High-Mg diorite from the Archaean Pilbara Craton; anorogenic magmas derived from a subduction-modified mantle

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Abstract

Archaean high-Mg diorite (sanukitoid), hitherto described only from Canadian Archaean provinces, is identified in the Mallina Basin of the Pilbara Craton, Western Australia, where it intrudes the metasedimentary rocks in a late-tectonic, extensional setting associated with felsic alkaline magmatism. High-Mg diorite is characterized by unusually high $Mg^{\#}$ (~60), Cr, and Ni for Archaean felsic rocks. The suggested source for these rocks is mantle, metasomatized by a tonalitic melt possibly derived from subducted oceanic crust. However, while subduction appears a necessary precursor, a direct relationship between high-Mg diorite and subduction is negated by the late- to post-tectonic setting. The Pilbara high-Mg diorite suite is a result of remelting of a metasomatized subcrustal source, during a c. 2950 Ma thermal event that probably represented either a plume or lower crustal delamination. Archaean terrains that contain high-Mg diorite also display independent evidence of subduction. These rocks are absent from the eastern part of the Pilbara Craton, where evidence for a post-3440 Ma subduction history is contentious. A spatial relationship between high-Mg diorite and gold mineralization may reflect a common structural control.

KEYWORDS: Archaean, magnesium diorite, granitoid, Pilbara Craton

Archaean high-Mg diorite was first described from the Superior Province of Canada by Shirey and Hanson (1984), who referred to it as 'Archaean sanukitoid' because of geochemical similarities to Miocene high-Mg andesite (sanukite) of the Setouchi volcanic belt in Japan. High-Mg diorite shows higher $Mg^{\#}$[3] (>60) and significant enrichments in Cr and Ni, as well as large ion lithophile elements (LILE e.g. Ba, Sr), compared to most other Archaean igneous rocks of comparable silica content (55–60 wt%). It is parental, via a process of fractional crystallization, to rocks in the compositional range of granodiorite and (rarely) monzogranite, in which these compositional features persist and clearly distinguish this 'high-Mg diorite series' from other Archaean granites. Estimates that these rocks may comprise up to 25% of the Superior Province, and compositional similarities to average Archaean crust, have led to the suggestion that their origin is an important factor in evaluating Archaean crustal evolution (Sutcliffe et al., 1990; Stern and Hanson, 1991; Kelemen, 1995).

We have identified a series of intrusions in the Mallina Basin of the Pilbara Craton (Fig. 1) that together form a high-Mg diorite suite. Like their Canadian counterparts, they intruded a late- to post-tectonic (anorogenic) setting. One pluton, the Peawah Granodiorite, is dated at 2948 ± 5 Ma (Nelson, 1996), and the remainder show intrusive or structural relationships (or both) consistent with a similar emplacement age. The suite was emplaced before voluminous, K-rich, crustally derived syenogranite and monzogranite at c. 2935 Ma, but synchronous with the alkaline Portree Granitoid Complex. In this paper, we briefly document field, petrographic, and geochemical features of the Pilbara high-Mg diorite suite, and discuss their petrogenesis, their significance in terms of crustal evolution, and conclude with some observations related to their possible economic significance.

Regional geology

The granite–greenstone terrane of the Pilbara Craton can be divided into eastern, central, and western components on the basis of distinct structural styles and stratigraphy, and the temporal patterns of granite intrusion. Tonalite–trondhjemite–granodiorite

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3 $Mg^{\#} = Mg^{2+}/(Mg^{2+}+Fe_{Total})\times 100$ with Fe_{Total} as Fe^{2+}.

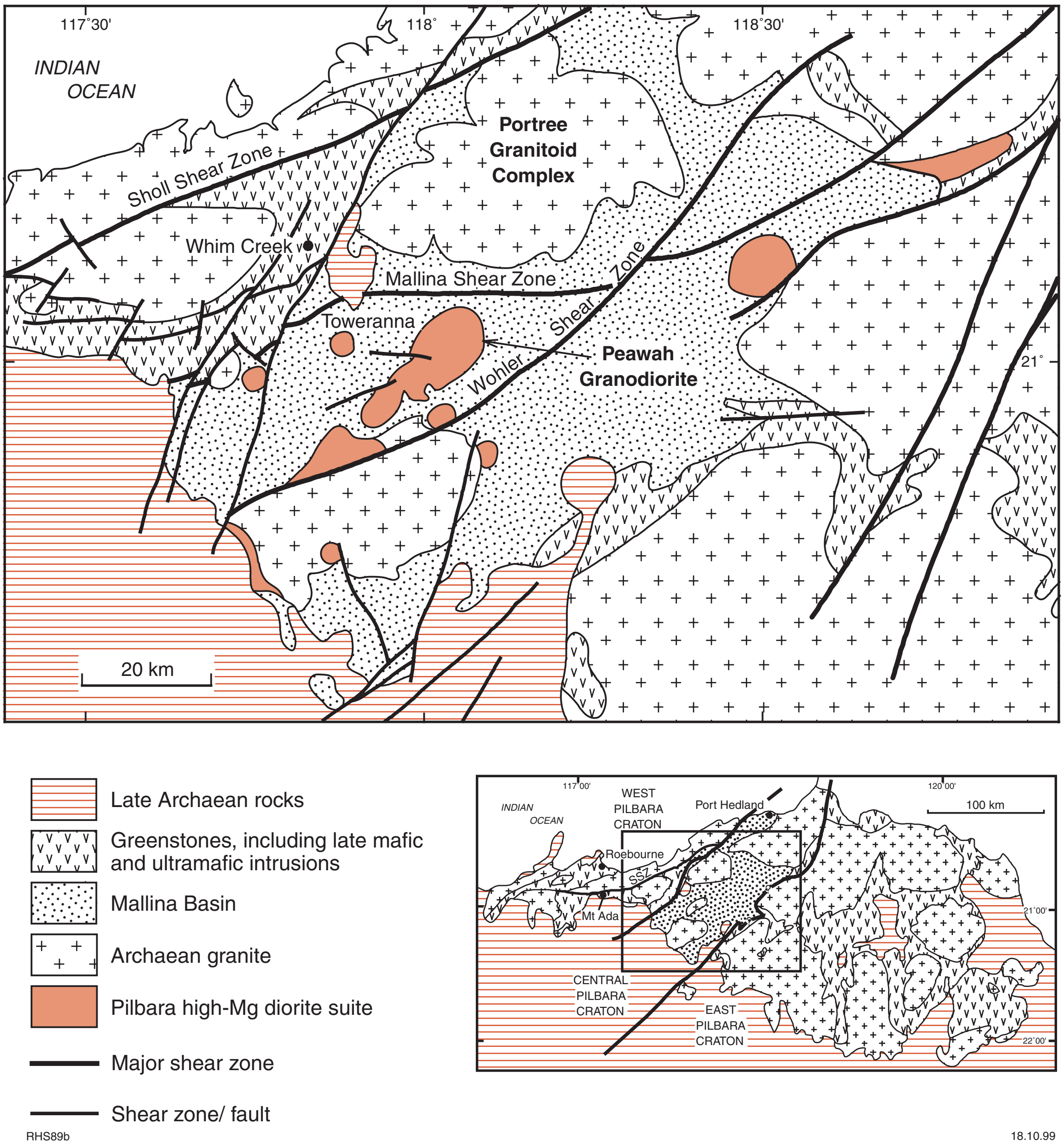

Figure 1. The geology of the central part of the Pilbara granite–greenstone terrane

(TTG)* is a significant but not dominant component of the overall felsic magmatism in the craton (Champion and Smithies, 1998). The older (c. 3600 to 2850 Ma), eastern part of the craton is dominated by large, ovoid, domal, granitoid complexes and enveloping greenstones (Fig. 1). Here, intrusion of TTG, possibly representing juvenile continental crust, was restricted to the period before c. 3420 Ma, thus being essentially confined to the older portions of the Shaw (Bickle et al., 1993) and Mount Edgar (Collins, 1993) Granitoid Complexes. In contrast, the western part of the region is characterized by linear, north-easterly trending outcrop patterns (Fig. 1), with younger and episodic TTG magmatism at c. 3260 Ma, 3100–3120 Ma, and 2990 Ma. The remaining felsic intrusive rocks in the eastern and western parts of the craton include tonalites, trondhjemites, and granodiorites, and later monzogranites and syenogranites. These have higher K_2O (Fig. 2), Y and Yb, lower Al_2O_3, and usually lower La/Yb and Sr, and complex zircon inheritance patterns compared to TTG. They are interpreted to result from low-pressure partial melting, probably of earlier TTG crust (Champion and Smithies, 1998).

* Our use of TTG equates with the high-Al rocks of Barker (1979), characterized at SiO_2 of 70 wt% by Al_2O_3 >15 wt%, low K_2O, low Yb (<1 ppm), high La/Yb (generally >30), Sr and Ba both >500 ppm, and Na_2O/K_2O >1.

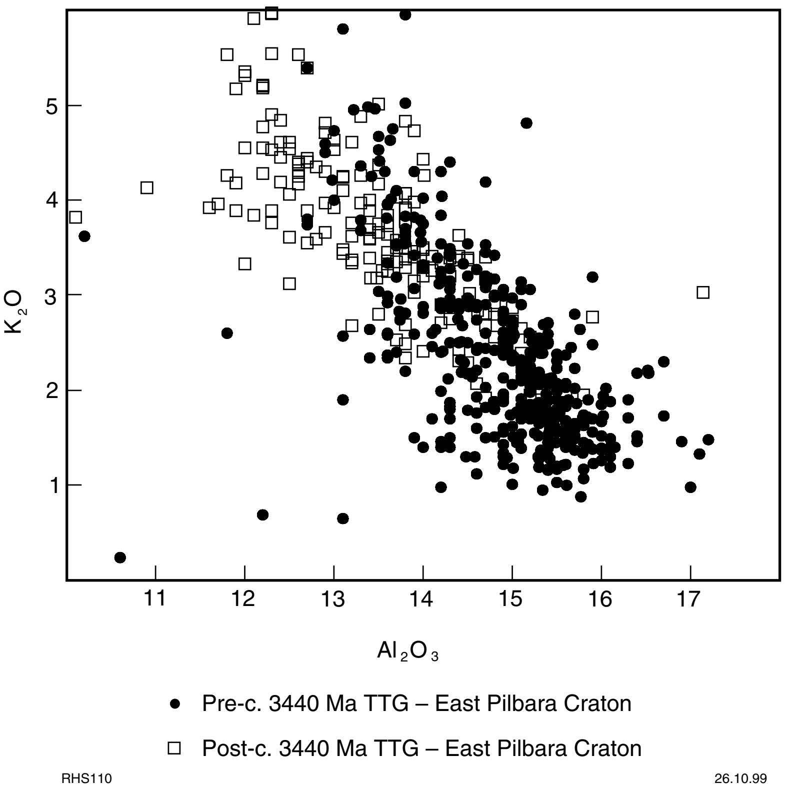

Figure 2. Compositional variation diagram showing the generally more potassic composition of the younger (post-c. 3400 Ma) TTG rocks of the eastern part of the Pilbara Craton

The eastern and western parts of the northern Pilbara Craton are separated by the thick and extensive turbiditic deposits of the c. 3015 to 2940 Ma Mallina Basin, which forms the bulk of the central part of this region (Fig. 1). No TTG outcrops in this region. The high-Mg diorite suite and the alkaline Portree Granitoid Complex intruded the Mallina Basin at c. 2950 Ma and represent virtually the entire exposed products of magmatism of that age. Both suites of rocks intruded the basin at a subvolcanic level, during a second phase of basin extension and deposition that does not appear to be related to subduction. Intrusions that form the high-Mg diorite suite together define an east-northeasterly trending belt that extends for over 200 km (Fig. 1), and parallels the long axis of the Mallina Basin. Late, K-rich granites, which intruded at c. 2935 Ma, are also focused on this central region, and become less voluminous to the west and east.

High-Mg diorite suite

Petrography

The rocks of the Pilbara high-Mg diorite suite range from diorite and monzodiorite through to granodiorite and rare monzogranite. Mesocratic granodiorite dominates within all intrusions of the suite. Plagioclase is the main constituent. Hornblende is the dominant mafic mineral, commonly with cores of either diopside, or actinolite after clinopyroxene. Biotite commonly mantles hornblende. Some samples of diorite also contain bronzite as discrete subhedral grains or as anhedral cores to clinopyroxene phenocrysts. One conspicuous feature of the high-Mg diorite suite is the presence of common, mostly ovoid, enclaves up to 1 m long, which represent the earlier crystallized parts of the magma.

Geochemistry

According to Stern and Hanson (1991), the essential characteristics of least fractionated high-Mg diorite (i.e. with <60 wt% SiO_2) include MgO >6 wt%, $Mg^{\#}$ >60, Ni and Cr each >100 ppm, Sr and Ba each >500 ppm, and high Na_2O, K_2O, light rare-earth elements, and La/Yb. The least fractionated rocks of the Pilbara high-Mg diorite suite approximate these compositions, with $Mg^{\#}$ between 55 and 62, SiO_2 as low as 59 wt%, and up to 224 ppm Cr (Fig. 3) and 120 ppm Ni. The rocks of the Pilbara high-Mg diorite suite vary in silica content (Fig. 3) between approximately 59 and 70 wt%, with high $Mg^{\#}$ (>60 to 40). The rocks show moderate concentrations of Na_2O and K_2O, from 3.5 to 4.8 wt% and 1.7 to 3.3 wt% respectively. High $Mg^{\#}$ are accompanied by high concentrations of Cr (up to 210 ppm), Ni (up to 100 ppm) and V (up to 110 ppm). Amongst the LILE, the concentrations of Sr and Ba are high (Sr of 300–950 ppm; Ba of 450–1600 ppm), but show no clear correlation with silica or $Mg^{\#}$, or with each other. Chondrite-normalized La/Yb ratios increase from approximately 18 to 53 with decreasing $Mg^{\#}$, largely reflecting decreasing concentrations of the heavy rare-earth elements. No Eu anomaly is observed throughout the range of silica contents.

A comparison of the Pilbara high-Mg diorite suite with TTG from the eastern part of the Pilbara Craton shows that both groups have distinctively high LILE and low Nb, Ta, Y, and Yb concentrations, even though the Pilbara high-Mg diorite suite has lower SiO_2, and higher $Mg^{\#}$, MgO, Cr, and Ni. Notable exceptions are some c. 3.45 Ga tonalite gneisses from the Shaw Granitoid Complex (Bickle et al., 1993), which appear to lie compositionally between the high-Mg diorite series and TTG (Fig. 4).

Petrogenesis

A fundamental tenet of igneous petrology is that partial melting cannot produce a liquid with a higher $Mg^{\#}$ than the source (Wilson, 1993). The low $Mg^{\#}$ of crustal rocks suggests that they cannot be a source for high-Mg diorite. This is true even for Archaean basalt, including those of the Pilbara Craton, which typically have $Mg^{\#}$ <60 (Glikson et al., 1986). The source for high-Mg diorite must have

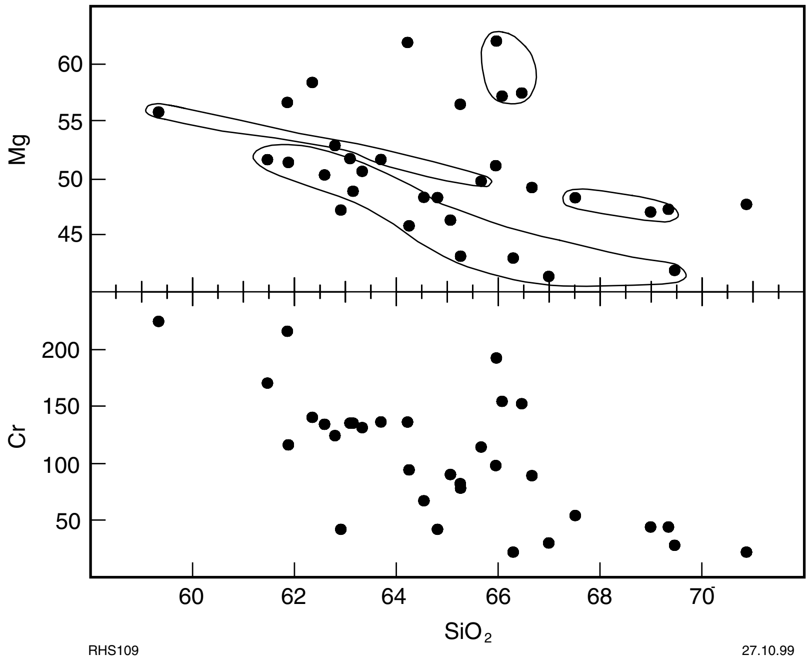

Figure 3. Compositional variation diagram for rocks of the Pilbara high-Mg diorite suite. Groups represent individual intrusions

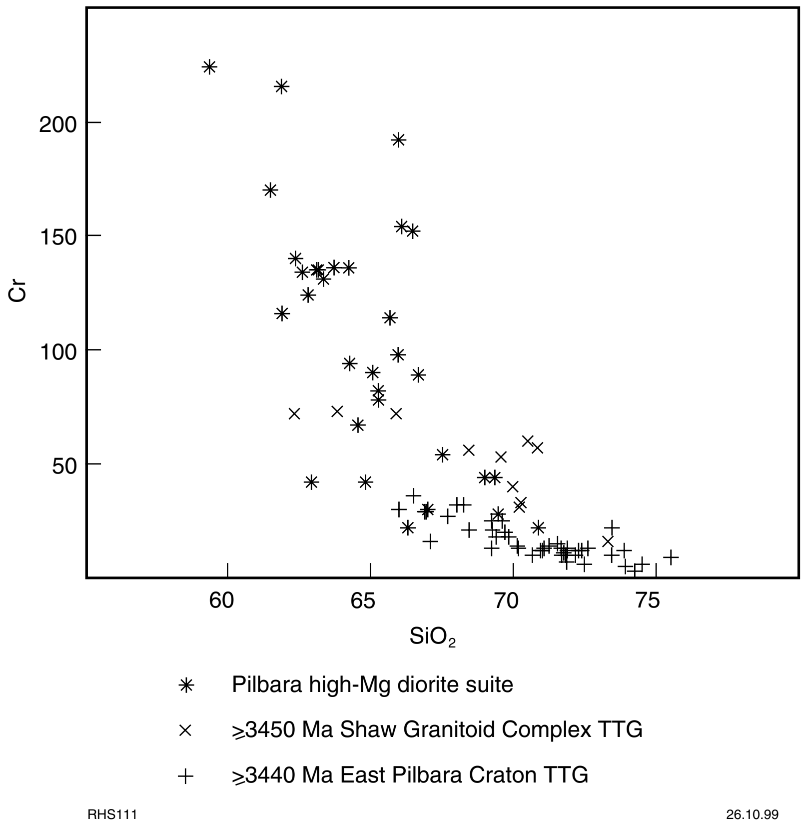

Figure 4. Compositional variation diagram comparing old (≥3450 Ma) TTG rocks of the Shaw Granitoid Complex with other TTG rocks from the eastern part of the Pilbara Craton and with rocks of the Pilbara high-Mg diorite suite

incorporated material with higher $Mg^{\#}$, such as mantle. However, this is unlikely to occur via crustal contamination of a mantle melt, as high-Mg diorite typically has higher LILE concentrations than most crustal material (Stern et al., 1989). Similarly, for the Pilbara high-Mg diorite suite, the fact that some intrusions with higher SiO_2 have higher $Mg^{\#}$ than intrusions with lower SiO_2 (Fig. 3) also suggests that crustal contamination of mantle-derived melt is not a viable mechanism. High LILE concentrations in high-Mg diorite are also accompanied by depletions in Nb, Ta and TiO_2, imparting a distinctive subduction zone signature on the rocks, and suggesting LILE enrichment of a mantle source in an arc environment (Pearce, 1982).

Shirey and Hanson (1984) recognized the compositional similarities between high-Mg diorite and Miocene high-Mg andesite – mantle melts related to active subduction, and accordingly postulated melting of a subduction-modified mantle source. Extending this idea further, Drummond et al. (1996) suggested that high-Mg diorite may form via contamination of Archaean TTG, produced through partial melting of subducting oceanic crust, with mantle peridotite. Archaean TTG is a close *compositional* analogue of Phanerozoic adakite (dacitic magmas with low Cr and Ni, and high LILE and La/Yb ratios) that is produced via melting of subducted hot, young, oceanic crust. Interaction of ascending adakite melt with peridotite is postulated to cause an increase in $Mg^{\#}$, Cr, and Ni, and a decrease in SiO_2, but also essentially preserves the adakite trace-element characteristics (Yogodzinski et al., 1995).

If subduction occurred in the Archaean, the calculated high ancient geotherms suggest that slab melting should have resulted, and may have been a common mechanism for production of Archaean adakitic (TTG) rocks (Martin, 1994). Primitive TTG commonly has slightly higher $Mg^{\#}$, Cr and Ni than experimental melts of basalt under the appropriate pressure and temperature (P/T) conditions (Rapp, 1997), and this perhaps provides evidence for limited interaction between TTG and peridotite, and a priori, for subduction. However, models that compare high-Mg diorite to orogenic high-Mg andesite, and to TTG of possible subduction origin, ignore the anorogenic setting of high-Mg diorite.

Heat flow models (Abbott, 1991) and P/T regimes required for TTG generation (Martin, 1994) suggest that flat subduction is the most appropriate subduction model for the Archaean. In view of the transitional geochemistry of TTG and high-Mg diorite, and the evidence for limited interaction between TTG and peridotite, we suggest that ascending TTG derived from subducted oceanic crust locally ascends through, interacts and, in places, accumulates within mantle wedged between flat subducted oceanic crust and the base of the continental crust. Later remelting of the localized and now strongly metasomatized relict mantle, and metasomatized portions of the adjacent lower crust, could produce high-Mg diorite and alkali granite respectively. Tectonic processes that may cause this remelting include plume tectonics and lower crustal delamination. Both processes would be expressed at the surface by extension, and it is interesting to note that the Pilbara high-Mg diorite suite was intruded along the axis of the extensional Mallina Basin, during a regional thermal event lacking evidence for coeval subduction, and was shortly followed (c. 2935 Ma) by high-K magmatism related to extensive crustal recycling.

It should also be noted that although itself typically anorogenic in setting, high-Mg diorite is found in Archaean terrains that do preserve good independent evidence of subduction, for example the Slave and Superior Provinces of Canada (Davis et al., 1994) and the central and western parts of the Pilbara Province (Ohta et al., 1996). The virtual restriction of TTG to the early (pre-3420 Ma) history of the eastern part of the craton, and the corresponding absence of high-Mg diorite is interesting, and may reflect post-3420 Ma crustal evolution dominated by processes other than subduction.

Possible economic significance

The intrusional locus of the Pilbara high-Mg diorite suite parallels the axis of the Mallina Basin, the site of numerous old and recent gold discoveries. At least one of the intrusions, at Toweranna, approximately 16 km south-southeast of Whim Creek, is mineralized by late, fracture-controlled veins, and at least one other intrusion is within the Mallina Shear Zone, the site of numerous gold discoveries. It is notable that compositionally similar mafic rocks form a very minor component of the Archaean Yilgarn Craton, and appear to be preferred granite hosts for gold mineralization, for example Granny Smith, Liberty, Lawlers, and Porphyry (Champion, 1997). The fact that mineralization appears to post-date intrusion, in both the Yilgarn and Pilbara Cratons, negates a direct genetic link, but it is clear that these small-volume, subcrustally derived magmas are focused into major crustal structures, and represent favourable structural or chemical (or both) traps for gold mineralization.

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