Highly oxidized deep metamorphic zones: occurrence and origin

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Hematitic zones tens of kilometres wide occur in highly metamorphosed terranes; several lie within shear zones. Rocks are characterized by hematite-rich Rhombohedral, now represented by exsolved hematite and ilmenite, coexisting with magnetite and by Mg-rich pyroxenes, the result of Fe being partitioned into oxides. Causes for oxidation have not been discussed in the literature, other than some being attributed to oxidized sedimentary protoliths. However, rocks of diverse origins are affected. We suggest that oxidation was by SO_2-bearing magmatic fluids; infiltration was facilitated by dilation during deformation. There is invariably evidence for intrusion of mafic magma into or below the hematite-bearing zones.

Occurrences of high-temperature metamorphic oxidation

Bamble Shear Belt, Norway: The sedimentary-volcanic sequence of this 30 km-wide shear deformation zone was metamorphosed at 1.1 Ga, accompanied by intrusion of voluminous mafic rocks, followed by isobaric cooling at 8 kbar from 800°C to 540°C. Granulites contain magnetite, hematite-rich Rhombohedral and orthopyroxene with XMg averaging 0.54 for tonalite gneiss and 0.61 for metamorphosed mafic rocks. CO_2 infiltration is evidenced by abundant CO_2-rich inclusions and hydrothermal dolomite rocks with $\delta^{13}C$ in the range of igneous C (Dahlgren *et al.*, 1993). Sulphide and hematite in the dolomite indicate introduction of S under high high f_{O_2}.

Labwor Shear Belt, Uganda: This intensely foliated sapphirine granulite belt, 4 km wide by 13 km long, of Archean age, reached a temperature of ~1000°C, followed by isobaric cooling at 7–9 kbar, suggesting metamorphism during crustal extension and underplating of mafic melt. There is widespread occurrence of hematite-rich Rhombohedral and *X*Mg for orthopyroxenes average 0.71 (Nixon *et al.*, 1973; Sandiford *et al.*, 1987).

Wilson Lake, Labrador: The 100 by 30 km Red Wine Mountains massif is composed of intensely foliated, hematite-rich, sapphirine-quartz granulites, with lenses of two-pyroxene mafic and felsic granulites. Specular hematite layers, and hematite-bearing veins are common. The metamorphic peak at 1.7 Ga, and intrusion of mafic rocks, was followed by near-isobaric cooling from 900°C and 9 kbar to 700°C (Arima *et al.*, 1986). A strong Bouguer anomaly is interpreted to represent mafic rock immediately below the gneiss extending to 10 km depth (Thomas, 1974). Orthopyroxene XMg average 0.79 (Currie and Gittens, 1988) and is similar for gneiss, mafic rocks and oxide-rich bodies, suggesting homogenization of f_{O_2}.

Lofoten-Vestrålen, Norway: At 1.8–1.7 Ga, Archean migmatitic gneisses, granitoids, and Proterozoic supracrustal rocks were metamorphosed at 900°C and 10 kbar, coincident with intrusion of gabbro, anorthosite, and charnockite. Hematite-rich Rhombohedral is widespread (Schlinger, 1985). Depletion in $\delta^{13}C$ at the margins of marble bodies, greatest near to intrusions, is attributed to infiltration of CO_2 from magma (Baker and Fallick, 1988).*Gawler Craton, South Australia*: Metamorphism of these rocks, consisting of quartz, oxides (Rhombohedral and Css) and sillimanite, was near 1000°C, 7–9 kbar and f_{O_2} near the hematite-magnetite (HM) buffer, followed by isobaric cooling (Oliver *et al.*, 1988).

Discussion. For metamorphosed mafic rocks (metabasites) in the Bamble belt, Cameron *et al.* (1993) estimated $\Delta\log f_{O_2}$ (f_{O_2} relative to the FMQ buffer) as +2.7 at 800°C from oxide-orthopyroxene equilibria. Qualitative estimates of $\Delta\log f_{O_2}$ from +1 to more than +3 are obtained from analyses or descriptions of Rhombohedral (Fig. 1). High f_{O_2} for different lithologies contrasts with granulitization under 'dry' conditions, where variation in f_{O_2} inherited from protoliths is retained. Thus, in the Adirondacks, there is a wide range of f_{O_2}, > 8 log units (Valley *et al.*, 1990) and in Angus, Scotland, regional metamorphism retained sharp gradients in f_{O_2} from the original sediments (Chinner, 1960).

A consistent feature is intrusion of large volumes of mafic magma during metamorphism, evidenced by the presence of mafic rocks at Bamble, Lofoten-Vestrålen, and at Wilson Lake. High temperatures of metamorphism, at Labwor,

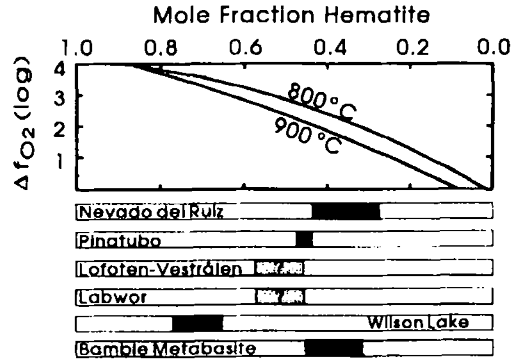

FIG. 1. Top. Curves showing mole fraction hematite in Rhombohedral in relation to (log f_{O_2} (from QUILF, Andersen *et al.*, 1993). Bottom: Compositions of R_{ss}. Solid bars where analyses are available (Wilson Lake, Currie and Gittins, 1988; Bamble metabasite, Cameron *et al.*, 1993); shaded bars estimates based on descriptions of grains (references in text). Also R_{ss} in dacitic pumices from Nevado del Ruiz (Melson *et al.*, 1990) and Mount Pinatubo (Hattori, 1993).

Gawlor and Wilson Lake indicate intrusion below the hematitized zones, which at Wilson Lake is confirmed by gravity data. The occurrence of isobaric cooling paths is consistent with intrusion of melts during extension. At Bamble and Lofoten-Vestrålen there is evidence for mantle melts being the vector for transfer of CO_2-rich fluids, while, at Wilson Lake, hematite in veins in and around the mafic rocks, suggest a relationship between fluids and magma. During degassing, melts release SO_2, along with CO_2. In part, the amount of SO_2 degassed depends on the presence of CO_2. Solubility of CO_2 in melt is low and decreases with declining pressure. When CO_2 is released from melts, other volatiles, such as H_2O and SO_2, are extracted even when their solubility limits have not been exceeded. On passing through cooler rocks, SO_2-bearing fluid increases in f_{O_2} relative to silicate-oxide buffers (Hattori, 1993), and will act as an oxidant: $2\ SO_2 + 2\ H_2O = 2\ H_2S + 3\ O_2$.

For the Bamble belt, mass balance calculations show that oxidation requires an approximately equivalent mass of mafic magma. Sulphur-isotope homogenization in Bamble rocks is consistent with infiltration of S-rich fluid. The spread of $\delta^{34}S$ in metasedimentary rocks decreases with increasing metamorphic grade and in the highest grade zone $\delta^{34}S$ values for sulphides approach 0 ‰, similar to that of mafic rocks (Andreas, 1974).

The proposed mechanism is a lower crustal analogue of the oxidation of dacitic magma at Mount Pinatubo and Nevado del Ruiz by SO_2 released from mafic melt (Hattori, 1993). Estimated f_{O_2} for the dacites is similar to that for the deep metamorphic occurrences. Seismic monitoring of active volcanoes commonly record activity relating to gas release to depths of over 35 km. Deformation-related dilation would permit fluids released from magma emplaced in shear zones to permeate host rocks.

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