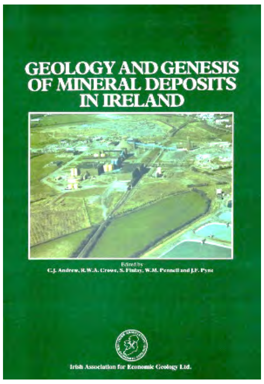

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To cite this article: Williams, B. & Brown, C.(1986) A model for the genesis of Zn-Pb deposits in Ireland. *In:* Andrew, C.J., Crowe, R.W.A., Finlay, S., Pennell, W.M., and Pyne, J.F. '*Geology and Genesis of Mineral Deposits in Ireland*', Irish Association for Economic Geology, Dublin. 579-590. DOI:

To link to this article: https://

A model for the genesis of Zn-Pb deposits in Ireland.

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Abstract

An analysis of the gravity and magnetic data for the Irish Midlands has suggested a framework around which a genetic model for Irish zinc-lead mineralization can be proposed. An interpretation of these data and the published work of other authors suggests that the location of the major mineralized zones are closely related to major faults. The gravity data show that these faults are near the margins of upstanding Caledonide volcanic blocks, indicating that the ore bodies may be associated with the dewatering of adjacent sandstone or shale-filled troughs. The effects of enhanced heat flow and temperature gradients on these trough sediments show that they are consistent with depositional temperatures of Irish ore bodies. It is suggested that periodic crustal stretching/subsidence and loading of the deep shale troughs led to episodic expulsion of metal-bearing fluids to the trough margins. This mechanism probably operated from the mid Courceyan through to the Viséan.

It is suggested that the mineralization is intimately related to the evolution of growth faults at the trough margins. These were important for the development of high permeability zones which focussed metal-bearing fluids into the host rocks. The style of mineralization then depends mainly on the state of lithification of the carbonate host rocks which generally lie on top of the upstanding Caledonide blocks. An interpretation of the gravity data over five major mineralized zones is discussed to support this thesis.

Introduction

In a recent paper (Brown and Williams, 1985), we presented a gravity and magnetic interpretation of regional structures within the Irish Midlands. The existence of a series of NE-trending, linear, volcanic, horst blocks separated by troughs containing great thicknesses of Carboniferous sediments provided the empirical evidence for a simple crustal-stretching model for the evolution of the Irish Midlands Basin. The proximity of the known major mineralized zones to the margins of these troughs led us to suggest that the genesis of the mineralized bodies was closely associated with the de-watering of the trough sediments. This paper is an attempt to examine the implications and physical constraints of our model for the evolution of the Midlands on the genesis of Irish carbonate-hosted ore bodies. It relies extensively on the results presented in the study referenced above, and this should be consulted for details of many of the ideas contained in the first part of the paper.

Geology and gravity and the formation of the Irish Midlands

The Irish Midland Plain consists of blanket bog and till underlain by Carboniferous limestones with inliers of red sandstones, some of which have cores of Silurian rocks (Fig. 1). The Lower Palaeozoic rocks of the Longford-Down Inlier fringe most of its northern margin, and the Leinster Granite occupies a large area at its SE corner. The Precambrian rocks in the area are probably composed of granulite facies gneisses which may be the source of seismic p-wave velocities of $\sim 6.1 \mathrm{kms}^{-1}$ (Jacob et al., 1984). The depth of this seismic refractor is estimated to be about 3 to 4km and is roughly coincident with the depth to the top of the deep sources of magnetization within the Irish Midlands. Although there is evidence of considerable volcanism with extensive pyroclastic deposition, the Ordovician volcanic rocks are often only weakly magnetic. The known exceptions in the study area, viz. The Strokestown (north of Navan), Slieve Aughty and Kildare Inliers, are thought to be the exposed parts of volcanic centres which have prominent gravity and moderate magnetic expressions.

Volcanic activity decreased during the Ordovician and was followed by deposition of shales, sandstones and greywackes during the Silurian. The Iapetus Ocean closed by the end of the Silurian, and the Midlands was then an area which was subsequently uplifted and eroded during the later Silurian and Devonian. There seems to be no true Old Red Sandstone in the Central Midlands (Feehan, 1982), and the early Carboniferous marine transgression from the south was the first major depositional event on the highly eroded Silurian and Ordovician peneplaned surface.

Although the Carboniferous rocks show a complex variation in facies, their densities are almost indistinguishable from the underlying succession of Silurian and Ordovician sediments, i.e. $\sim 2.75 \mathrm{Mgm}^{-3}$. Therefore, the gravity field over the Midlands will contain some information on the topographic variations of the interface between the Ordovician volcanic rocks and the overlying succession of Ordovician to Carboniferous sediments. We can only isolate this information after we have removed the effects of other sources which contribute to the gravity field.

Professor T. Murphy of the Dublin Institute of Advanced Studies kindly supplied us with the gravity data for the Midlands. The sources which dominate the gravity data are the granites surrounding the central Midlands (e.g. the Leinster Granite and buried granites beneath Glenamaddy and Kentstown/Bellewstown) and variations in the density distribution at crustal depths greater than ~4km. If we wish to isolate the gravity effects due to the required interface, we must first remove the gravity effects of the major granites and then eliminate the long-wavelength components of the gravity field which arise principally from sources in the mid to lower crust. The residual gravity field so obtained emphasizes the gravity effects of the near-surface structures in which we are interested.

The residual gravity map (Fig. 2) is dominated by a series of linear anomalies trending northeasterly. Similar patterns have been observed by Professor T. Murphy (pers., comm.). These alternating high and low gravity anomalies have extremely steep gradients, and we believe that they are caused by low density sediments that have accumulated in troughs separated by high density volcanic blocks. The density contrast of $0.07Mgm^{-3}$ is caused by the Carboniferous rocks (plus a thin layer of Silurian and Ordovician siltstones and shales in the troughs) lying on top of the Ordovician volcanics. A simple geological model giving rise to the residual gravity has been constructed for a profile along AA$^{\prime}$ (Fig. 3). If the density contrast is less than $0.07Mgm^{-3}$ (e.g. due to compaction of trough sediments with depth), the troughs may be as much as 1km deeper than shown.

We believe that the volcanic blocks are antiforms created in a late Caledonian compressional regime. The field evidence from extensive exploration drilling suggests that repeated faulting during the Carboniferous occurred in linear zones close to these block margins (Poustie, A., pers.comm., Crowe, R., pers.comm.; Slowey, E., pers.comm.). This suggests that these margins were zones of structural weakness along which differential subsidence commenced in the earliest Courceyan. This subsidence, together with a general subsidence of the Midlands, enabled the accumulation of sandstones followed by shales and limestones in troughs bounded by multiple listric faults.

The extensional features so interpreted may be the consequence of a tensional regime which developed in late Devonian to early Carboniferous times due to the closure of the Hercynian Mid-European Sea. The slab-pull forces stretched the continental crust beneath the Irish Midlands causing extension by normal faulting in the brittle upper crust and extension by ductile flow with mafic material emplacement in the lower crust. A similar mechanism has been suggested for the formation of Carboniferous basins in Northern England (Bott et al., 1984). The stretching in Ireland seems to have been limited to the north by the Longford-Down Inlier and possibly by the Glenamaddy Granite to the west.

Within the troughs there were deposited basal sandstones grading up into highly variable, limestone, calcareous-shale, mudstone sequences (e.g. Sheridan, 1972). By the late Courceyan, sediments had been deposited that graded upwards through bioclastic limestones to Waulsortian mudbank limestones. The Waulsortian is known to vary dramatically in thickness over distances of hundreds of metres as a consequence of the irregular configuration of its lower surface (Sevastopulo, 1983). We suggest that these irregularities are intimately related to the block-trough structures.

The combination of the regional stress regime and sedimentary loading gave rise to major differential subsidence during the late Courceyan. In the Trim No. 1 well near Rathmolyon, located in one of the troughs delineated by the residual gravity map, some 400m of Waulsortian and 200m of oolitic limestones overlie an 825m thick calcareous-shale sequence. This shale sequence is underlain by ~270m of sandy limestones and is founded on a basal layer of early Courceyan sandstones of unknown thickness (Sheridan, 1972).

Implications for mineralization

The delineation of several major block-trough structures within the Irish Midlands and the identification of an early Carboniferous crustal stretching event present some interesting aspects to the debate on Irish carbonate-hosted ore genesis. The principal and well-known association between mineralization and local structure has, in the past, led to the theory that extensional fault systems acted as conduits up which the mineralizing fluids have ascended. There is, however, little concensus on the timing and source of these fluids. This paper is an attempt to place the controversy of the genesis of Irish zinc-lead deposits within our model of the geological development of an Irish Midlands Basin.

The geographical and structural locations of the known major mineralized bodies within the Midlands are summarized in Figure 5. Their apparent proximity to the margins of deep sedimentary troughs suggests that Irish carbonate-hosted ore bodies may be related to processes associated with these troughs. We have examined in detail the feasibility of a basin-brine expulsion mechanism in the light of our geological model.

Early and mid Courceyan temperatures, pore-fluids and mineralization

The sandstones and, later, shales accumulated in troughs that deepened relative to the horst blocks. It is quite likely that their original porosity was large (>60%); hence, their thermal conductivity was low. A typical value of the thermal conductivity within the shales can be estimated from data given in Figure 13 of Royden et al. (1983). An average value of $\sim 1.4Wm^{-1}{}^{\circ}C^{-1}$ appears to be appropriate for a 1km column of shales of the type we are considering. An estimate of the range of heat flows during the development of the Irish Midlands is probably best made by comparison with similar basins which are currently undergoing extension. The Pannonian Basin system provides such a comparison, and its evolution and thermal history have been extremely well documented by Royden et al. (1983). Typical heat flow values some 15Ma after the initiation of basin formation are $\sim 80 \pm 8mWm^{-2}$, a value some 35% higher than the normal heat flow through neighbouring parts of the European plate. Initial heat flow values for the Irish Midlands Basin may therefore have been in the range of 100 to $120mWm^{-2}$, and heat flow calculations suggest that a temperature gradient of $80^{\circ}C\ km^{-1}$ was not difficult to attain within the troughs.

As the shales accumulated in the troughs, they were subjected to a vertical compressive stress which initially produced an increase in pore pressure until the pore pressure reached the lithostatic value. With time, fluids were expelled until the pore pressure decreased to the lowest limit compatible with the hydrostatic column (Sclater and Christie, 1980). At this point, continued sedimentary loading recompacted the shales, and fluid pressures were increased to lithostatic values, whereupon fluids were again expelled. The net effects of this process were that fluids were expelled episodically and the porosity of the shales decreased. The volume of shales may have decreased by a factor of 3 or more. Thus the 825m of shales in the Trim No. 1 well were probably the result of continual, but episodic, expulsion of fluids from an 'unloaded' shale column at least 2km thick.

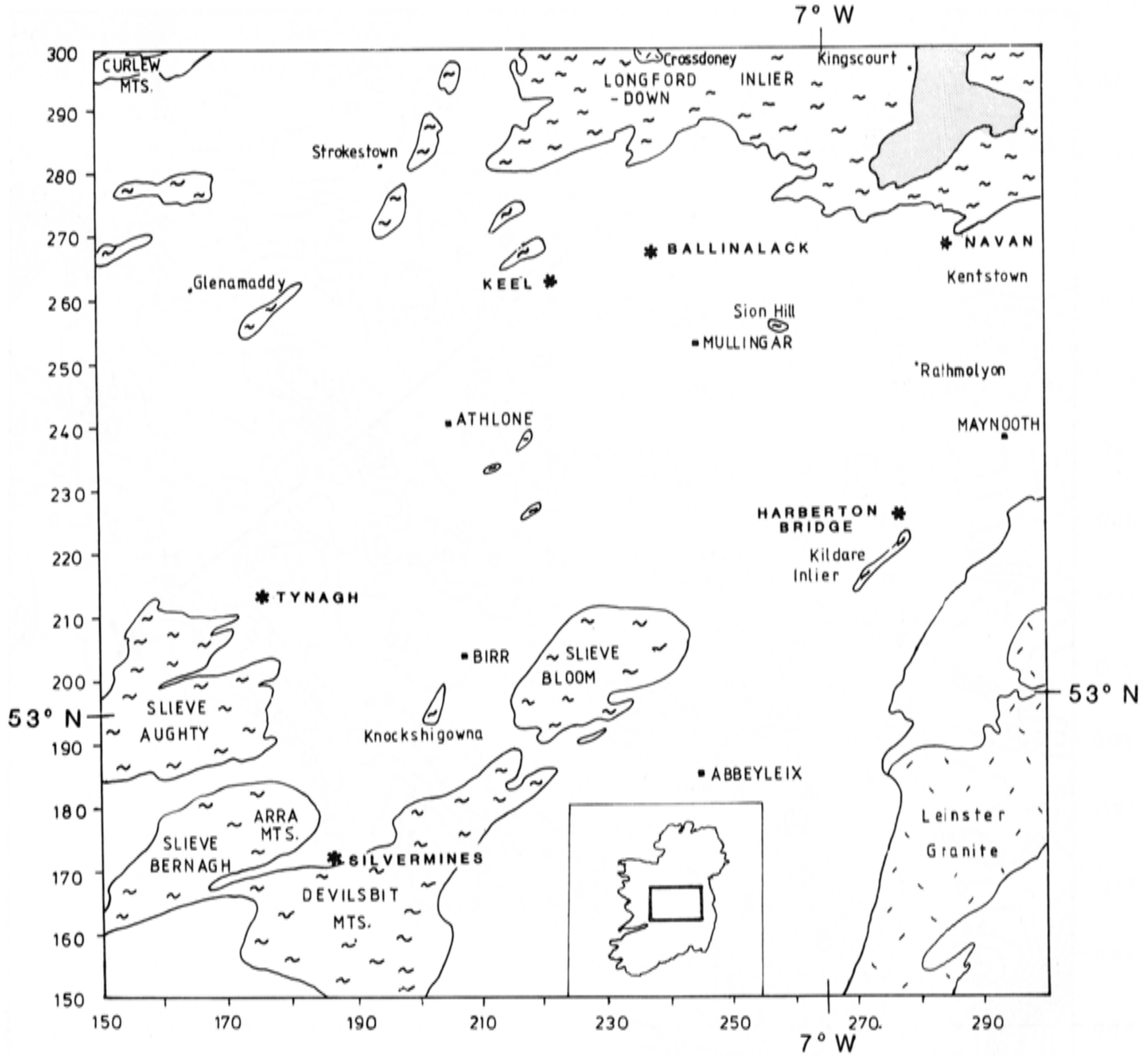

Figure 1. A simplified geological map of the Irish Midlands together with the locations of the known major mineralized bodies:— Ballinalack, Navan, Silvermines, Tynagh, Keel and Harberton Bridge. The Lower Palaeozoic inliers and Leinster Granite are also shown. Co-ordinates are Irish National Grid in kilometres.

When this sedimentary column reached a minimum thickness (~1km), the pressure also induced mineralogical changes in the shales; it rearranged the lattice of the clays so that they were transformed from compressible to non-compressible clay minerals (Lydon, this vol.). The collapse of the lattice due to sedimentary loading resulted in the expulsion of metal-bearing fluids which migrated along an appropriate pressure gradient. Smith et al. (1983) have suggested that dewatering of shale troughs near the Pine Point lead-zinc deposits can occur by fluid migration through an underlying porous horizon if the upper parts of the shale sequence are capped by an impermeable layer. Thus the metal-bearing fluids may have migrated from the deeper parts of the shale trough and the basal Carboniferous sandstones to the trough margins.

Late Courceyan and Viséan temperatures, faulting and mineralization

The temperature range of the fluids expelled from the shales was dependent on the average temperature gradient in the whole of the sedimentary sequence and the depth of burial of the shales. The temperature gradient was unlikely to be as high as 80°C km^{-1} as in the early or mid Courceyan because (1) there was an increase in the thermal conductivity of the shales during compaction, (2) the sequence contained moderately conducting limestones, and (3) the heat flow associated with crustal stretching was probably smaller. A temperature range of 100 to 150°C seems reasonable at depths of ~2 km.

The continuing differential subsidence gave rise to listric normal faulting at the trough margins. These faults have been subjected to multiple reactivation, and this was probably the result of the stress-concentration mechanism of Kuznir and Bott (1977). The lithosphere was stretched, and the stress was lowered in the lower ductile layer at the expense of its amplification in the upper, brittle crust. This concentration of stress proceeded until the deviatoric tension exceeded the tensile strength of the upper crustal rocks, and faulting occurred along lines of crustal weakness. The stress in the upper crust was immediately reduced but built up again, in a time of the order of 1 Ma, after which a further phase of faulting was initiated.

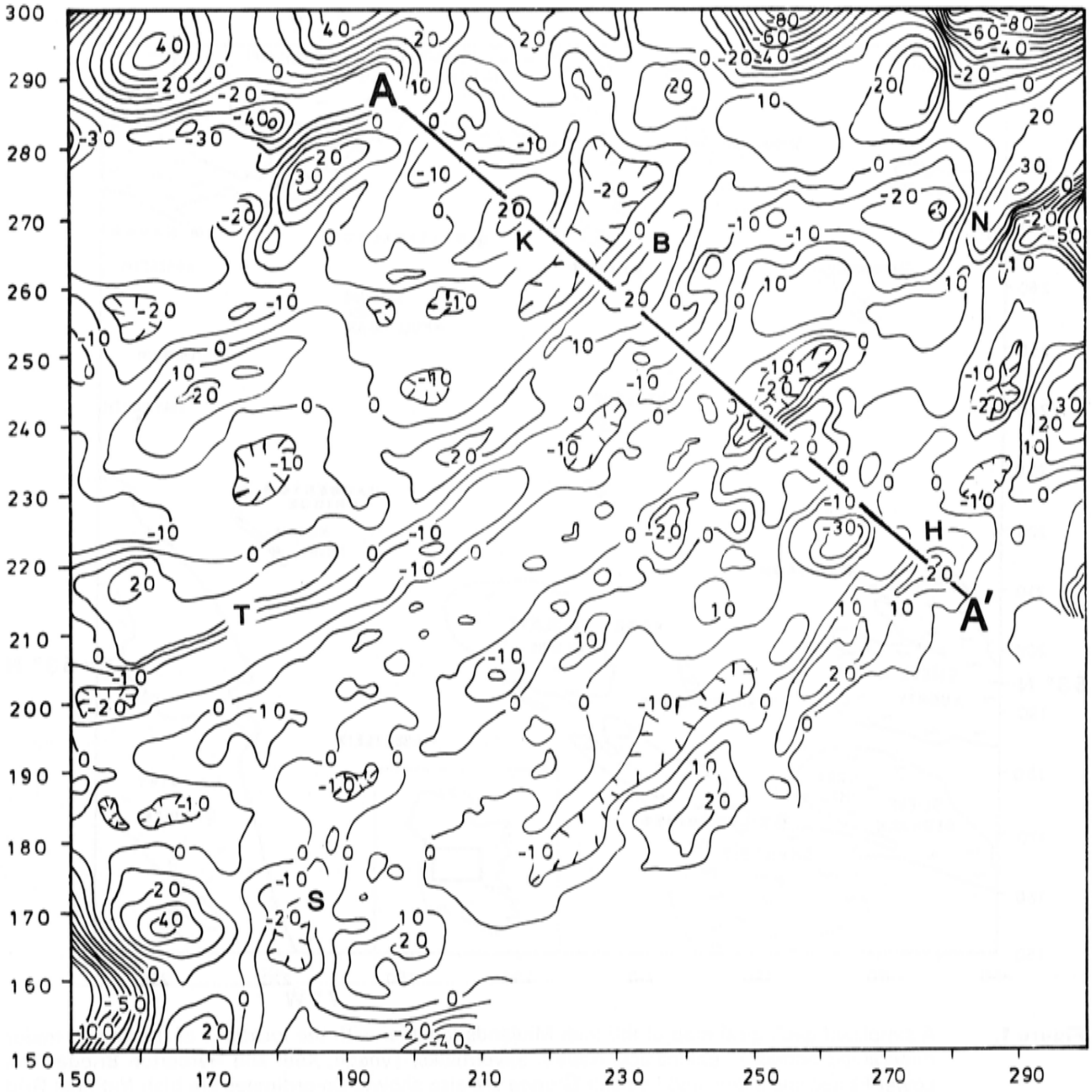

Figure 2. The residual gravity map of the Irish Midlands after the effects of the known granites have been removed and after long-wavelength components of the gravity field have been suppressed by filtering. The line AA′ corresponds to the section shown in Figure 3. The locations of the known mineralized bodies are also marked: Co-ordinates are Irish National Grid in kilometres Contours are every 10g.u. Map contoured after processing simple Bouguer anomaly point data supplied by Professor T. Murphy of the Dublin Institute for Advanced Studies.

The effect was to generate at the trough margins a series of growth faults which continued to move throughout the early Carboniferous. The evolution of faulting and differential subsidence at these margins may have been of importance to the expulsion of metal-bearing fluids from the troughs. The periodic faulting possibly initiated phases of sedimentary deposition. The Waulsortian limestones may have acted as an impermeable cap for the shales, and thus the subsequent episodic expulsion of pressurized, metal-bearing fluids from the shale troughs may have occurred through the porous basal sandstones and the high permeability zones created by the faulting. This episodic faulting and fluid expulsion was necessary to satisfy temperature constraints of Irish-type ore bodies. Their depositional temperatures tend to be in the range of 100 to 150°C (Boast, 1978). For such temperatures to be attained near the surface, fluid expulsion rates must be high enough to minimize heat losses during fluid migration to the deposition site. Cathles and Smith (1983) have shown that this is difficult to achieve with steady outflow of basin fluids; they appeal to a dewatering model consisting of episodic fluid expulsion (with periods ~1Ma) along structures which channel flow from a thin basal aquifer. Thus, we are suggesting that in the Irish Midlands the basal Carboniferous sandstones channelled the flow of pressurized, metal-bearing fluids from the troughs, and that the trough margin faults acted as the conduits which focussed these fluids to their final deposition sites.

The varied mineralization styles depended crucially on temporal relations between source and host rocks. We suggest that metal-bearing fluids were expelled episodically from basinal shales over the long period of time from the

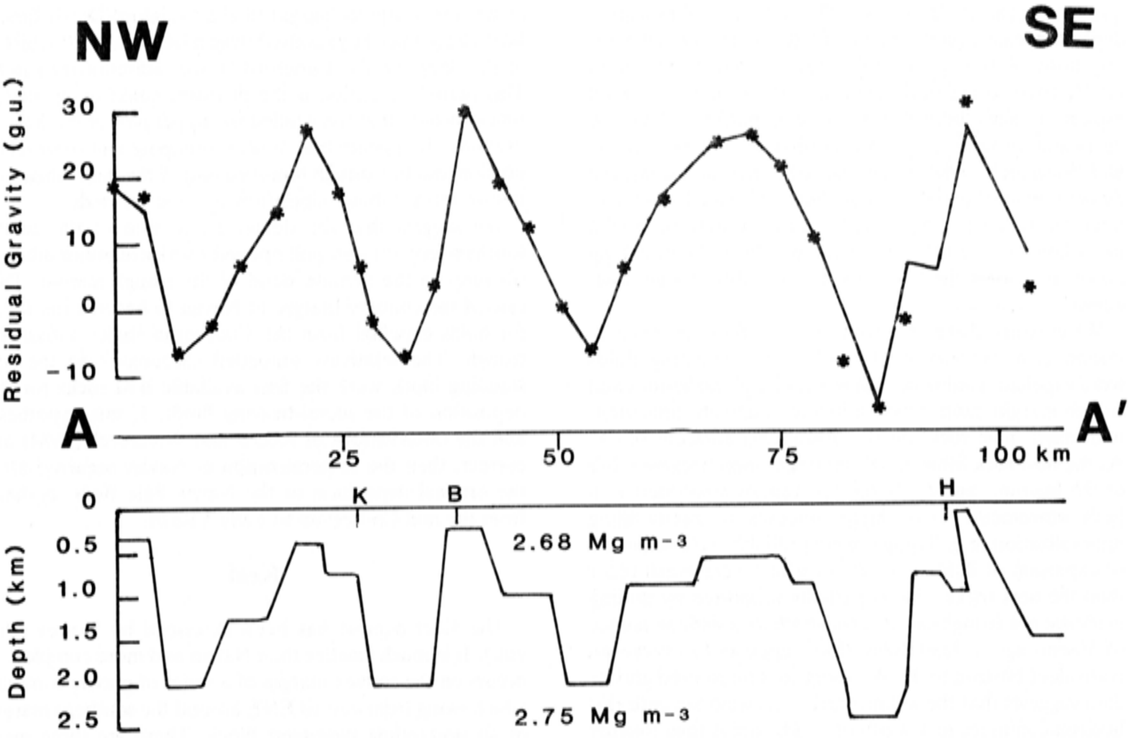

Figure 3. The upper part of the diagram shows the residual gravity profile along AA′ taken from the map in Figure 2. The crosses represent the theoretical values for the density model shown in the lower part of the diagram. The model shows the interface between the dense (2.75 Mg m^{-3}) Ordovician volcanics and the overlying succession of less dense (2.68 Mg m^{-3}) Ordovician to Carboniferous sediments. The troughs are typically 10-15 km wide, at least 2km deep and have steep margins. The approximate positions of known mineralized zones are marked: K=Keel; B=Ballinalack; H=Harberton Bridge.

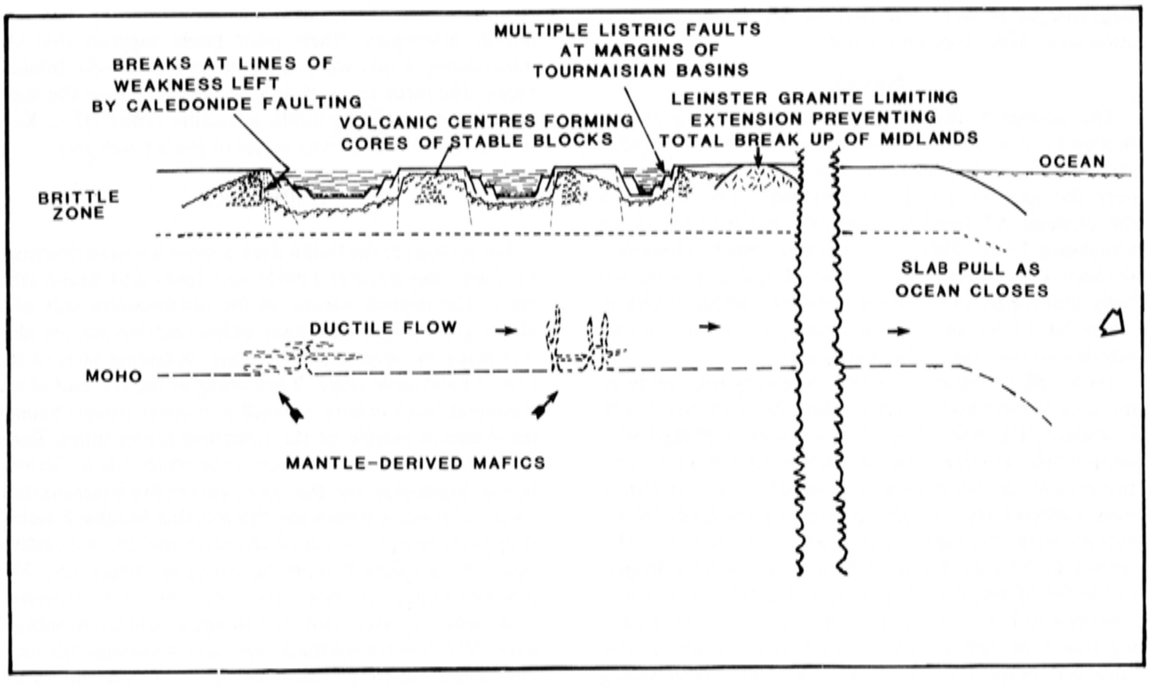

Figure 4. A sketch illustrating the model for the formation of the Irish Midlands Basin.

mid Courceyan to the Viséan. The style of mineralization depended mainly on the state of lithification of the sedimentary hosts on the up-standing blocks. Schlager and James (1978) have shown that carbonate oozes can, if covered rapidly, remain unlithified for several hundred thousand years and, in some cases, tens of millions of years. Kucha and Wieczorek (1984) have suggested that, at Navan, the emplacement of metal-bearing fluids may have been facilitated by the earlier deposition of low concentrations of a metastable zinc carbonate complex which, on breaking down, increased the host rock permeability during diagenesis.

We envisage that early, stratiform, replacement mineralization (e.g. Navan) occured when metal-bearing fluids were expelled from shales via porous basal sandstones and trough-margin fault zones into the relatively unloaded, unlithified, host rocks on the upstanding adjacent block. As the host rock lithified, the mineralization became more of the fracture- and cavity-fill-type usually associated with fault movement. Thus, large amounts of cavity-filling mineralization (e.g. Tynagh) were probably a consequence of expulsion of fluids from shales which were much older than the host rocks. This is partially supported by drilling evidence in a trough east of Tynagh where a shale sequence of Viséan age at least 700m thick, appears to overlie an equivalent horizon to the Waulsortian. Our filtered gravity data suggests that the sedimentary succession beneath this horizon continues to a depth of ~2km and is thus roughly contemporaneous with the "Calp" limestones and "reef equivalent" which host the fracture- and cavity-fill mineralization. We suggest that the soft sediment mineralization features seen at Tynagh originated from (mid?) Courceyan shales at the base of this succession, while the major cavity-filled mineralization originated from the younger Viséan shales.

Structural controls on major Irish ore deposits

Each of the major base metal deposits appears to lie on an upstanding horst block relatively close to the margins of large troughs. However, each deposit has its own mineralization styles and structural controls.

Navan

The geological and structural features of the Navan deposit have been detailed by Andrew and Ashton (1982) and Ashton et al. (this vol.). The Navan deposit occurs over the apex of a major gravity high. The source of this elongate NE-trending anomaly is partially due to an upstanding Lower Palaeozoic basement block. However, the anomaly is emphasized by a major Caledonide intrusive body that forms an intense gravity high whose centre is ~6km NE of Navan. This intrusive gives rise to syenitic and dioritic outcrops in the Navan area.

To the SE of Navan, a broad low gravity zone outlines the deep sedimentary trough in which the Trim No. 1 well is situated. The NW margin of this trough is marked by a steep gravity gradient, and the Navan deposit adjoins an embayment on this margin. The sweep of the structures from northeasterly to easterly is probably influenced by the massive intrusive on the underlying Caledonide block. The tension in the early Carboniferous created a deep trough to the SE of this basement high, but there is also some indication of later, tensional fractures across the NE-trending basement high to the SW of Navan, shown by the "necking" of the gravity contours. The dark, Viséan shales that occur within this secondary, pull-apart trough continue across the southern margin of the Longford-Down Inlier. We believe that they resulted from a later Viséan fracturing of the deep-rooted, Longford-Down, accretionary prism. This period of tension is the probable cause of the major unconformity that has eroded the upper part of the Navan orebody. It appears that Viséan slumping and submarine erosion into this trough removed part of the mineralization before further shale deposition covered the body.

We suggest that the deviatoric tension of the south-southeasterly (?) slab-pull opened a series of major dilation fractures in the arcuate bend of the trough margin. This caused the concave margin at Navan to become the focus for fluids expelled from the Courceyan shales within the trough. The relatively unloaded carbonates on the up-standing block were the first available host rocks for the deposition of the metal-bearing fluids. If this hypothesis and the observations of Kucha and Wieczorek (1984) are correct, then the mineralization at Navan occurred after the original deposition of the Navan Pale Beds, perhaps from the mid Courceyan to early Viséan.

Keel

The Keel deposit has been described by Slowey (this vol.). It is much smaller than Navan and more complex. It occurs on the convex margin of a series of gravity contours which swing from east to ENE around the southern margin of an upstanding basement block. There are three main styles of mineralization which are all associated with the swing of this margin and the creation of fractures.

The main Keel deposit is comprised of fracture-fill mineralization in a series of sub-parallel zones on the southern margin of an inlier; these zones splay to the west. Near the intersection of these zones with the main gravity linear, a small tonnage, stratiform, pyrite/barite deposit occurs below the Waulsortian limestones. To the north of the inlier-bounding fault, extensive lead-zinc mineralization occurs in basal Carboniferous rocks (Navan Beds) which outcrop on the flank of the inlier. These low-grade deposits extend for over a kilometre within the basal beds and represent mineralization which has been injected into porous lithologies. Their poor grade suggests that the mineralizing fluids were injected into relatively lithified rocks. The three types of deposit appear to have the same source of mineralizing fluids, a fracture centre NE of Keel on the apex of the convex series of gravity contours.

Ballinalack

The geology of the Ballinalack deposit has been described by Jones and Bradfer (1982) and Jones and Brand (this vol.). The deposit occurs on the northwestern side of a major gravity high. The three ellipsoidal deposits are aligned along the upper, NE-trending, bounding fault of the Lower Palaeozoic ridge. They occur at the NE end of the basement block where a small pull-apart trough bounds the southern margin of the Longford-Down Inlier. Early mineralization is known from pore-filled, basal Carboniferous lithologies, but the major part of the mineralization occurs in cavities within the Waulsortian Mudbank facies. It appears from its linear distribution that the mineralization was associated with NE-trending structures. The rapidly lithified, micritic limestones may have fractured easily when stressed while the trough continued to subside in the NW. The trough fluids may have filled these fractures after migrating to the fault bounding the NW side of the basement block.

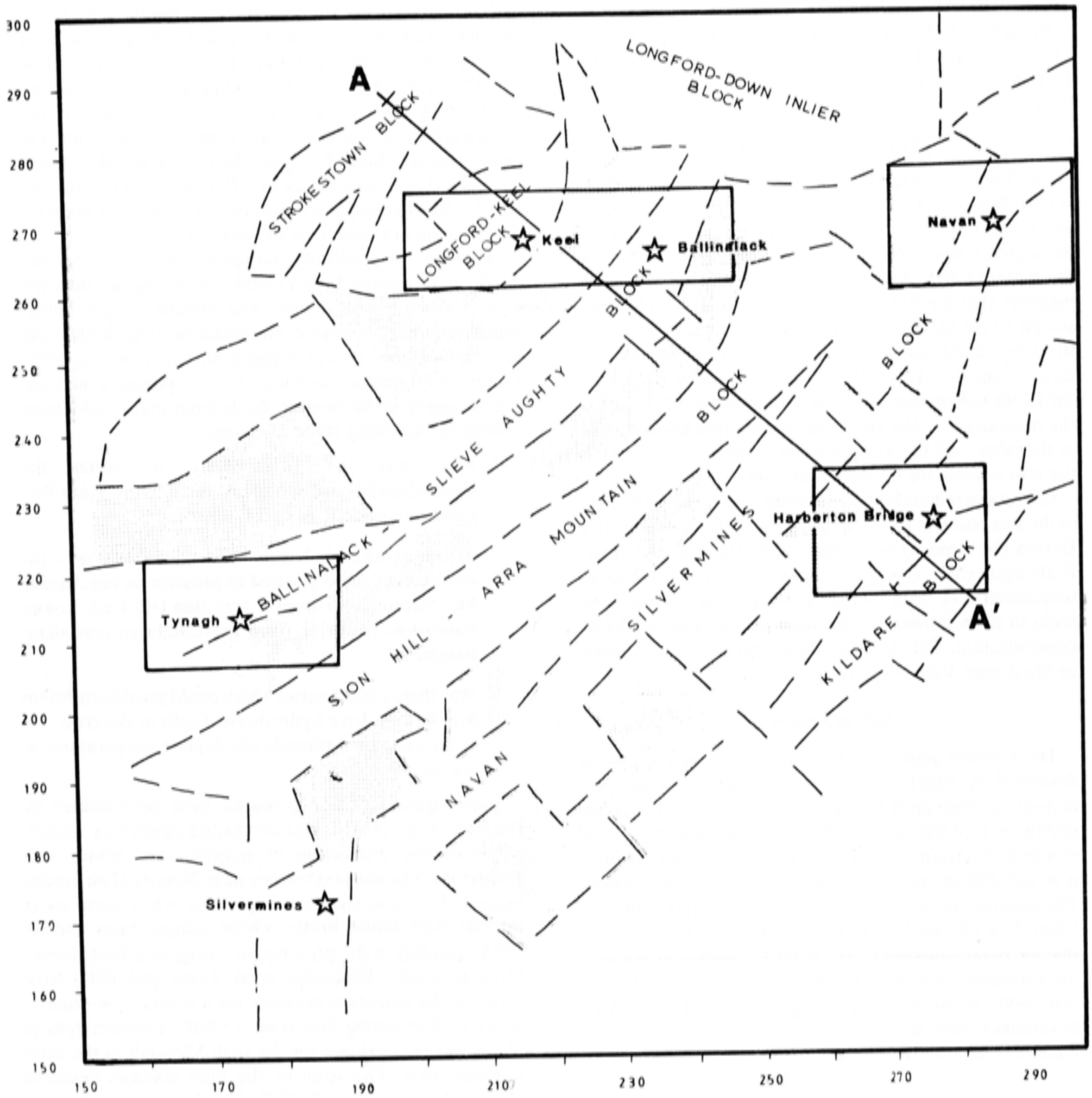

Figure 5. A simplified structural map of the Irish Midlands based upon our interpretation of the residual gravity data. The map illustrates the close relation between block-trough structures and the locations of the known major mineralized bodies at Ballinalack, Navan, Silvermines, Tynagh, Keel and Harberton Bridge. The boxes around each mineral deposit demarcate the areas in which the residual gravity data is studied in detail in the following diagrams. Stippled areas are the troughs between the named blocks. Co-ordinates are Irish National Grid in kilometres.

Tynagh

The Tynagh deposit has been described by Morrissey et al. (1971) and Clifford et al. (this vol.). It occurs on the northern side of an almost easterly fault at a point where the gravity field suggests the fault has a maximum throw. Most of the lead-zinc mineralization occurs in fractures within the Waulsortian Mudbank Limestone and the overlying Visean "Calp" shales. The deposit is thickest next to the fault and thins out completely within 120m of the fault. The underlying limestones are relatively thin on the upstanding block, and it is possible that the mineral-bearing fluids migrated westwards from the main shale-filled trough to the east. The easterly trending Tynagh Fault, which is downthrown to the north, lies on the crest of a ridge. The main boundary fault to the ridge lies to the SE, is downthrown to the south and appears to intersect the Tynagh Fault to the east of Tynagh. This means that we have to invoke westward channelling of metal-bearing fluids through the Tynagh Fault from the shale trough. These fluids may have emerged at a dilation zone in the area of maximum throw of the Fault.

The major part of mineralization in this deposit is Viséan fracture- and cavity-fill, but the fine-grained, stratiform mineralization may have been deposited in the mid Courceyan. This mineralization may have been derived from the dewatering of early to mid Courceyan shales which we believe to exist below the "reef equivalent" in the trough to the east.

We may speculate that the Tynagh iron formation near the base of the Waulsortian limestones represents mineralizing fluids that were expelled early into sea-water to form a widespread iron-oxide horizon in the slowly accumulating carbonates of the upstanding block. Later episodes of expulsion may have forced the metal-bearing fluids into prepared porous lithologies to form the stratiform sulphide ores.

Harberton Bridge

The Viséan, breccia-hosted, mineralized bodies at Harberton Bridge have been described by Holdstock (1982) and Emo (this vol.). They occur in collapse structures in brecciated limestones near the northwestern boundary of the Kildare inlier. An interpretation of the magnetic data indicates that the basic rocks in the core of the inlier dip steeply to the SE. This structure may have been formed by thrusting of the inlier northwestwards by compressional forces from the SE; these were probably associated with the Hercynian orogeny. This compression may have caused the brecciation of the limestones on the northeastern side of the inlier, and the collapse of these limestones provided the host cavities for the mineralization.

Courceyan mineralization probably formed near the base of the succession in this area (in a style similar to the nearby Boston Hill deposit) by an initial dewatering of the deep, Rathangan shale trough to the west. The later Viséan brecciation may have increased the porosity of the host rocks to allow further fluid passage and subsequent Viséan mineralization. This style of mineralization relates closely to Mississippi Valley-type deposits.

Silvermines

The regional geology of the Silvermines area has been described by Brück (1982), and a summary of the ore deposit has been given by Taylor and Andrew (1978). The gravity map of the Silvermines area is unreliable because of a lack of terrain corrections in the data. In spite of this, it is still difficult to explain this deposit with our model. The mineralization in the originally porous, approximately 100m thick Old Red Sandstone is significant. It is possible that the basal sandstones have acted as conduits to dewater the carbonate trough to the NE. The intersection of the NW faults in the area with the almost easterly trending Silvermines Fault may have concentrated the expulsion of fluids into the host limestones.

Isotopic evidence and alternative sources for the metal-bearing fluids

The geochemistry of the metal-bearing fluids places some constraints on any genetic model for mineralization. In Ireland, there is an apparent requirement of the lead isotope data for either a deep crustal origin for the lead (Caulfield et al., this vol.) or its derivation from the Lower Palaeozoic sediments in the central Midlands (Boast et al., 1981). We believe that these data merely allow an estimate of the U^{238}/Pb^{204} and Th^{232}/Pb^{204} ratios in the source material at the time of emplacement of the lead as galena. These estimates are not unique (Oldenburg, 1984) and are based on the premise that the lead is neither selectively leached from the source material nor contaminated on its way to the deposition site. Before a source rock can then be identified, the average relative proportions of U^{238} and Th^{232} to Pb^{204} in the material contributing to the mineralizing solution and the time available before extraction of the lead must both be taken into account (Richards et al., 1983). Therefore, the source of the lead cannot be unambigously identified. We suggest that the observed lead isotope ratios can be derived from mineralizing fluids leached from the early Carboniferous shales which probably included Ordovician volcanic materials having a relatively low U^{238}/Pb^{204} ratio. Furthermore, the geographical variations of the Irish lead isotope data may be explained as the consequences of different sedimentary sources for the shales; source fluids for each deposit, generally, would have originated from shales in different troughs. Thus, we believe that existing lead isotope data can be accommodated within our model for ore genesis.

However, the possibility still remains that the mineralizing fluids originated from crustal sources deeper than the early Carboniferous shales. The trough margin faults, which may have focussed the metal-bearing fluids, may be reaching into Lower Palaeozoic rocks or even Pre-Cambrian crystalline basement. In our opinion, a mechanism to supply metal-bearing fluids from these rocks must answer the following three questions:

1. How was the permeability of either the Ordovician/Silurian sediments or the Ordovician/Pre-Cambrian crystalline rocks enhanced?
2. Which geochemical mechanisms would allow sufficient metals to be leached to produce an ore deposit like Navan either from a very thin (<2 km), Lower Palaeozoic prism or from Pre-Cambrian crystalline basement?
3. Was there a mechanism which could provide sufficient heat flow to drive hydrothermal cells in the crust, yet at the same time provide ore deposit temperatures as low as 100-150°C?

Some aspects of these problems have been tackled by Bischoff et al. (1981) who conducted laboratory experiments on the interaction of seawater and brines with Ordovician/Silurian greywackes near Navan. Their results suggest that mineralization is possible when these rocks interact with saline brines whose temperatures exceed 300°C, possibly in the presence of a magmatic heat source. More generally, Etheridge et al. (1983 and 1984) have reviewed the abundant evidence for a mobile, low-salinity, aqueous fluid during low-grade (<400°C) metamorphism of the type we envisage for the Irish Midlands in the early Carboniferous. The scale of the fluid volumes demands enhanced permeability ($>10^{-18}m^2$), and some geochemical evidence favours thermal, convective circulation restricted to different levels within the crust. High fluid flows may then occur along discrete, high permeability conduits such as fault zones which penetrate into the hydrothermal reservoir. Thus, there is some geological evidence to support large-scale, fluid advection along microcracks during metamorphism, but the geochemical processes involved, in either the Lower Palaeozoic or Pre-Cambrian rocks of the Irish Midlands, are not well understood.

We must concede the possibility that Irish zinc-lead ore bodies were derived from source fluids originating from Lower Palaeozoic or Pre-Cambrian rocks. Our principal reservation at present concerns the details of how fluid movement in these rocks removed substantial quantities of certain elements from the rock volume through which it passed. Furthermore, if the hypothesis of episodic emplacement of metal-bearing fluids into the host rock proves to be correct, then we find it difficult to envisage how a large-scale convection mechanism can explain this. Therefore, we suggest that further research on the genesis of Irish zinc-lead mineralization be directed towards the refutation or otherwise of the simpler model presented in this paper.

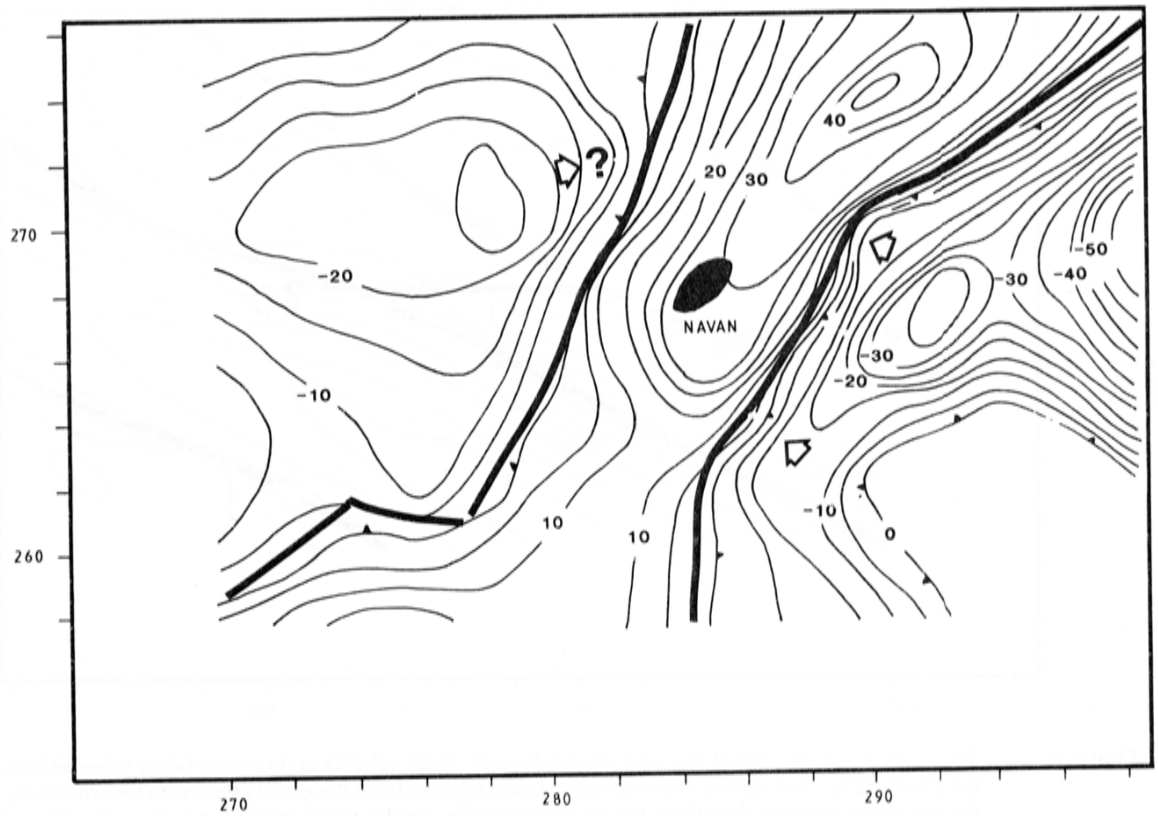

Figure 6. The residual gravity map of the area around Navan. Thick lines represent faults inferred from the gravity data. Arrows show possible directions for the source fluids. Contours are every 5 g.u. Co-ordinates are Irish National Grid in kilometres. Map contoured after processing of simple Bouguer anomaly point data supplied by Professor T. Murphy of the Dublin Institute for Advanced Studies.

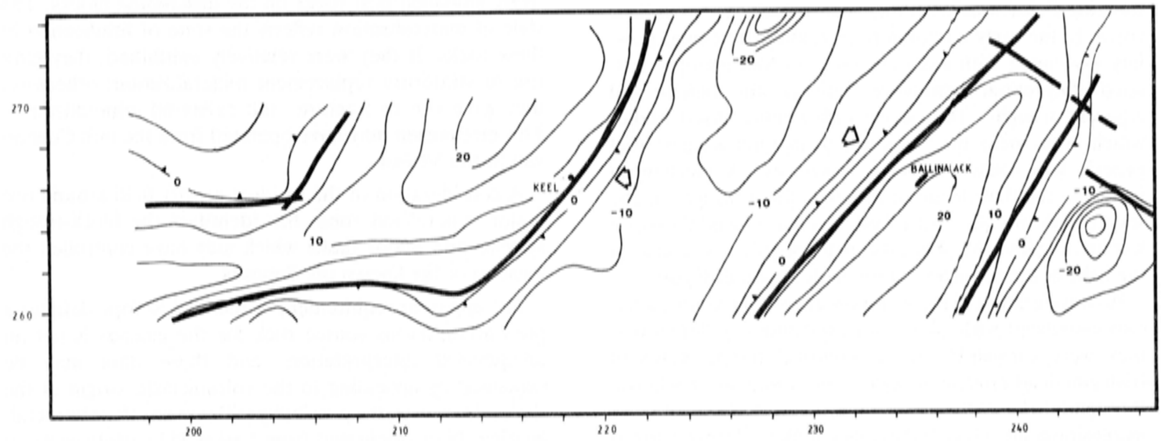

Figure 7. The residual gravity map of the area around Keel and Ballinalack. Thick lines represent faults inferred from the gravity data. Arrows show possible directions for the source fluids. Contours are every 5 g.u. co-ordinates are Irish National Grid in kilometres. Map contoured after processing of simple Bouguer anomaly point data supplied by Professor T. Murphy of the Dublin Institute for Advanced Studies.

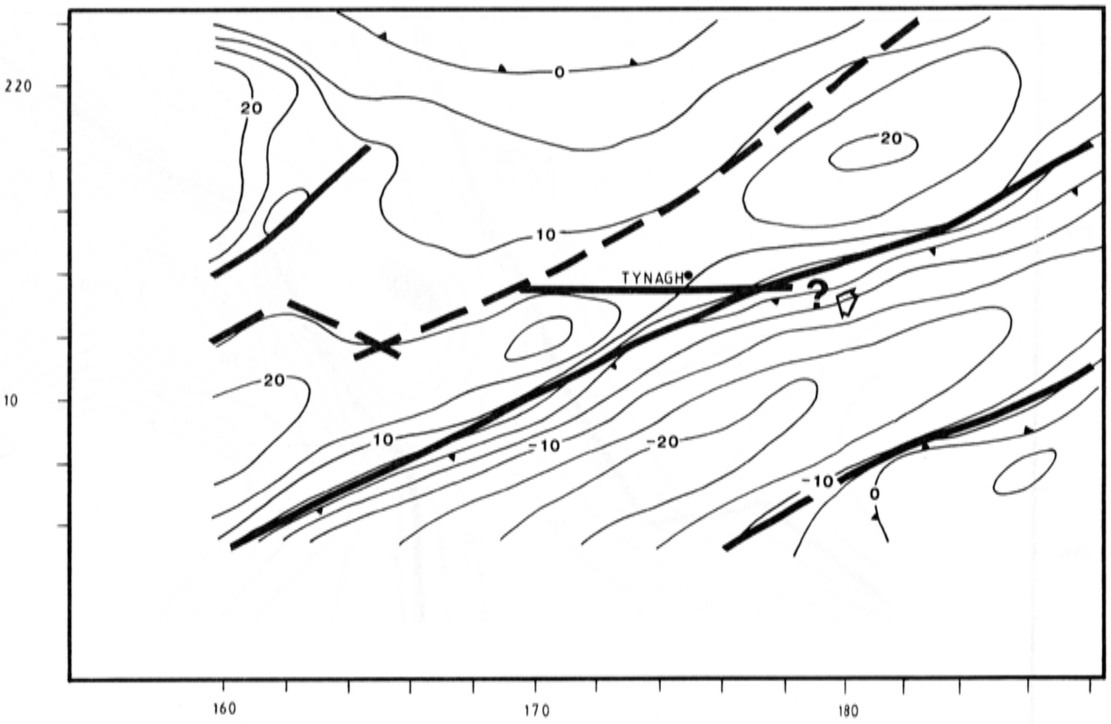

Figure 8. The residual gravity map of the area around Tynagh. Thick solid lines represent faults inferred from the gravity data; thick dotted lines represent faults inferred from the gravity data with less reliability. Arrows show possible directions for the source fluids. Contours are every 5 g.u. Co-ordinates are Irish National Grid in kilometres. Map contoured after processing of simple Bouguer anomaly point data supplied by Professor T. Murphy of the Dublin Institute of Advanced Studies.

Conclusions

A mechanism for the genesis of Irish zinc-lead mineral deposits has been presented. It is consistent with the interpretation of the gravity and magnetic data from the Irish Midlands. These show that Pre-Cambrian crystalline basement, possibly at a depth of 3-4km, underlies five major block-trough structures. The blocks were originally NE-trending Caledonian antiforms with volcanic rocks in their cores. In the early Carboniferous, crustal stretching, possibly associated with slab-pull forces in Mid-Europe, initiated differential subsidence between the blocks and adjacent troughs. The known major mineralized bodies which occur near the block-trough margins suggest that genesis was related to these structures. A mechanism involving the dewatering of the shale-filled troughs as the source of the metal-bearing fluids is favoured, and the paper has investigated the physical constraints on ore genesis in the light of the formation of the Irish Midlands Basin.

A consideration of the heat flow and temperature gradients associated with the crustal stretching has shown that they were consistent with depositional temperatures of Irish zinc-lead mineral deposits. The continual subsidence throughout the early Carboniferous was accompanied by increasing compaction of the trough shales. The pressurized expulsion of fluids from the deeper parts of the trough to its margins provided a single source of mineralizing solutions. A mechanism involving the transformation of clay minerals in the shales has been suggested to explain the leaching of metals into these fluids.

Stress-concentration in the upper crust gave rise to periods of intense faulting and differential subsidence at the trough margins. The subsequent increases in loading of the trough shales led to episodic expulsion of metal-bearing fluids probably through the basal sandstones in the troughs. The high-permeability growth-faults at the trough margins were important for focussing migrating fluids into the relatively unloaded host rocks on the upstanding blocks. The style of mineralization reflects the state of lithification of these rocks. If they were relatively unlithified, they gave rise to stratiform replacement mineralization; otherwise, they gave rise to fracture- and cavity-fill mineralization. This mechanism may have operated from the mid Courceyan to the Viséan.

A consideration of the residual gravity field around five major mineralized zones has identified the block-trough systems and major faults which may have controlled the location of the known ore deposits.

The apparent requirement of the lead isotope data for a pre-Carboniferous source rock for the galenas is not an unequivocal interpretation, and these data may be explained by appealing to the volcaniclastic origin of the shales. However, the possibility still remains that the metal-bearing fluids originated from Lower Palaeozoic rocks or Pre-Cambrian crystalline basement. It is emphasized that, if fluids from these rocks were the source of mineralization, then the block-trough structures identified from the gravity field must have profoundly influenced their transport to the deposition sites.

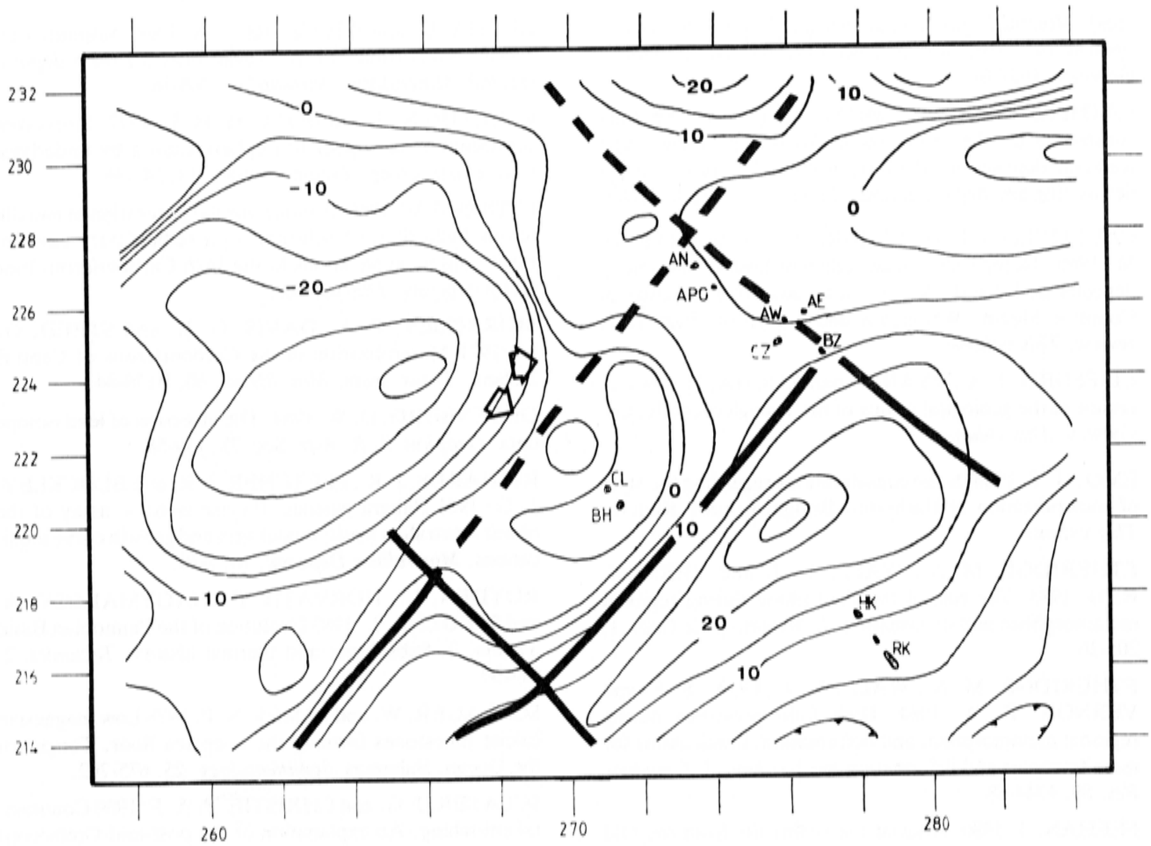

Figure 9. The residual gravity map of the area around Harberton Bridge. Thick solid lines represent faults inferred from the gravity data; thick dotted lines represent faults which can be inferred from the gravity data with less reliability. Arrows show possible directions for the source fluids. Letters refer to known mineral deposits. Contours are every 5 g.u. Co-ordinates are Irish National Grid in kilometres. Map contoured after processing of simple Bouguer anomaly point data supplied by Professor T. Murphy of the Dublin Institute of Advanced Studies.

Acknowledgements

We are grateful to Professor Tom Murphy for allowing us the use of gravity data collected by the Dublin Institute for Advanced Studies; John Davies kindly supplied these data on a magnetic tape. We thank Professor Andrew Brock of the applied Geophysics Unit, University College, Galway for providing continuing support and constructive criticism throughout the duration of this research. We also appreciate the help of numerous exploration and mine geologists in Ireland who have offered many useful ideas to us in the course of our work over the last year. Finally, we are indebted to Liz Williams, Kevin Barton and Eddy McCormack for their help in preparing the diagrams.

References

ANDREW, C. J. and ASHTON, J. H. 1982. Mineral textures metal zoning and ore environment of the Navan orebody, Co. Meath, Ireland. *In*: Brown, A. G. and Pyne, J. (eds). *Mineral Exploration in Ireland: Progress and Developments 1971-1981*. Dublin: Irish Association for Economic Geology. 35-46.

ASHTON, J. H., DOWNING, D. T. and FINLAY, S. 1986. The geology of the Navan Zn-Pb orebody. *This volume*.

BISCHOFF, J. L., RADIKE, A. S. and ROSENBAUER, R. J. 1981. Hydrothermal alteration of greywacke by brine and seawater: Roles of alteration and chloride complexing on metal solubilisation at 200°C and 350°C. *Econ. Geol.* 76, 659-76.

BOAST, A. M. 1978. A textural and isotopic study of Irish base metal mineralization of Lower Carboniferous age, with specific reference to the Tynagh deposit. Ph.D. thesis. Imperial College London.

BOAST, A. M., SWAINBANK, I.G., COLEMAN, M. and HALLS, C. 1981. Lead isotope variation in the Tynagh, Silvermines and Navan base-metal deposits, Ireland. *Trans. Instn. Min. Metall. (Sect. B. Appl. Earth Sci.)* 90, B115-19.

BOTT, M. H. P., SWINBURNE, P. M. and LONG, R. E. 1984. Deep structure and origin of the Northumberland and Stainmore Troughs. *Proc. Yorkshire Geol. Soc.* 44, 479-95.

BROWN, C. and WILLIAMS, B. 1985. A gravity and magnetic interpretation of the structure of the Irish Midlands and its relation to ore genesis. *J. Geol. Soc. London*. v. 142, p. 1059-1076.

BRÜCK, P. M. 1982. The regional lithostratigraphical setting of the Silvermines zinc-lead and the Ballynoe barite deposits, Co. Tipperary. *In*: Brown, A. G. and Pyne, J.

(eds). *Mineral Exploration in Ireland: Progress and Developments 1971-1981*. Dublin: Irish Association for Economic Geology. 162-70.

CATHLES, L. M. and SMITH, A. T. 1983. Thermal constraints on the formation of Mississippi Valley type lead-zinc deposits and their implications for episodic basin dewatering and deposit genesis. *Econ. Geol.* 78, 983-1002.

CAULFIELD, J. B. D., LEHURAY, A. P. and RYE, D. M. 1986. Isotope studies of sediment-hosted base-metal deposits in Ireland: Part 1, New data from deposits in Counties Meath, Westmeath and Longford; Part 2, A review. *This volume.*

CLIFFORD, J. A., RYAN, P. and KUCHA, H. 1986. A review of the geological setting of the Tynagh orebody, Co. Galway. *This volume.*

EMO, G. T. 1986. Some considerations regarding the style of mineralization at Harberton Bridge, County Kildare. *This volume.*

ETHERIDGE, M. A., WALL, V. J. and VERNON, R. H. 1983. The role of the fluid phase during regional metamorphism and deformation. *J. Metamorphic Geol.* 1, 205-26.

ETHERIDGE, M. A., WALL, V. J., COX, S. F. and VERNON, R. W. 1984. High fluid pressures during regional metamorphism and deformation: implications for mass transport and deformation mechanisms. *J. Geophys. Res.* 89. 4344-58.

FEEHAN, J. 1980. Alluvial fan sediments from the Old Red Sandstone of Devilsbit Mountain, County Tipperary. *J. Earth Sci. R. Dubl. Soc.* 3, 179-94.

HOLDSTOCK, M. P. 1982. Breccia-hosted zinc-lead mineralisation in Tournaisian and Lower Viséan carbonates at Harberton Bridge, Co. Kildare. *In*: Brown, A. G. and Pyne, J. (eds) *Mineral Exploration in Ireland: Progress and Developments 1971-1981*. Dublin: Irish Association for Economic Geology. 83-91.

JACOB, A. W. B., KAMINSKI, I. W., MURPHY, T., PHILLIPS, W. E. A. and PRODEHL, C. 1985. A crustal model for a NE/SW profile through Ireland. *Tectonophysics*. Vol. 113, 75-103.

JONES, G. V. and BRADFER, N. 1982. The Ballinalack zinc-lead deposit, Co. Westmeath, Ireland. *In*: Brown, A. G. and Pyne, J. (eds). *Mineral Exploration and Development in Ireland-Progress and Developments 1971-1981*. Dublin. Irish Association for Economic Geology. 47-62.

JONES, G. V. and BRAND, S. F. 1986. The setting, styles of mineralization and mode of origin of the Ballinalack Zn-Pb deposit. *This volume.*

KUCHA, H. and WIECZOREK, A. 1984. Sulphide-Carbonate relationships in the Navan (Tara) Zn-Pb deposit, Ireland. *Mineralium Deposita*. 19, 208-16.

KUSZNIR, N. J. and BOTT, M. H. P. 1977. Stress concentration in the upper lithosphere caused by underlying visco-elastic creep. *Tectonophysics*. 43, 247-56.

LYDON, J. W. 1986. A model for the generation of metalliferous hydrothermal solutions in a sedimentary environment, and its applications to the Irish Carboniferous base metal deposits. *This volume.*

MORRISSEY, C. J., DAVIS, G. R. and STEED, G. M. 1971 Mineralization in the Carboniferous of Central Ireland. *Trans. Instn. Min. Metall.* 80, B178-84.

OLDENBURG, D. W. 1984. The inversion of lead isotope data. *Geophys. J. R. Astr.* Soc. 78, 139-58.

RICHARDS, J. R., FLETCHER, I. R. and BLOCKLEY, J. G. 1981 Pilbara galenas: Precise isotopic assay of the oldest Australian leads; model ages and growth curve implications. *Mineralium Deposita*. 16, 7-30.

ROYDEN, L., HORVATH, F., NAGYMAROSY, A. and STEGENA, L. 1983 Evolution of the Pannonian Basin System: 2. Subsidence and thermal history. *Tectonics*. 2, 91-137.

SCHLAGER, W. and JAMES, N. P. 1978 Low magnesian calcite limestones forming the deep sea floor, Tongue of the Ocean, Bahamas. *Sedimentology*. 25, 675-702.

SCLATER, J. G. and CHRISTIE, P. A. F. 1980 Continental stretching: An explanation of the post-mid-Cretaceous subsidence of the central North Sea Basin. *J. Geophys. Res.* 85, 3711-39.

SEVASTOPULO, G. D. 1983. The age and depositional setting of Waulsortian limestones in Ireland. *In: Symposium on the Palaeo-environmental Setting and Distribution of the Waulsortian Facies*. El Paso Geological Society and University of Texas at El Paso.

SHERIDAN, D. J. 1972. The stratigraphy of the Trim No. 1 well, Co. Meath and its relationships to Lower Carboniferous outcrop in East-Central Ireland. *Geol. Surv. Ireland Bull.* 1, 311-34.

SLOWEY, E. P. 1986. The Keel Zn-Pb deposit, County Longford; A review and update. *This volume.*

SMITH, N. J., KYLE, J. R. and MAGARA, K. 1983. Geophysical log documentation of fluid migration from compacting shales: A mineralization model from the Devonian strata of the Pine Point Area, Canada. *Econ. Geol.* 78, 1364-74.

TAYLOR, S. and ANDREW, C. J. 1978. Silvermines ore bodies, Co. Tipperary, Ireland *Trans. Instn. Min. Metall.* 87, B111-24.