreted to have been deposited in an intraplate setting. This view was challenged several years ago as a result of 1:5000 field mapping (unpublished) by Y. Isozaki and his Tokyo Institute of Technology colleagues. Based on their extensive field experience with modern accretionary complexes (e.g., Isozaki et al. 1990: Tectonophysics, 181, 179–205; Isozaki & Blake 1994: Journal of Geology, 102, 283–296), Isozaki et al. (1991: EOS, 72, 542) interpreted this sequence as tectonically repeated slices of oceanic crust separated by multiple layer-parallel faults in an accretionary complex generated by subduction of oceanic lithosphere. After a recent visit to the Cleaverville area, R. Blewett (AGSO, personal communication 1999) suggested that the presence of melange, subsequently folded and sheared, may support their hypothesis.

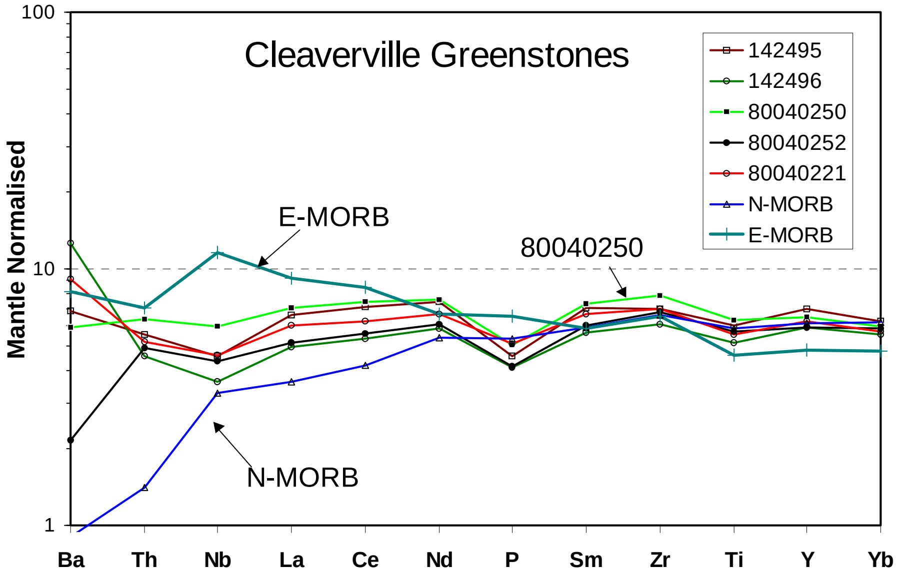

Fig. 31. Mantle-normalised immobile trace-element (except Ba) diagram for MORB-like Cleaverville greenstones. Data of normal mid-ocean-ridge basalt (N-MORB) and enriched MORB (E-MORB) are plotted for comparison.

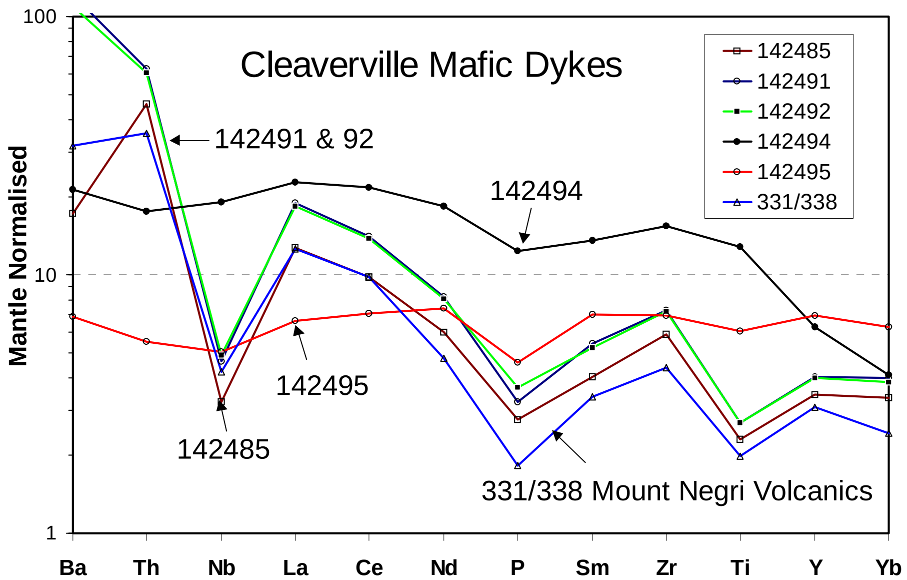

Fig. 32. Mantle-normalised immobile trace-element (except Ba) diagram for ~3.0-Ga Cleaverville dolerite dykes and high-magnesian Louden Volcanics. The pronounced light REE and Th enrichment, and Nb depletion, suggest source modification by subduction zone processes. Sample 142494 (mafic dyke intruding the Cleaverville greenstones) shows intraplate chemical features. A sample (142495) of MORB-like basalts of the Regal Formation is also shown for comparison.

Low-grade greenstones of the Regal Formation in the Cleaverville area were previously studied by Glikson et al. (1986: BMR/AGSO Record 1986/14) and Ohta et al. (1996: Lithos, 37, 199–221). Ohta et al. reported a large variation in Nb/Th (5–60, mostly 5–10) and considerable depletion of Nb (Nb/La=0.4-0.6) for Cleaverville MORB-like basalts with only slightly light REE-depleted patterns. They interpreted this apparent depletion in Nb to core formation. They also attributed a high estimate of total iron in the mantle source of the Cleaverville greenstones relative to pyrolite mantle as a result of incomplete core formation in the early Archaean. This contradicts their interpretation of Nb depletion in their samples.

Ohta et al. suggested that chert and clastic rocks associated with the MORB-like basalts represent an accretionary complex generated by scraping off the subducted oceanic crust. They proposed a gradual change in depositional setting upsequence from a distal oceanic environment (lacking terrestrial input) to a continental margin (sourcing clastic sediments). This conclusion is supported by a detailed study of rare-earth elements (REE) in the Cleaverville Formation (Kato et al. 1998: Geochimica et Cosmochimca Acta, 62, 3475–3497).

In contrast to the model of Isozaki et al., Kiyokawa & Taira (1998: Precambrian Research, 88, 109–142) proposed an oceanic island-arc environment for the Cleaverville greenstones and associated rocks. They interpreted their field observations in terms of three volcano-sedimentary cycles — basalt–rhyolite bimodal volcanism followed by chemical sedimentation. However, the geochemical data they presented appear to be inadequate to support their model.

New chemical and Nd-isotope data

As a contribution to the ‘North Pilbara’ NGMA project†, we investigated the chemistry of Regal Formation greenstones at three localities in the Cleaverville area: south of Karratha; in the study area of Ohta et al. (1996: op. cit.; samples 142495 and 142496; Fig. 30), to cross-check their

† The ‘North Pilbara’ project, a collaborative undertaking by AGSO and GSWA for the National Geoscience Mapping Accord, supported the work documented herein.

data; and southeast of their study area. We also investigated the chemistry of mafic dykes in the Cleaverville area.

Cleaverville greenstones

Major- and trace-element analyses were carried out at AGSO by XRF and ICP–MS for 18 samples. To check the quality of the resulting data, selected samples were further analysed by ICP–MS at the University of Queensland and the Institute for Study of the Earth Interior, Misasa, Japan.

Our new geochemical data (representative samples in Table 2) confirm the MORB-like features of the Cleaverville greenstones (Fig. 31). They show good consistency in Nb/Th (7–8) and Nb/La (0.7–0.9), in marked contrast with the data of Ohta et al. They call into question not only the Nb and Th analyses of Ohta et al. but also the consequential interpretation that the apparent Nb depletion was due to core formation. Furthermore, we suspect that the apparent Fe enrichment relative to pyrolite (estimated for the mantle source of Cleaverville greenstones by Ohta et al.) was due to an increase of MgO as a result of seafloor alteration associated with chlorite formation. Our samples from higher-grade areas do not share this feature.

Table 2. Chemical composition of mafic igneous rocks of the Cleaverville area and south of Karratha

Sample no.	*142495*	*142496*	*80040221*	*80040223*	*80040250*	*80040252*	*142485*	*142491*	*142492*	*142494*
	Basalt	*Basalt*	*Basalt*	*Basalt*	*Basalt*	*Basalt*	*Dolerite dyke*	*Dolerite dyke*	*Dolerite dyke*	*Dolerite dyke*
SiO2	47.41	48.5	49.6	48.1	50.0	49.3	52.06	53.00	53.6	47.99
TiO2	1.31	1.12	1.20	1.14	1.37	1.24	0.50	0.58	0.58	2.79
Al2O3	14.62	14.52	14.7	15.2	14.9	15.2	13.02	16.06	15.54	12.24
Fe2O3	1.96	1.77	2.46	2.46	1.76	2.37	0.87	1.48	1.93	2.46
FeO	10.17	10.07	10.20	9.75	9.65	10.4	8.42	6.98	6.63	11.94
MnO	0.17	0.16	0.25	0.20	0.2	0.15	0.14	0.13	0.13	0.15
MgO	7.54	7.67	7.00	8.00	7.00	7.50	9.9	5.26	5.13	6.06
CaO	10.28	9.75	10.00	9.65	11.2	8.70	7.28	8.45	8.95	10.32
Na2O	1.85	1.97	2.34	1.86	2.16	3.78	2.97	2.55	2.46	1.88
K2O	0.15	0.21	0.15	0.35	0.06	0.04	0.07	1.75	1.13	0.7
P2O5	0.10	0.09	0.11	0.10	0.11	0.09	0.06	0.07	0.08	0.27
LOI	4.23	3.83	0.94	1.92	0.20	0.20	4.37	3.42	3.54	2.76
Rest	0.15	0.14	0.05	0.10	0.10	0.05	0.23	0.22	0.22	0.17
Total	99.94	99.80	100.02	99.76	99.68	100.05	99.89	99.95	99.92	99.73
Li	16.3	15.6	12.8	23.1	5.4	8.5	22	12.7	11.2	4.3
S	290	680	200	160	481	521	830	180	180	1930
Sc	33	36	40	36	36	40	31	28	30	31
V	288	289	323	304	316	310	179	172	181	330
Cr	136	174	186	139	236		937	173	214	109
Ni	144	140	124	147	111	139	203	89	95	110
Cu	95	99	139	104	104	101	53	58	57	124
Zn	110	101	94	90	83	54	84	76	77	147
Ga			16.6	17.0	16.5	16.5				
Rb	6.7	6.9	5.72	16.3	1.7	0.5	1.7	60.3	35.8	22.5
Sr	185.7	115.2	84.2	100.4	110.4	63	59.9	185.7	160.9	374.7
Y	31.8	26.9	28.5	25.4	29.5	27	15.7	18.4	18.2	28.7
Zr	78	68	78	71	88	76	66	82	82	173
Nb	3.6	2.9	3.3	3.0	4.2	3.1	2.3	3.3	3.5	13.6
Cs	0.14	0.27	0.67	1.02	0.06		0.77	3.15	1.56	6.81
Ba	48	88	64	89	41	15	122	850	765	150
La	4.55	3.41	4.15	3.89	4.82	3.55	8.73	13.00	12.64	15.72
Ce	12.61	9.48	11.14	10.25	13.17	9.90	17.5	25.14	24.48	38.60
Pr	1.9	1.50	1.76	1.60	2.08	1.62	1.99	2.72	2.83	5.35
Nd	10.08	7.90	8.99	8.00	10.31	8.22	8.13	11.09	10.95	25.07
Sm	3.13	2.51	2.95	2.64	3.24	2.68	1.78	2.4	2.31	6.05
Eu	1.14	0.93	1.01	0.96	1.12	1.00	0.58	0.77	0.72	2.17
Gd	3.66	3.15	3.83	3.41	4.09	3.97	2.14	3.87	3.71	6.17
Tb	0.74	0.62	0.70	0.62	0.74	0.71	0.37	0.45	0.44	1.01
Dy	4.82	4.15	4.50	4.00	4.74	4.44	2.38	2.94	2.93	5.55
Ho	1.05	0.93	1.00	0.88	1.03	1.06	0.53	0.65	0.63	1.07
Er	2.89	2.54	2.87	2.56	2.98	3.03	1.47	1.81	1.73	2.49
Tm	0.46	0.39	0.44	0.39	0.47		0.23	0.28	0.27	0.34
Yb	3.09	2.74	2.81	2.49	2.93	2.88	1.65	1.97	1.90	2.02
Lu	0.45	0.39	0.43	0.39	0.45	0.43	0.24	0.29	0.28	0.27
Ta	0.22	0.18	0.27	0.20	0.26	0.27	0.19	0.27	0.27	0.86
Pb	0.83	0.52	1.82	0.95	0.85	0.5	4.70	9.03	8.45	1.67
Th	0.47	0.39	0.44	0.42	0.54	0.42	3.91	5.33	5.16	1.50
U	0.12	0.10	0.11	0.10	0.13	0.10	1.14	1.56	1.51	0.41
Nb/La	0.79	0.85	0.80	0.77	0.87	0.87	0.26	0.25	0.28	0.87
Nb/Th	7.66	7.44	7.50	7.14	7.78	7.38	0.59	0.62	0.68	9.07
Th/U	3.92	3.90	4.00	4.20	4.15	4.20	3.43	3.42	3.42	3.66

All samples have slight Nb depletion relative to La, and Th enrichment relative to Nb (Fig. 31). This relative Th enrichment is an atypical MORB character. Unless it is an alteration effect, like Ba, it may instead be due to quicker recycling of crustal material through a subducted zone back into the hotter (100–150°C?) convecting Archaean upper mantle, which is the source region of MORB (e.g., Kerrich et al. 1999: Lithos, 46, 163–187). These MORB-like Cleaverville samples have initial εNd values of +1.0 to +2.5 at 3150 Ma, similar to other early Archaean greenstones.

Northeast-trending doleritic dyke

A mafic dyke (represented by samples 142491, 142492, and 142485) which intrudes the MORB-like basalts is characterised by pronounced light REE and Th enrichment and Nb depletion (Fig. 32). These features are identical with ~2.95-Ga high-magnesian basalts of the Louden Volcanics and Mount Negri Volcanics (sample 331/338 of Sun et al. 1989: in A. J. Crawford, Editor, 'Boninites and related rocks', Unwin Hyman, 148–173). The Louden and Negri Volcanics crop out in the Whim Creek belt (~40–100 km southeast and east of Cleaverville), on the other side of the Sholl Shear Zone (Sun & Hickman 1998: AGSO Research Newsletter 28, 25–28); the distance would have been less than this before post-3020-Ma major sinistral movement along the shear zone.

Sample 142492 has an initial εNd value of –1.5 at 2.95 Ga. This is similar to samples of the Louden and Mount Negri Volcanics, which have initial εNd values of about –2.0 at 2.95 Ga. These initial values are considerably lower than that (~+3) of the depleted mantle at that time and the Cleaverville greenstones. A reasonable explanation for these low initial εNd values, and for the trace-element spidergram patterns of the Cleaverville dolerite dyke and Louden and Mount Negri Volcanics (cf. Fig. 32), is that their mantle source was contaminated by sediments derived mainly from ~3250-Ma source rocks in the region. We suggest that mantle sources of ~3.0-Ga dolerite dykes in the Cleaverville area have been modified by subduction processes (Sun, Nakamura, & Hickman, research in progress). Similarly, geochemical data for basalts in the ca 3.1-Ga Whundo Group (Glikson et al. 1986: op. cit.) south of Cleaverville, across the Sholl Shear Zone, are consistent with juvenile crust generated in a subduction zone environment at this time.

North-trending mafic dyke

A north-trending mafic dyke represented by sample 142494 has intraplate chemical features (Fig. 32). This is similar to the ~2.0?-Ga mafic dyke (sample 86330020) in the Andover Complex, ~20 km to the southeast (Sun & Hoatson 1992: AGSO Bulletin 242, 141–149; Wallace 1992: BMR/AGSO Record 1992/13). If these mafic dykes were emplaced at 1850 Ma, samples 142494 and 86330020 would have initial εNd values of +1.6 and +2.2 respectively. Intraplate mafic dykes of this age (~2.0 Ga) may have been generated in response to interaction between the Pilbara and Yilgarn Cratons.

Implications for crustal accretion and tectonic history of the west Pilbara

Our new geochemical data support the view that the Cleaverville greenstone succession of the Regal Formation represents MORB-like oceanic crust overlain by chert–BIF and clastic rocks of the Cleaverville Formation. Away from the Cleaverville–Karratha area, the Regal Formation is not as structurally complex, and evinces no stratigraphic repetition in this basalt–BIF–chert succession. It appears that only at Cleaverville is there sufficient structural complexity to make a case for some type of accretionary complex produced by subduction of the oceanic crust at a continental margin. One of us (Hickman in preparation) believes that the local structural complexity has another explanation. In terms of Hickman's model, the Regal Formation (with MORB-like basalts) has been thrust across the 3260-Ma units, and — along with the overlying Cleaverville Formation — more likely represents the upper part of an obducted ophiolite.

Subduction zone processes apparently modified the mantle source of ~2.95-Ga mafic rocks over a large area of the northwest Pilbara; similar rocks crop out in the Mallina Basin, southeast of the Whim Creek Belt (Smithies et al. 1999: Precambrian Research, 94, 11–28). The trace-element characteristics of the northeast-trending Cleaverville doleritic dyke and the ~2.95-Ga Louden and Mount Negri Volcanics, such as Nb depletion and Th and Ba enrichment (Fig. 32), may be generated by subduction zone processes. However, an island-arc or cordilleran environment is not essential for the generation of these basalts; rather, many basalts originating in an intraplate environment could have had their mantle source regions modified by prior subduction processes. A closer examination of all pertinent geological information and an integrated interpretation of the data of the Whim Creek Belt and Mallina Basin might reveal the evidence for such processes.

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