

8. Critical metals for high-technology applications: mineral exploration potential in the north of Ireland

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There is global concern about the availability of 'critical' metals: those of growing economic importance but vulnerable to supply shortage. Production from domestic resources could contribute to security of supply. However, we have little information on how critical metals are concentrated in the Earth's crust and the resources that exist in the British Isles. Ireland's diverse geology provides many geological environments in which critical metals may be enriched. This review considers mineral exploration potential for selected 'critical' metals identified by the European Commission and others considered important for high-technology applications. Known mineral deposits and the Tellus and Tellus Border geochemistry suggest that the north of Ireland is prospective for some of these metals and warrants further investigation. Extraction of these metals as by-products could facilitate the development of otherwise sub-economic ore bodies in Ireland, thus supporting economic growth.

INTRODUCTION

Global concerns are growing over the long-term availability of secure and adequate supplies of the minerals and metals needed by society. Of particular concern are the 'critical' raw materials, so called because of their growing economic importance and high risk of supply shortage. This group of raw materials is variously referred to as 'critical', 'strategic', 'E-tech elements' and 'technology metals'. These materials are typically characterised by increasing demand and concentration of production in a small number of countries (Graedel *et al.*, 2014).

Critical metals

Several studies have attempted to identify 'critical' raw materials. These studies use various metrics to measure criticality and have delivered widely varying results. The European

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Commission's assessment defines the following 13 metals or metal groups as critical: antimony (Sb), beryllium (Be), chromium (Cr), cobalt (Co), gallium (Ga), germanium (Ge), indium (In), magnesium (Mg), niobium (Nb), platinum-group metals (PGMs), rare earth elements (REEs), silicon (Si) and tungsten (W) (European Commission 2014, 4). Other studies have highlighted increasing demand for additional metals such as tellurium (Te), selenium (Se), silver (Ag), cadmium (Cd), molybdenum (Mo) and lithium (Li) (e.g. American Physical Society, 2011; Moss *et al.*, 2011; US Department of Energy, 2011). However, any list of critical raw materials will change over time as supply and demand factors evolve.

Demand for most of the metals listed above is increasing, with a supply deficit predicted for some, as a result of their increasing use in a range of high-technology and 'clean' energy applications. In contrast to the major industrial and precious metals, only in the past two decades have widespread applications for many critical metals been developed. As a result they have been of limited economic interest and the geological processes responsible for their deposition and distribution in the Earth's crust have been of peripheral interest. There is now an urgent need for research on all parts of the life cycle of these commodities, and for more exploration, both in frontier regions and in areas that have been traditionally targeted for other metals, such as Ireland.

Economic importance

In its 2011 inquiry into 'strategically important metals', the Science and Technology Committee of the House of Commons concluded that:

We consider that domestic mining for strategic metals could alleviate the risk associated with sourcing metals from external supply monopolies ... The evidence shows that there are unexploited deposits of various strategic metals in the UK but, in many areas, it is unclear whether extraction is economically viable ... [it is desirable] to ensure that Government has a comprehensive and up-to-date understanding of potentially valuable domestic mineral resources. (House of Commons, 2011)

The European Commission also highlights the need 'to improve the knowledge base of mineral deposits in the EU' (European Commission, 2010).

Concerns about security of supply and an increased emphasis on assessing Europe's domestic mineral resources, coupled with growing levels of geopolitical, security and environmental risk in many mineral producing regions, provide an opportunity for low-risk jurisdictions such as Ireland, notable for its favourable policy climate for minerals investment.

The critical metals are typically found in low concentrations in the ores of major metals, and many are currently produced exclusively as by-products. While this reliance

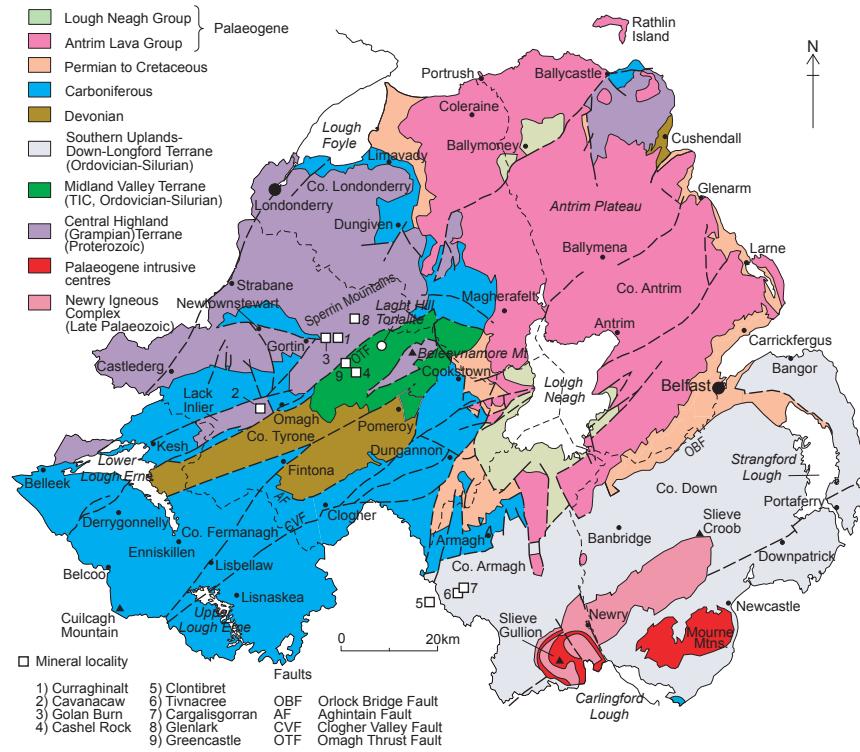


Figure 8.1. Simplified geological map of Northern Ireland, showing the mineral localities referred to in the text.

contributes to their supply risk, by-products can significantly enhance the economic viability of a mining operation. Therefore an opportunity may exist where critical metals can be produced as by-products from mines producing other commodities. Although Northern Ireland has a long history of mineral production and significant economic geology research has taken place since the Mineral Development Act 1976, the potential for critical metals has not been systematically assessed.

Using the Tellus and Tellus Border geochemistry, we have made an initial assessment of the potential for selected critical metals in the north of Ireland, focusing on geological environments in which they are known to be concentrated. This review is not intended to be an exhaustive evaluation of Ireland’s critical metal potential, but aims to highlight areas for possible academic research and/or commercial mineral exploration.

GEOLOGICAL SETTING

The geology of Northern Ireland is described by Mitchell (2004) and is usually considered in four quadrants, representing distinct geological environments, which are relevant to the subsequent discussion on mineral potential (Fig. 8.1):

1. the north-west, representing the oldest, commonly termed basement rocks, composed of the Proterozoic Dalradian Supergroup (an ‘orogenic’ geological environment) and the Ordovician Tyrone Igneous Complex (TIC), which is broadly

divided into two parts – the Tyrone Plutonic Group (TPG) (a ‘magmatic’ geological environment) and the Tyrone Volcanic Group (TVG) (a ‘submarine’ volcanic geological environment);

2. the south-east, composed of Ordovician and Silurian sedimentary rocks of the Southern Uplands – Down–Longford (SUDL) Terrane (an ‘orogenic’ geological environment), intruded by Caledonian and Palaeogene granitoids (an ‘intrusion-related’ geological environment);
3. the south-west, predominantly underlain by Carboniferous and Devonian rocks (a ‘basin’ geological environment); and
4. the north-east, dominated by the basaltic rocks of the early Palaeogene Antrim Lava Group (a ‘magmatic’ geological environment).

This spectrum of geological environments, discussed in turn below, results in a range of mineral deposit styles in which critical metals are potentially enriched.

CRITICAL METAL POTENTIAL IN THE NORTH OF IRELAND

Orogenic environments

Orogenic mineral deposits are associated with the geological processes that occur during deformation of the Earth’s crust to form mountains. Vein gold (Au) mineralisation formed under these conditions occurs in the Dalradian basement rocks of the Sperrin Mountains, in counties Tyrone and Londonderry, and in the Southern Uplands – Down-Longford (SUDL) Terrane in counties Armagh and Down (Fig. 8.1).

These types of gold deposit are frequently enriched in a range of metals in addition to gold, including silver, antimony, tellurium, tungsten and molybdenum. Tellurium is highly enriched in some orogenic gold deposits and many of the Dalradian-hosted gold occurrences in the Tyndrum area of Scotland are telluride-bearing, with concentrations of greater than 47 ppm tellurium reported in some veins (Scotgold, 2011). The most significant deposit, Cononish, is thought to contain in the order of seven tonnes of tellurium (House of Commons, 2011), largely present as silver tellurides and sulpho-tellurides.

In Northern Ireland gold-bearing tellurides occur as inclusions in pyrite in the vein mineralisation at Curraghinalt and Cavanacaw (Fig. 8.1). The tellurides contain accessory Sb and Ag (Earls *et al.*, 1996). The mineralisation also contains the antimony-bearing mineral tetrahedite (Earls *et al.*, 1996). Antimony concentrations at Curraghinalt are generally low (<30 ppm), although >1200 ppm Sb is reported from the main vein at Cavanacaw (Earls *et al.*, 1996).

Although tellurium, selenium and antimony are included in the Tellus Project geochemical data set, the challenge of exploring for mineralisation enriched in these elements using conventional (aqua regia digestion and ICP-OES/MS analysis) geochemistry is apparent from these data, as greater than 80% of ‘deep’ (S-horizon) soil samples analysed have below the minimum detectable value for tellurium (0.05 ppm) and selenium

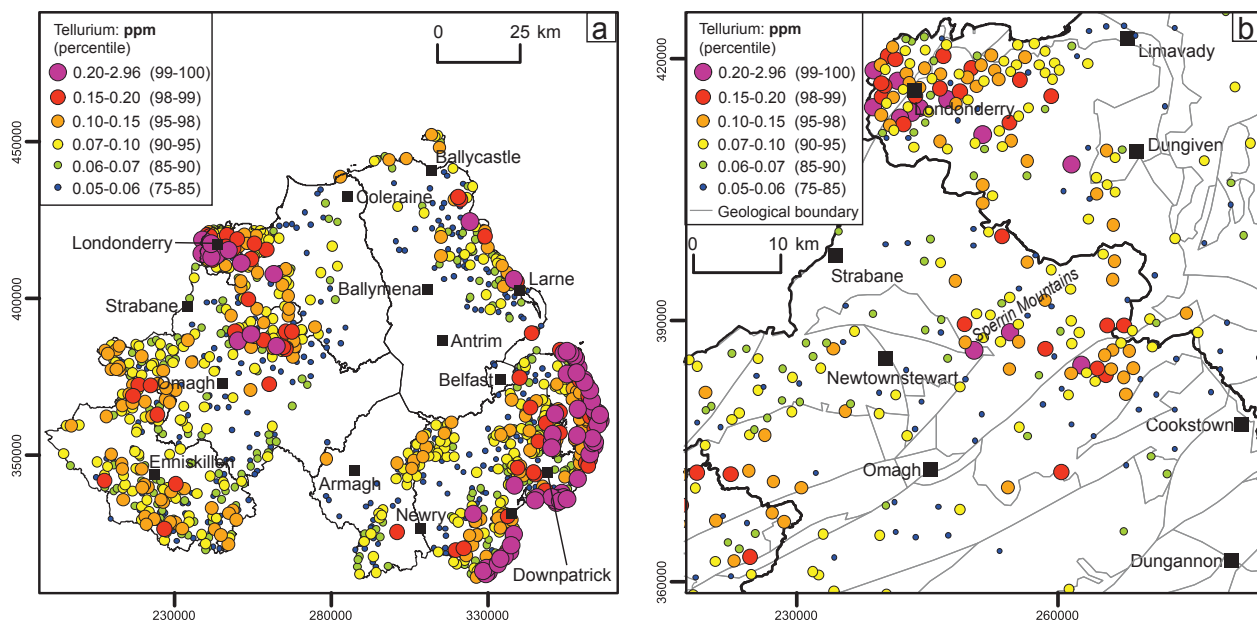


Figure 8.2. The distribution of selected metals in the Tellus Project S-horizon (deep) soil samples over parts of Northern Ireland (samples with lower concentrations are omitted for clarity): (a) tellurium; (b) tellurium over the Sperrin Mountains and surrounding areas.

(1.0 ppm). In general, caution must be taken in attributing geochemical anomalies to natural processes or mineralisation due to the potential for anthropogenic contamination, particularly in agricultural and urban areas. Furthermore, many natural processes besides mineralisation can result in geochemical anomalies.

High² to very high (maximum 0.37 ppm) tellurium concentrations occur in deep soils overlying the Lacht Hill Tonalite (a high-level igneous intrusion) within the Tyrone Volcanic Group and could be associated with known volcanogenic gold mineralisation (Fig. 8.2a, 8.2b). An extensive tellurium anomaly extends across the Sperrin Mountains, with very high (maximum 0.31 ppm) Te concentrations in the deep soils around Londonderry, overlying the Dalradian age Ballykelly and Londonderry formations. Without further investigation it is not possible to determine whether the very high tellurium concentrations around Londonderry are the result of natural elevation or pollution. The deep soils of the Tellus Border survey have not yet been analysed and in the topsoil data tellurium values are generally below the detection level; consequently it is not possible yet to verify whether the Te anomalies persist across the border, but it is likely given the continuity of the geology. High to very high (maximum 0.22 ppm) concentrations of tellurium in deep soils occur in the Golan Burn–Curraghinalt area and overlying the north-eastern part of the Mullaghcarn Formation (Fig. 8.2b). These may be associated with the well-known gold mineralisation in this area (Fig. 8.1). There appears to be limited lithological control

² With reference to the whole Tellus deep soil (S-horizon) data set: very high, >99th percentile class; high, >95th percentile class; intermediate, 50–95th percentile class; low, <50th percentile class.

on tellurium distribution across the Sperrins. High (maximum 0.15 ppm) tellurium concentrations in deep soils occur to the west of the Lack Inlier overlying the Carboniferous Mullaghmore Sandstone Formation (Fig. 8.2b). Tellurium is one of the rarest elements in the Earth's crust, with concentrations in the range of 0.36–10 ppb (Hein *et al.*, 2003). Therefore the anomalies in the Sperrin Mountains may reflect bedrock mineralisation enriched in tellurium.

Tellurium is often found in association with selenium, which is also rare in the Earth's crust (0.13 ppm: Rudnick *et al.*, 2005). In the Sperrin Mountains an extensive selenium anomaly with high (>2 ppm) to very high (>3.3 ppm; maximum 5.0 ppm) selenium concentrations in deep soils overlying Dalradian bedrock extends northwards from the Cranagh area, across the Glenelly Formation, becoming most pronounced over the Dart Formation, but also extending across the outcrop of the Dungiven and Claudy formations. This anomaly may reflect the accumulation of selenium in peat (Smyth, 2013, 99), but isolated high to very high selenium values between Glenlark and Curraghinalt could be related to known gold mineralisation (Fig. 8.1). Deep soil samples with intermediate selenium concentrations extend west of Newtown Stewart, across the Castlederg area, with concentrations generally increasing (maximum 5.0 ppm) close to the border. Westward continuation of this anomaly is apparent in the Tellus Border topsoil data set, with a broad zone of intermediate to very high (maximum 9.0 ppm) selenium concentrations in topsoil extending north-east from the border to the Reelan River. A much broader intermediate to very high (maximum 11.0 ppm) Se anomaly in topsoil extends northwards across Fintown to the coast near Brinlack.

Mineralisation of possible porphyry-style (copper and other minerals occurring in networks of cross-cutting veins and as fine-grained particles dispersed through the host rock) occurs at Cashel Rock in the TIC. Despite selenium being enriched in some porphyry deposits (Skirrow *et al.*, 2013), deep soils over the TIC generally have selenium concentrations below the minimum detectable value.

In the Sperrin Mountains an extensive antimony anomaly with high to very high (maximum 1.4 ppm) Sb concentrations in deep soils extends south from the Claudy Formation across the Dungiven and Newtown Stewart formations (Fig. 8.3a). A similar pattern is evident over these formations to the west of Newtown Stewart, with a maximum concentration of 3.6 ppm antimony in deep soils. Although antimony is typically enriched in porphyry-epithermal (mineralisation formed at shallow crustal levels by circulation of magmatic fluids through volcanic rocks and spatially related to porphyry systems) deposits associated with magmatic (relating to molten material beneath or within the earth's crust) ore-forming environments (Skirrow *et al.*, 2013), high antimony concentrations are very rare in deep soils overlying the TIC (Fig. 8.3a).

Au–As–(Sb) mineralisation occurs in the Palaeozoic sedimentary rocks and associated intrusions of the SUDL Terrane of Scotland and Ireland. The most significant deposit is Clontibret, County Monaghan, with additional gold occurrences along strike

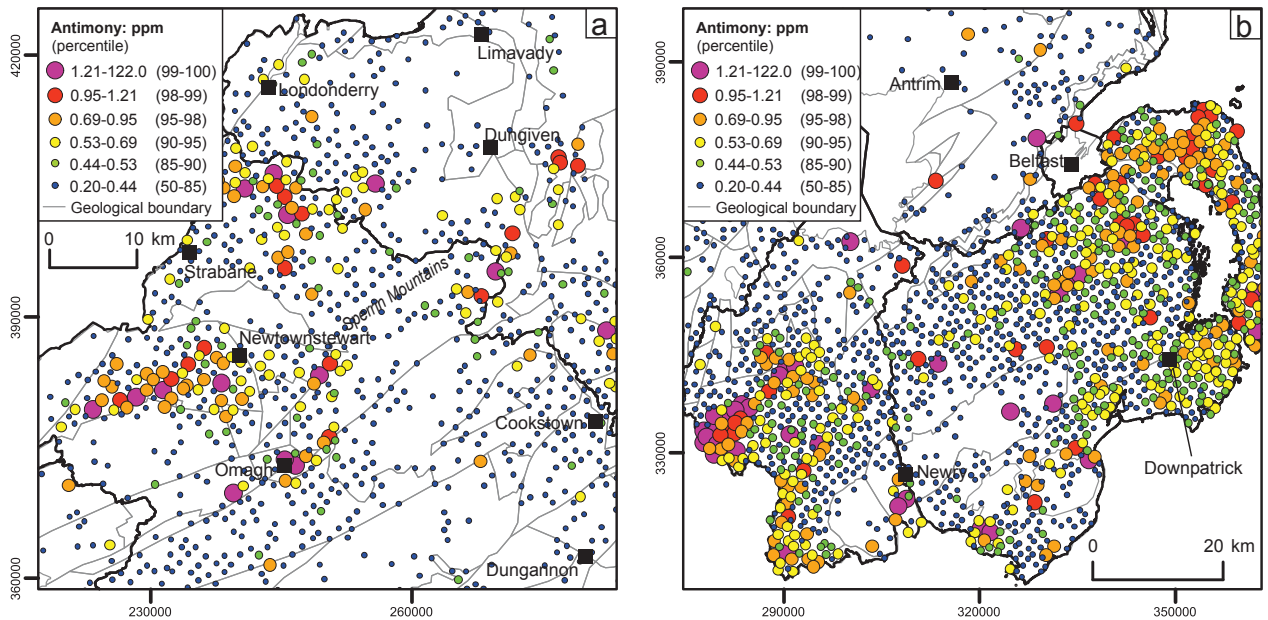


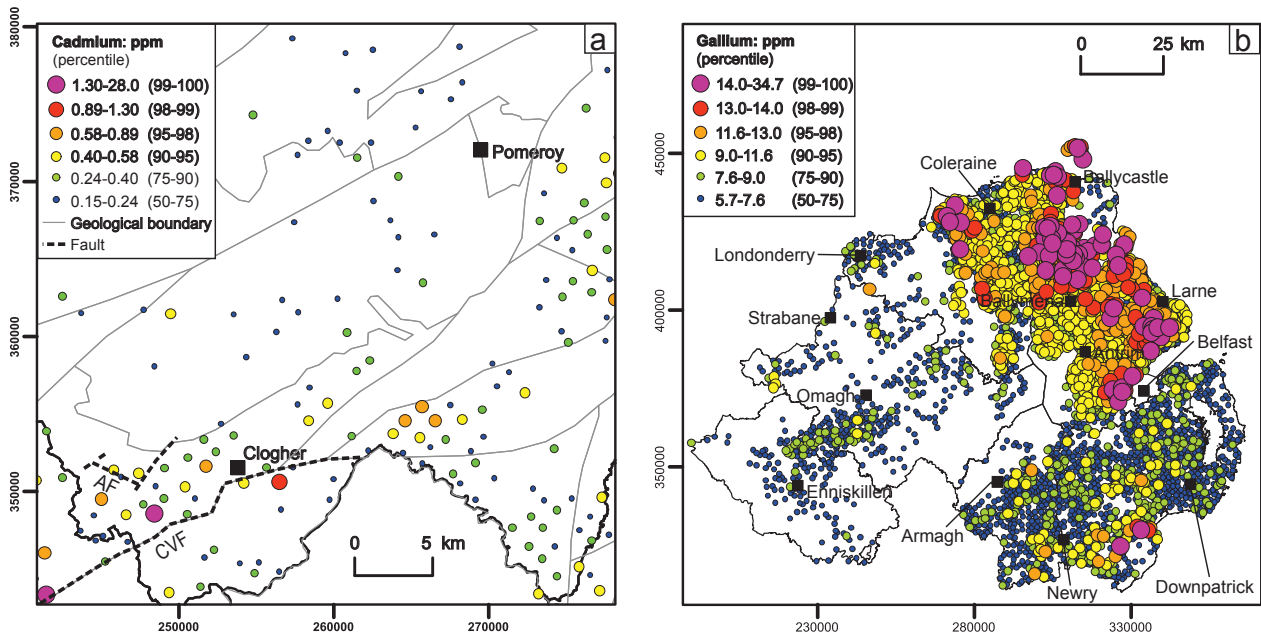
Figure 8.3. The distribution of selected metals in the Tellus Project S-horizon (deep) soil samples over parts of Northern Ireland (samples with lower concentrations are omitted for clarity): (a) antimony over the Sperrin Mountains and surrounding areas; (b) antimony over the SUDL Terrane.

at Cargalishgorgan and Tivnacree, County Armagh (Fig. 8.1). Clontibret was historically worked for antimony, which occurs as locally massive and finely dispersed stibnite. The Tellus Border Survey data show an extensive east–west-trending antimony anomaly, with high to very high (maximum 2.5 ppm) antimony concentrations in the topsoil of the Clontibret area. A zone of intermediate antimony concentrations in topsoil extends southwards, with high to very high concentrations between Latton and Creeve (maximum 1.1 ppm) and between Loughmorne and Corduff (maximum 1.6 ppm). This intermediate tenor anomaly extends south-east to Drogheda.

High to very high antimony (maximum over sedimentary rocks: 6.2 ppm) concentrations are also common in the deep soils overlying the SUDL Terrane in Northern Ireland (Fig. 8.3b). Many anomalies are associated with major faults and boundaries between specific rock groups. The deep soil antimony data clearly depicts the Cargalishgorgan area and its immediate environs in the vicinity of the Orlock Bridge Fault (Figs 8.1 and 8.3b) as being highly prospective for Sb-bearing precious metal mineralisation. Additional antimony anomalies to the south and those correlating with the westward extension of the major tract-bounding faults warrant follow-up.

Basin-hosted and submarine volcanic-related environments

Low-lying regions and geological depressions (basins) dominated by sedimentary rocks, and areas of underwater volcanism are important environments for the formation of base metal-rich (e.g. lead (Pb), zinc (Zn), copper (Cu)) mineralisation.



Base metal mineralisation occurs widely in Northern Ireland, including in the Sperrin Mountains. A range of elements including cadmium, gallium, germanium, indium and antimony may be contained in the zinc sulphide mineral sphalerite in Zn-rich mineralisation (Cook *et al.*, 2009; Skirrow *et al.*, 2013). Stratabound, semi-massive and disseminated Zn–Pb–Au–Ag mineralisation occurs in the Dalradian rocks at Glenlark (Fig. 8.1). Glenlark is Zn rich (*c.*4%), containing coarsely crystalline sphalerite (Earls *et al.*, 1996). The deep soils around Glenlark and its immediate environs have low Cd (maximum 0.26 ppm), Ga (maximum 5.4 ppm) and In (maximum 0.02 ppm) concentrations, and low to intermediate Sb (maximum 0.35 ppm) values.

The Lower Carboniferous rocks of counties Fermanagh and Tyrone, particularly in the area of the Aghintain Fault (Figs 8.1 and 8.4a), are considered prospective for carbonate-hosted Pb–Zn–Ag deposits, and exploration has identified minor disseminated and vein-hosted sphalerite in the Clogher Valley area. Intermediate to very high Cd (maximum 1.57 ppm) concentrations occur in deep soils in the area between the Aghintain and Clogher Valley faults (Fig. 8.4a). Gallium (maximum 6.9 ppm) and indium (maximum 0.03 ppm) concentrations are generally low in this area, while antimony reaches intermediate levels (maximum 0.24 ppm). Samples with higher (maximum 0.07 ppm) indium concentrations occur to the south and east of Clogher. To the south-east, immediately over the border in County Monaghan, in an area underlain by similar age geology, isolated samples with intermediate antimony concentrations (maximum 0.72 ppm) are apparent in the Tellus Border Survey topsoil data. This area has low gallium concentrations in the topsoil. An absence of trace element data for sphalerites from the Sperrins and the Clogher Valley areas

Figure 8.4. The distribution of selected metals in the Tellus Project S-horizon (deep) soil samples over parts of Northern Ireland (samples with lower concentrations are omitted for clarity): (a) cadmium over the Clogher Valley, Tyrone Igneous Complex and surrounding areas (CVF: Clogher Valley Fault, AF: Aghintain Fault); (b) gallium.

means it is not possible to assess the by-product critical metal potential of the base metal mineralisation in these areas.

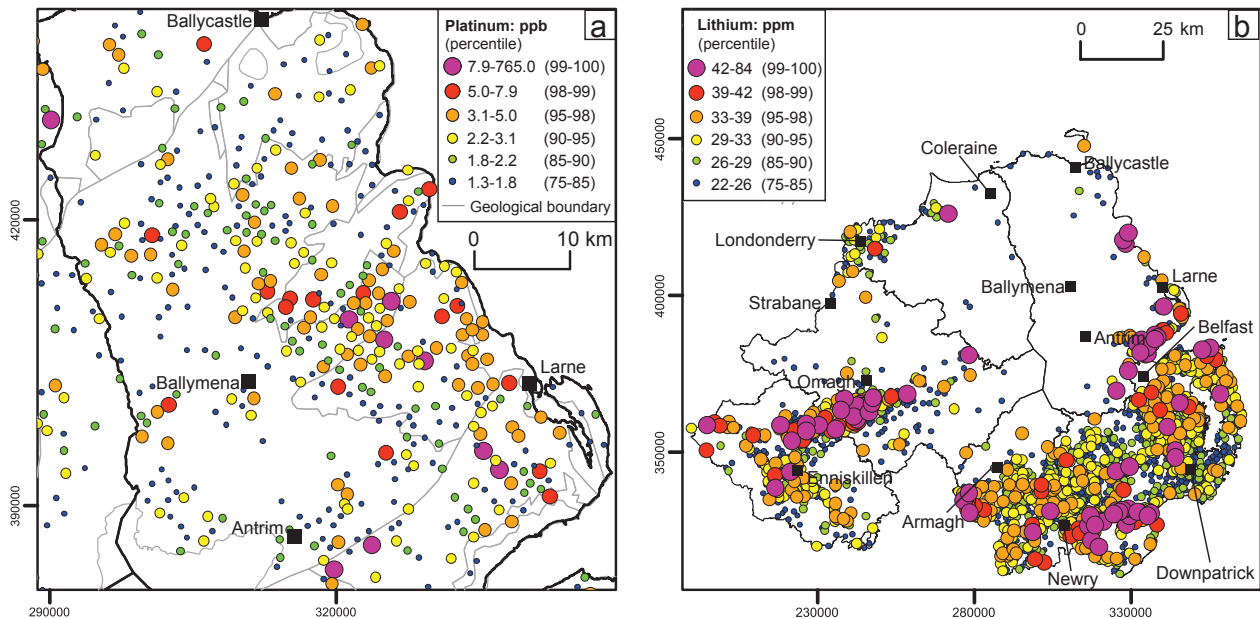
The TIC is considered prospective for polymetallic volcanogenic massive sulphide (VMS) deposits, associated with submarine volcanism and formed through the discharge of metal-rich fluids (e.g. Hollis *et al.*, 2014). Identified mineralisation in the TIC (e.g. at Greencastle, Fig. 8.1) contains up to 10% zinc (Hollis *et al.*, 2014). VMS deposits can contain very significant concentrations of critical metals, particularly those that occur in sphalerite (e.g. Cd, Ga, In and Ge). Elevated concentrations of antimony and other metals of growing economic importance (e.g. bismuth and tin) may also be present. Further important metals (e.g. molybdenum, rhenium, selenium and tellurium) may be associated with copper-bearing minerals (Skirrow *et al.*, 2013).

Published geochemical data for most of these elements in rocks from TIC are limited. Rock samples from the TIC contain maximum concentrations of 26 ppm gallium (for comparison USA zinc deposits have a typical value of 50 ppm Ga; Butcher and Brown, 2014) and Ga has a weak correlation ($R = 0.11$, $n = 85$) with Zn (Hollis *et al.*, 2014). The gallium content of sphalerite is temperature dependent and generally increases as the temperature of mineral deposition reduces (Butcher and Brown, 2014). Accordingly, the low gallium concentrations in samples from the TIC are expected as VMS systems typically have relatively high fluid temperatures compared with some other styles of base metal mineralisation. Carbonate-hosted Pb–Zn deposits, which generally have cooler ore-forming fluids, may represent more gallium-enriched targets in Ireland. Gallium concentrations in deep soils over the TIC range from low to intermediate (maximum 8.8 ppm) (Fig. 8.4b). With the exception of the Laght Hill Tonalite and its immediate environs, which have intermediate to very high (maximum 0.09 ppm) indium concentrations in deep soils, indium concentrations over the TIC are generally low with isolated anomalous samples (maximum 0.09 ppm). Cadmium concentrations in deep soils over the TIC are generally <75th percentile (0.24 ppm) (Fig. 8.4a). Germanium concentrations are consistently low in deep soils over the TIC.

Mafic–ultramafic magmatic environments

Magmatic sulphide deposits are associated with magmas of various types, particularly those containing abundant iron–magnesium minerals (termed mafic and ultramafic) and that form igneous rocks such as basalt. Relative enrichment of platinum and palladium in the geochemical data suggests potential for PGM-bearing mineralisation in a number of parts of Northern Ireland. Target areas highlighted by the Tellus Project geochemistry include the Antrim Plateau, the Sperrin Mountains and the Omagh Thrust Fault (Fig. 8.1).

The most prospective area is the Antrim Plateau, which is dominated by basaltic rocks, where extensive zones of ‘high’ platinum (>2.2 ppb) and ‘intermediate’ palladium (1.2–2.2 ppb) concentrations occur in soils and stream sediments (2–6 ppb Pt) (Flight and



Lister, 2013; Smyth, 2013). Some of the anomalies (Fig. 8.5a) coincide with lineaments identified from the Tellus Project geophysics. While the elevated values primarily reflect natural enrichment of PGMs in basaltic magmas (Smyth 2013), this geological setting has the potential to host PGMs in association with magmatic nickel–copper sulphide deposits, which are spatially and genetically related to bodies of mafic or ultramafic rocks. On the basis of known minor PGM occurrences in the North Atlantic Igneous Province (NAIP) in Scotland (Andersen *et al.*, 2002), it is clear that conditions were favourable for the concentration of PGMs, and Andersen *et al.* (2002) concluded that there is potential for Noril'sk-type Ni–Cu–PGM deposits in the UK sector of the NAIP. There is current exploration for platinum group and related metals in County Antrim and recent research projects have considered the PGM potential of this area (e.g. Leeman *et al.*, 2014). In summary, published information on PGMs in the Antrim Lava Group is very limited. However, by analogy with models for magmatic Ni–Cu–PGM deposits elsewhere, the potential for the occurrence of this style of mineralisation related to the Antrim Lava Group and its underlying high-level feeder zones merits further consideration.

The TPG is considered to represent an ophiolite (oceanic crust that has been uplifted and emplaced onto continental crust). Ophiolites elsewhere are important sources of a number of metals including chromium. In the Unst ophiolite in Shetland, PGM concentrations locally exceed 100 ppm Pt+Pd (Gunn and Styles, 2002). Anomalous PGM values, up to 1.7 ppm Pt+Pd+Rh, are reported in rocks from the Davagh Forest area near Belevnamore Mountain. The Tellus geochemical data do not provide convincing support

Figure 8.5. The distribution of selected metals in the Tellus Project S-horizon (deep) soil samples over parts of Northern Ireland (samples with lower concentrations are omitted for clarity): (a) platinum over the Antrim Plateau; (b) lithium.

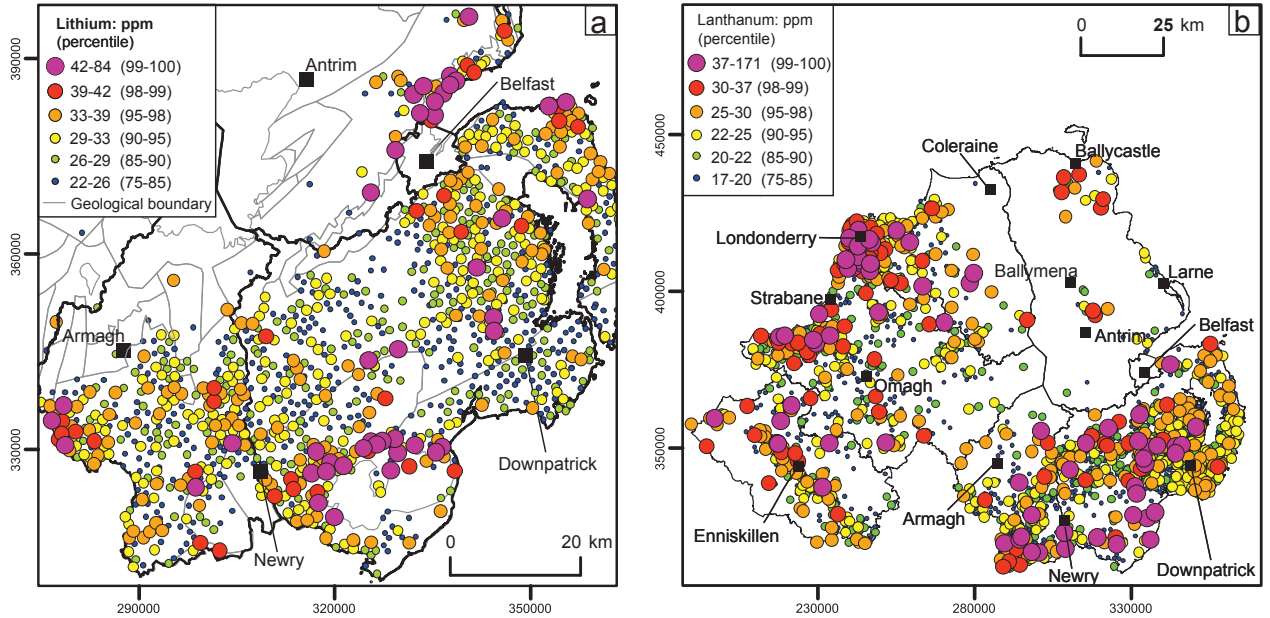
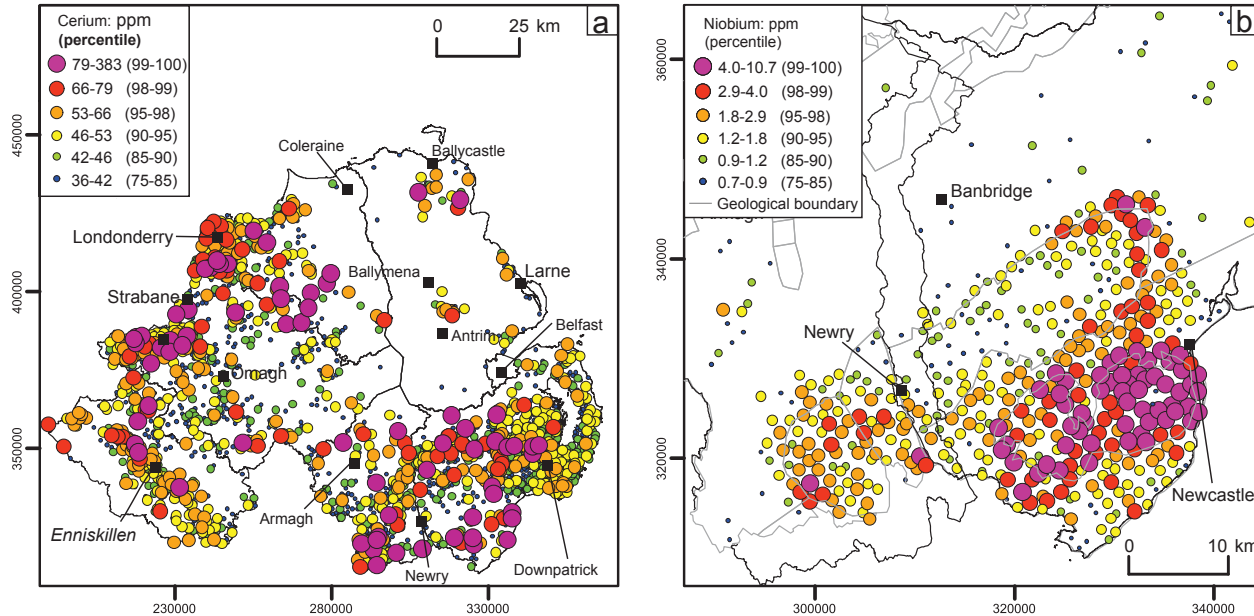


Figure 8.6. The distribution of selected metals in the Tellus Project S-horizon (deep) soil samples over parts of Northern Ireland (samples with lower concentrations are omitted for clarity): (a) lithium over the SUDL Terrane; (b) lanthanum.

for PGM enrichment in this area, although a low-tenor Pd anomaly (14 ppb) in stream sediments does exist nearby.

Alkaline intrusion-related environments

Economic deposits of REEs and associated elements (yttrium, niobium, lithium, etc.) are most commonly associated with igneous rocks. Some of the most significant concentrations of these elements occur in alkaline igneous environments and pegmatites (very coarse-grained crystalline rocks generally of granitic composition) (Ercit, 2004; Salvi and Williams-Jones, 2004). Accordingly, the three main granitic intrusive centres in Northern Ireland (the Newry Complex, Slieve Gullion and the Mourne Mountains) are prospective for REEs and other critical metals (Fig. 8.1). The Caledonian age Newry Complex is the largest body and exploration around the similar age and style Leinster Granite in the Republic of Ireland has identified lithium-bearing pegmatites, with a grade of 1.6% lithium, with accessory niobium and tantalum minerals (Kennan *et al.*, 1986, 206). Relative to most of Northern Ireland, lithium concentrations in deep soils across the SUDL Terrane are generally elevated to anomalous (Fig. 8.5b). Notable clusters of high to very high lithium values occur along the southern margin of the Newry Complex, principally overlying the sedimentary rocks (maximum 60 ppm), which contain abundant minor intrusions, and close to the border around Derrynoose (maximum 44 ppm) (Fig. 8.6a). It is possible that the former are related to lithium-bearing mineralisation associated with the Newry Complex. The Tellus Border Survey topsoil data show an extensive lithium anomaly (maximum 44 ppm) over the SUDL terrane of counties Monaghan and Cavan.



The Palaeogene age Mourne Mountain Complex has been periodically explored for a range of metals, particularly uranium. The subalkaline composition of the complex suggests it is prospective for REEs and other critical metals, as discussed by Moore *et al.* (Chapter 9, this volume). Relative to some parts of Northern Ireland, the REEs, lanthanum (La) and cerium (Ce) are generally elevated in the deep soils overlying the SUDL Terrane (Fig. 8.6b, 8.7a). However, high to very high concentrations (maximum 157 ppm La; 205 ppm Ce) of these elements are not restricted to the Mourne Mountain Complex, occurring across the sedimentary rocks that dominate the Terrane. The Tellus Border Survey topsoil data show a broad, generally intermediate tenor lanthanum and cerium anomaly (maximum 80 ppm La; 172 ppm Ce), extending west from Creaghanroe to beyond Cavan and south-east to Drogheda.

The majority of soil samples collected over the Mourne Mountain Complex and its immediate environs in Northern Ireland have high to very high niobium concentrations (maximum 10 ppm) (Fig. 8.7b). The extension of the igneous rocks into the Republic of Ireland is associated with a pronounced niobium anomaly in the Tellus Border Survey topsoil data. The highest niobium concentrations (maximum 4.1 ppm) extend around the northern side of the Carlingford Complex in County Louth.

A further critical metal associated with pegmatites is beryllium, and beryl (a beryllium mineral) is recorded in the Mourne Mountains. The deep soils over the Mourne Mountains are enriched in beryllium relative to other parts of Northern Ireland (maximum 37 ppm Be). The Tellus Border data indicate that a broad zone of relatively high beryllium concentrations in topsoil extends south from the border across County Louth, although

Figure 8.7. The distribution of selected metals in the Tellus Project S-horizon (deep) soil samples over parts of Northern Ireland (samples with lower concentrations are omitted for clarity): (a) cerium; (b) niobium over the Mourne Mountains Complex.

absolute values are relatively low (maximum 3.6 ppm Be) compared with those in Northern Ireland.

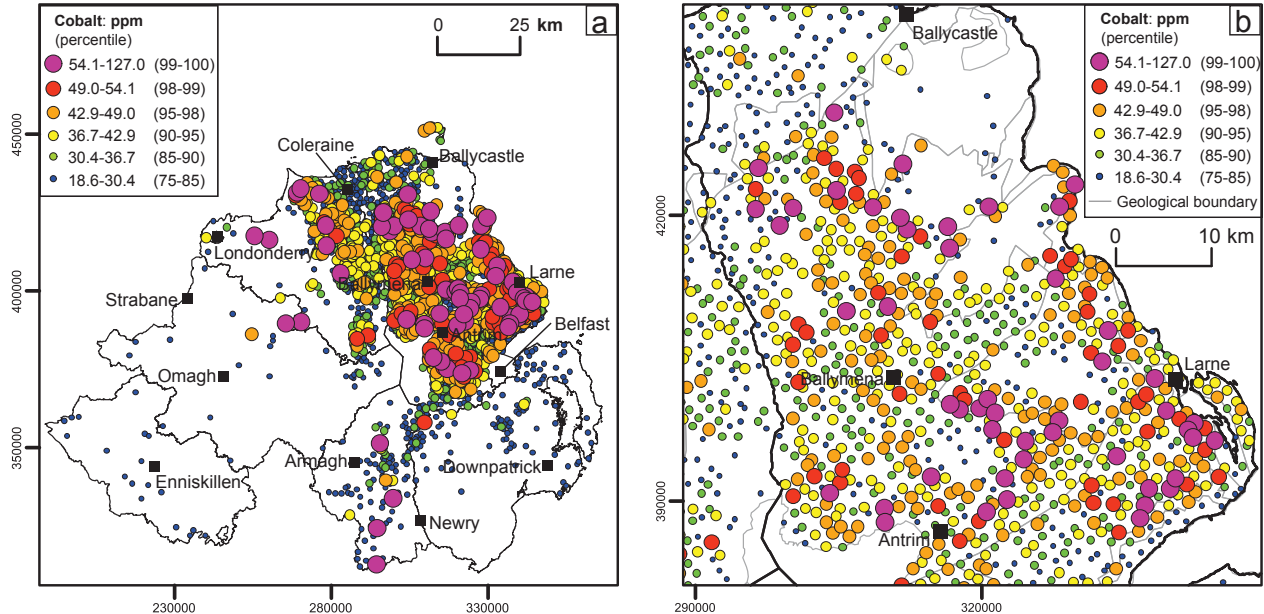
Recent work has examined the mineralogical sources of some of the geochemical anomalies apparent in the Tellus Project soil and stream-sediment data from the Mourne Mountains in Northern Ireland (Moore *et al.*, 2013; Moore *et al.*, Chapter 9, this volume). Although no economic concentrations of REEs or other critical metals were identified, this research begins to elucidate the complex relationship between the Tellus Project geochemical anomalies and magmatic–hydrothermal processes operating during specific phases in the evolution of the complex. This type of study is vital for improving our understanding of the processes that concentrate critical metals in magmatic–hydrothermal systems, and forms a valuable basis for future exploration for critical metals in the Mourne Mountains.

With regard to potential for REEs in other parts of Northern Ireland, the Tellus deep soil data identify high to very high concentrations of lanthanum (maximum 171 ppm) and cerium (maximum 383 ppm) in deep soils overlying the Claudy, Ballykelly and Londonderry formations in counties Londonderry and Tyrone (Fig. 8.6b, 8.7a). The Tellus Border Survey topsoil data indicate that this anomaly continues into County Donegal, with a zone of intermediate to very high lanthanum (maximum 80 ppm) and cerium (maximum 198 ppm) concentrations extending from Muff south-west to beyond Ballybofey.

Surficial environments

Laterites, formed from intense *in situ* tropical weathering, are important sources of many metals, in particular iron, aluminium, nickel and gold (Freyssinet *et al.*, 2005). Critical metals can become significantly enriched in laterites; for example, bauxite is the world's most important source of gallium (Butcher and Brown, 2014); lateritic ion adsorption clays are the principal source of heavy REEs (Kynicky *et al.*, 2012); and significant rare metal enrichment occurs in Brazilian laterites (Horbe and Costa, 1999). On account of their noble metal character the PGMs may also be expected to undergo residual concentration under appropriate weathering conditions. Very few data are available on PGM concentrations in nickeliferous laterites, although those in the Dominican Republic illustrate the potential importance of supergene processes in the generation of economic PGM grades (Aiglsperger *et al.*, 2015). Other trace metals that can be concentrated by surficial weathering include cobalt, germanium, selenium, silver, cadmium and antimony (Skirrow *et al.*, 2013).

Lateritic iron ore and bauxite is extensively developed in the Interbasaltic Formation (IBF) of the Palaeogene volcanic sequence of the Antrim Lava Group (Fig. 8.1). Although the general characteristics of the IBF and laterite, including its formation and geochemical evolution, are well documented (e.g. Cole *et al.*, 1912; Hill *et al.*, 2000), there has been no systematic evaluation of its critical metal potential.



Cobalt is relatively enriched in deep soils over much of the Antrim Plateau (Fig. 8.8a). Very high-tenor anomalies (maximum 80 ppm) exist in a number of areas, particularly over the southern half of the Plateau and to the west of the Dalradian rocks in this area (Fig. 8.8b). Gallium concentrations in deep soils are also elevated across the Antrim Plateau, and high concentrations (maximum 34 ppm) (Fig. 8.4a) broadly correlate with areas anomalous for cobalt. Presence of the IBF does not appear to influence the distribution of anomalies for these elements.

Figure 8.8. The distribution of selected metals in the Tellus Project S-horizon (deep) soil samples over parts of Northern Ireland (samples with lower concentrations are omitted for clarity): (a) cobalt; (b) cobalt over the Antrim Plateau.

CONCLUSIONS

In the context of a broad range of ore-forming environments and the limited data available on critical metal concentrations in known deposits, a preliminary review of the Tellus geochemistry suggests that the north of Ireland might host resources of some critical metals.

Most critical metals are produced as by-products of other commodities, and unless an exceptional deposit is discovered this is also likely to be the case in Ireland. By-product metal production can significantly enhance the viability of a mining operation and is particularly important during periods of commodity price volatility. The added value of critical metal by-products could support the development of relatively small, complex or difficult to access ore bodies in Ireland, which will generally be near the lower limits of commercial viability. These types of ore body are increasingly being viewed as a potentially important future source of European metal supply.

Despite the geological potential of Ireland, in common with many parts of the world, knowledge of the critical or minor element composition of most deposits is either absent or

too poor to judge their future economic importance. Routine geochemical analysis during mineral exploration programmes for a broader suite of analytes, with appropriate detection limits and particularly for litho-geochemical samples, would substantially contribute to the knowledge base. Detailed field-based investigations, sampling and laboratory studies, using the approach of Moore *et al.* (2013), and focusing on the geological environments discussed in this review, are essential to explain the source of many critical metal geochemical anomalies apparent in the Tellus data. This might:

1. identify and prioritise targets for follow-up academic research and/or commercial mineral exploration, helping to promote Ireland's mineral potential to a global audience, with the aim of capturing a greater share of European mineral exploration expenditure;
2. contribute to the refinement of geological models for critical metal concentration, which would be directly relevant to other parts of the British Isles and could inform mineral exploration strategies;
3. improve knowledge of Ireland's critical raw materials resources and their potential to reduce European dependence on mineral imports and improve security of supply; and
4. ultimately inform the development of national and European government policy to ensure that economic growth and competitiveness are not compromised by restricted material availability.

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Table of Contents:

Prelim

DOI: <https://doi.org/10.7486/DRI.b851k323d>

Chapter 1

The Tellus geosciences surveys of the north of Ireland: context, delivery and impacts

DOI: <https://doi.org/10.7486/DRI.st74s528d>

Chapter 2

The Tellus airborne geophysical surveys and results

DOI: <https://doi.org/10.7486/DRI.t148tx96z>

Chapter 3

The Tellus geochemical surveys, results and applications

DOI: <https://doi.org/10.7486/DRI.t722wq645>

Chapter 4

Stakeholder engagement for regional geoscientific surveying: the Tellus Border communications campaign

DOI: <https://doi.org/10.7486/DRI.w089fr763>

Chapter 5

Mineral resources and Tellus: the essential balance

DOI: <https://doi.org/10.7486/DRI.wd37kb12s>

Chapter 6

Gold exploration in the north of Ireland: new targets from the Tellus Projects

DOI: <https://doi.org/10.7486/DRI.wh24m696v>

Chapter 7

Using soil geochemistry to investigate gold and base metal distribution and dispersal in the glaciated north of Ireland

DOI: <https://doi.org/10.7486/DRI.wm11n3806>

Chapter 8

Critical metals for hightechnology applications: mineral exploration potential in the north of Ireland

DOI: <https://doi.org/10.7486/DRI.wp98p0649>

Chapter 9

A natural laboratory for critical metals investigations in the Mourne Mountains granites

DOI: <https://doi.org/10.7486/DRI.cc08ww45f>

Chapter 10

Geothermal potential of granitic rocks of the Mourne Mountains

DOI: <https://doi.org/10.7486/DRI.ff36jm09f>

Chapter 11

Shape and intrusion history of the Late Caledonian Newry Igneous Complex, Northern Ireland

DOI: <https://doi.org/10.7486/DRI.2v248822m>

Chapter 12

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

DOI: <https://doi.org/10.7486/DRI.5x226w262>

Chapter 13

The geological significance of electrical conductivity anomalies of the Ordovician- Silurian Moffat Shale Group, Northern Ireland

DOI: <https://doi.org/10.7486/DRI.6m31f4149>

Chapter 14

Faults, intrusions and flood basalts: the Cenozoic structure of the north of Ireland

DOI: <https://doi.org/10.7486/DRI.90205h306>

Chapter 15

Information for agriculture from regional geochemical surveys: the example of soil pH in the Tellus and Tellus Border data

DOI: <https://doi.org/10.7486/DRI.dv14c8060>

Chapter 16

An ecohydrological investigation of wetlands in the border counties of Ireland: a framework for a holistic understanding of wetland systems

DOI: <https://doi.org/10.7486/DRI.hd775d90j>

Chapter 17

Assessing nutrient enrichment risk to groundwater-dependent ecosystems in the border counties of Ireland
DOI: <https://doi.org/10.7486/DRI.k356pk18j>

Chapter 18

Mapping the terrestrial gamma radiation dose
DOI: <https://doi.org/10.7486/DRI.k930rb86z>

Chapter 19

Soils and their radiometric characteristics
DOI: <https://doi.org/10.7486/DRI.mp495t62g>

Chapter 20

Modelling in-house radon potential using Tellus data and geology to supplement inhouse radon measurements
DOI: <https://doi.org/10.7486/DRI.ns06hm86z>

Chapter 21

Determining geochemical threshold values from the Tellus data sets: the examples of zinc and iodine|
DOI: <https://doi.org/10.7486/DRI.r2087418g>

Chapter 22

Identification of the geochemical signatures of diffuse pollution in the Tellus Border soil data set, using source apportionment
DOI: <https://doi.org/10.7486/DRI.wh24m698d>

Chapter 23

Stream sediment background concentrations in mineralised catchments in Northern Ireland: assessment of 'pressures' on water bodies in fulfilment of Water Framework Directive objectives
DOI: <https://doi.org/10.7486/DRI.x633tf86g>

Chapter 24

Mapping metallic contamination of soils in the Lower Foyle catchment
DOI: <https://doi.org/10.7486/DRI.9k42bv355>

Chapter 25

Refining the human health risk assessment process in Northern Ireland through the use of oral bioaccessibility data
DOI: <https://doi.org/10.7486/DRI.9p29cr199>

Chapter 26

Combining environmental and medical data sets to explore potential associations between environmental factors and health: policy implications for human health risk assessments
DOI: <https://doi.org/10.7486/DRI.9s16dn03n>

Chapter 27

Mapping a waste disposal site using Tellus airborne geophysical data
DOI: <https://doi.org/10.7486/DRI.9w03fh87q>

Chapter 28

The use of aero-magnetics to enhance a numerical groundwater model of the Lagan Valley aquifer, Northern Ireland
DOI: <https://doi.org/10.7486/DRI.9z90gd711>

Chapter 29

Carbon sequestration in the soils of Northern Ireland: potential based on mineralogical controls
DOI: <https://doi.org/10.7486/DRI.b277h9556>

Chapter 30

Spatial distribution of soil geochemistry in geoforensics
DOI: <https://doi.org/10.7486/DRI.b564j6392>

End matter

DOI: <https://doi.org/10.7486/DRI.bc38m007j>