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# The geology and genesis of the Gortdrum Cu-Ag-Hg orebody.

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## Abstract

The Gortdrum Cu-Ag-Hg orebody is the strangest, and in some respects the most interesting, of all the base metal deposits in Irish Carboniferous rocks. It lies in a superficially similar structural setting to the major Zn-Pb orebodies at Tynagh and Silvermines in basal Carboniferous (Courseyan) limestones on the northern side of an ENE-trending normal fault adjacent to a pre-Carboniferous inlier. Uniquely at Gortdrum, however, there is a close spatial association between epigenetic mineralization and high level basic intrusions; these comprise two plugs, each more than 20m in diameter, and a series of dykes which have been intensely altered after emplacement due to hydrothermal circulation. They are post-dated by irregular bodies of intrusive breccia and, in turn, by the mineralization. The Gortdrum igneous rocks are related to the Limerick syncline Chadian to Asbian volcanic complex, not far to the west, and thus they were probably emplaced some 5 to 15 Ma after the limestones.

The orebody is divided into two parts. That at the western end lies between the main fault and an easterly trending vertical dyke complex which intersects the fault at about the centre of the mine area. To a minor extent patches of ore are also concentrated along the line of the dyke. At the eastern end the ores are relatively high grade and occur for the main part in a narrow fault-bounded wedge of crushed and partially dolomitized limestones and breccias, which extends down into the Devonian sandstones for about 100m below the normal limestone base.

In the near-surface part of the deposit, chalcopyrite and mercurian tennantite are the most abundant ore minerals. They occur with calcite and ferroan dolomite in veinlets within shattered, massive bioclastic limestones of Courseyan 2 and 3 age. At greater depth bornite and chalcocite are the predominant ore minerals, and these occur within shaly partially dolomitized Courseyan 1 and 2 limestones and mixed units. Minor but subeconomic mineralization has been traced to depths of 800m below the deposit in the Devonian Old Red Sandstone and Silurian metasediments. Pyrite is a common but minor component of the ore, galena and sphalerite are rare. Accessory minerals include cinnabar, cobaltite, arsenopyrite, native amalgam, stromeyerite, wittichenite and a Cu-Hg-S phase now known as gortdrumite.

Fluid inclusion results show that the main tennantite-chalcopyrite mineralization was deposited within a temperature range of about 140 to 180°C from mildly saline fluids. Later phases of mineralization were formed as temperatures declined to less than 100°C.

It is considered that the ores were formed as a consequence of convective water circulation, mainly above the unconformity between Devonian and Silurian rocks, due to high geothermal gradients related to, but post-dating, the Carboniferous volcanic activity in the area. The presence of hydrocarbons in some fluid inclusions indicates that these may have catalysed abiogenic reduction of seawater-derived sulphate, thus causing preferential deposition of metallic sulphides within the organic-rich Courseyan marine beds.

## Introduction

The deposit at Gortdrum was discovered during 1963 as a consequence of wide ranging exploration within central Ireland by the Lower Limestone Syndicate Company in the years following the discovery of commercial-grade lead-zinc-silver mineralization at Tynagh. The methods employed were stream sediment and soil sampling geochemistry, supported by Induced Polarization surveys. Drilling commenced in 1963 and carried on intermittently to the end of 1965, when 145 holes totalling about 12,500m of drilling had been completed. Details of the exploration programme are given by Thompson (1966).

The ore reserves were defined during 1966 as 3,810,100t containing 1.19% Cu and 25.1 g/t Ag, and the decision to mine the deposit was made during that year. The ore also contained substantial concentrations of As, Sb and Hg.

Production began late in 1967 and continued until mid 1975. During that time substantial further exploration was carried out, but resulted in no significant additions to the

original reserves. It also proved impossible to mine the deepest parts of the orebody due to stability problems within the open pit. During the life of the mine 34,737t of copper, 82,878kg of silver and 16,975kg of mercury were produced (Tyler, 1979). This represents 76.6% of the original reserve estimate for Cu and 92.8% for Ag.

## Regional geology

### General

The orebody lies within the basal units of the Carboniferous limestone sequence in the southwestern part of the Irish Central Plain. Immediately to the SW of the orebody there is an ENE aligned gentle upwarp about 12km long, cored by sparsely outcropping Devonian sandstones, known as the Emly Inlier (Fig. 1). A few miles to the north the surface elevation increases markedly into the most extensive of all the upland blocks within the Central Plain,

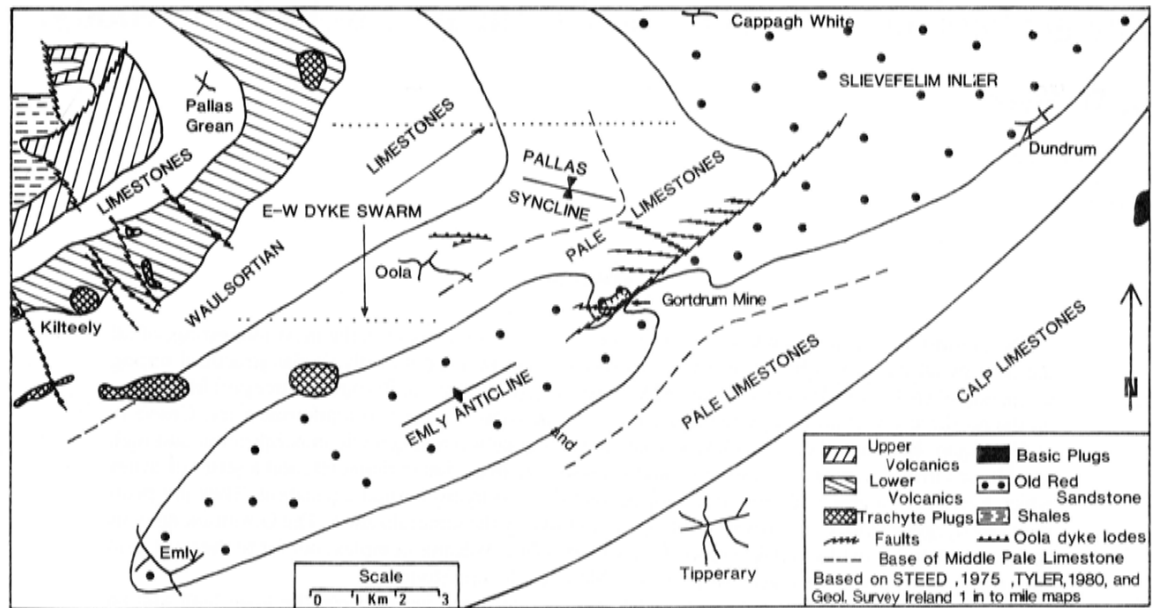


Figure 1. Geology of the Gortdrum district.

the Slieve Felim Inlier. In its central parts this is composed of Silurian metasediments, and on its flanks of Devonian sandstones. The latter dip radially outwards from the central parts of the Inlier and pass conformably under the limestones of the Carboniferous succession. The northern edge of the Slieve Felim Inlier is marked by the Silvermines fault zone with its associated important deposits of Pb, Zn, Ag, Cu and barite.

The margins of the Limerick Syncline volcanic complex lie about 8km to the west and stratigraphically about 500m above the Gortdrum deposit. This was the largest centre of Carboniferous volcanic activity in Ireland, and now covers an area of about 180km<sup>2</sup>. Outlying patches of tuff and lava, mainly on its northern side, indicate that it was once considerably larger.

### Stratigraphy

A general stratigraphic section for the area is given in Figure 2. The succession is conformable above the marked unconformity between Silurian metasediments and Devonian sandstones. The precise position of the boundary between the Devonian and Carboniferous Systems is not known; for convenience the boundary is taken at the position in the section marking the change from Old Red Sandstone-type continental deposition to Courceyan marine deposition.

The mineralization at Gortdrum lies mainly in limestones of the Courceyan 2 and early Courceyan 3 Stages, and to a lesser extent in mixed shaly units of probable Courceyan 1 Stage. (The term Courceyan has recently been proposed for a stage roughly equivalent to the Tournaisian of Belgium.) The end of Courceyan 2 deposition is marked by a widespread, probably isochronous, mudstone unit known as the Ballyvergin Shale (Fig. 2) (Sevastopulo, 1979). Radiometric dates suggest an age for Courceyan 2 of approximately 360Ma (George et al., 1976).

The basal Carboniferous units have been intersected by many diamond drill holes, both within the district and up to about 10km from Gortdrum. These reveal a consistently

similar succession with no systematic variations related to any local structural feature. In particular a series of drill holes across the Emyly Inlier reveal no variations which might indicate that it existed as a structural high during the time of Lower Carboniferous sedimentation.

### Volcanic rocks

Unlike other major deposits within the Carboniferous rocks of Ireland, the Gortdrum deposit is directly associated with igneous rocks. Thus, the volcanic history of the area is of especial importance.

There is no evidence in the district for any Courceyan volcanism contemporaneous with the deposition of the Gortdrum host rocks. Elsewhere in Ireland this seems also to have been a time of relative stability, and only a few minor tuff horizons are recognized (MacDermot and Sevastopulo, 1972).

During the Devonian, however, there was comparatively widespread but minor volcanicity, mainly within the northern part of Ireland (Charlesworth, 1963), but also at Lough Guitane about 100km to the SW of Gortdrum where there are thin rhyolitic units (Strogen, pers. comm.). Geikie (1897) describes two other localities at Ballinleeney and Knockfeerina, about 40km to the west, but these have been reinterpreted as intrusive bodies of probable Courceyan to Chadian age (Strogen, pers. comm.).

More intense volcanism took place widely in Ireland during the Chadian. The major Limerick syncline centre to the west of Gortdrum contains two extensive and roughly concentric rings of volcanic rock within a pronounced oval basin about 19km in an easterly direction by 10km in a northerly direction. The lowermost and more extensive of these rings is of Chadian age, and is composed of basaltic lavas, vitric and lithic tuffs and trachytes (Ashby, 1939; Strogen, 1977) with a total thickness between 250m and 500m around the syncline (Strogen, pers. comm.). The lavas have not been precisely dated but lie within Chadian limestones for which the best radiometric dates indicate an age of approximately 355Ma (George et al., 1976).

The central, less complete, ring of volcanics is Asbian in

System	Stage	Stratigraphic Unit	Lithology	Approx. thickness (metres)		
Carboniferous	Asbian	Upper Volcanics	Ankaramites, limburgites	Variable		
		Middle Limestones	Clean bioclastic limestones			
		Lower Volcanics	Basalts, trachytes and tuffs			
	Chadian	G	Waulsortian Limestones	Clean micritic 'reef' limestones	~300	
			Upper Pale Limestone		170	
			Middle Pale Limestone	Bioclastic limestones—comparatively clean	120	
			Lower Pale Limestone		40	
			Ballyvergin Shale	Sharply defined mudstone band	3	
			Dark Limestone	Bioclastic limestone with appreciable intermixed black shaly material	25	
			Courseyan	Laminated Shales	Finely banded calcareous shale	8
				(1) Transition Limestone	Fairly uniform sandy limestone	9
				Mixed Beds	Complex sequence of finely interbedded dark shales, fine sandstones and limestones	15
Devonian				Upper Old Red Sandstone	White to pale buff dolomitic sandstones typically about 8m thick interbedded with red shales, about 4m thick	270
Major unconformity						
Silurian	—	—	Greywackes and shales metamorphosed to lower greenschist grade	Unknown		

(1) Together called Transition Beds.

G—Highest level preserved at Gortdrum.

**Figure 2.** Stratigraphy of the Gortdrum district.

age (Strogen, pers. comm.) and is separated from the outer ring by a unit of limestones with a variable thickness; the total thickness of the two volcanic units plus the limestone is about 800m (Strogen, pers. comm.). The central lavas are ankaramites and limburgites (Strogen, 1977) which locally contain analcite (Prior, 1910), and occur in associ-

ation with lithic tuffs. Radiometric datings for the Asbian imply an age of about 335Ma (George et al., 1976).

Within the inner volcanic ring, and filling the centre of the basin, there is an isolated outlier composed of later Dinantian limestones unconformably overlain by Namurian clastic sediments.



**Table 1.**  
Analyses of Limerick Volcanic Centre and Gortdrum igneous rocks.

%	Upper <sup>(1)</sup> volcanics	Lower volcanics <sup>(2)</sup>			Gortdrum intrusives <sup>(3)</sup>			
	Ankaramite	Basalt	Basalt	Trachybasalt	Ankaramite	Mafic <sup>(a)</sup> altered	Mafic <sup>(b)</sup> very altered	Intrusive <sup>(c)</sup> breccia
SiO <sub>2</sub>	40.81	44.43	45.26	51.13	41.21	40.04	32.34	27.22
Al <sub>2</sub> O <sub>3</sub>	13.08	12.74	14.87	16.58	12.42	11.80	13.90	6.48
Fe <sub>2</sub> O <sub>3</sub>	6.40	7.41	3.34	4.14	3.83	2.58	0.77	0.19
FeO	7.20	5.34	8.38	6.22	7.90	8.54	5.89	6.13
MgO	10.03	6.43	4.51	2.73	11.32	7.50	3.31	5.70
CaO	10.12	12.05	9.81	6.11	10.04	9.30	15.97	22.05
Na <sub>2</sub> O	2.43	2.85	2.70	4.24	1.34	2.06	0.29	0.34
K <sub>2</sub> O	0.31	1.42	1.58	2.89	2.10	1.09	3.09	1.54
TiO <sub>2</sub>	3.86	3.45	3.45	2.22	2.89	2.73	3.13	0.93
MnO	0.07	0.25	0.17	0.19	0.15	0.15	0.17	0.20
P <sub>2</sub> O <sub>5</sub>	0.88	0.43	0.76	0.54	0.78	0.71	0.99	0.25
CO <sub>2</sub>	2.5	1.28	2.58	0.56	3.20	11.28	18.77	27.63
H <sub>2</sub> O	2.3	2.23	2.40	2.33	4.46	2.88	2.09	0.65
ppm								
Cr	—	190	110	275	335	400	190	—
V	—	—	—	—	—	—	—	—
Ni	—	200	200	50	250	3 90	120	160
Co	—	—	—	—	70	70	70	50
Cu	—	80	70	20	90	150	70	1090
Zn	—	180	190	180	210	210	80	240
Ba	—	340	460	450	1360	450	150	—
Sr	—	410	530	—	700	450	160	—
Nb	—	40	50	—	110	110	120	—

Sources:

<sup>(1)</sup>Prior (1910).

<sup>(2)</sup>Ashby (1946): major elements.

Steed (1975): trace elements on replicated samples.

<sup>(3)</sup>Steed (1975).

<sup>(a)</sup>Extensive alteration, but primary textures and traces of pyroxene preserved.

<sup>(b)</sup>Completely altered, no primary textures or silicates preserved.

<sup>(c)</sup>Altered mafic and sedimentary fragments.

Within the outer ring of volcanics there are several fairly large plugs of trachyte, much less basic than the lavas which surround them. A number of similar plugs are present in the limestones beyond the limits of the volcanic basin (Fig. 1).

On the eastern side of the volcanic basin, in the limestones trending towards Gortdrum, there is a broad belt in which there are many hundreds of altered basic dykes. The largest reported dyke is about 3m thick, but most are between 0.1 and 0.5m thick. They are near vertical and trend almost due east. Within the belt there are also a number of comparatively small-scale altered basic stocks. The most easterly known igneous body of the belt is near Dundrum, about 15km to the east of Gortdrum. This is very poorly exposed, but is most probably a small breccia-filled vent (Strogen, pers. comm.). Fragments derived from a small disused quarry are of hyaloclastic tuff.

Traces of lead-zinc mineralization are known at a number of places in limestones adjacent to dykes. In addition, a very large altered dyke is the locus for lead-zinc-copper ores at the historic Oola mine, about 5km west of Gortdrum. At this locality the sulphides occur in barite veins within the dyke.

In some of the larger dykes there are remnants of the primary igneous rock which is very mafic, generally ankaramite (Strogen, pers. comm.). In general, however, this is

strongly altered to a soft buff-green rock composed mainly of carbonates, clay minerals, chlorite, leucoxene and secondary quartz. The adjacent limestones show characteristically little if any evidence of alteration.

Drilling at Gortdrum has shown that there are comparable dykes in the underlying Old Red Sandstone and in Silurian metasediments at depth. Also, nineteenth century 6 inch to the mile maps of the Geological Survey of Ireland indicate two localities where dykes cut across Lower Volcanic Units of the Limerick Complex, but unfortunately both exposures have since been covered.

Published analyses for representative samples from the Upper and Lower Volcanic Units are given in Table 1. In addition analyses for ten igneous samples, three from the Upper Unit, four from the Lower Unit and three from dykes and minor intrusives, have been carried out (Steed, 1975), and more detailed mineralogical and geochemical information is also available (Strogen, 1983).

The results show that the igneous rocks are members of an alkali volcanic suite (according to the scheme of Irvine and Barager, 1971). They are clearly comparable in chemistry with the extensive Carboniferous alkali volcanic rocks of the Scottish Midland Valley, which have been described by many authors (e.g. Walker, 1965; MacDonald et al., 1977; Francis, 1979). Results for both the Irish and Scottish suite plot within the same fields on alkali-silica, lime-silica

and FMA diagrams, and both give an alkali-lime index of about 50. The Limerick Syncline volcanic rocks do, however, contain notably higher concentrations of  $TiO_2$ ,  $P_2O_5$  and Nb.

### Structure

The most important control to mineralization at Gortdrum is a major ENE-trending normal fault, with a dip of approximately  $70^\circ$  to the north, which brings Devonian sandstones on the south in contact with Carboniferous limestones on the north. The ore grade mineralization was contained almost entirely within the limestones in a zone about 600m long and extending for up to about 100m to the north of the fault. Beyond the limits of the ore zone the fault has been traced for only a few hundred metres to the west, into sandstones of the Emly Inlier, and for about 5km to the east, into sandstones on the flanks of the Slieve Felim Inlier (Fig. 1).

Faults with an ENE trend have long been recognized as especially important controls to the location of mineral deposits in Irish Carboniferous rocks. Their orientation is parallel to that of faults which were known to be active during the Caledonian, such as the Highland Boundary Fault (Charlesworth, 1963). It has thus been suggested that faults of this type lie along lines of weakness in the underlying Silurian and Ordovician rocks, and that the faults were reactivated during later tectonic episodes.

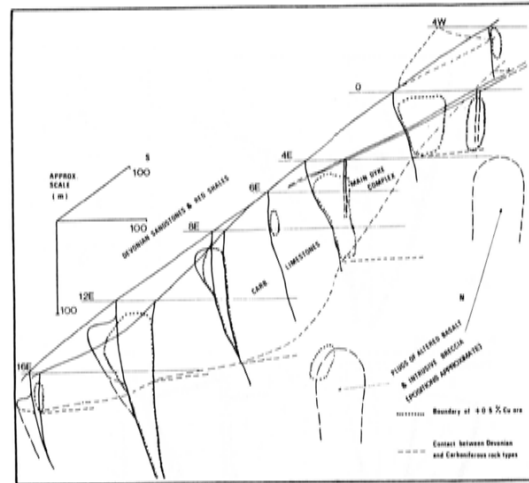
There is some evidence that major ENE-trending normal faults, controlling the positions of both the Tynagh and Silvermines orebodies, were active during Courceyan sedimentation (Taylor and Andrew, 1978; Hutchings, 1979). This would be essential if the faults were to act as channels for proposed syndimentary ore deposition at these locations. Critchley et al. (1983) consider that the Silvermines fault was initiated during late Courceyan sedimentation as a dextral shear zone, and probably reactivated an earlier Caledonian fracture. On an accompanying map they indicate that both Tynagh and Gortdrum lie on similar dextral shear zones. There is no evidence at Gortdrum, however, that the fault had any effect on local Carboniferous sedimentation, and thus it could not have been active until at the earliest, late Courceyan or, more probably, Chadian. This is in conformity with the entirely epigenetic character of the ore at Gortdrum.

Regardless of when the faults were initiated, they were subjected to several phases of movement during the Hercynian orogeny. Moore (1975) considers that initial major normal movements on the Tynagh Fault were followed by reverse oblique-slip movements. Further evidence given by him for a compressive phase of deformation is the development of a slaty cleavage immediately adjacent to the fault in the hangingwall and the presence of open flexural folds in the limestones. Later comparatively small-scale cross-faults were formed, and finally there was a phase of sinistral strike slip movement of uncertain extent.

Gortdrum lies much further south than Tynagh and only about 40km north of the Armorican thrust front, within a district beyond the zone of recognizable Armorican metamorphic features, but characterized by extensive concentric folding generally trending ENE and containing southwards dipping thrust faults, with displacements of up to 200m (Gill, 1962), in addition to normal faults of the type described above.

### Geology of the Gortdrum deposit

The main structural features are shown in Figure 3. It



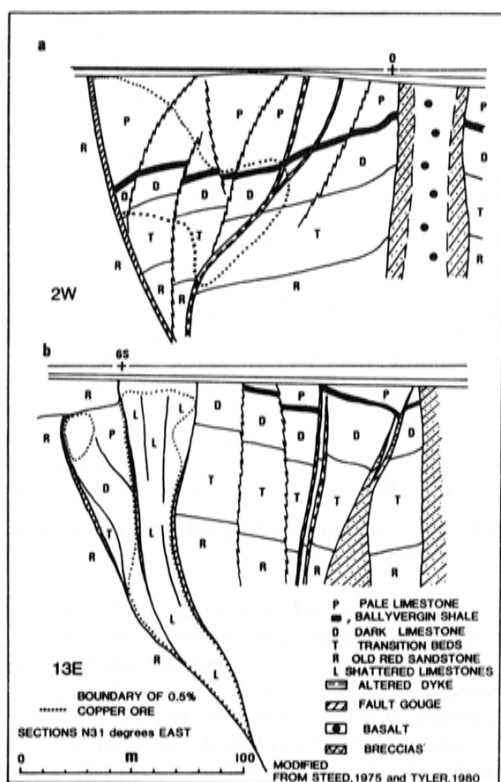
**Figure 3.** Major structural features of the Gortdrum ore deposit.

can be noted that the Gortdrum Fault cuts off the orebody, almost entirely, along its southern side. Even so the cut-off is not absolute since subeconomic amounts of copper mineralization occur widely within the footwall sandstones over a distance of at least 100m from the Fault.

The conformable boundary between the Carboniferous and the Devonian lies at a depth of more than 120m in the central parts of the mine area, and at progressively lesser depths with distances to the east, west and north from there. Near to the fault the depth is reduced to about 50m at Section 16E and 65m at Section 6W (Fig. 5 for lines of section). Some 230m to the north on the central sections it is reduced to about 65m. Thus it can be seen that the beds lie in a small structural basin which is cut off on the south side by the Gortdrum Fault. It is also evident that the ore zones lie almost entirely within the Carboniferous rocks. Again the cut-off is not absolute, and minor copper mineralization has been traced by diamond drilling to a depth of about 800m below the deposit, both in the Old Red Sandstone and in the underlying Silurian metasediments.

Figure 3 illustrates that there are two distinct structural blocks. One of the blocks is on the western side and extends approximately between Sections 6E and 6W, and the other block is on the eastern side, extending between Sections 6E and 16E. There is a marked division of the orebody itself between these two blocks. At the western end the greater part of the orebody lies between the Gortdrum Fault, which is a singular gouge-filled feature about 1m thick in this region (Plate 2a) and a major dyke zone. In this area it has a maximum width of about 100m and extends from the surface to a depth of about 100m. There is a zone of comparatively intense dolomitization along the line of the dyke complex, and within this zone there are some rich patches of mineralization.

Near the centre of the mine, from about Sections 5E to 7E, there is a region where the orebody almost pinches out. This coincides with a marked change in the character of the main fault. Further to the east it splits into a series of fractures, the two most prominent of which contain between them a narrow wedge of shattered limestones, shales and dolomites and mixed breccias, commonly including fragments of altered igneous material, which extends to a depth of some 200m, about 100m below the normal base of Carboniferous limestones in the area. Almost all of the eastern orebody lies within this wedge structure



**Figure 4.** Cross-sections through the Gortdrum deposit. (see Figure 3 for location of sections.)

(Plate 1) and pinches out with it at the eastern edge of the mine area. To the south of it there is a block of limestones which have been overthrust by Devonian sandstones from the south.

On the northern side of the orebody there are at least two plugs of altered basalt. The full extent of these is not known as, for the main part, they lie beyond the limits of the open pit in an area which has not been drilled in detail; they are, however, in excess of 20m in diameter.

Two representative cross-sections are shown in Figure 4, one for the central part of the eastern ore zone, and the other for the central part of the western zone. They show clearly the contrasting forms of the two ore zones. The eastern zone is narrow, extends to considerable depth, and is sharply confined within the wedge structure. The western zone is wider, but has less vertical extent and is not as sharply bounded on the north side.

Details of the geology and ore distribution at the Bench 3 level (about 25m below surface) are shown on Figure 5. At this level beds exposed north of the Fault were entirely of Pale Limestone with the exception of one small patch of Ballyvergin Shale close to the north wall.

The Gortdrum Fault in the western part of the mine area has a consistent strike of S65°W and an overall dip of about 75°N, though locally this varies between 65°N and 90°. The basal part of the Mixed Beds Unit (Fig. 2) is preserved just below surface on the southern side of the Fault at the extreme western end of the open pit. Since the equivalent position on the north side is known from drill holes, the total normal displacement on the fault can be determined as about 115m. There is no definitive evidence to indicate the sense or magnitude of any strike slip displacement.

Tyler (1979) has, however, observed that a sinistral displacement of the order of 300m could explain the present positions of the two ore zones, based on the assumption that these were once parts of a single continuous ore deposit.

Between Sections 6E and 8E the Fault splits into three major parts (Fig. 5). The two branches containing the wedge reach a maximum separation of about 35m between Sections 10E and 14E, and close together again at about 17E. The wedge zone thus has a lensoid shape and dips very steeply to the north (Plate 1). The rocks within it are, for the main part, shattered and deformed bioclastic limestones with intermixed black shaly material, and breccias, some of which contain fragments of highly altered igneous material (Plates 3b and 3d). Bedding is intensely disrupted but where recognisable generally dips very steeply to the north.

On the southern side of the main wedge is a subsidiary slice of rather less deformed but steeply dipping limestones overthrust by a block of sandstones (Fig. 4). Further to the east these limestones level out to a dip of about 20°N and are progressively cut out as the Devonian-Carboniferous contact rises until at about 17E the overthrust directly overlies comparable sandstones. The overthrust block itself (Plate 2b) is about 30m wide and 25m thick over most of its length, and it dies out to the west between Sections 10E and 6E. A second overthrust block of sandstones occurs at the extreme eastern end of the open pit on the northern side of the wedge (Fig. 5). This is apparently underlain by a thrust dipping at about 35° to the east, and in consequence the block thickens beyond the mine area so that there are continuous sandstones on either side of the wedge where this terminates at about 17E.

The rocks within the entire mine area have been intensely shattered. They are cut by large numbers of both normal and reverse minor faults with displacements ranging from a few centimetres to over 30m. This complexity makes it very difficult to trace even the more significant of the minor faults over any distance. On the Bench 3 map (Fig. 5) only faults traceable for more than 15m have been plotted, and in some cases extrapolations from adjacent levels have been made. Similarly on the sections (Fig. 4) only faults which can be correlated between drill holes about 30m apart are shown. The true picture is certainly more complex, as can be gathered from Plate 1.

The nature of folding is to some extent dependent on lithology. Both sandstones and massive limestones show cylindrical folds. Within the limestones these have wavelengths between 10m and 60m and interlimb angles from 160° to 110°. Slippage has taken place along shaly interbeds, but the limestones themselves have been broken up by numerous fractures, which are more or less radial to the fold axes. When the interlimb angles are forced below about 110° the folding apparently breaks down as the fractures break across the interbeds and create a chaotic mixture of shale and limestone. Beds of Devonian sandstone are typically about 8m thick, and they alternate with beds of red shale about 4m thick. In consequence, folds typically have fairly long wavelengths of about 100m, and have shallow interlimb angles of about 160°.

For units with a high shale content, folding is commonly irregular due to plastic deformation. This is especially marked in the Ballyvergin Shale with variations in thickness from 1m to 5m and pods and lenses squeezed out into the surrounding rocks.

The orientations of fold axes show considerable variation about an average of N70°E, plunge 0°. This is comparable to the trend of folding in the surrounding district, and



**Plate 1.**

The wedge structure at Gortdrum, as viewed in 1975 looking across the open pit towards the ENE. Old Red Sandstone to the right, Carboniferous units to the left. Compare with section at 13E (Fig. 4b).

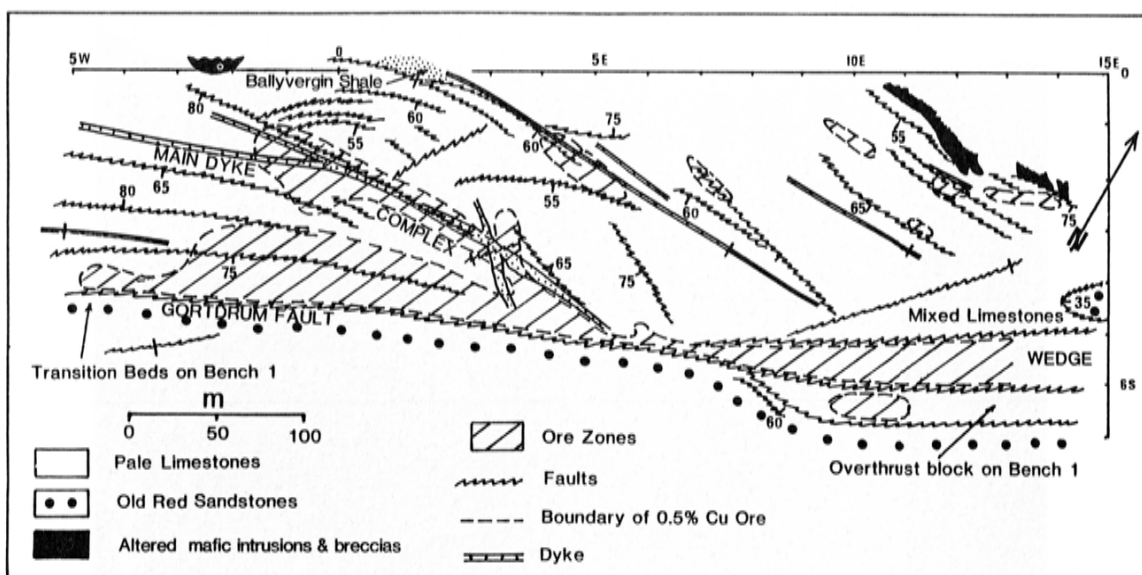
also nearly parallels the strike of the Gortdrum Fault. Stereoplots of joint attitudes indicate several sets, two of which are particularly significant. One set in limestones is comparatively early since it pre-dates folding and parallels the easterly, near-vertical dyke direction. The other, in limestones and sandstones, is at right angles to the folding, and is probably contemporaneous with it, and parallels a regional joint trend of  $160^\circ$  vertical.

### Gortdrum intrusives

The overall shapes of the two main pipes on the northern side of the orebody (Fig. 3) are not known with certainty,

and it is possible that they are parts of a much larger elongate body roughly paralleling the fault and underlying to the north. Only one flank of the westerly plug was exposed by the open pit. It appears to be a rather irregular body at least 20m across with a comparatively fresh basic core, but with highly altered margins. The mafic matrix is very fine-grained, but contains numerous fragments of much coarser altered basic or ultrabasic rock (Plate 3a). Comparable fragments noted in other Irish Carboniferous mafic bodies have been described as mantle xenoliths (Strogen, 1974 and pers. comm.). Chemical analyses on the freshest possible samples from the core indicate a very basic (10 to 15% normative olivine) alkaline ankaramitic





**Figure 5.** Geology of the Gortdrum deposit, Bench 3 level.

character (Table 1). Concentrations of  $TiO_2$ ,  $P_2O_5$ , Cr and Nb are abnormally high. In comparison with the Limerick Syncline volcanic suite they are chemically most similar to the ankaramites from the inner ring (Table 1). In parts of the plugs there are numerous vesicles, generally filled by carbonates; this indicates high level emplacement. Only minor copper mineralization occurs in proximity to the plugs, though in places cinnabar is especially prominent along hair-line fractures in the igneous rocks.

Some 10 dykes of altered mafic rock were exposed within the open pit. Of these only the main dyke complex is especially notable (Figs. 3, 4 and 5). This is a composite zone between 5m and 10m wide containing a number of altered dykes 0.2m to 1m wide with intervening sheets of limestone. In places these limestones and those adjacent to the zone are strongly dolomitized and contain rich patches of mineralization. The dykes show the normal alteration, except that they contain pockets with unusually high concentrations of green chromian muscovite (fuchsite) (Plate 3c).

Except in the central parts of the main pipes the mafic rocks all show evidence of intense secondary alteration. The initial stage is to a hard grey-buff material in which ghosts of primary phenocrysts and microtexture are preserved, and which has yielded to deformation by brittle fracturing. The ensuing and more general stage is to a soft pale green or buff material composed mainly of clay minerals and carbonates, with little evidence of any original igneous fabric, which has yielded plastically during periods of deformation.

Samples from both alteration stages have been analysed (Table 1). The results show that, in comparison with the fresh ankaramites, the most marked chemical changes are the addition of CaO and  $CO_2$  and the depletion of MgO,  $Fe_2O_3$ ,  $Na_2O$  and  $SiO_2$ . Microscope studies show that primary Fe-Ti oxides are replaced by leucoxene with little if any loss of  $TiO_2$ , and that primary picotite breaks down to liberate Cr which is transported only short distances before being incorporated in fuchsite. There is no chemical or textural evidence that the alteration caused a substantial volume change.

The character of the alteration indicates that it was almost certainly caused by extensive hydrothermal activity in the period following the emplacement and solidification of the mafic magmas.

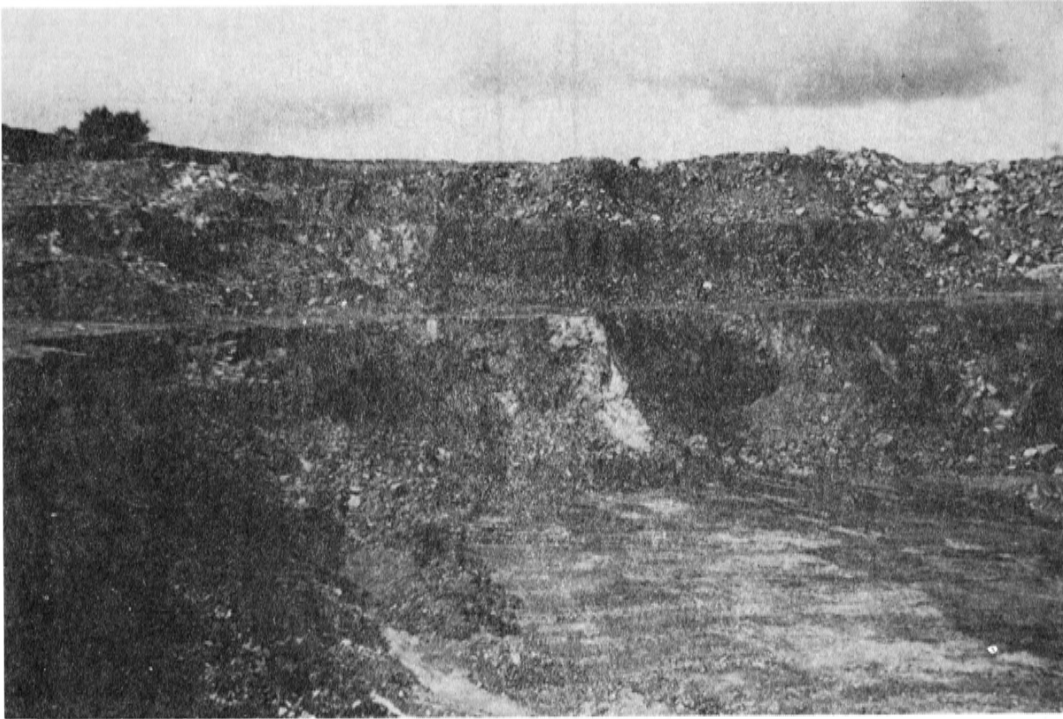
Near, and in places cutting into, the main mafic plugs there are irregular pipes or dykes of intrusive breccia (Plate 3b), locally up to 20m thick.

Comparable but smaller breccia structures occur elsewhere within the mine area, some in close association with the dykes. The breccias are heterogeneous mixtures of angular and rounded rock fragments in a fine-grained matrix of rock flour and carbonates. They commonly contain abundant irregular fragments of the most altered buff form of mafic igneous material, but never contain any fragments of fresher igneous rock. Sedimentary fragments are typically of a size range up to 3cm, but exceptionally up to 15cm. They are unaltered and contain all the various rock types in the succession; some of sandstone have been carried upwards for at least 100m into the overlying limestones.

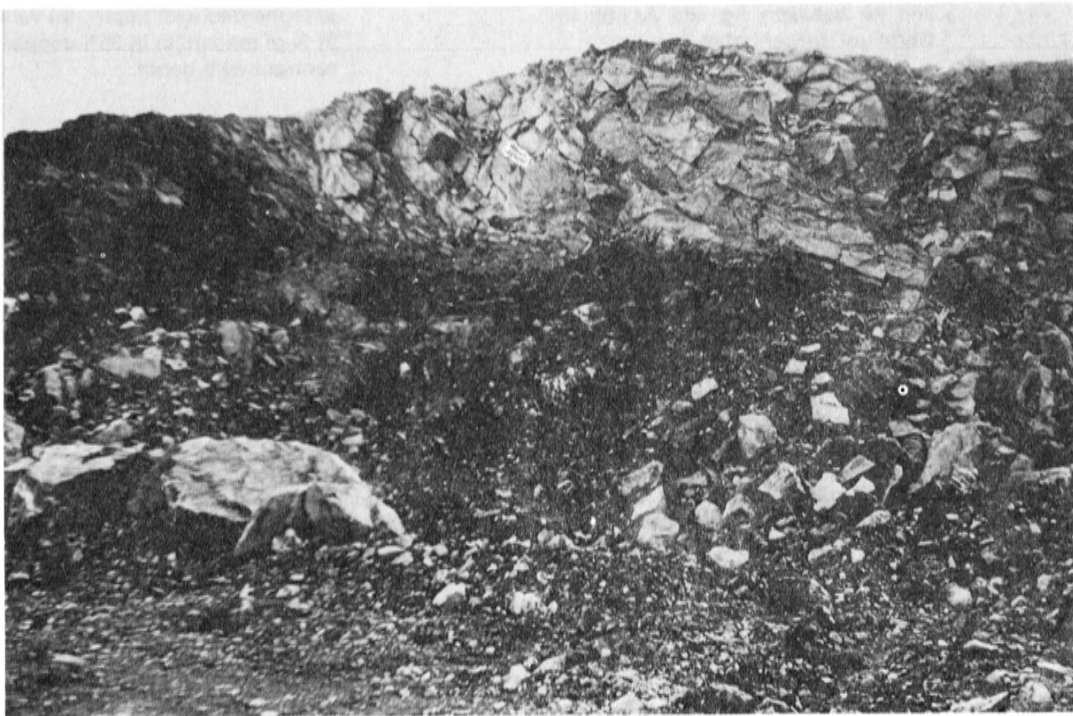
Bryant (1968) has described breccias of remarkably similar character at Warren, Arizona. These he considers were formed by fast-flowing, non-viscous, hydrothermal fluids with a flow velocity of 10 to 20m/s. A comparison with rates for known hot spring activity indicates that this is reasonable.

In some breccias there are fine-grained dispersions of pyrite or copper sulphides which appear isolated from adjacent limestones. These may have been deposited in the breccias when these were actively forming. The main episode of copper mineralization must, however, have occurred after their consolidation. This is indicated by veins of carbonates containing copper minerals which cut into the intrusive breccias and across enclosed fragments. Within the main mineralized zones breccias commonly contain rich ore. Outside them, however, there is an uncertain association of some low grade ore zones within, and near, large bodies of breccia, whereas other breccias are completely unmineralized.

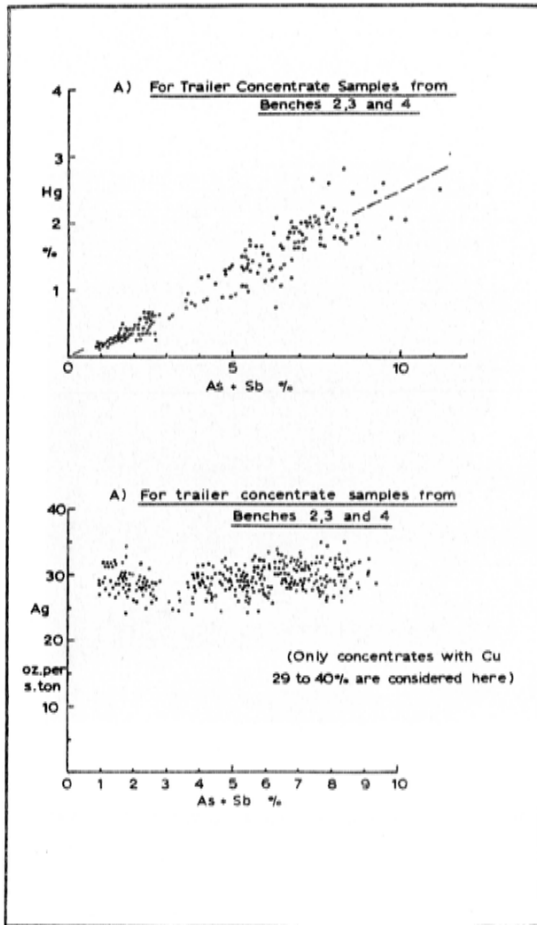
The breccias were all emplaced before any deformation or folding of the rocks took place.



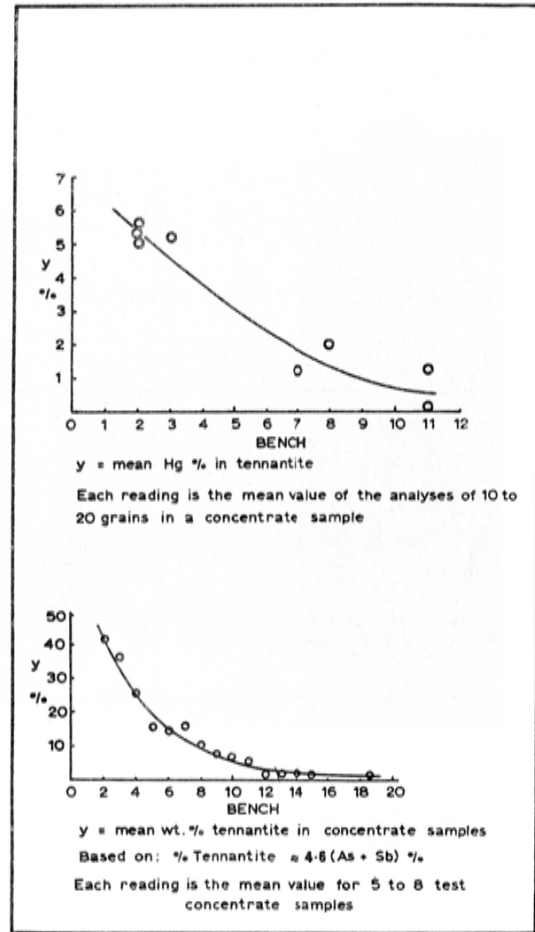
**Plate 2a.** The Gortdrum Fault at the west end of Bench 3. Old Red Sandstone to the left, Lower Pale Limestones to the right.



**Plate 2b.** The overthrust at the SE end of Bench 2. Old Red Sandstone overriding Lower Pale Limestones.



**Figure 6.** Relation (a) between Hg and As+Sb, and (b) between Ag and As+Sb in Gortdrum concentrates.



**Figure 7.** (a) Variation of average mercury tenor in tennantite with depth; (b) variation in % of tennantite in 35% copper concentrate with depth.

### Mineralization

Gortdrum is the only orebody in Irish Carboniferous rocks which has been worked in recent years for copper and for associated mercury and silver. Lead and zinc are almost completely absent from the deposit, despite the apparently favourable setting. Both of these metals are, however, present in minor patches of mineralization within a kilometre or two of the deposit, and in comparative abundance at the 19th century Oola lead-copper mine some 5km to the west.

Comprehensive mineralogical studies indicate that there are four principal ore minerals, mercurian tennantite, chalcopyrite, bornite and chalcocite. Other sulphides apart from minor pyrite are uncommon. There is a broad vertical zonation with tennantite and chalcopyrite predominant in the upper parts of the orebody, and bornite and chalcocite in the lower parts (Plates 4a and 4b).

Estimates of the relative concentrations of the sulphide minerals in the upper parts (surface to 25m depth) of the western ore zone were made by point counting of 6 polished sections of finely ground concentrate samples. Based on 3000 points, the average weight concentrations (calculated from the volume concentrations) are 28.8% tennantite, 28.0% bornite, 11.6% chalcopyrite, 5.8% chalcocite, 1.6%

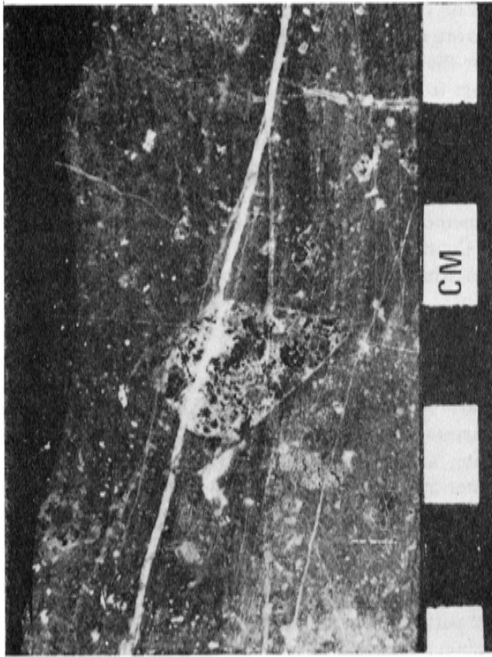
pyrite, and 24.2% gangue minerals. The highest content of tennantite was 38.7% and the lowest 14.3%.

Microscope studies of comparable concentrates and many ore specimens from other parts of the orebody confirm that there are no other common sulphides, and that galena and sphalerite are rare throughout. Cinnabar is generally a very minor phase, but in a few restricted zones it comprises as much as 1% by weight of concentrates. Surficial oxidation effects are generally only evident in the uppermost 15m of the deposit, and result in minor amounts of digenite, covellite, malachite, azurite and rare native copper and erythrite.

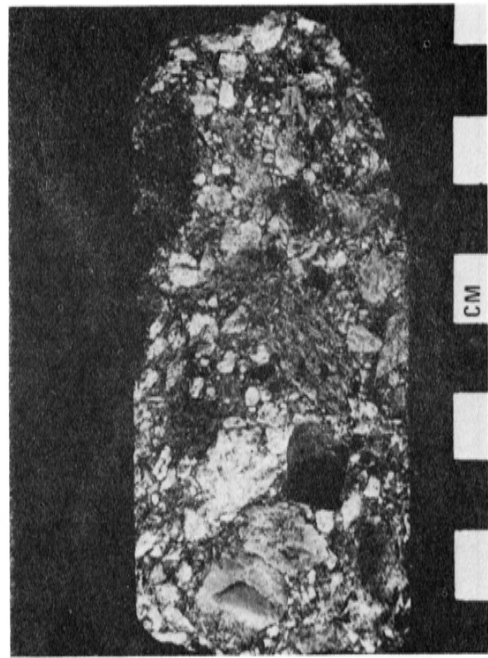
An important conclusion of these studies is that tennantite is the only important host for As and Sb in the ores. A series of electron probe analyses for tennantites showed that their average combined As and Sb content is 21.6%. This means that it is possible to determine tennantite weight proportions in concentrates directly from assay data as 4.63 (As+Sb) %. Results based on this method tie closely with those obtained from point counting.

This was not only of academic interest, as during the early history of the mine the much higher than anticipated As and Sb values in the ore were greatly reducing the value of the concentrates. This problem was compounded during 1968 when substantial amounts of mercury were first

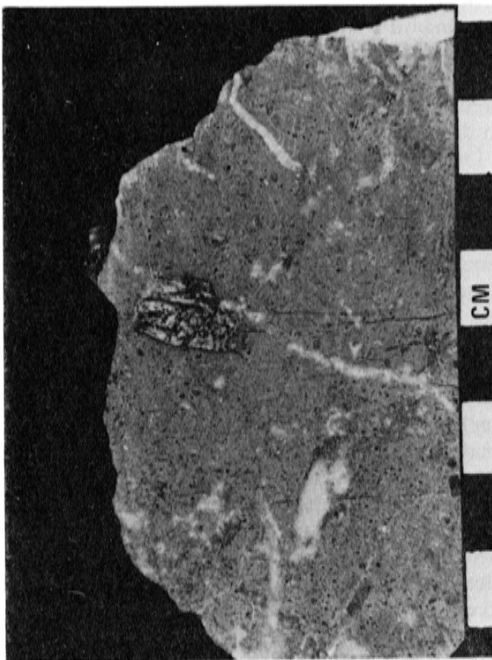




**Plate 3a.** Ankaramite sample from plug-like intrusion on NW side of the open pit. Note fragment of coarser-grained mafic igneous rock.



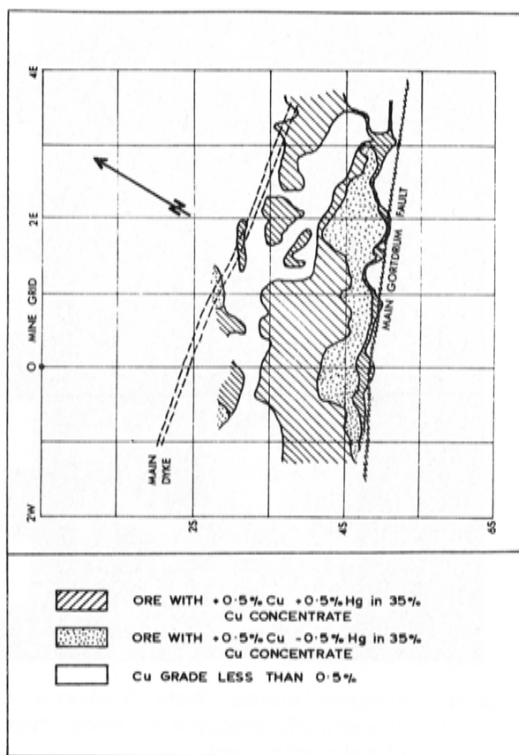
**Plate 3b.** Intrusive breccia. Note fragments of altered mafic igneous and of several types of sedimentary rock.



**Plate 3c.** Intensely altered mafic rock containing abundant dolomite in irregular masses and stringers. Fuchsite concentrated in the large clast near the top.



**Plate 3d.** Intrusive breccia from the central part of the wedge. Contains bornite-chalcocite mineralization. Note altered igneous and sedimentary rock fragments.



**Figure 8.** Mercury distribution at west end of Bench 4.

detected in the ores. Extensive metallurgical testing was then carried out, resulting in a decision to construct a calcining plant. While this was being erected it was necessary selectively to mine parts of the deposit in which the tennantite proportion of total sulphides was as low as possible.

The confirmation that tennantite is the main host mineral for Hg in the orebody is seen in Fig. 6a. This displays the excellent correlation between As+Sb and Hg values for large numbers of concentrate samples; not a single plot indicates the high Hg with low As+Sb, a correlation that would indicate a substantial cinnabar content. A similar correlation diagram (Fig. 6b) for Ag vs. As+Sb shows that silver and tennantite contents are unrelated. This is unexpected since tetrahedrite-tennantite can readily incorporate several percent of silver, and despite being comparatively rare, is the principal silver host mineral in most Irish Carboniferous Zn-Pb deposits.

About 130 grains of tennantite in 8 specially prepared concentrates from different levels in the ore deposit were analysed for mercury with the electron probe. In the four concentrates from Benches 2 and 3 (within 25m of the surface) there is a wide range of values up to a maximum of nearly 12%. In all four, however, the average content is between 5 and 6% (Fig. 7a) and the overall average of 5.3% Hg is nearly identical to that predicted from Figure 6a. At deeper levels, however, the average mercury content progressively declines to less than 1% about 75m from the surface (Fig. 7a).

This decline in mercury tenor of tennantite is paralleled by an even more marked decline in the overall proportion of tennantite to total copper sulphides (Fig. 7b). These two factors taken together mean that more than 75% of the total mercury was present in the uppermost 35m part of the orebody.

Even on individual benches, however, the ratios of Cu to Hg in ore were far from uniform. Figure 8 is a distribution map for the western part of Bench 4 based on assays of chippings from several hundred holes drilled for blasting. The mercury results are those for specially prepared laboratory concentrates modified to a standard copper concentration of 35%. The zones with high mercury concentrations contain abundant tennantite and chalcopyrite, probably supplemented by cinnabar in the narrow band along the Fault. Contained within them is a zone paralleling the Fault in which bornite and chalcocite are comparatively abundant.

Microscope and electron probe studies show that there are two silver minerals in the ores. The most conspicuous is native amalgam (kongsbergite) containing on average about 60% Ag and 40% Hg. This occurs mainly along grain boundaries and in tiny cracks in crystalline calcite, dolomite or barite, and rarely as inclusions in copper sulphides. The other is stromeyerite (CuAgS) which occurs as small rounded inclusions in chalcocite (which it closely resembles) and also in association with the native amalgam. Another rare mineral to occur as inclusions in chalcocite is wittichenite (Cu<sub>3</sub>BiS<sub>3</sub>).

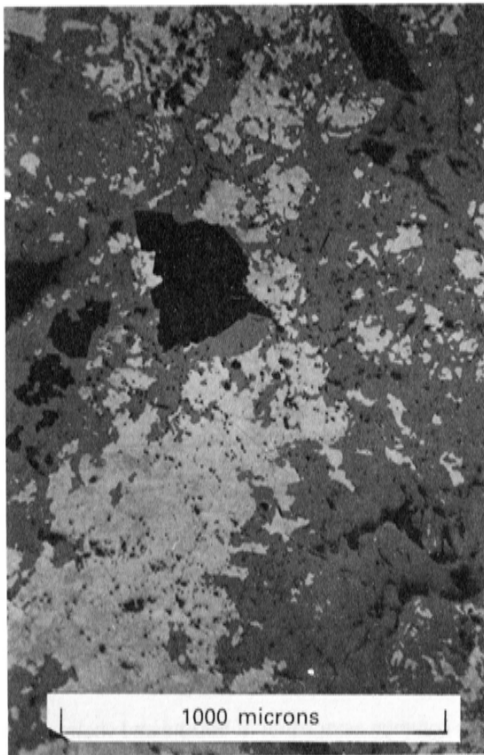
Small particles of cobaltite, some with well-defined crystal zoning, are comparatively common, especially in tennantite-chalcopyrite ores from the upper parts of the deposit. Arsenopyrite is a rarity but occurs as disseminated needles in a few lenses in bioclastic limestones which are generally devoid of copper mineralization.

Gortdrumite (Cu,Fe)<sub>6</sub>Hg<sub>2</sub>S<sub>8</sub>, a new mineral named for the deposit, was found in locally dolomitized limestones about 25m below the pre-mining rock surface. It is present in a composite barite-dolomite vein in association with cinnabar and copper sulphides. The largest grains are about 200 by 50 microns, and the phase superficially resembles chalcocite, but is more distinctly anisotropic (Steed, 1983) (Plate 4c).

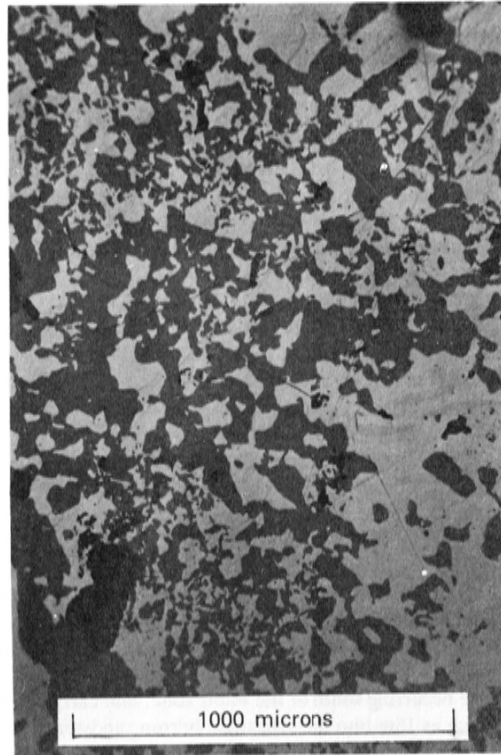
The changes in character of the mineralization with depth are to some extent a reflection of the changes in nature of the host rocks. In the deeper zone bornite and chalcocite are the predominant sulphides and occur finely disseminated within dark shaly limestones of the Transition Beds and Dark Limestone (Fig. 2). These rocks are comparatively ductile, and the sulphides occur interlaced with, and replacing, the rock carbonates rather than in veins. Mineralization is generally more abundant where the rocks have been deformed and partially dolomitized. The richest grade sections are dark breccias, some of which contain altered igneous fragments (Plate 3d); these are common in the deeper parts of the wedge zone. In general terms the ore zones are controlled by the positions of faults, intrusive bodies and other related structures, and without doubt were epigenetically emplaced. On the eastern side the ore terminates at considerable depth as the wedge pinches out, whereas on the western side the grades progressively decline in the basal part of the Transition Beds as the content of arenaceous material in them increases.

Bornite and chalcocite always occur together in myrmekitic intergrowths (Plate 4b), typically with bornite about four times as abundant as chalcocite. The mechanism for the formation of this texture is unknown, although Ramdohr (1969) considers that phenomena akin to surface tension play a part, with the minerals simultaneously precipitated from aqueous solutions. Grains of tennantite are fairly common within concentrations of bornite and chalcocite, and appear in part to have been replaced by them.

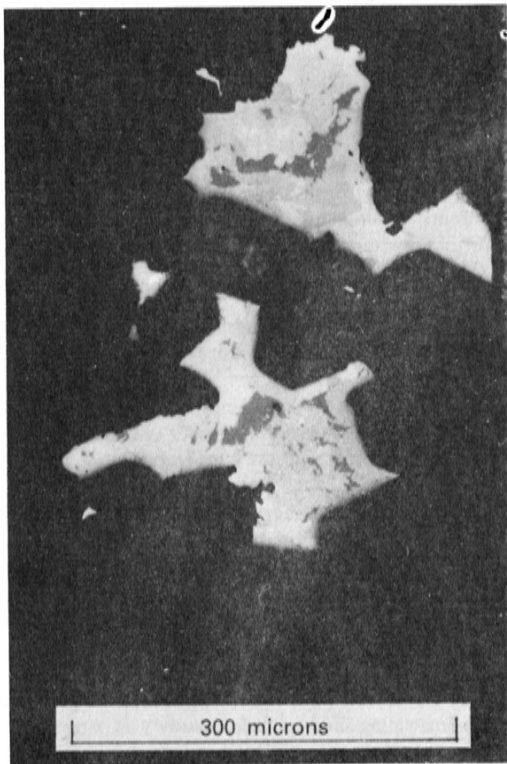
In the upper parts of the deposit the host rocks are



**Plate 4a.** Tennantite-chalcopyrite ore from a vein. Inclusions are mainly of dolomite.



**Plate 4b.** Bornite-chalcocite ore showing the typical myrmekitic intergrowths.



**Plate 4c.** Grains of gortdrumite with minor associated bornite.



**Plate 4d.** A vein of massive cinnabar with crystalline dolomite.

comparatively massive and brittle limestones. These have been fractured and contain mineralization in generally irregular and complex networks of carbonate veins. The majority of the veins are less than 5mm wide, and are composed of either pure dolomite or pure calcite. The larger veins are commonly zoned with layers about 5mm wide of medium-grained dolomite adjacent to the walls, and cores of more coarsely crystalline calcite. In exceptional veins the thickness of the dolomite bands is not much greater, but the calcite core may be comparatively wide, and coarsely crystalline. Some of these larger veins contain open vugs lined by crystals of calcite and/or dolomite, and rarely by small euhedral crystals of chalcopryrite, cinnabar or barite. Electron probe analyses reveal that the average content of Fe in the vein dolomite is about 6%, and indicate that this is also the main site for Mn in the ore zone, at a concentration of about 0.7%.

The common sulphide minerals are tennantite and chalcopryrite (Plate 4a) which occur both within the veins and patchily in the adjacent limestones. The grain sizes are typically between 1mm and 5mm, but in exceptional settings in large veins they can be as great as 75mm. Within unaltered limestones the content of disseminated mineralization is generally small, whereas in dolomitized zones concentrations may be high. Altered dykes can be favourable traps for tennantite-chalcopryrite mineralization, one such case occurring south of the Fault zone, and carrying ore as much as 15m into the otherwise barren sandstones. Barite veins are fairly common in the upper parts of the deposit, both in the limestones and in the sandstones near the Fault. They cross-cut the mineralized rocks, but in most cases are nearly barren of sulphides. The most notable exceptions are some small barite veins with prominent red staining due to disseminated cinnabar; very rare examples contain concentrations of bornite, chalcocite and native amalgam.

The transition between the two main types of mineralization is not sharply defined, and even in the upper parts of the deposit there are substantial amounts of disseminated bornite-chalcocite in the darker limestones.

A final component in the zonal pattern is represented by a unique vein of massive cinnabar and dolomite which cuts limestones at the very top of the deposit. This was removed unrecognized during the first weeks of mining, but fortuitously one small sample was retained by a miner as a curio. This cinnabar encloses about 1.5% Cd in solid solution, and also contains inclusions of two other Cd-rich minerals, metacinnabarite and mercurian sphalerite (Plate 4d). Electron probe analyses are as follows:

	Zn %	Fe %	Hg %	Cd %	S %
Metacinnabarite	8.1	>0.1	63.7	11.1	17.8
Sphalerite	53.6	0.1	12.9	2.4	30.2

The sphalerite is as anomalous as the cinnabar, since other (rare) examples contain less than 0.5% of both Cd and Hg, and between 0.3 and 0.5% Fe.

The form of the vein is comparable to others containing copper sulphides. The evidence is thus compelling that it represents a last remnant of a type of mineralization otherwise eroded away.

### Fluid inclusions and other geothermometric indicators

The following chemical and mineralogical factors provide consistent, and thus convincing, indications as to the tem-

perature of ore emplacement, even though each on its own would be inconclusive:

1. The elements most strongly enriched are Cu, As, Sb, Ag, Hg and Co. This is an almost unique assemblage, and is more compatible with an epithermal than with a higher temperature origin.
2. Experiments in air at atmospheric pressure show that mercury release from tennantite commences at a temperature of 240°C. Ignoring other chemical factors, and a probably small pressure effect, the indication is that the temperature of its formation was not very high.
3. The limestone host rocks, despite being intensely fractured, are not strongly altered. They have been patchily dolomitized, but this could have taken place at low temperatures. It is notable that silicification is very minor and localized, and that quartz is an insignificant component in the veins. It is known that SiO<sub>2</sub> solubility is strongly dependent on temperature, but largely independent of pressure, pH or concentration of other salts. At 350°C the solubility is about 1000ppm, but at 150°C it is only about 100ppm (Holland, 1967).
4. The common association of bornite and chalcocite in myrmekitic intergrowths. Ramdohr (1969) considers that this commonly results from simultaneous precipitation of the two minerals from a polynary solution at a temperature perhaps as low as 100°C.
5. The rarity of twin lamellae in primary chalcocite may be an indication that this mineral was laid down initially with orthorhombic symmetry and thus at a temperature below 103°C (Roseboom, 1966).
6. Stromeyerite and chalcocite are components of a system in which there is complete miscibility above 104°C (Skinner, 1966). Thus, particles of stromeyerite which are present mainly along dislocations in chalcocite probably formed below this temperature. The absence of "oleander" structure in the grains is a further pointer to deposition at less than 100°C (Ramdohr, 1969).
7. The native amalgam, kongsbergite, is only stable at comparatively low temperatures.
8. Crystals of cobaltite are commonly zoned. Ramdohr (1969) has noted that this occurs only in cobaltites which were formed at low temperatures.

These observations all suggest a relatively low temperature range for the deposition of the ores. The tennantite-chalcopryrite mineralization was probably formed below about 200°C. The bornite-chalcocite ores and associated Hg, Ag and Bi phases are known from textural studies to be later, and were probably deposited from cooler solutions, perhaps at about 100°C or even less.

To test the validity of these conclusions, a lengthy and at times frustrating fluid inclusion study was carried out. The character of the mineralization made this particularly difficult, as the mineralization lacks any of the phases which are generally favoured for this type of work, such as sphalerite or fluorite. Even worse, the main vein consti-



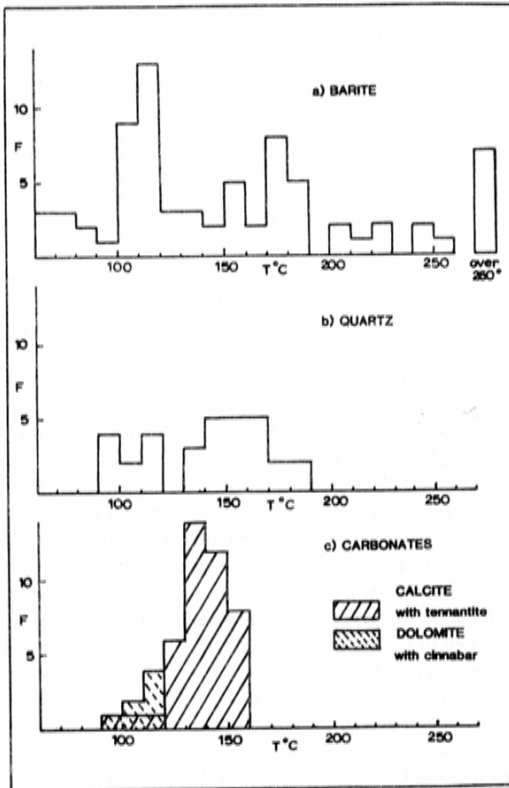


Figure 9. Fluid inclusion homogenization temperatures.

tments, the carbonates and barite, are normally finely granular and/or clouded by masses of tiny solid inclusions. Within them, even in apparently favourable settings, the fluid inclusions are difficult to locate, and are typically so small as to test the resolution of the equipment and the observer to the limit. Both these main host minerals have multiple sets of cleavages, and thus have a high potential for leakage. Finally, great care is required to distinguish between primary and secondary inclusions, and the normal criteria listed by Roedder (1979) can rarely be applied with absolute certainty.

Initially barite was selected as the most suitable mineral to study, even though this is known generally to post-date the main phase of copper mineralization. Some 20 samples, mostly from the upper parts of the deposit, but a few from deeper levels, were examined and were found to contain rare to moderately common two-phase inclusions of sufficient size for heating determinations. Initial work was carried out mainly for inclusions of comparatively large size (about 10 to 20 microns) and gave apparently promising results clustered between 150°C and 200°C. However, later more comprehensive results failed to confirm this picture, and indicated a very broad spread of values from 65°C to over 260°C, in all cases for inclusions which showed no evidence of leakage during repeated heating and cooling cycles (Fig. 9a). It was particularly noted that there was a broad general relationship between size of inclusion and temperature. No consistent differences were noted, however, between samples from different parts of the deposit. Clearly, results for barite can only be regarded with considerable suspicion, since there has evidently been widespread leakage and later resealing of inclusions at some time in the geological past. The only peak with any real

meaning is probably that between 100°C and 120°C for inclusions less than 10 microns size. This may mark the top end of a wider band, as otherwise similar single phase liquid inclusions are common in some samples.

Comparable investigations were then carried out for quartz present in small stringers, in irregular networks or as near euhedral crystals in some early carbonate veins associated with chalcopyrite and tennantite, generally from strongly dolomitized zones. This is not common, and only 4 suitable samples were obtained, all from the upper parts of the deposit. Results are, however, very much more satisfactory than for barite (Fig. 9b). The overall range is from 90°C to 184°C but with a distinct peak between 140°C and 170°C. One sample is particularly important since it contains quartz crystals with comparatively large two-phase inclusions directly associated with clots of tennantite-chalcopyrite; this yields a range from 133°C to 184°C.

The third study was for calcite and dolomite, from veins with associated copper minerals, from the upper parts of the deposit. Some 25 specimens were examined, but in the great majority of these the material proved unsatisfactory. Typical examples of the minerals are too finely crystalline to contain useful inclusions, or too cloudy to observe them; the few inclusions that can be found are generally secondary, and usually leak on heating. In some vugs there are layers of very pure and clear calcite, but these contain no inclusions.

Two exceptional samples, however, contain relatively large, and undoubtedly primary, inclusions within very coarsely crystalline calcite associated with large crystals of tennantite. These give excellent and closely grouped homogenization temperatures between 120°C and 160°C (Fig. 9c). The results were found to be the same in normal doubly polished slices and in cleavage fragments.

In view of its significance, a special study was made for the dolomite associated with the single massive cinnabar vein from the top of the deposit. This was so cloudy that measurements were only possible in selected tiny cleavage flakes. Consistent results were, however, achieved within the range from 98°C to 116°C (Fig. 9c).

Freezing experiments were only carried out successfully for three samples. One of these was the specimen with quartz crystals in close association with tennantite-chalcopyrite. This gave first melting at  $-22^{\circ}\text{C}$  and last melting at  $-5.5^{\circ}\text{C}$ , for a group of inclusions homogenizing at 165°C. The other samples were the two very coarsely crystalline calcites containing large tennantite crystals. These gave first melting at  $-20.5^{\circ}\text{C}$  and last melting temperatures of  $-8.5^{\circ}\text{C}$  and  $-8.4^{\circ}\text{C}$  for groups of inclusions homogenizing at 142°C and 157°C respectively. These results indicate that the ore solutions were NaCl-dominated brines with salinities between about 8.5% and 12%.

No pressure corrections have been applied to any of the temperatures determined by homogenization. These would add about 10°C, based on a rough estimate for the depth of emplacement of the mineralization as about 1km, for solutions with 10% salinity under assumed hydrostatic load (see Tables in Potter, 1977). As pointed out by Cathles (1977) in an active convecting system with reasonably uniform permeability, fluid pressures will be close to hydrostatic values.

Two samples of early dolomite-quartz veins within intensely dolomitized limestones contain very anomalous inclusions. These contain aqueous liquid, liquid hydrocarbon, and gaseous hydrocarbon components. The latter two homogenize together on heating to temperatures between 62°C and 89°C. The significance of this is uncertain, how-

ever, since the precise compositions of the hydrocarbons are unknown.

No samples show any evidence of boiling, which would not be anticipated at the comparatively low temperatures concerned. Curves drawn by Haas (1971) indicate that a water column 100m high would be sufficient to prevent this at the maximum temperature of about 180°C.

## Genesis

The first step to understanding the genesis of the Gortdrum ores is to consider the sequence of events in which the mineralization occurred.

The limestone sediments which now host the deposit were laid down under shallow marine conditions about 355 Ma ago. They were buried and lithified in an environment which remained undisturbed until the Chadian, when large scale volcanism commenced some kilometres to the west, in the area of the Limerick Syncline. At about this time, or somewhat later, E-trending near-vertical fractures were formed in the limestone and underlying rocks, and were infilled by mafic dykes during a period of N-S regional relative tension. These dykes cannot have been emplaced at great depth, since they are moderately vesicular. It is probable that movements then took place along an earlier Caledonian line of weakness in basement rocks and that the Gortdrum Fault was created. Elsewhere within Ireland other ENE-trending faults were probably active at much the same time, for example the Silvermines Fault for which Critchley et al. (1983) proposed dextral displacements during the late Courcyeen to early Chadian.

Following the intrusion of dykes and small mafic stocks, there was an episode when hydrothermal circulation of waters of probable connate origin, driven by igneous heat, caused intense alteration of the basaltic rocks. This in turn gave way to high energy hydrothermal emissions from considerable depth along fractures and other channelways, which formed extensive bodies of intrusive breccia. It is very significant that neither of these two hydrothermal episodes, which probably took place before the end of the Dinantian, caused any appreciable deposition of sulphide minerals.

The next and most critical stage is unfortunately that for which the timing is least certain. Continued movement on the Fault probably took place and may have concentrated fracturing and deformation at the Gortdrum site, because of the presence of igneous stocks just to the north. A minor change in the orientation of the stress field could also explain zones of shearing which are evident along the walls of some of the larger dykes. The exact stage at which mineralization took place is uncertain, but definitely post-dates the episodes of igneous intrusion and alteration, and thus cannot be earlier than Chadian. This means that Gortdrum was formed after the major Zn-Pb orebodies at Silvermines, Tynagh and Navan which all lie in Courcyeen limestones (Sevastopulo, 1979), provided that the syndiagenetic concepts proposed for their origins are correct (as stated by Taylor and Andrew, 1978; Boast et al., 1981; Andrew and Ashton, 1982; and many others).

The author considers that the mineralization at Gortdrum was probably emplaced between late Chadian and early Namurian and thus between about 345 Ma and 320 Ma ago. On the basis of geological evidence alone, however, it could have been emplaced at any time between the Chadian and the Hercynian orogeny. A set of four recently published K-Ar dates (Halliday and Mitchell, 1983) for illites associated with altered basalts and mineralization at Gortdrum,

ranging from 276 Ma to 308 Ma, do not resolve this problem, since they may record a post-mineralization thermal event related to Hercynian tectonic episodes. Even so, they confirm that the mineralization is not post-Hercynian in age.

Hercynian movements strongly affected the Gortdrum orebody. At this stage further and considerable strike-slip movements may have taken place, followed by minor thrusting of sandstone blocks from the south over the limestone.

The ore solutions were moderately saline NaCl-dominated brines with a maximum temperature of about 180°C. In these respects they were thus comparable to the solutions which formed Zn-Pb mineralization at localities further north such as Tynagh and Moate (Probert, 1983). Under normal geothermal gradients, a source area at these temperatures would be at a depth of about 5km. In the Gortdrum area, however, during the period of mineralization it is likely that gradients were abnormally high, in view of the extensive recent volcanism; thus, the depth of the source area could have been considerably less than 5km.

Underneath the orebody there are only about 300m of Old Red Sandstone clastics above the unconformity with Lower Palaeozoic rocks. Thus any essentially vertical convective cell of the type advocated by Russell (1978) would scavenge metals predominantly from Lower Palaeozoic metasediments. With such a system it is very difficult to account for the highly unusual suite of elements enriched in the Gortdrum ores.

The Limerick volcanic centre to the west of Gortdrum lies in the axial zone of an area of rapid Dinantian subsidence, giving a thickness of nearly 2km of Lower Carboniferous rocks (Strogen, 1977). There is, however, no evidence that the area was a sedimentary basin during the Chadian. (Strogen, pers. comm.). Much further to the west, about 100km from Gortdrum, is a much deeper basin with probably 3km to 4km of Devonian to Viséan sediments extending out from the far end of the present Shannon Estuary (MacDermot and Sevastopulo, 1972). This was however, probably too distant to have had any direct influence on mineralization.

Moiseyev (1971) has considered the general settings for mercury-rich ore deposits. He notes that 65% of them lie either in volcanic rocks or in closely associated sedimentary rocks. In addition, 60% are in Cainozoic rocks, and this implies a high mobility for mercury in active geological environments. He explains that volcanic rocks may not be important only as a source for mercury, but may mobilize mercury from sedimentary rocks by thermal effects. A temperature rise of 300°C would be sufficient to liberate almost all Hg from clay minerals. In a suitable convective system this mercury could be concentrated into subsurface waters, especially if there were hot brine solutions. Recently Varekamp and Busek (1984) have shown that considerable amounts of mercury can be transported in moderate temperature hydrothermal systems, mainly in the form of  $Hg_{aq}^{0}$ , and in saline waters also as Hg-Cl complexes.

The evidence of high mercury mobility implies that it is unlikely that the Gortdrum mineralization was formed very long after the cessation of volcanism. Mercury-bearing solutions were probably derived from the main volcanic areas to the west and channelled towards Gortdrum in the limestones and sandstones along the Pallas Syncline (Fig. 1). Migrating ore solutions in this area are indicated by minor mineralization within, and adjacent to, sheared altered basic dykes, which locally must have acted as minor conduits.

Some deep circulation must also have taken place, since solutions moving along the Gortdrum Fault zone caused minor mineralization in Silurian rocks at least 500m below the Devonian-Silurian unconformity. Additionally, some input into the ore solutions directly due to igneous processes is very likely. These two components were probably comparatively hot.

Thus, a complex pattern of hydrothermal flow is envisaged, with components derived from volcanic areas, from deep convection in underlying metasediments, and from igneous sources. The manner whereby the metals were transported in solution remains uncertain. Except for mercury, which has been mentioned previously, it is most likely that in the type of brine indicated by the fluid inclusion studies, chloride complexes played a dominant role. Solution temperatures are, however, extremely low for the creation of a copper deposit. Solomon and Walshe (1979) have considered the most likely system conditions for the formation of volcanogenic deposits, and they find that almost all copper is deposited between 300°C and 250°C. Data on other complexing agents such as organic matter and  $\text{NH}_3$  is very limited, and thus their role is uncertain. Since the type of mineralization at Gortdrum is exceptional, it might well be that some type of unusual transportation mechanism was involved. Despite this uncertainty, it seems unlikely that much reduced sulphur could be transported within the brine solution under any reasonable conditions. Herr and Helz (1978) have studied the possible role of bisulphide ion pairs and conclude that these can have played little role at temperatures below 150°C. Anderson (1975) notes that reduced sulphur could be carried in a solution with copper (or lead) only if this was very acid. The ore solutions at Gortdrum have caused no large-scale dissolution of carbonates, and so this is out of the question; available evidence suggests that the solutions were neutral or mildly alkaline.

The intense fracturing and brecciation at Gortdrum caused by both igneous and faulting processes made the zone an ideal channelway for upwelling hydrothermal solutions. It is still necessary to consider, however, the reasons for ore emplacement predominantly within marine limestones in the basal 200m of the Carboniferous succession. Despite a depth of emplacement of the order of 1km, there is pronounced vertical zonation within the orebody. The initial and probably highest temperature phase of mineralization, at about 140°C to 180°C, caused deposition of tennantite and chalcopyrite, mainly in veins and in dolomitized zones in the limestones. The mercury content in this tennantite declines from an average of 5.3% at the position of the present land surface, to only 1% about 100m below it. Only one other locality is known to the author where a similar variation pattern exists; this is the Spis-Gemer region of Czechoslovakia, where concentrations of mercury in tetrahedrite in a vein system decrease from 10–19% near the surface to 1–2% at depths of about 500m (Bernard, 1957).

The uppermost existing component of the Gortdrum zonal sequence in veins is the single example containing massive cinnabar, which was emplaced at a temperature of about 120°C. The deposition of bornite and chalcocite probably overlapped that of chalcopyrite-tennantite and was, in part, controlled by a lithological change to more shaly limestone. It is likely, however, that bornite-chalcocite formation continued later and at lower temperatures, perhaps to less than 100°C. The final mineralized features were barite veins formed at temperatures from about 110°C to lower than 70°C. These contain minor cinnabar

and native amalgam, the cinnabar probably in part derived from the breakdown of earlier tennantite.

Only five sulphur isotopic determinations are known for Gortdrum, four of these are for chalcopyrite-tennantite, and have  $\delta^{34}\text{S}$  values between -7 and -21‰ and one for barite with a  $\delta^{34}\text{S}$  of +17.5‰ (Greig et al., 1971). The barite value is most interesting, being compatible with results for other Irish Carboniferous barites, and close to the value suggested by Sangster (1967) for Lower Carboniferous seawater sulphate. The observed range in sulphide values could be due to solution mixing, wall rock reactions, or precipitation from single fluid with slightly variable temperature, pH and/or oxygen fugacity (Ohmoto, 1972).

The vertical zonation of the orebody has been shown from fluid inclusion studies not to be a consequence of either thermal gradients or boiling. It is similarly unlikely that changes in pH or pressure had a significant effect. Its position is not a consequence of carbonate in the limestones, since carbonates are an abundant cement in the underlying sandstone.

The most significant factor controlling the site of deposition may be indicated by the presence of hydrocarbons in some fluid inclusions. It is considered that carbonaceous matter in the organic-rich basal Carboniferous beds acted as a reducing agent for sulphates in solution. Abiogenic reduction of this type can be effective at temperatures as low as 75°C (Macqueen and Powell, 1983) but is slow at temperatures below about 200°C.

Some reduced sulphur may also have been directly liberated due to the thermal cracking of bituminous components by the hot solutions welling up in the vicinity of the Fault. In the Gortdrum situation slow generation of reduced sulphur appears consistent with the mineralogy. Pyrite is a minor constituent, and most iron in the ores is present within dolomite rather than in sulphides. The most common copper minerals are tennantite and bornite, both with higher copper to sulphur ratios than the normally dominant chalcopyrite.

It is possible that the sulphates were brought in with solutions from depth. Alternatively they may have been brought in laterally, perhaps in the same solutions that transported Hg, through limestones above the level of impermeable shale horizons at the base of the Carboniferous succession. In these circumstances it is notable that a comparatively cool brine solution could have had a greater density than surrounding more normal connate waters (see Tables in Haas, 1971) and only become buoyant when affected by localized heating and/or mixing in the vicinity of the ore zone.

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