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Distribution, mineralogy and geochemistry of silica-iron exhalites and related rocks from the Tyrone Igneous Complex: Implications for VMS mineralization in Northern Ireland

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ABSTRACT

Iron formations, hematitic cherts (jaspers), 'tuffites', silica-iron exhalites and other metalliferous chemical sedimentary rocks are important stratigraphic marker horizons in a number of volcanogenic massive sulfide (VMS) districts worldwide, forming during episodes of regional hydrothermal activity. The VMS prospective ca. 484–464 Ma Tyrone Igneous Complex of Northern Ireland represents a structurally dissected arc-ophiolite complex that was accreted to the composite margin of Laurentia during the Grampian orogeny (ca. 475–465 Ma), and a potential broad correlative to the VMS-rich Buchans–Robert's Arm arc system of the Newfoundland Appalachians. Silica-iron-rich rocks occur at several stratigraphic levels in the Tyrone Igneous Complex spatially and temporally associated with rift-related basalts (e.g., Fe–Ti-rich eMORB, IAT, OIB) and zones of locally intense hydrothermal alteration. In the ca. 475–474 Ma lower Tyrone Volcanic Group, these rocks are characterized by massive, 1–5 m thick blood-red jaspers, hematitic siltstones and mudstones, and intensely silica-hematite altered tuffs and flows. Their mineralogy is dominated by quartz–hematite ± magnetite–(chlorite-sericite ± tremolite/actinolite), with Fe concentrations rarely exceeding 10 wt.%. Relict textures (including the presence of coalesced spherules of silica-iron oxides) in rocks exposed at Tanderagee NW, Creggan Lough and Tory's Hole are indicative of seafloor exhalation, whereas replacement of the original volcanic stratigraphy is evident to varying degrees at Tanderagee, Beaghbeg and Bonnety Bush. In the structurally overlying ca. 473–469 Ma upper Tyrone Volcanic Group, chemical sedimentary rocks include recrystallized: (i) thin and laterally-restricted jaspers in thick sequences of graphitic pelite at Boheragh; and (ii) laterally-persistent sulfidic cherts and ironstones dominated by quartz–hematite–magnetite–(chlorite) or quartz–pyrite–(chlorite) in sequences of tuff at Broughderg. Compared to chemical sedimentary rocks associated with VMS deposits worldwide, their geochemical characteristics are most similar to silica-iron exhalites of the Mount Windsor Subprovince (SE Australia) and jaspers of Central Arizona, Bald Mountain (Northern Maine), the Urals, Iberian Pyrite Belt and Løkken ophiolite (Norway). Positive Eu anomalies (at Slieve Gallion and Tanderagee NW), elevated Cu + Pb + Zn, Au, Fe/Ti, Fe/Mn, Sb, Ba/Zr and Fe + Mn/Al, together with low REE, Sc, Zr and Th, are indicative of a greater hydrothermal component and potentially more VMS-proximal signatures. Based on bulk ironstone geochemistry, Bonnety Bush, Tanderagee NW-Creggan Lough, Broughderg and Drummuck (Slieve Gallion) are considered the most VMS prospective areas in the Tyrone Igneous Complex and warrant further exploration.

1. Introduction

Iron formations, hematitic cherts (jaspers), 'tuffites', umbers, silica-iron exhalites and other metalliferous chemical sedimentary rocks (e.g., sulfidic cherts and mudstones; Table 1) form important stratigraphic

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Table 1
Definitions for chemical sedimentary rocks used herein.

Term	Definition	References
Ironstone (sensu stricto)	Sedimentary rock that contains >15 wt.% Fe. Includes: iron formations, metalliferous sediments, Fe–Mn nodules, pavements and crusts.	Stow (2005)
Iron formation	Layered, bedded or laminated rocks with >10 wt.% Fe, where iron minerals are interlayered with quartz, chert or carbonate. Divisible into Superior- and Algoma-types. Referred to as banded iron formation (BIF) in Precambrian terranes.	Gross (1980), Spry et al. (2000), Bekker et al. (2010)
Chert	Fine-grained siliceous sedimentary rock of biogenic, biochemical or chemogenic origin. Composed predominantly of fine-grained silica with small quantities of impurities. Green colors are typically associated with chlorite or smectite clays from volcaniclastics, and dark colors with clays and organic carbon.	Stow (2005)
Hematitic chert/jasper	Red colored chert, with its color imparted by finely disseminated hematite. May be recrystallized or show poikilitic textures with cryptocrystalline hematite dispersed in a silica matrix. Of variable thickness (few cm to >10 m).	Maslennikov et al. (2012)
Sulfidic chert/mudstone	Chert/mudstone with visible sulfide minerals above trace amounts (i.e. >1%).	Defined herein
Iron-rich chert	Chert with a high content of iron oxide minerals and 5–15 wt.% Fe.	
Jaspillite	Interbedded jasper and hematite. Australian term for a banded iron formation (BIF).	Allaby (2013)
Tetsusekiei	Iron quartz in Japanese. Generic name used for silica-iron rich chemical sedimentary rocks of the Kuroko district, Japan. Interpreted as a mixture of both clastic (tuffaceous) and exhalative (chemical) material.	Kalogeropoulos and Scott (1983)
Tuffite (sensu lato)	Generic name used for tuffaceous chemical sedimentary rocks (often referred to as tuffaceous exhalites) in the Abitibi greenstone belt, Canada. Examples: Key Tuffite, Main Contact Tuff.	Kalogeropoulos and Scott (1989)
Tuffite (sensu stricto)	A rock which contains a mixture of pyroclastic (25–75%) and epiclastic material. May be divided according to average clast size into tuffaceous conglomerate/breccias, tuffaceous sandstone, tuffaceous siltstone, and tuffaceous mudstone/shale.	Le Maitre (2004)
Umber (or umbrite)	A sedimentary deposit of Fe–Mn oxyhydroxides admixed with variable amounts of biogenic and detrital material (e.g., chlorite, silica and carbonate) forming trace-metal enriched mudstones.	Maslennikov et al. (2012) and references therein
Ochre	Gossan-derived unmetamorphosed ferruginous sediments (e.g., Semail Nappe and Troodos, Cyprus).	
Jasperite	Orange hematite–quartz rocks differentiated from jaspers on account of microbreccia-like textures and abundant features indicative of replacement inherited from former hyaloclastite. Fragments of fine grained hematite–quartz aggregates are cemented by a blocky quartz matrix. Jasperites can occur as veins, interpillow interstitial infillings, stratiform lenses, beds and interbeds.	
Gossanite	A submarine gossan-derived sedimentary rock and the lithified analogues of ochres. Generally comprise oxidized clastic sulfides mixed with hematitized carbonate and/or hyaloclastic material almost entirely replaced by silica, chlorite and hematite.	
Exhalite	A unit formed through precipitation of mainly amorphous Fe ± Mn ± Si ± S ± Ba ± B phases from VMS-related hydrothermal vents and plumes at or below the seafloor.	Peter and Goodfellow (1996, 2003), Grenne and Slack (2005), Slack (2012)
Vasskis	Beds of silicate- and sulfide-facies iron formation in Norway (e.g., Løkken district).	Slack (2012)

horizons in a number of volcanogenic massive sulfide (VMS) districts worldwide. These units often mark the most prospective sequences for mineralization and can occur stratigraphically above, below, in, or along strike from orebodies (Galley et al., 2007; Kalogeropoulos and Scott, 1983, 1989; Leistel et al., 1998; Peter, 2003; Peter and Goodfellow, 1996; Spry et al., 2000). Classic examples include the tetsusekiei (iron quartz) of the Fukazawa Mine, Japan (Kalogeropoulos and Scott, 1983; Tsutsumi and Ohmoto, 1983); 'tuffites' of the Abitibi greenstone belt, Canada (Genna et al., 2014a; Kalogeropoulos and Scott, 1989; Liaghat and MacLean, 1992); jasperites, gossanites and umbers of the Urals (Herrington et al., 2005; Maslennikov et al., 2012); and iron formations of the Brunswick Horizon of the Bathurst Mining Camp, Canada (Peter and Goodfellow, 1996).

Based on interpreted depositional settings, silica-iron-rich chemical sedimentary rocks were originally divided into two groups by Gross (1980, 1983): Algoma- and Superior-type iron formations. Although Algoma-type iron formations are mineralogically similar to Superior-type iron formations, the former are volcanic-hosted, deep-water and commonly associated with VMS mineralization (Bekker et al., 2010; Slack et al., 2007). Algoma-type iron formations form in volcanic arcs, backarcs, spreading ridges and rifts, and have been interpreted by a number of workers to precipitate from the venting of hydrothermal fluids contemporaneous with volcanism (Peter, 2003; Slack et al., 2007). Jaspers form as silica-iron gels, precipitated from the non-buoyant parts of hydrothermal plumes; ferrous iron is oxidized to insoluble ferric iron oxyhydroxides, which in turn promotes the flocculation of seawater-derived amorphous silica (Slack et al., 2007). Deposits of silica-rich iron oxyhydroxides have been documented on the modern seafloor associated with a number of hydrothermal systems (German et al., 1993; Halbach et al., 2002; Hekinian et al., 1993; Juniper and Fouquet, 1988), although many of these are laterally restricted (Grenne and Slack, 2003). Superior-type iron formations, by contrast, are characterized by interlayered chert and iron oxides in shallow-water sedimentary sequences (Slack et al., 2007). As these rocks are not associated with VMS-mineralization, they are not discussed further.

The Caledonian–Appalachian orogenic belt (Fig. 1A) hosts significant VMS mineralization along its length from Quebec, through New Brunswick and Newfoundland (Piercey, 2007; van Staal, 2007), into Ireland (e.g., Avoca; McConnell et al., 1991), Great Britain (e.g., Parys Mountain; Colman and Cooper, 2000; Barrett et al., 2001) and Scandinavia (Grenne and Vokes, 1990; Grenne et al., 1999). The ca. 484–464 Ma Tyrone Igneous Complex of Northern Ireland (Fig. 1B), a structurally dissected arc-ophiolite complex, has been a target for base and precious metal exploration since the early 1970s (Clifford et al., 1992; Leyshon and Cazalet, 1978; Peatfield, 2003). Recently established temporal, lithological and geochemical similarities with the VMS-rich Buchans–Robert's Arm arc system of central Newfoundland (Cooper et al., 2011; Hollis et al., 2012, 2013a; see Table 2), indicate that the Tyrone Igneous Complex is prospective for VMS mineralization (Hollis et al., 2014, in press). The Buchans–Robert's Arm belt hosts high-grade Kuroko-type VMS deposits at Buchans (16.2 Mt mined at 14.51% Zn, 7.56% Pb, 1.33% Cu, 126 g/t Ag and 1.37 g/t Au: Thurlow, 2010), as well as smaller Cyprus-type and Noranda-type deposits elsewhere (Piercey and Hinchey, 2012; van Staal et al., 2007). Stratigraphic horizons have been identified in the Tyrone Igneous Complex that are prospective for VMS mineralization, characterized by rift-related mafic flows (e.g., IAT, eMORB), geochemically 'fertile' felsic rocks (i.e. indicative of melting at shallow levels and elevated crustal heat flux; after Lesher et al., 1986; Hart et al., 2004), zones of locally intense hydrothermal alteration, base and precious metal occurrences, geophysical anomalies, and in some instances