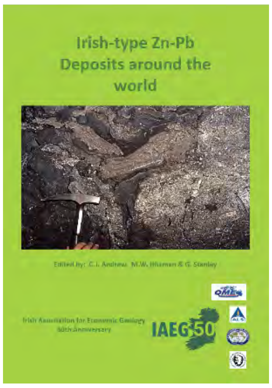

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Irish-type Zn-Pb deposits in the context of global zinc supply

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Irish-type Zn-Pb deposits in the context of global zinc supply

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Abstract: Zinc is the fourth most consumed metal globally and its corrosion resistance properties contribute significantly to the longevity, reliability, and sustainability of construction and infrastructure projects, vehicle manufacturing, and green technologies. By extending the lifespan of these assets and promoting durability, zinc supports the goals of the green transition by reducing resource consumption, minimizing waste, and enhancing overall environmental performance.

Four broad ore deposit types account for over 90% of global zinc production and known resources. These are, in order of importance, shale-hosted massive sulphide ('VHMS') deposits, volcanogenic massive sulphide ('VMS') deposits, carbonate replacement ('CRD') deposits, and Irish-type / Mississippi-valley type ('IT' / 'MVT') deposits. Each ore deposit type contains a relatively small number of world-class ore deposits which are characterized by their large size, high-grades, and economic viability. These world class deposits represent the most significant deposits within their respective deposit types and generally attract substantial attention and investment from mining and exploration companies.

The Irish Midlands basin is a globally significant area for zinc exploration and mining and discoveries over the past 60 years have demonstrated its potential to generate world-class deposits. One notable example is the Navan deposit, which is one of the largest known Irish-Type/Mississippi Valley-Type (IT / MVT) deposits in the world. Navan has been a prolific producer of zinc and lead ores for the past 45 years, contributing significantly to the mineral wealth and economic development of the region. Irish-type deposits, such as Navan and Lisheen/Galmoy, have the advantage of being metallurgically straightforward and of producing clean concentrates with minimal impurities. Such clean concentrates are highly sought after by zinc smelters worldwide, as they allow for efficient blending with other zinc concentrates of lower quality.

After decades of mineral exploration, the potential for new discoveries in the Irish Midlands basin still remains high. The metal endowment of the basin and quality of its deposits, coupled with advances in exploration technologies, such as seismics, make it an attractive exploration play. Large areas of the basin also remain relatively underexplored, particularly under cover rock sequences, such as the Tober Colleen Formation (the lowermost part of the "Calp"). Indeed, the combination of accumulated geological knowledge, technological advancements, and ongoing exploration programmes greatly enhances the likelihood of new and exciting mineral discoveries in the Irish Midlands basin in the coming years.

In summary, the Irish Midlands basin's track record of discoveries and the characteristics of Irish-type deposits, including their size, grade and concentrate quality, reinforce the basin's significance in global zinc exploration and mining. Production of zinc from the Irish Midlands basin also contributes to the European Union's (EU) mineral self-sufficiency objectives and sustainability agenda thereby enhancing resource security, reducing carbon emissions, and fostering a more sustainable and resilient mineral supply chain within the EU.

Keywords: Irish Midlands Basin, Irish-type deposits, zinc use and importance, concentrate quality.

Introduction

Zinc is the fourth most consumed metal, being exceeded only by iron, aluminium, and copper (USGS, 2023). Global zinc supply plays a vital role in meeting the demands of various industries worldwide. Zinc is primarily used for galvanizing steel to protect it from corrosion, making it an essential component in the construction, infrastructure, and automotive sectors. Other important uses of zinc include its use in agricultural fertilizer to address the issue of zinc deficiency in soils which is common globally and can severely impact crop yields and quality. Zinc is also an essential element that plays a crucial role in various bodily functions, including growth, immune system development, and cognitive function. Sadly, zinc deficiency is prevalent among children in many parts of the world, particularly in low-income countries, and is being addressed by providing access to zinc supplements and implementing educational programmes (International Zinc Association, 2022).

The primary purpose of this paper is to provide a brief summary of the key characteristics of the four principal types of zinc deposit that dominate global zinc production. In addition, this paper seeks to place the zinc-lead deposits of the Irish Midlands Basin within a global context and highlight the basin's importance to the global zinc mining and exploration industry. It is important to note that this paper does not present a detailed synthesis of deposit characteristics and genetic models. These topics have already been extensively discussed and documented by other authors in the field. Instead, the focus of this paper is to highlight the essential characteristics of the major zinc deposit types. By summarizing these salient features, it aims to provide readers with a high-level understanding of the general positives and negatives of the various deposit types that play a crucial role in global zinc supply.

The paper begins with an overview of global zinc supply and uses data from a number of different sources, including the USGS and Wood Mackenzie, with additional data on historical production compiled by the author from other sources (company reports, scientific papers etc.). Wood MacKenzie analysis of global zinc supply is also summarized in this volume by Wojcik (2023). To facilitate analysis and discussion, zinc deposits have been classified into four broad deposit types, which collectively account for over 90% of the world's zinc supply. The main characteristics of each deposit type are briefly summarized, and this is followed by a discussion of the current trends within, and potential challenges that may impact, the global zinc industry. Factors such as evolving market demands, more stringent permitting and environmental considerations, and consolidation across the industry are considered in this forward-looking analysis. By considering these factors, the paper offers a glimpse into the future of zinc production, highlighting areas of potential growth and areas that may require further attention and research. The paper ends with a discussion of the role that the zinc deposits of the Irish Midlands basin could play in the context of future global zinc supply.

Global Zinc Supply

Global zinc supply comes from both primary and secondary sources. According to the International Zinc Association, approximately 70% of the zinc produced worldwide originates from mined ores with the other 30% coming from recycled or secondary zinc sources. Primary production involves mining zinc ores from different ore deposit types. Secondary production involves recycling zinc from sources such as scrap galvanized steel and the zinc contained in batteries and helps to reduce the reliance on primary production. This paper focusses on primary zinc production and does not delve into secondary sources.

Various governmental organizations and private companies gather data on zinc production, resources, and reserves. Although different organizations employ different criteria for compilation, leading to some variance in estimates, there is a general consensus on the countries, deposit types, and individual mines that play a pivotal role in global zinc production.

The USGS estimates that world mine production of zinc was 12.7 million tonnes in 2021 and total global production of refined zinc was 14.1 million tonnes (USGS, 2023). China was the largest producer of zinc with 4.2 million tonnes or 33% of the global total. Other major producers include Peru, Australia and the United States accounting for another 3.6 million tonnes or 28% of global production in 2021. The USGS also estimates global zinc reserves were approximately 210 million tonnes and identified zinc resources are approximately 1.9 billion tonnes in 2021 (USGS, 2023). Australia, China, Russia, Mexico, Peru and Kazakhstan are among the nations with the largest zinc reserves and collectively comprise around 75% of known global reserves.

Wood Mackenzie (Wojcik, 2023) estimates that world mine production of zinc over the last five years has averaged 12.8 Mt, with production dipping by 5% in 2020 due to the Covid pandemic and also provides a breakdown of zinc production by country (Wojcik, 2023, Figure 5).

In terms of understanding the relative importance of different ore-forming processes and ore deposit types, it is also useful to know the total pre-production size of individual deposits (i.e., past production, plus current resources/reserves). However, historical production data is more difficult to source and is generally not included in the most commonly available databases and zinc industry analysis reports which focus on recent production and current resource/reserve numbers. The fact that many zinc deposits are polymetallic in nature further complicates the estimation of deposit size and relative importance in terms of global production but is obviously a positive in terms of project economics, for example at the Antamina Cu-Zn skarn deposit.

The size of an ore deposit plays a crucial role in determining the economic viability of a project, the potential lifespan of a mine, and the overall attractiveness of different ore deposit types from an exploration perspective. In this paper, zinc deposits are classified according to their estimated pre-mining contained zinc-equivalent metal, as indicated in the legend on Figure 1. Notably, giant deposits (10-20 Mt ZnEq) and super-giant deposits (>20 Mt ZnEq) emerge as important contributors to production within each of the four ore deposit types.

Zinc Ore Deposit Types

Ore deposit classification is a complex and challenging subject within the field of economic geology. It involves categorizing and organizing various types of mineral deposits based on their geological characteristics, formation processes, mineralogy, and economic potential. The classification of ore deposits helps geologists and resource professionals understand deposit origins, explore for new deposits, and develop exploration and mining strategies. One of the reasons that ore deposit classification is difficult is the wide range of geological processes and conditions that contribute to the formation of different types of deposits. Ore deposits can form through diverse mechanisms such as magmatic processes, hydrothermal activity, and sedimentary processes and can be subsequently modified by metamorphism and weathering. Each of these processes can produce distinct mineral assemblages and deposit characteristics. Furthermore, ore deposits can occur in a variety of geological settings, including volcanic packages, sedimentary basins, and metamorphic terrains. The complex interplay of ore-forming

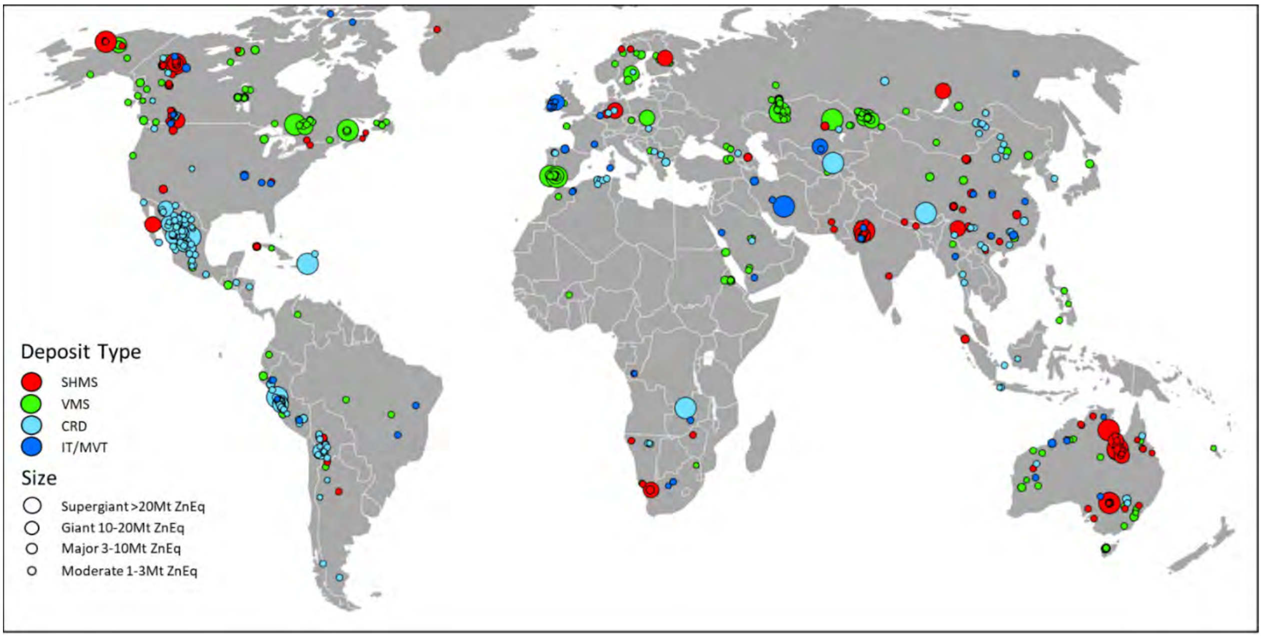

Figure 1: *Global zinc deposits by deposit type and size range. Deposit size is based on pre-mining total contained zinc equivalent metal (ZnEq).*

processes and geological setting contributes to the diversity and complexity of ore deposit types.

As a result, ore deposit classification is not always clear-cut or universally agreed upon. Different classifications and schemes have been proposed by various researchers and organizations, and there can be overlap or ambiguity between different deposit types. Another factor contributing to the difficulty in classifying deposits is the presence of transitional or hybrid deposit types. Moreover, the classification of ore deposits is an ongoing and evolving field of study. New discoveries, technological advancements, and improved understanding of geological processes continually contribute to refining existing classifications and proposing new deposit types.

Sediment-hosted zinc deposits supply the majority of the world's zinc and also present unique challenges in classification due to their diverse nature and the complex geological processes involved in their formation. The classification of these deposits has been discussed at length in the economic geology literature. Leach *et al.,* (2005) divide the sediment-hosted Pb-Zn deposits into two broad subtypes: Mississippi Valley-type ('MVT'), sedimentary exhalative ('SedEx') and consider Irish-type deposits to be a subset of MVT deposits. Leach *et al.,* (2010) divide sediment-hosted Pb-Zn deposits into two major subtypes. The first subtype is clastic-dominated lead-zinc ('CD Pb-Zn') ores, which are hosted in shale, sandstone, siltstone, or mixed clastic rocks, or occur as carbonate replacement, within a CD sedimentary rock sequence. This subtype includes deposits that have been traditionally referred to as sedimentary exhalative (SedEx) deposits. The CD Pb-Zn deposits occur in passive margins, back-arcs and continental rifts, and sag basins, which are tectonic settings that, in some cases, are transitional into one another. The second subtype of sediment-hosted Pb-Zn deposits is the Mississippi Valley-type (MVT Pb-Zn) that occurs in platform carbonate sequences, typically in passive-margin tectonic settings.

Neither the MVT nor SedEx subtypes are ideal classification terms nor do these categories have criteria that allow unequivocal classification for all sediment-hosted Pb-Zn deposits. Despite efforts to identify a more suitable term, the widespread usage SedEx in the literature, coupled with the absence of better alternatives, led Leach *et al.,* (2005) to continue using the term SedEx. Initially, the term SedEx was used to describe laminated sulphide deposits that were thought to form through the exhalation of ore fluids onto the seafloor (Carne & Cathro, 1982). However, current understanding suggests that SedEx ore fluids are primarily basin brines, which either exhaled onto the basin floor or replace sediments within the shallow subsurface of the basin. A common feature of these deposits is a close affinity with carbonaceous mudstones and siltstones, meaning shale-hosted massive sulphide (SHMS) has been a commonly used term among industry and academic geologists alike. SHMS is preferred in this paper as it does not imply a genetic process and Broken Hill-type deposits are also included in the SHMS category.

With all the above in mind, I have chosen to be a "lumper" rather than a "splitter" and have grouped the zinc deposits of the world into four broad categories or types which collectively account for approximately 85% of the world's primary zinc production and around 86% of known zinc resources (Table 1). The remaining production and resources come from a variety of other deposit types, including non-sulphide zinc deposits, and in deposits of unknown type. Inherent in this grouping approach is a view that zinc deposits within each type are "variations on a theme," a term originally used by Gustafson & Hunt (1975). The term "variations on a theme" highlights the idea that many deposits have common underlying processes and features, but they manifest differently due to specific local conditions. So, for example, I have grouped Irish-type and Mississippi Valley-type deposits in the same ore deposit type because they share many common characteristics and processes but

	Deposit Type	Primary Zinc Production (%)	Share of total Resource (%)
1	Shale-hosted massive sulphide (SHMS)	36	43
2	Volcanogenic massive sulphide (VMS)	22	18
3	Carbonate replacement (CRD)	18	14
4	Irish-Type and Mississippi Valley-type (IT/MVT)	9	10
5	Other	15	14
	Total	**100**	**100**

Table 1: *Zinc production by ore deposit type (2022)*

also exhibit variations in their deposit characteristics and geologic settings. Similarly, I have included Broken-Hill type deposits within the larger Shale-hosted Massive Sulphide grouping. I have also grouped a large and diverse group of deposits under the Carbonate Replacement Deposit type, including skarns and epithermal zinc deposits, all of which are related to magmatic-hydrothermal ore-forming processes.

Wojcik (2023) classifies zinc deposits into eight types and estimates that SHMS and MVT deposits contribute approximately 45% of global production in 2022.

Shale-Hosted Massive Sulphide (SHMS or SedEx)

SHMS deposits are the primary source of zinc (and lead) globally, contain the largest known resources/reserves of these metals and dominate their production (Table 1, Figure 2). Six of the top ten producing mines are SHMS deposits and account for 1.9Mt (15%) of contained zinc production in 2022 (Wojcik, 2023). SHMS deposits exhibit a widespread distribution, with notable occurrences in North America, Australia, and Asia (Fig. 1). This deposit type is dominated by giant and supergiant deposits, such as Red Dog, Rampura Agucha, Mount Isa, Broken Hill and formerly Sullivan and Rammelsberg.

Red Dog, located in Alaska, is the largest zinc mine in the world producing 555 thousand tonnes of zinc in concentrate in 2022. The deposit is a strata-bound accumulation of silica rock, barite, and sulphides hosted in black siliceous shale and chert of the Mississippian to Pennsylvanian Kuna Formation (Moore *et al.*, 1986). Silica rock consists dominantly of growth-zoned mosaic aggregates of translucent quartz grains with accessory sulphides and occurs within and peripheral to the main mass of sulphides. The barite facies contain accessory sulphides, silica, and rare calcite and is concentrated toward the top and periphery of the deposit. Barite is commonly coarse grained and massive to poorly bedded. Sulphide rock textures vary from massive, chaotic, or fragmental to poorly bedded. Major sulphides in decreasing order of abundance are sphalerite, pyrite, marcasite, and galena. The dominant gangue constituents are quartz, barite, and minor shale. The sulphides are generally fine grained, although coarse-grained crustiform and comb-textured sphalerite occurs in feeder veins which are best developed at the base and on the periphery of the deposit. The Red Dog mine was developed by Cominco and is now operated by Teck Resources in partnership with The Nana Regional Corporation (NANA), an Alaska native Corporation representing the interests of the local Inupiat people. The Red Dog Main deposit contained a pre-mining resource of 55.9 Mt at 20.5% Zn and 5.6% Pb and the adjacent Aqqaluk deposit an additional 52.7 Mt at 16.7% Zn and 4.3% Pb. The current open pit mine life is to 2032 but the inferred resources at the nearby Anarraaq and Aktigiruq zones are likely to significantly extend the mine life. Teck reported in 2017 that drilling at Aktigiruq suggested an exploration target size of 80-150 Mt at 16-18% Zn+Pb, which if realized would make the Aktigiruq deposit one of the top undeveloped zinc deposits in the world (Teck, 2017).

Rampura Agucha located in Rajasthan, India and owned by Vedanta Resources, is another giant SHMS deposit and produced an estimated 434,000 tonnes of zinc in concentrate in 2022. Ore from underground stopes began supplementing open pit ore feed to the mill in 2013 and between 2009 and 2014 the mine averaged 650,000 tonnes of zinc per year in concentrate.

The large size of many SHMS deposits supports long-life mines and their flat-lying geometries also make them relatively easy to mine. However, many SHMS deposits contain deleterious elements such as Cd, As, Tl and Se and the fine-grained nature of the mineralization can be metallurgically challenging in some deposits. In terms of explorability, SHMS deposits commonly have a large footprint and flat lying geometry which is a positive in terms of exploration and discovery. However, there have been relatively few recent discoveries. Some notable exceptions are the Teena deposit discovered in 2013 in the McArthur River district in the Northern Territory, Australia (discovered 2013, Taylor *et al.*, 2017; Hayward *et al.*, 2021) and Anarraaq and Aktigiruq in the Red Dog district in Alaska, USA (discovered 1999 and 2001, respectively, USA; Jennings & King, 2002; Blevings *et al.*, 2013). It is also worth noting that several large SHMS deposits, such as Howards Pass, remain undeveloped due to grade, metallurgical and location challenges.

Leach *et al.*, (2005) describe SHMS deposits as a diverse group of ores hosted by a wide variety of siliciclastic and carbonate rocks that, with few exceptions, have no direct genetic association with igneous activity. They are the products of a range of ore-forming processes in a variety of geologic and tectonic environments. The metals were precipitated through a variety of processes that include synsedimentary precipitation on the sea floor (SedEx), diagenesis, epigenetic replacement, and low-grade metamorphism. Given that sediment-hosted Pb-Zn deposits originate mainly from sedimentary brines and from similar ore-forming processes, Leach *et al.*, (2005) concluded that

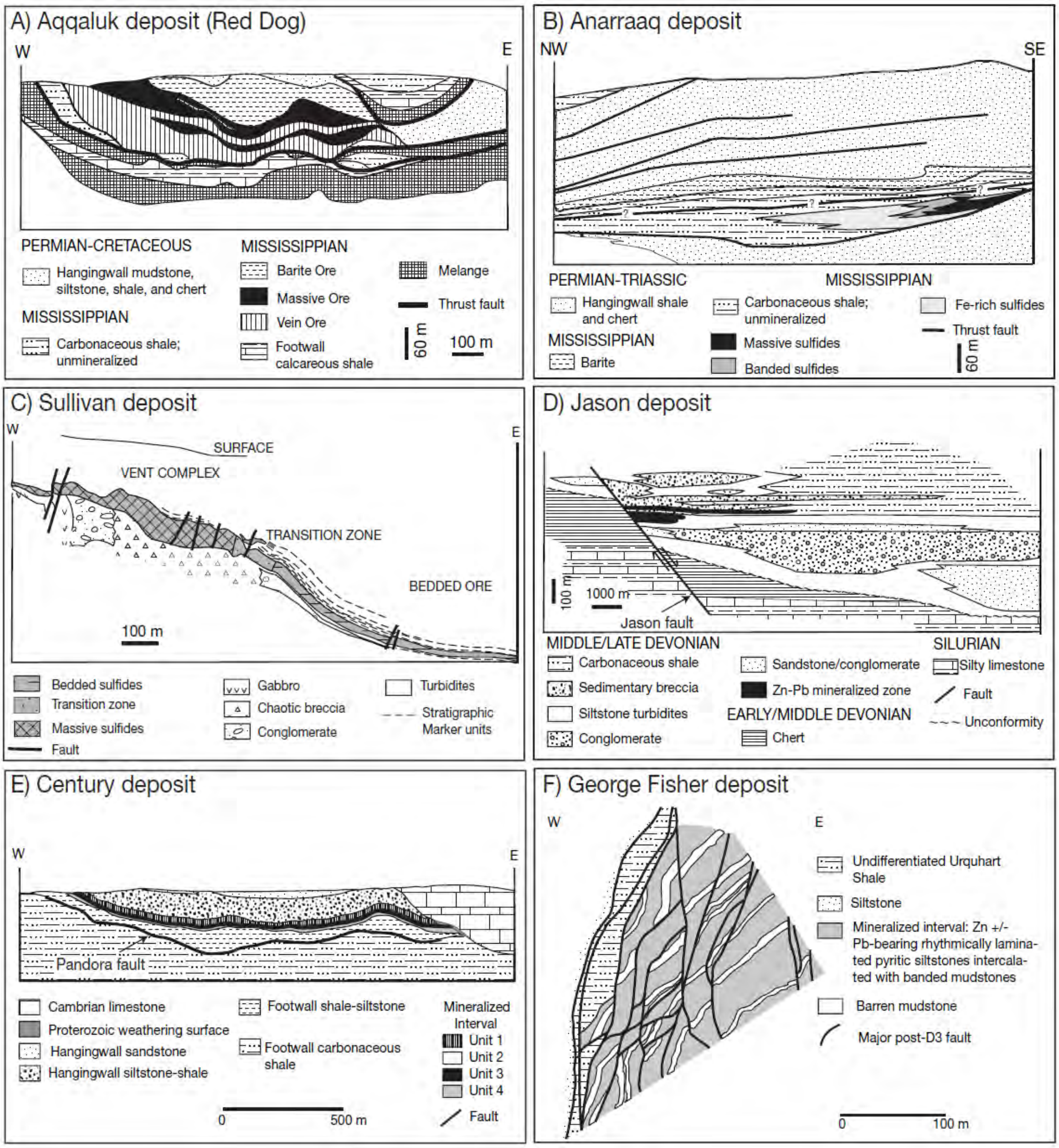

***Figure 2:** From Leach et al., (2005) and references therein. Generalized cross sections showing the diversity in morphology of SedEx deposits. **A)**. Aqqaluk deposit, one of four deposits at Red Dog. **B)**. Anarraaq deposit. **C)**. Sullivan deposit. **D)**. Jason deposit. **E)**. Century deposit. **F)**. George Fisher deposit.*

the attributes, ore controls, and nature of the deposits are mainly determined by the tectonic setting where ore deposition occurred.

The ores consist mainly of sphalerite, galena, and generally lesser amounts of iron sulphides. Pyrite is generally the iron sulphide mineral present in the deposits and its abundance can vary from rare or minor (e.g., Red Dog, Howards Pass, Century) to comprising the most abundant sulphide (e.g., Cirque, Meggen, McArthur River). In some Proterozoic deposits (Mt. Isa, Sullivan), pyrrhotite is common and can exceed pyrite abundance in certain parts of the deposit (Large *et al.*, 2005). The main Pb-Zn minerals are sphalerite and galena. Although the Mt. Isa and Sullivan deposits contain near-equal proportions of Pb and Zn in some parts of the deposits, most SedEx deposits are Zn rich relative to Pb and have Zn/(Zn + Pb) ratios that average about 0.7 (Leach *et al.*, 2010). Silver is commonly an important commodity, whereas Cu is generally low but is economically important in some deposits. Gold values are reported for a small set of deposits in clastic rock-dominated sequences but absent from ores in host rocks dominated by carbonates. Gangue minerals may include carbonates (dolomite, siderite, ankerite, calcite) and typically minor to major barite. Barite may be peripheral to or stratigraphically above the deposit (e.g., Anarraaq), or it may form crudely segregated mixtures with sulphide minerals (Red Dog, Rammelsberg, Jason), but many deposits have no associated barite. Silicification of the host rocks (or quartz gangue) is generally minor but is abundant in a few deposits. Apatite (fluorapatite) is a common constituent in some deposits (Anarraaq, Red Dog, Howards Pass).

SHMS deposits have a broad range of relationships with their host rocks that includes stratiform, strata-bound, and discordant ores; in some deposits, vein ore is important. The large deposits in north Australia (Century, McArthur River, Lady Loretta, Hilton, and George Fisher) occur as a series of thin stacked sulphide-rich sheets with intervening unaltered sedimentary rocks and are close to major faults interpreted to be the conduits for ore fluids (Leach *et al.*, 2005).

Definitive fluid inclusion evidence on the temperature, composition, and source of the ore-forming fluids for SedEx deposits is extremely limited. Temperatures reported for the Jason deposit (in ankerite) range from 234° to 274°C, with salinities of 8.1 to 15.2 wt%t NaCl equivalent (Gardner & Hutcheon, 1985). A wide range of salinities (<1 wt% to > 45 wt% NaCl equivalent) and temperatures (<100°–>400°C) are reported for the Sullivan deposit (Leitch & Lydon, 2000). Primary fluid inclusions in sphalerite yielded homogenization temperatures of between 100° to 200°C and ice melting determinations indicated salinities of about 14 to 19 wt% NaCl equivalent (Leach *et al.*, 2004). In spite of the fact that direct fluid inclusion data are limited, it is generally assumed that the ore-forming fluids were principally hot metalliferous basinal brines. The sulphur isotope values ($\delta^{34}S$) of galena and sphalerite in SedEx deposits show a spread of data from about –10 (Sullivan) to nearly 30‰ (Aguilar), but the bulk of the values fall within the –5 to 15‰ range (Leach *et al.*, 2005). In most cases, the data are consistent with the ultimate source of the sulphur as marine sulphate (either as seawater, porewater, or in preexisting sulphate minerals such as barite), with reduction of sulphate to sulphide usually involving biogenic sulphate reduction (BSR), thermochemical sulphate reduction (TSR), or both, depending on the temperature and the availability of reductant.

Irish-Type / Mississippi-Valley Type Deposits (IT / MVT)

IT / MVT deposits are found throughout the world (Fig. 1) but are most abundant in North America and Europe. These deposits have been reviewed in detail by multiple authors including Leach & Sangster (1993), Sangster (1996) and Leach *et al.*, (2005 and 2010) and the work of these authors (and references therein) is summarized below.

Mississippi Valley-type deposits owe their commonly accepted name to the fact that several classic districts are located in the drainage basin of the Mississippi River in the central United States. Diversity between MVT districts resulted in the historic application of MVT subsets or alternative classifications to characterize specific sets of deposit attributes deemed unique within the broader family of MVT deposits. The use of subsets mainly reflects a philosophical difference between geologists that are "splitters" and focus on the differences between ore deposits versus the "lumpers" that view diversity among the ores as the norm. Important subsets historically used include the Appalachian-, Alpine-, Bleiberg-, Upper Silesia-, Reocin-, and Irish-type deposits. The concept of "Irish-type" deposits emerged as a distinct classification during the 1970s and early 1980s, particularly when several significant deposits in the Irish Midlands were thought to have originated from synsedimentary or early diagenetic processes (syndiagenetic), e.g., Silvermines (Taylor, 1984; and Taylor & Andrew, 1978). Subsequently, this Irish-type classification was formally established as a distinct genetic ore type by Hitzman & Large in 1986. For the purposes of this paper, I regard Irish-type and Mississippi Valley-type deposits, as “variations on a theme” as used by Gustafson & Hunt (1975) who used this phrase to express the concept of different deposits exhibiting similar themes but with distinct local variations. MVT and Irish-type deposits share many common characteristics and processes but there are also significant variations in their deposit characteristics and geologic settings.

Advancements in understanding the genesis of MVT deposits began with the study of fluid inclusions, which revealed that the ore fluids shared similarities with brines found in oil fields. A crucial development was the proposal that these deposits formed through the mixing of multiple basinal fluids with varying levels of reduced sulphur and metal content (e.g., Dunham, 1966). Initially, it was believed that MVT deposits had no association with tectonic processes. However, research in the 1980s and 1990s highlighted the connection between MVT ore genesis and significant crustal tectonic events (e.g., Garven, 1985). Notably, significant progress in understanding MVT ore genesis has been achieved through advances in dating techniques applied to MVT ores (e.g., Leach *et al.*, 2001, and references therein).

The most important characteristics of MVT deposits, modified from Leach & Sangster (1993) are (1) they are epigenetic; (2) they are not associated with igneous activity; (3) they are hosted mainly by dolostone and limestone, rarely in sandstone; (4) the dominant minerals are sphalerite, galena, pyrite, marcasite, dolomite, and calcite; barite is typically minor to absent and fluorite is rare; (5) they occur in platform carbonate sequences commonly on the flanks of basins or in foreland thrust belts; (6) they are commonly strata bound but may be locally stratiform; (7) they typically occur in large districts; (8) the ore fluids were basinal brines with ~10 to 30 weight percent salts; (9) they have crustal sources for metals and sulphur; (10) temperatures of ore deposition are typically 75° to about 200°C; (11) the most important ore controls are faults and fractures, dissolution collapse breccias, and lithological transitions; (12) the sulphides are coarsely crystalline to fine-grained, massive to disseminated; (13) the sulphides occur mainly as replacement of carbonate rocks and to a lesser extent, open-space fill; and (14) alteration consists mainly of dolomitization, host-rock dissolution, and brecciation.

Irish-type (IT) deposits are described in detail in this volume (Ashton *et al*, 2023) and the reader is referred to that paper, and references therein for more detail on this deposit type. Seven

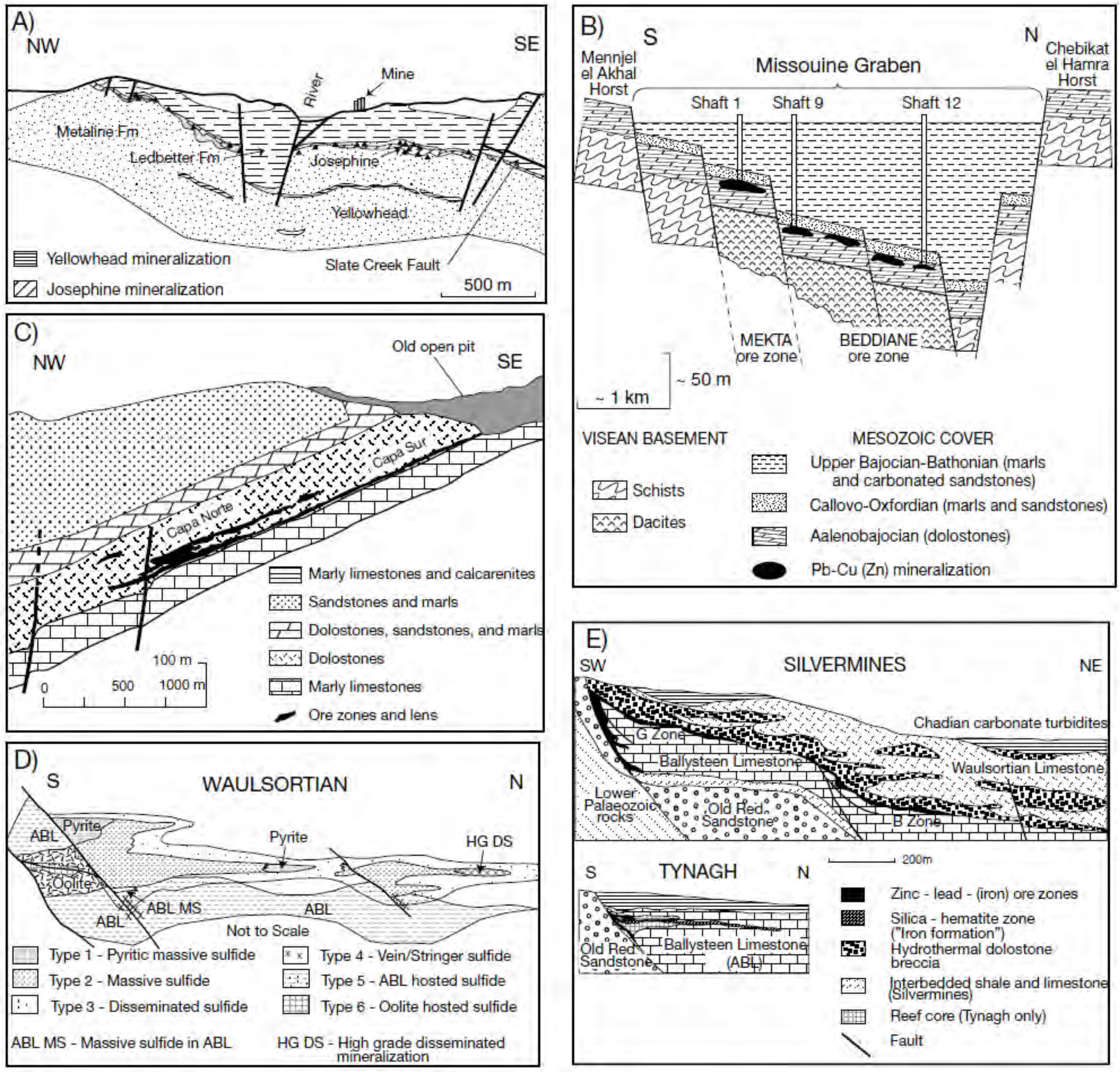

Figure 2: *From Leach et al., (2005) and reference therein. Sections showing geology and mineralization in select MVT deposits.* ***A).*** *Cross section of the Metaline area, Washington State, United States.* ***B)****. Generalized section showing piano keylike horst/graben structure of the Toussit-Bou Bou-Beker mining district, Morocco.* ***C)****. Cross section through the central part of the Reocin deposit, Spain, showing the relationship of the ore lenses and the host dolostones.* ***D).*** *Conceptual model (not to scale) for mineralization at Lisheen, Ireland.* ***E)****. Cross sections through the Silvermines and Tynagh deposits, Ireland.*

IT deposits (Tynagh, Gortdrum, Magcobar, Silvermines, Navan, Galmoy and Lisheen) have been mined in Ireland since 1960, representing a resource base of around 22 Mt of metal (Ashton *et al*, 2023). As a high level summary, the following characteristics are noted for Irish-type deposits by Hitzman & Beaty (1996, p. 499): (1) ore is located in the lowest non-argillaceous unit; (2) ore is associated with normal faults; (3) sphalerite and galena dominate, pyrite may be abundant, and minor to abundant barite is present; (4) they are strata bound; and (5) they have complex textures including replacement, colloform, and fine-to-coarse-grained sulphides and cavity fillings. Wilkinson (2003, p. 980) added the following to the above list of characteristics: (1) the normal faults are synsedimentary; (2) ore formation occurred during diagenesis; (3) orebodies are dominated by massive sulphides with lateral metal zonation; and finally (4) reduced sulphur is dominantly of bacteriogenic origin.

The Waulsortian-hosted deposits, Silvermines, Galmoy, Lisheen Tynagh, are sufficiently similar to warrant a co-genetic interpretation (Wilkinson & Hitzman, 2015). The giant Navan deposit (+100 Mt of ore production) is different in some respects and is mostly hosted in the stratigraphically lower (but time equivalent) Pale Beds of the Navan Group. These five deposits represent nearly 80% of metal in the Orefield and most clearly define the IT classification (Ashton *et al.*, 2023). None of the above 5 deposits are associated with contemporaneous igneous rocks, with the exception of minor, thin (1-5 cm) tuff ("green shale") horizons in the underlying Ballysteen and supra Waulsortian Formations. However, more recent discoveries by Xstrata-Minco at Pallas Green (Blaney *et al*., 2003) and by Teck-Connemara at Stonepark (Redmond, 2010) while broadly similar to other Waulsortian-hosted deposits in terms stratigraphic setting, hydrothermal breccia textures, and sulphide mineralogy, have a spatial and temporal association with igneous rocks (Elliot *et al*., 2019). However, the relationship between base metal mineralization and Lower Carboniferous magmatism is not well understood. But it is possible that these coeval igneous rocks could have contributed heat to the nearby hydrothermal ore-forming system and may also have contributed ore-forming components, including metals and acid-forming volatiles, to the system (Blaney & Redmond, 2015). Further work will be required to address these questions.

In the past, there were significant disagreements among geologists regarding the formation of IT / MVT deposits, with some advocating for syngenetic, early diagenetic, or epigenetic origins. The syngenetic interpretations were primarily based on the presence of stratiform ores and ore textures that were later recognized as products of host-rock replacement mimicking sedimentary features. Similarly, the carbonate-hosted Pb-Zn deposits of the Irish Midlands basin have sparked intense debates surrounding their origin, classification, and age of mineralization. Deposits such as Tynagh, Silvermines and Navan were considered to have formed through syngenetic processes, meaning the mineralization precipitated contemporaneously with the deposition of the host sediments. This interpretation aligned with the broader concept of SedEx deposits, where the mineralization was thought to be closely associated with the sedimentation process on the seafloor. However, as more research and detailed studies were conducted, the understanding of Irish-type deposits shifted towards an epigenetic model and a current broad consensus has been reached that the ores replaced carbonate rocks with only a minor component interpreted to have formed on the sea floor.

IT / MVT deposits are attractive from a metallurgical perspective because they generally produce clean, low-Fe, and high-grade concentrates that are sought after by zinc smelters as they can be blended with lower quality concentrates from other deposit types. From an exploration perspective, this deposit type tends to occur in large districts containing multiple deposits. Large MVT districts include Southeast Missouri (3,000 km^2), Tri-State (1,800 km^2), Pine Point (1,600 km^2), Alpine (10,000 km^2), Upper Silesia (2,800 km^2), Irish Midlands (8,000 km^2), and the Upper Mississippi Valley (7,800 km^2) (Leach *et al.*, 2005). However, while this deposit type contains a small number of giant and supergiant deposits, such as Mehdiabad and Navan, may districts comprise multiple smaller deposits. For example, the Pine Point district contains more than 80 deposits with individual deposits being generally small in size, containing between 0.2 and 2 million tonnes of ore, with the largest containing around 18 Mt (Sangster, 1990).

Volcanogenic Massive Sulphide (VMS) Deposits

The following summary is based on Franklin *et al.*, (2005) and references therein. VMS deposits contributed approximately 22% of global zinc production in 2022. These deposits comprise strata-bound accumulations of sulphide minerals that precipitated at or near the sea floor in spatial, temporal, and genetic association with contemporaneous volcanism. The deposits generally consist of two parts: a concordant massive sulphide lens (>60% sulphide minerals), and discordant vein-type sulphide mineralization located mainly in the footwall strata, commonly called the stringer or stockwork zone.

The term volcanogenic massive sulphide is used by Franklin *et al* (2005), in preference to other common terms such as volcanic-hosted massive sulphide (VHMS; Large *et al.*, 2001) and volcanic-associated massive sulphide (VAMS; Franklin *et al.*, 1981) which are not completely interchangeable, as VMS refers to a genetic class of deposits, whereas the others specify volcanic host rocks. The term VMS includes deposits that are hosted by, or occur in, a volcanic-dominated environment but also those that are genetically related to volcanism, regardless of whether they are in successions dominated by either volcanic or sedimentary strata. Ancient VMS deposits formed in collisional environments (ocean-ocean or ocean-continent convergence) and during periods of extension and rifting. Rifting, subsidence, and thinning of the crust accompanied by the rise of hot asthenospheric mantle into the base of the crust, caused bimodal mantle-derived mafic and crustal-derived felsic volcanism. Magmatism associated with rifting, which manifests itself by the emplacement of cogenetic intrusions at shallow and mid-crustal levels, caused heating and modification of entrapped seawater within adjacent volcanic and/or sedimentary strata. Extensional arc environments are recognized by the change from a sequence of VMS-prospective primitive arc basalt and high silica rhyolite, intruded by tonalite-trondjhemite sills and dike swarms, to an overlying succession of MORB basalt-dominated terrane in oceanic back-arc basins, or alkaline basalt and MORB in mature continental back-arc basins.

Heat-induced water-rock reactions resulted in metal leaching and the formation of hydrothermal convection systems within the lower semi-conformable alteration zones of VMS deposits. -lived systems ultimately discharged fluid from deep-penetrating, syn-volcanic faults onto the sea floor or into permeable strata immediately below the sea floor, to form VMS deposits. In addition, in a few districts some of the metals may have been obtained directly from subvolcanic magmas (e.g., Cu, Au, and Sn).

The metal content of a deposit is controlled by the temperature, a_S, and pH of fluids in the reaction zone, adiabatic cooling of the fluid during its ascent (related to water depth), and the amount of subsea-floor fluid mixing, and zone refining. Fluids formed by reaction with basalt typically have a maximum temperature of 350° to 400°C and produce Zn-Cu deposits with minimal Pb. Fluids formed by the reaction with sedimentary or felsic volcaniclastic strata may have been of lower temperature and produced Zn ±Pb ± Cu deposits, usually with higher (Zn + Pb)/Cu ratios than the former. The gold content of deposits in any setting is controlled by temperature, a_S, boiling (related to water depth), and precipitation mechanisms, as well as redistribution (zone refining), plus input from magmatic sources. Subsea-floor replacement provides a more efficient mechanism to trap a higher proportion of metals and may be responsible for forming larger, more tabular VMS deposits. Some components of the hydrothermal fluid escape to be trapped in hanging-wall sediments and sea-floor precipitates. Silica (as

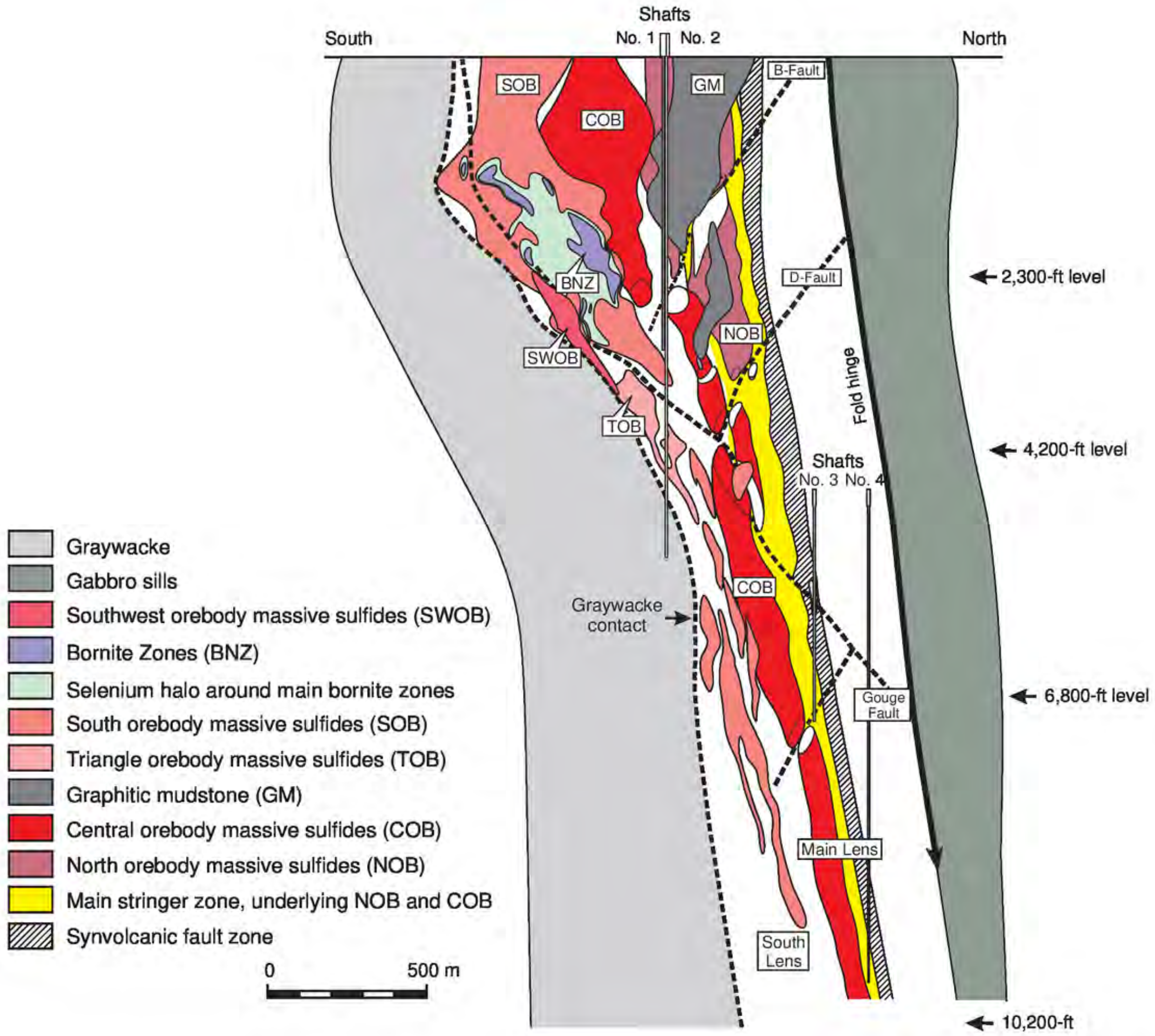

Figure 4: *From Hanington et al (2000) and references therein. Schematic representation of the restored longitudinal section of the Kidd Creek deposit. The South orebody extended from surface to about 3,400 ft (1,040 m) but was cut out of the stratigraphy at depth by the northward migration of the graywacke contact. Several small sulfide lenses that are situated at about the same stratigraphic height as the former South orebody occur between 3,400 ft (1,040 m) and 6,800 ft (2,070 m). At depth in the deposit, the graywacke contact steepens again, revealing more of the hanging-wall succession. The approximate locations of the Main and South lenses of Mine D are indicated to the bottom of the mine. The Main lens in Mine D is interpreted to be the down-plunge continuation of the Central orebody. The South lens is interpreted to be the down-plunge continuation of the South orebody.*

chert) and conserved elements (Mn, Eu, P, Tl, base and precious metals) all accumulate in these sediments, forming useful vectors to potential ore.

Franklin *et al.*, (2005) classified VMS deposits into five lithostratigraphic types, using sequence boundaries defined by major time-stratigraphic breaks, faults, or major subvolcanic intrusions. The five types are as follows:

1. Bimodal-mafic settings, exemplified by the deposits of the Noranda camp and the Urals, occur in early stages of rifted supra-subduction oceanic arcs. These settings are characterized by a combination of mafic volcanic flows and a smaller percentage (<25%) of felsic strata.
2. Mafic settings, seen in deposits in Cyprus and Oman, occur in primitive oceanic backarcs. These settings are associated with ophiolite sequences with <10% sediment.
3. Pelite-mafic settings, represented by deposits like Windy Craggy and Besshi, occur in mature oceanic backarcs. These settings are characterized by a roughly equal proportion of pelite (sedimentary rocks) and basalt (including mafic sills).
4. Bimodal-felsic settings, found in the Skellefte district and Tasmania, occur in early incipient-rifted supra-subduction epicontinental arcs, typified by 35 to 70 percent felsic volcaniclastic strata.

5. Siliciclastic-felsic settings, seen in deposits in the Iberian pyrite belt and the Bathurst camp, occur in mature epicontinental backarcs, characterized by continent-derived sedimentary and volcaniclastic strata.

While the first three types are predominantly Cu-Zn deposits, the last two types also contain significant amounts of Pb in addition to Cu and Zn.

Polymetallic VMS deposits, often with both base and precious metals can generate high economic margins. VMS deposits commonly occur in districts and there are a number of giant and supergiant deposits in this deposit type category (e.g., Kidd Creek). VMS deposits are also widely distributed and are attractive in terms of explorability for both junior explorers and major companies. However, in many districts the average deposit size is small and many of the large districts are relatively mature in terms of exploration potential. VMS deposits also commonly contain deleterious elements which can pose metallurgical and environmental challenges. Managing and mitigating the impact of these elements is important for sustainable mining.

The supergiant Kidd Creek VMS deposit is one of the world's largest and highest-grade Cu-Zn deposits, with total past production, reserves, and resources to 2990 m elevation of 171 million tonnes (Mt) of ore. The following description is summarized from Hannington *et al.*, (2017) and references therein. The deposit was discovered in 1963 with the discovery hole intersecting 190 m grading 1.21% Cu, 8.5% Zn, 0.8% Pb, and 138 g/t Ag. After 50 years of continuous mining (1966–2016), the deposit has produced a total of 140.4 Mt of ore at grades of 2.29% Cu, 6.15% Zn, 0.22% Pb, and 86.2 g/t Ag, worth an estimated US$50 billion. The contained metal (3.8 Mt of Cu, 10.5 Mt of Zn, 0.38 Mt of Pb, and 12.7 million kg of Ag) accounts for nearly one-third of all metal in Archean Cu-Zn massive sulphide deposits worldwide.

The deposit is hosted by the Kidd Volcanic Complex which is part of the 2.710 to 2.717 Ga Kidd-Munro assemblage, that in turn lies within the western Abitibi-Wawa Sub-province of the Superior Province. At Kidd Creek, the Kidd Volcanic Complex is a coherent, although structurally complicated lithostratigraphic package containing a strongly bimodal suite of komatiitic and high silica rhyolite flows overlain by tholeiitic basalts. It is structurally underlain by younger Porcupine Group wackestones, across a contact that takes the form of a steeply dipping folded thrust or unconformity. In the mine area, the sequence if overturned, strikes north-south, face west and dip at 70 to 80° east, to define an asymmetric, S-shaped, steeply north plunging F1 fold. The Kidd ore system comprises the three geochemically distinct and physically separated North, Central and South sulphide orebodies (Figure 4). Each orebody is characterized by

a). pyritic tops and lateral fringes,

b). Zn-rich interiors (sphalerite-pyrite),

c). massive to semi-massive, Cu-rich bases (chalcopyrite-pyrrhotite-pyrite-sphalerite), and,

d). underlying chalcopyrite-pyrrhotite-pyrite stringer mineralization.

In addition, the South orebody also had a bornite zone within the Cu-rich massive and stringer ore. Significant sections of all three orebodies were developed by replacement of the adjoining footwall volcaniclastic units, as indicated by:

a). post-depositional replacement of rhyolitic fragments and matrix by pyrite and sphalerite.

b). preservation of relicts of massive pyrite and sphalerite within the chalcopyrite-pyrrhotite ore; and

c). discordant contacts between massive sulphides and bedding.

In general, each of the orebodies is composed of stringer and massive banded and brecciated pyrite, sphalerite and galena associated with carbonaceous rocks. The composite shape of the massive and breccia, and the stringer ore respectively, for the three orebodies may be broadly represented as two parallel, adjoining, elongate flattened cylindrical masses, with gaps and offsets. The massive sulphide lens is generally 100 to a maximum of 400m wide and around 30m thick, with a down plunge extent of more than 3000m. A broad halo of sericitization envelopes the massive sulphide orebodies, characterized by K_2O enrichment and Na_2O depletion. This alteration is preferentially developed within the footwall but which also extends into the overlying QP Rhyolite. Fe-chloritization is restricted to the margins of footwall chalcopyrite stringer zones. Both the sericitization and chloritization overprint a broad and widespread silicification.

Carbonate Replacement Deposits (CRD)

CRDs include a number of different deposit sub-types, including skarns, mantos, and epithermal vein and breccia-hosted deposits. However, Skarn deposits dominate this deposit type in terms of zinc production and contribute approximately 12% of global zinc production in 2022 (Wojcik, 2023) and contain around 9% of known global zinc resources. Many Skarn deposits are polymetallic which can yield high profit margins. They are often large and bulk-mineable in open pits which also improves mining economics.

Meinert *et al.,* (2005) provides a detailed review of "World Skarn Deposits" and notes that skarn deposits are one of the more abundant ore types in the earth's crust and form in rocks of almost all ages. They are characterized by a relatively straightforward mineralogy, typically dominated by calc-silicate minerals like garnet and pyroxene. While the majority of skarns are associated with lithologies containing some limestone, they can form in almost any rock type through regional or contact metamorphism and various metasomatic processes involving fluids of magmatic, metamorphic, meteoric, and/or marine origin. Skarns are commonly found adjacent to plutons, but they can also occur along faults, major shear zones, shallow geothermal systems, on the sea floor, and at greater depths within deeply buried metamorphic terranes. Thus, the presence of a pluton or limestone is not necessarily a requirement for skarn formation. Most skarn deposits exhibit zonation, with proximal garnet, distal pyroxene, and minerals such as wollastonite, vesuvianite, or massive sulphides and/or oxides occurring near the marble front. Meinert *et al.*, (2005) recognizes seven major skarn types (Fe, Au, Cu, Zn, W, Mo, and Sn) and notes a general correlation between igneous major and trace

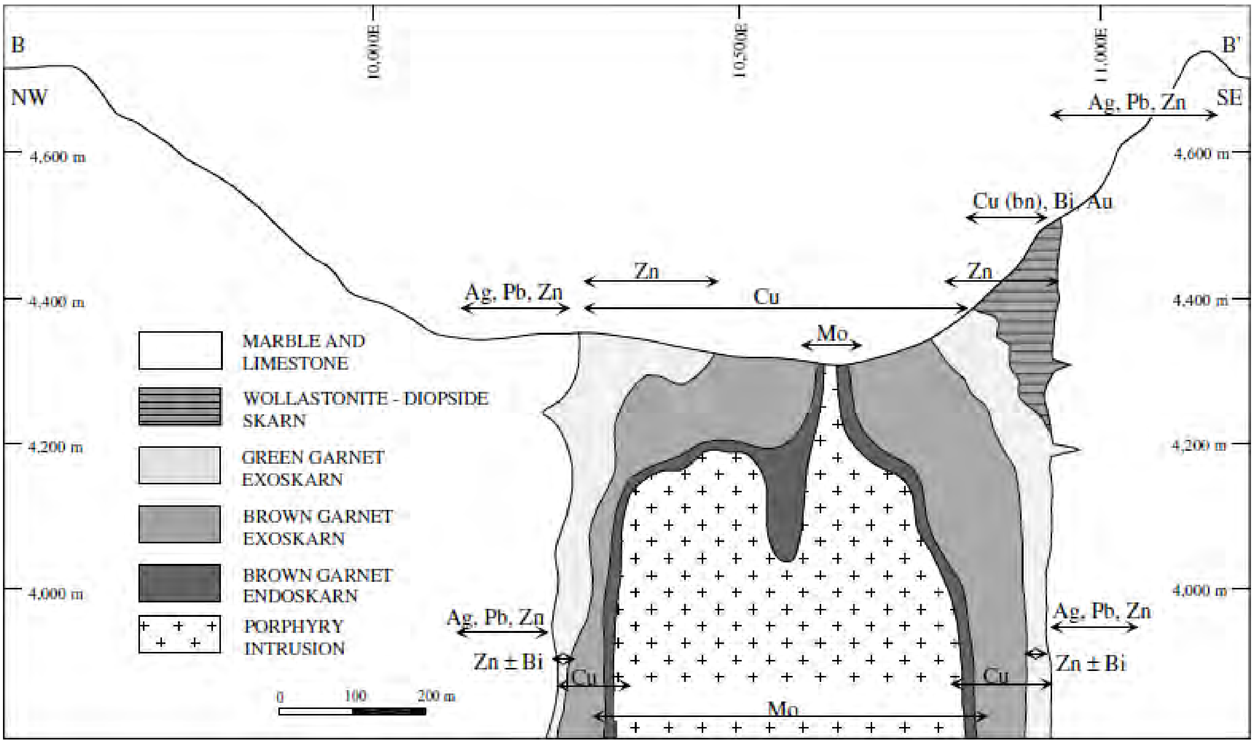

Figure 5: *From Redwood (2005) NW-SE cross section (looking NE) of the Antamina copper-zinc skarn deposit, showing zonation of skarn and metals. All Cu present as chalcopyrite except for bn = bornite.*

element composition and skarn type. Most Zn skarn deposits are found in continental settings associated with either subduction or rifting. These deposits are primarily mined for ores containing Zn, Pb, and Ag, with Zn being the dominant metal. They are known for their high-grade, typically containing 10-20 wt% Zn+Pb and 30-300 g/t Ag. The related igneous rocks associated with Zn skarns exhibit a wide range of compositions, ranging from diorite to high-silica granite. These skarn deposits are found in diverse geological environments, including deep-seated batholiths and shallow dike-sill complexes to surface volcanic extrusions. A common characteristic among most Zn skarn ores is their occurrence at a distance from associated igneous rocks.

Located in the central Andes of Peru, the Antamina Cu-Zn skarn is recognized as the world's largest skarn deposit, containing a resource of approximately 2,968 million tonnes (Mt). As of 2015, the average grades of the deposit are estimated at 0.89% Cu, 0.77% Zn, 11 g/t Ag, and 0.02% Mo. The deposit was explored in the modern era beginning in 1952 and the mine entered production in 2001. The mine produces around 250 Mt of zinc in concentrate per year making it the fifth largest zinc producer.

The following description of the deposit is taken from Redwood (2005). Skarn mineralization forms a shell over and around a quartz monzonite porphyry stock of late Miocene age, which itself hosts subeconomic porphyry copper-molybdenum mineralization. The skarn body is approximately 2,500m long in a northeasterly direction and up to 1,000m wide, with a known vertical extent of 1,000m. (Figure 5). The skarn consists mainly of andraditic garnet. It is symmetrically zoned around the intrusion from proximal brown garnet endoskarn and exoskarn outward to green garnet exoskarn, with peripheral wollastonite-diopside exoskarn. Significant copper mineralization is hosted by endoskarn. Retrograde chlorite skarn and hydrothermal breccia are minor.

Metals are zoned laterally from a central copper-only zone to a peripheral copper-zinc zone. Chalcopyrite is distributed throughout all skarn zones. Appearance of sphalerite approximately coincides with the transition from brown to green garnet. The copper-zinc zone thins at depth and originally appears to have closed over the top of the intrusion, although most of it has been eroded. The main copper mineral in the wollastonite-diop-side skarn is bornite, and this zone also has elevated gold values. Silver, lead, and bismuth values are highest in the outer part of the copper-zinc zone and adjacent marble. Molybdenite occurs in the intrusion and adjacent skarn, as well as being abundant in the wollastonite-diopside skarn. Sulphides were deposited during the late prograde and retrograde phases and occur disseminated interstitial to garnet; as irregular massive sulphide zones; and as veinlets. The deposit was unroofed by glaciation and is exposed in a glacial valley; hence there is no significant oxidation or enrichment.

Included also in the CRD type are the various epithermal breccia and vein-hosted deposits. Examples include the giant Peñasquito Au-Ag-Zn-Pb deposit, currently the largest Au-producing mine in Mexico which also produces significant biproduct zinc, amounting to around 214 thousand tonnes of zinc in concentrate in 2021. Mineralization is centered on the Peñasco and Brecha Azul diatreme breccias with mineralization associated with early Oligocene quartz-feldspar porphyries and intruded into an Upper Jurassic to Upper Cretaceous marine carbonate-dominated sedimentary sequence.

Zinc Industry Trends

The zinc industry is experiencing several notable trends in recent years that are shaping its trajectory and influencing market dynamics. These trends include an increase in polymetallic producers, stricter environmental and mine permitting regulations, and the consolidation of zinc producers. Here are some key trends:

1. **More polymetallic zinc producers:** Wojcik (2023) notes that zinc mines have been increasingly polymetallic in nature since the turn of the millennium. Larger polymetallic mines that came into production during this time, include Antamina and Penasquito, and smaller more recent examples include Aripuana, Juanicipio, and Woodlawn starting since 2019. Being polymetallic means more financial and risk diversification through the exposure to more than one metal price and the ability to selectively increase production from areas that will benefit from high prices of a particular metal.

2. **Challenges in Project Development:** Many potential zinc projects face challenges such as sovereign risk, low ore quality, inadequate infrastructure, and limited availability of financing. Wojcik (2023) estimates that the average lead time from exploration to construction for zinc projects is 14 years and dependent on a variety of risk factors. These factors impede the development of new projects and contribute to the scarcity of new discoveries.

3. **Low Global Discovery Rates:** Global exploration expenditures for copper and gold far exceed expenditures for zinc/lead and the rate of new zinc/lead discoveries worldwide is low (Schodde, 2017). Limited exploration success and the depletion of high-quality deposits both contribute to concerns about a potential supply shortfall in the future. Linked to lower discovery rates is the decline over the past 20 years in the number of both junior and major companies that are interested in zinc. Having said that, Wojcik (2023) notes that since 2020, junior and development company financing has shown strong activity and the size of funding is loosely correlated to the stage of development at which the zinc project is currently in. This suggests that right now, zinc projects are of interest to investors irrespective of which stage of development they are in.

4. **Zinc industry consolidation:** The zinc industry has experienced a significant level of consolidation over the years which has resulted in less companies in the zinc exploration and mining business. Since 2000 over 50% of the top ten zinc producing companies and 65% of the top ten zinc mines have changed hands. Several mergers, acquisitions, and partnerships have taken place among mining companies, leading to the consolidation of zinc assets and operations with the market share of the top 10 producers now standing at around 50%. Some notable examples of consolidation in the zinc industry include the merger of Glencore and Xstrata in 2013, which brought together two major players in the zinc market. Another significant consolidation occurred with the acquisition of mining companies such as Nyrstar by Trafigura and Chihong Zinc & Germanium by Yunnan Copper Industry Co. Ltd. In 2017, Vedanta Limited acquired the zinc business of Anglo-American plc. The acquisition included several zinc assets such as mines, smelters, and associated operations. These consolidation activities have resulted in the formation of larger mining and zinc trading and smelting entities with expanded zinc portfolios and enhanced market influence.

5. **Less Tolerance for Harmful Elements**: Market demands for high-quality zinc concentrates are increasing, leading to less tolerance for deleterious elements. Impurities such as cadmium (Cd), mercury (Hg), and other harmful elements are being closely monitored and restricted due to their environmental and health impacts. REACh (Registration, Evaluation, Authorization, and Restriction of Chemicals) regulation, adopted globally, aims to ensure the safe use of chemicals, including zinc and its associated trace elements. Additionally, the United Nations Global Mercury Treaty, focused on reducing mercury emissions and usage, has implications for the zinc industry. Collectively these regulatory measures encourage responsible and sustainable practices in zinc production and usage and as a result smelters and consumers of zinc concentrates are implementing stricter requirements to ensure cleaner and purer zinc products.

   China, a significant player in the zinc industry, has implemented restrictions on receiving zinc concentrates with high cadmium (Cd) content. This policy aims to control Cd emissions and ensure the production of cleaner zinc products. Consequently, concentrates with elevated Cd levels face limited market opportunities in China.

6. **Zinc demand will continue to grow:** Wojcik (2023) states that the medium to long term outlook remains positive for new zinc project as 5.6Mt of new mine supply will be required by 2032, rising to 14.5Mt by 2050. For zinc mines, this is the equivalent to three medium sized mines every year. Which will be a challenge given the capital expenditure and time required to design, permit and construct new mines.

Trends in the zinc industry include efforts to improve environmental performance, enhance product quality, and adapt to changing market dynamics. As the zinc industry continues to evolve, stakeholders are actively working towards sustainable practices, reduced environmental impacts, and the production of high-quality zinc products demanded by global markets. Against this backdrop, it is worth noting that zinc production from the Irish Midlands basin fit well with the evolving needs of the industry, including environmental sustainability, product quality, and market demand and the need for a sustainable and responsible zinc supply chain.

Summary and Conclusions

Global zinc production and known resources are primarily derived from four major ore deposit types, which collectively contribute about 85% of zinc production and 86% of known zinc resources. These deposit types, ranked in terms of their significance, include shale-hosted massive sulphide (SHMS) deposits, volcanogenic massive sulphide (VMS) deposits, carbonate replacement (CRD) deposits, and Irish-type/Mississippi-valley type (IT / MVT) deposits. Each of these four deposit types represents a distinct geological setting and set of zinc ore-forming processes which result in a range of ore deposit characteristics which in turn determine the economic attractiveness and sustainability of each deposit type. Each of these four deposit types has also produced a small number of world class deposits which stand out due to their exceptional size, high grades, and economic viability. Their long mine life and attractive economics make them particularly attractive for mining and exploration companies, drawing considerable attention and exploration investment. These world-class deposits are considered the flagship assets within their respective deposit types and though relatively few in number, play a crucial role in meeting the global demand for zinc. As a result, these deposits continue to be a focal point for ongoing exploration, development, and production efforts in the zinc mining industry.

The Irish Midlands basin is globally significant in terms of zinc exploration and mining. Over the course of the past six decades, numerous discoveries in the basin have highlighted its potential to host world-class zinc deposits. One particularly noteworthy deposit is Navan, renowned as one of the largest Irish-Type / Mississippi Valley-Type (IT / MVT) deposits worldwide. Navan has produced substantial quantities of zinc and lead ores for the past 45 years and has played a pivotal role in the economic prosperity of the surrounding area. One advantage of Irish-type deposits, exemplified by Navan as well as Lisheen / Galmoy, is their metallurgical simplicity. These deposits lend themselves to straightforward ore processing techniques, resulting in the production of clean zinc concentrates with minimal impurities. Such high-quality concentrates are highly sought after by zinc smelters across the globe as they can be blended with other lower quality zinc concentrates, leading to improved smelting economics.

Despite several decades of intensive mineral exploration in the Irish Midlands basin, the potential for new discoveries within this region remains remarkably high. The basin's substantial metal endowment and the quality of its existing deposits make it an appealing and promising area for further exploration activities. While substantial progress has been made in exploring various parts of the basin, there are still vast areas that remain relatively underexplored. This is particularly true for regions covered by rock sequences, such as the Tober Colleen, Lucan and Boyne Formations, commonly referred to as the "Calp." The presence of these cover rocks has shielded underlying mineralization from direct observation and has presented a unique challenge for explorers. However, it also represents a tremendous opportunity for new discoveries, as these unexplored areas hold the potential for hidden mineral deposits that have yet to be tapped.

Moreover, advancements in exploration technologies, such as cost-effective collection of onshore seismic reflection data, have significantly enhanced our ability to uncover hidden mineral deposits and expand our understanding of the basin's geological complexities. Teck Ireland collected 2D seismic data across the Ballinalack deposit in 2010 and these data clearly imaged the stratigraphy and structure of the deposit (de Morton *et al.*, 2015) and demonstrated the usefulness of seismic reflection data for mineral exploration in the Irish Midlands. As a result, seismic reflection surveys have been an integral part of Teck’s exploration program in Ireland since that time. In 2012, Boliden also collected 2D seismic across the Navan deposit and these data were a “game changer” in terms of subsurface visualization and leading to priority target being identified 2 km south of the mine. Drill testing of this target resulted in the blind Tara Deep discovery in 2012 (Ashton *et al.*, 2018). Since 2010, large amounts of seismic reflection data have been collected across the Irish Midlands basin, but to-date no new greenfields discoveries have been announced. Nonetheless, the usefulness of seismic data in finding permissive structural settings for ore-formation, at depth and below cover rock sequences, means that it will likely plan a role in future discoveries in the Irish Midlands Basin.

The combination of accumulated geological knowledge, technological advancements, and ongoing exploration programmes has greatly increased the likelihood of future mineral discoveries in the Irish Midlands basin. The insights gained from previous exploration efforts, coupled with state-of-the-art exploration tools and methodologies, provide a solid foundation for identifying and targeting prospective areas within the basin. This collective knowledge and expertise, combined with a commitment to continued exploration and investment, create an optimistic outlook for exciting new mineral discoveries in the Irish Midlands basin in the years to come.

In summary, the Irish Midlands basin's rich history of mineral discoveries and the distinctive attributes of Irish-type deposits underline its enduring importance in terms of global zinc exploration and mining. The presence of world-class deposits within the basin, characterized by their large size, good grade, metallurgical simplicity and production of clean concentrates, solidify its reputation as a significant zinc-producing region.

The extraction of zinc from the Irish Midlands basin also contributes significantly to the European Union's pursuit of mineral self-sufficiency and sustainability goals. By harnessing the basin's mineral resources, the EU aims to enhance its resource security and reduce its dependence on external zinc supplies. This strategic objective not only bolsters the EU's economic resilience but also promotes a more sustainable and environmentally responsible approach to mineral extraction and utilization.

Furthermore, the production of zinc from the Irish Midlands basin aligns with the EU's broader sustainability agenda. By accessing local zinc deposits, the EU reduces its reliance on long-distance transportation of minerals, thereby minimizing carbon emissions associated with the mineral supply chain.

This localized approach to zinc production fosters a more sustainable and resilient mineral industry within the EU, contributing to the region's transition towards a greener and more environmentally conscious future.

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