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Orthomagmatic Ni-Cu-Au-PGE mineralisation in Ireland and Northern Ireland: A review of historic exploration and future prospectivity

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EXECUTIVE SUMMARY

Platinum group elements (PGEs) are essential for green technologies, yet their European supply is derived from a small number of very large deposits concentrated in only a few countries, necessitating the identification of alternative domestic sources. PGE mineralisation is typically associated with large magma chambers or feeder conduits and commonly occurs in sulphide minerals alongside Ni, Cu and Au. Mafic-ultramafic (Mg- and Fe-rich) intrusions in Ireland and Northern Ireland have been explored for Ni-Cu-Au-PGE mineralisation since the 1960s. While these programmes have identified widespread geochemical anomalies and sulphide-bearing intrusions, they have not delineated deposits of economic scale, likely reflecting the small, localised and, in some cases, deeply buried nature of mineralisation. While Ireland and Northern Ireland do not host deposits comparable in scale to current major producers, such large systems are unlikely to occur elsewhere in Europe. In this context, small-scale magmatic mineralisation of the type identified in Ireland and Northern Ireland may represent a realistic model for future domestic European PGE supply. These systems also provide an important natural laboratory for understanding mineralising processes and improving exploration strategies for structurally controlled deposits elsewhere.

ABSTRACT

Platinum group elements (PGEs) are essential constituents in established and emerging green technologies, yet European supply is dominated by a small number of very large deposits, necessitating the identification of alternative domestic sources. Most economic mineralisation is associated with orthomagmatic Ni-Cu-Au-PGE systems, where chalcophile elements are concentrated within sulphide minerals in mafic-ultramafic layered intrusions or conduit systems. Irish and Northern Irish centres have been identified among the most prospective European PGE targets and have been subject to exploration since the 1960s, largely focused on Paleogene intrusions. This study reviews the geological framework, exploration history and prospectivity of PGE mineralisation in Ireland and Northern Ireland, synthesising published data and exploration records. Historic exploration has failed to identify deposits of economic scale, likely because mineralisation is highly localised and controlled by magma system architecture, with country rock contacts and fault-controlled dyke geometries influencing sulphide saturation and accumulation. Although Ireland does not host mineralisation comparable in scale to existing world-class deposits, such systems are unlikely to occur anywhere in Europe. In this context, mineralisation of the type proposed in Ireland may represent a realistic model for future European supply, while providing a natural laboratory for understanding tectonomagmatically controlled mineralising processes at local scales.

INTRODUCTION

The platinum-group elements (PGEs) comprise platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os), which share similar chemical behaviour and strong chalcophile affinities. PGEs are used in a wide range of industrial applications, many of which underpin low-carbon and environmental technologies. Historically, demand has been dominated by their use in emission-reducing automobile catalytic converters (Mudd *et al.*, 2018), but demand patterns are evolving, with increasing importance in modern electronics and electrochemical energy technologies, including fuel cells and advanced electrolysers used for hydrogen production and energy storage within renewable electricity systems (Hughes *et al.*, 2021; Liu, 2021; Lundaev *et al.*, 2023). Additional applications include chemical catalysts, medical alloys and jewellery (Mudd, 2012). Despite their strategic importance, primary supply of PGEs remains highly concentrated in a small number of producing nations, raising concerns over long-term supply security. Consequently, they are classified as critical raw materials in multiple jurisdictions, including the European Union (European Commission, 2020), the UK (Mudd *et al.*, 2024) and the USA (U.S. Geological Survey, 2025).

South Africa dominates primary PGE production, accounting for ~60–65 % of total extraction and a comparable proportion of global reserves, with a particular dominance in Pt supply (Fig. 1a; Mudd *et al.*, 2018; Idoine *et al.*, 2025). All current South African production is derived from the Bushveld Complex, which hosts extensive economic PGE mineralisation within the Merensky Reef, Upper Group 2 (UG2) chromitite and Platreef horizons (Cawthorn *et al.*, 2002). Russia is the next most significant producer, contributing ~20–25% of global extraction, with similarly substantial reserves and a relative dominance in Pd supply (Idoine *et al.*, 2025). Russian production is largely associated with ore districts in the Norilsk-Talnakh system (Barnes *et al.*, 2020). Beyond these large producers, national contributions are comparatively minor, including Zimbabwe (Great Dyke; Stribrny *et al.*, 2000), Canada (Sudbury; Ames *et al.*, 2008) and the United States (Stillwater Complex; Keays *et al.*, 2012), which account for ~7%, ~5% and ~4% of global production, respectively (Mudd *et al.*, 2018; Idoine *et al.*, 2025). European primary production is extremely limited, constituting <1% of global output through minor by-product extraction in Finland (Kevitsa) and historically Poland (Zechstein; Kucha, 1982; Santaguida *et al.*, 2015; Idoine *et al.*, 2025). This distribution in production is reflected in European Union import dependency, which relies heavily on supply from South Africa, the

USA and Russia (Fig. 1b), with only ~26% of European PGEs derived from secondary refined sources (European Commission Joint Research Centre, 2026).

Dependence on imports from a limited number of countries creates vulnerability within PGE supply chains, arising from local environmental, social and governance (ESG) constraints in producing regions as well as broader geopolitical tensions (Cole, 2023; Li *et al.*, 2023). In South Africa, labour unrest and socio-political instability have periodically disrupted production, notably during the 2012 strike at Lonmin's Marikana mine (Capps, 2015; Mudd *et al.*, 2018; Baskaran, 2021). Elsewhere, sanctions and operational safety concerns have contributed to volatility in global PGE prices (Burlakovs *et al.*, 2020).

In this context, identifying and developing domestic production within Europe and the UK is strategically significant. Active exploration for orthomagmatic PGEs is underway in northern Europe, including intrusions in Finland (Sakatti) and Norway (Råna; Anglo American, 2023; Jonsson *et al.*, 2023; Metals One plc, 2023), and a defined resource has been delineated in the Skaergaard Intrusion, Greenland (Nielsen *et al.*, 2015). Irish and Northern Irish igneous intrusions have been identified as prospective for PGE mineralisation (Andersen *et al.*, 2002; Hughes *et al.*, 2015) and have been subject to both historic and ongoing exploration. They are recognised as potential targets by both the UK Critical Minerals Intelligence Centre (Deady *et al.*, 2023; Currie & Elliott, 2024) and by the Irish Government (DECC, 2025), but remain underdeveloped relative to northern European projects. In this contribution, we briefly outline the key geological processes responsible for generating orthomagmatic mineralisation before describing the tectonomagmatic history of Ireland and Northern Ireland, demonstrating that Palaeogene centres in particular share key commonalities with major global deposits. We then review the history of PGE exploration on the island of Ireland, focussing on areas of most extensive exploration in Carlingford (Co. Louth) and minor Northern Irish intrusions. Finally, we assess their future prospectivity and argue that, although inherently limited in scale relative to Bushveld or Norilsk, smaller orthomagmatic systems of the type recognised in Ireland may contribute to European supply diversification while providing valuable natural laboratories for understanding PGE deposit-forming processes.

Genetic framework for Ni-Cu-Au-PGE mineralisation

Although PGEs occur in a range of geological environments, including hydrothermal systems (e.g. Zechstein) and alluvial placers (e.g. Urals), the vast majority of global resources are associated with mafic-ultramafic orthomagmatic deposits, principally stratiform layered intrusions and magmatic conduit systems (Macdonald, 1987; Mungall & Naldrett, 2008). In these settings, PGEs are closely associated with Ni-Cu sulphides, commonly accompanied by elevated Au abundances. In the largest provinces (e.g. Bushveld, Norilsk), they are mined as primary commodities or significant co-products alongside Ni and Cu, whereas in smaller systems they contribute as by-products during extraction of other chalcophile metals (Zientek *et al.*, 2017; Mudd *et al.*, 2018).

The formation of an economic Ni-Cu-Au-PGE deposit requires a sequence of interdependent magmatic processes (Naldrett, 2004, 2013); inefficiency at any stage may ultimately limit economic viability. Although system behaviour is inherently complex and varies between deposits, the principal processes include:

1) Primary mantle melts are generated with elevated Ni, Cu and PGE concentrations, either from high-degree partial melting of the asthenosphere or melting of metal-enriched subcontinental lithospheric mantle (SCLM) at the margins of Archean cratons. Accordingly, most major orthomagmatic provinces are associated with large-volume tholeiitic (or komatiitic) mafic magmatism, commonly developed in plume-influenced settings and frequently situated along cratonic margins and/or temporally associated with large igneous provinces (LIP; Barnes & Lightfoot, 2005; Groves & Bierlein, 2007; Maier

& Groves, 2011; Arndt, 2013; Hughes *et al.*, 2015), although elevated PGE concentrations are also reported in some supra-subduction ophiolites (Ahmed & Arai, 2002).

2) Magmas ascend through the crust without significant olivine fractionation or premature sulphide saturation which would extract Ni and other chalcophile metals from the melt and sequester them at depth (Barnes & Lightfoot, 2005). An increase in sulphide solubility with decreasing pressure drives ascending magmas further from sulphide saturation at constant temperature, assisting preservation of metal budgets (Mavrogenes & O'Neill, 1999).
3) Following crustal emplacement, magmas attain sulphide saturation. Although closed-system cooling and fractional crystallisation may induce sulphide saturation, the sulphide volumes produced are commonly limited and insufficient to form economic deposits (Ripley & Li, 2013). Rather, magma mixing and crustal assimilation are widely invoked as mechanisms for triggering the large-scale sulphide saturation required for economic mineralisation (Li *et al.*, 2001). Assimilation may directly add S to the magma (Li *et al.*, 2009; Ripley & Li, 2013), reduce sulphide solubility through SiO_2 addition (Irvine, 1976; Li & Naldrett, 1993), and/or shift the system towards sulphide saturation via modification of oxygen fugacity (e.g. carbonate or coal contamination; Barnes *et al.*, 2020; Thompson *et al.*, 2025).
4) Once sulphide saturation is achieved, PGEs and other chalcophile metals partition strongly into immiscible sulphide liquids. In economic systems, these sulphides are further upgraded through equilibration with large volumes of silicate melt at high effective R-factors, increasing metal tenors (Campbell & Naldrett, 1979; Naldrett, 2010). Such interactions may occur during sulphide settling within magma chambers, during magma transport between crustal storage regions, or through repeated magma injections within dynamic conduit systems (Barnes & Ripley, 2016).

5) Finally, sulphide liquids are physically accumulated to increase their local modal abundance. In conduit environments, this may occur where sulphides are deposited in fluid-dynamic traps (Barnes & Lightfoot, 2005; Barnes *et al.*, 2016; Barnes & Robertson, 2019). In layered intrusions, accumulation may occur through a range of processes forming stratabound 'reefs', including silicate-sulphide density segregation and fluid redistribution (Maier, 2005; Holwell & McDonald, 2010).

TECTONOMAGMATIC FRAMEWORK FOR PGE PROSPECTIVITY IN IRELAND AND NORTHERN IRELAND

Although Ireland has extensive igneous bedrock (Fig. 2), including large granitic batholiths (Feely *et al.*, 2003; Cooper *et al.*, 2016; Fritschle *et al.*, 2018; Leake, 2023), orthomagmatic Ni-Cu-Au-PGE mineralisation is restricted to mafic-ultramafic magmatism. Irish mafic-ultramafic centres can be grouped into three principal tectonomagmatic episodes: 1) Lower Palaeozoic (predominantly Ordovician) supra-arc magmatism associated with Iapetus convergence, 2) Carboniferous intraplate extension, and 3) Palaeogene plume-related magmatism linked to the North Atlantic Igneous Province (NAIP).

Neoproterozoic metabasites: The Dalradian Supergroup includes Neoproterozoic metabasites emplaced during rifting of the Laurentian margin and opening of the Iapetus Ocean, and subsequently deformed and metamorphosed during the Grampian phase of the Caledonian Orogeny (Fettes *et al.*, 2011). These bodies are small, structurally dismembered and extensively metamorphosed, and do not preserve the intrusive plumbing architectures required for economic Ni-Cu-Au-PGE mineralisation (e.g. Flowerdew, 1998; Chew, 2001; Leake, 2016).

Lower Palaeozoic centres: Lower Palaeozoic (principally Early–Middle Ordovician) mafic-ultramafic centres formed in supra-subduction zone settings during Iapetus convergence. The Tyrone Igneous Complex represents an obducted supra-subduction sequence comprising ophiolitic plutonic and arc-volcanic components (Chew *et al.*, 2010; Cooper *et al.*, 2011; Hollis *et al.*, 2013). Within the plutonic group, layered gabbros and dolerite dykes are analogous to other Caledonian ophiolitic sequences hosting minor PGE mineralisation (Grenne *et al.*, 1999; Hollis *et al.*, 2014). Similarly, metamorphosed mafic-ultramafic centres in Connemara (e.g. Dawros-Currywongaun-Doughruagh and the Cashel-Lough Wheelaun intrusion; Leake, 1989; Tanner, 1990; O'Driscoll *et al.*, 2005; O'Driscoll & Chew, 2021) and the southeast volcanic belt (e.g. Lambay, Avoca, Copper Coast; Stillman & Williams, 1979; McConnell, 2000; Breheny *et al.*, 2016; Steiner, 2018) record supra-subduction magmatism. Collectively, these Lower Palaeozoic systems record subduction-related mantle sources and comparatively restricted mafic magma systems which are tectonomagmatically incongruous with extensive orthomagmatic Ni-Cu-PGE mineralisation.

Carboniferous magmatism: Carboniferous magmatism is volumetrically minor and largely confined to the Limerick Basin and dykes in the west of Ireland (Strogen, 1983; Mitchell & Mohr, 1987; Pracht & Kinnaird, 1997). It was generated during intraplate lithospheric extension influenced by far-field stresses associated with Variscan convergence (Upton *et al.*, 2004; Elliott *et al.*, 2015). These magmas are exclusively alkaline and reflect low-degree partial melting (Slezak *et al.*, 2023), geochemically distinct from the high-flux tholeiitic magma systems typical of major orthomagmatic provinces.

Palaeogene magmatism: Palaeogene igneous centres form part of the NAIP, a plume-related LIP initiated at ~64 Ma following lithospheric impingement of the proto-Icelandic plume (Saunders *et al.*, 1997; Ganerød *et al.*, 2010; Wilkinson *et al.*, 2017). The Antrim Lava Group comprises an extensive succession of tholeiitic flood basalts emplaced during two periods of intense volcanism (forming the Upper and Lower Basalt Formations - UBF and LBF, respectively; Lyle & Patton, 1989; Barrat & Nesbitt, 1996; Cooper *et al.*, 2026), separated by a period of relative repose during which magmatism was limited to a few small rhyolitic centres and only rare basaltic eruptions (Old, 1975; Carter *et al.*, 2024; Cooper *et al.*, 2026). Contemporaneous central complexes at Carlingford and Slieve Gullion consist of bimodal suites including mafic-ultramafic layered series (Reynolds, 1952; Le Bas, 1960; Elwell, 1962; Gamble, 1979; Meade *et al.*, 2014; Beckwith *et al.*, in review), whereas the Mourne Mountains are exclusively granitic and represent a later magmatic phase (Meighan *et al.*, 1984; Gibson *et al.*, 1987; Cooper *et al.*, 2026). The Dromore Gravity High may represent an additional sub-surface Palaeogene central complex, although its origin remains debated (Shaw *et al.*, 2022; Morrison *et al.*, in review). Palaeogene magmatism also includes numerous minor intrusions, with gabbroic sills, dyke swarms and plugs extending across Ireland and Northern Ireland (Ledevin *et al.*, 2012; Anderson *et al.*, 2016; Anderson *et al.*, 2018; Lindsay *et al.*, 2019; Holness *et al.*, 2025). Geochemical evidence indicates relatively high degrees of mantle melting during early plume impingement (Carter *et al.*, 2024), and early lavas and intrusions record contributions from SCLM comparable to Hebridean centres, with the disappearance of this component broadly coinciding with the interbasaltic hiatus (Hughes *et al.*, 2014; Hughes *et al.*, 2015; Morrison *et al.*, in review). Collectively, the Palaeogene episode differs fundamentally from earlier Irish arc-related and alkaline intraplate magmatism in scale, melt flux and tholeiitic affinity, and more closely aligns with the tectonomagmatic conditions required for orthomagmatic Ni-Cu-Au-PGE mineralisation.

EXPLORATION HISTORY OF THE CARLINGFORD COMPLEX

The Carlingford Complex has been dated at 61.4 ± 0.8 Ma and is generally regarded as the oldest Irish Palaeogene central complex (Mitchell *et al.*, 1999), broadly contemporaneous with emplacement of the LBF (Cooper *et al.*, 2026). Although available dates indicate that it slightly pre-dates Slieve Gullion, the close spatial and temporal association between the two centres suggests they formed during the same magmatic episode. The bimodal intrusion comprises a granite ring-dyke, gabbroic lopolith and doleritic cone sheets emplaced within Silurian metagreywacke and Carboniferous limestone host rocks (Meade *et al.*, 2014; Beckwith *et al.*, in review). Early studies distinguished two phases of gabbroic intrusion: a small body of alkaline 'Early Gabbros' exposed around Rampark, followed by the volumetrically dominant tholeiitic 'Later Gabbros', although the former remains almost entirely unstudied (Charlesworth, 1960; Le Bas, 1960). The Later Gabbros comprise four major layers: a basal Lower Zone containing olivine gabbroic cumulates overlain by petrographically distinct Middle Zone, Upper Zone A and Upper Zone B units; rare anorthosites occur at the top of Upper Zone B, exposed only at Eagles Rock (Le Bas, 1960; Beckwith *et al.*, in review). The complex was a key site in the early development of igneous petrology (Fig. 3), informing formative ideas on bimodal magmatism (Haughton, 1856; Traill & Baily, 1878; Sollas, 1892), metasomatic skarn formation (Richey, 1932; Nockolds, 1935; Nockolds, 1938; Harry, 1952) and magmatic layering (Le Bas, 1960, 1965, 1970).

Mineral exploration in Carlingford began in 1967 when Rio Tinto (under Riofinex/Rio Tinto-Zinc Corporation) acquired prospecting licences across the Cooley Peninsula (Rio Tinto Finance & Exploration Ltd., 1968). The company initially undertook reconnaissance mapping, regional stream-sediment and soil geochemical surveys, analysing several thousand samples. In the early 1970s they investigated a Ni-Cu soil anomaly on the west flank of Slieve Foy for potential orthomagmatic sulphide mineralisation, conducting geophysical surveys (resistivity and magnetics) and drilling three boreholes totalling ~270 m (Rio Tinto Finance & Exploration Ltd., 1973). However, as geophysical anomalies were interpreted as magnetite rather than sulphides and drilling encountered only trace Ni-Cu mineralisation, exploration shifted towards evaluating the potential for skarn-related carbonate-hosted base metal mineralisation; this was ultimately deemed sub-economic and the licences were relinquished (Rio Tinto Finance & Exploration Ltd., 1975).

Carlingford exploration resumed in 1980 when Irish Base Metals acquired licences across the Cooley Peninsula, initially intending to investigate the uranium potential of the granites. However, early stream sediment sampling identified chalcophile anomalies in drainage sediments northwest of Slieve Foy, and the discovery of a sulphide-mineralised float boulder (CAR, now lost) within a scree slope on the eastern flank of the mountain redirected exploration towards orthomagmatic Ni-Cu-PGE mineralisation (Irish Base Metals Limited, 1982). Subsequent assays on the CAR boulder returned extremely high Ni, Cu and PGE concentrations, up to ~3 g/t Pt + Pd, which generated significant exploration interest and prompted comparison with the world-class Sudbury and Merensky Reef orthomagmatic deposits (Table 1; Irish Base Metals Limited, 1984; Buchanan, 2012). The gabbroic boulder is described as having a jigsaw fit brecciated texture with cracks containing sulphides and olivines with altered rims; this was interpreted as evidence for a near-solidus 'explosion', driven by fluids which transported sulphides (Irish Base Metals Limited, 1982). Bedrock containing similar mineralisation was subsequently identified ~450 m south of the boulder within an 'isolated ultrabasic sill stratigraphically below the main layered complex' (Irish Base Metals Limited, 1984). Integrating new soil geochemistry with Rio Tinto's earlier datasets, the company determined that chalcophile anomalies correlate with the stratigraphically lowest exposed part of the intrusion (LZ of Beckwith *et al.*, in review). Six boreholes totalling ~340 m were drilled targeting geochemical and geophysical anomalies within this unit on the south and southeast side of Slieve Foy (Fig. 4a,b; five in licence 676, one in licence 1553). However, the gabbros contained only sub-economic sulphide mineralisation (max. 250 ppb Pt + Pd), and boreholes failed to intersect similar mineralisation comparable to the CAR boulder or the base of the intrusion, leading Irish Base Metals to relinquish the licences (Irish Base Metals Limited, 1984).

Westland Exploration Limited acquired the licences in 1984–85 and initially undertook a work programme re-evaluating the existing core and float material (Westland Exploration Limited, 1985). They commissioned an expert report by Buchanan (1985), which summarised previous exploration and provided a detailed description of the CAR boulder. The sample is described as containing 80% plagioclase, equal proportions of clinopyroxene and olivine, and <5% sulphides (chalcopyrite, pentlandite and minor pyrrhotite), again displaying a clastic, fragmented texture. However, because clinopyroxene and plagioclase are unaltered and fresh olivine cores remain, Buchanan (1985) rejected the earlier fluid-driven 'explosion' hypothesis and instead attributed fragmentation to brecciation within a fault zone, with sulphides interpreted as primary magmatic phases. The report concluded that the system remains prospective for orthomagmatic mineralisation, but that sulphide saturation was likely triggered by country rock contamination (e.g. S addition from Silurian sediments or carbonate contamination from Carboniferous limestones). Existing boreholes were interpreted to be too shallow to intersect the mineralised horizon, as none reached the basal gabbro-country rock contact, and mineralisation was predicted to be discontinuous, implying that characterisation of any economic zone would require extensive additional drilling. Westland subsequently drilled one additional borehole (~216 m; in licence 676) attempting to test this model and intersect the basalt contact, but the hole failed to reach sedimentary country rock and only encountered minor mineralisation (Westland Exploration Limited, 1987).

In 1987 Fleck Resources Limited entered as a joint-venture partner and the companies continued soil and stream sediment sampling on the east side of Slieve Foy, identifying further chalcophile anomalies (Fleck Resources Limited, 1987). This work led to the discovery of PGE-mineralised bedrock (0.4 g/t Pt + Pd) containing disseminated chalcopyrite and pyrrhotite within a narrow lens hosted by a mafic dyke at the top of the scree slope where the CAR boulder was discovered. However, the showing was extremely limited in extent, and the companies ultimately relinquished the licences in 1990.

BHP obtained a prospecting licence close to Carlingford in 1995 and undertook a limited two-year exploration campaign. Soil sampling transects confirmed previously identified anomalies (Fig. 5), and a number of doleritic dykes were noted to contain visible mineralisation in hand specimen (Fig. 4c,d); a single assayed dyke sample collected near the CAR boulder returned 142 ppb Pt + Pd. Although the company concluded that the intrusion remained prospective for orthomagmatic mineralisation, either associated with the gabbro-sediment contact (analogous to the Platreef) or structurally controlled by faults, the licence was not renewed (BHP, 1997). In 2005, Belmore Resources sought to obtain the licence and continue exploration for PGEs, but the application faced local opposition and did not progress (Ryan, 2005).

EXPLORATION HISTORY OF NORTHERN IRISH MINOR INTRUSIONS

Ireland and Northern Ireland host numerous Palaeogene minor intrusions which form a conduit system associated with the ALG. Anderson *et al.* (2018) mapped six major regional dyke swarms extending hundreds of kilometres across Ireland, generally striking NW–SE but with slight offsets from one another. These are ubiquitously mafic and comprise the Erne (61.346 ± 0.085 Ma) swarm which is contemporaneous with emplacement of the LBF, the Killala and Donegal–Kingscourt swarms which were emplaced during the interbasaltic hiatus, the Ardglass-Ballycastle and St. John's Point–Lisburn swarms which coincide with the UBF, and the Fleetwood swarm which post-dates the UBF (Cooper *et al.*, 2026). Morrison *et al.* (in review) map an additional interbasaltic Connacht swarm and suggest that a Southern Erne sub-swarm is potentially derived from Carlingford and Slieve Gullion, whereas a Northern Erne sub-swarm is possibly related to the Dromore Gravity High. The later post-LBF swarms are inferred to originate from North Atlantic submarine magmatic centres (e.g. Blackstones Bank, Anton Dohrn). These dykes are interpreted as feeding the ALG flood basalts through linear fissure systems, with evidence of eruptive vents preserved by at least 30 plugs exposed across Northern Ireland (e.g. Slemish, Craigcluggan; Cooper & Johnston, 2004). In addition, numerous doleritic–gabbroic sills (e.g. Portrush, Scrabo, Fair Head, Magilligan) intrude beneath or into the ALG across Northern Ireland, extending off the north coast (GSNI, 1997; Young & Donald, 2013), with fewer Palaeogene sills in Ireland (e.g. the Killala Gabbro; Preston, 1979). These span the timescale of flood basalt emplacement (Cooper *et al.*, 2026), reach thicknesses up to ~170–180 m, and preserve evidence of internal magmatic processes including fractionation and assimilation (Holness *et al.*, 2025).

Minor early exploration for orthomagmatic PGE mineralisation targeted the Killala Gabbro, with Glencar Exploration plc acquiring prospecting licences in 1988 following the identification of chalcophile element anomalies in earlier base metal exploration (Glencar Exploration plc, 1989). Petrographic observations and geochemical analyses identified disseminated sulphides (e.g. pyrrhotite, chalcopyrite) and associated enrichments in chalcophile trace elements (Cu, Cr, Ni, Co), particularly towards the basal contact of the intrusion. These features were interpreted to record sulphide saturation driven by country rock contamination along the floor of the intrusion. However, PGEs were below detection limit in all samples, and the company concluded that any significant mineralisation would likely occur down-dip, beyond the limits of surface exposure and requiring drill testing. Given the relatively low sulphide concentrations and difficulties in correlating internal gabbro units, the licences were relinquished in 1989 (Glencar Exploration plc, 1989).

Lonmin Plc began large-scale exploration for orthomagmatic Ni-Cu-Au-PGE mineralisation associated with the ALG in 2008, initially acquiring 11 prospecting licences covering most of the Antrim Plateau (Lonmin Limited, 2008). This was largely motivated by the release of the Northern Irish Tellus geochemical and geophysical datasets, which revealed significant PGE and associated chalcophile element anomalies in the region (Figs. 6, 7; Young & Donald, 2013). Early work focused on compilation and interpretation of the Tellus datasets and verification of anomalies through regional soil surveys, together with a full-tensor gravity gradiometry survey, comprising ~3,500 line km data (Lonmin Limited, 2008). These datasets were used to identify dense subsurface targets interpreted as potential mafic intrusions, which were subsequently investigated through higher-resolution soil and bedrock sampling, microgravity surveys and drill testing (~40 boreholes drilled in total; Lonmin Limited, 2009a; Lonmin Limited, 2011).

Two early licences in the south of Lonmin's exploration area (close to Lough Neagh) were relinquished following first appraisal of the Tellus data in 2009 (LON 06/08 and 07/08; Lonmin Limited, 2008; Lusty, 2010). In the same year the company acquired an additional licence in the vicinity of the Dromore Gravity High (LON 12/09), representing their only exploration outside of the Antrim Plateau (Lonmin Limited, 2009b). Tellus geochemical data show a clear PGE anomaly in this area (Fig. 6a), coincident with a prominent gravity high (e.g. Young & Donald, 2013). Lonmin evaluated this target using Tellus geophysical data with limited soil and bedrock geochemistry, determining that the anomaly originated from a deep source (>2 km). Exploration therefore focused on dykes containing 'deep crustal xenoliths' which might record the lithology at depth. The company concluded that the anomaly might reflect either part of the Tyrone ophiolite or a deeply buried Palaeogene intrusion but the licence was relinquished after only one year due to poor geochemical results and the significant depth of the source reducing its economic prospectivity (Lonmin Limited, 2009b).

Lonmin's regional programme identified a large number of individual targets across the Antrim Plateau, reflecting abundant geochemical and geophysical anomalies in Tellus and their regional reconnaissance surveys. Follow-up work showed that some anomalies were unrelated to Palaeogene magmatism and instead reflected structures within the Dalradian basement rather than concealed intrusions (e.g. Dunloy target; Lonmin Limited, 2013a). Other targets were interpreted as magmatic but were either considered low priority, for example where logistical constraints limited follow-up work (e.g. the Gortnamoyagh Forest gravity anomaly; Lonmin Limited, 2013b), or were found to have limited mineralisation potential during initial exploration (e.g. the Rathlin Basin Mafic Sill; Lonmin Limited, 2013c). In 2014, the company restructured its licence holdings, reducing the geographic coverage to focus on their most prospective targets, with one licence containing potential epithermal-orogenic gold occurrences (LON01/14) separated into a joint venture with Koza Ltd (Lonmin Limited, 2014a). High-prospectivity orthomagmatic targets retained by Lonmin were primarily associated with interactions between Palaeogene magmatism and major fault systems, and included:

1) The Boughshane anomaly, a large gravity feature potentially associated with the Camlough Fault. The anomaly was interpreted either as a pre-Dalradian intrusion with potential for gold mineralisation or as a concealed Palaeogene intrusion capable of hosting PGE mineralisation. Its large geophysical footprint and structural association suggested a potentially significant intrusive centre at depth, but its geometry and composition remained poorly constrained due to limited drilling (Lonmin Limited, 2014c).

2) The 'Lough Foyle Igneous Complex', interpreted as an extensive differentiated or layered Palaeogene intrusion, largely submarine, with only the Magilligan Sill representing a potential onshore lateral extension and corresponding to a lower magnetic anomaly than other parts of the system (Lonmin Limited, 2014d). The complex is interpreted as a fault-controlled intrusive system associated with the Lough Foyle Fault, and exploration of this target was guided by a Norilsk-style orthomagmatic model. Magmas associated with the complex show evidence for significant crustal S contamination, driving sulphide saturation (e.g. pyrrhotite, chalcopyrite, pentlandite). Later magma injections may have upgraded the PGE and other chalcophile metal tenors, and although only sub-economic concentrations were identified within the Magilligan

Sill, geochemical evidence suggests potential for Ni-Cu-Au-PGE mineralisation at depth (Lindsay *et al.*, 2019).

3) The Corkey conduit system, comprising two olivine-dolerite plugs (conduits) which ascend through Dalradian metasediments exposed on the floor of Corkey Quarry and merge close to the present surface, forming a sill within the stratigraphically overlying ALG exposed in the quarry wall. The principal conduit investigated by Lonmin dips steeply to the west and intersects the Loughguile Fault, suggesting a structural control on magma emplacement (Walker, 1959; Lonmin Limited, 2014b). Exploration of this target was guided by a deposit model in which the conduit system might act as a fluid-dynamic sulphide trap. Although several boreholes drilled around the quarry did not intersect economic mineralisation, one encountered a disaggregated ‘black sand’ horizon containing abundant pyrrhotite. This material was tentatively interpreted to record a mineralised gabbroic layer, although the possibility that it resulted from drilling artefacts could not be excluded (Lonmin Limited, 2013a).

Despite these prospects, Lonmin relinquished their Northern Irish licences in 2017 during a period of financial pressure on the company following the Marikana strikes and a decline in PGE commodity prices (BBC News, 2015; Hill & Maroun, 2015). Their exploration portfolio was subsequently acquired by Walkabout Resources Ltd, but the company rapidly shifted focus towards the gold-based joint venture with Koza Ltd, with little or no further exploration for orthomagmatic Ni-Cu-Au-PGE mineralisation (Independent Investment Research, 2019; Independent Investment Research, 2023).

In 2022, Karelian Diamond Resources plc obtained prospecting licences to initiate Ni-Cu-PGE exploration around the Colebrooke River, following the discovery of chromite and other orthomagmatic indicator minerals in stream sediment samples from a nearby existing licence area (Karelian Diamond Resources, 2022). This lies close to the Dromore Gravity High anomalies previously investigated by Lonmin (Lonmin Limited, 2009b). Subsequent identification of further indicator mineral anomalies, together with re-analysis of Tellus datasets, led the company to commission an expert report confirming the prospectivity of the area, again drawing parallels with the Norilsk magmatic sulphide system (Karelian Diamond Resources, 2024). Exploration is ongoing, and the company is currently in the process of obtaining additional prospecting licences on the Antrim Plateau, including areas proximal to other magmatic conduit targets previously explored by Lonmin (Karelian Diamond Resources, 2025).

Comparable indications of conduit-hosted orthomagmatic mineralisation have also been reported in Ireland, with Group Eleven Resources Corp. recently discovering anomalous PGE concentrations (0.403 g/t) and other chalcophile enrichments in a Palaeogene dyke within their Ballinalack licence area (Co. Westmeath; Chew *et al.*, 2014; Group Eleven Resources Corp., 2020). These observations raise the possibility that conduit-hosted Ni-Cu-Au-PGE mineralisation associated with Palaeogene magmatism may occur across both Ireland and Northern Ireland.

OTHER IRISH AND NORTHERN IRISH PGE INTERESTS

Although all significant PGE exploration in Ireland and Northern Ireland has focused on Palaeogene magmatism, there have been other historic interests. The earliest documented Pt occurrence in Ireland was reported from Au-bearing stream sediments collected close to Croghan Kinsella on the Wicklow–Wexford border (Mallet, 1850; Greg & Lettsom, 1858). Although the precise location of these samples is unknown (likely the Goldmines River), subsequent geochemical analysis and placer gold exploration have verified the grain identification in these early studies (Doughty *et al.*, 1982; Dana Exploration plc, 1988). Local Au occurrences in the area are associated with hydrothermal quartz veins and stratabound Fe-

As-S-Au mineralisation, neither of which are reported to have significant PGE associations; glacial transport modelling also precludes the nearby Avoca VMS deposit as a source for the Pt grains (Moles & Chapman, 2019). Mafic-ultramafic centres associated with the Ordovician southeast volcanic belt may be a more plausible source. Small mafic intrusive centres crop out in the region (Schiener, 1974; Stillman & Williams, 1979; Deutsch, 1980), and the nearby chromite-bearing Cummer serpentinite has previously been identified as a potential target for PGE mineralisation (Gallagher, 1989; Gallagher *et al.*, 1994).

In the 1980s, a Pt nugget (89.44 wt% Pt) discovered in a raised beach deposit at Larne briefly garnered interest but was quickly dismissed as being derived from local bedrock, owing to the absence of a proximal mafic-ultramafic source, even when accounting for potential glacial transportation. Subsequent geochemical analysis demonstrated that it was distinct from the Croghan Kinsella sands (then the only recognised Irish PGE occurrence) but showed a close match to PGE nuggets from placer deposits in the Urals. On this basis, it was suggested that the nugget was likely introduced anthropogenically, either as ships ballast or from a minerals collection (Doughty *et al.*, 1982; Nawaz, 1993).

Metamorphosed mafic-ultramafic centres in Connemara have been suggested as potential targets for orthomagmatic Ni-Cu-PGE mineralisation, following identification of minor PGE anomalies associated with the Cashel-Lough Wheelaun intrusion (Long *et al.*, 1995), and soil and stream sediment chalcophile anomalies in regional base metal exploration programmes (Irish Base Metals Limited, 1978). The Dawros-Currywongaun-Doughruagh Complex comprises deformed layered mafic-ultramafic units formed in an open system intrusion, and includes chromitite layers that are characteristic of magmatic systems capable of hosting orthomagmatic Ni-Cu-Au-PGE mineralisation (Hunt *et al.*, 2012; Mathez & Kinzler, 2017). In 1999, Falconbridge Limited acquired prospecting licences in the area, targeting orthomagmatic Ni-Cu mineralisation. The company identified a moderate strength electromagnetic anomaly at

Cashel-Lough Wheelaun, a soil Ni anomaly proximal to the Dawros Peridotite, and a semi-massive sulphide occurrence at Errisbeg Hill (the Cloch na Oraiste Showing), comprising 5–7% chalcopyrite and 20–30 % pyrrhotite with grades up to 0.83 wt% Ni, 0.40 wt% Cu and 192 ppb total PGE. However, the licences were relinquished in 2000 due to generally low soil metal concentrations and the absence of near-surface geophysical anomalies that could be related to economically significant Ni-Cu mineralisation (Falconbridge Limited, 2000a, b).

Mafic-ultramafic components of the Tyrone Plutonic Group are associated with soil geochemical anomalies in PGE and other chalcophile elements (Hollis *et al.*, 2013), contain podiform chromite which may be associated with PGE mineralisation (Leblanc, 1991; GSNI, 2019), and are genetically comparable to Ni-Cu-PGE mineralised Caledonian ophiolites in Scandinavia (Grenne *et al.*, 1999; Hollis *et al.*, 2014). Limited exploration by Rio Tinto (Riofinex) from 1969 into the 1970s and again in 1988–89 concluded that any mineralisation was sub-economic (Rio Tinto Finance & Exploration Ltd., 1989; Gunn *et al.*, 2007). Metallum Exploration Limited subsequently acquired a prospecting licence covering the plutonic group in 2007, but work was restricted to reprocessing Tellus data and minor lithogeochemistry, which were used to identify targets but yielded no significant results prior to licence relinquishment in 2010 (Metallum Exploration Limited, 2010). The area has not been subject to systematic, comprehensive exploration for orthomagmatic sulphide mineralisation, partly reflecting the relatively late recognition of the plutonic group as an ophiolite sequence in the mid-1980s (GSNI, 2019).

FUTURE ORTHOMAGMATIC NI-CU-AU-PGE PROSPECTIVITY IN IRELAND AND NORTHERN IRELAND

Irish and Northern Irish mafic-ultramafic magmatic systems record many of the key processes involved in the formation of orthomagmatic Ni-Cu-Au-PGE deposits, with numerous magmatic sulphide occurrences, and early Palaeogene centres in particular showing evidence of a SCLM melting component (Morrison *et al.*, in review). However, exploration to date has failed to identify mineralisation of economic scale or grade. While this could reflect inefficient operation of the physical processes responsible for concentrating sulphide liquids in major deposits (e.g. Maier, 2005; Barnes *et al.*, 2016; Barnes & Robertson, 2019), recurrent soil and stream sediment metal anomalies (e.g. BHP, 1997; Lonmin Limited, 2008), geophysical anomalies (Lonmin Limited, 2014d), and evidence for magma chalcophile depletion (Morrison *et al.*, in review) collectively suggest the presence of sulphide accumulations which are small and/or located at depth. Although Ireland does not host mineralisation on the scale of world-class deposits such as Bushveld or Norilsk (Cawthorn *et al.*, 2002; Barnes *et al.*, 2020), such deposits are unlikely to occur anywhere in Europe, and smaller-scale mineralisation of the type potentially present in Ireland may be important for domestic supply of these critical raw materials. In this context, Irish magmatism represents not only a viable exploration target, but also an important natural laboratory for understanding small-scale orthomagmatic mineralising processes.

We suggest that the highest prospectivity for future Irish and Northern Irish orthomagmatic Ni-Cu-Au-PGE exploration remains the Palaeogene Carlingford Complex and proven Antrim feeder systems (i.e. excluding geophysical anomalies interpreted by Lonmin as basement features), following Platreef- and Norilsk-type deposit models, respectively (BHP, 1997; Lindsay *et al.*, 2019). In both cases, soil surveys have repeatedly identified chalcophile metal anomalies but have failed to determine their source, and in Carlingford the nature of the mineralised CAR float boulder and associated bedrock exposure remains unresolved (Irish Base Metals Limited, 1984). Drilling in Carlingford was spatially limited in extent and likely insufficient in depth (Buchanan, 1985), whereas drilling in Antrim, although more extensive, was frequently constrained by logistical issues, in some cases resulting in boreholes missing geophysical targets (e.g. Lonmin Limited, 2013b).

The Dromore Gravity High represents a moderate-priority target, owing to a prominent PGE anomaly in the Tellus soil survey (Young & Donald, 2013) and its potential coincidence with the Northern Erne sub-swarm dykes, which exhibit a SCLM-derived melting signature (Morrison *et al.*, in review). The gravity anomaly itself likely reflects a deep-seated intrusive body, with surface geochemical anomalies potentially derived from associated dykes or subsidiary intrusions. Lonmin's exploration in the area was limited to a single year and focused primarily on xenolith-bearing dykes, failing to identify the source of soil anomalies (Lonmin Limited, 2009b).

Non-Palaeogene targets are more speculative and associated with lower-grade or unconventional deposit types. While the Tyrone Plutonic Group is associated with PGE and other chalcophile element soil anomalies (Hollis *et al.*, 2013), it has not been systematically explored for Ni-Cu-PGE mineralisation (GSNI, 2019), and ophiolite-hosted PGE resources are globally minor (Leblanc, 1991; Zaccarini *et al.*, 2022). Similarly, although metabasites can host Ni-Cu-PGE mineralisation (e.g. Ciborowski *et al.*, 2013), exploration by Falconbridge in Connemara failed to identify any significant targets (Falconbridge Limited, 2000b). The source of Pt grains in Croghan Kinsella stream sediments also remains uncertain and, while placer deposits are known globally (e.g. Urals; Tolstykh *et al.*, 2005), their presence in Ireland is unlikely given the extent of regional Au exploration (Moles & Chapman, 2019).

Previous exploration suggests that the distribution of prospective Palaeogene orthomagmatic Ni-Cu-Au-PGE mineralisation in Ireland is primarily controlled by the local magma system architecture within relatively small intrusions, rather than large, long-lived magmatic systems (e.g. Cawthorn *et al.*, 2002; Barnes *et al.*, 2020). In Carlingford, sulphide saturation is interpreted to result from country rock assimilation, with mineralisation localised at the base of the intrusion (Buchanan, 1985; BHP, 1997). In minor intrusions, magmas appear to be saturated in sulphides during crustal transport (Morrison *et al.*, in review), with changes in dyke geometry and interactions with regional fault systems potentially forming fluid-dynamic traps for sulphide accumulation (e.g. Lonmin Limited, 2014b, d; Lindsay et al., 2019). Early Palaeogene centres, emplaced prior to the interbasaltic hiatus, may represent priority targets due to a greater SCLM contribution to primary magmas (Morrison *et al.*, in review). Given the likely small scale of any mineralisation, surface geochemical anomalies may be spatially dispersed relative to their source, and identification of mineralised zones will require targeted drilling supported by high-resolution geophysical surveys.

CONCLUSIONS

Exploration for orthomagmatic Ni-Cu-Au-PGE mineralisation in Ireland and Northern Ireland has been ongoing since the 1960s, with multiple campaigns targeting both mafic-ultramafic central complexes and minor intrusions (as well as more novel deposit types). Despite differences in approach and deposit models, these programmes have repeatedly identified chalcophile element anomalies, sulphide-bearing intrusions and localised PGE enrichments, but have failed to delineate mineralisation of an economic scale. Irish igneous centres record many of the key processes required for Ni-Cu-Au-PGE mineralisation, including SCLM melting, assimilation-induced sulphide saturation and local sulphide accumulation, but their mineralisation potential is fundamentally limited by magma system size and the scale of sulphide accumulation processes.

Geological, geochemical and geophysical datasets collectively indicate that orthomagmatic mineralisation in Ireland is primarily controlled by local tectonomagmatic architecture rather than long-lived, large-scale magmatic systems, with Palaeogene centres representing the most prospective targets. In the Carlingford Complex, sulphide saturation is interpreted to result from country rock contamination, with sulphide liquids locally accumulated at the chamber floor. In Palaeogene conduit systems, magmas are often sulphide-saturated during transport, with sulphide accumulation governed by dyke geometries and fault-controlled emplacement. As a result, any mineralisation is likely to be small, spatially discontinuous and, in some cases, located at depth.

While Ireland does not host world-class deposits comparable to Bushveld or Norilsk, such deposits are unlikely elsewhere in Europe. In this context, small-scale orthomagmatic systems of the type proposed in Ireland may represent realistic targets for future domestic European PGE supply, and Irish centres provide a valuable natural laboratory for understanding these systems. However, the economic viability of such resources will depend on their size, depth and accessibility, alongside societal and regulatory constraints; in Ireland, this includes public opposition to mining, which has previously limited PGE exploration.

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FIGURES

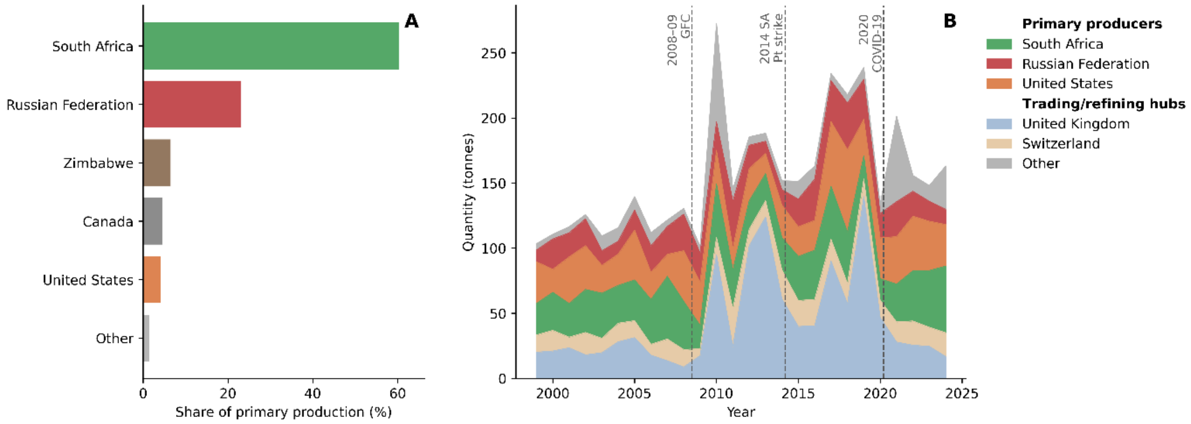

Figure 1. (A) Global primary PGE production by country**. (B)** European PGE imports by country, distinguishing primary producers and secondary trading/refining hubs. Vertical dashed lines mark major global events affecting PGE markets: the 2008–09 Global Financial Crisis, 2014 South Africa Platinum Strikes, and the 2020 Covid-19 pandemic. Data are from European Commission Joint Research Centre (2026) and Eurostat (2026).

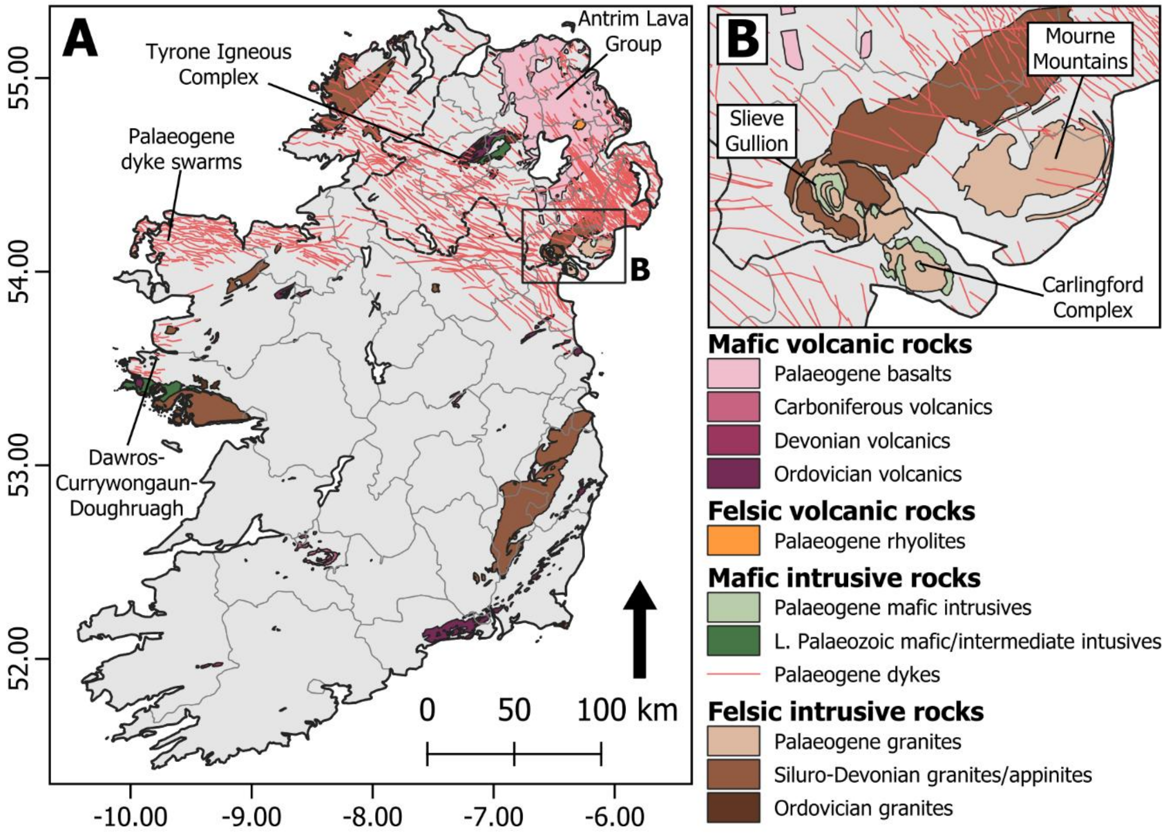

Figure 2. (A) Generalised igneous geological map of Ireland, with units grouped by age and dominant lithology. (**B)** Inset map showing the principal Palaeogene central complexes. Bedrock geology is from GSI and GSNI (2024); Palaeogene dyke locations are from Morrison *et al.* (in review).

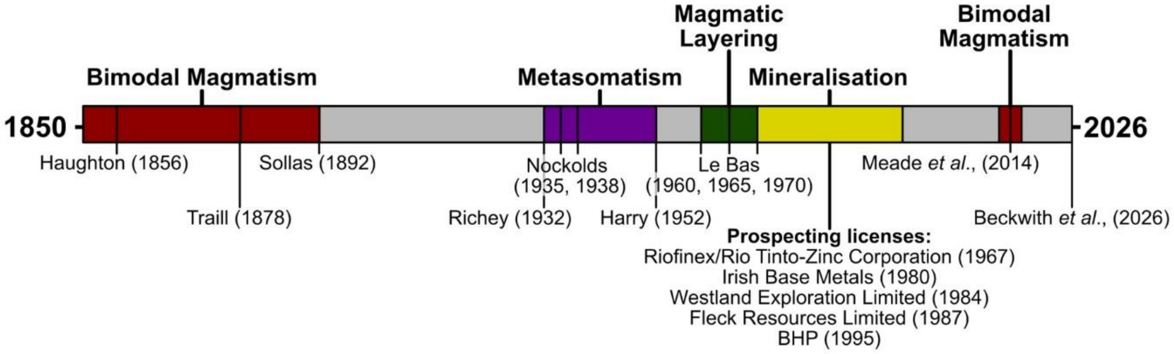

Figure 3. Timeline of research and exploration activity in the Carlingford Complex. Nineteenth and early twentieth-century studies focused on bimodal magmatism, metasomatism at intrusion margins, and igneous layering, whereas orthomagmatic exploration dominated during the mid- to late twentieth century.

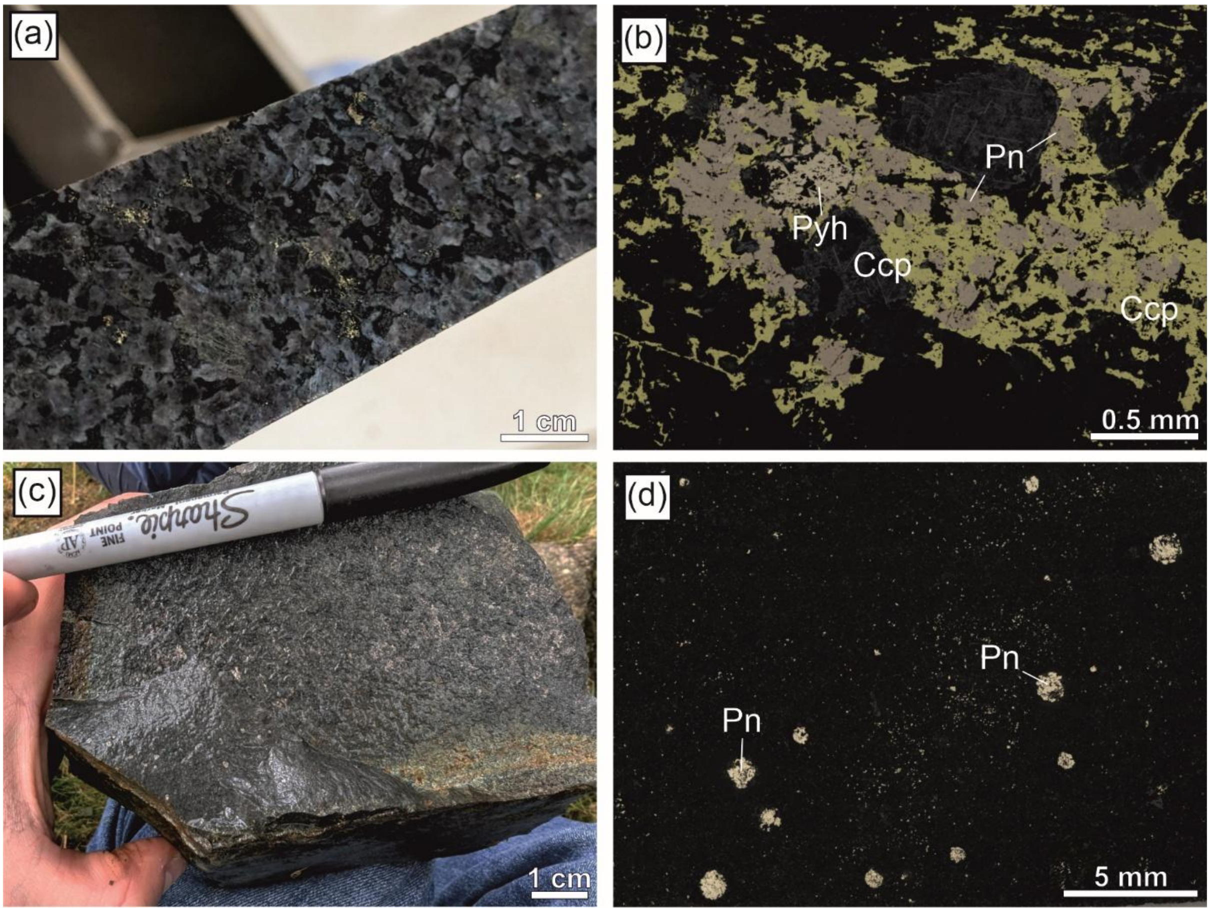

Figure 4. Example sulphide occurrences associated with the Carlingford Complex. **(A, B)** Stratigraphically constrained (reef-style) interstitial sulphides in LZ layered gabbros from core drilled by Irish Base Metals Limited (1984), shown in hand specimen **(A)** and reflected-light photomicrograph **(B)**. **(C, D)** Disseminated sulphides within a cone sheet (conduit-style), comparable to those identified by BHP (1997), shown in hand specimen **(C)** and reflected-light photomicrograph **(D)**. Pyh - pyrrhotite; Pn - pentlandite; Ccp - chalcopyrite.

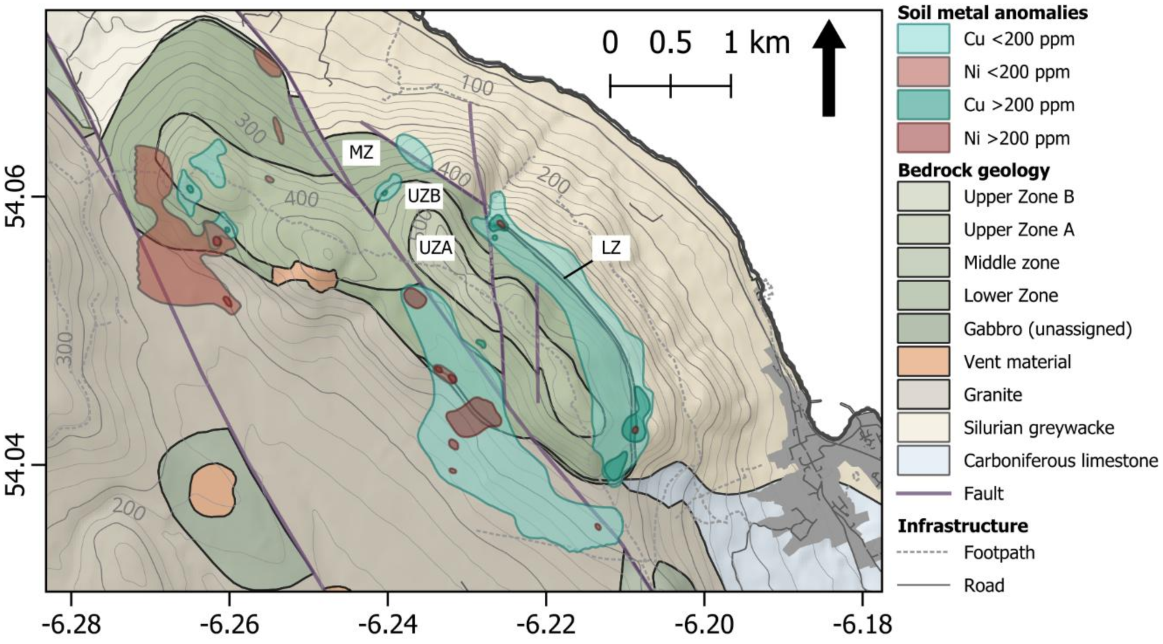

Figure 5. Distribution of soil chalcophile (Cu and Ni) anomalies proximal to the Carlingford Complex, adapted from BHP (1997). Bedrock geology from Beckwith *et al.* (in review). LZ, Lower Zone; MZ, Middle Zone; UZA, Upper Zone A; UZB, Upper Zone B.

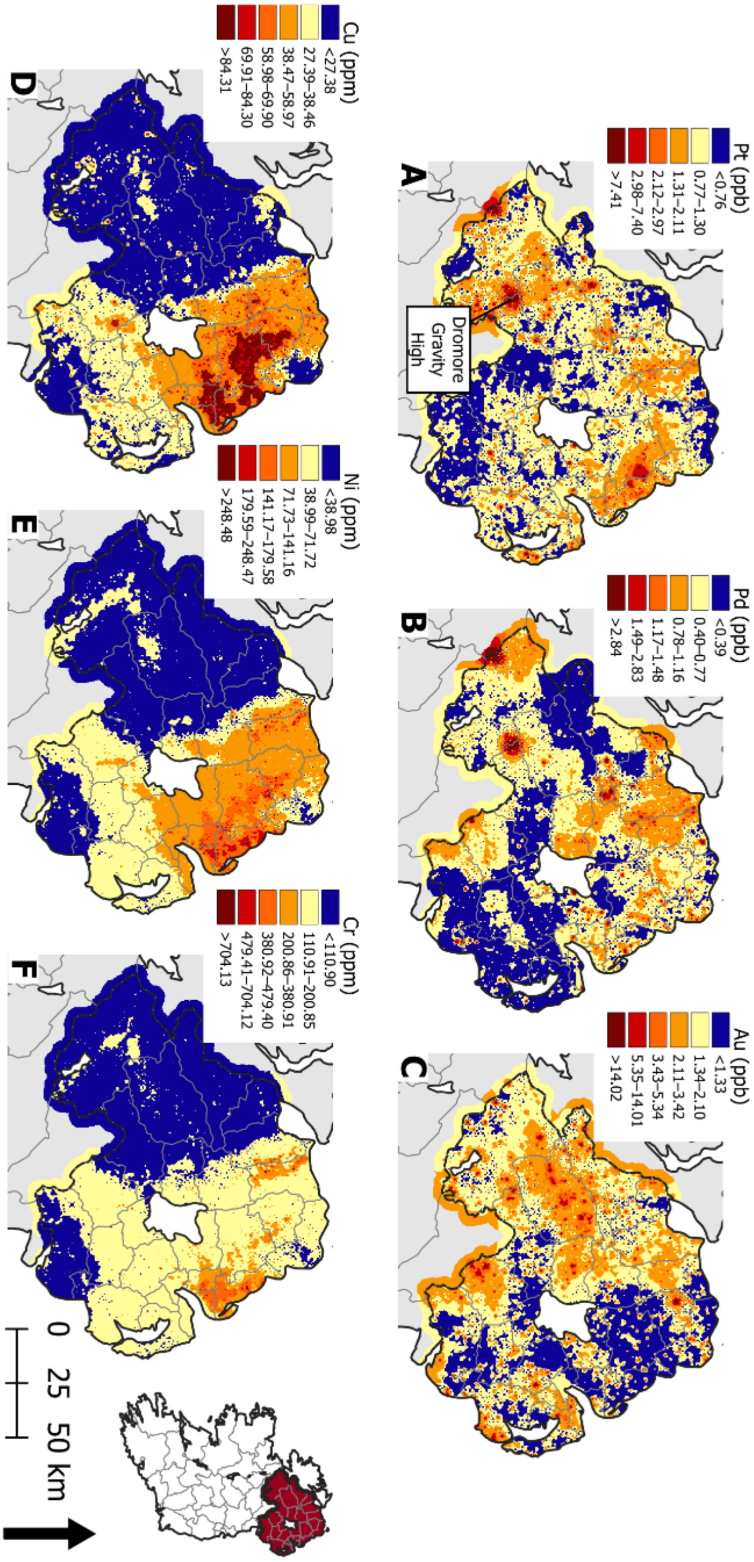

Figure 6. PGE, Au, and other chalcophile element concentrations in Northern Irish deeper topsoil 'S' from the GSNI Tellus Geochemical Survey. PGEs and Au were analysed by fire assay; other elements by near-total digestion. Data from GSNI (2007).

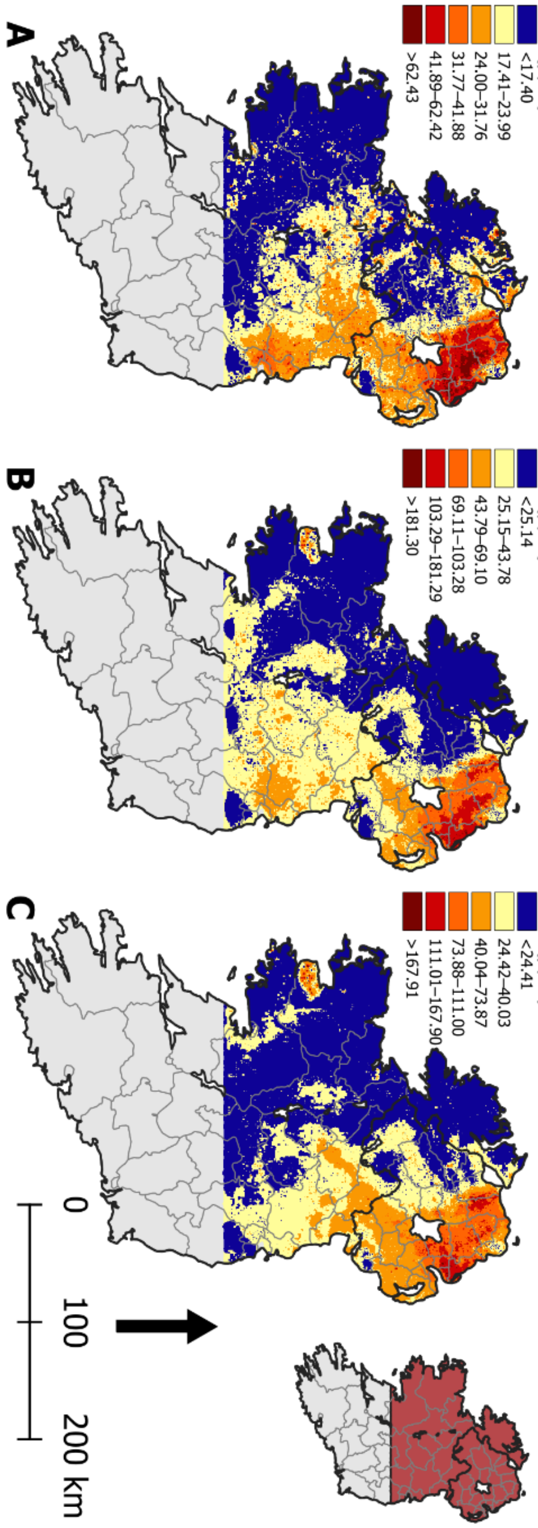

Figure 7. Chalcophile element concentrations in Irish and Northern Irish deeper topsoil 'S' from the integrated GSI and GSNI Tellus and Tellus Border Geochemical Surveys. All elements were analysed by ionising coupled plasma-mass spectrometry. Data from GSI (2021).

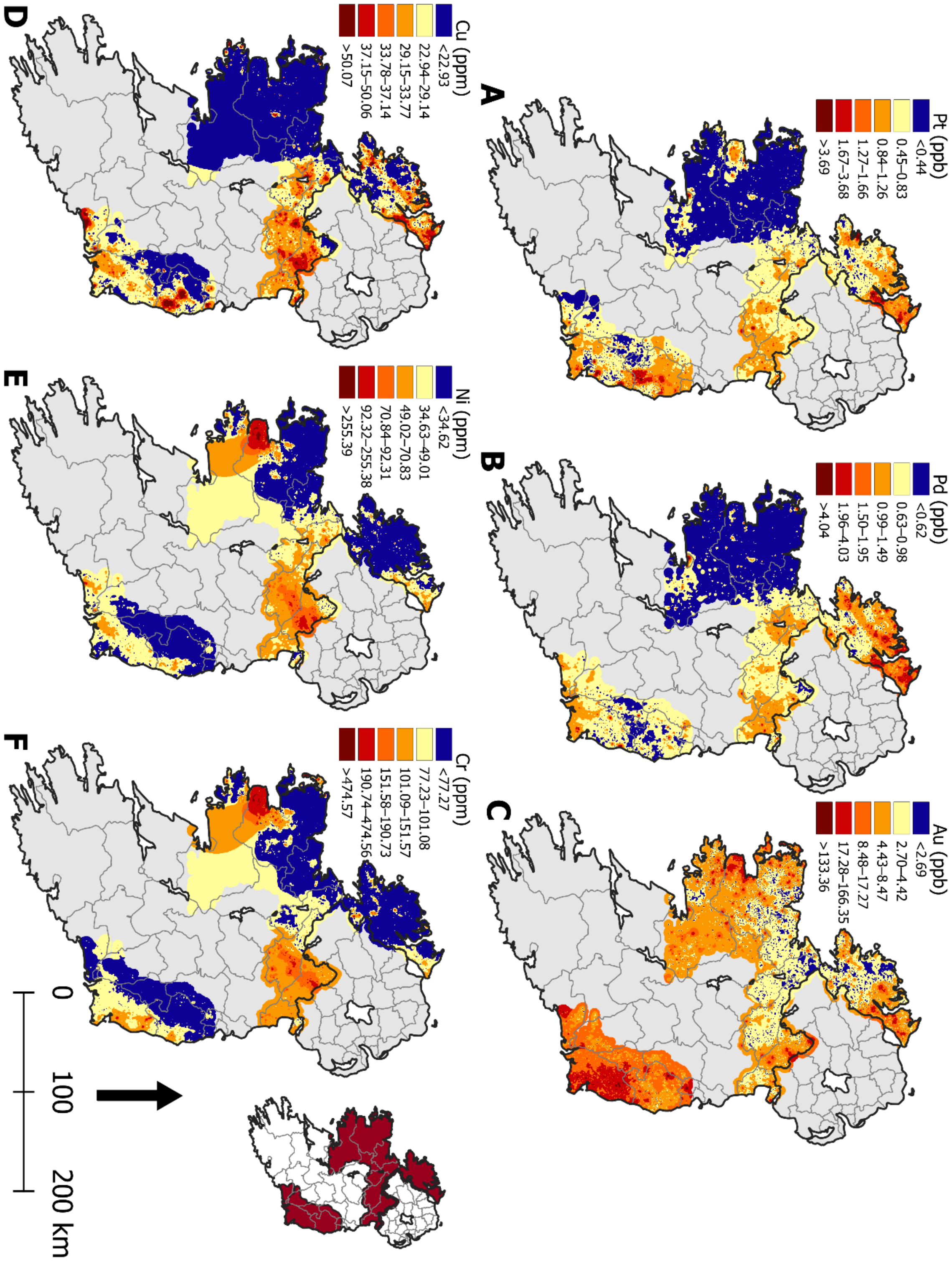

Figure 8. PGE, Au, and other chalcophile element concentrations in Irish stream sediments ‘C’ from the GSI Tellus Geochemical Survey. PGEs and Au were analysed by fire assay; other elements by X-ray fluorescence spectrometry. Data from GSI (2021).

TABLES

	O'Neill-McHugh	Bondar Clegg	Knights	Falconbridge
Cu (wt%)	1.73		1.52	
Ni (wt%)	1.00		0.73	
Pb (ppm)	21			
Zn (ppm)	52			
Pt (ppm)		0.34	96	1.50
Pd (ppm)		1.60	30	1.50
Au (ppm)		1.08	29	0.40

Table 1. Metal concentrations measured in the Carlingford CAR float boulder by different analytical laboratories. Analytical methods are not specified, except for the Bondar Clegg data, which were obtained by assay. Data from Irish Base Metals Limited (1984). Reported variability between laboratories has been attributed to analytical difficulties, and Falconbridge has been suggested as providing the most reliable results (Buchanan, 1985).

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