

12. Using Tellus data to enhance targeting of volcanogenic massive sulphide mineralisation in the Tyrone Igneous Complex

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The Tyrone Igneous Complex of Northern Ireland has been a target for base and precious metal exploration since the 1970s. Historic exploration was hampered by poor exposure and consequently a limited understanding of the local geology. Extensive new field mapping, utilising the high-resolution Tellus geophysical survey, coupled with U-Pb zircon geochronology and whole-rock geochemistry, has greatly improved our understanding of the complex and its potential to host volcanogenic massive sulphide (VMS) mineralisation. Targeting of Tellus and historic, geochemical and geophysical anomalies along VMS prospective stratigraphic horizons has identified new mineral occurrences and areas for further exploration. A correlation has been made with the Buchans–Robert's Arm arc system of Newfoundland, host to numerous economic deposits.

INTRODUCTION

VMS deposits are ancient accumulations of base and precious metal sulphides that formed at or under the seafloor (Fig. 12.1). Deposits formed through the precipitation of sulphides from metal-enriched, high-temperature hydrothermal fluids during mixing with seawater. Heat was derived from contemporaneous volcanism, with metals such as iron (Fe), copper (Cu), lead (Pb) and zinc (Zn) leached from underlying rocks (Galley *et al.*, 2007). Modern analogues are well documented, and firmly established in the public

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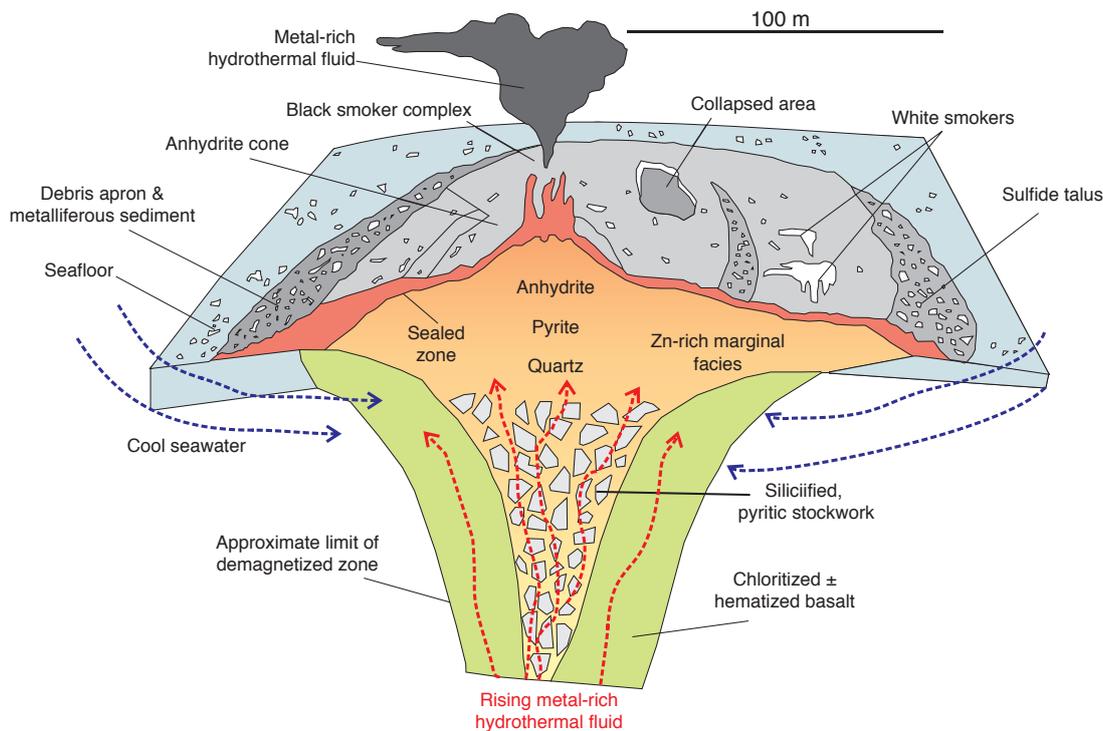
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consciousness through media interest in black smoker systems teeming with life at water depths of ~500 to 5000 m.

The Ordovician Tyrone Igneous Complex of Northern Ireland (Fig. 12.2) covers ~350 km² within counties Tyrone and Londonderry, and includes the remnants of an island arc system and subduction-related ophiolite accreted to the continental margin of Laurentia at *c.*470 Ma (Cooper *et al.*, 2011). This event represents an early phase of the closure of the Iapetus Ocean, which eventually resulted in the amalgamation of Great Britain and Ireland by *c.*420 Ma (the Caledonian orogeny). This mountain belt continues through North America (the Appalachians), where over 40 VMS deposits have been recognised in Newfoundland alone (Piercey, 2007). Although the Tyrone Igneous Complex has been a target for base and precious metal exploration since the 1970s, no occurrences of economic size have yet been identified. Mineral exploration across much of Ireland is hampered by poor exposure, due to extensive peat cover and thick glacial deposits. This contribution details how Tellus data were used for field mapping and the subsequent targeting of mineralisation.

METHODS

Approximately six months of geological mapping was undertaken across the Tyrone Igneous Complex during the summers of 2009 and 2010 (Hollis, 2013), preceded by visual

Figure 12.1. Schematic diagram of the modern TAG volcanogenic massive sulphide deposit on the Mid-Atlantic Ridge, which represents a classic cross-section through a mafic-hosted VMS deposit (redrawn after Galley *et al.*, 2007).

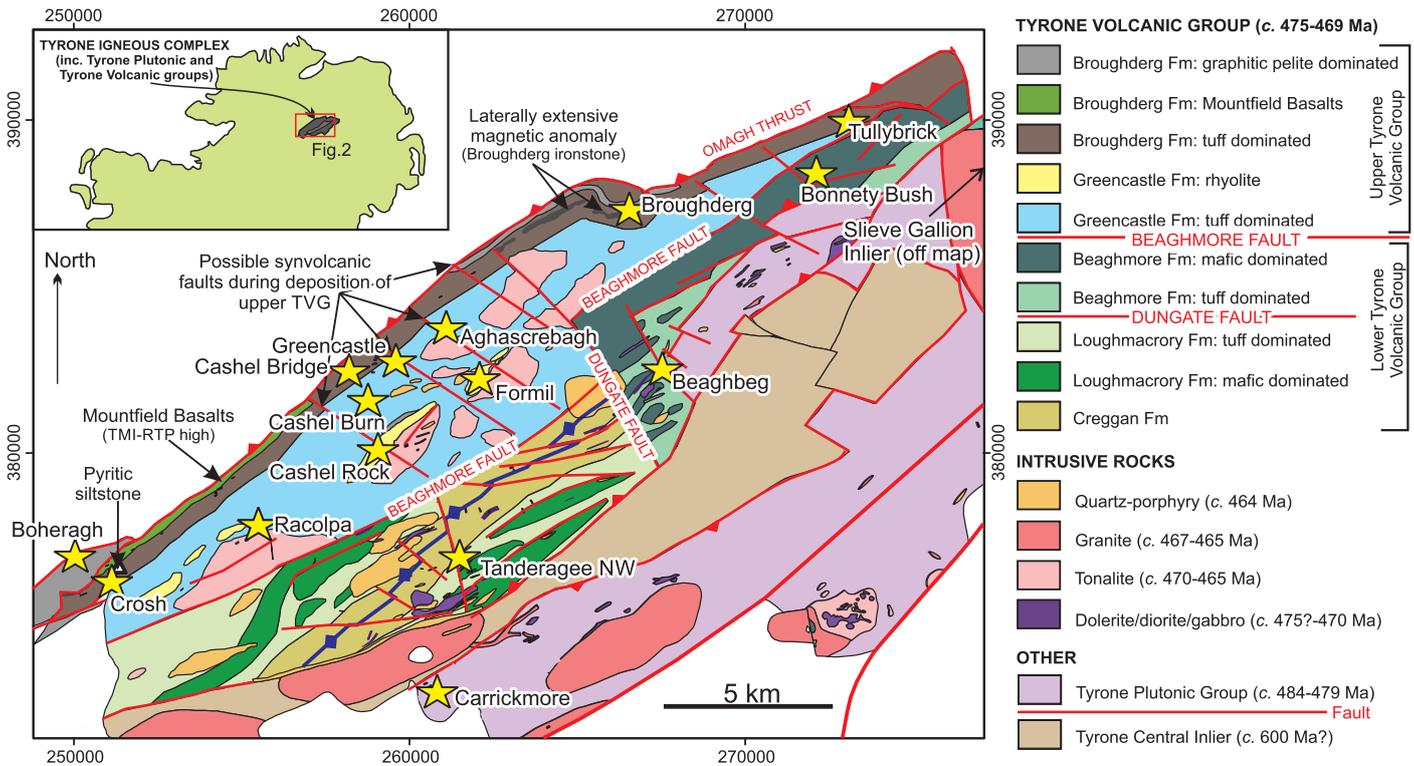


Figure 12.2. Geological map of the Tyrone Igneous Complex (modified after Hollis *et al.*, 2012, 2014). Possible synvolcanic faults are identified based on the termination of stratigraphic units along strike. Stars denote areas discussed herein.

interpretation of Tellus geophysical imagery. As exposure across much of the complex is poor, all stream sections in the volcanic sequence were traversed and known outcrops examined to characterise the stratigraphy and select appropriate samples for geochemistry. This detailed mapping targeted geological boundaries and areas of increased exposure (e.g., Tanderagee, Crosh, Formil; Hollis, 2013; Fig. 12.2). Tellus total magnetic intensity (TMI) imagery and its digital transformations of reduced to pole (RTP; Fig. 12.3a), first vertical derivative (IVD) and tilt-angle were used to define the extent of magnetite-bearing basalt, dolerite, gabbro and ironstone in the structurally lower levels of the complex. Electrical conductivity imagery highlighted the lateral extent of thick sequences of graphitic pelite around Broughderg and Boheragh in the uppermost part of the stratigraphy (Fig. 12.3b), confirmed through fieldwork, and subsequently in 2011 by drilling. Faults are clearly identified from the offset of magnetic units along strike (e.g. Slieve Gallion, Tanderagee). Tellus geophysical data allowed isolated outcrops in the Tyrone Igneous Complex to be placed in a detailed structural and stratigraphic framework for the first time (Hollis *et al.*, 2012, 2013a). This then provided the context for whole-rock geochemical analysis and high-resolution uranium–lead (U-Pb) zircon geochronology.

Approximately 450 samples from outcrop and historic drillcore were analysed for whole-rock geochemistry at the British Geological Survey and University of Southampton (described in Hollis *et al.*, 2012). Sixteen samples from the Tyrone Igneous Complex

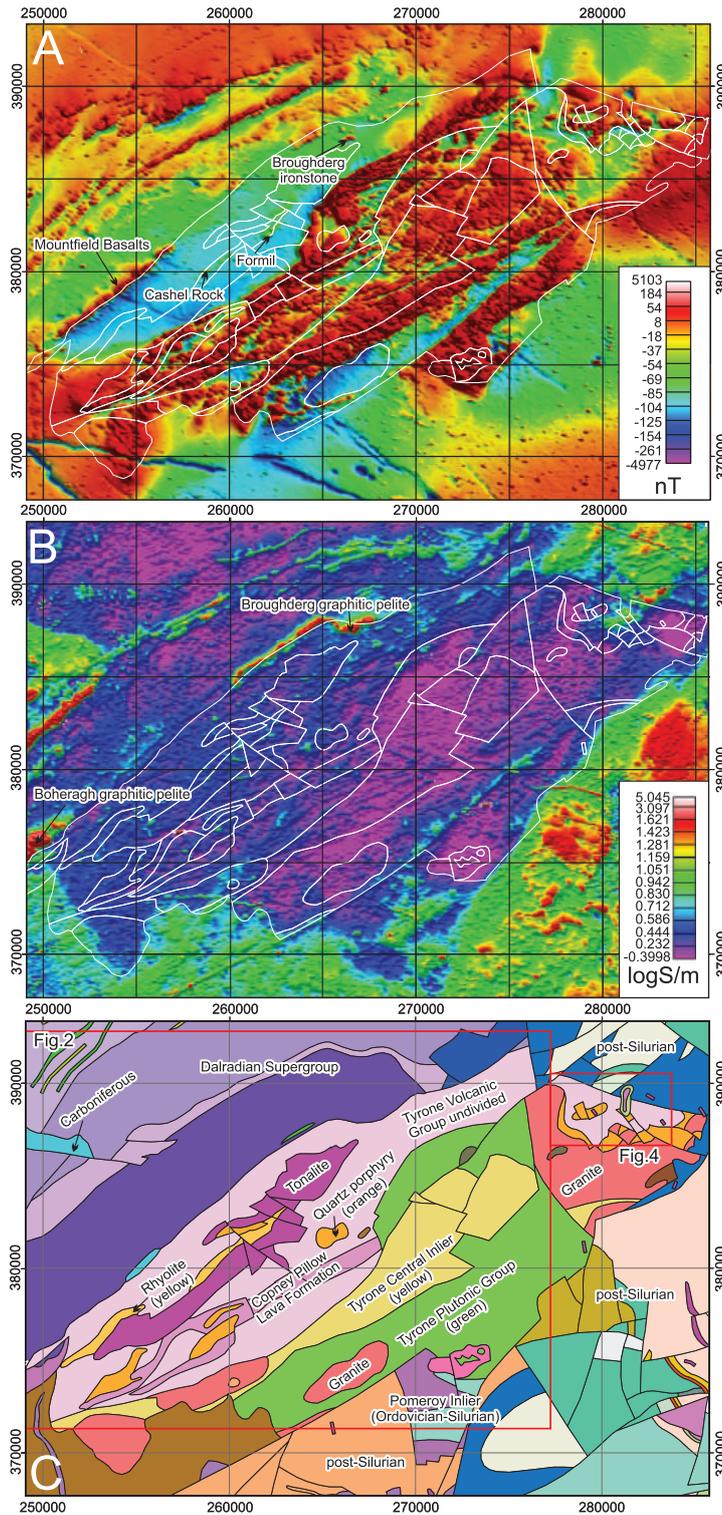


Figure 12.3. (A) Tellus TMI-RTP map with previous GSNI 1:250,000 geological linework of the Tyrone Igneous Complex shown in white. (B) Tellus Low Frequency EM map with GSNI linework as in (C). (C) GSNI 1:250,000 geological map over the Tyrone Igneous Complex. Red boxes highlight the extent of Figs 12.2 and 12.4.

were dated by high-resolution isotope dilution thermal ionisation mass spectrometry U-Pb zircon geochronology at the NERC Isotope Geosciences Laboratory (see Cooper *et al.*, 2008 and subsequent publications).

Historic data from ground magnetic, induced polarisation, very low frequency electromagnetic (EM) resistivity (VLF/EM-R) geophysical surveys, deep overburden geochemistry and prospecting were compiled by Aurum Exploration Services. Tellus airborne EM anomalies were verified on the ground as cultural, bedrock or unexplained. Following the main phase of research, a prospecting campaign was implemented in 2011 throughout the entire Tyrone Volcanic Group by Dalradian Resources. During a second prospecting campaign, geophysical and geochemical anomalies of the Tellus and historic data sets were targeted around Crosh–Racolpa. Five diamond drill holes were also drilled in 2011 and early 2012 at Broughderg, Tullybrick and Cashel Rock (Fig. 12.2).

GEOLOGY OF THE TYRONE IGNEOUS COMPLEX

Interpretation of the Tellus geophysical data showed that the unexposed geology was much more complex than previously thought. Tellus geophysical imagery has revealed the structure of the Tyrone Igneous Complex in unprecedented detail (Fig. 12.3a, 12.3b), enhancing previous GSNI mapping (Fig. 12.3c). As a result, the evolution of the Tyrone Igneous Complex and its relationship to the Caledonian orogeny are now well understood (e.g. Cooper *et al.*, 2011). The Tyrone Igneous Complex is broadly divisible into: (1) a structurally dissected *c.*484–479 Ma slice of subduction-affinity oceanic crust (Tyrone Plutonic Group); (2) the remnants of a *c.*475–469 Ma volcanic arc (Tyrone Volcanic Group); and (3) a late *c.*470–464 Ma suite of arc-related intrusive rocks. Several new formations have been identified and mapped in the Tyrone Volcanic Group (Figs 12.2, 12.4).

Of particular relevance to mineral exploration is the clear link now established between the Tyrone Igneous Complex and the Buchans–Robert’s Arm arc system of Newfoundland (Hollis *et al.*, 2012, 2013a), where historic mining at Buchans produced 16.2 Mt of ore at 14.51% Zn, 7.56% Pb, 1.33% Cu, 126 g/t silver (Ag) and 1.37 g/t gold (Au) (Piercey, 2007). Several episodes of extension and high-temperature heat flow have been identified in the Tyrone Volcanic Group. VMS prospective stratigraphic horizons are associated with rift-related basalts, ‘fertile’ felsic rocks, ironstones (i.e. silica- and iron-rich rocks associated with hydrothermal activity; Fig. 12.5a), locally intense hydrothermal alteration (Fig. 12.5b), geophysical anomalies and base metal occurrences (Hollis *et al.*, 2014).

Typical whole-rock geochemical variations associated with VMS deposits, due to the hydrothermal alteration of the host stratigraphy, are shown in Fig. 12.5b. Large gains in magnesium (Mg), iron (Fe) and sulphur (S) occur in chloritised and mineralised footwall rocks under VMS deposits, associated with the movement of hydrothermal fluids through synvolcanic faults (>250°C). Intensely chlorite-altered volcanic rocks have been identified in diamond drillcore from Cashel Rock, underlying zones of minor base metal mineralisation. Broader zones of quartz–sericite–(pyrite) alteration are associated with lower

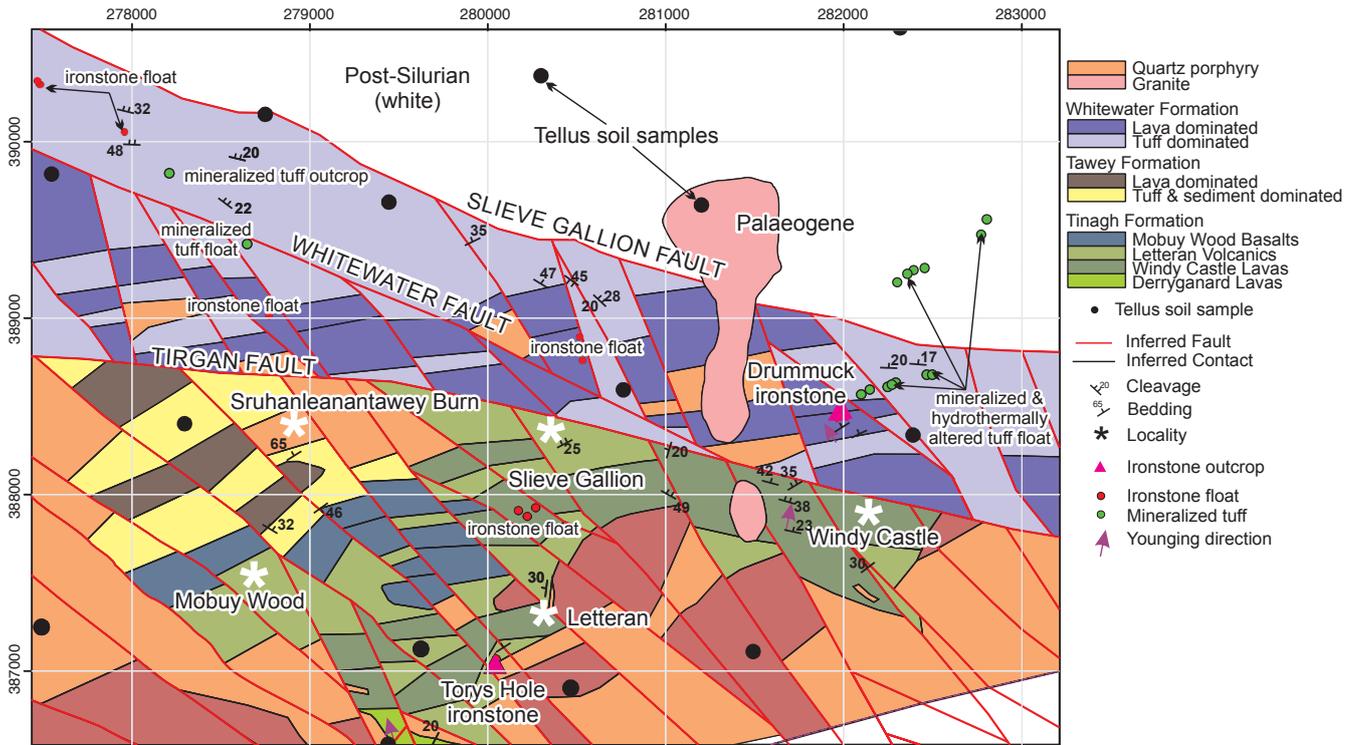


Figure 12.4. Geological map of the Slieve Gallion Inlier (after Hollis *et al.*, 2013b).

temperature, distal hydrothermal alteration surrounding VMS deposits. Similar alteration has been recognised at Tullybrick, Cashel Burn, Cashel Rock, Crosh, Racolpa and Formil (see Hollis *et al.*, 2014; Fig. 12.2). In terms of geophysical responses, massive sulfides often have an EM response (although this can be masked by the presence of black shales in the stratigraphy). Magnetic highs may be associated with individual rock units in the host stratigraphy (e.g. ironstones), and massive sulfides or stringer mineralisation if pyrrhotite or magnetite are present. Demagnetised zones can occur in basaltic footwall rocks due to hydrothermal alteration.

TARGETING MINERALISATION USING TELLUS DATA

Extensive hydrothermal alteration across the Tyrone Igneous Complex has recently been detailed in Hollis *et al.* (2014). Here we highlight previously undescribed geochemical and geophysical anomalies identified from Tellus and historic data sets, building on previous work by Gunn *et al.* (2008) conducted for Metallum Resources. We focus on areas that are interpreted to have the greatest potential to host economic VMS mineralisation, and contain either outcropping mineralisation or abundant high-grade float.

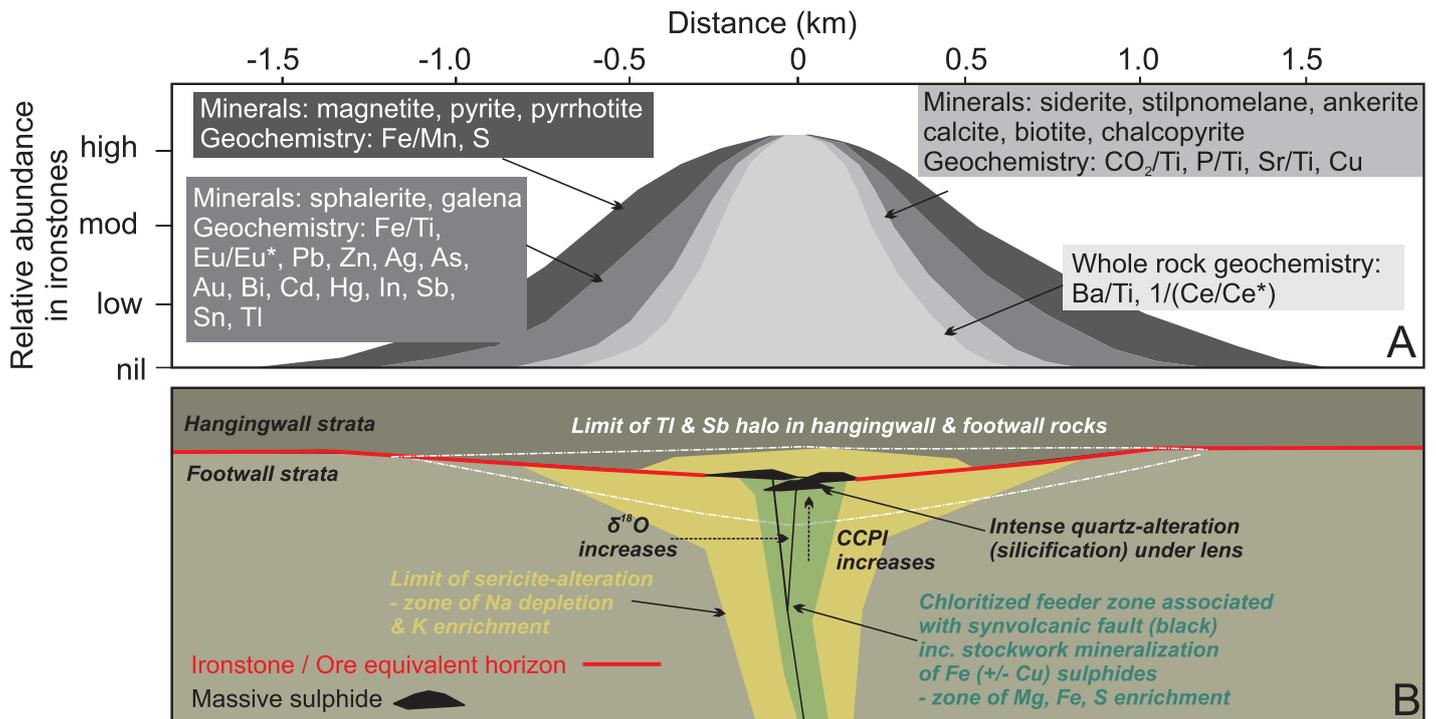
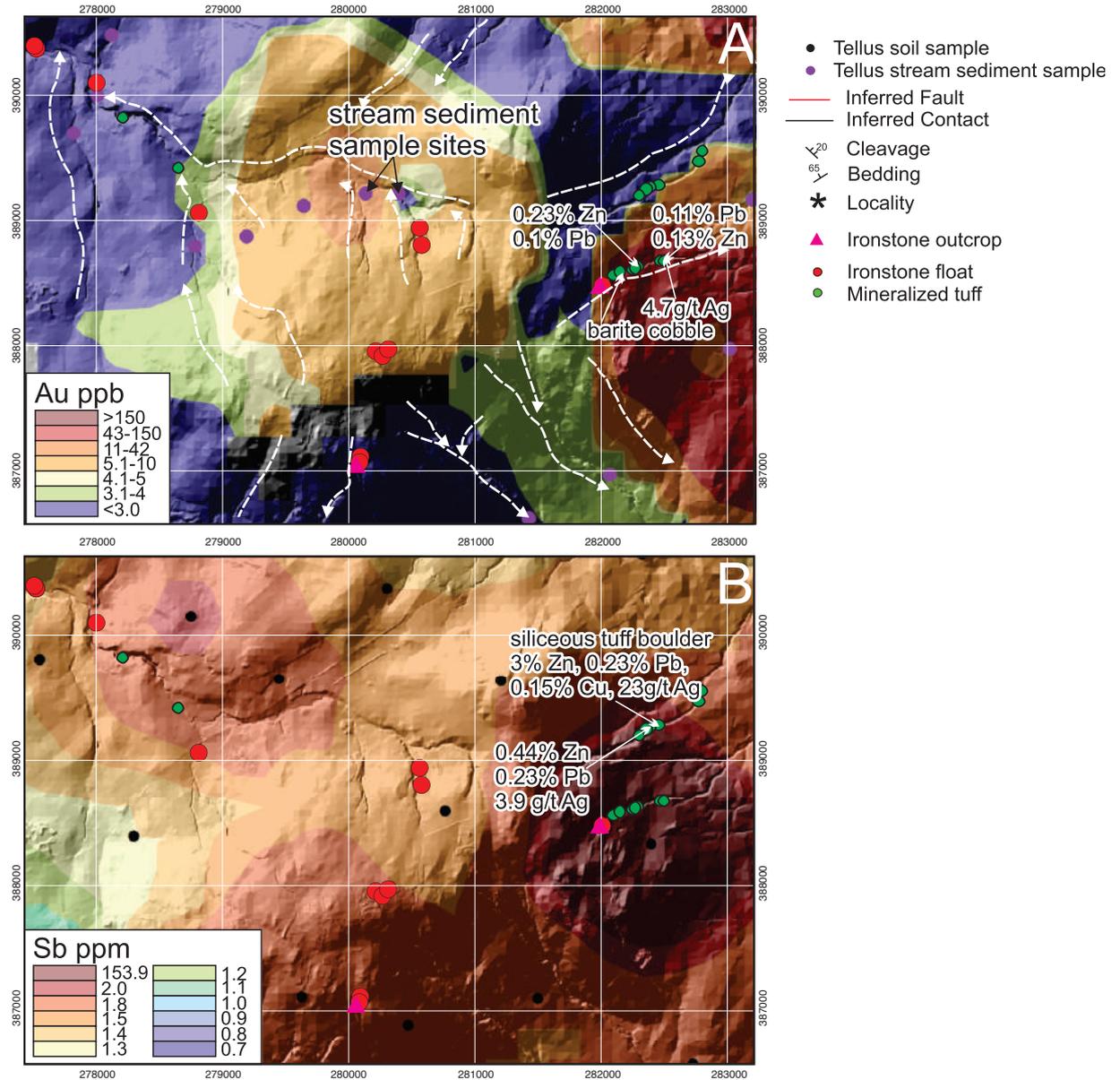


Figure 12.5. (A) Schematic diagram showing the lateral extent of mineral and bulk geochemical halos that surround VMS deposits in ironstones/iron formations of the Bathurst Mining Camp, Canada (after Peter and Goodfellow, 1996). Samples from Drummuck contain high Ba/Zr, Fe/Ti, Sb and Eu/Eu* and are considered to be VMS-proximal (discussed in Hollis *et al.*, 2015). (B) Typical whole rock geochemical variations surrounding VMS deposits due to the hydrothermal alteration of the host stratigraphy.

Slieve Gallion

Little exploration for VMS mineralisation has been undertaken in the *c.*475–474 Ma volcanic rocks exposed at Slieve Gallion (Fig. 12.4). Recent work has identified geochemically identical rift-related basalts to those in the main exposures of the Tyrone Volcanic Group to the south-west (Hollis *et al.*, 2013b). At least two ironstones crop out in the area (Fig. 12.4), one of which (at Drummuck) displays geochemical characteristics typical of deposits proximal to VMS systems (Fig. 12.5a). These characteristics include high iron/titanium (Fe/Ti) ratios, elevated concentrations of barium (Ba) and antimony (Sb), and higher concentrations of europium (Eu) with respect to the other rare earth elements (i.e. $\text{Eu}/\text{Eu}^* > 1$; Fig. 12.5a) (see Hollis *et al.*, 2015). Historic prospecting results from downstream of the Drummuck ironstone include barite cobbles and silicified tuffs with 0.23% Zn, 0.11% Pb and 0.5 ppm Ag (Fig. 12.6a). Abundant mineralised float also occurs ~900 m to the north-east in an adjacent stream section (Fig. 12.6b). The Drummuck ironstone (Fig. 12.7a) corresponds to a Tellus magnetic (TMI-tilt and 1VD) anomaly which extends for ~400 m along strike before it is cut off at each end by north-west to south-east trending faults. This area represents a key target for exploration, with Tellus soil and stream sediment Sb anomalies immediately downstream (Fig. 12.7b), and areas of high Au in stream sediments 1.5 km to the east (Fig. 12.7a). Zinc and Pb stream sediment anomalies (to 269 and 59 ppm respectively) occur ~1.5 km to the north-east associated with ironstone float



at a similar stratigraphic level (Fig. 12.4). High arsenic (As), Zn, Pb and Cu in stream waters are restricted to the Whitewater River area, where intensely silica–sericite–pyrite–(fuchsite) altered tuff and ironstone float have been identified (Fig. 12.4). Gold has been panned from both Whitewater River and Iniscarn Water (Drummuck area).

Greencastle Formation

In the *c.* 473–470 Ma Greencastle Formation of the upper Tyrone Volcanic Group, rhyolites prospective for VMS mineralisation occur at Formil, Cashel Rock and Racolpa

Figure 12.6. (A) Tellus stream sediment gold (Au) map over a digital terrain model of the Slieve Gallion Inlier. (B) Tellus soil antimony (Sb) map over the same digital terrain model. Areas of ironstone float and mineralised tuff are also highlighted. This figure covers the same area as shown in Fig. 12.4. White arrows show flow directions for major rivers and streams.

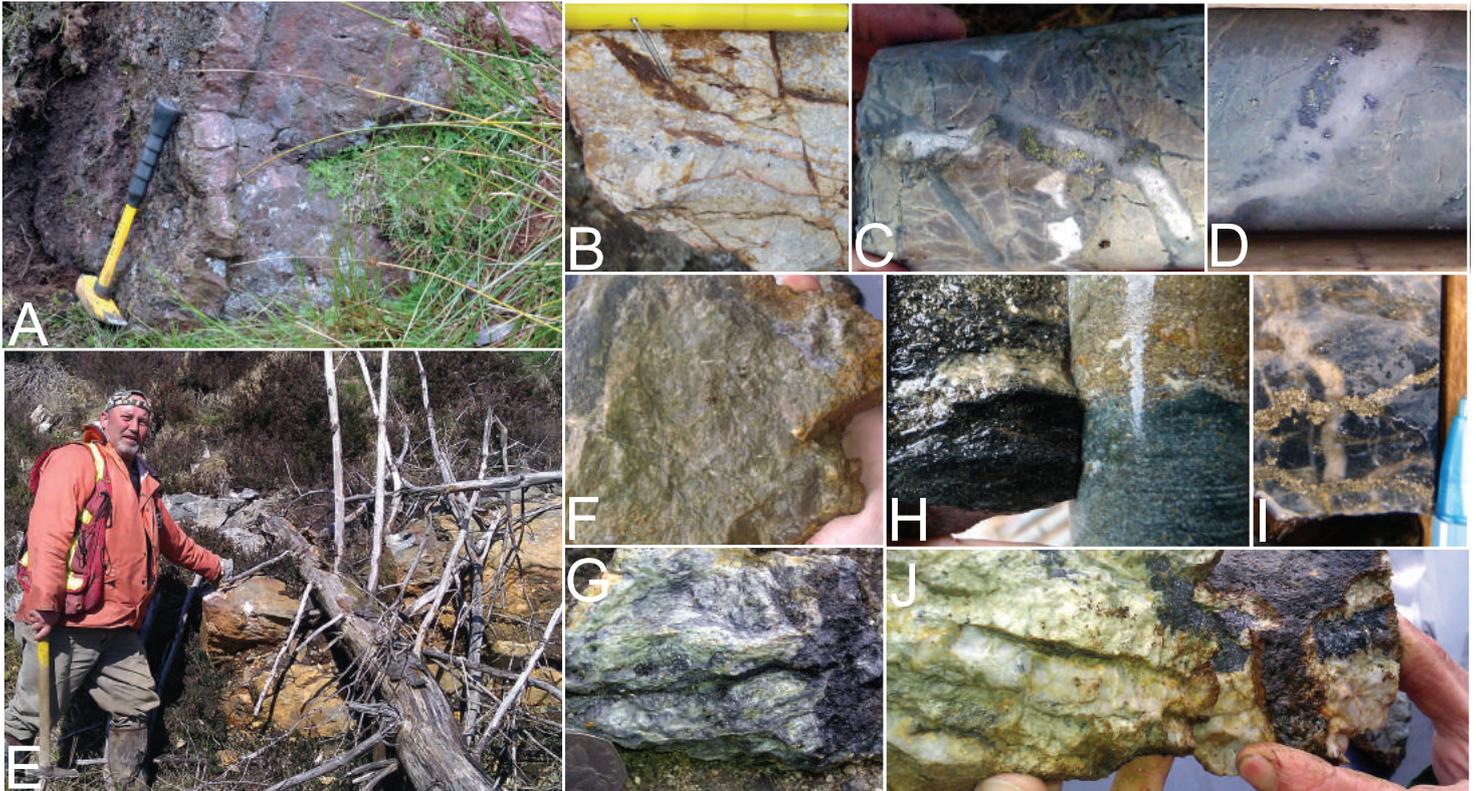


Figure 12.7. Representative mineralised volcanic rocks from the Tyrone Volcanic Group. (A) Ironstone from Drummuck (Slieve Gallion) that displays VMS-proximal geochemical characteristics (see Fig. 12.5a) and is associated with mineralised float downstream. (B) Silicified rhyolite from Cashel Rock (to 112 g/t Au in grab samples). (C–D) Silicified rhyolite with visible chalcopyrite and galena (drillhole 11-CR-01). (E) Massive pyrite at Formil. (F) Silicified and sericite-altered rhyolite from Racolpa. (G) Mineralised tuff outcrop, Cashel Burn. (H) Mineralised pyrite-bearing chloritic tuff, Cashel Bridge (drillhole 106-200). (I) Mineralised chert/ironstone at Broughderg (drillhole 91-1). (J) Silicified and sericite-altered rhyolite, Crosh base metal occurrence.

(Fig. 2). Mineralised tuffs also occur at Aghascrebagh (4% Pb, 1.22% Zn and 5.94 g/t Au), Greencastle (10% Zn, 2.83% Pb and 1.23% Cu), Cashel Burn, and Tullybrick (0.92 g/t Au) (Fig. 2).

The Cashel Rock VMS occurrence has been known for some time (Clifford *et al.*, 1992) and has received the most attention of all localities. A Tellus TMI-tilt magnetic anomaly extends for ~2.6 km, with the southernmost TMI-RTP magnetic ‘bullseye’ (Fig. 12.3a) located at the site of drilling and outcropping mineralisation (Fig. 7b). A 1–4 m wide zone of Au mineralisation associated with silica-flooding (e.g. 3.63 m at 30.51 g/t Au, including 1.23 m at 1.14% Cu and 1.85% Pb) extends for at least 200 m down dip. On the most southerly drill section this is underlain by a chloritic stockwork (see Fig. 12.5b) and is associated with minor base metal mineralisation (Fig. 12.7c, 12.7d). A Tellus EM conductivity anomaly further south remains unexplained.

At Formil, a ~800 m long Tellus magnetic (TMI-RTP and TIM-tilt) anomaly (Fig. 12.3a) is coincident with outcropping massive pyrite with disseminated magnetite (Fig. 12.7e). Prospecting and mapping in 2011–12 identified abundant secondary Cu mineralisation (malachite) in new rock exposures to the west and north associated with high concentrations of Cu (226 ppm), Zn (330 ppm) and Pb (to 245 ppm) in historic deep overburden geochemistry. Historic drilling around Formil by Riofinex during the 1970s intersected only weak Cu mineralisation. Induced polarisation anomalies targeted by Ennex

during the 1980s were largely barren. A series of Tellus EM anomalies in the vicinity are unexplained. No drilling has occurred in the vicinity of the massive pyrite, and mineralisation at Formil remains poorly understood.

At Racolpa, base and precious metal mineralisation was recognised during the 2011 prospecting campaign, with 2.19 g/t Au in outcrop (Fig. 12.7f). Mineralised rhyolite was also sampled to the north near Faccary Bridge (2.69% Cu+Pb+Zn and 0.34 g/t Au in float), and subcrops further east at Mulnafye (1.33% Cu+Pb+Zn and 0.3 g/t Au). Several small (~300 m long) unexplained Tellus magnetic anomalies occur in the vicinity of the Racolpa rhyolite, though none are coincident with outcropping mineralisation. At Mulnafye, white quartz float (to 71.5 g/t Au) with visible gold, chalcopyrite and malachite staining brecciates tonalite near its contact with the Racolpa rhyolite.

Outcropping VMS mineralisation at Cashel Burn (1.63 g/t Au and 4.3% Cu+Pb+Zn; Fig. 12.7g) remains a high priority target for drilling. However, all Tellus geophysical anomalies in the vicinity of mineralisation are interpreted as either cultural or related to glacial deposits.

Broughderg Formation

VMS prospective and mineralised volcanic rocks in the *c.*469 Ma Broughderg Formation occur at Cashel Bridge, Crosh and Broughderg (Fig. 12.2). Historic drilling at Cashel Bridge by Ennex intercepted narrow zones of base metal mineralisation (e.g. 40 cm at 3.36% Pb+Zn; Fig. 12.7h), and there are no clear Tellus geophysical anomalies to guide further drilling.

At Broughderg, a large Tellus magnetic (TMI-RTP) ‘bullseye’ is associated with an ironstone unit (Fig. 12.3a), where historic shallow drilling by Ennex intercepted minor Au mineralisation (0.62 m at 1.68 g/t Au; Fig. 12.7i). Trace-element geochemistry, such as elevated Ag, As, Au, cadmium (Cd), Cu, molybdenum (Mo), Pb, thallium (Tl) and Zn, indicates this ironstone may be related to VMS mineralisation (Hollis *et al.*, 2015; Fig. 12.5a). Drilling of this bullseye anomaly in 2011 (down dip of historic exploration) intercepted background levels of Au only. Any potential VMS-related EM anomalies are masked by the thick sequences of overlying graphitic pelite (Fig. 12.3b). However, the potential for VMS mineralisation along strike remains.

At Crosh, outcropping base-metal mineralisation (2.99% Cu+Pb+Zn; Fig. 12.7j) is associated with one of two 500 m long Tellus EM anomalies and remains untested by drilling. Anomalous Zn (134 ppm) in Tellus soil samples occurs to the south. Targeted prospecting of historic EM and Tellus geophysical anomalies in the vicinity of the Crosh base metal occurrence in 2011–12 identified new Au occurrences associated with silicified volcanic rocks and resistivity highs.

Carrickmore

The rocks of the *c.*484–479 Ma Tyrone Plutonic Group have only limited potential as targets for Cu-rich VMS mineralisation. Most parts of the preserved stratigraphy were not conducive to VMS formation (Hollis *et al.*, 2014). Historic Cu mineralisation has been noted in the sheeted dykes around Carrickmore Quarry (Fig. 12.2), broadly coincident with Tellus soil Cu (545 ppm) and Zn (167 ppm) anomalies. Cu-Au mineralisation has also been recorded from malachite-stained quartz float among diorite outcrop to the north-east (e.g. 0.7 g/t Au, 0.74% Cu).

CONCLUSIONS

The Tellus survey has revealed the structure of the Tyrone Igneous Complex in unprecedented detail. With high-resolution geophysics aiding bedrock mapping, isolated outcrops were put into a detailed stratigraphic framework for the first time. This allowed detailed geochemistry and U-Pb zircon geochronology to be put into context, permitting robust correlations to be made across the Caledonian-Appalachian orogen. Furthermore, key stratigraphic horizons were identified that are prospective for VMS mineralisation. Targeting of Tellus geochemical and geophysical anomalies along these horizons has identified several new mineralised outcrops and zones ripe for further exploration.

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