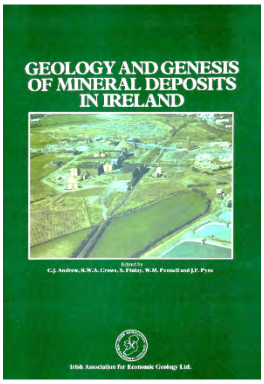

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Extension and convection: a genetic model for the Irish Carboniferous base metal and barite deposits.

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Abstract

The major base metal deposits in the Lower Carboniferous rocks of Ireland are all of the same age. At Silvermines, where the rate of sedimentation was very low in the Middle Courceyan, exhalation and ore deposition took place after sudden foundering to ~250m of the previously shallow sea floor. At Navan, which was adjacent to Carboniferous land, Andrew and Ashton (1982, 1985) have shown that sedimentation kept pace with an increased rate of subsidence so that while some of the ore was exhalative sedimentary, much was introduced into horizontal veins and as replacements just below the sea floor. This sudden subsidence is an aspect of extensional strain. During this period of extension, shearing movements along uneven fault and fracture planes created interconnecting pore spaces in the upper crust which were invaded by the overlying Carboniferous seawater. The fluid pressure enhanced brittle failure of rocks at temperatures up to ~250°C. (Above this temperature and at depths >5km, pressure solution and hydration have the effect of closing pore spaces.) Convection cells involving modified saline seawater developed in the upper crust, and, by a process of hydrothermal metamorphism, these fluids became enriched in base metals, barium and, to a lesser extent, H_2S. As the crust was cooled by this process the cells deepened and in some cases widened with time. The mineralizing solutions at temperatures of ~220°C in the updraughts invaded open joints and voids just below the seafloor prior to exhalation into brine-filled depressions. Metal sulphides and barite were precipitated in these various environments from slightly acid hydrothermal solutions on mixing with rather alkaline early Carboniferous brines or seawater. Recent deep drilling lends support to the model. Throughout the 12km depth of the Kola (USSR) super-deep drill-hole, which intersected rock up to 220°C, strongly mineralized waters and hydrocarbons were encountered circulating in broad deformed zones (Kozlovsky, 1982 and 1984). The geothermal drilling project at Camborne, Cornwall, UK, (Pine and Batchelor, 1982) has shown that $\sigma_h:\sigma_H$ in the crust there is 1:2.5, so that water pumped into a 2km hole fills joints that then propagate downwards to 4.8km beneath the surface thus increasing the volume of the reservoir. Only one quarter of the water returns up a second borehole. This behaviour is consistent with the model postulated here for ore genesis.

Introduction

This paper seeks to explain the distribution and common age of the major lead + zinc orebodies in the Lower Carboniferous of Ireland. The data-base comprises the mines and prospects themselves rather than publications concerned with the fine detail of geochemistry and mineralogy, data hard won by prospectors, field geologists and consultants.

The initial discoveries were due to the vision and purposefulness of Pat Hughes and Mike McCarthy of Northgate and Tara Prospecting respectively, coupled with the foresight of the then Director of the Geological Survey of Ireland, Murrogh OBrien who suggested the Tynagh area, among others, worthy of special attention (see OBrien, 1959, p.12). The lead+zinc orebodies at Tynagh were discovered in 1961 and subsequently were the subject of a remarkable paper by consultant Duncan Derry, exploration geologist Glen Clark, and mine geologist Noel Gillatt in 1965. In spite of the cross-cutting nature of much of the primary ore they recognised that mineralization took place just below the early Carboniferous sea floor, hence they assigned a precise age to the mineralizing event. David Banks has put the finishing touches to their model in this volume. Other consultants, such as W. W. "Peck" Weber, Jocelyn Pereira and Ian S. Thompson made contributions to the discoveries of Silvermines, Keel and Gortdrum respectively, using, variously, geochemistry as well as theories of syngenesis and/or lineament controls. Tom Murphy's (1960, 1962a, b) pioneering geophysical survey maps provided an important adjunct to the excellent 19th century Geological Survey maps available. All of the discoveries were team efforts, although individual initiative was important; this is exemplified by the achievements of Derek Romer, who, using a bold yet persevering approach, was involved in the discovery of Navan, as well as Aherlow and many other prospects. Geologists Brian Byrne and Mike Robinson were also involved in some of these finds. During this time mining and exploration relied on geochemical analysts such as Mike O'Neill and Peter Cazalet. In recent years mine geologists such as Stewart Taylor, Colin Andrew and John Ashton have made major inroads into the understanding of mineral deposition, demonstrating that much mineralization took place at, or just below, the sea floor, and we now know, from the detailed palaeostratigraphy provided by consultants Mike Philcox and George Sevastopulo, that the large deposits are coeval.

So, it is from the data amassed by these men, and with the help of my colleagues and research students at Strathclyde, Dr. Allan Hall, Dr. Roger Anderton, David Banks, Adrian Boyce, Paul Duller, Gary Gray, Dick Larter and Iain Samson, that I propose the following model.

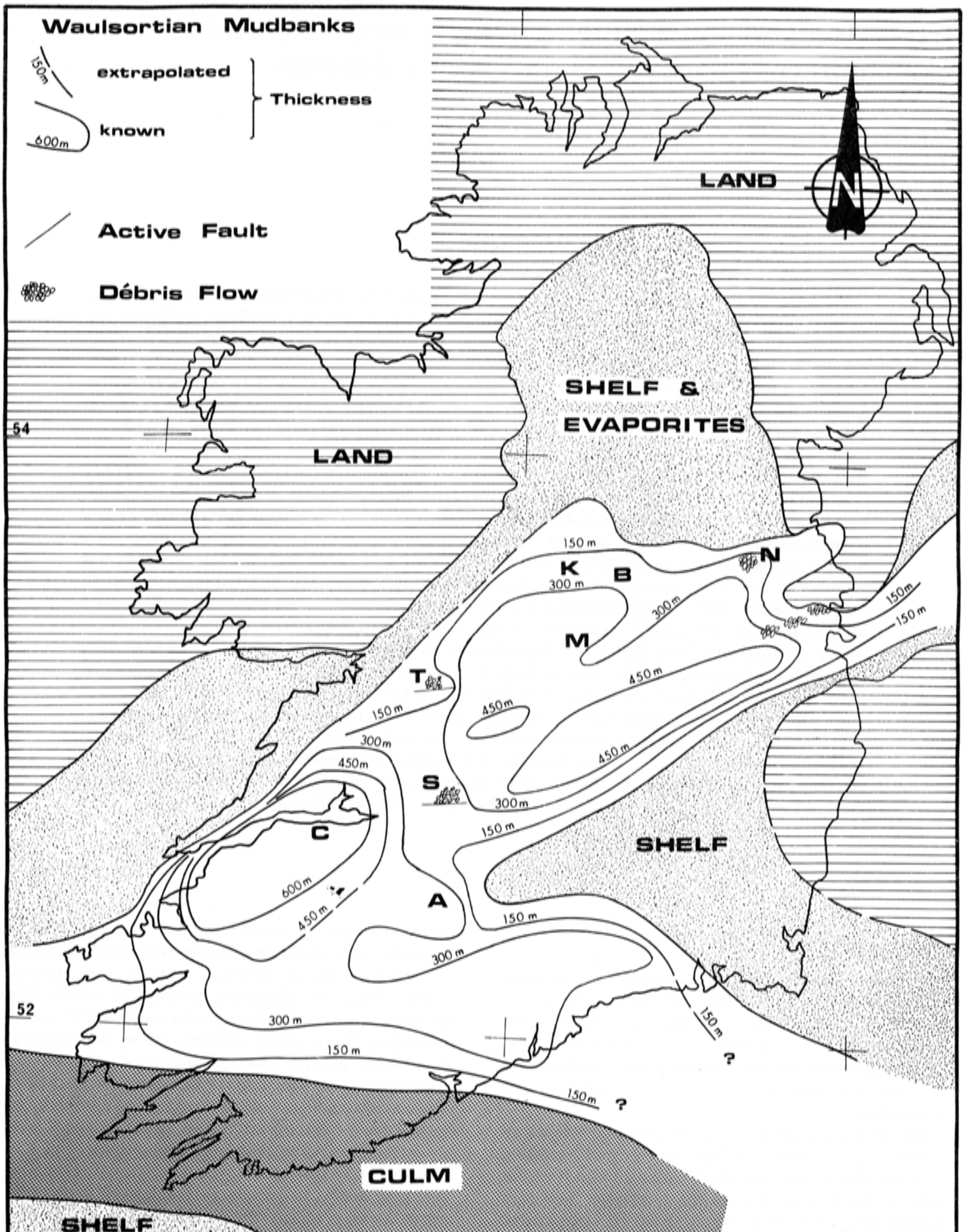

Figure 1. Deposits with synsedimentary aspects figured in relation to a diachronous late Courceyan palaeogeography: C, Courtbrown; A, Aherlow; S, Silvermines; T, Tynagh; M, Moate; K, Keel; B, Ballinalack; N, Navan; (after many authors but especially Sevastopulo, 1979, and Colin Andrew, pers. comm. 1985).

Distribution and structural controls

The observation that the larger mineral deposits in the Carboniferous of Ireland are "widely separated" (Russell, 1968) still holds, and there are no obvious clusters (Fig. 1). Where more than one deposit occurs in a mineralized area then the orebodies are either contiguous, e.g. the Silvermines G, B, and Ballynoe deposits, or they are separated by only a few hundred metres as at Tynagh (Hutchings, 1979). Attempts to relate the distribution of mineral deposits to fundamental structures trending NE (Pereira, 1963), northerly (Russell, 1968) or NW (Horne, 1975) have not been substantiated, although the "rose-of-direction" of the distribution of deposits (Fig. 2) does give food for thought.

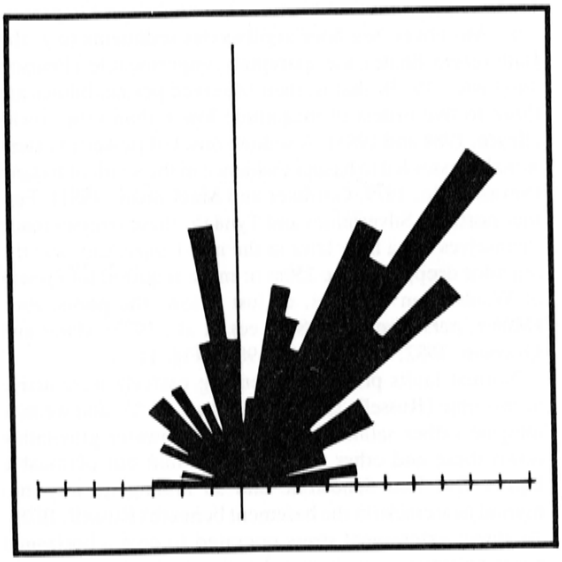

Figure 2. Rose-of-direction of lines linking all deposits of probable early Carboniferous age (Smythe, 1981, unpublished).

That there is a diffuse NE, or Caledonoid, trend is clear, but the view that this relates more to the thickness of the Caledonian prism (Russell, 1978) rather than the importance of reactivated structures can no longer be held with confidence. Even in 1978, Strogen's (1974) discovery of quartzo-feldspathic gneissic xenoliths in the Carboniferous volcanics of central Ireland seemed at variance with this view. The thick accretionary prism under the Southern Uplands of Scotland favoured by Bamford et al. (1977) on geophysical grounds and extrapolated into Ireland by Leggett et al. (1979) has been put in doubt by the geophysical survey of Hall et al. (1983), as well as by the mapping of Archer (1981). The general NE trend to the distribution of ore deposits (Fig. 1) does, however, reflect the reactivated Caledonoid structures (Phillips et al., 1976) which controlled both the shape of the early Carboniferous sedimentary basin (Fig 1) (Sevastopulo, 1979), and possibly the siting of some mineralizing centres (Pereira, 1963; Andrew and Ashton, 1982, 1985). We cannot tell at present whether the upper crustal rocks beneath the deposits are granitic, gneissose or merely low grade metasediments.

Major local controls are faults trending between N70°E and easterly. These new faults, which controlled the margins to depressions hosting sedimentary ores, to some extent also controlled the siting of the hydrothermal conduits. The easterly faults are essentially normal at Silvermines (Andrew, this vol.) and at Tynagh (Clifford et al., this vol.). There is *no* evidence for major transcurrent motions along these faults during sedimentation and coeval mineralization (Moore, 1975; Andrew; Ashton et al.; Clifford et al., all this vol.). Nor is there evidence for large scale sinistral shear along the Caledonoid grain in the early Carboniferous (Irving and Strong, 1984a and b).

Of overwhelming importance, however, is the sudden onset of basin subsidence immediately prior to the mineralizing episode (Boyce et al., 1983), a phenomenon that at least in part must be related to extensional stresses, which, judging from the array of then active faults, must have changed orientation from time to time, although the "extensional" stress trajectories were generally oriented northerly in the middle Courceyan. So we may imagine a stress field in which there was a high horizontal stress anisotropy. A high ratio between minimum and maximum horizontal stresses would have ensured constant minor conjugate shearing along previous weaknesses, and some tensional jointing. We will return to this point in the genetic model.

Criteria for dating the deposits

Although varying proportions of the ore in the deposit is clearly cross-cutting, Derry et al. (1965) recognized that at Tynagh this mineralization took place just below the seafloor and they realized that the Tynagh Iron Formation represented an exhalative facies. At Silvermines the sedimentary exhalative nature of the host facies to much of the ore was demonstrated by Weber (1964) and by Taylor and Andrew (1978). Sedimentary exhalative facies have also been noted at Navan (Andrew and Ashton, 1982) and at Garrycam (Keel) (Slowey, this vol.).

Other criteria may be used to establish a "synsedimentary" age for the deposits. Extensive manganese and/or zinc aureoles to Tynagh (Russell, 1974 and1975), Navan (Finlay et al., 1983), Silvermines, Moate and Ballinalack (Gray, in prep.) are evidence for exhalations into the Carboniferous sea near to or at these deposits. Pyrite chimneys and mounds at Silvermines (Larter et al., 1981; Russell et al, 1982; Boyce et al., 1984) and at Tynagh (Banks, 1985 and this vol.) also clearly indicate an exhalative process.

More subtly, bedding-parallel sulphide veins at Navan contain thin palaeo-vertical pyrite tubes and rods, many of which extend from the ceiling to the floor of the veins (Ashton and Duller, pers. comm., 1983). Andrew and Ashton (1982 and 1985) have also reported pyrite "stalactites" in these veins which appear identical to those reported in Jurassic ammonites by Hudson (1982). We have reproduced analogous structures in chemical gardens in the laboratory (Russell et al., 1984) using two solutions, one of Na_2S and the other, a mixture of $FeCl_2$ and $FeCl_3$. The iron chloride solution represents the slightly acid mineralizer, whereas the Na_2S solution is the analogue for the sulphur-bearing Carboniferous brine occupying pore spaces in the Courceyan limestones. We surmise from these experiments that the horizontal joints were invaded by hot iron-bearing solutions which reacted slowly with warm, rather alkaline, brine derived from the Carboniferous sea ($\delta^{34}S_{barite} \sim +21‰$ and a salinity of ~20 wt. ‰ NaCl, Radtke pers. comm., 1980), containing both $SO_4^{=}$, and HS^- occupying the Navan sediments as connate water. This brine passed through fine cracks in the hangingwall, precipitating an iron sulphide membrane at the interface that grew as a tube with internal diameter of ≤1mm under the influence of the widening of the vein. We have also simulated the growth of the pyrite stalactites by forcing sodium sulphide solution downwards through fine holes into a solution of iron chlorides. The iron sulphide structures grow as a sulphide gel at the interface between the two solutions.

In contrast to growth of stalactites in cavities at Navan, pyrite chimneys at Silvermines and Tynagh grew on the sea floor by slow mixing of an acid, iron-bearing mineralizing solution and an alkaline brine containing reduced sulphide species during periods of gentle exhalation, a phenomenon giving rise to some similarities between chimneys and some of the pyrite tubes at Navan (Boyce et al., 1983).

The *initial* mineralization at Navan, Silvermines, Tynagh and Keel took place during deposition of a single conodont zone in the middle Courceyan, the *Polygnathus communis carina* zone (Andrew, pers. comm., 1983), a remarkable observation that has to be accounted for in any genetic model.

Of the strictly epigenetic deposits, ages may only be estimated from host-rock (maximum and/or minimum), structural considerations (minimum age) and K-Ar on wall rock (minimum age) (Halliday and Mitchell, 1983). On this basis Gortdrum is post-Asbian but pre-Hercynian.

Whether we treat all the deposits in the Carboniferous or only those known to be 360Ma makes little difference in regard to the observation of the minimum separation between deposits, so we assume here that all but the Cu-Ag deposits at Gortdrum, Ballyvergin, Aherlow and Mallow (which are certainly younger than the lead+zinc deposits) may have been generated in the same way.

Other important characteristics of the deposits to be explained by a genetic model are (i) their syngenetic occupation of at least 10m but generally ~100m of Courceyan, Chadian and lower Arundian stratigraphy, implying $>10^6$ years of activity, (ii) the absence of adjacent deep basin aquifers, (iii) fluid inclusion temperatures of up to 220°C, (iv) the overall throughput of $>10^{15}$kg of water at between 10-100 kg/s for a million years or, in some cases, longer.

Physical model

The model outlined below is based on Russell (1978 and 1983) and Russell et al. (1981) but it has been updated to conform to growing knowledge of behaviour of water in the upper crust gleaned from recent drilling (Anderson et al., 1982; Kozlovsky, 1982 and 1984; Pine and Batchelor, 1982), combined with knowledge of horizontal stress contrasts (Pine and Batchelor, 1982), and an increase in the understanding of the micromechanisms of deformation in the brittle-to-ductile zone (White and White, 1983). Given that the model has been characterized as "largely conjectural" (Sawkins, 1984) it is worth emphasizing the findings of Brace (1985) regarding the depth to which even normal crust is permeable. Calling upon drill-hole measurements, reservoir-induced earthquakes, and certain heat flow anomalies, Brace (1985) considers the crust to have permeabilities as high as 10 millidarcies ($10^{-14}m^2$) to depths of 8 or 10 kilometres. Such permeabilities imply that pore pressures will be approximately hydrostatic.

The pre-Upper Devonian rocks underlying the Carboniferous Limestones of the Central Plain of Ireland comprise a variable thickness of folded Lower Palaeozoic greywackes and shales metamorphosed, at least near the present surface, to pumpelleyite-prehnite facies (Oliver, 1978). Below this, Long et al. (1983) surmised a mosaic of pre-Caledonian basement. The pre-Upper Dalradian rocks were fractured with several trends, notably northeasterly and northwesterly.

Extensional stresses operating in the area of the Central Plain led to a gradual subsidence of the peneplained Caledonian Orogen and the Carboniferous sea transgressed northwards. Synsedimentary anhydrite beds (Sheridan et al., 1967; Andrew and Ashton; 1982, 1985) and gypsum pseudomorphs are indicative of high salinities.

This seawater probably did not manage to penetrate the basement because, down to 500m or so, the minimum principle stress is normally vertical (Pine and Batchelor, 1982) and near-vertical fractures are "tight" and impermeable. Moreover, sea floor argillaceous sediments (e.g. the Ballyvergin Shale) are extremely impermeable (Pearson and Lister, 1973), that is, their observed permeabilities are three to five orders of magnitude lower than other rocks (Brace, 1984 and 1985). A sudden onset of powerful extensional stresses led to basin subsidence in the south of Ireland (Sevastopulo, 1979; Gardiner and MacCarthy, 1981). Further north, at Silvermines and Tynagh, these stresses made themselves felt a little later in the mid-Courceyan, and the sea floor dropped to the 250m or more required for growth of Waulsortian banks at, or just below, the photic zone (Miller, pers. comm., 1984; Lees et al., 1977; Miller and Grayson, 1982; Boyce et al., 1983) (Fig. 1).

Normal faults principally trending easterly were active at this time (Russell, 1975; Boyce et al., 1983) and we may imagine rather saline Carboniferous seawater gravitating down these and other faults into the thin but permeable Upper Old Red Sandstone and so finding its way into myriad new cracks in the basement beneath (Russell, 1978). As direct extensional stress operated to give a horizontal stress anisotropy, conjugate shearing took place on weakness planes and ancient shear zones and the uneveness of the walls ensured an increase in permeability and porosity. The saline seawater was thus able to migrate into the fractures where, by a feed-back mechanism, its internal pressure encouraged further fracturing.

We can see such behaviour today in the Camborne School of Mines geothermal drilling project in Cornwall, where the ratio between the minimum and maximum horizontal stress components at one to two kilometres is about 1:2.5 (Pine and Batchelor, 1982). At Camborne, judging from microseismic evidence, water pumped at pressure from a borehole at 2km is exploiting joints with a spacing of ~100m which have been activated down to ~4.8km (Batchelor, pers. comm., 1984). During pumping, 17kg/s of water were driven down the deeper of the two holes and only 4kg/s returned (Batchelor, pers. comm., 1982). The remaining $3x10^{11}$g of water now occupy these joints. A similar phenomenon was observed at DSDP drilling site 504b beneath 2.5km of the Pacific Ocean where drilling fluid was lost down the hole at <1km below the sea floor. We imagine Carboniferous seawater to have helped cause, and then to have exploited, new and reactivated fractures in the same way. These fractures then propagated both horizontally and vertically downwards.

We may expect fracturing to have ceased at depths where the crust was sufficiently hot and ductile to prevent brittle fracture at a given stress contrast. Following White and White (1983) I consider that the base of the brittle zone would have been at approximately the depth of the 250°C

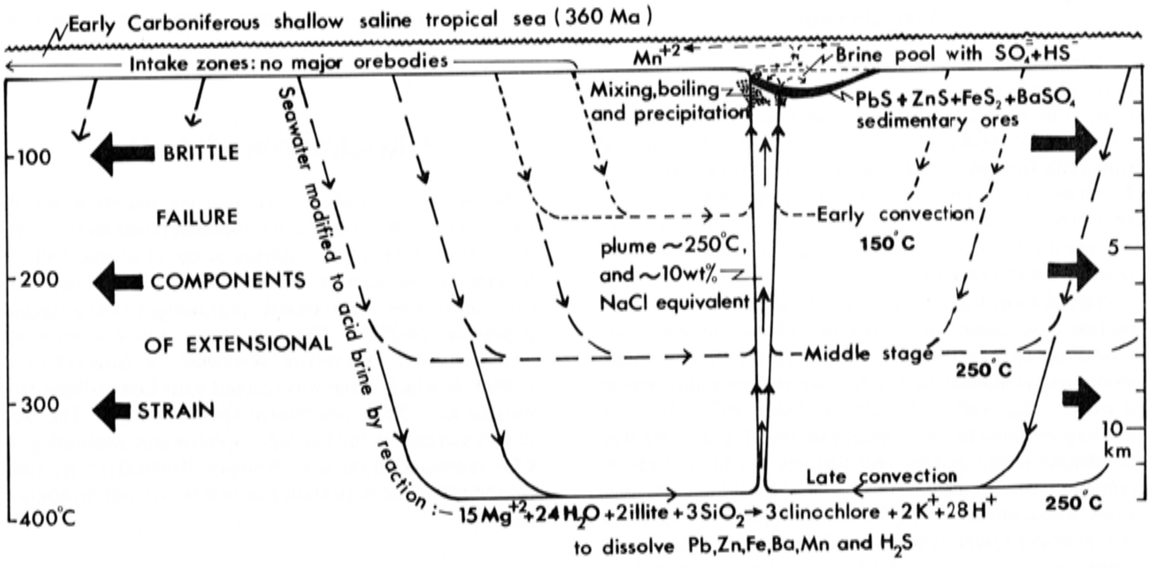

Figure 3. Model of expanding convection cell generating a Silvermines type of ore deposit.

isotherm. From their work on the Alpine Fault Zone of New Zealand we learn that the brittle-to-ductile zone occurs independently of the geothermal gradient between temperatures of 250°C and 300°C, and results from stress corrosion, i.e. from micro-cracking, fluid infiltration and hydration, pressure solution and reprecipitation. At temperatures below 250°C deformation takes place by brittle fracture. As the upper crust was cooled at the base of the hydrothermal cell, fractures gained elastic strength as a result of cementation and intragranular annealing (Rice, 1975). The reapplication of stresses then caused a renewal of fractures which in turn led to the deepening of the base of the hydrothermal cell with time (Fig 3). The geothermal gradient in Ireland during the earliest Carboniferous was probably in the region of 35°C/km (Russell, 1978), so seawater would initially have penetrated to a depth of about 7km. This seawater, modified chemically as explained in the next section, gained heat from the wall rocks, and once it reached the fracture floor it would have migrated horizontally through a network of approximately vertical fractures towards a convective updraft exploiting a high permeability zone such as an intersection of two or more major fractures. Given a minimum aspect ratio for a convection cell of ~2.7 (Lapwood, 1948), then the diameter of the intake zone to a fully developed convective hydrothermal updraught would have been ~19km. In a homogeneous crust this would define a minimum spacing to updraughts and for any consequent mineral deposits. The crust would lose heat through such a process both by mass transfer and conduction to the walls of the channelways, and, of most importance to us, to the base of the cell. Hence, as the crust cooled, fractures would continue to have propagated downwards. I have speculated that the hydrothermal cells feeding giant orebodies such as Navan may finally bottom at ~15km i.e. at the base of the so-called brittle crust (see also Sibson, 1977), because of the incapability of the hydrothermal convection cell to transport heat sufficiently quickly from the top of the lower crust. So in this region of an extremely steep temperature gradient at lithostatic pressures of ~400MPa, the bottom of the cell is defined by pressure solution and hydration reactions enhancing ductility. The cell may be expected to run at this level for at least the length of time it took to reach this depth (Elder, 1976) and in some cases far longer, although it will carry little metal from the exhausted source rock. That the crust can support the flow of metal-bearing saline solutions at such depths is demonstrated by the deep drilling in the Kola Peninsula (Kozlovsky, 1982 and 1984) where the drilling has intersected fractures in which metalliferous solutions circulate at a depth of over 12km and a temperature of ~220°C.

By the time the cells deepen to 15km the aspect ratio is substantially distorted to near unity, and we may expect cell capture to take place so that a long-lived system may end with an intake zone ~40km in diameter. We may predict then that of two reasonably sized deposits ~20km apart, the influence of the mineralizing process in one will continue for about twice the duration of the other, because, as mentioned above, Elder (1976) has pointed out that systems take as long to run down as they do to build up.

Evidence for long-lived systems are afforded by the Boulder Conglomerate ore and the hanging-wall trace element aureoles in the Arundian above the Navan deposit (Finlay et al., 1984), the thickness of the mineralized stratigraphy at Tynagh, and, more speculatively, the extent of the breccia-hosted mineralization at Harberton Bridge which reaches up into the Chadian (Holdstock, 1982). Where two substantial deposits are ~18km apart, namely, the Keel and Ballinalack deposits, the latter may be the result of a much longer lived system as mineralization exploits the entire Waulsortian succession (Jones and Bradfer, 1982), whereas at Keel only the very base of the Waulsortian is mineralized (Morrissey et al., 1971).

A further prediction is that in cases where a known orebody has been cut off "in its prime" then we may expect to find at least evidence for a long-lived hydrothermal system ~20km distant. Whether there will be an accompanying orebody will depend on the vagaries of the depositional environment and the erosional history. A deposit born of a relatively short-lived system is that at Silvermines (Taylor, 1984; Andrew, this vol.; Gray, in prep.).

Discussion

Many geologists have been tempted to assume that an igneous body is required to explain hydrothermal convection. The model proposed above does not require an igneous heat source for the 360Ma deposits; I argue that mineralization and basaltic activity are distinct aspects of Earth heat loss, made possible during times of tension. The two mass transfer processes are essentially independent, the one directly from the mantle, the other by intermediary conduction to groundwaters.

Only at Gortdrum, Mallow and Ballyvergin could magmatism have caused mineralization (Thompson, 1967). At Gortdrum the ore occupies Courceyan argillaceous limestones and is spatially related to, though later than, Asbian trachytic plugs and basaltic dykes (Tyler, 1979). We may envisage basaltic magma freezing on meeting the Old Red Sandstone saline aquifer and forming trachytic pods by contamination from the sandstone and from aqueous solutions. These intrusions may have been capable of engendering small short-lived hydrothermal convection cells in which copper was dissolved in the heated saline groundwaters. Given that the aquifer is Old Red Sandstone (ORS) the oxygen fugacity of the fluid would have been high enough to allow it to carry hundreds of parts per million of copper and some silver dissolved from the ORS (Radtke and Russell, 1978). Mercury and antimony may have been dissolved from the basalts. Precipitation took place where the uprising solutions interacted with H_2S and with sulphides in the Courceyan limestones.

The Mallow copper-silver deposit may have formed in the same way, judging from the mapping of Wilbur and Royall (1975) as well as the magnetic map of Ireland (Max and Inamdar, 1983) which shows an anomaly typical of a basic intrusion in the area. At Mallow intrusives also exploited the E-W fault cutting the Kilmaclenine anticline. The absence of mercury could relate to a dearth in the source rocks or to a loss by dissipation or erosion. At Ballyvergin the proximity to the Steele's Turrett volcanics can be viewed in the same light.

Another popular view is that crustal thinning itself will lead to a higher geothermal gradient sufficient to engender hydrothermal convection (Leeder, 1982). I have argued elsewhere (Russell, 1983) that even if we assume an ideal increase in the geothermal gradient, as the crust was thinned in tension (McKenzie, 1978) this would certainly not trigger off convection. Following Solomon (1976) we may address the Rayleigh equation to assess the likelihood of mixed convection in certain circumstances. Simply put, when the dimensionless number R in the equation

$$R = \frac{k\alpha g H \Delta T}{K_m \nu}$$

reaches a critical value, convection is engendered (where k=permeability; α = coefficient of cubical expansion; g = gravitational constant; H = thickness of the medium; ΔT = temperature difference between top and bottom of the permeable slab; K_m = thermal diffusivity of the water-saturated medium; ν = kinematic viscosity).

Assuming a constant temperature of 250C° for the base of the cell, then a decrease in H, concomitant upon crustal thinning, will slightly inhibit convection. On the other hand we know that permeability k can vary by orders of magnitude, e.g. from $10^{-18}m^2$ to $10^{-14}m^2$ (Norton and Knapp, 1977; Davis et al., 1980; Brace, 1984) when there is a sudden horizontal stress contrast imparted to the crust. Such an increase in permeability could increase R by several orders of magnitude.

Chemical considerations

We have previously argued that the metals within the large mid- to late-Courceyan mineral deposits were derived by hydrothermal metamorphism of upper crustal rocks by modified saline seawater (Russell et al., 1981). There is no experimental evidence exactly pertaining to the envisaged process at 220-250°C. The study that is closest to the model is a particular experiment described by Bischoff et al. (1981), in which brine was reacted with Lower Palaeozoic greywacke at 200°C resulting in a pH drop to 4.5. The cause of this increase in the hydrogen ion content is complex. As CO_2 increased from 6 to 550ppm Bischoff et al. (ibid) reasoned that an important reaction was dedolomitization, namely:

$$3 \text{ dolomite} + 4 \text{ quartz} + \text{water} \rightarrow \text{talc} + \text{calcite} + 3CO_2$$

The CO_2 reacts with water to give carbonic acid, which in turn provides H^+ to the fluid (see also Muffler and White, 1968). This process obviously relies on the presence of dolomite in the upper crust, a factor that cannot be guaranteed! In this same experiment the Mg concentration decreased from 2906 to 2728ppm and H^+ was produced by the reaction:

$$5Mg^{2+} + \text{anorthite} + 8H_2O + SiO_2 \rightarrow \text{clinochlore} + Ca^{2+} + 8H^+$$

As magnesium is involved in both reactions, the latter may be more important in cases where dolomite is absent. Nevertheless, where dolomite is present we might expect some gold, arsenic and antimony to be stable in solution as carbonate complexes (Kerrich and Fryer, 1981; Kay and Strong, 1983) as well as Pb, Zn, Ag and Ba as chloride complexes, although the envisaged temperatures of up to 250°C are lower than those generally accepted for significant gold solubility.

As such a solution rises towards the surface and cools on invading greywacke, the pH rises on account of the dissociation of carbonic and other acids. Carbonatization of wall rocks to form iron-magnesium-calcium carbonates from silicates would lead to the breakdown of carbonate complexes in solution and precipitation of gold, arsenic and antimony. As this same fluid rises and mixes with alkaline ground and seawater brines, sulphides and sulpho-salts would be rapidly precipitated using H_2S carried in the hydrothermal solution. Hence silver will be enriched in the sulpho-salts beneath and around the hydrothermal vents (Boyce et al., 1983; Taylor, 1984). Further out into the fault-bounded depressions or within voids beneath the seafloor, much of the remainder of the lead and zinc will be precipitated with the aid of biogenically reduced sulphur; barite will be precipitated on mixing with seawater sulphate (Coomer and Robinson, 1975; Boast et al., 1981; Boyce et al., 1983).

The physical model for explaining the hydrothermal process is sufficiently well described as to allow predictions to be made regarding the chemical evolution of a mineralized system (Russell et al., 1981). The reservoir feeding the hydrothermal system comprises proportions of Carboniferous seawater and brine, groundwater and perhaps some meteoric water. Judging from fluid inclusions at Silvermines (Samson and Russell, 1983) the average salinity was ~2M NaCl (~11 wt.% NaCl equivalent). On the down-draught limb this fluid will first lose sulphate as anhydrite as the water is heated by the rock through which it passes, and oxygen to oxidation of pyrrhotite, pyrite, magnetite and organic carbon. Along its path it will also lose Mg^{++} to chloritoid and talc and concomitantly this highly reduced acid solution will dissolve out Mn^{++} at the expense of the newly produced hydrogen ions. So the first batch of hydrothermal solution returned to the Carboniferous sea will give rise to a pre-ore phase enrichment of iron and manganese (Russell et al., 1981). As the convection cell becomes more organized base metals and barium will be more effectively stripped from the rock walls and major-phase mineralization begins. Temperatures of the updraught will have approached 250°C. Mineralization of approximately the same tenor and metal ratio will continue as the cell deepens with time and "fresh" rock is attacked. Copper is not appreciably soluble in solutions of such low oxidation state and temperature.

After a single pass of the hydrothermal cell at its maximum depth, the lead and zinc concentrations will be reduced, giving an opportunity for silica, which will continue to be dissolved from the rock pile at depth, to nucleate without being swamped by sulphides. The fracture walls will become fully armoured in chloritoid, chlorite and talc so the ensuing aliquots of aqueous fluid will maintain Mg^{++} in slightly alkaline solution. So we may expect a hanging wall enrichment in silica and dolomite.

This expectation is fulfilled at Silvermines where a 30 to 60m stratiform massive or banded nodular chert and dolomite body overlies ~100m of dolomite breccia, itself overlying the orebodies. At Tynagh, where much of the mineralization was epigenetic, silica-dolomite plugs occupy barren zones between the lead + zinc bodies (Russell, 1983; Banks, pers. comm. 1984). Such a relationship cannot be demonstrated in the other Irish Carboniferous orebodies, although there is evidence for an extraordinarily long-lived system at Navan judging by the hanging wall trace element anomalies which penetrate into the Arundian (Finlay et al., 1984).

Conclusions and predictions

1. **Exploration should either be concentrated within three kilometres of the periphery of a known deposit (cf. the HYC and Emu Plains deposits at McArthur River described by Walker et al., 1977), or at a distance of at least 17km, the intervening ground being the down-draw zones of the putative hydrothermal convection cells (Fig. 4).**

2. Ore grade exhalative-sedimentary to early replacement mineralization will be found generally only in middle to upper Courceyan sediments, although feeder and epigenetic replacement ore may be found in older rocks.

3. In cases where two deposits are ~20km apart then only one of these will boast a stratigraphically late hanging wall trace element aureole or remobilized base metal mineralization.

4. Silver will be enriched near and below the feeders. There may yet be gold to be found in main stage

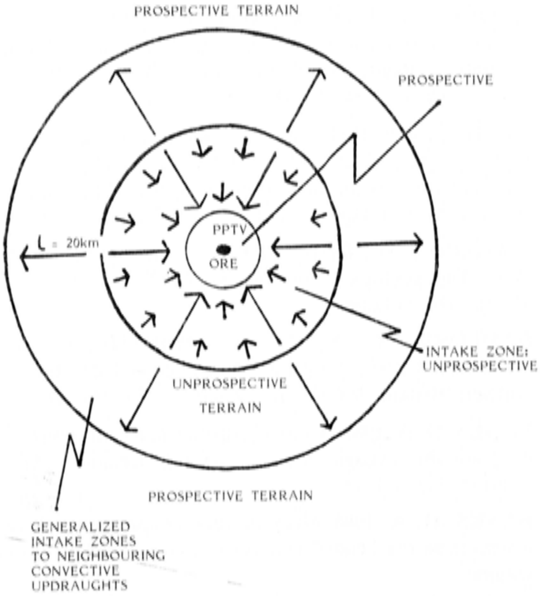

Figure 4. Sketch showing the predicted prospective (PPTV) and unprospective terrains related to major ore deposits fed from convection cells. Minimum spacing, L, between sizeable orebodies ~20km. Arrows denote flow paths of convecting solutions.

carbonate mineralization low down in the feeders. This latter speculation rests on the possibility that gold is carried at ~250°C as a carbonate complex.

5. Pyrite stalactites and "chemical gardens" were produced on the mixing of hydrothermal iron-bearing solutions with alkaline HS^--rich surface brines just below the Courceyan sea floor. Pyrite chimneys were produced at exhalative centres where the rate of egress was low (centimetres per second).

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References

ANDERSON, R, N., HONNOREZ, J., BECKER, K., ADAMSON, A. C., ALT, J. C., EMMERMANN, R., KEMPTON, R. D., KINOSHITA, H., LAVERNE, C., MOTT, M. J. and NORMARK, R. L. 1982. DSDP. Hole 504 B, the first reference section of 1km through Layer 2 of the ocean crust. *Nature,* 300, 589-598.

ANDREW, C. J. 1986. The tectonic-stratigraphic controls to mineralization in the Silvermines area, Co. Tipperary. This volume.

ANDREW, C. J. and ASHTON, J. H. 1982. Mineral textures, metal zoning and ore environment of the Navan orebody, Co. Meath, Ireland. *In: Mineral exploration in Ireland: Progress and Developments 1971-1981.* Brown, A. G. and Pyne, J. F. (eds.). Irish Assoc. Econ. Geol. 35-45.

ANDREW, C. J. and ASHTON, J. H. 1985. Regional setting, geology and metal distribution patterns of Navan orebody, Ireland. *Trans. Inst. Mining Metall. (Sect. B: Appl. Earth Sci.)* 94, B66-B93.

ARCHER, J. B. 1981. The Lower Palaeozoic rocks of the northwestern part of the Devilsbit-Keeper Hill inlier and their implications for the postulated course of the Iapetus suture zone in Ireland. *J. Earth Sci., Dublin,* 4, 21-38.

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

BAMFORD, D., NUNN, K., PRODEHL, C. and JACOBS, B. 1977. LISPB-III. Upper crustal structure of northern Britain. *J. Geol. Soc. London,* 133, 481-488.

BANKS, D. A. 1985. A fossil hydrothermal vent community from the Tynagh lead-zinc deposit, Ireland. *Nature* London, 313, 128-131.

BANKS, D. A. 1986. Hydrothermal chimneys and fossil worms from the Lead Zinc deposit, Tynagh, Ireland. This volume.

BISCHOFF, J. L., RADTKE, A. S. and ROSENBAUER, R. J. 1981. Hydrothermal alteration of greywacke by brine and seawater: roles of alteration and chloride complexing on metal solubilization at 200°C and 350°C. *Econ. Geol.,* 76, 659-676.

BOAST, A. M., COLEMAN, M. L. and HALLS, C. 1981. Textural and stable isotopic evidence for the genesis of the Tynagh base metal deposit, Ireland. *Econ. Geol.,* 76, 27-55.

BOYCE, A. J., ANDERTON, R. and RUSSELL, M. J. 1983. Remarkably rapid subsidence and Early Carboniferous base metal mineralization in Ireland. *Trans. Instn Min. Metall. (Sect. B: Appl. earth sci.)* 92, B55-B66.

BOYCE, A. J., COLEMAN, M. L. and RUSSELL, M. J. 1983. Formation of fossill hydrothermal chimneys and mounds from Silvermines, Ireland. *Nature,* 306, 545-550.

BRACE, W. F. 1984. Permeability of crystalline rocks: new in situ measurements. *J. Geophys. Res.,* 89, 4327-4330.

BRACE, W. F. 1985. To what depth is the crust permeable? 3rd Deep Geology Workshop. Programme and abstracts 3-4th Jan. 1985, University of Durham.

CAMERON, D. E. and ROMER, D. M. 1970. Denison copper-silver deposit at Aherlow, County Limerick, Ireland. *Trans. Instn. Min. Metall. (Sect. B: Appl. earth sci.)* 79, B171-173.

COOMER, P. G. and ROBINSON, B. W. 1976. Sulphur and sulphate-oxygen isotopes and the origin of the Silvermines deposit, Ireland. *Mineralium Deposita,* 11, 155-169.

DAVIS, E. E., LISTER, C. R. B., WADE, U. S. and HYNDEMAN, R. D. 1980. Detailed heat flow measurements over the Juan de Fuca ridge system. *J. Geophys. Res.,* 85, 299-310.

DERRY, D. R., CLARK, G. R. and GILLATT, N. 1965. The Northgate base-metal deposit at Tynagh, County Galway, Ireland. *Econ. Geol.,* 60, 1218-1237.

ELDER, J. W. 1976. Model of hydrothermal ore genesis. *In: Volcanism and ore genesis.* Institution of Mining and Metallurgy, 4-13.

FINLAY, S., ROMER, D. M. and CAZALET, P.C.P. 1984. Lithogeochemical studies around the Navan Zn-Pb orebody, Ireland. *In: Prospecting in areas of glaciated terrain, 1984.* Institution of Mining and Metallurgy, 35-46.

GARDINER, P. R. R. and MacCARTHY, I. A. J. 1981. The late Palaeozoic evolution of southern Ireland in the context of tectonic basins and their Translatlantic significance. *In:* KERR, J. W. and FERGUSSON, A. J. (Eds.), *Geology of the North Atlantic borderlands.* Canadian Society of Petroleum Geologists, Memoir 7, 683-725.

GRAY, G. J. and RUSSELL, M. J. 1984. Regional Mn-Fe lithogeochemistry of the Lower Carboniferous Waulsortian "Reef" Limestone in Ireland. *In: Prospecting in areas of glaciated terrain, 1984.* Institution of Mining and Metallurgy, 57-68.

HALL, J., POWELL, D. W., WARNER, M. R., EL-ISA, Z. M. M., ADESANYA, O. and BLUCK, B. J. 1983. Seismological evidence for shallow-crystalline basement in the Southern Uplands of Scotland. *Nature,* 305, 418-420.

HALLIDAY, A. N. and MITCHELL, J. G. 1983. K-Ar ages of clay concentrates from Irish orebodies and their bearing on timing of mineralisation. *Trans. R. Soc., Edinburgh Earth Sciences,* 74, 1-14.

HOLDSTOCK, M. P. 1982. Breccia-hosted zinc-lead mineralization in Tournaisian and Lower Visean carbonates at Harberton Bridge, County Kildare. *In: Mineral exploration in Ireland: progress and development 1971-1981.* Brown, A. G. and Pyne, J. F. (eds.). Irish Association for Economic Geology, 83-91.

HORNE, R. R. 1975. Possible transverse fault control of base metal mineralisation in Ireland and Britain. *Ir. Nat. J., 18, 140-144.*

HUDSON, J. D. 1982. Pyrite in ammonite-bearing shales from the Jurassic of England and Germany. *Sedimentology,* 29, 639-667.

HUTCHINGS, J. 1979. The Tynagh deposit. *In: Prospecting in areas of glaciated terrain Ireland 1979. Excursion handbook.* Brown A. G. (ed.). Irish Assoc. Econ. Geol., 34-46.

IRVING, E. and STRONG, D. F. 1984a. Evidence against large-scale Carboniferous strike-slip faulting in the Appalachian-Caledonian orogen. *Nature,* 310, 762-764.

IRVING, E. and STRONG, D. F. 1984b. palaeomagnetism of the Early Carboniferous Deer lake Group, Western Newfoundland: no evidence for mid-Carboniferous displacement of "Acadia". *Earth Planet. Sci. Lett.,* 69, 379-390.

JONES G. V. and BRADFER, N. 1982. The Ballinalack zinc-lead deposit, Co. Westmeath, Ireland. *In: Mineral exploration in Ireland: Progress and Development 1971-1981.* Brown, A. G. and Pyne, J. F. (eds.), Irish Assoc. Econ. Geol., 47-61.

KAY, A. and STRONG, D. F. 1983. Geologic and fluid controls on As-Sb-Au mineralization in Moretons Harbour area, Newfoundland. *Econ. Geol.* 78, 1590-1604.

KERRICH, R. and FRYER, B. J. 1981. The separation of rare elements from abundant base metals in Archean lode gold deposits: implications of low water/rock source regions. *Econ. Geol.,* 76, 160-166.

KOZLOVSKY, Y. A. 1982. Kola super-deep: interim results and prospects. *Episodes, 1982,* No. 4, 9-11.

KOZLOVSKY, Y. A. 1984. The World's deepest well. *Scientific American,* 251, no. 6, 106-112.

LAPWOOD, E. R. 1948. Convection of a fluid in a porous medium. *Proc. Cambridge Philos. Soc.*, 44, 508-521.

LARTER, R. C. L., BOYCE, A. J. and RUSSELL, M. J. 1981. Hydrothermal pyrite chimneys from the Ballynoe baryte deposit, Silvermines, County Tipperary, Ireland. *Mineral. Deposita*, 16, 309-318.

LEES, A., NOEL, P. and BOUW, P. 1977. The Waulsortian "reefs" of Belgium: a progress report. *Mem. Instn geol. Univ. Louvain*, 29, 289-315.

LEFORT, J. P. and MAX, M. D. 1984. Development of the Porcupine Seabight: use of magnetic data to show the direct relationship between early oceanic and continental structures. *J. Geol. Soc. London*, 141, 663-674.

LEGGETT, J. K., McKERROW, W. S., MORRIS, J. H., OLIVER, G. J. H. and PHILLIPS, W. E. A. 1979. The north-western margin of the Iapetus ocean. *In: The Caledonides of the British Isles — reviewed.* Harris, A. L., Holland, C. H. and Leake, B. E. (eds.). Geol. Soc. London, 8, 499-512.

LONG, C. B., MAX, M. D. and YARDLEY, B. W. D. 1983. Compilation Caledonian Metamorphic Map of Ireland. *In: Regional Trends in the Geology of the Appalachian-Caledonian-Hercynian-Mauritanide Orogen*, Schenk, P. E. (ed.) D. Reidel Publishing Company, 221-233.

MAX, M. D. and INAMDAR, D. D. 1983. Detailed compilation magnetic map of Ireland and a summary of its deep geology. *Geol. Surv. Ireland, Rep. Series, RS 83/1.*

MCKENZIE, D. P. 1978. Some remarks on the development of sedimentary basins. *Earth Planet. Sci., Lett.* 40, 25-32.

MILLER, J. and GRAYSON, R. F. 1982. The regional context of Waulsortian Facies in northern England. *In: Symposium on the palaeoenvironmental setting and distribution of the Waulsortian facies, 1982.* El Paso Geological Society, University of Texas, 17-33.

MOORE, J. McM. 1975. Fault tectonics at Tynagh mine, Ireland. *Trans. Instn Min. Metall.* (Sect. B: Appl. Earth Sci.). 84, B141-145.

MORRISSEY, C. J., DAVIS, G. R. and STEED, G. M. 1971. Mineralisation in the Lower Carboniferous of central Ireland. *Trans. Instn Min. Metall. (Sect. B: Appl. Earth Sci.)*, 80, B174-185.

MUFFLER, L. J. and WHITE, D. E. 1969. Active metamorphism of Upper Cenozoic sediments in the Salton Sea Geothermal Field and the Salton Trough, southeastern California. *Geol. Soc. America. Bull.*, 80, 157-182.

MURPHY, T. 1960. Gravity anomaly map of Ireland, Sheet 5 — South West. Dublin Institute for Advanced Studies. *Geophysical Bulletin No. 18.*

MURPHY, T. 1962a. Some unusual low Bouger anomalies of small extent in central Ireland and their connection with geological structure. *Geophy. Prosp.*, 10, 258-270.

MURPHY, T. 1962b. Gravity anomaly map of Ireland, Sheet 4 — South East. Dublin Institute for Advanced Studies. *Geophysical Bulletin No. 22.*

NORTON, D. and KNAPP, R. 1977. Transport phenomena in hydrothermal systems: the nature of porosity. *American J. Sci.*, 277, 913-936.

OBRIEN, M. V. 1959. The future of non-ferrous mining in Ireland. *In: The future of non-ferrous mining in Great Britain and Ireland.* The Institution of Mining and Metallurgy, 5-26.

OLIVER, G. J. H. 1978. Prehnite-pumpellyite facies metamorphism in Co. Cavan, Ireland. *Nature, 242-243.*

PEARSON, W. C. and LISTER, C. R. B. 1973. Permeability measurements on a deep-sea core. *J. Geophys. Res.*, 78, 7786-7787.

PEREIRA, J. 1963. Further reflections on ore genesis and exploration. *Mining Mag.*, 109, 265-280.

PHILLIPS, W. E. A., STILLMAN, C. J. and MURPHY, T. 1976.A Caledonian plate tectonic model. *J. geol. Soc., London*, 132, 579-609.

PINE, R. J. and BATCHELOR, A. S. 1982. *In situ* stresses and jointing in the Carnmenellis granite and the implications for hydraulic behaviour. *Camborne School of Mines Journal, 82, 40-48.*

RADTKE, A. S. and RUSSELL, M. J. 1978. Relationship between minor elements in Palaeozoic sedimentary rocks and the distribution and chemical composition of base metal deposits in Ireland (abs.). *Econ. Geol.*, 73, 1396.

RICE, J. R. 1975. On the stability of dilatant hardening for saturated rock masses. *J. Geophys. Res.*, 80, 1531-1536.

RUSSELL, M. J. 1968. Structural controls of base metal mineralization in Ireland in relation to continental drift. *Trans. Instn Min. Met. (Sect. B: Appl. earth sci.) 77.*, B117-B128.

RUSSELL, M. J. 1973. Base-metal mineralization in Ireland and Scotland and the formation of Rockall Trough. In: Tarling, D. H. and Runcorn, S. K. (eds) *Implications of continental drift to the earth sciences. vol. 1.* Academic Press, London and New York, 581-597.

RUSSELL, M. J. 1974. Manganese halo surrounding the Tynagh ore deposit, Ireland: a preliminary note. *Trans. Instn Min. Met. (Sect. B: Appl. Earth Sci.)* 83, B65-B66.

RUSSELL, M. J. 1975. Lithogeochemical environment of the Tynagh base-metal deposit, Ireland and its bearing on ore deposition. *Trans. Instn Min.* Met. *(Sect. B: Appl. Earth Sci.) 84. B128-B133.*

RUSSELL, M. J. 1978. Downward-excavating hydrothermal cells and Irish-type ore deposits: importance of an underlying thick Caledonian prism. *Trans. Instn Min. Met. (Sect. B: Appl. Earth Sci.)* 87, B168-B171.

RUSSELL, M. J., SOLOMON, M. and WALSHE, J. L. 1981. The genesis of sediment hosted exhalative zinc-lead deposits. *Mineralium Deposita*, 16, 113-127.

RUSSELL, M. J. 1983. Major sediment-hosted exhalative zinc+lead deposits: formation from hydrothermal convection cells that deepen during crustal extension. *In: Sediment-hosted stratiform lead-zinc* deposits, Sangster, D. F. (ed). Min. Assoc. Canada. Short Course Handbook 8, 251-282.

RUSSELL, M. J., BOYCE, A. J., LARTER, R. C. L. and SAMSON, I. M. 1982. The significance of hydrothermal pyrite chimneys in the Silvermines deposits. *: Mineral Exploration in Ireland: Progress and Developments* 1971-1981. Brown, A. G. and Pyne, J. F. (eds.). Irish Association for Economic Geology, 171-172.

RUSSELL, M. J., HALL, A. J. and DULLER, P. 1984. Implications of chemical garden growth to the understanding of certain ore morphologies in the Navan ore-body. *Mineralogical Soc. Newsletter, Sept.*, No. 64, 2-3.

SAMSON, I. M. and RUSSELL, M. J. 1983. Fluid inclusion data from the Silvermines Zn+Pb+$BaSO_4$ deposits, Ireland. *Trans. Instn Min. Met. (Sect. B Appl. Earth Sci.)* 92, B67-B71/

SAWKINS, F. J. 1984. Ore genesis by episodic dewatering of sedimentary basins: application to giant Proterozoic lead-zinc deposits. *Geology*, 12, 451-454.

SEVASTOPULO, G. D. 1979. The stratigraphical setting of base-metal deposits in Ireland. In: *Prospecting in areas of glaciated terrain 1979.* Institution of Mining and Metallurgy, 8-15.

SHERIDAN, D. J. R., HUBBARD, W. E. and OLDROYD, R. W. 1967. A note on Tournaisian Strata in NOrthern Ireland. *Sci. Proc. R. Dublin Soc. A3*, 33-37.

SIBSON, R. H. 1977. Fault, rocks and fault mechanisms. *J. Geol. Soc. London, 133,* 191-213.

SLOWEY, E. P. 1986. The zinc-lead and barite deposits at Keel, County Longford. This volume.

SOLOMON, M. J. 1976. "Volcanic" massive sulphide deposits and their host rocks — a review and an explanation. *In: Handbood of Stratabound and Stratiform Ore Deposits,* Wolfe, K. H. (ed.) Vol. 6, Amsterdam, Oxford, New York: Elsevier 21-54.

STROGEN, P. 1974. The sub-Palaeozoic basement in central Ireland. *Nature,* London, 250, 562-563.

TAYLOR, S. 1984. Structural and palaeotopographic controls of lead-zinc mimeralization in the Silvermines orebodies, Republic of Ireland. *Econ. Geol.* 79, 529-548.

TAYLOR, S. and ANDREW, C. J. 1978. Silvermines orebodies, County Tipperary, Ireland. *Trans. Instn Min. Metall. (Sect. B: Appl. Earth Sci.) 87,* B111-B124.

THOMPSON, I. S. 1967. The discovery of the Gortdrum deposit, Co. Tipperary, Ireland. *Can. Min. Metall. Bull. 70,* 85-92.

TYLER, P. 1979. The Gortdrum deposit. *In: Prospecting in areas of glaciated terrain, Ireland 1979 Excursion handbook.* Brown, A. G. (ed.). Irish Assoc. Econ. Geol. 73-81.

WALKER, R. N., LOGAN, R. G. and BINNEKAMP, J. G. 1977. Recent geological advances concerning the H. Y. C. and associated deposits, McArthur River, N. T. *J. Geol. Soc. Aust.* 24, 365-380.

WEBER, W. W. 1964. Modern Canadian exploration techniques reveal major base metal occurrence at Silvermines, Co. Tipperary, Eire. *Can. Mining J.* 85, 54-57.

WHITE, J. C. and WHITE, S. H. 1983. Semi-brittle deformation within the Alpine fault zone, New Zealand. *J. Struct. Geol.*, 5, 579-589.

WILBUR, D. H. and ROYALL, J. J. 1975. Discovery of Mallow copper-silver deposit, Co. Cork, Ireland. *Prospecting in Areas of Glaciated Terrain,* Institution of Mining and Metallurgy, 60-75.

Discussion

GEOFF STEED (University College Cardiff) asked:

Could the author explain his ideas as to the heat source which induced convection on the scale required for the Navan deposit?

REPLY:

The heat source for the envisaged convective process is that stored in the upper crust plus that flowing into the upper crust during convection. I have estimated that there was ten times the amount of heat required to generate a Navan-sized deposit available in the Early Carboniferous upper crust, assuming temperatures of updraught of 250°C (see also Russell, 1978).

DAVID J. BURDON (Minerex Ltd.,) asked:

At what depth under the ocean would water vaporize at, say, 200°C? In the hot ore-forming springs of the Californian Gulf, a head of some 2,500m of sea-water held the spring water there liquid at a temperature of 600°C. It proved difficult to measure the temperature of liquid water at 6°C. Depth-pressure will hold water liquid at high temperatures. When reduced pressure allows the water to vaporize, there the metallic ions in solution will be precipitated; they may be precipitated in the rock aquifer under the sea-floor, or on the sea-floor, or in the sea-water above the sea-floor. The depth of sea covering the hot spring will strongly influence the stratigraphical position in which the ore is deposited.

REPLY:

A vertical column of 140m of Carboniferous sea-water would have prevented boiling of the hydrothermal solution at 200°C. There is little evidence for boiling at Silvermines, and the metals were precipitated from a mildly acid hydrothermal solution on mixing with rather alkaline brines on, or below, the sea floor. Given that quartz with inclusions indicating temperatures of 200°C was collected from veins at what must have been 60m beneath the sea floor, we estimate Carboniferous seawater depths to have been at least 80m above the conduits at the southern end of the ore horizon (Samson, 1983; Samson and Russell, 1983).

References

RUSSELL, M. J. 1978. Downward-excavating hydrothermal cells and Irish-type ore deposits: importance of an underlying thick Caledonian prism. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.),* 87, B167-B171.

SAMSON, I. M. 1983. Fluid inclusion and stable isotope studies of the Silvermines orebodies, Ireland and comparisons with Scottish vein deposits, Unpublished thesis, University of Strathclyde.

SAMSON, I. M. and RUSSELL, M. J. 1983. Fluid inclusion data from Silvermines deposits, Ireland. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci),* 92, B67-B71.