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POLYMETALLIC COPPER AND ZINC-LEAD MINERALISATION IN SOUTHERN IRELAND - WITH EMPHASIS ON THE ROSS ISLAND AND MUCKROSS DEPOSITS NEAR KILLARNEY, SOUTHWEST IRELAND

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by

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ABSTRACT

Lead isotope studies have been undertaken on the economically important Zn-Pb deposits of central Ireland but there are few data for low-grade, Cu-dominated, Red Bed-hosted deposits of southwest County Cork, or the minor carbonate-hosted Courceyan Cu-polymetallic deposits in the southwest of Ireland. The origin of lead and other metals in the Carboniferous carbonate-hosted base metal deposits of the Irish Midlands is regarded as the underlying Caledonian basement. Published isotopic data show a very restricted range for any particular deposit, a linear trend of data on the $^{206}Pb/^{204}Pb$ v $^{207}Pb/^{204}Pb$ plot and a systematic geographical variation of $^{206}Pb/^{204}Pb$ data in Carboniferous Zn-Pb deposits, becoming more radiogenic from northeast to southwest irrespective of mineralisation style, age or host. These trends are attributed to mixing of lead derived from an old non-radiogenic northwest source and a more radiogenic southeast source.

Devonian Red Bed-hosted deposits in the Munster Basin occur either as low-grade stratiform disseminated bornite and djurleite and minor veinlets, as at Mt. Gabriel, or as major quartz veins with copper-dominated polymetallic deposits, as at Allihies, Dhurode and Ballycummisk. Lead-isotopic ratios vary according to the style of mineralisation. For disseminated sulphides, there is a considerable scatter of data on both $^{206}Pb/^{204}Pb$ v $^{207}Pb/^{204}Pb$ and on $^{206}Pb/^{204}Pb$ v $^{208}Pb/^{204}Pb$ plots, especially for Mt. Gabriel. They appear to define a mixing line between a basement source and a more radiogenic component, which may have been granite-derived detrital minerals in the Red Beds. For the minor veinlets there is a more restricted distribution of lead-isotopic data, which could be interpreted in terms of fluid flow homogenising the wide spread of Pb-isotope ratios from the disseminated sulphides. This is consistent with published sulphur-isotope data. The major quartz veins show a clustered array of isotopic ratios and it is suggested that the bulk of the metals were derived from a basement source with a minor contribution from Red Beds. In these deposits remobilised disseminated ores were deposited along spaced cleavages and minor veinlets and major sulphide-bearing veins formed after folding during continued Variscan compression

The Courceyan carbonate-hosted Cu-Ag deposits form three groups: (1) Cu-Ag ± Hg-As-Sb-U epigenetic vein-hosted deposits, as at Gortdrum; (2) Cu-As ± Zn, Pb, Ag, Co, Ni stratabound deposits characterised by chalcopyrite-pyrite or, sphalerite-galena, both with sulpharsenides and tennantite, as at Muckross, Crow Island and Blue Hole on Ross Island; and (3) Cu-As ± Pb, Ag, Mo, Co, Ni epigenetic vein deposits characterised by chalcopyrite-tennantite veins at Western Mine on Ross Island and Ardtully. Lead-isotope data for the stratabound deposits show a very restricted range of compositions for each locality and plot close to the same mixing line as the Carboniferous Zn-Pb deposits, but towards the end-member defined by the southeast basement source. These plots suggest that lead has been derived from a basement source similar to the Zn-Pb of the Irish Midlands. Their model age of 350 Ma ± 10 Ma for stratabound mineralisation is close to that of their host rocks. Lead-isotope data for the epigenetic Cu-As vein deposits at Western Mine suggest a similar source, but a younger age of 280 ± 10 Ma for mineralisation. This 280 ± 10 Ma age has important implications for the timing of the Variscan orogeny in southwest Ireland. Chalcopyrite-tennantite mineralisation that partly lies along pressure-solution cleavage planes, developed prior to major folding and thrusting. The thrusting episode that emplaced the mineralised tectonic sheet of Ross Island west of Killarney must, therefore, postdate *c.* 280 Ma, as the pressure-solution cleavage was deformed by the thrusting.

There appears to be a temporal relationship between stratabound Cu-polymetallic deposits in southwest Ireland, which formed during Carboniferous basin extension and the Zn-Pb deposits of the Irish Midlands. The difference in the ore assemblage between the two areas may be due to copper derivation from Red Beds in the southwest where the carbonates that host the stratabound Cu-polymetallic deposits are underlain by up to 6 km of Red Beds. In the Midlands, the Zn-Pb ore-bearing carbonates are underlain by lower Palaeozoic greywackes with a minimal thickness of late Devonian Red Beds. It is only for Ardtully that the isotopic evidence indicates a major source of metals from within Red Beds. For Ross Island, Crow Island and Muckross, unless the metals in the Red Beds originated from a basement rather than a granite source, a significant Red Bed contribution to the metals seems unlikely. An alternative possibility is that the Palaeozoic basement in the southwest, from which the carbonate-hosted copper ores were derived, was more copper rich than that beneath the Irish Midlands, perhaps derived from the continuation of Ordovician island-arc volcanics in southeast Ireland beneath the cover of the Munster Basin.

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INTRODUCTION

The geological work on Ross Island presented in this paper is a result of a study of the copper mineralisation as part of an interdisciplinary project investigating the geology, mineralisation and geoarchaeology of the Ross Island copper mines. Ross Island and especially the Bronze Age workings of sulphide and sulpharsenide ores at Western Mine and Blue Hole are of great importance in our understanding of the origins of metallurgy in the British Isles. This significance has been strengthened because radiocarbon dating has now shown that the earliest of these workings date to *c.* 2400-2000 BC making them the earliest yet identified in the British Isles (O'Brien, 1995; Ixer and Budd, 1998).

The copper ores, which have formed the basis for the extensive Bronze Age development, are of considerable interest geologically as well as of archaeological importance. The copper ores are hosted in rocks of the same age and type as those which host the economically important lead-zinc deposits of the Irish Midlands. In addition, the assemblage of ores at Ross Island is similar to that in small-scale copper deposits of southwest Ireland (Ni Wen *et al.*, 1996, 1999). These deposits have also been important in Bronze Age copper workings (O'Brien, 1994).

Geological studies at Ross Island have, therefore, helped considerably in an understanding of ore forming processes during the Carboniferous in Ireland and combined with lead isotope studies, have shown that the timing of the lead-zinc mineralisation in the Irish Midlands, the copper mineralisation of the southwest area, and the copper-silver-lead-zinc mineralisation of Ross Island, occurred more or less at the same time. The difference in ore assemblage in each area is a function of the source of the metals. These findings have important implications for archaeological studies, as it indicates that variations in lead isotopes in ores are a function of the depth and rock type from which they were derived, and will not pin-point the locality from which archaeological artifacts were sourced.

GEOLOGICAL FRAMEWORK OF IRELAND

The geological framework of Ireland consists of a mosaic of domains, each of which records a part of the geological timescale stretching back almost two billion years (Fig. 1). Although only fragments of very old rocks are found on surface in Ireland today, they may be more extensive at depth beneath the younger cover since volcanic vents of Carboniferous age have brought fragments of much older material from depth to the surface. The rocks of Ireland can be divided into four broad geological groups or time periods:

-	Early to mid-Proterozoic	>900 million years (Ma)
-	Late Proterozoic to Palaeozoic (Caledonian)	900-400 Ma
-	Devonian to Carboniferous	200-290 Ma
-	Permian to Tertiary	<290 Ma

Only the first three of these time periods are of relevance to the rocks and copper mineralisation at Ross Island. A list of the major geological time periods and events in Ireland is given in Table 1 and a simplified geology of Ireland is illustrated in Figure 2, as a framework for understanding the background to the geology of Ross Island.

Table 1. Simplified geological timescale of Ireland showing the four broad geological time divisions as discussed in the text and the major events in the evolution of the island of Ireland (compiled from numerous sources mentioned in this paper)

Age (Ma)	**Period**	**Areas of outcrop**	**Rock-forming processes**	**Structural events**
1.6	Quaternary	Evidence of two glacial events in south-west Ireland	Alternating cold and warmer interglacial stages	
65	Tertiary	Antrim and Giant's Causeway	Extensive basalt eruptions in NE Ireland, elsewhere extensive surface erosion	North Atlantic Ocean still widening
135	Cretaceous	Originally extensive but preserved in Antrim and Kerry	Limestone deposited and later removed by erosion	Continued opening of the North Atlantic Ocean
205	Jurassic		Uplift and erosion; Celtic basins develop east and south of Ireland	Initial opening of the North Atlantic Ocean
250	Triassic	NE Ireland and Kingscourt	Desert sands and gravels	Development of numerous faults
290	Permian			
355	Carboniferous	throughout Ireland	Land slowly submerged from SW; coastal plain sands and swamp muds followed by extensive limestone deposition in tropical seas	Variscan mountain building in late Carboniferous caused by closure of Rheic Ocean as Gondwana collided with Baltica. Only SW Ireland strongly affected.
410	Devonian	Red beds widespread Leinster, Galway and Donegal granites intruded as Iapetus suture closed	Crustal sag formed Munster Basin: deposition of more than 5km thickness of fluvial deposits and desert sands. Invasion of the sea in SW in latest Devonian times	Continued collision of Laurentia and Gondwana, Ireland becomes a single landmass. Then collision of Baltica with Laurentia-Gondwana
438	Silurian	Dingle Peninsula, Aherlow,Slieve Phelim Westport, and other small areas	Dingle Basin formed: widespread volcanism and marine turbidite sediments derived from island arc	Caledonian mountain building event caused by closure of the Iapetus Ocean and continental collision of Laurentia and Gondwana
510	Ordovician	SE Ireland, Longford-Down and Dingle Peninsula	Eruption of lavas from oceanic islands: deposition of muds on ocean floor	Earth movements end uplift of the Cambrian Basin, subduction of ocean floor
544	Cambrian	Cullenstown terrane, SE Ireland	Muds and sand Deposition continued	Formation of ocean floor in newly formed Iapetus Ocean to the northwest
1000	Late Proterozoic	Donegal, NW Mayo Connemara, Tuskar terrane, SE Ireland	Thick sediments deposited in Ocean Basin	Earliest rifting which led to the development of the Iapetus Ocean
1600	Mid Proterozoic	NE Ox Mountains; Doolough gneisses, of Annagh Gneiss Complex		Grenville mountain building event
2500	Early Proterozoic	Rosslare basement; Mullet gneiss, AnnaghHead; Inishtrahull		
	Archaean	No evidence of these ancient rocks in Ireland		

Figure 1. *Map of the British Isles showing the mosaic of domains formed by the amalgamation of different terranes (after Hutton, 1987).*

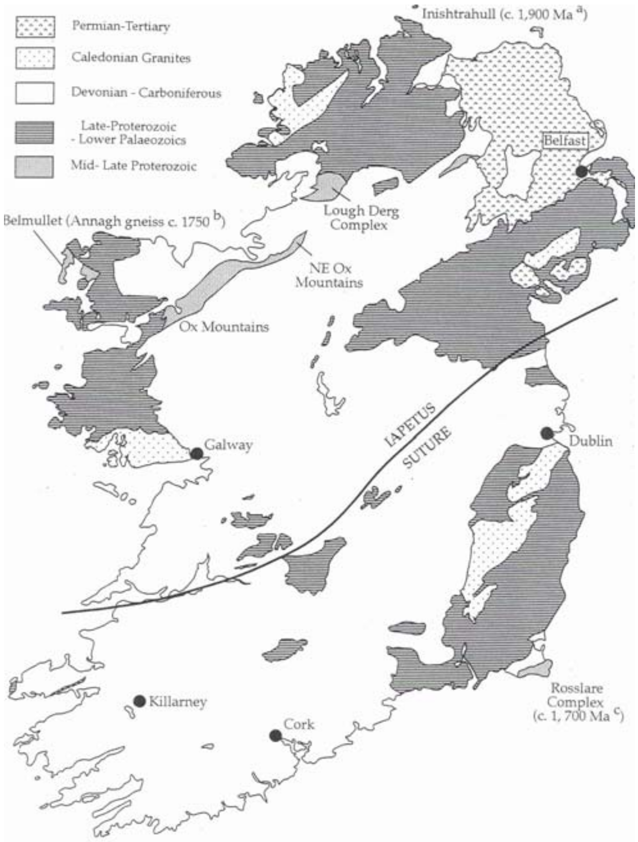
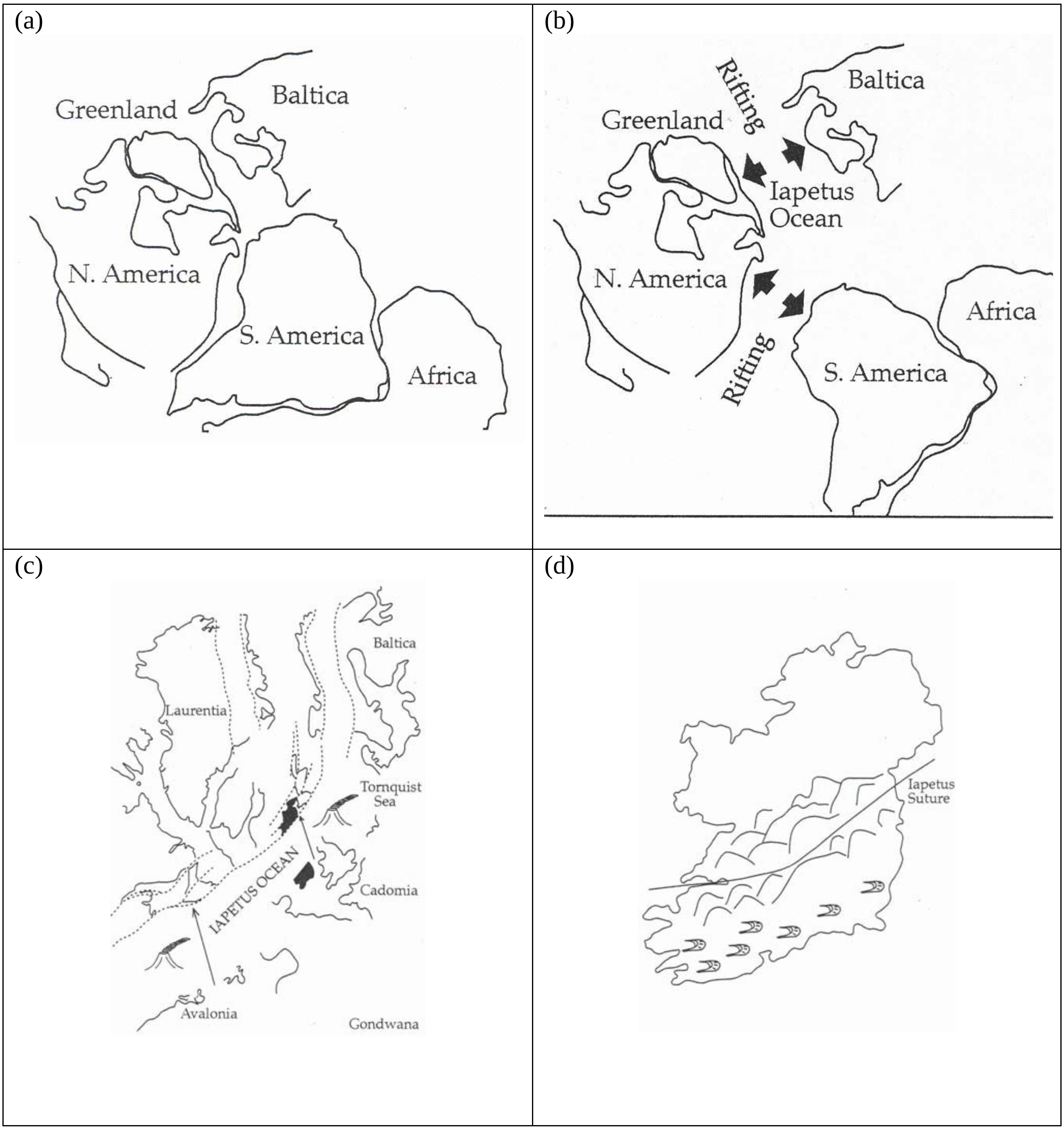


Figure 2. *Simplified geological map of Ireland, showing the ages of the oldest basement rocks. Ages are from: (a) Daly* et al. *(1991); (b) Daly, (1996); and (c) Davies* et al. *(1985).*

Early to Mid Proterozoic

Remnants of the oldest rocks are exposed in north and northwest Ireland on the island of Inishtrahull, in Mayo on the Belmullet Peninsula, and in the Rosslare area of the southeast (Fig. 2), although there is some disagreement to the absolute ages of these rocks.

The oldest rocks occur on Inishtrahull. These are gneisses of approximately 1900 Ma (Daly *et al*., 1991), which once were part of an ancient Laurentia-Baltica continent. This landmass included Greenland, part of present-day Canada and the northern part of Scotland, north of the Great Glen Fault (Fig. 3a). The Mullet Gneisses of the Annagh Gneiss Complex in northwest Mayo (Daly, 1996) have an age of *c*. 1750 Ma. To the south, rocks that may be as old as 1700 Ma also occur in the Rosslare area (Davies *et al*., 1985) although these are thought to have been part of a more southerly continent known as Avalonia-Cadomia, and may correlate with similar rocks on Anglesey (Murphy, F.C., 1990).



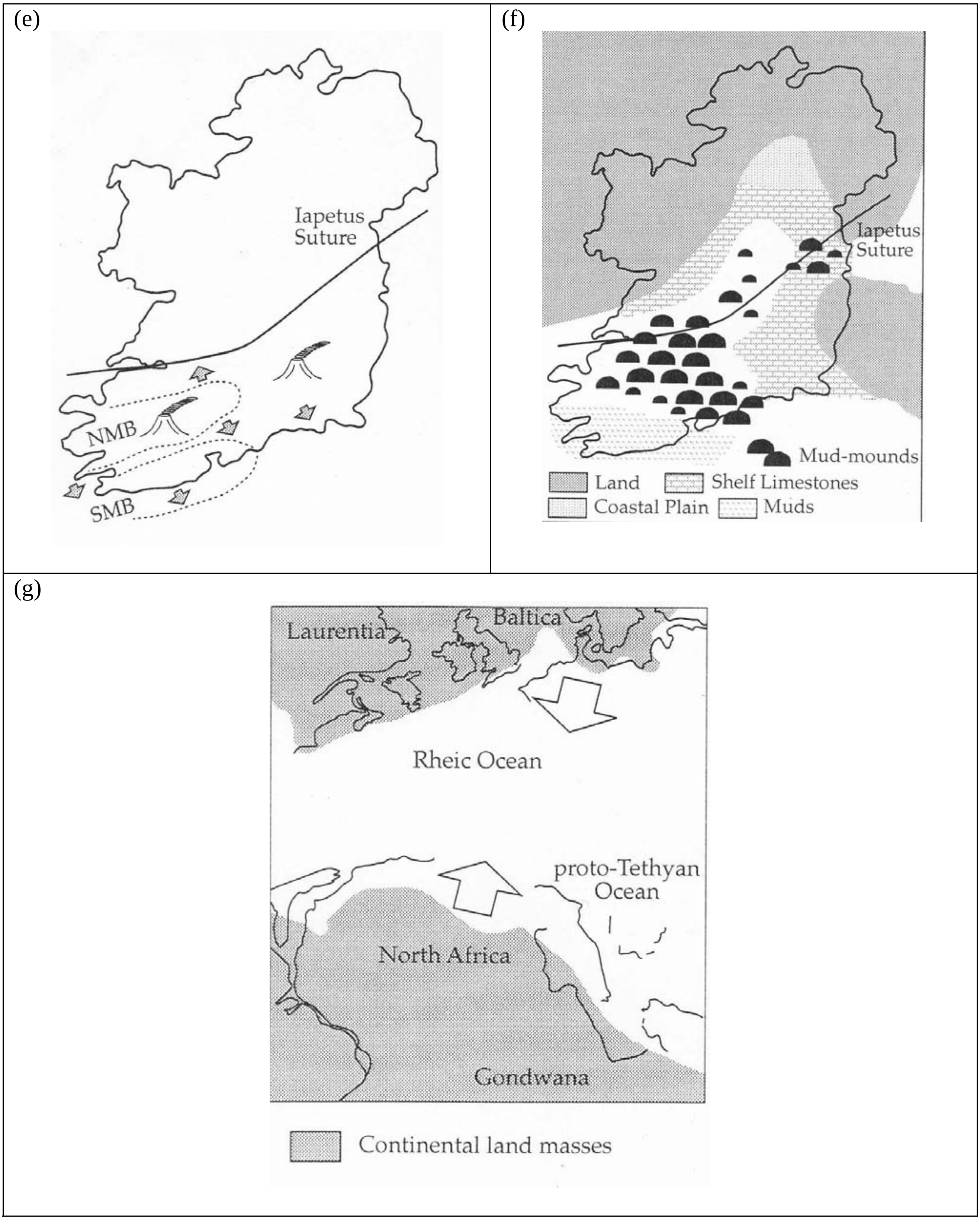


Figure 3. *Stages in the geological evolution of Ireland. (a) Proterozoic super-continent (after Park, 1992); (b) breakup of the Proterozoic super-continent (after Park, 1992); (c) three plate configuration for the Caledonian orogeny (after Soper and Hutton, 1984); (d) Devonian physiography with mountains and dunes; (e) formation of the Munster Basin; NMB = north Munster Basin; SNB = south Munster Basin; (f) limestone facies variation during the Dinantian after (Sevastopulo, 1979); (g) Variscan collision (after Paris and Robardet, 1990).*

The zone between the Great Glen Fault and the Fairhead-Clew Bay line, which includes parts of Donegal, the Ox Mountains and the Cross Point and Doolough Gneisses of the Annagh Complex of North Mayo, contains remnants of Grenvillian gneisses that are 1300 to 1000 Ma. All of these various fragments of old Ireland were formed south of the equator.

Late Proterozoic to Early Palaeozoic

During the late Proterozoic, around 900Ma, rifting began, which led to the formation of the Iapetus Ocean (Fig. 3b). This ocean separated ancient North America and Greenland from ancient Europe. In the period 800 to 530 Ma, thick sediments accumulated in a long, narrow basin that stretched at least 700 km from Connemara and Donegal to the Shetland Islands off northeast Scotland. Sands and muds continued to be deposited in the basin during Cambrian and then sedimentation was terminated by uplift of the Cambrian basin margin to form a landmass to the southeast.

The Proterozoic and early Palaeozoic rocks were overlain by basaltic lavas erupted during the Ordovician, from island-arc volcanoes in the Iapetus Ocean, similar to the Philippines in the Pacific today. These Ordovician lavas are exposed on the Dingle Peninsula (Pracht, 1996), in southeast Ireland and in Longford-Down. They were subsequently covered by a thick pile of Silurian turbidite sediments that were derived from the arc, and which slumped from the continental shelves into the oceanic basin.

Caledonian Orogeny

The Caledonian mountain building period, between the late Silurian and middle Devonian, resulted from the collision of three plates, Laurentia, Avalonia/Cadomia and Baltica, after the closing of the proto-Atlantic (Iapetus) Ocean (Fig. 3c). Between 435 and 410 Ma, Cadomia collided with Laurentia and the consolidation of these two crustal blocks produced the landmass that we now know as Ireland. The collision suture zone, which marks the weld where the two continents collided, extends from between Clogher Head and Dundalk on the east coast, south-westwards through the Silvermines-Slieve Phelim area and then westwards to the Atlantic, north of the Dingle Peninsula. This Iapetus suture zone, which extends across Central Ireland, divides Ireland into two crustal blocks, northwest Ireland and southeast Ireland, which have quite different histories prior to the Silurian. The high-heat flow and deformation associated with continental collision resulted in metamorphism during the Caledonian orogeny and also the intrusion of major granite bodies 400 Ma, in Leinster, Connemara and Donegal. In the Devonian, from 410-380 Ma ago, Baltica collided with Laurentia-Gondwana (Hutton, 1987) to end the Caledonian collision and mountain building.

Devonian to Carboniferous

In Devonian times, Ireland was a single landmass for the first time situated close to the equator (Fig. 3d). The mountains that had developed during the Caledonian orogeny suffered rapid erosion under semi-desert conditions. In southwest Ireland, extension during the Devonian caused the continental crust to sag and resulted in the formation of the Munster Basin, which itself consisted of a series of subbasins that subsided at different rates (Fig. 3e). The faults that formed during extension generally developed along pre-existing Caledonian structures. The northern edge of the Munster Basin is bounded by a fault-zone that passes through Dingle Bay. The sediments that filled the Munster Basin, which are of Devonian to Upper Carboniferous age, were deposited on the Ordovician-Silurian rocks, which had been tilted, folded and metamorphosed and are, therefore, separated by an unconformity which represents a period of non-deposition.

In southern Ireland, from middle Devonian to Lower Carboniferous, sandstones were deposited by river systems in a relatively flat desert environment. Tongues of coarser sands and gravels were deposited on the basin margins with finer material carried towards the centre of the basin. These sediments consolidated to form a group of rocks known as Red Beds. In the Irish Midlands the Red Beds are up to 300 m thick, although typically less than 100 m. In contrast, in the southwest of Ireland, Red Beds are over 6 km-thick in the Kenmare Valley, which is the centre of the Munster Basin.

In latest Devonian time (Figs. 3f, 4), the sea invaded south County Cork and the land was gradually submerged northwards. Sands and muds were deposited in deltas and swamps along the coastal plains. As the sea deepened, limestones were deposited in shallow tropical seas and by early Carboniferous, shallow-marine conditions extended over much of Ireland. It is these "layer-cake" Courceyan carbonates that host most of the lead-zinc metal deposits in Ireland and the copper deposits of Ross Island, Muckross and Ardtully in the Kenmare Valley. These widespread carbonates were followed during Chadian to Arundian times by a more complex set of depositional environments of juxtaposed shallow-marine shelf limestones and deeper basins, in which fine-grained carbonate muds, known as 'Calp' were deposited (Fig. 3f). By Holkerian time, basinal areas were infilled and there was little deposition of shelf limestones on top of basinal carbonates (Hitzman, 1999). A major phase of earth movements during the Asbian and early Brigantian caused faulting and some volcanic eruptions and although poorly documented, the palaeogeography was probably similar to that during Chadian to Arundian times (Hitzman, 1999). The Carboniferous carbonate sequence generally thins northwards because the sea invaded from the southwest.

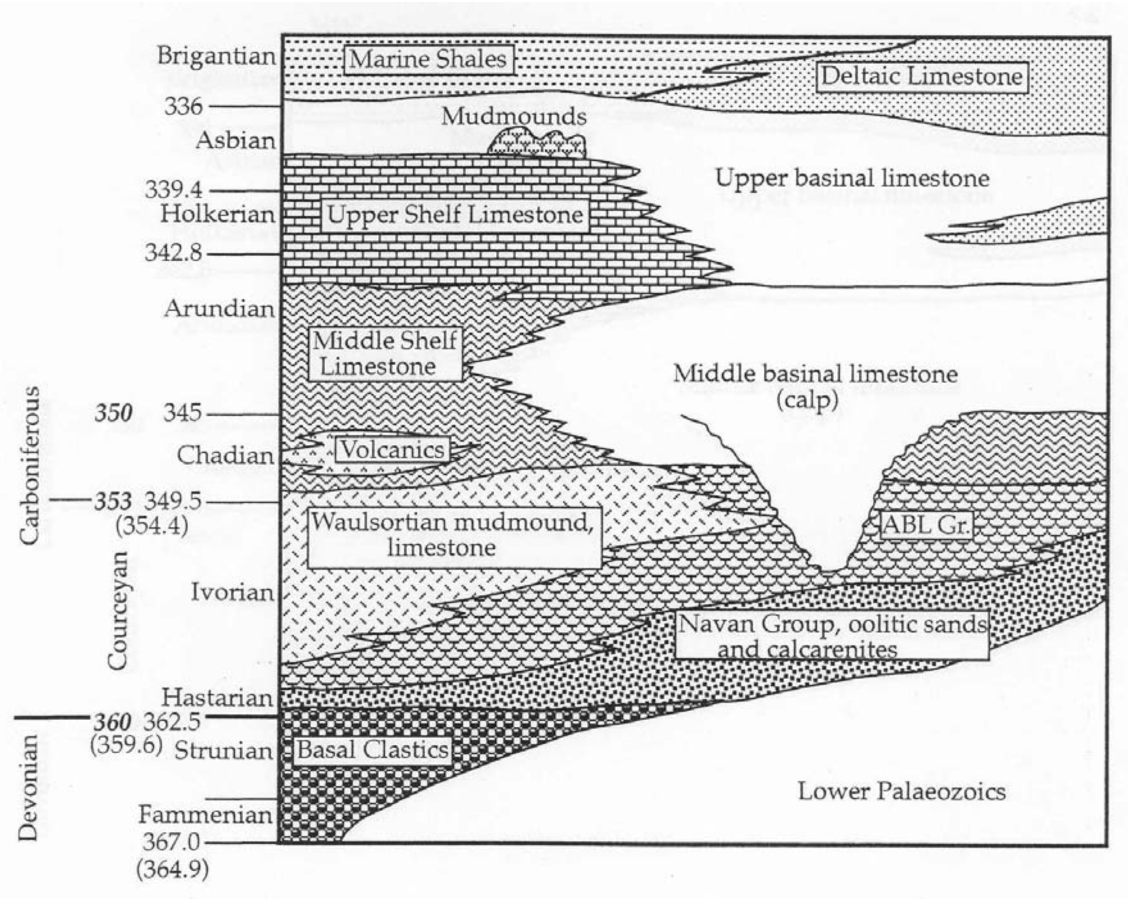


Figure 4. *Generalised stratigraphy of the Upper Devonian and Lower Carboniferous of the Irish Midlands (after Andrew, 1993). Dates for these various subdivisions vary in the literature, those on the right are from Harland* et al. *(1990) while those on the left, in italics, are from Andrew (1993). The most recent dates for Devonian rocks from the UK and Australia, shown in brackets, are based on single zircon SHRIMP dating by Compston (2000).*

Variscan Orogeny

Towards the end of the Carboniferous period, the continent of Africa (Gondwana) collided with Europe (Laurentia-Baltica), resulting in a period of mountain building and the closure of Rheic and Proto-Tethyan Oceans, remnants of which survive in the Mediterranean Sea (Fig. 3g). Only the south of Ireland was significantly affected by these earth movements and deformation intensity decreased from the southwest towards the north. Large-scale folding developed in the southwest due to the compression and, as this stress continued, eventually the folds fractured. Part of the lower succession of rocks were forced from the south, northwards over younger rocks, to form a series of stacked slices bounded by faults (or thrusts) as the crust continued to shorten. Age dating, based on lead-isotope studies of mineralisation at Ross Island (Kinnaird *et al.*, 2000) suggest that ores of 270-290 Ma age, formed before major folding, faulting and thrusting, and implies that the major thrusting episode must be younger than this. Since Devonian times, there has been a steady northwards drift of Ireland to its present day position.

Permian to Quaternary

Ireland has clearly been affected by younger geological processes than the Variscan orogeny, such as the opening of the North Atlantic, which began in the late Jurassic (Table 1). However, although the Ross Island area may have been influenced by glacial and periglacial periods, post-Variscan events have not substantially modified the geology of Ross Island.

MINERALISATION IN THE CENTRAL MIDLANDS AND SOUTHWEST IRELAND

In the last 30 years, studies of Irish mineral deposits have concentrated on the economically important lead-zinc deposits of central Ireland (reviewed in Andrew, 1993). In addition, there are well-documented occurrences of low-grade, copper-dominated mineralisation in Devonian sandstones of SW County Cork (Reilly, 1986; Ni Wen *et al*., 1996). Between these two areas are a series of poorly described small deposits of polymetallic copper-silver ores, which may not necessarily be of current economic significance, but which are of considerable importance in contributing to an understanding of the mineralisation processes elsewhere in southern Ireland (Fig. 5). Ross Island is one of these deposits, which has characteristics of both styles of mineralisation. The importance of Ross Island in understanding the whole of the Irish mineralisation in Carboniferous times requires a general appreciation of the mineralisation of the Munster Basin as well as of the Irish Midlands.

The essential points of the geological history of the Munster Basin can be considered in two major stages, one of extension, the other of compression:

(1) crustal sag in the mid- to late- Devonian, which formed the Munster Basin, was followed by extension; desert and river sands and gravels were deposited in the basin (Fig. 3d, e). Extension continued from late Devonian through to mid-Carboniferous, with a considerable decrease in the rate of sedimentation and the development of the South Munster Basin (Meere, 1995b). Extension and subsidence ceased at the end of the Carboniferous; and

(2) Variscan compression began in the late Carboniferous due to continental collision, and large-scale folds developed. Eventually, these folds fractured, and thrusting of packages occurred as the crust continued to shorten. These slices were thrust from the south, resulting in the stacking of the crust with older rocks on top of younger (Meere, 1995a).

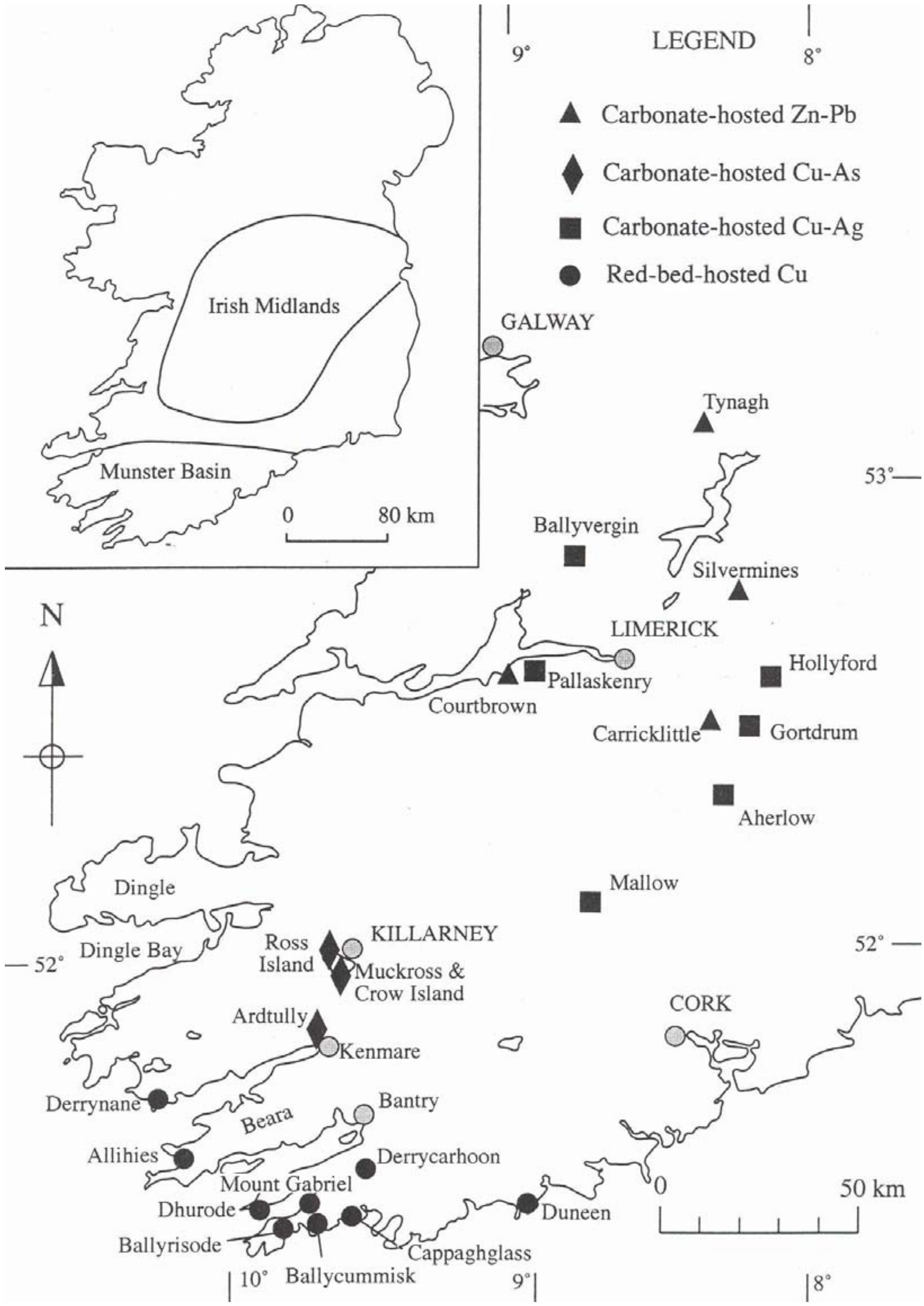


Figure 5. *Map showing the distribution of significant lead-zinc, copper-silver and copper deposits in the southwest of Ireland.*

The heat flow associated with these events was much higher than normal, which resulted in metamorphism of the whole Red Bed succession. Temperatures reached a peak of around 300°C during the early extensional phase (Meere, 1995b; Ni Wen *et al*., 1999), with later deformation occurring under falling temperatures (Meere, 1995b). There has been considerable discussion about when mineralisation took place and whether metal movement occurred during the extensional crustal thinning, or during the compressional phase. The major features of each of the different ages and styles of mineralisation is given, in order to emphasise the importance of the new understanding of Irish geology derived from the work at Ross Island.

Copper Deposits Hosted by Devonian Red Beds

There are a number of occurrences of copper mineralisation in southwest Ireland (Fig. 5) although these are on a very small scale when compared with the lead-zinc deposits of the Irish Midlands. Some of these copper-bearing localities in the Munster Basin have been mined since the Bronze Age (O'Brien *et al*., 1990; O'Brien, 1994), although the main period of extraction was the nineteenth century (Cowman and Reilly, 1988; Reilly, 1986). One important deposit of this type is at Allihies in the Beara Peninsula (Sheridan, 1964), while others are in the Mount Gabriel area.

There are three different types of deposit. These have been distinguished on the basis of their size, and the form in which they occur (Table 2 and Fig. 6):

(1) ***disseminated copper ores***: in these the copper minerals are scattered in the host rock resulting in low-grade deposits. Occurrences of this type are recorded in more than 100 widely spaced localities (Snodin, 1972). The copper minerals only occur in thin green to grey shaley horizons within the Red Beds mainly towards the top of the Castlehaven Formation. Mineralised beds are generally <3 m thick, with ore grades typically <1 wt% copper even in those deposits that were mined (O'Brien *et al*., 1990; O'Brien, 1994). Originally, the disseminated sulphide mineralogy was simple copper sulphides (bornite, djurleite) and chalcopyrite, but where alteration occurred due to fluid flow, more complex secondary copper ores developed (bornite, many with lamellae of chalcopyrite and covellite) (Ni Wen *et al*., 1999);

(2) ***simple copper ores in minor quartz veins***: the copper ores occur in thin quartz veinlets accompanied by calcite ± chlorite. The copper minerals are the same as those in the disseminated ores and the veins also occur close to the shaley horizons in the Red Beds. The veinlets are abundant and form a network, with two sets roughly at right angles to each other; and

(3) ***polymetallic ores in major quartz veins:*** the ores are more complex and occur in major quartz veins, up to 2 m thick, that are laterally extensive structures, often associated with east-west faults. In the far southwest they occur in the Toe Head and Old Head Sandstone Formations higher in the stratigraphic succession than the disseminated stratiform mineralisation (Ni Wen, 1991; Ixer, 1994; Ni Wen *et al*., 1996). In contrast, at Allihies, major vein mineralisation is lower down in the succession than disseminated mineralisation and is found in the Caha Mountain Formation. The main ores are copper- and copper-iron sulphides, with lesser molybdenite, galena and bismuthinite, sulpharsenides and antimony-bearing sulphosalts (Ni Wen, 1991; Ni Wen *et al*., 1996).

The compositions of the various minerals mentioned in the text are shown in Table 3, and a broad summary of these ore deposits is given in Andrew *et al*. (1986). They have variously been interpreted as diagenetic in origin, related to processes during lithification of the unconsolidated sediments (Snodin, 1972; Reilly, 1986), or as magmatic, and related to unexposed granites (Evans, 1976; Daltry, 1985). More recent interpretations, based on field and laboratory studies, have provided considerable evidence that the ores, especially those associated with the vein deposits, were metamorphic in origin. They probably resulted from remobilisation of material at the time of elevated temperatures during the high-heat flow associated with the Variscan mountain building (Ni Wen, 1991; Meere, 1995b; Ni Wen *et al*., 1996, 1999).

Table 2a. Descriptive details of the host rock lithology, and ore mineralogy of selected deposits hosted by Devonian Red Beds. Locations of the ore deposits are shown in Figure 5. The Formation names below the table are in stratigraphic order with the Caha Mountain Formation being the oldest (data from Ni Wen *et al*., 1996; 1999; Snodin, 1972; Jackson, 1980; Reilly, 1986); for composition of minerals see Table 3

Deposit	**Host rock lithology**	**Characteristics of mineralisation**
DISSEMINATED	**Ore grades typically < 1wt.% Cu (Snodin 1972, Jackson 1980)**	
Derrynane	Ballytrasna Formation - the medial equivalent of the distal Castlehaven Formation (MacCarthy 1990)	disseminated djurleite $\pm$ chalcopyrite $\pm$ bornite infill pore spaces; later copper sulphides along spaced cleavage.
Derrycarhoon	Castlehaven Formation	Disseminated chalcocite with minor bornite
Mount Gabriel	Green-grey siliclastics and minor carbonate-bearing horizons (cornstones) of the Castlehaven Formation.	Stratiform disseminated bornite and djurleite $\pm$ wittichenite infill pore spaces in sandstones and siltstones; later sulphides within thin (<5cm), quartz-phyllosilicate, veinlets along spaced cleavage.
Ballyrisode	Castlehaven Formation	Stratiform copper sulphides
MINOR VEINS	**Thin quartz + calcite $\pm$ chlorite veins**	
Cappaghglass	Top Castlehaven Formation Toe Head Formation	Thin quartz veins, bornite-chalcopyrite-galena, minor chalcocite, tennantite, pyrite.
MAJOR VEINS	**Thick laterally extensive quartz veins**	
Dhurode	Fluvial Toe Head and Old Head Sandstone Formations.	Vein, > 300m long, 2m wide, along a dextral ESE fault, cross-cutting folds, (Snodin 1972) Two mineral associations: (i)chalcopyrite-arsenopyrite-tetrahedrite -bournonite - meneghinite - galena, with rare molybdenite, pyrite and sphalerite (ii) late chalcocite-djurleite-bornite-molybdenite-native bismuth, rare wittichenite. (Ni Wen et al. 1991),
Ballycummisk	Top Castlehaven formation	Three paragenetic stages (1) early quartz + barite + haematite, with sericite, carbonates, chlorite and TiO_2 minerals (2) quartz with molybdenite, tetrahedrite, bornite, chalcopyrite. and pyrite with calcite, ankerite, sericite, chlorite and TiO_2 minerals (3) quartz-carbonate with minor tetrahedrite and chalcopyrite.
Allihies	Sandstones of the Caha Mountain Formation	Chalcopyrite + tetrahedrite in quartz veins (Cole 1922). Estimated l Mt of copper ore mined at 3% Cu grade (Reilly 1986).

Table 2b. Stratigraphic correlation of ORS Formations between the Toe Head area on the southern basin margin and the Beara-Bantry area close to the depocentre. Superscripts denote different deposits Dh = Dhurode, Ca = Cappaghglass, Bal = Ballycummisk, Der = Derrycarhoon, Bar = Ballyrisode, Al = Allihies. Data are from Williams *et al.* (1989), Pracht (1997) and Pracht (pers. comm.)

Toe Head area Basin margin thickness 1.8 km	**Beara-Bantry area** Close to depocentre Thickness > 5 km	**Comments**
Strunian (Upper Devonian) Old Head Sandstone Formation		Only seen in the South Munster Basin
Toe Head Formation[Dh] 280 m	Toe Head Formation 110-474 m	Ballytrasna Fm. is the medial eqivalent of the distal Castlehaven Fm. & correlated with Castlehaven, Gun Point and Caha Mt. Fms. by Pracht (1997)
Castlehaven Formation[Ca,Bal,Der,Bar.] 750 m	Castlehaven Formation 0-250 m	
	Gun Point Formation 300-2500 m	
	Caha Mountain Formation[Al] 1500-2150 m	Fluvial sands
Sherkin Formation 1050 m		
	Slaheny Formation 0-300 m	
	Bird Hill Formation 0-500 m	
Base not seen		

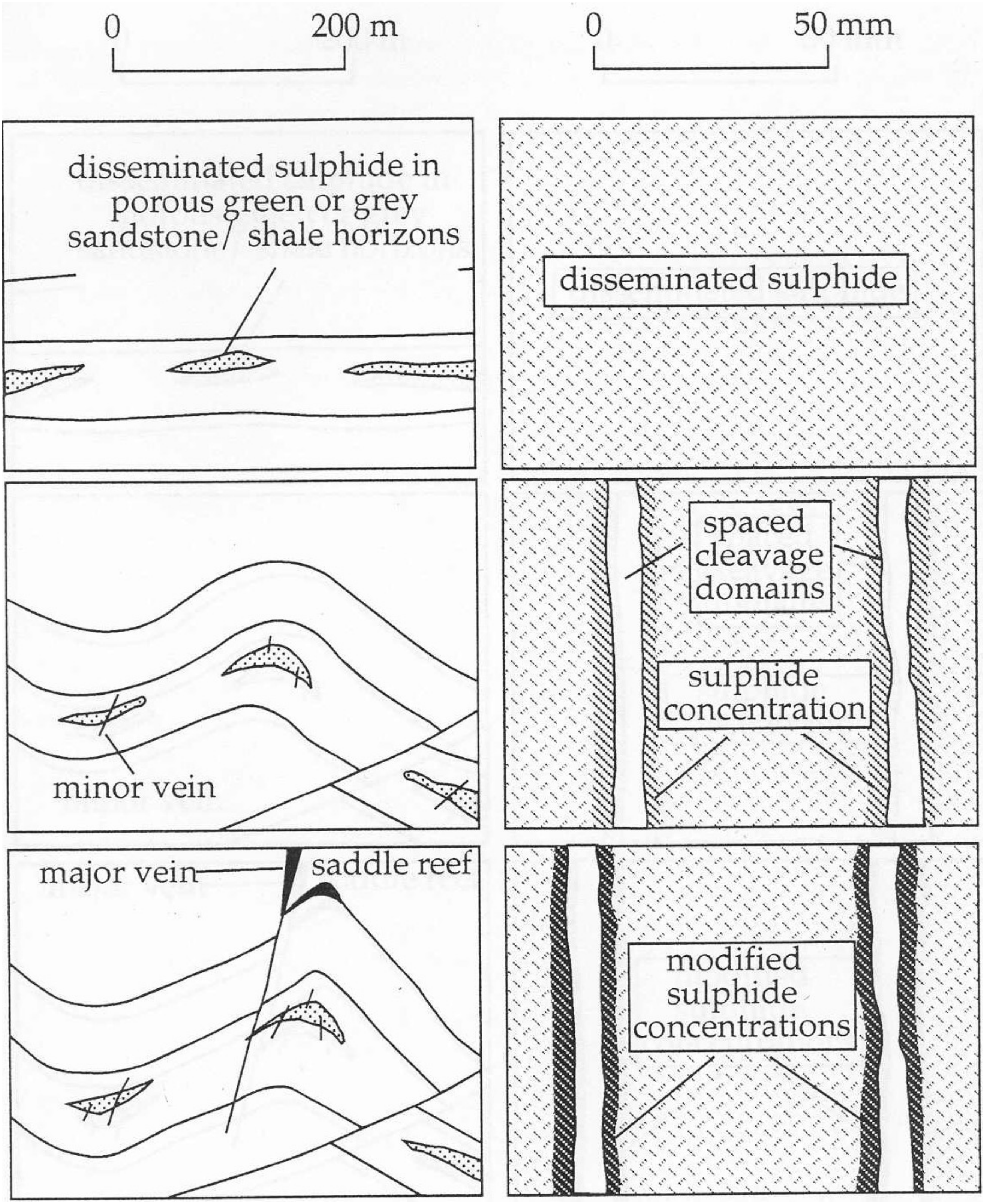


Figure 6. *Schematic sketch of the three different styles of copper mineralisation hosted in Red Beds; diagrams on the left show the overall setting of the deposits while those on the right show the specific location of mineralisation (after Ni Wen* et al *., 1999).*

Table 3. Mineral compositions mentioned in the text

Mineral name	Chemical composition	Chemical name
arsenopyrite	FeAsS	Iron-arsenic sulphide
barite	$BaSO_4$	Barium sulphate
bismuthinite	Bi_2S_3	Bismuth sulphide
bornite	Cu_5FeS_4	Copper-iron sulphide
boulangerite	$Pb_5Sb_4S_{11}$	Lead-antimony sulphide
bournonite	$CuPbSbS_3$	Copper-lead-antimony sulphide
calcite	$CaCO_3$	Calcium carbonate
chalcocite	Cu_2S	Copper sulphide
chalcopyrite	$CuFeS_2$	Copper-iron sulphide
covellite	CuS	Copper sulphide
djurleite	$Cu_{1.96}S$	Copper sulphide
dolomite	$Ca,Mg(CO_3)_2$	Calcium-magnesium carbonate
galena	PbS	Lead sulphide
hematite	Fe_2O_3	Iron oxide
idaite	Cu_3FeS_4	Copper-iron sulphide
lollingite	$FeAs_2$	Iron arsenide
marcasite	FeS_2	Iron sulphide
molybdenite	MoS_2	Molybdenum sulphide
pyrite	FeS_2	Iron sulphide
rutile	TiO_2	Titanium dioxide
siderite	$FeCO_3$	Iron carbonate
sphalerite	Zn(Fe)S	Zinc (iron) sulphide
tennantite	$(CuFe)_{12}As_4S_{13}$	Copper-iron-arsenic sulphide
tetrahedrite	$(CuFe)_{12}Sb_4S_{13}$	Copper-iron-antimony sulphide
wittichenite	Cu_3BiS_3	Copper-bismuth sulphide

Lead-zinc Deposits of the Irish Midlands Hosted by Carboniferous Carbonates

There are a number of lead-zinc deposits within Lower Carboniferous carbonates in the Irish Midlands (Fig. 7). These range in size from the world-class Navan deposit, which contains more than 70 million tonnes of ore (Table 4) to numerous smaller deposits of less than 1 million tonnes of ore. Mining of these deposits generally dates from the mid 1960s, although records indicate that mining at Silvermines may date as far back as the ninth century.

Within these deposits the principal ore minerals are sphalerite, galena, pyrite and marcasite. Barite is widespread and in some places has been the major economic resource (Table 4). Where copper occurs, it is generally as chalcopyrite. Most of the mineralisation is restricted to carbonate host rocks of the Navan Group and Waulsortian (Fig. 4), although there is a general trend for the host rocks to become progressively younger towards the north. Broadly, there are three different groups of deposits, distinguished by their style of mineralisation (Johnston, 1999):

Table 4. Tonnages and grades of selected ore deposits of the Irish Midlands; other localities had a total tonnage of less than 1 million tones of combined ore (data from Johnston, 1999)

	Total tonnes ore	Zinc %	Lead %	Silver g/t	Others	Discovery
Navan	>70 Mt	10.1	2.6	3.5		1970
Lisheen	>20	12	1.5	32		1990
Silvermines	17.7	6.4	2.5	23		1963
Tynagh	9.9	5.84	0.42	78	8.3 barite	1961
Galmoy	6.7	10.9	1.0			1986
Aherlow	6			33	0.9 copper	1965
Magcobar	5				85 barite	1959
Mallow	4.2	7.7	1.0	27.5	0.7 copper	1973
Harberton	3.9	8.1	1.2			1975
Gortdrum	3.8			23	1.2 copper	1964
Tatestown	3.6	5.3	1.5	37		1975
Ballinalack	3.5	5.9	1.1			1969
Rickardstown	3.5	2.2	1.1			
Oldcastle	3.0	4.3	0.6			1976
Keel	1.9	7.7	1.1	39.6		1962
Garrycam	1.4	2.7	0.2		36.1 barite	1975
Abbeytown	1.1	3.8	1.5	40		1785
Courtbrown	1.0	3.5	2.0	14		1980

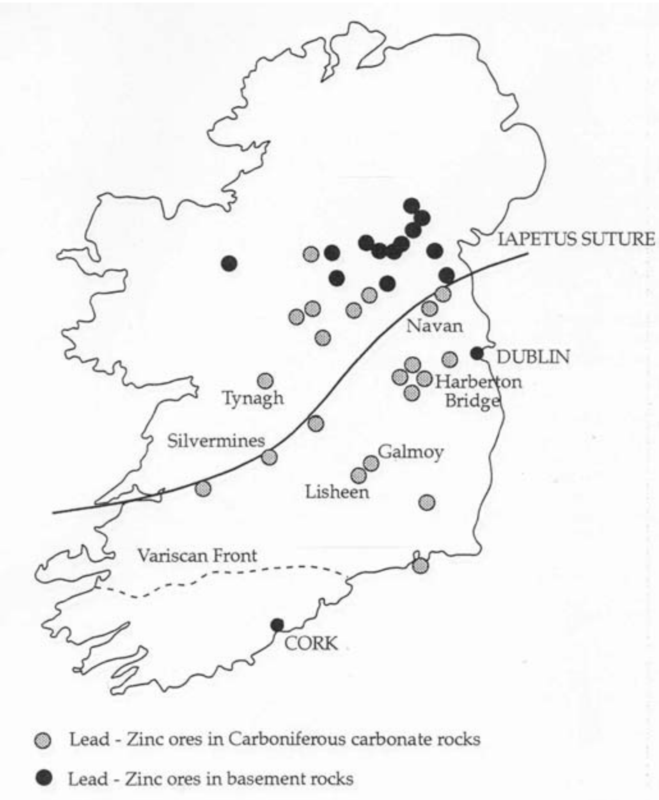


Figure 7. *Map showing significant lead-zinc deposits of the Irish Midlands in both Carboniferous carbonates and basement hosts. The major producing mines given in Table 4 are named. The position of the Variscan Front is based on recent seismic evidence given in Masson* et al. *(1998).*

(1) ***Midlands Province Navan Group stratabound ores***: (e.g., Navan, Tatestown, Oldcastle). In this style of deposit, the ores occur as elongate lenses within carbonates, parallel to the bedding planes, and are therefore known as stratabound deposits (Fig. 8a). Navan is the most important of the stratabound deposits and supports the largest zinc mine in Europe. The main ore body consists of 5 elongate lenses, 0.3-4 m thick, stacked one upon the other and terminating against faults. The main ore replaces the 'Pale Bed', with minor ore horizons hosted by the overlying Conglomerate Group. The maximum total thickness of the ore body is 100 m. High-grade ore horizons are formed at the contact between limestone and overlying muddy dolomite with sulphides deposited in open spaces. The ore minerals are sphalerite and galena in a 5:1 ratio, with accessory silver and bournonite. Pyrite and marcasite are subordinate in the Pale Beds, but dominate in the Boulder Conglomerate (Anderson *et al*, 1998). Development of the ore body began in 1973 and production started in June 1977. About 2.6 million tonnes are mined annually and in 1998 the mine produced 141 000 tonnes of zinc concentrate and 34 700 tonnes of lead;

(2) ***Limerick Province Waulsortian-hosted ores associated with dolomitic breccias:*** Lisheen, Silvermines, Tynagh and Courtbrown are the principal deposits showing an association of mineralisation with Waulsortian mudmounds. Dolomitisation is an important part of hydrothermal alteration, which has resulted in extensive brecciation and replacement of the original carbonate, so that the ores occur in the breccias as cavity-fill mineralisation at the base of carbonate mud mounds. At Lisheen (Fig. 8b), individual sulphide lenses vary from <0.5 to >30 m, which thicken and increase in ore grade southwards towards the normal faults at a depth of 170-210 m below surface. The main ore minerals are pyrite-marcasite-sphalerite and galena with minor chalcopyrite, tennantite, silver, arsenopyrite and lead sulphosalts. The location of ore deposition was controlled by faults that channelled the upward movement of mineralised fluids. Ores were deposited in cavities in breccia, as bedding-parallel lenses by replacement of carbonate, and as an infill to veins. The hydrothermal alteration cuts across dolomitised Arundian rocks and ores replace breccias that had fractured already consolidated carbonates, so mineralisation must have occurred significantly after the host rocks were deposited.

At Silvermines (Fig. 8c), the geology and ore distribution is also dominated by a complex east-northeast oriented fault system, locally known as the Silvermines Fault, but widely regarded as part of the Iapetus suture. There are two ore zones: an *Upper Zone* – in which ores occur in irregular stratiform lenses, up to 35 m thick, deposited at the base of the Waulsortian in troughs between knolls of reef limestone. Ores comprise massive pyrite at the base, with massive barite (locally haematitic), siderite, and variable base metal sulphides. In the *Lower Zone,* the ores occur in cavities and fractures in the Lower Dolomite breccia along faults and are regarded as a feeder to the upper zone. The ore minerals are sphalerite, galena and pyrite and minor chalcopyrite, arsenopyrite, tennantite, boulangerite and sulphosalts. Mineralisation also occurs above and below these horizons. At Magcobar (Fig. 8c), a barite body that is 31 m thick overlies the Waulsortian. A 1 m-thick layer of solid pyrite caps the barite. It is envisaged that the barite was deposited in basins on the Carboniferous seafloor, as hot hydrothermal fluids mixed with brine pools (Mullane and Kinnaird, 1998). A similar process is now occurring on the floor of the Red Sea; and

(3) ***Ores in discordant breccia pipes:*** These deposits are significantly different from others in the Irish Midlands, both because the ores occur in fractures and breccias that crosscut the bedding, and also the host rocks are much younger than in the other types of mineralisation. Deposits of this type include Harberton Bridge (Fig. 8d), Rickardstown, Keel and Abbeytown.

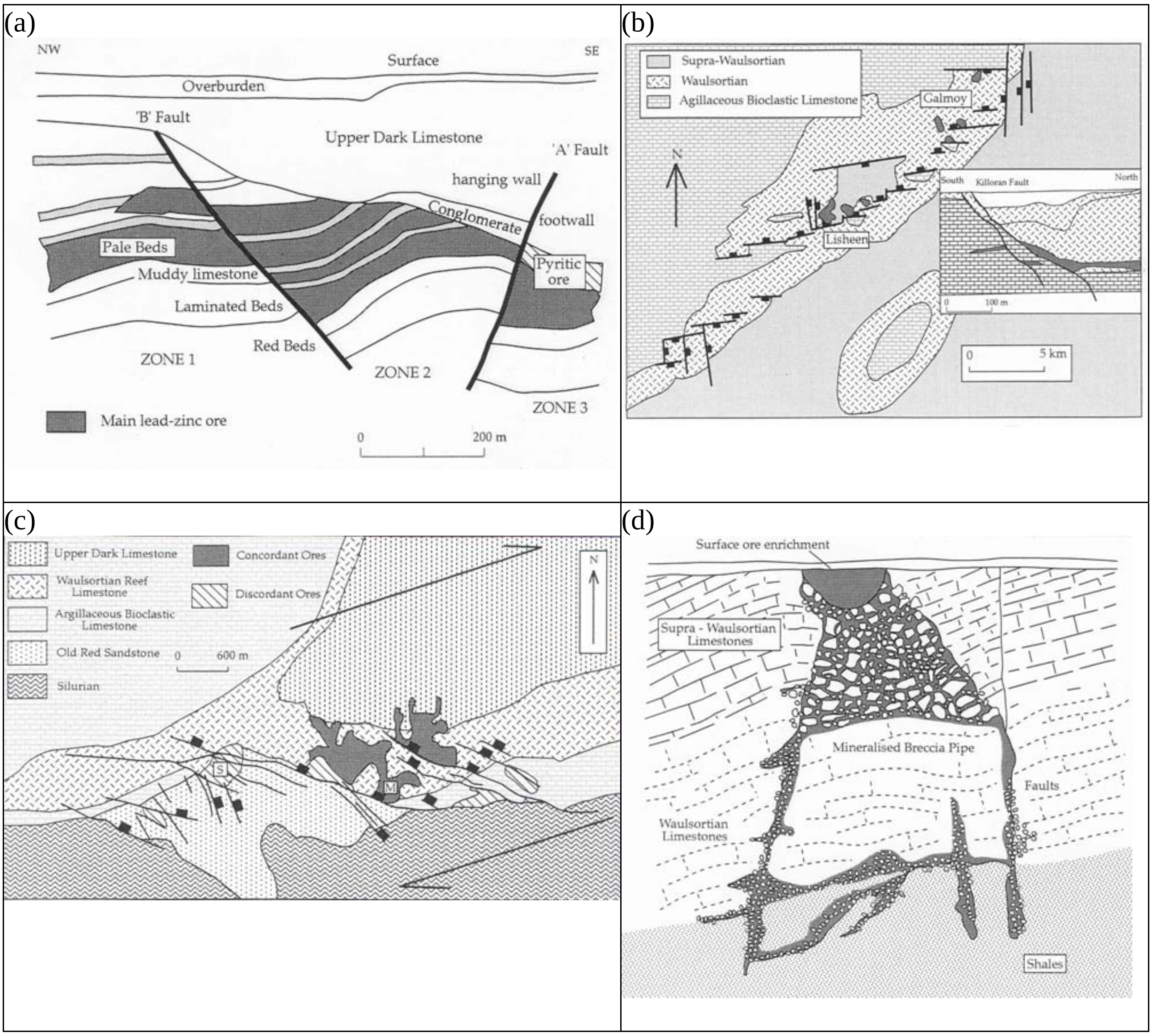


Figure 8. *Diagrams and maps showing the main styles of mineralisation of the lead-zinc deposits at: (a) Navan; (after Brown, 1979); (b) Lisheen: Sketch map in the Lisheen-Galmoy region showing the short fault segments of a major 40 km fault system that extends along the Rathdowney trend, a NE-SW trending structurally controlled belt of carbonate rocks. The fault pattern of E-W and N-S faults subdivides the ore body into >30 fault-bounded blocks. The segmented normal fault array controls the location of ore deposits, the majority of which occur on the north-side-down faults (after Johnston, 1999; (c) map of the Silvermines area (after Johnston, 1999). S=Silvermines M= Magcobar. Major arrows indicate dextral movement on the Silvermines fault system; and (d) schematic cross-section of Harberton Bridge; not to scale (after Emo, 1986).*

All the Irish Pb-Zn deposits are associated with faults. Most of the deposits, which lie to the north of the Iapetus suture, like Navan, are associated with southerly dipping faults, whilst the deposits to the south such as Silvermines, Lisheen and Galmoy, are associated with northerly dipping faults. These faults, as exemplified by the 'B' Fault in the cross-section of Navan (Fig. 8a) have a normal throw. The faults trend predominantly east-northeast or northeast and have exerted a major influence on sedimentation, hydrothermal alteration, dolomitisation and mineralisation. All of the faults have had some movement post mineralisation and at Navan a late set of faults exemplified by the 'A' Fault, are attributed to Variscan tectonism (Johnston *et al*., 1996).

Mineralised veins also occur in the basement beneath the mineralised Carboniferous beds and some of these are found in areas away from known carbonate-hosted mineralisation (Fig. 7). The ore-bearing assemblage in these veins is similar to the carbonate-hosted veins and both are believed to have formed at the same time. For example, in the Silvermines area at Shalee, veinlets of quartz and barite with minor sphalerite, galena, pyrite, arsenopyrite, lollingite, boulangerite, and chalcopyrite occur in simple NNW-trending veins cutting Silurian basement.

Models for the way in which the ore deposits formed remain controversial. There are two more popular models:

(1) as the crust stretched during the Carboniferous, faults allowed access of surface fluids deep into the earth where as they got hotter, metals were dissolved in the hot acid water and the fluids rose to the surface as metal brines (Russell, 1978, 1986) (Fig. 9a); and

(2) compression in the south, during Variscan plate collision, resulted in a regional flow of fluid through the porous Red Beds and major fracture zones, northwards into the Irish Midlands (Duane and De Wit, 1988; Hitzman and Beatty, 1996; Hitzman *et al*., 1998) (Fig. 9b).

One of the main differences between these two models is the role of the underlying lower Palaeozoic rocks. In the deep fluid convection model (Fig. 9a), fluids reached >200°C and derived most of their metals from the lower Palaeozoic rocks, whereas the topographically driven fluid-flow model envisages that the metals were derived from the Red Beds. Currently, the weight of evidence on the composition of fluids and lead-isotope evidence described later, coupled with the restriction of alteration in the underlying Red Beds to fault margins, tends to favour the model of deep circulating fluids during extension (Everett *et al*., 1999)

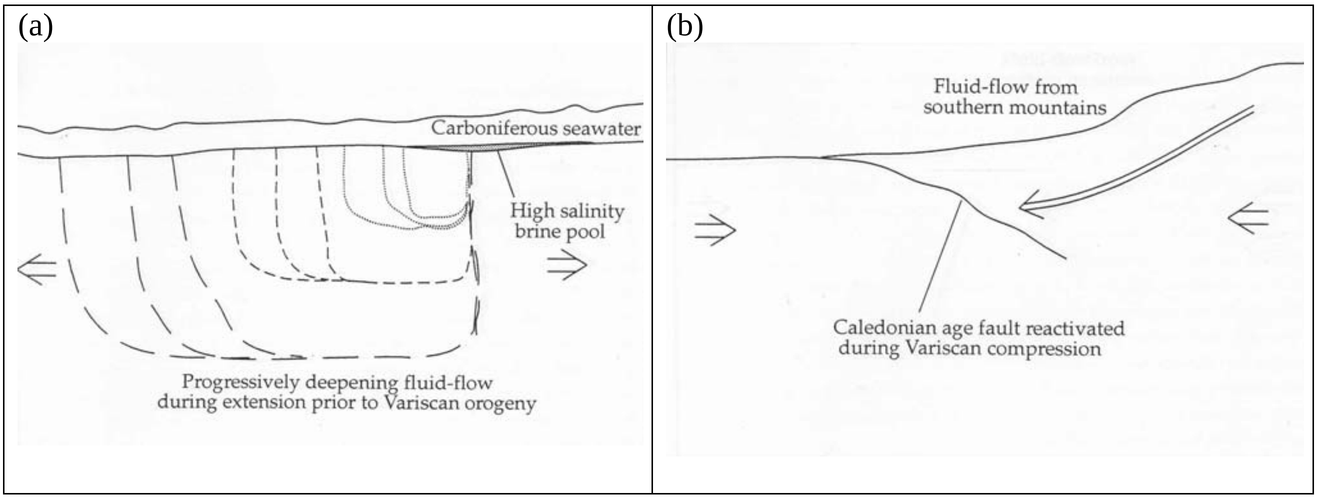


Figure 9. *Diagrammatic illustration of the two major models to explain the formation of the Irish lead-zinc deposits: (a) Carboniferous extension and deep fluid circulation (after Russell, 1978); and (b) fluid flow during Variscan collision (after Hitzman* et al.*, 1998).*

Because of rivalry between these two models there has been extensive discussion as to the exact timing of the mineralisation, whether it was related to extension during Lower Carboniferous basin development, or to fluid flow during Variscan crustal shortening. A maximum age of mineralisation is given by the age of the host rocks to the ores. The majority of the deposits (Lisheen, Galmoy, Silvermines, Navan and Tynagh) occur within carbonates of Courceyan age, with the base of the Waulsortion mudbank limestones being a favoured place for concentrations of mineralisation. It is generally accepted that the discordant deposits, which extend into hosts above the Waulsortian (Harberton, Allenwood, Rickardstown), formed when the consolidated host rocks were brecciated. Navan is one of the few deposits for which a precise age has been suggested, with an age of late Chadian to early Arundian (345 Ma) proposed for the mineralisation (Anderson *et al*., 1998) although a post-Arudian age has been suggested by Peace and Wallace (2000). Uncertainties as to the precise timescale of the Irish Carboniferous rocks, coupled with analytical errors of radiometric dates for Irish mineralization, make an exact timescale difficult to produce.

Polymetallic Copper-silver-arsenic Deposits Hosted by Carboniferous Carbonates

Geographically situated between the Red Bed-hosted copper mineralisation of the southwest, and the economically important carbonate-hosted lead-zinc deposits of the Midlands, there are several small copper-silver deposits hosted within Carboniferous limestones (Fig. 5). As well as having an intermediate geographical position, they also display characteristics of both types of mineralisation. The composition of the copper ores, such as at Ross Island, are similar to those in the Red Bed mineralisation of the southwest, whereas the occurrence of lead and zinc, in a limestone host rock, has obvious similarities to the lead-zinc deposits of the Midlands. Three groups of copper-silver-arsenic deposits can be distinguished based on the assemblage of metals that occur, and the style of mineralisation:

(1) ***copper-silver vein deposits****;* an irregular network of cross-cutting carbonate veins associated with a breccia, carry copper and silver minerals ± mercury-arsenic-antimony. Ore minerals are characterised by chalcopyrite and tennantite near the surface, locally with mercury enrichment, and by disseminated bornite and chalcocite at depth. The most important of these deposits is Gortdrum (Fig. 10a), which was exploited for copper and mercury from 1964 to 1975 (Thompson, 1966; Steed, 1986). Similar mineralisation occurs at Aherlow, Ballyvergin and Mallow;

(2) ***copper-arsenic bedded ores:*** occur within specific Carboniferous carbonates, the Ballysteen limestone (Fig. 10b). Horizons of copper or lead-zinc sulphides, carry minor iron, cobalt, nickel, arsenic and silver ores. The deposits are small and occur at Ross Island, Crow Island and Muckross (Fig. 11), and appear to form an “intermediate” type of deposit between the copper-silver vein deposits of Group (1) and the lead-zinc deposits of the Irish Midlands. On the Muckross Peninsula, about 2.5 km south of Ross Island, stratabound ores are confined to a particular horizon close to a shale unit within the Ballysteen Formation; and

(3) ***copper-arsenic vein deposits;*** thin cross-cutting veinlets and disseminations carry copper and arsenic minerals ± silver-molybdenum, cobalt and nickel. The deposits are small and well developed at Western Mine on Ross Island and Ardtully (Kenmare Valley). The veins crosscut the bedded ores and are clearly later than the stratabound mineralisation. Nowadays, there is almost no trace of the original copper mineralisation at Ardtully, except some spoil-heap material, although Cole (1922), reported eight copper lodes with tetrahedrite and bornite and four lead lodes in a group of mines that produced 59 tons of ore with 4% copper in 1911.

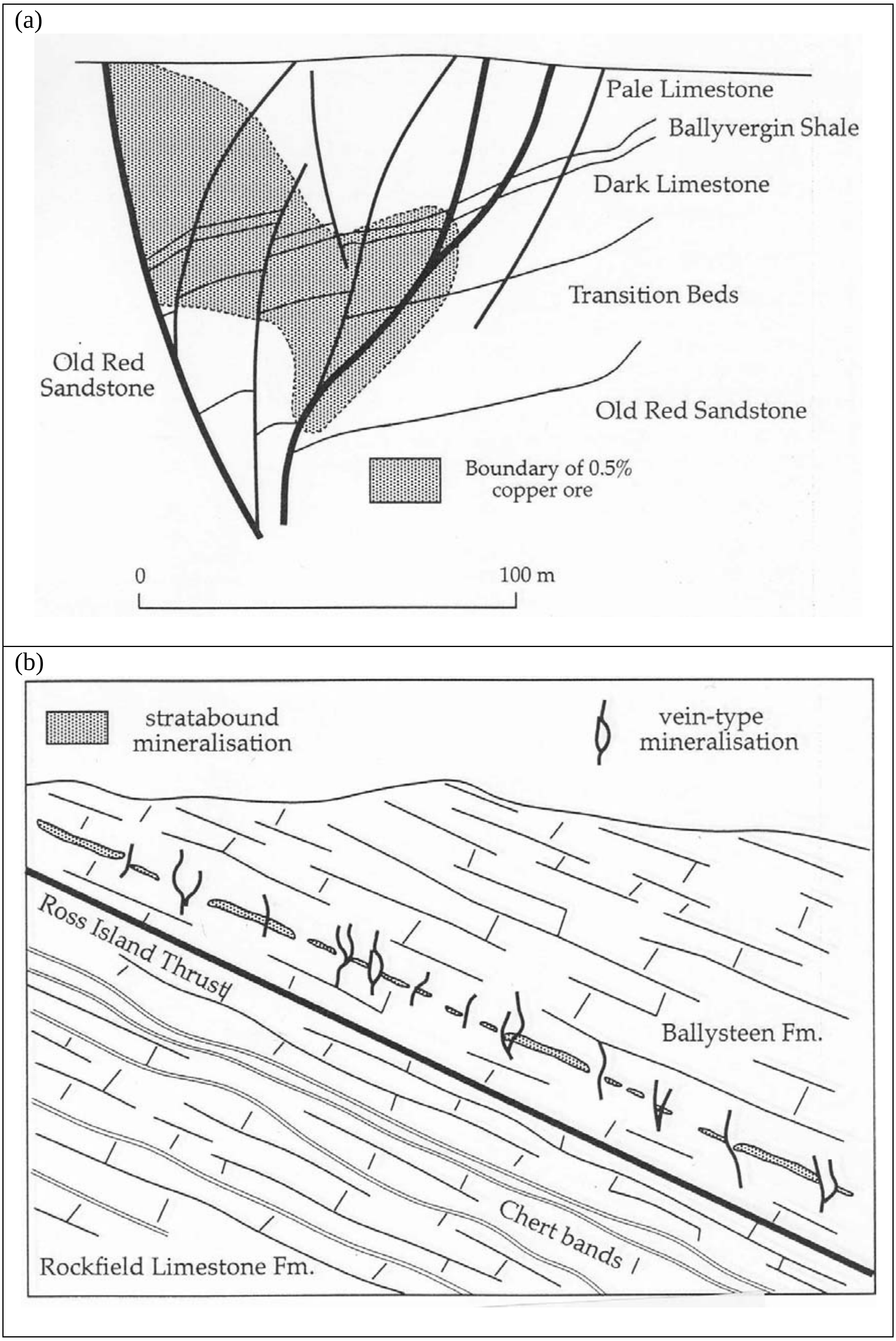


Figure 10. *Sketch diagram showing the styles of mineralisation of the copper-silver-arsenic occurrences: (a) Gortdrum showing extensive faulting of the deposit (after Steed, 1986); (b) Ross Island with stratabound mineralisation above the thrust in the Ballysteen Formation, which typifies Blue Hole, and vein-type mineralization, which is characteristic of Western Mine.*

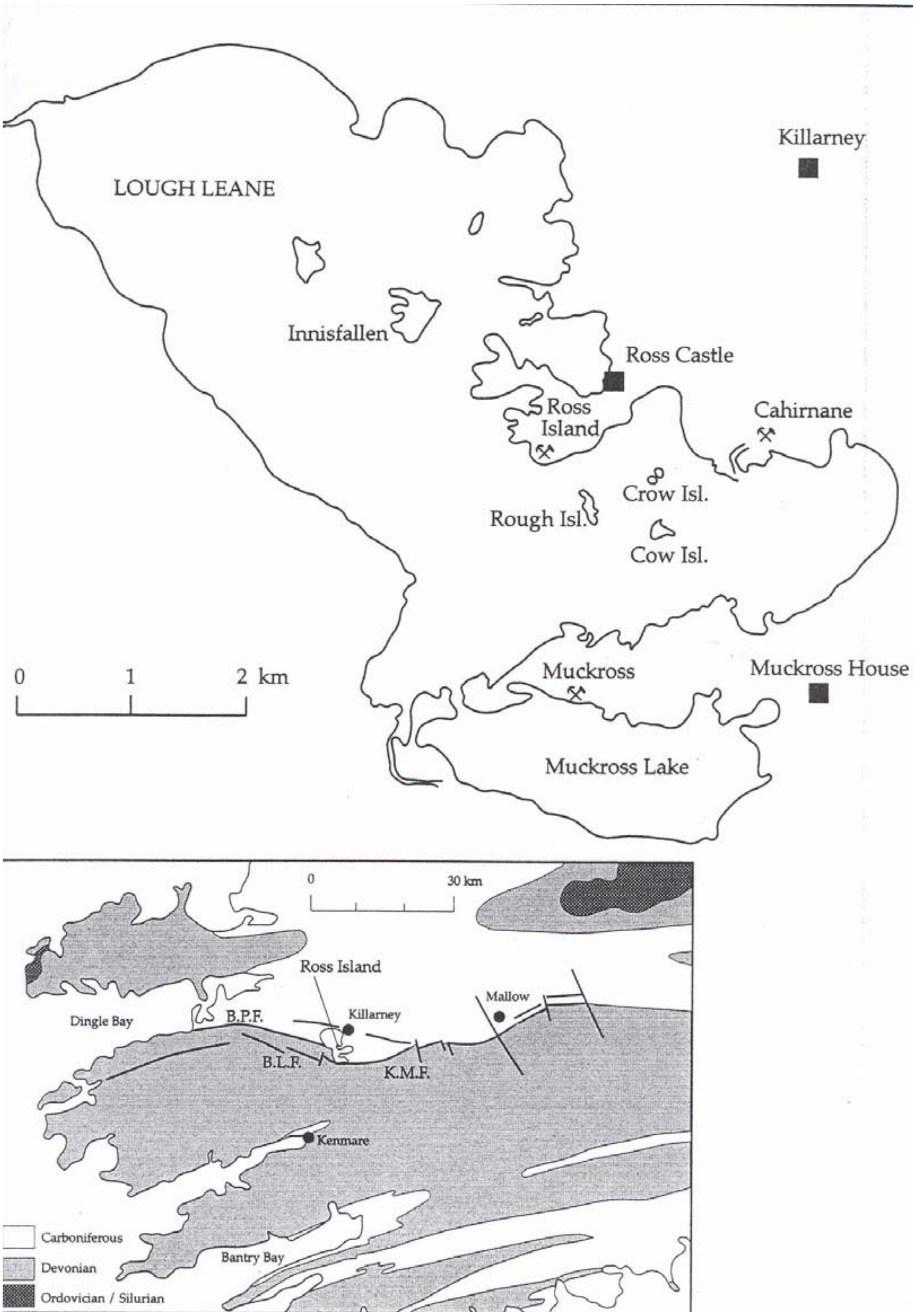


Figure 11. *Map showing the regional location of Ross Island, Muckross and Crow Island. Inset shows the simplified regional geology. Abbreviations used are: B.P.F., Benson's Point Fault; K.M.F., Killarney-Mallow Fault; and B.L.F., Black Lake Fault (after Ford* et al.*, 1991; Meere 1995a).*

GEOLOGY OF ROSS ISLAND

Introduction

The metal mines of the Killarney area lie close to the junction between two major rock types. To the south and west the mountains are composed of Devonian sandstones, whereas to the north are the undulating lowlands that are underlain by limestones deposited during the Carboniferous. These limestones are well exposed around the old mines on Ross Island, a promontory on the shores of Lough Leane southwest of Killarney (Fig. 11). The first major geological study of Ross Island was undertaken by Weaver in 1838 and Du Noyer mapped the whole island in 1861. Since then it has been mapped geologically as part of various postgraduate theses and more recently described by the Geological Survey of Ireland (Pracht, 1997). Although a small area, Ross Island is geologically complex. Du Noyer commented in 1861 - *"it is difficult to define any one geological horizon in a set of rocks so contorted as those of Ross Island"*. A geological map of Ross Island compiled for this project is shown in Figure 12.

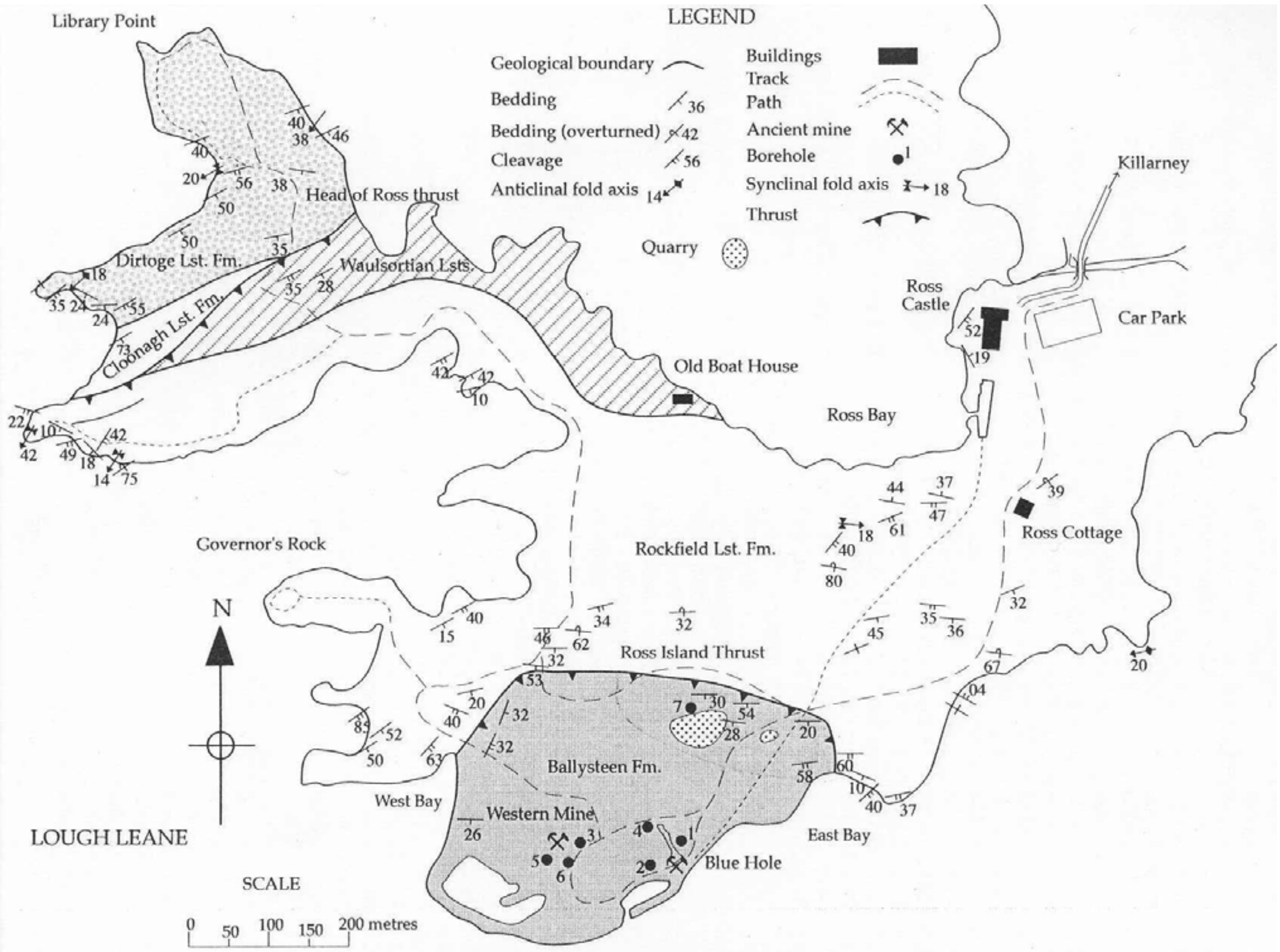


Figure 12. *Geological map of Ross Island showing the various rock types, the location of the Head of Ross and Ross Island thrusts, and the position of boreholes drilled as part of the study.*

Table 5 Lithostratigraphy of the Munster Basin in the Killarney area

Geological Survey Nomenclature (Pracht, 1997)	Price (1986)	Age based on conodont data Price (1986)
Dirtoge Lst. Fm.	Reen Lst.and Chert Fm.	Asbian
Cloonagh Lst. Fm. Cracoean Reef Mbr.	Leane Dolomite Fm.	Asbian (although characteristic Asbian species not found)
Rockfield Lst. Fm.	Carriganforta Chert Fm.	Chadian - Arudnian
Waulsortion Lsts.	Waulsortian Fm.	Courceyan - Chadian
Victoria Point Mbr. Ballysteen Fm.	Victoria Point Mbr. Ballysteen Lst. Fm. Colleen Baun Lst. Mbr.	Courceyan

Stratigraphy

The area is composed of a series of Courceyan limestones, which were deposited on the northern shelf of the Munster Basin. These are remarkably constant across most of southern Ireland (Pracht, 1997) and were laid down at a time around 350 Ma when the south of Ireland was covered by a warm tropical sea. The limestones of Ross Island have been divided into different formations according to the normal geological conventions. These have been correlated with other similar rock types on a regional basis in Table 5. For Ross Island, the most detailed work is in a postgraduate thesis by Price (1986). For the regional synthesis, the nomenclature adopted by the Geological Survey in the regional geological description is most useful (Pracht, 1997). The term micrite describes those limestones that have mud-sized grains, whereas a packstone is a limestone that has self-supporting coarser fragments with finer lime mud in the matrix.

Ballysteen Formation

The Ballysteen Formation, which is at least 40 m thick, is well exposed on the south of Ross Island especially around the Bronze Age mines. The limestone is generally poorly bedded and consists of dark, blue-grey packstones, sometimes with visible fragments of crinoid stems (sea lilies) as seen on the foreshore of the south of Ross Island. Bedding is defined locally by continuous parallel surfaces that have been accentuated by weathering, with individual beds 20-40 cm in thickness. Bedding dips gently to the south at 20-30°. Additional rock types are seen in the borehole core, most notably a brown and locally silicified dolostone (magnesian carbonate) with abundant relic fossil fragments.

In thin section, at a magnification of x 40 under the microscope, flattened and deformed crinoid segments are abundant with other fossil fragments, mainly corals and brachiopods, with some conodont microfossils less common. It is apparent that the Ballysteen Formation has undergone a widespread early dolomitisation, whereby the original calcium carbonate has been replaced by a calcium magnesium carbonate and, locally, the fine-grained matrix has recrystallised to become slightly coarser (Nex *et al*., 2001). A later generation of dolomite is associated with chalcopyrite and tennantite mineralisation (Ixer, pers. comm.). The Ballysteen Limestone Formation at Ross Island has been assigned a mid-Courceyan age based on conodont data (Ps. multistriatus conodont Biozone; Jones and Somerville, 1994).

Waulsortian Limestones

The Waulsortian Limestone is of limited extent and occurs as small isolated outcrops within the core of an anticline north of the old boathouse, on the north side of Ross Island (Fig. 12). These represent mud mounds formed on the floor of a clear warm sea. It is a uniform pale- to dark-grey, unbedded micrite, with very minor crinoid debris and is distinguished from the Dirtoge Limestone Formation to the west and the Rockfield Limestone Formation to the south, by its colour and textural uniformity and lack of cherty horizons.

Rockfield Limestone Formation

The Rockfield Limestone Formation, which is at least 60 m thick, is extensively exposed on Ross Island and is characteristically a pale-weathering, well-bedded, nodular packstone typified by lenses of chert and sometimes by laterally persistent chert bands up to 5 cm thick. The formation forms the foundations of Ross Castle where it is well-bedded with individual carbonate beds 10-20 cm thick, separated by dark-grey shale and chert horizons (Fig. 13). The chert is commonly a dark blue-grey, but can be pale cream, or at Governor's Rock, it is a deep red colour. Core logs show that the number of chert bands is fewer at the top of the succession. Non-siliceous, dark, elongated, pea-sized inclusions up to 5 mm in length, in a lighter groundmass occur in places, particularly in East Bay. The Rockfield Limestone Formation is unfossiliferous in hand specimen, but microscopic examination of thin sections shows that conodont microfossils are locally abundant (Price, 1986).

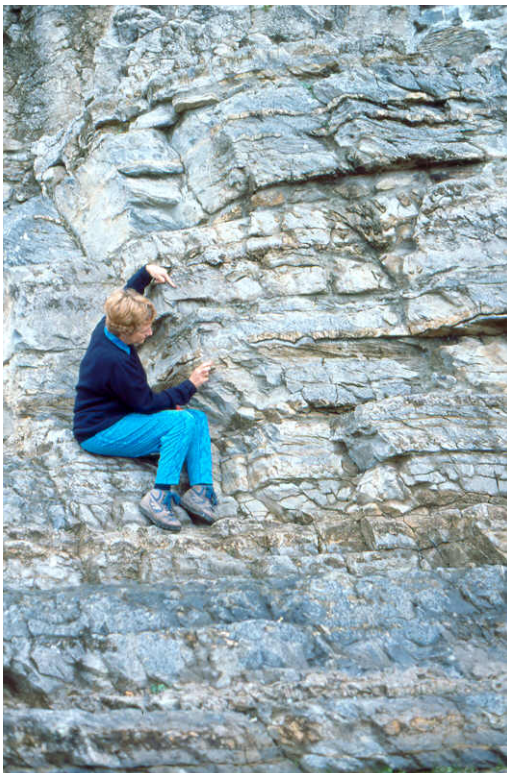


Figure 13. *Rockfield Limestone at Ross Castle, showing some of the darker shale bands, for example by author's right hand.*

In thin section, at a magnification of x 40, the Rockfield Limestone Formation can be seen to consist of more of the finer-grained component and more replacement of the carbonate by silica than the Ballysteen limestone. It is recognisable by a fine-grained carbonate, replacing chert, and by a honeycomb of dolomite-calcite veinlets cutting chert-rich areas. Post-consolidation alteration effects of dolomitisation, silicification and calcite recrystallisation are widespread. Dolomitisation occurs by replacement of the original calcium-carbonate fine-grained matrix by dolomite, as coarse-grained dolomite crystals growing in micro-cavities in micrite, or as rims around chert nodules. Silicification occurs by the growth of quartz grains in the matrix, or the development of quartz patches at the junctions between sparite- and micrite-rich areas or as radiating chalcedony (Ixer, pers. comm.).

Cloonagh Limestone Formation

The Cloonagh Limestone Formation is very limited in extent and can only be seen on surface on the shore south of the Head of Ross, within the hinge of an overturned anticline (Price, 1986). It is a homogeneous, pale-grey micrite, which is more massively bedded than the Dirtoge Limestone Formation, having individual beds 10-50 cm thick. It is characterised by a pale-pink weathered surface and is variably dolomitised. Although the contact with the underlying Rockfield Limestone Formation is not well exposed, Price (1986) suggested that there is a thrust fault between the two formations.

Dirtoge Limestone Formation

The Dirtoge Limestone Formation occurs on surface at the northwestern end of Ross Island around Library Point (Fig. 12). It is a mixture of pale-weathering packstone with minor lenses of pale- to dark-grey chert in a darker matrix. The chert often forms a series of elongate lenses rather than a continuous bed. The rocks look similar to those of the Rockfield Limestone Formation, although the individual beds are thinner. Bedding is prominent due to differential weathering of thin resistant horizons (typically 5-20 mm) separating the slightly harder carbonate beds that are 5-15 cm thick.

The depositional environment of these various limestones differed through the Carboniferous. The Ballysteen limestone was deposited in a subtidal zone of a tropical sea. As the shoreline moved northwards, Waulsortian mudbanks were deposited in a gradually deepening Carboniferous sea. The Rockfield limestone was deposited in Chadian to Arundian time on a shallow shelf, at the same time as the ‘Calp’ limestones were forming in deeper-water basins. Both the Cloonagh and Dirtoge limestones were formed in Asbian times as mud mounds, and the environments of deposition were probably similar to those during Chadian to Arundian times.

STRUCTURAL SETTING OF ROSS ISLAND

Structurally, Ross Island is complex and records a continuum of deformation from the effects of initial compression through folding, faulting and thrusting as Variscan compression continued. On a regional basis, large-scale east-west folds formed, and as these folds tightened, locked and then fractured, thrust faults developed as the crust continued to shorten. Some of these thrust faults have been interpreted as the original extensional faults on the margins of the Munster Basin that were reactivated during compression (Price and Todd, 1988; Meere, 1995a). Ross Island is situated north of the major Killarney-Mallow Fault, which has frequently been interpreted as the Variscan Front (Fig. 11). This fault zone also forms the boundary between two different structural zones, with extensive deformation to the south and less significant effects to the north (Cooper *et al.*, 1984).

The first effect of compression recorded at Ross Island was the formation of a spaced cleavage, observed in some rocks as a series of faint parallel lines at an angle to the bedding planes. As the rock was compressed by the tectonic forces, individual grains in the rock started to dissolve and the material moved and recrystallised in low-pressure areas. This formed irregular thin stripes in the rock that are perpendicular to the direction of greatest stress. It is difficult to appreciate these effects within the largely homogeneous Ballysteen Formation. In contrast, in the inhomogeneous Rockfield and Dirtoge Limestone Formations it is easier to observe the spaced pressure-solution cleavage because it is refracted between cherts, limestones and shale-rich beds. Cleavage disrupts the bedding and individual chert beds are now discontinuous and commonly form elongated pods (augen) parallel to the spaced cleavage and oblique to the bedding. The cleavage-bedding relationships within these formations are extremely useful as a way-up indicator of these rocks, since some of the beds have been overturned during folding (Fig. 14).

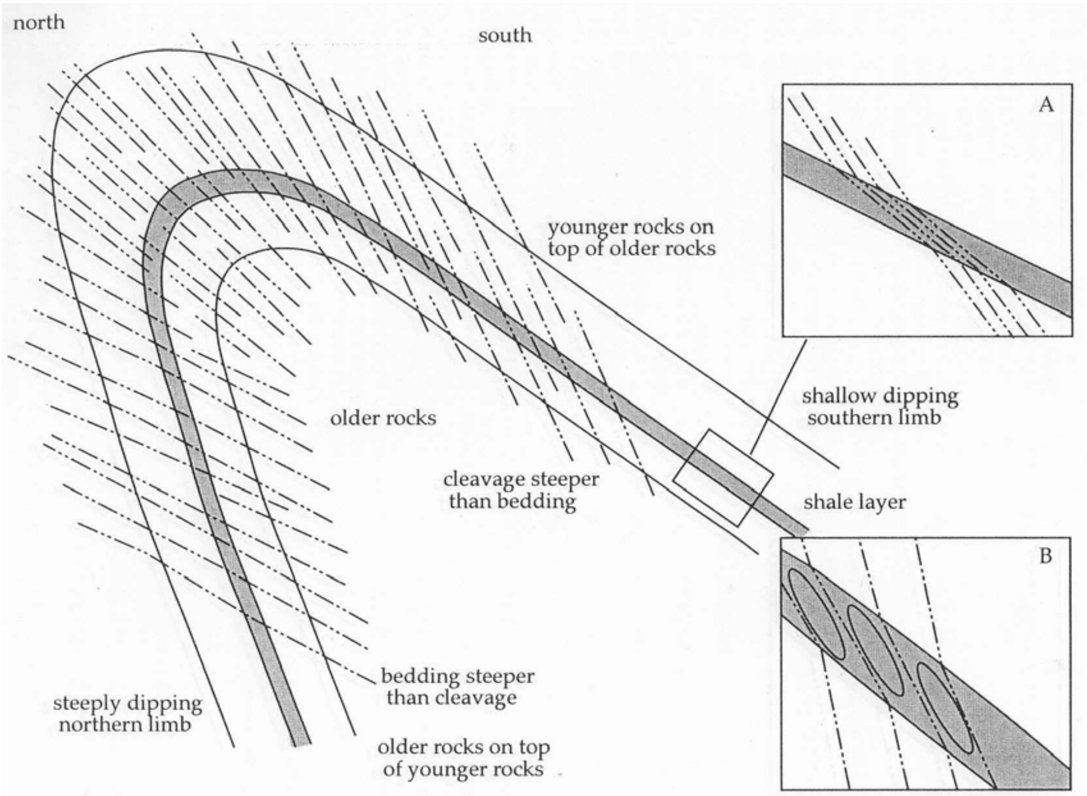


Figure 14. *Sketch of a moderately open fold with a shallow-dipping south limb and a steeply dipping overturned northern limb. Inset A shows how the cleavage is refracted between the limestone and a shale horizon. Inset B shows the development of lensoidal structures oblique to bedding in shale and chert layers.*

Minor folds seen in outcrop within the Rockfield and Dirtoge Limestone Formations are moderately open and asymmetric, although locally isoclinal with parallel fold limbs. Antiforms have steeply dipping overturned northern limbs (~ 80°) with southern limbs of such structures that are right-way-up, and of shallower dip (~ 30°). Folds are picked out by chert bands, which frequently show minor parasitic folds that are also asymmetric, and all folds verge to the northeast. Cleavage is axial planar to these folds and the fold axes plunge at a shallow angle (20-30°) to the southwest.

Two thrust faults occur on Ross Island; the Head of Ross Thrust and the more southerly Ross Island Thrust. As Variscan regional compression continued, the early folds tightened and locked, some folds fractured and older rocks from the south were pushed over younger rocks to the north. The Head of Ross Thrust, has emplaced Waulsortian Limestones on top of Cloonagh Limestone and Dirtoge Limestone Formations (e.g., Wingfield, 1968; Price, 1986). Although exposures are poor in this area, and no drill core was available, lithostratigraphic correlation is possible and confirmed by the microfossil data of Price (1986).

The Ross Island Thrust is exposed both on the south shore of Ross Island and in an abandoned stone quarry (Fig. 12) and has also been identified and located in the seven drill cores from Ross Island. The Ross Island Thrust has structurally emplaced, dark, blue-grey Ballysteen limestone of Courceyan age, over younger, pale grey-brown Rockfield Limestone Formation of Chadian -

Holkerian age. Within the Ballysteen Formation, calcite veining generally forms a rectangular network (Fig. 15). However, closer to the thrust, veining increases in frequency, individual veins become thinner, parallelism of calcite veins increases, and a mylonitic and sheared appearance develops (Fig. 16). The asymmetry of the major folds, minor asymmetric chert lenses and shear bands indicate that the dominant sense of movement is top to the north, consistent with the interpretation of the structure as that of a thrust.

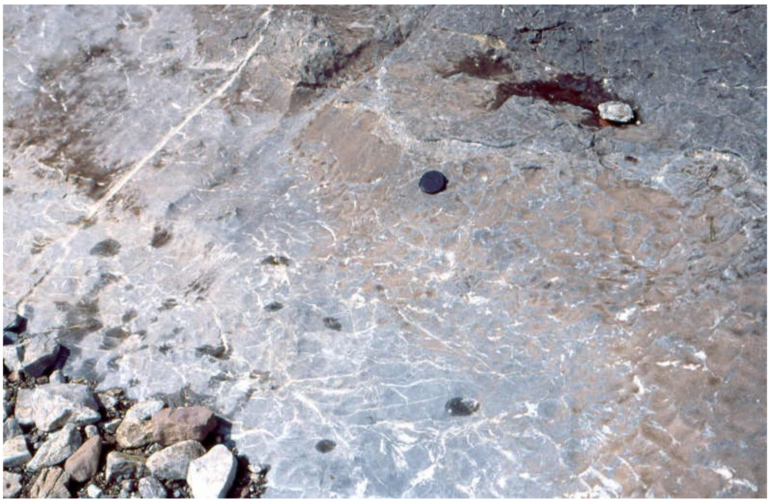


Figure 15. *Ballysteen limestone on the lake-shore showing a rectangular box-work veining.*

Figure 16. *Ballysteen limestone, in a disused quarry, showing the mylonitic appearance and parallelism of calcite veining close to the thrust.*

The thrust zone is exposed on shore in East Bay (Fig. 12) in streaky, somewhat greenish, heavily veined slabs at the water's edge. The zone can be traced northwards, through the intersection of paths with the old haul road, and then it more or less follows the line of the path towards Governor's Rock. At the intersection of the Library Point and Governor's Rock paths, it then curves southwards towards the coast. An exposure of streaky sheared rock was observed in Western Bay on one visit, although on subsequent occasions it was covered by pebbles or water. Mapping of rock outcrop of the various carbonate rock types, together with a record of the variation in abundance of veins and the style of calcite veining within the Ballysteen Formation, helped to constrain the thrust location on the ground, although it was only possible to locate its precise position by logging drill core.

CORE LOGGING

Seven diamond drill cores (47 mm diameter) comprising over 125 m of core material were obtained from Dr. W. O'Brien. Detailed logs of structural features, calcite veining and mineralisation of the two lithologies were made and the location of the thrust plane noted as shown in diagrammatic form in Figure 17. These cores were taken in the vicinity of the old mines and comprise Ballysteen and Rockfield limestones (Fig. 12). In all but one of the cores the distinction between the pale grey-brown Rockfield Limestone Formation and darker blue-grey Ballysteen Formation was easily made both on visual inspection of the core and in thin section under the microscope. However, in borehole 7 an indeterminate lithology was observed at 3.5 m depth that could not be identified as either Rockfield Limestone Formation or Ballysteen Formation. It comprises unmineralised, finely laminated, micritic limestone with minor chert altering to micrite, which has some affinity with the Rockfield Limestone Formation, but the carbonate veining in the chert which characterises the Rockfield limestones is absent and instead sparite like that seen in the Ballysteen limestone occurs.

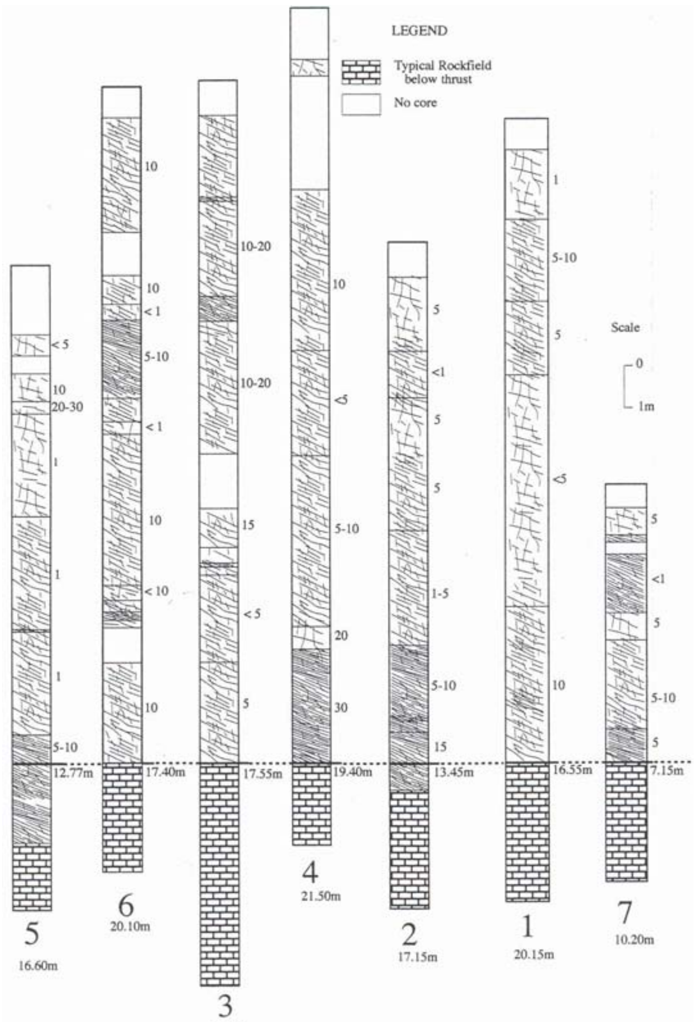


Figure 17. *Logs of the seven borehole cores from Ross Island showing variation in the veining and fabric within the two lithologies, Ballysteen limestone occurs above and Rockfield limestone occurs below the thrust plane. The thrust plane is shown by a thick line with depths to thrust plane shown to the right of the column. However, although actually shown as a horizontal line in the diagram for simplicity, note that the thrust plane in each core is parallel to the veining and structural fabric. Other figures to the right of the column are the percentage of carbonate veins. Length of core is indicated by numbers below the log in metres. The location of these cores is shown on Figure 12.*

In the core the thrust plane was identified as the junction between two dissimilar lithologies and is parallel with the early spaced cleavage developed prior to folding, which is present in both rock types and also with the calcite veining within the Ballysteen Formation. The parallelism of veining is particularly noticeable within 0.5m of the thrust plane. Above the thrust, the fabric of the Ballysteen limestone is defined by flattened crinoid ossicles and elongate quartz, together with angular stylolites, which are generally parallel to the plane of flattening. Samples from cores 3 and 4, close to the thrust plane have a streaky mylonitic appearance due to intense ductile deformation within this zone. Below the thrust, the main fabric in the Rockfield Limestone Formation is defined by original chert and micrite bands, and any tectonic fabric is less obvious except in cores 2 and 5, although flattening of crinoids has always occurred. Elongation and stretching of the carbonates during thrusting has either eliminated the Waulsortian Limestone from the typical carbonate sequence, or has obscured the lithological characteristics of the limestones close to the thrust plane. Within borehole 7, the presence of an indeterminate lithology at 3.5 m depth described above, suggests that the lithology just above the thrust plane could be attenuated Waulsortian, or may be Ballysteen or Rockfield limestones, whose normal characteristics have been obscured during thrusting.

A combination of field mapping and core logging has shown that the location of the Ross Island thrust is parallel both to the prominent pressure-solution cleavage and the southerly dipping limb of an asymmetrical anticline and is characterised by extensional microstructures in thin section and the stretching and rotation of calcite veins close to the thrust plane (Fig. 18). Thus, the sequence of events is formation of pressure-solution cleavage, initiation of folding, calcite vein development, followed by thrusting (Fig. 19a-d). It is concluded that the formation of this thrust is controlled, at least in part, by the asymmetric fold structures developed earlier in the Variscan deformation, rather

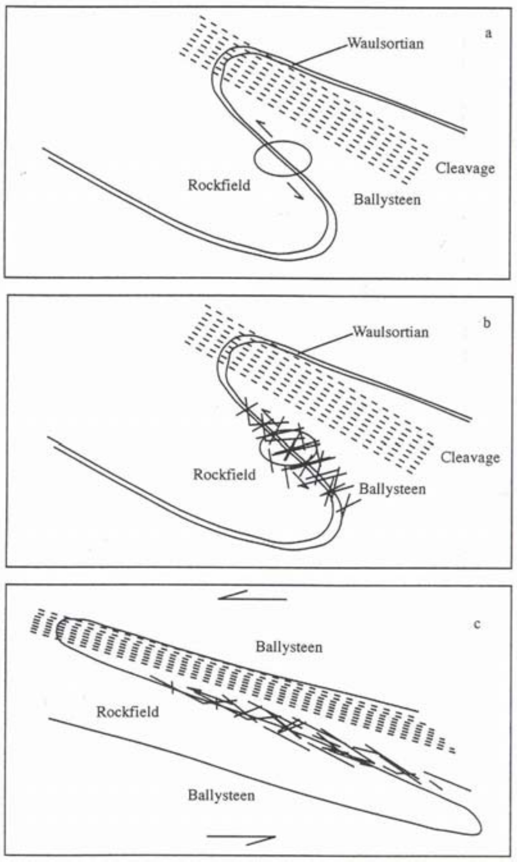


Figure 18. *Diagram showing the possible evolution of the Ross Island thrust: (a) asymmetric folding with extension on fold limbs; (b) development of calcite boxwork veining; and (c) shearing of the fold limb with localised extension, attenuation of calcite veins, and the formation of a ductile thrust (Nex* et al., *2001).*

than along pre-existing faults as is more common in the Munster Basin. The Killarney-Mallow Fault Zone, the major extensional fault delimiting the northern margin of the Munster Basin (Price and Todd, 1988), that was reactivated during Variscan compression as a thrust (Meere, 1995a), features Devonian sandstones emplaced on top of Carboniferous (Namurian) shales and sandstones (Pracht, 1997), and has a significant topographic expression. In contrast, on Ross Island, thrusting occurs within limestones of Carboniferous age and has little if any topographic expression, and thus provides a structural contrast to the dominant style of deformation seen in the north of the basin.

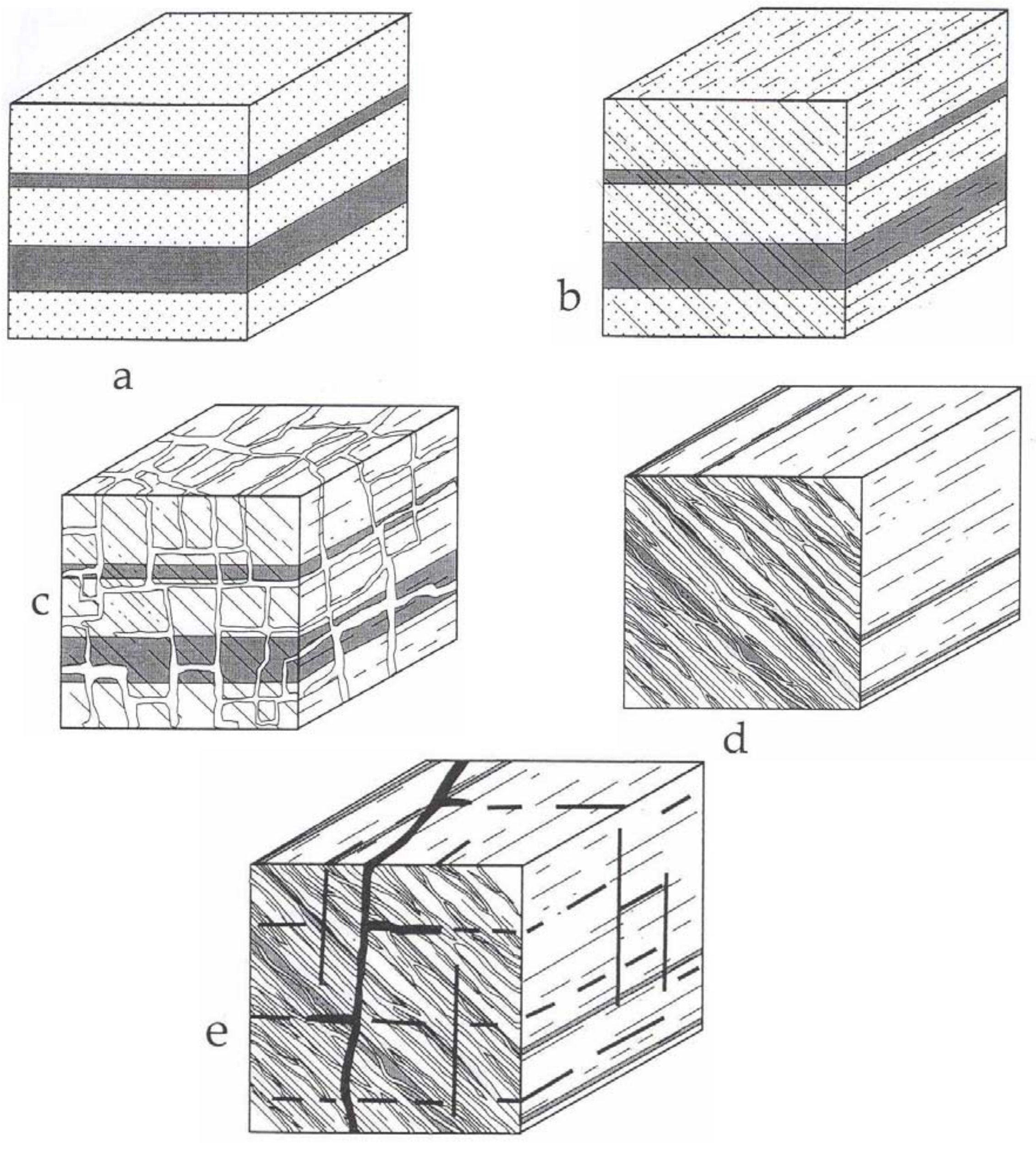


Figure 19. *Diagram showing the formation of the different stages of mineralisation seen in limestone-hosted deposits of the Munster Basin: (a) metals were disseminated in the Ballysteen limestone or accumulated into beds of either lead-zinc or copper-iron sulphides; (b) as compression increased, individual grains in the rock were dissolved and re-precipitated in low-pressure areas to form a stripy, spaced cleavage, perpendicular to the direction of greatest stress. Ores were deposited as stringers and blebs along this spaced cleavage; (c) a network of calcite veins 1-2 mm thick, with quartz borders, contains a remobilised assemblage of ore minerals; (d)* d*uring folding and thrusting, veins were rotated into a subparallel alignment with the cleavage and*

further movement of metals occurred; and (e) further faulting and joint development formed minor rakes and localised concentrations of ore minerals, which post-dates thrust formation.

Studies of core material, which was not available to previous workers, has also shown that the mineralisation at Ross Island is restricted to the Ballysteen Formation and does not occur in the Rockfield Formation, and further, that it is unrelated to, and earlier than, thrusting and is associated with cleavage formation and calcite veining.

MINERALISATION OF ROSS ISLAND

Ross Island is one of several locations where mining is known to have taken place in the past. The two richest of these were at Ross Island and on the Muckross Peninsula, with smaller occurrences on Crow Island and nearby Cahirnane (Fig. 11). Copper has also been worked in the past at Ardtully in the Kenmare Valley. All five of these deposits occur in lower Carboniferous limestone and contain varying amounts of copper, lead, zinc, silver and cobalt. Ross Island was important for copper mineralisation in the earliest Bronze Age, *c.* 2400 years ago, when metal was first used in Ireland (O'Brien, 1995; Ixer and Budd, 1998, Ixer and Pattrick, 2003). Mining resumed there in the early Christian era around the eighth century AD. However, there was still sufficient copper remaining to produce 3220 tons of ore at a grade of 17.5% copper between 1804 and 1810 (Cole, 1922), and a further 1529 tons at 13.7% copper between 1827 and 1829 (Weaver, 1838). At Ross Island, mining during each of these periods focussed on copper-rich deposits that were found to extend to a maximum depth of 13-16 m along the lakeshore, as they could be mined with relative ease, water levels permitting. An artificial dam had to be constructed on the lakeshore to prevent the perennial problem of flooding. The mine workings survive today as large cave-like openings at Western Mine and as partly flooded excavations at Blue Hole (Fig. 20).

Figure 20. *Blue Hole Mine.*

In the 1820s, Weaver made a considerable effort to understand the subsurface geology north of the mine, which included the archaeological site. He sank 30 boreholes through the Ballysteen limestone (Blue Limestone) into the Rockfield (Siliceous Limestone), and cut trenches in the Ballysteen northwards almost to the Rockfield outcrop. In addition, a crosscut was driven from shaft number 8 in the Ballysteen limestone from which an exploration hole was then sunk in the Rockfield Limestone. Unfortunately for Weaver, these revealed no new information and the conclusion was that there was no further mineralisation beyond the precincts of the mine.

Because the mineralisation on Ross Island is restricted to small areas on the south of the island and on Crow Island (Fig. 11), which lie close to the Ross Island Thrust, most previous workers have assumed that the mineralisation was associated with thrusting, perhaps envisaging fluid flow along the thrust plane (e.g., Price, 1986). However, there is no mineralisation at the thrust plane in any of the seven cores. In the core material, only the Ballysteen Formation is mineralised and not the underlying Rockfield Limestone Formation, a feature also noted by Weaver (1838); indeed sulphides in the Rockfield are essentially restricted to small granules of pyrite, which formed during lithification of the original sediment (Ixer, pers. comm.). Remobilisation of sulphides in the Ballysteen Formation has concentrated ores along the spaced cleavages, with further redistribution during the formation of the calcite vein network. This evidence clearly suggests that a phase of mineralisation occurs during cleavage formation and calcite veining, both of which demonstrably predate the thrusting (Fig. 19).

A wide range of primary copper-iron-lead-zinc sulphides and sulpharsenides, together with minor cobalt and molybdenum mineralisation has been described from Ross Island and Muckross (Ixer and Pattrick 1995; Ixer and Budd, 1998; Moreton *et al*., 1998/9; Ixer, 2004), and the significant silver component may have been extracted in ancient times. The mineralisation occurs in two different styles and ages of formation, one the earlier bedded ores of Blue Hole and Muckross, the other the later cross-cutting vein deposits of Western Mine and Ardtully (Table 6).

Table 6 Descriptive details of the carbonate-hosted copper-polymetallic deposits in the Munster / Shannon Basin. Host rock lithology is Courceyan Ballysteen Limestone, the lateral equivalent of the Argillaceous Bioclastic Limestone in the Irish Midlands. Locations of the ore deposits are shown in Figure 5 (data from Ixer and Pattrick, 1995; Cole, 1922)

Location of Deposit	Characteristics of mineralisation
Ross Island stratabound ore at Blue Hole	Chalcopyrite-pyrite, with lesser amounts of galena and sphalerite and trace amounts of arsenopyrite, tennantite and marcasite. The ores are pyrite- or chalcopyrite-rich. They underlie sphalerite-rich banded ores that have galena- , chalcopyrite- or tennantite-rich bands. Pyrite, arsenopyrite and tennantite are present in minor to trace amounts.
Crow Island stratabound ore	Cu-As ± Zn, Pb, Co, Ni, Ag stratabound deposit characterised by chalcopyrite-tennantite-bornite and sphalerite-galena mineralisation, ± Fe, Co and Ni sulpharsenides. Mined for copper 1812 - 1813.
Muckross stratabound ore	Stratabound Cu-Pb-Zn with minor Co and Ag, Mo sulphides and sulpharsenides (Ixer and Pattrick 1995; Ixer and Budd 1998). Banded pyrite-chalcopyrite and sphalerite-chalcopyrite-galena ores with arsenopyrite and minor tennantite, cobaltite, molybdenite and stromeyerite Coarse-grained chalcopyrite-tennantite-arsenopyrite ores.The amount of arsenopyrite and its wide-ranging chemistry are noteworthy. Later cross-cutting chalcopyrite-tennantite.
Ross Island	Thin cross-cutting chalcopyrite-tennantite veinlets with minor copper- and nickel-bearing cobaltite and rare trace amounts of pyrite,

epigenetic veins at Western Mine	marcasite, arsenopyrite, molybdenite, bornite, galena, sphalerite and stromeyerite. Bunches of coarse-grained massive chalcopyrite-bornite/"idaite" and tennantite accompanied by minor to trace amounts of cobaltite, arsenopyrite, molybdenite, galena, sphalerite and pyrite.
Ardtully epigenetic veins	Veins of bornite-'idaite'- tennantite, chalcopyrite and trace amounts of cobaltite. Copper-dolomite association. Four lodes with galena (Cole, 1922)

Bedding-parallel Copper-arsenic Ores of Blue Hole

Bedding-parallel deposits occur as layers of ore within the Ballysteen Limestone Formation. On the Muckross Peninsula, about 2.5 km south of Ross Island, these stratabound ores can be seen on the shoreline to occur within a particular horizon close to a shale unit within the Ballysteen Limestone Formation, although at Blue Hole, no shale unit is apparent and only the limestone can be seen at the surface.

The Blue Hole Mine is situated close to the shore on Ross Island (Fig. 12). The upper cliff faces above the workings are moderately well bedded with individual beds 20-40 cm thick. On the western side of the excavations, close to the water level, horizons of yellow chalcopyrite-pyrite with minor galena and sphalerite and traces of arsenopyrite and tennantite, weathering to a rusty surface colour, pass up into banded, dark ore comprising sphalerite and galena with minor pyrite, chalcopyrite and traces of arsenopyrite and tennantite (Ixer and Pattrick, 1995). Much of the evidence of the original ore deposits has been flooded although loose specimens of the ore types can still be seen on the beach. The remaining evidence in the west rock face of Blue Hole is that individual horizons of these bedded ores are only a few centimetres thick, but little is known of their occurrence at depth, or in the surface area that has been mined out. Records suggest that all of the mineralisation lies close to the surface with a maximum depth of 20 m, which is consistent with a calculated depth of ~16 m for the Ross Island Thrust. Directly north of Blue Hole are other old workings, now also in-filled with water. These might lie along a fault plane, although it is difficult to prove.

Weaver (1838) also produced maps and sections for the similar deposits at Muckross, about 2.5 km south of Ross Island. These were worked in the mid-eighteenth and early nineteenth centuries before becoming exhausted in 1818. Mineralisation occurs in a thin, 10-50 mm layer with copper ores associated with arsenic-rich, dark-blue cobalt ore (erythrite). Mining reached depths of 60 m with reported grades up to 26.7% copper. The occurrence of lead-zinc mineralised horizons parallel to bedding in the host limestone at Muckross and Ross Island is similar to the style of lead-zinc occurrence in the Irish Midlands, and also the host limestones are of approximately similar age, suggesting a similar time of formation of the ores.

Cross-cutting Veins with Copper-arsenic Ores of Western Mine

Thin cross-cutting calcite veinlets, typically 1-3 mm thick, form a rectangular network of veins at Western Mine. These veinlets carry copper and arsenic minerals ± silver-molybdenum, cobalt and nickel. Although Western Mine is situated only 150 m to the west of the bedded ore at Blue Hole, there is no stratabound ore at Western Mine. However, because thin veins crosscut the bedded ores at Blue Hole the vein mineralization, both at Blue Hole, and also at Western Mine, must be later than stratabound mineralisation. The veinlets and disseminations are dominated by copper minerals with intergrown chalcopyrite-tennantite, accompanied by nickel-bearing cobaltite, molybdenite and pyrite, secondary stromeyerite and native silver (Ixer and Pattrick, 1995). Around the entrance to the old mine workings, the abundance of calcite veins can be seen forming a reticulate network, particularly in the roof of the workings.

Spoil material is extensive, especially near the shore of Lough Leane, and shows abundant calcite veining with up to 50% of the rock being formed of veins, although 20-30% veining is more typical. There is no surface alteration of the copper ores to malachite and azurite to indicate the occurrence of the primary copper ores at depth, which testifies to the skills of the Bronze Age miners to prospect for ores.

Copper was also extracted from veins in the Roughty Valley around Ardtully near Kenmare. Several lodes are marked on the Geological Survey’s “six-inch” maps of the area; Ardtully, Forge, Trinity and Slaheny lodes with the principal workings located in the Ardtully and Forge lodes (Pracht, 1997). There is almost no trace now of the original copper mineralisation in the veins at Ardtully except some spoil heap material, although Cole (1922), reported eight copper lodes with tetrahedrite and bornite that produced 59 tons of ore with 4% copper in 1911. Lead was also worked from four lead-bearing veins; Annagh, Galena, Shanagarry and Killowen lodes. More than 400 tons of silver-bearing galena was mined at Annagh in the three years following discovery in 1788, and a further 9 tons with a silver content of 43 oz per ton were extracted after re-opening in 1825. The lead-bearing veins were entirely within limestone, whereas the copper-bearing veins occurred either in the limestone, the Carboniferous shale, or in the Old Red Sandstone. Only copper ores, comprising bornite, tennantite, minor chalcopyrite and cobaltite have been found in the surface spoil (Ixer, pers. comm.).

Summary of Ore-forming Processes

The sequence of processes that has affected metal distribution in the Ross Island area is shown in Figure 19. Metals were disseminated in the Ballysteen limestone or accumulated into beds of either lead-zinc or copper-iron sulphides (Fig. 19a). As pressure built up in the south Munster Basin early in the Variscan orogeny, it propagated northwards. Rocks were compressed by the tectonic forces, and individual grains in the rock were dissolved and re-precipitated in low-pressure areas to form a stripy spaced cleavage perpendicular to the direction of greatest stress (Fig. 19b). A different assemblage of ores was deposited at this stage as stringers and blebs along the spaced cleavage. Subsequently a network of calcite veins, 1-2mm thick and edged with quartz, developed (Fig. 19c), which contains a remobilised assemblage of ore minerals. With more intense pressure, folding and ultimately thrusting, veins were rotated into a subparallel alignment with the cleavage (Fig. 19d) and further movement of metals occurred. Virtually all mineralisation pre-dated the thrusting and was restricted to the Ballysteen limestone, which confirms the original observations of Weaver that ores did not appear to occur far beyond the Blue Hole and Western Mines. Further faulting and joint development, which formed minor rakes and localised concentrations of ore minerals occurred (Fig. 19e) which post-dates thrusting.

GEOPHYSICAL DATA FOR ROSS ISLAND

In 1992, a joint venture began between the Applied Geophysical Unit and the Archaeology Department of University College, Galway. The initial purpose of the geophysical study was for archaeological site investigation, but in 1993 the research extended to investigate the possible extension of mineralisation with depth. The two main objectives that geophysical methods were asked to address were:

(1) are there extensions to the copper mineralisation that have not been found with drilling?; and

(2) can the thrust plane between the Ballysteen and Rockfield limestones be determined geophysically?

Due to the constraints of working in a national park the amount and distribution of data collected was severely limited and restricts the interpretation that can be put on the results. Methods employed in the geophysical survey included time domain IP, gravity, geochemical and borehole geophysics (Mebrate, 1995), VLF-R, VES, electric tomography (Wenner profile) and seismic refraction (Cullen, 1995). The drilling programme and core sampling sites were based on the geophysical work and downhole geophysical borehole logging was also completed to check that no ore horizons were lost in the core, due to altered ore material not being recovered.

Survey Techniques

The initial geophysical study was carried out along survey lines, which were constrained in their positioning by Killarney National Park requirements, so it was difficult to obtain data on a regular grid because no tree felling was allowed, although a regular grid is a pre-requisite of a good geophysical survey. The lines were laid out using a compass and ranging rod although this was later improved using electronic distance measuring (Cullen, 1995). For most of the geophysical methods, station spacing was 25 m along the survey lines, with lines nominally 100 m apart and between 300 and 500 m long; these survey lines are shown in Figure 21.

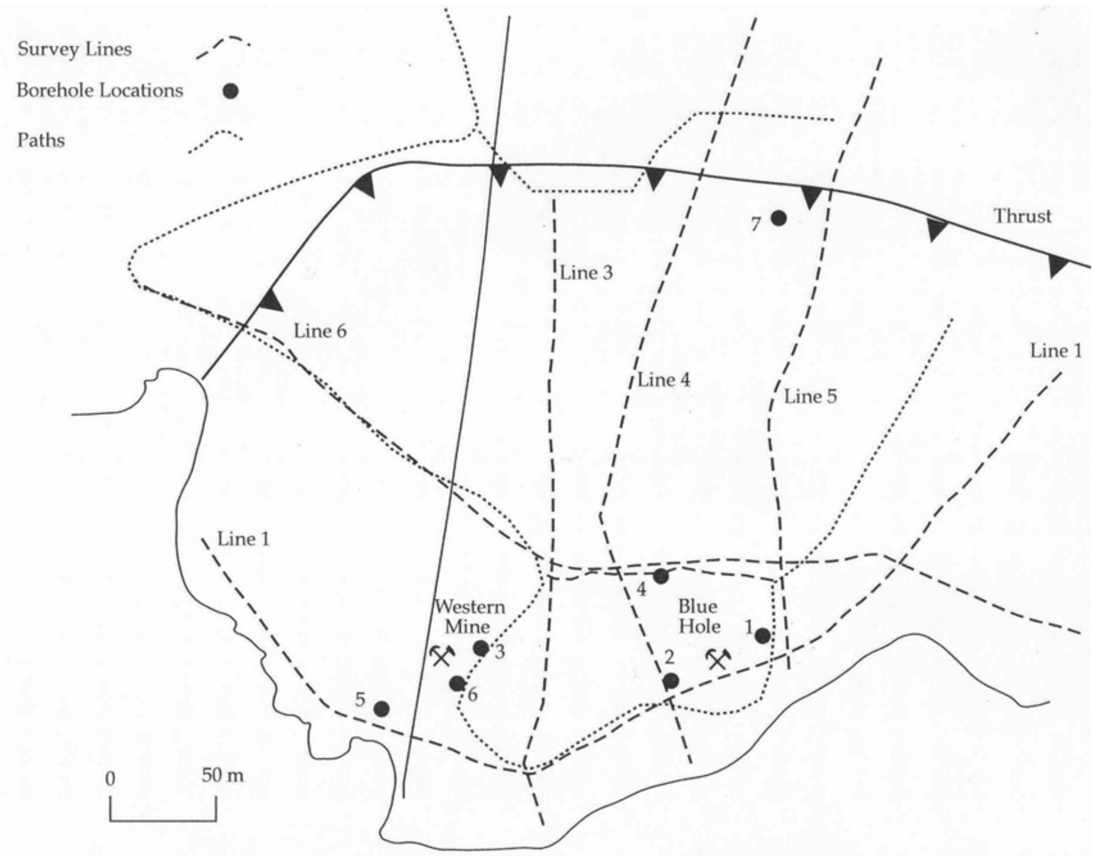


Figure 21. *Map showing the geophysical survey lines and the location of boreholes in the mined areas at Ross Island (after Cullen, 1995).*

The IP method was used to determine whether there were any extensions to the known sulphide ore deposits. This is an "active" source method: an electric current is applied to the ground, when the applied current is turned off, the voltage in the ground does not dissipate instantaneously. The time domain IP method measures this ground voltage at a particular time or how it changes with time.

The gravity method was employed in an attempt to determine geological structures, the thickness of sedimentary rocks, the size and shape of the ore bodies, to trace the thrust plane between the Ballysteen and Rockfield Limestones, and to delineate old mining shafts and workings.

The VLF and VLF-R (R for Resistivity) methods were used to investigate any areas with high resistivity contrast. These are active methods that depend on Very Low Frequency (VLF) distant radio transmitters, that are located throughout the world, primarily for communications with ships and submarines. The electromagnetic energy creates eddy currents in buried conductors, such as in ore deposits. The secondary magnetic field created then interacts with the primary magnetic field, causing it to change direction. The VLF instrument detects this change in direction. The VLF-R configuration adds two electrodes to the sensor enabling it to also determine the resistivity at the reading site.

The VES (Vertical Electrical Sounding) method is an active method requiring the input of electric current into the ground and is used to determine variations in resistivity beneath a point on the surface.

The borehole geophysics consisted of SP (surface and downhole), resistivity (dipole-dipole and Werner) and natural Gamma logs. SP and natural Gamma logs are passive methods; SP simply measures the potential difference between two electrodes in contact with the ground, and the natural Gamma log detects the total count of Gamma rays.

Results

The interpretation of the ground surveys was restricted by the somewhat limited data due to constraints imposed by working in a national park; borehole logging was rather more successful. The ground IP and VLF methods showed potential for locating the thrust plane subsurface, although the data density caused by the restriction of grid lines was insufficient to reach a conclusive interpretation. Some variation was observed between Blue Hole and Western Mine and although this may be due to varying styles of mineralisation it may also be due to spoil at the base of the shafts or to varying amounts of water within the rock.

An example of geophysical and lithological logs for one of the boreholes is presented in Figure 22. In most of the boreholes there was a lack of response on gamma logs, which is not too surprising because in sedimentary rocks the radioactive elements tend to concentrate in clays and shales rather than in limestones. The electrical Wenner and dipole-dipole arrays were able to detect the thrust plane, characterised by a decrease in resistivity, possibly due to fluid flow along this zone of weakness (Fig. 18). Abundant calcite veining and associated mineralisation were also detected in some instances,although the characteristics appear to change from borehole to borehole (high on some, low on others) making it difficult to relate to a single cause. The SP survey defined areas of mineralization,but not the thrust plane or veining. The method was able to detect the sulphide mineralisation associated with the Blue Hole mine, defining the edges of the body with accuracy, although this may simply be due to mine spoils at the bottom of the water-filled hole.

No further mineralisation was located by geophysical methods beyond the immediate surrounds of the workings at Blue Hole and Western Mine, a conclusion supported by the results of Weavers prospecting during the 1820s.

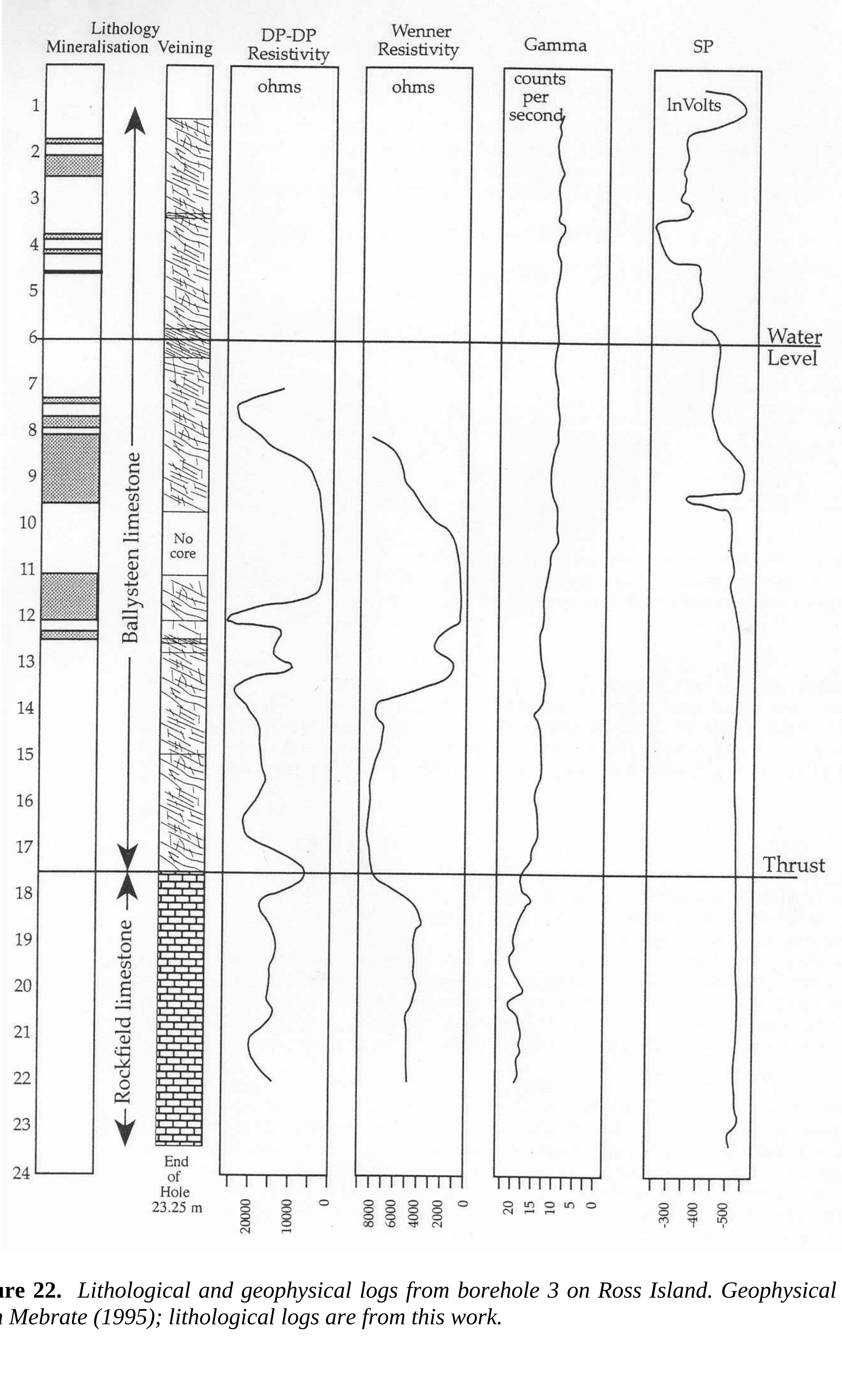


Figure 22. *Lithological and geophysical logs from borehole 3 on Ross Island. Geophysical data from Mebrate (1995); lithological logs are from this work.*

LEAD ISOTOPIC STUDIES

Introduction

Lead exists with several different 'species'. These species, or isotopes, are of the same chemical element, that is having the same number of protons in the nucleus, but differing from one another by having a different number of neutrons. The isotopes of an element have slightly different physical characteristics, owing to their mass differences, enabling the different isotopes to be separated. Lead has four isotopes, one of which, with an atomic number of 204 (^{204}Pb), has remained constant in abundance since the formation of the Earth. The other three isotopes, ^{206}Pb, ^{207}Pb, and ^{208}Pb have gradually increased in abundance due to their formation from the progressive decay of uranium or thorium.

The breakdown of uranium or thorium to lead, is measured in terms of a half-life, that is the length of time that is takes for half of the parent to decay. Table 7 shows the parent-daughter isotope pairs. It is noticeable that the ^{238}U half-life is comparable to that of the age of the Earth, whereas that for ^{235}U is much shorter so that almost all the original 235 uranium isotope in the Earth has now decayed to ^{207}Pb. In contrast, the ^{232}Th half-life is comparable with the age of the Universe. Since the atomic decay has a known rate, it is possible to measure the proportions of one isotope against another and calculate an age for the rock in which the isotopes occur.

Table 7 Decay scheme of radiogenic elements showing parent, daughter isotopes, together with half life of decay (from Dickin, 1995)

Parent and daughter isotopes	Half life in billions of years
$^{238}U \Rightarrow {}^{206}Pb$	4.47
$^{235}U \Rightarrow {}^{207}Pb$	0.704
$^{232}Th \Rightarrow {}^{208}Pb$	14.01

Originally, isotopic studies were mainly used to determine the age of the host rocks or of mineralisation. More recently, such studies have been used to address a number of different geological and archaeological problems. A preliminary discussion of lead isotope data for the low-grade copper-dominated mineralisation in Devonian Red Beds and the Carboniferous rocks of the Munster Basin was given in Ixer and Pattrick (1995). The data were subsequently used in an attempt to determine the source of early Bronze Age metal artefacts from the British Isles (Ixer, 1999; Rohl and Needham, 1998) but with little success as acknowledged by Ixer (2000). More recently, a comprehensive study of the lead-isotope data for copper ores in Devonian Red Beds, and Ross Island-Muckross ores, has been presented by Kinnaird *et al*. (2000). These data have been used to compare and contrast the source of the copper metal, with the source for the lead and zinc metals in the vast deposits of the Irish Midlands.

Applications to Irish Ore Studies

There is an abundance of lead-isotope data published on the base-metal deposits of central Ireland with detailed studies of Navan (Mills *et al*., 1987) and Harberton Bridge (Gallagher *et al*., 1992). Russell (1968) first proposed that the origin of lead and other metals in the Carboniferous carbonate-hosted base-metal deposits of the Irish Midlands was the underlying Caledonian basement rocks. Subsequently, Dixon *et al*. (1990) used the published data, combined with new whole-rock lead-isotope results on unmineralised basement underlying or hosting base-metal mineralisation, to show that the Carboniferous-hosted lead-zinc deposits can be interpreted as being derived from underlying basement rocks. From the published data on mineralisation in the Irish Midlands, there are two key features:

(1) linear trend of isotopic data on the $^{206/204}$Pb versus $^{207/204}$Pb and $^{208/204}$Pb (Figs. 23a, b); and

(2) systematic geographical variation of the $^{206/204}$Pb data, in the Carboniferous lead-zinc deposits across Ireland (Dixon *et al*., 1990). They become more radiogenic from north to south irrespective of mineralisation style, age, or host rock (Fig. 24). Most authors consider that this data array for the Carboniferous carbonate-hosted deposits represents a mixing line between leads derived from two source areas, one a radiogenic-poor source in the north and the other a more radiogenic source in the southeast (Caulfield *et al*., 1986; O'Keeffe, 1986).

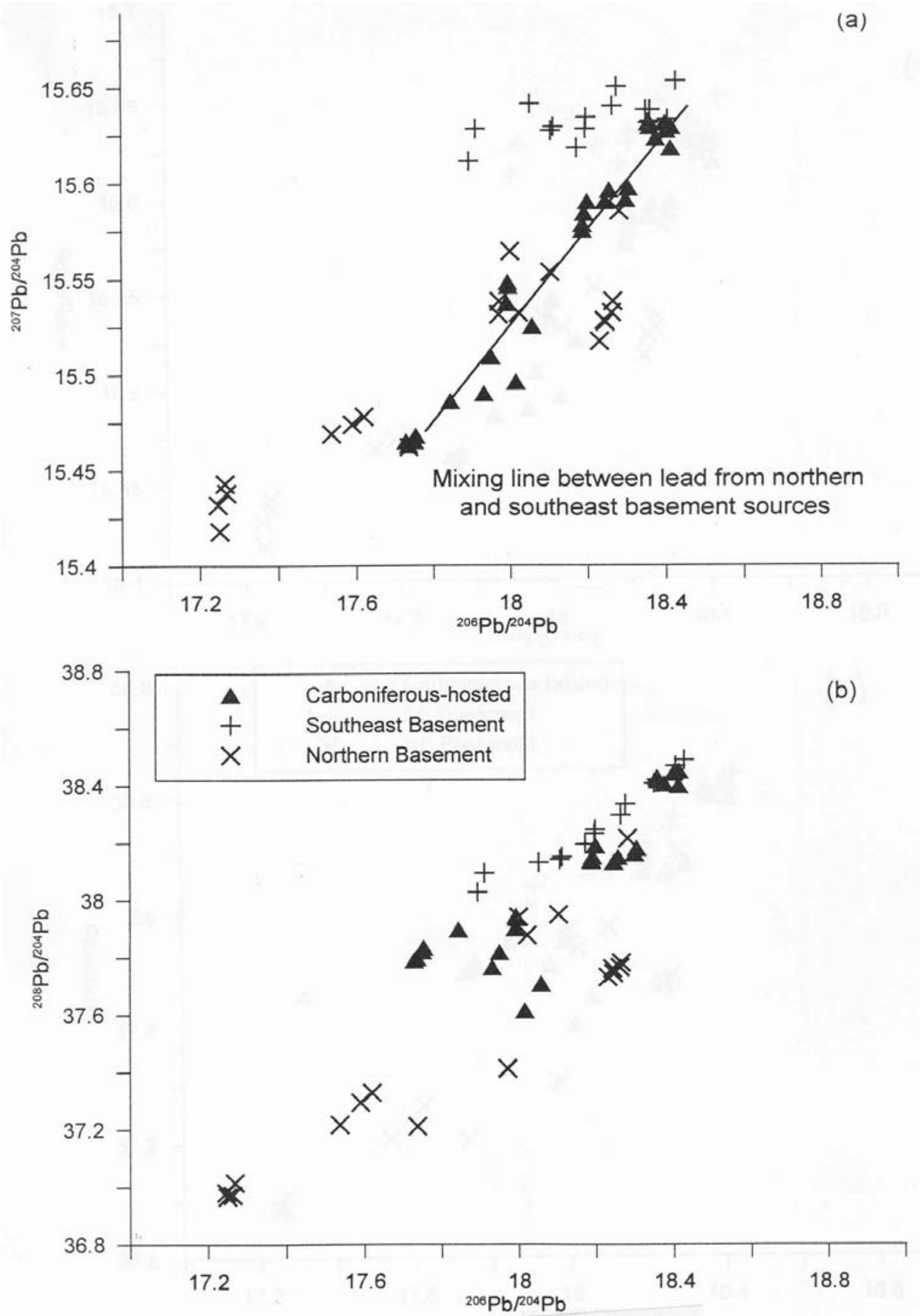


Figure 23. *Lead-isotope data for Carboniferous lead-zinc mineralisation of the Irish Midlands and for lead-zinc deposits in the northern and southeast basement of Ireland: (a) $^{206}Pb/^{204}Pb$ v $^{207}Pb/^{204}Pb$; and (b) $^{206}Pb/^{204}Pb$ v $^{208}Pb/^{204}Pb$ (data from O'Keeffe, 1986).*

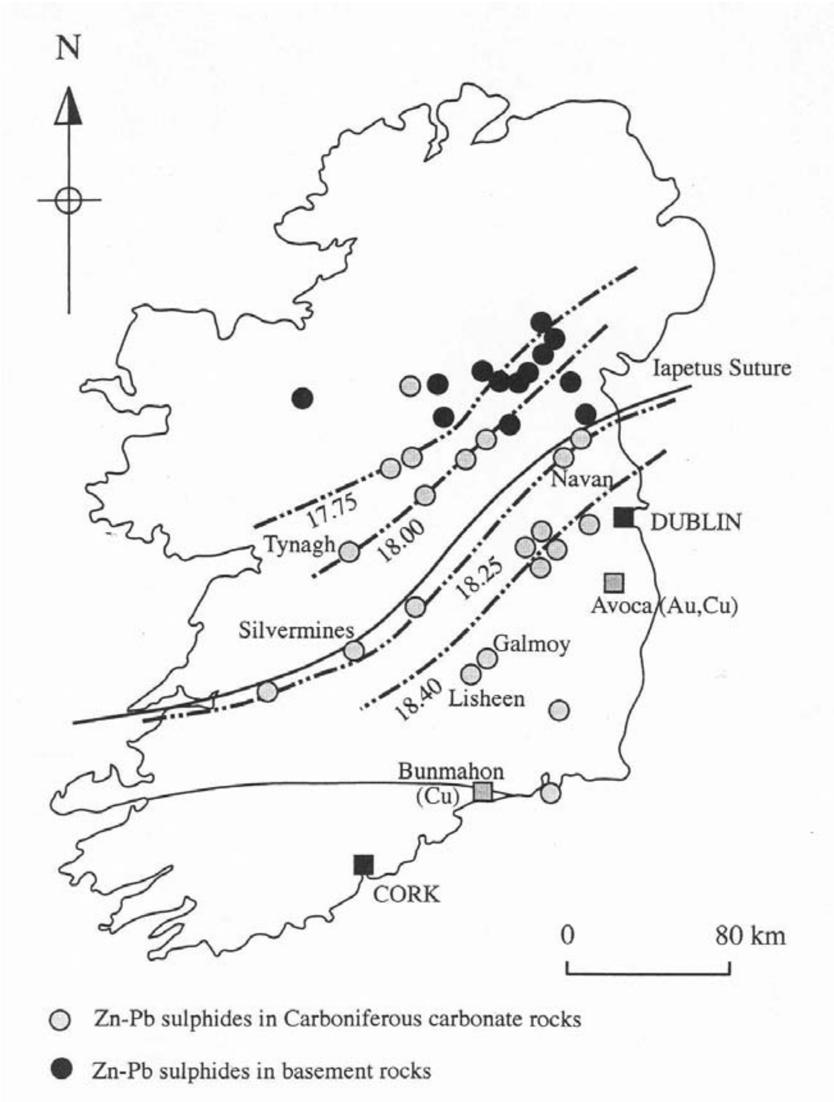


Figure 24. *Contoured values of $^{206}Pb/^{204}Pb$ for Irish lead-zinc deposits (after Dixon* et al.*, 1990). N = Navan, T=Tynagh, S = Silvermines, G = Galmoy, and L = Lisheen.*

The occurrence of ore-bearing veins in the basement beneath the Carboniferous beds, and also ores in the basement away from known carbonate-hosted mineralisation also supports the concept of the basement as a source of lead (Halliday and Mitchell, 1983; Morris, 1984; Andrew, 1986; O'Keeffe, 1986). Sulphur-isotope data from Navan (Mills *et al*., 1987), and fluid-inclusion temperatures derived from ore-bearing rocks, suggest that fluids may even have penetrated to depths of around 4 km (Everett *et al*., 1999). In addition, carbon- and oxygen-isotope data on vein minerals from Lower Palaeozoic rocks beneath the ore deposits imply that the hot hydrothermal fluid in the mineralising systems was in equilibrium with the metasedimentary basement (Everett *et al.*, 1999). For the Old Red Sandstone-hosted copper deposits and the Ross Island and Muckross ores, the lead-isotope studies have also provided some useful insights into the origin of the ore metals. For the Old Red Sandstone hosted copper deposits and the Ross Island and Muckross ores, the lead isotope studies have also provided some useful insights into the origin of the ore metals although lead isotope data for the low grade Cu-dominated mineralisation hosted in Devonian red beds and the Carboniferous rocks of the Munster Basin are limited, other than for Gortdrum, (Steed, 1986; Duane, 1988). A preliminary discussion of these data in Ixer and Pattrick (1995) suggested that they showed a number of different mineralising events. A comprehensive suite of ore types for this study has been collected *in situ*, from drill core when available, and also from spoil heaps of old mines both because they contain unexposed lithologies and because the sulphide minerals are generally less weathered than in surface outcrops. Data from this study have been combined with earlier data obtained from mineralised samples selected by Ixer and briefly discussed by Ixer and Pattrick (1995), and partially published by Rohl (1995, 1996).

Analytical Procedures

Samples, all of which had previously been studied and described in reflected light, were crushed in a tungsten carbide mortar and pestle at the NIGL laboratory at BGS Keyworth. When possible, individual grains of galena were hand-picked under ethanol with the aid of a binocular microscope. Galenas were then digested in 8N nitric acid, evaporated, re-dissolved in 6N hydrochloric acid and evaporated. Minerals other than galena, were dissolved in 1N hydrobromic acid and put through an AG1x8 anion exchange column to purify the lead. The 6N HCl eluant was evaporated. All samples were then picked up in 2 per cent nitric acid and diluted to the appropriate strength for the Plasma 54. The solution was spiked with thallium at 10 ppb to correct for mass discrimination. Analysis was undertaken on a PIMMS Plasma 54 (plasma ionisation multimass spectometer). The reproducibility of NBS 981 standard (n=27) during the period of analyses were: $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ were all ± 0.05% (2σ) whereas the reproducibility of the $^{208}Pb/^{206}Pb$ was 0.02% (2σ). Replicate analyses of three of the samples analysed by Rohl (1996) were included in this study (Mount Gabriel MG3A; Ross Island, Ross 5/10.35* and Ross 93A) to compare data produced in this study with those obtained by Rohl (1996). The data (Tables 7 and 8) show very similar $^{206/204}Pb$ ratios for all three pairs of samples as might be expected although there is more variation in the $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios. There is no consistent pattern, two of Rohl's samples show higher ratios for both isotopes (5.10.35 and 93A) and one is lower (93A), therefore both sets of data can be combined to form a more comprehensive data set as there is no systematic difference in the data sets.

Results

All the lead isotope data from this study are given in Tables 8 and 9 and are listed along with the data of Rohl (1995). Also included are data for Duneen, a galena-bearing deposit in upper Devonian - early Carboniferous basin margin clastics of southwest Co. Cork (O'Keeffe, 1986). These data are graphically presented in Figures 25-28. Lead isotope studies show that the Red Bed hosted deposits of the Munster Basin, and the carbonate-hosted polymetallic deposits of Ross Island and the Irish Midlands fall in two separate and distinctive groups:

(1) s***ulphide mineralisation hosted by Old Red Sandstone Red Beds***
There is a considerable variation in the isotopic ratios depending on the style of mineralisation. For the disseminated copper mineralisation, there is a considerable inhomogenity of data on both $^{206}Pb/^{204}Pb$ v $^{207}Pb/^{204}Pb$ (Fig. 25a) and on the $^{206}Pb/^{204}Pb$ v $^{208}Pb/^{204}Pb$ plots (Fig. 25b). In particular, the disseminated ores from Mount Gabriel samples, show a variation to considerably high radiogenic values indicating that the source rocks were rich in both uranium and thorium. In contrast, ores from the minor, copper-bearing veinlets, and ores from the major quartz veins are much more tightly constrained; and

(2) ***sulphide mineralisation, hosted by carbonates of the Courceyan Ballysteen Formation***
Lead-isotope data for Ross Island and Muckross is shown in Figure 26. The isotope data are more consistent than the red bed-hosted deposits. Except for the Ardtully sample, which is anomalously radiogenic, the ratios are similar to those for the Carboniferous hosted Zn-Pb deposits of the Irish Midlands such as Silvermines and Courtbrown (Fig. 5). There is a consistent variation within the set of isotopic data (Fig. 27) with the stratabound mineralisation from Muckross giving slightly lower $^{206}Pb/^{204}Pb$ and higher $^{207}Pb/^{204}Pb$ than stratabound mineralisation from Blue Hole or Crow Island, in contrast to the more radiogenic nature of the veins at Western Mine.

Table 8 Lead isotope data for Old Red Sandstone-hosted copper deposits. For details of ore assemblages of material analysed see Rohl (1995, 1996). The Duneen galenas analysed by O'Keefe are from a 30 cm wide quartz vein in upper Devonian - early Carboniferous Kinsale Formation (see Fig. 1 for geographic location). Qu = quartz; arsenopy = arsenopyrite; born = bornite; ccite = chalcocite; cpy = chalcopyrite; gal = galena; haem = haematite; tenn, = tennantite. Note data for sample MG3A, shown with an asterisk, has been provided from Rohl, and has been re-analysed in this study.

Sample No.	Analyst	Main mineral assemblage	$^{208}/^{204}$Pb	$^{208}/^{206}$Pb	$^{207}/^{204}$Pb	$^{207}/^{206}$Pb	$^{206}/^{204}$Pb
Derrynane - disseminated							
95-DN1	Rohl 1995		39.569	1.9651	15.742	0.7818	20.136
95-DN2	Rohl 1995		39.361	1.9596	15.738	0.7835	20.086
Derrycarhoon - disseminated							
95-DC	Rohl 1995		38.310	2.0719	15.565	0.8418	18.490
DCH	Rohl 1995		38.217	2.0453	15.626	0.8363	18.685
Ballyrisode - disseminated							
95-B1	Rohl 1995	copper ores	39.460	2.0223	15.678	0.8035	19.512
BRS	Rohl 1995	copper ores	39.175	1.9777	15.699	0.7926	19.808
Mount Gabriel - disseminated							
MG3 A*	This study	ccite, born	38.502	2.0132	15.654	0.8185	19.125
MG3 A*	Rohl 1995	ccite, born	38.355	2.0053	15.646	0.8180	19.127
MG 3 B	This study	ccite, born	38.263	2.0936	15.594	0.8532	18.276
Skeagh 1	This study	qu, born	38.627	2.0384	15.647	0.8257	18.950
CS 92.1	Rohl 1995		38.560	1.9042	15.710	0.7758	20.250
Mine 9	Rohl 1995		40.095	1.9673	15.693	0.7700	20.381
MG 311-A	Rohl 1995	ccite, born	40.245	1.9495	15.741	0.7625	20.644
MG 311-E	Rohl 1995	ccite, born	41.423	1.9000	15.784	0.7240	21.802
Cappaghglass- minor veins							
Cappagh 1	This study	born	38.963	2.0604	15.614	0.8257	18.911
Cappagh 3	This study	born	38.145	2.0986	15.593	0.8578	18.177
CAPP	Rohl 1996	gal	38.183	2.1006	15.608	0.8586	18.177
C12	Rohl 1995		38.371	2.0993	15.644	0.8559	18.278
Dhurode – major veins							
DHU	Rohl 1996	gal	38.320	2.0925	15.622	0.8530	18.313
Dhrode 2	This study	cpy-ccite	38.439	2.0788	15.614	0.8444	18.491
Dhrode 6	This study	arsenopy	38.798	2.0605	15.608	0.8289	18.830
Dhrode 21.8	This study	gal	38.287	2.0922	15.610	0.8530	18.300
Ballycummisk - major veins							
1.87.11	Rohl 1995	cpy	38.126	2.0813	15.579	0.8505	18.318
BCM	Rohl 1995	cpy	38.190	2.0804	15.596	0.8496	18.357
Bally A	This study	born	38.245	2.0569	15.621	0.8402	18.593
Bally 19-6	This study	haem-rich qu-vein	38.253	2.0425	15.623	0.8342	18.729
Bally 19-13	This study	cpy, tenn, haem	38.620	2.0396	15.629	0.8254	18.935
Cork 2	This study	complex Au- ore	38.198	2.0932	15.573	0.8534	18.249
Allihies – major veins							
95-All	Rohl 1995	cpy, born	38.701	2.0751	15.633	0.8382	18.650
BMR All 93.1	Rohl 1995	cpy, born	38.654	2.0762	15.610	0.8384	18.618
BMR All 93.2	Rohl 1995	cpy, born	38.665	2.0531	15.621	0.8295	18.833
Duneen							
Dnm.1	O'Keeffe 1986	gal	38.221	2.1036	15.606	0.8589	18.169
Dnm.2	O'Keeffe 1986	gal	38.217	2.1034	15.605	0.8589	18.169
Dnm.3	O'Keeffe 1986	gal	38.224	2.1033	15.609	0.8589	18.173
Dnm.4	O'Keeffe 1986	gal	38.242	2.1038	16.610	0.9137	18.178

Table 9 Lead isotope data for carbonate-hosted copper-polymetallic ore deposits. For details of ore assemblages of material analysed by Rohl (1995,1996). born = bornite; ccite = chalcocite; cpy = chalcopyrite; gal = galena; haem = haematite; pyr = pyrite; sphal = sphalerite; tenn = tennantite. Note data for samples Ross 5/10.35 and Ross 93A, both shown with an asterisk, have been provided from Rohl, and has been re-analysed in this study.

Sample No.	Analyst	Main mineral assemblage	$^{208}/^{204}$Pb	$^{208}/^{206}$Pb	$^{207}/^{204}$Pb	$^{207}/^{206}$Pb	$^{206}/^{204}$Pb
Ross Island epigenetic - Western Mine							
Ross 1	Rohl 1995	cpy, tenn	38.123	2.088	15.593	0.854	18.261
Ross3/12. 35	This study	cpy, tenn	38.093	2.085	15.576	0.853	18.271
Ross 4	This study	cpy, tenn	38.087	2.087	15.578	0.853	18.252
Ross 5	This study	cpy, tenn	38.088	2.093	15.587	0.856	18.202
Ross 5/2.90	Rohl 1995	cpy	38.126	2.087	15.594	0.854	18.266
Ross 5/10.35*	This study	cpy, tenn	38.116	2.086	15.583	0.853	18.269
Ross 5/10.35*	Rohl 1995	cpy, tenn	38.194	2.088	15.607	0.853	18.290
Ross 6	This study	cpy - born	38.025	2.085	15.585	0.854	18.239
Ross Island stratabound – Blue Hole							
Ross 7	Rohl 1995	sphal, gal	38.099	2.096	15.562	0.856	18.175
Ross 8	This study	sphal, gal	38.065	2.097	15.583	0.858	18.155
Ross 9	Rohl 1995	sphal, gal, py	38.122	2.097	15.600	0.858	18.178
Ross 10	Rohl 1995	sphal, gal	38.149	2.097	15.610	0.858	18.190
Ross 93	Rohl 1995	cpy, py, gal	38.099	2.097	15.594	0.859	18.164
Ross 93A*	This study	cpy, py, gal	38.084	2.097	15.589	0.858	18.164
Ross 93A*	Rohl 1995	cpy, py, gal	38.136	2.098	15.601	0.858	18.174
Ross 122.3	Rohl 1995	cpy, pyr	38.094	2.096	15.593	0.858	18.175
Ross 122.9	This study	pyr, cpy, gal	38.036	2.096	15.576	0.858	18.148
Ross 397	This study	cpy, py	38.127	2.096	15.606	0.858	18.188
Blueholes X	This study	sphal, gal	38.028	2.096	15.568	0.858	18.145
Crow Island							
Crow1	Rohl unpubl	gal	38.074	2.097	15.591	0.859	18.156
Crow2	Rohl unpubl	gal	38.057	2.097	15.586	0.859	18.147
Muckross starabound							
Muckross 6	Rohl 1995	sphal-gal	38.071	2.098	15.590	0.859	18.144
Muckross 7	Rohl 1995	cpy-py	38.063	2.098	15.588	0.859	18.143
Muck 9	This study	tenn-cpy	38.005	2.098	15.567	0.859	18.119
Muck X	This study	cpy-py	38.161	2.101	15.613	0.860	18.166
Ardtully epigenetic							
AK-1	This study	cpy, tenn	38.243	1.743	15.797	0.720	21.943

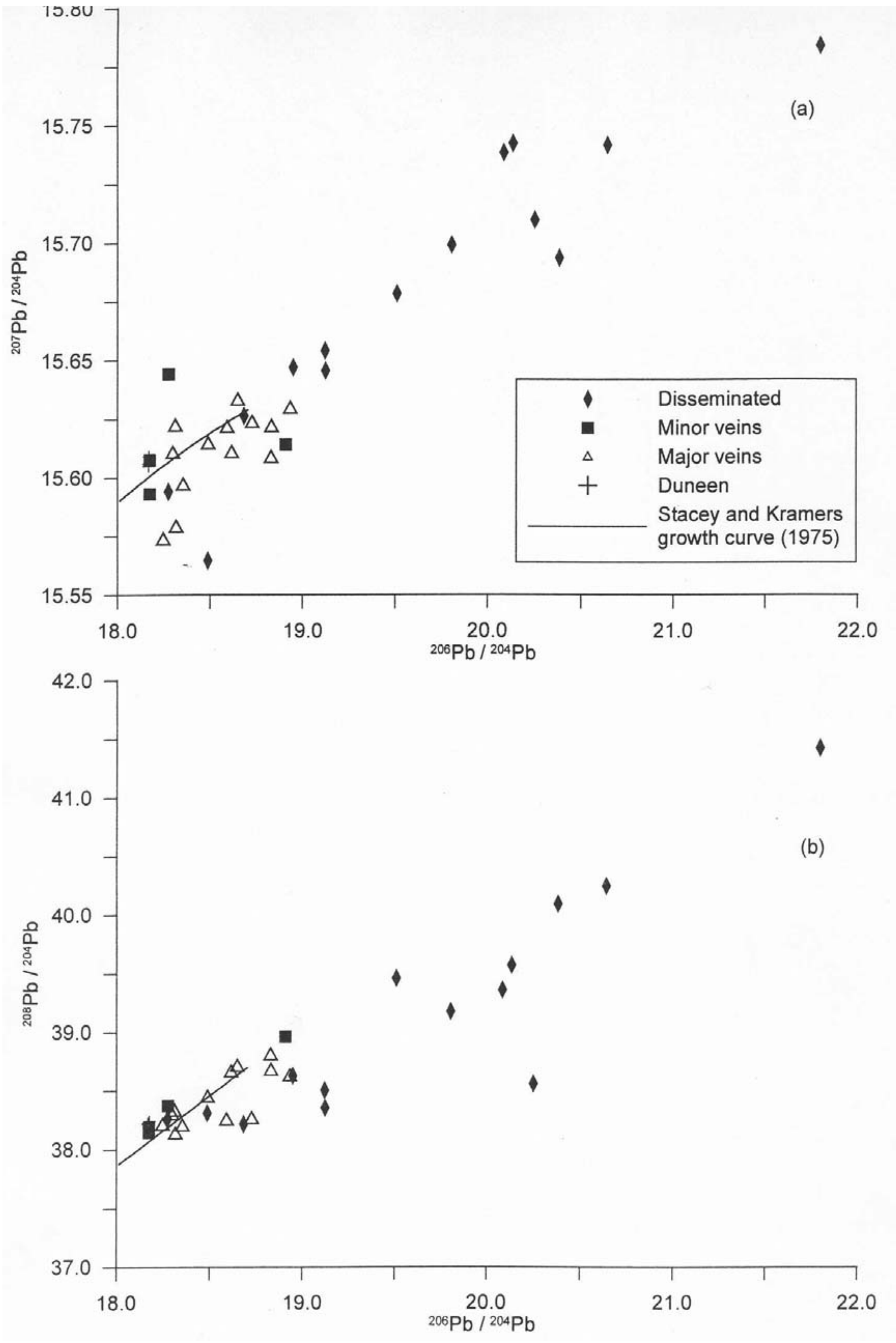


Figure 25. *Lead-isotope data for Red Bed-hosted copper mineralisation in southwest Ireland, showing the spread of data for the disseminated ores, and more tightly constrained data for ores from the minor and major quartz veins: (a) $^{206}Pb/^{204}Pb$ v $^{207}Pb/^{204}Pb$; and (b) $^{206}Pb/^{204}Pb$ v $^{208}Pb/^{204}Pb$ (data from Rohl and Needham, 1998).*

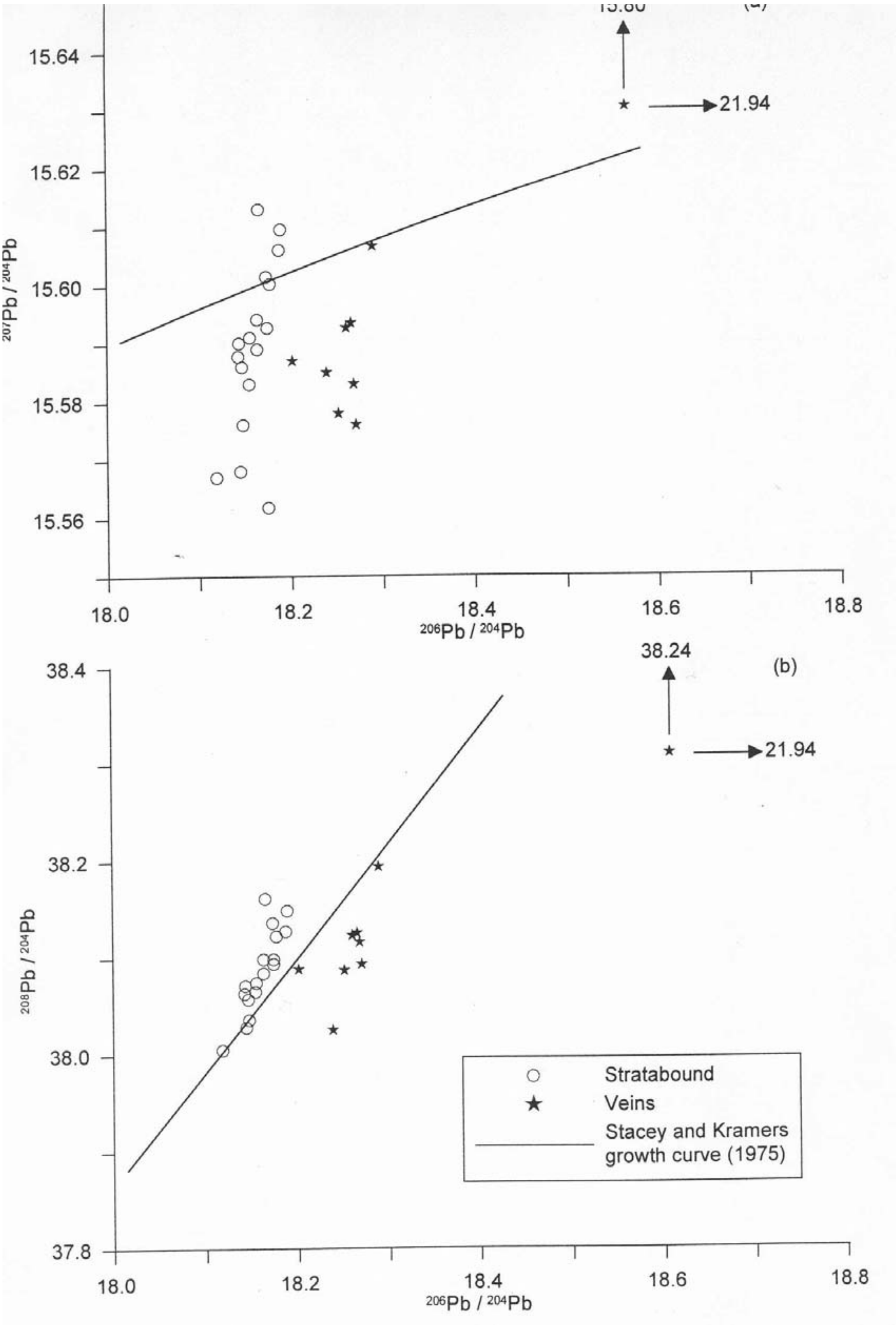


Figure 26. *Lead-isotope data for Carboniferous-hosted, stratabound and vein copper-silver-lead-zinc mineralisation at Ross Island and Muckross: (a) $^{206}Pb/^{204}Pb$ v $^{207}Pb/^{204}Pb$; and (b) $^{206}Pb/^{204}Pb$ v $^{208}Pb/^{204}Pb$ (data from Rohl and Needham, 1998).*

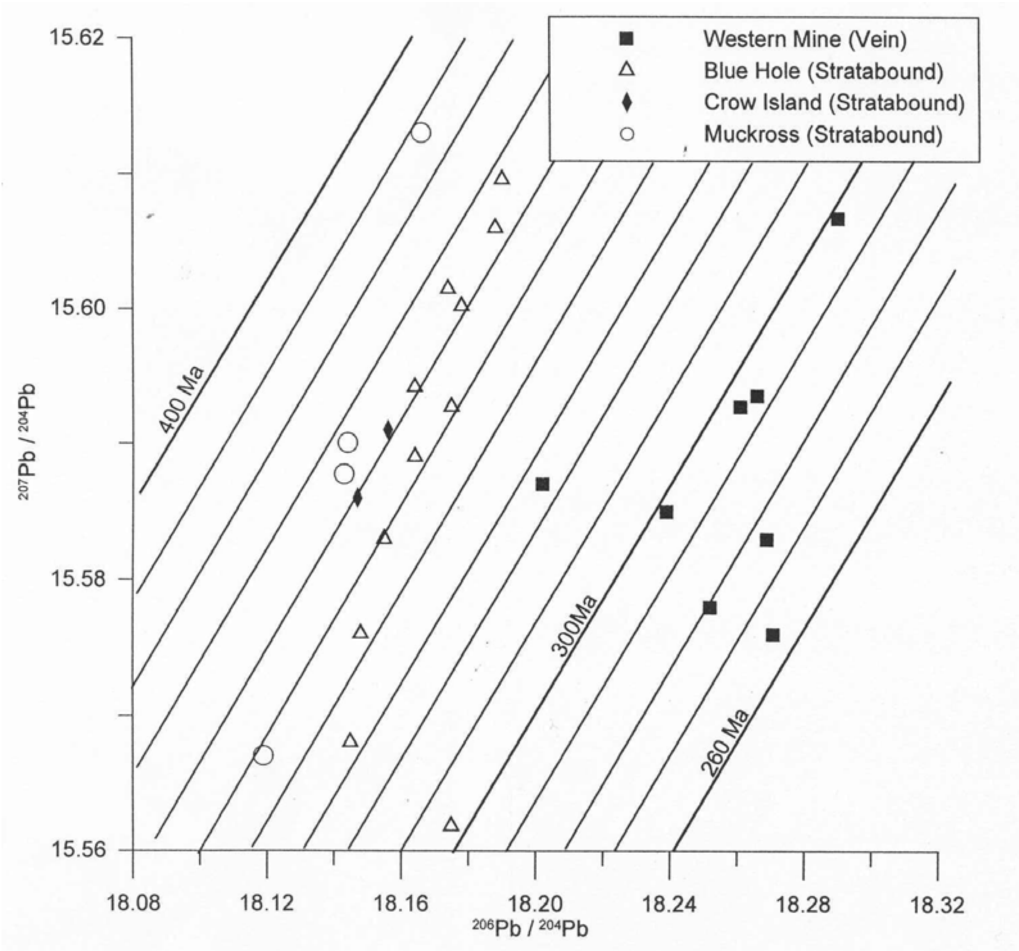


Figure 27. *Combined lead-isotope data for Red Bed-hosted copper deposits of southwest Ireland, the Carboniferous-hosted stratabound ores (Blue Hole and Muckross) and vein-type ores (Western Mine). Lead from the southeast basement and northern basement are shown in symbols, whilst the data for the Carboniferous-hosted lead-zinc deposits given in Figure 19(a) is illustrated as a field. A mixing line is shown for the Red Bed-hosted deposits, between a high-radiogenic granitic source, and a source that is similar to that of the Carboniferous lead-zinc deposits* (*data from O'Keeffe, 1986; Duane, 1988; Rohl and Needham, 1998).*

AGE OF THE MINERALISATION

If the lead-isotope data are interpolated graphically to determine an age of mineralisation (using the values of Boast *et al*., 1981), Muckross stratabound ores give an age of 355 $\pm$ 10 Ma, Crow Island 350 $\pm$ 10 Ma and Blue Hole stratabound ore gives 340 Ma $\pm$ 10 Ma (Fig. 27). Although many isotope geochemists do not like using lead-isotope data to derive age dates, the quoted ages are, nevertheless, consistent with field observations that Muckross mineralisation occurs at a slightly lower stratigraphic level than Blue Hole and therefore might be slightly older. They are also broadly consistent with an age of 355 Ma for Ross Island estimated from microfossil data (Ps. multistriatus conodont Biozone; Jones and Somerville, 1994). Vein deposits at Western Mine, that are later than the stratabound ores of Blue Hole, give an age of 280 $\pm$ 10 Ma. These are all geologically reasonable ages, consistent with field observations and are similar to published ages for the lead-zinc mineralisation at Navan, Tynagh and Lisheen (Table 10).

Table 10 Published age dates for Irish base-metal mineralization

	Age in Ma	Technique	Source of data
Navan	~345	Sedimentological and structural studies	Anderson *et al*. (1998)
Tynagh	348±22	Pb/Pb	Boast *et al*. (1981)
Lisheen	350-337	stepwise $^{40}Ar/^{39}Ar$ heating of micas	Hitzman *et al.* (1994)
Gortdrum	340±20	U/Pb	Duane *et al*. (1986)
	359±26	Pb/Pb	Duane *et al.* (1986)
	>300 & 275	K/Ar	Halliday and Mitchell (1983)
Muckross	~355±10	Pb/Pb	Kinnaird *et al.* (2002)
Courtbrown	350-307	Sedimentological evidence	Reed and Wallace (2001)
Ross Island	340±10 stratabound	Pb/Pb	Kinnaird *et al.* (2002)
Silvermines	~271±24	Pb/Pb	Boast *et al.* (1981)
Ross Island	280±10 epigenetic	Pb/Pb	Kinnaird *et al*. (2002)
SW Cu-ores	~290	K/Ar	Halliday and Mitchell (1983)

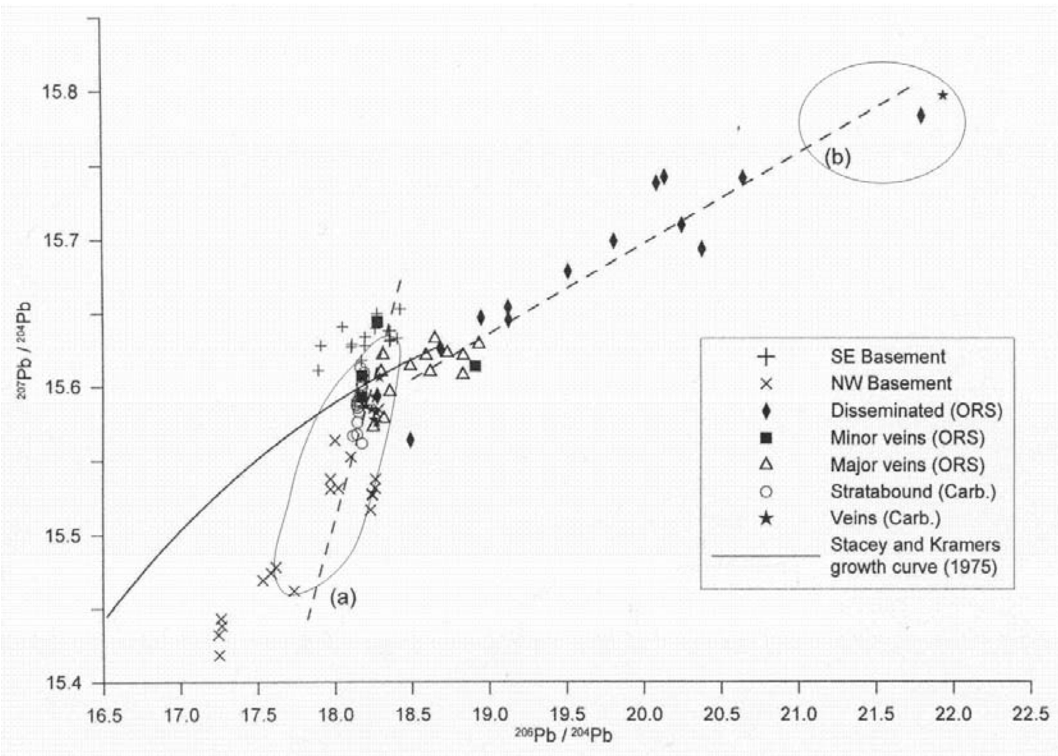


Figure 28. *Lead-isotope data for the Carboniferous-hosted stratabound copper-silver-lead-zinc mineralisation of Muckross and Blue Hole and for the vein mineralisation at Western Mine. Isochrons are drawn on the $^{206}Pb/^{204}Pb$ v $^{207}Pb/^{204}Pb$ plot indicating that the Muckross mineralisation is slightly older than other deposits, and that the veins of Western Mine are a younger event (data from Rohl and Needham, 1998).*

The bedded ores at Muckross and Ross Island are in the same limestone formation as the barite at Silvermines, although calculated ages for the Silvermines deposit of 271±24 Ma (Boast *et al*., 1981) implies a much younger Permian age for the mineralisation. This age has always been regarded as anomalous, and was difficult to explain. In particular, Silvermines and Navan lie just above the Iapetus suture whilst Tynagh lies to the north of the suture, so that the lead in ores at

Silvermines and Navan should both come from a similar source and might be expected to contrast with the source of lead in the Tynagh deposit, which originated from a different basement terrane. However, the 270-290 Ma age derived for the younger phase of vein mineralisation at Western Mine, Ross Island, is of a similar age to the calculated age for Silvermines. This has led to the suggestion that there were two phases of mineralisation in some places; an early ore deposition during Carboniferous extension and a later phase during early Variscan compression (Kinnaird *et al.*, 2002).

The younger phase of copper mineralisation at Ross Island can sometimes be observed along pressure-solution cleavage, especially in borehole core. Since pressure-solution cleavage developed well before major folding, faulting and thrusting, the 270-290 Ma age date for ores associated with the cleavage implies that the thrusting episode at Ross Island must be younger than this. Certainly, in the seven borehole cores from the vicinity of the Bronze Age mines which cut through the thrust plane (Nex *et al*., 2001), there is no evidence of any mineralisation associated either with the thrust plane, or in the carbonates structurally below, suggesting that there was limited remobilisation after thrusting at Ross Island.

INTERPRETATION - CONSTRAINTS ON METAL SOURCES

Lead isotope data published for Carboniferous-hosted Zn-Pb deposits of central Ireland define a linear $^{206}Pb/^{204}Pb$ - $^{208}Pb/^{204}Pb$ trend (Dixon *et al*., 1990). This trend reflects a sedimentological mixing in Lower Palaeozoic greywackes of lead derived from two different sources, one a low radiogenic source in the basement of NW of Ireland, the other a more highly radiogenic basement source in the SE (Fig. 28). The carbonate-hosted Cu-polymetallic deposits described here show an affinity with the Carboniferous Zn-Pb deposits, whereas the Red Bed-hosted deposits of the Munster Basin and copper-dolomite association of Ardtully have different and distinctive isotopic ratios. These comparisons and contrasts are important for interpreting the source of the lead and other metals in the deposits.

Sulphide Mineralisation Hosted by Old Red Sandstone Red Beds

The Red Bed-hosted Cu deposits form a coherent data set although there is a considerable inhomogeneity of data on both $^{206}Pb/^{204}Pb$ v $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ v $^{208}Pb/^{204}Pb$ plots (Fig. 25), particularly for the radiogenic samples from Mount Gabriel.

Lead isotope ratios for the disseminated sulphides, especially those from Mount Gabriel, appear to define a mixing line between a source from the NW and SE basement and a more radiogenic component. This suggests that the metals were derived in part from a similar basement source to the Carboniferous-hosted lead-zinc ores, and in part from a source that was much more radiogenic (Fig. 23). Such high radiogenic values would be typical for the roof zone of a granite that contained both uranium and thorium. It seems likely therefore, that the lead has been derived from detrital fragments in the Red Beds, which originated from weathering of granite. This granite source may have been the Leinster Granite in southeast Ireland, or the unexposed granite now offshore to the west of the Munster Basin (Conroy - in Murphy, F.X., 1990). These Caledonian granites were intruded around 400 million years ago, and must have been exposed to weathering by upper Devonian time as other granite-derived fragments have been noted in upper Devonian rocks in the Ballyhoura Mountains (Penney, 1979) and in lowermost Courceyan limestones north of Mallow (Clipstone and Roycroft, 1992). Duane (1988) suggested an analogous origin for uranium in the Gortdrum deposit and a similar assemblage of detrital minerals to Gortdrum is found in the Red Beds. Zoned zircons, TiO_2 minerals, tourmaline, carbonaceous matter/graphite plus trace amounts of chromite, magnetite and ilmenite occur, with authigenic overgrowths on tourmaline and TiO_2 (Ixer, 1994). Duane (1988) envisaged that the unroofing of the HHP Leinster

Granite (O'Connor *et al*., 1982) provided the source materials for Gortdrum. However, sedimentary evidence indicates that the transport direction into the Munster Basin at the time of deposition of the Castlehaven Formation was from the west (MacCarthy, 1990), so the derivation of the radiogenic detrital minerals in the Red Beds from the granite source to the west seems more likely. Although the metals in the Red Bed-hosted copper deposits are derived from both a basement and Red Bed source, their lead-isotope signatures suggest that the dominant contribution of the metals was from within the Red Beds.

In contrast to the disseminated sulphides from Mount Gabriel and other areas, lead-isotope data for sulphides from the minor veinlets in the Red Beds are more tightly constrained with lower $^{206}Pb/^{204}Pb$ ratios than the disseminated mineralisation. Isotopic data for the minor veins could be interpreted in terms of a fluid flow homogenising the wide spread of Pb-isotope values from the disseminated sulphides. This is consistent with sulphur-isotope data (Ni Wen *et al.*, 1996), which indicates that sulphides in the minor veins were remobilised stratiform disseminated sulphides. For Duneen, where galena occurs in a 30 cm-wide quartz vein in the upper Devonian - early Carboniferous Kinsale Formation, the lead-isotope data given by O'Keefe (1987) are identical to that of other minor veins in the Red Beds.

For the major veins at Allihies, Dhurode and Ballycummisk, the lead-isotope data forms a well-defined group on the $^{206}Pb/^{204}Pb$ v $^{207}Pb/^{204}Pb$ plot. This group lies between the mixing line for the basement-derived Caboniferous-hosted Zn-Pb sulphides, and the mixing line for the disseminated Red Bed-hosted copper mineralisation (Fig. 25). It seems plausible to suggest that the bulk of the lead and other metals in the major veins were derived from the basement beneath the Red Beds, with only a minor contribution of metals from a Red Bed source.

Sulphide Mineralisation Hosted by Carboniferous Carbonates

The carbonate-hosted Cu-polymetallic deposits of SW Ireland described here, together with the Cu deposit of Gortdrum (Duane, 1988), show an affinity with the Carboniferous Zn-Pb deposits of central Ireland, as shown in Figure 23. The lead from the stratabound Cu-As-Pb-Zn ± Ag-Co-Ni-Mo assemblage plots close to the same mixing line as the carbonate-hosted Zn-Pb deposits of the Midlands, towards the end-member defined by the southeast basement source (Figs. 23 and 21). This implies that the lead in the stratabound carbonate-hosted Cu-polymetallic deposits was derived dominantly from a basement source in much the same way as for the Courceyan Zn-Pb deposits of central Ireland as described by Everett *et al*. (1999b). Such an interpretation is consistent with geological evidence. Ross Island and Muckross are close to the Variscan Front, where the Red Beds beneath the limestones are thin (e.g., Gortdrum is underlain by only 300 m of Red Beds). For the epigenetic veins, lead-isotope values have similar $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios to the stratabound ores, but have higher $^{206}Pb/^{204}Pb$ ratios. This may reflect a different time of extraction rather than a different source.

The Cu-Pb mineralisation at Ardtully differs from other deposits because of the copper-dolomite association, and its distinctive highly radiogenic isotopic signature. According to Russell (1983), this copper-dolomite association, forms when late-stage, 'spent' fluids pass through a significant thickness of oxidised continental red beds picking up copper and other metals. The depocentre of the Munster Basin is in the region of the Kenmare River, close to Ardtully, where the thickness of the Red Beds is in excess of 6 km (Williams *et al*., 1989; MacCarthy, 1990). It would seem feasible therefore, that the Ardtully carbonate-hosted Cu and Pb were derived solely from within the Red Beds. As with the metals at Mount Gabriel, it is envisaged that the highly radiogenic nature of the samples originates from granite-derived detrital minerals disseminated in the Red Beds.

DISCUSSION

Ross Island shows similarities both with the Zn-Pb deposits of the Irish Midlands and the Cu deposits of the far SW of Ireland. The Cu-As deposits on Ross Island are hosted in the same Courceyan carbonate formation as the Zn-Pb deposit at Silvermines and elsewhere, and carry the same metal assemblage in the stratabound mineralisation at Blue Hole as in the Irish Midlands. This implies that there is a temporal link between these two different types of deposits in spite of the fact that Ross Island is copper dominated and the Irish Midlands are Zn-Pb dominated. In addition, although the host rock differs, the ore petrology of the later epigenetic Cu mineralisation at Western Mine on Ross Island is very similar to the mineralogy of the late, Red Bed-hosted, major-vein sulphide assemblage of the Munster Basin. In both settings, sulphides lie along spaced cleavages. In core samples from Ross Island, in particular, it is clear that some chalcopyrite-tennantite grows along pressure-solution cleavage in the host limestones, and in the Munster Basin, Cu and Cu-Fe sulphides occur along spaced cleavages. This demonstrates that some ores are associated with cleavage formation and are, therefore, temporally linked to early Variscan tectonism.

In Ireland peak metamorphic temperatures of 300-400°C were achieved during extension and high-heat flow associated with the formation of the Munster Basin (Meere, 1995b; Ni Wen *et al*., 1996). Subsequent compressional tectonics of the Variscan orogeny resulted in the formation of a spaced pressure-solution cleavage during initial layer-parallel shortening (Cooper *et al*., 1984, 1986; Meere, 1995a). In the Red Beds, primary copper minerals were removed from domains where cleavage formed and re-deposited in adjacent narrow zones or in minor segregation veins. Later folding is thought to have controlled megascopic fluid flow in the Munster Basin (Meere and Banks, 1997) while subsequent high-angle reverse faults are thought to be either reactivated extensional structures, in the case of the Munster Basin (Price and Todd, 1988; Meere, 1992), or controlled by Caledonian basement architecture in the Irish Midlands (O’Reilly *et al*., 1999). The major Red Bed-hosted veins originated after peak metamorphism from lower temperature circulating fluids which scavenged metals from large volumes or rock and deposited sulphides in major veins, often in fault zones (Ni Wen *et al*., 1996, 1999). A decrease in temperature from peak metamorphic conditions is associated with trapped fluids from veins ascribed to the Variscan compressional phase, in Ireland (Ni Wen *et al*., 1996) and in northern France (Kenis *et al*., 2000), and a final stage of veins in France, associated with post-orogenic extension, which trapped fluids at even lower temperatures (Kenis *et al.*, 2000).

It is envisaged that the radiogenic lead in the Red Bed-hosted disseminated sulphides was derived from disseminated detrital minerals sourced from granite to the west of the basin. Sediment input to the Munster Basin was influenced by stable areas occupied by granitic plutons both to the east and west of the basin and, by late Devonian times, the major transport direction appears to have been from the west (MacCarthy, 1990). Geophysical evidence for an unexposed granite to the west of the Munster Basin is given by Conroy (*in:* Murphy, 1990). Assuming that this granite has a similar age to the Leinster Granite and other Caledonian plutons (*c*. 400 Ma), exhumation of the intrusion must have occurred by late Devonian times, since the Castlehaven Formation, which hosts the disseminated mineralization, has a stratigraphic age of *c*. 380 - 370 Ma. In addition, there is clear evidence, based on the sudden appearance of microcline feldspar (Penney, 1979) in the Ballyhoura Mountains, that a granite source was unroofed by Kiltorcan times (Upper Devonian-Lower Carboniferous). There is also granite-derived muscovite in lowermost Courceyan limestones north of Mallow (Clipstone and Roycroft, 1992). Exhumation and erosion of Caledonian granites must have occurred within 20 million years of emplacement. Such rapid exhumation of granite plutons following orogenesis is documented from elsewhere in the Caledonides, notably in Scotland (Oliver *et al*., 2000).

The Red Bed-hosted minor and major veinlets, which show more tightly constrained $^{206}Pb/^{204}Pb$ ratios than the disseminated mineralization, are interpreted in terms of a fluid flow homogenising the wide spread of Pb-isotope values from the disseminated sulphides. For the major veins at Allihies, Dhurode and Ballycummisk, which developed after major folding (Sheridan, 1964), the Pb-isotope data plot close to that of basement-derived Carboniferous sulphides. Stable-isotope data presented by Ni Wen *et al*. (1996) indicated that the metamorphic fluids responsible for deposition of sulphides in the major veins were trapped in the temperature range 280-350°C. Assuming an elevated gradient of *c*. 40°C per km, then these fluids either circulated to, or originated from depths of, at least 6 km in order to attain such high temperatures. Since the thickness of the Red Beds beneath Dhurode and Ballycummisk is between 2 and 3 km (Williams *et al.,* 1989; fig. 2) an involvement of the basement is implied. It is suggested therefore that the majority of the lead and other metals in the sulphides of the major veins were most likely derived from clay minerals within the Lower Palaeozoic rocks during dehydration reactions associated with greenschist facies metamorphism with only a minor component from breakdown of detrital minerals in the Red Beds.

There has been much debate as to whether metamorphic fluids escape in a single-pass flow or circulate in large-scale hydrothermal systems (Phillips *et al.,* 1994), and although there have been theoretical arguments against mass fluid flow, Ferry (1988a, b), Yardley *et al.* (1991) and others, suggest that fluid flow occurred during or after peak metamorphism in large hydrothermal systems. Although the evidence from fluid inclusion, stable isotope, and ore studies (Ni Wen *et al.,* 1996, 1999) indicated that major fluid movement was post peak metamorphism, the inhomogeneity of the lead-isotope data in this study does not suggest large-scale hydrothermal systems.

At Muckross, Crow Island and Ross Island, the early stratabound Cu-As-Pb-Zn ± Ag-Co-Ni-Mo assemblage is regarded as syngenetic to diagenetic. Because their isotope ratios plot close to the same mixing line as the carbonate-hosted Zn-Pb deposits, towards the end-member defined by the southeast basement source on Pb-isotope diagrams (Fig. 27) it is suggested the main source of the lead was basement-derived. Any contribution of lead from the Red Beds must either have been minor or else the lead and other metals originated from leachable clays and detrital minerals that had themselves been derived from the basement rather than a granite source. Certainly Ross Island, Muckross and Crow Island are close to the Variscan Front, where the siliciclastic Red Beds are thinner (*c.*1000 m) than at deposits such as Allihies (*c.* 5500 m of upper ORS; Williams *et al*., 1989) and Mount Gabriel (*c.* 2750 m; Williams *et al.,* 1989).

Chalcopyrite-tennantite with minor copper-and nickel-bearing cobaltite and rare trace amounts of pyrite, marcasite, arsenopyrite, molybdenite, bornite, galena, sphalerite and stromeyerite were deposited in veinlets and along spaced cleavages. For the epigenetic veins, lead-isotope values have similar $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios to the stratabound ores, but have higher $^{206}Pb/^{204}Pb$ ratios, which may reflect a different time of extraction from the same basement source as the stratabound lead. Ultimately, thrusting occurred on Ross Island and veins were rotated into a subparallel alignment with the cleavage. Virtually all mineralisation pre-dated thrusting and is restricted to the Ballysteen Limestone Formation, which confirms the original observations of Weaver (1838).

For the copper-dolomite vein mineralisation at Ardtully the distinctive radiogenic isotopic signature has been interpreted as originating from granite-derived detrital minerals disseminated in Red Beds. The copper-dolomite association has been attributed to late-stage fluids deriving metals from a significant thickness of oxidised continental Red Beds (Russell, 1983). A copper-dolomite association is very weak to absent at Ross Island, where the underlying Red Beds were much thinner than at Ardtully, but has been recorded from Tynagh (Banks and Russell, 1992). A similar copper-dolomite association at Great Orme, North Wales has also been shown to have a highly radiogenic signature (Ixer and Davies, 1996).

The difference in overall setting between the Courceyan carbonates Cu-dominated assemblage of Muckross, Crow Island, Ross Island and Ardtully and the Courceyan carbonate-hosted Zn-Pb deposits in the Irish Midlands, is the thickness of Red Beds beneath the carbonates between these two areas with < 300 m of Red Beds in the Irish Midlands. It is therefore tempting to suggest that the difference in ore assemblage between the two areas might be due to copper derivation from Red Beds in the southwest. Although the radiogenic lead-isotope data for samples from Ardtully, can be interpreted as due to derivation of metals entirely from within the Red Beds, there is little isotopic evidence for a major Red Bed contribution to the Cu-dominated assemblages of Muckross, Crow Island and Ross Island unless the lead and other metals in the Red Beds originated from minerals that had themselves been derived from the basement rather than a granite source. An alternative possibility is that the Palaeozoic basement in the southwest was more copper-rich than that beneath the Irish Midlands perhaps derived from an Ordovician island arc. Preserved remnants of a volcanic island arc, formed above a southeasterly-dipping subduction zone, occur in southeast Ireland. Cu-Zn-Pb mineralisation occurs at the top of a major cycle of acid volcanism of Llandeilo-Ashgill age at Avoca Mine, from where 16 Mt of Cu were extracted in the period 1958-1962 (Williams *et al*., 1986). Along strike at Bunmahon, copper mineralisation is associated with basic volcanics of Upper Ordovician age (Phillips and Sevastopulo, 1986). If this island arc were projected beneath the Devonian-Carboniferous cover of the Munster Basin, then it would subcrop in the vicinity of Kenmare.

Recent work has highlighted the fact that stratabound, replacive mineralization, dominates the Irish deposits (e.g., Johnston, 1999; Reed and Wallace, 2001). However, the occurrence of bedded barite at Ballynoe, Silvermines (Mullane and Kinnaird, 1998), together with pyritised worm tubes (Boyce *et al*., 1999) implies that seafloor hydrothermal exhalation did occur and that mineralisation was initiated by late Courceyan times (*c*. 355 Ma, Boyce *et al*., 1999). The stratabound mineralisation at Muckross, Crow Island and Ross Island is in the same limestone formation as the bedded barite in the Ballynoe pit at Silvermines. The model age assigned here of *c*. 360 ± 15 Ma for stratabound ores at Muckross, is close to the host rock Ballysteen limestone, which has been assigned an age of *c*. 355 Ma on the basis of conodont data (Ps. multistriatus conodont Biozone; Jones and Somerville, 1994). This coincidence of dates is consistent with a syngenetic to early diagenetic origin for the formation of the carbonate-hosted stratabound sulphides.

Field evidence indicates that in many localitites (e.g., Lisheen and Galmoy), mineralisation is intimately associated with faulting and the occurrence of extensive tabular bodies of dolomite matrix breccia (Johnston, 1999). At Navan, the main feeders to the ore deposit were minor ENE-, NE- and NNE-trending normal faults (Blakeman *et al.*, 1999). The Navan deposit has been dated as Chadian/early Arundian (*c*. 345 Ma) largely on the basis of mineralised clasts found in syndepositional conglomerates overlying an erosion surface that truncates the orebody (Ashton *et al.*, 1992; Anderson *et al.,* 1998). The age assigned to the mineralisation at Navan is consistent with previous ages obtained for the Navan, Tynagh, and Lisheen Zn-Pb and Gortdrum Cu-Ag±Hg deposits of Midland province (Table 10). Later mineralisation associated with post-Waulsortian breccia-hosted deposits (e.g., Kildare - Johnston, 1999) are evidence for the continuation of sulphide deposition into Arundian times (< *c*. 345 Ma). All available evidence therefore indicates the sulphide deposition spanned a period of > 20 Ma.

A much younger model age of *c*. 270-290 Ma has been determined for the carbonate-hosted epigenetic chalcopyrite-tennantite associated with minor veinlets at Western Mine (Fig. 27). This would imply a Permian age for the mineralisation if the lead had evolved in a single stage system. Halliday and Mitchell (1983) determined similar K-Ar ages on clay concentrates from samples associated with mineral deposits, including the Cu deposits of SW Ireland. The most unambiguously defined ages are from Duneen Bay (*c*. 281-293 Ma: 4 samples), Ballydehob (*c*. 280-285 Ma) and Derryginagh (*c*. 290-308 Ma). Ages from other deposits like Cappaghglass (*c*. 276-290 Ma) and Mountain Mine, Allihies (261-290 Ma), are also in general agreement. Halliday and Mitchell (1983) suggested that the within-site spread of data does not represent ore formation over tens of millions of years; rather it is due to minor effects of hydrothermal degassing and post-mineralisation disturbances. They suggested a mineralising event close to 290 Ma, which is the time of granite emplacement in SW England.

This *c.* 270-290 Ma model age for cleavage-controlled mineralisation has important implications for the timing of the Variscan orogeny in southwest Ireland. Since pressure-solution cleavage developed during folding and before faulting and thrusting, the *c.* 270-290 Ma age date for ores associated with the cleavage implies that the thrusting episode that emplaced the tectonic sheet of Ross Island must be younger than this. Certainly, in the seven borehole cores drilled in the vicinity of the Bronze Age Mines (Nex *et al.*, 2001), which cut through the thrust plane, there is no evidence of any mineralisation associated with either the thrust plane, or in the carbonates structurally below, suggesting that there was no remobilisation after thrusting at Ross Island.

Clearly, the spaced-cleavage controlled ore assemblage of Cu sulphides in both the Red Beds and carbonate-hosted deposits have similar ages. However, evidence for this later event is also evident in the Zn-Pb deposits of the Irish Midlands. Halliday and Mitchell (1983) stated that there is evidence for a later event *c*. 275 Ma at Gortdrum, whilst Boast *et al*. (1981) calculated model ages of 271± 24 Ma for galena from Silvermines.

The source of the fluids that penetrated into the basement of southwest Ireland has not been resolved. For the Zn-Pb deposits of the Irish Midlands, two main alternatives have been proposed: a hydrothermal circulation initiated during extension (e.g., Russell, 1983; Everett *et al.*, 1999b) or a topographically expelled fluid from the Variscan orogen (e.g., Hitzman, 1995; Hitzman *et al.*, 1999). Everett *et al.* (1999b) presented fluid inclusion data from Lower Palaeozoic-hosted sulphide-bearing veins and showed significant variation reflecting systematic lateral changes, which would be inconsistent with an aquifer-confined topographic flow model. However, Wright *et al.* (2000) showed that no single fluid flow model is valid. A hybrid model involving both regional and localised fluid flow systems is more appropriate (Garven *et al.*, 1999; Wright *et al.*, 2000).

CONCLUSIONS

The most important consequence of this work is the recognition of two phases of mineralisation in southern Ireland, one during Carboniferous basin extension - the other during Variscan compression. An age of *c.* 360-340 Ma has been calculated for the Carboniferous-hosted stratabound mineralisation at Muckross, Crow Island and Ross Island with mineralisation associated with Variscan compression suggested between *c.* 290-270 Ma.

The timing of the Carboniferous stratabound Cu-As-Ag-Zn-Pb polymetallic deposits in southern Ireland, and the Zn-Pb deposits of the Irish Midlands seem broadly contemporaneous. The difference in the ore assemblage between the two areas might be due to slightly differing sources of the metals. In the Irish Midlands where the carbonates are underlain by lower Palaeozoic greywackes with little or no Red Beds, the ore metals must have been derived entirely from the basement. In contrast, for the Red Bed copper deposits of the southwest, which are underlain by several kilometres of Red Beds there was a mixing between lead sources, some being derived from the Red Beds, and some from a deeper basement source. It is envisaged that there has also been a similar mixing of metals for the carbonate-hosted mineralisation although the isotopic evidence does not clearly indicate that the Red Beds have made a contribution to the copper in the deposits at Ross Island, Crow Island and Muckross unless the lead in the Red Beds originated from a basement rather than a granite source. It is only for the data from Ardtully that a derivation of metals from within Red Beds is implied. An alternative possibility is that the Palaeozoic basement in the southwest was more copper-rich than that beneath the Irish Midlands perhaps derived from an Ordovician island arc.

The later phase of mineralisation (*c*. 270-290 Ma) was associated with Variscan compression. In the Red Beds, remobilised disseminated ores were deposited along spaced cleavages and minor veinlets and major sulphide-bearing veins formed after folding. At the same time, in the carbonate-hosted deposits, a similar basement-derived chalcopyrite-tennantite assemblage was deposited along spaced cleavages and in veins.

It is concluded that disseminated mineralisation in the Red Beds, and the veins at Ardtully, are sourced entirely within the Red Beds, that minor veins in the Red Beds are remobilised sulphides from the disseminated ores, and that the metals within Red Bed-hosted major quartz veins and carbonate hosted ores are predominantly derived from a SE-type basement.

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