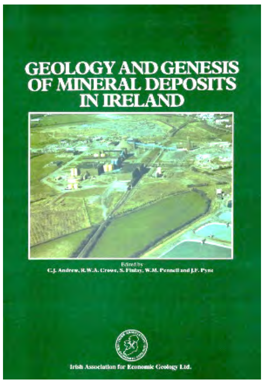

The stratigraphic and structural setting of Irish mineral deposits

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The stratigraphic and structural setting of Irish mineral deposits.

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Abstract

This paper is intended to give a brief introduction to the geological framework of the mineral deposits of Ireland.

The Pre-Cambrian basement consists of Lewisian (c.1 600Ma) and Grenvillian (c.1 000Ma) gneisses in the NW of the country, and late Pre-Cambrian gneisses in the SE. These rocks are overlain by late Pre-Cambrian and Lower Palaeozoic rocks which record the opening and closing of the Iapetus Ocean on either side of a suture which trends across central Ireland in the vicinity of the Navan and Silvermines regions. Mineral deposits hosted in late Pre-Cambrian (Dalradian) and Lower Palaeozoic rocks are related to sedimentation in graben and horst environments or to volcanic arc development. Mineralization is also associated with granite plutons of Ordovician and early Devonian age.

Lower and Middle Devonian rocks, deposited in fault-controlled continental basins, are preserved in the NE, NW and SW of the country; they may have been more extensive. These, and older rocks, are separated from late Devonian to early Carboniferous conglomerates and sandstones by an unconformity representing a major period of deformation, uplift and erosion.

Sedimentation during the late Devonian was restricted to the south of the country. In latest Devonian time the sea invaded south County Cork.

Continuing transgression through the early Carboniferous (Courceyan Stage) brought shallow marine conditions into Leinster, Connaught and Ulster. Courceyan stratigraphical successions (which host most of the base metal deposits) record overall deepening from littoral and sublittoral facies (mainly siliciclastics in the south and mixed peritidal carbonates, clastics and evaporites in the north) through offshore carbonate sands and argillites, to deeper water Waulsortian limestones. At this time, the South Munster Basin, a black shale to starved basin, developed south of the carbonate shelf in south County Cork. In the succeeding Chadian Stage, Waulsortian limestone deposition ceased and a pattern of basins (containing deeper water carbonates and argillites) and shelves (with shallow water carbonates) became established. The major stratiform lead and zinc deposits at Silvermines, Navan and Tynagh were formed during this late Courceyan-early Chadian period. The pattern of basins and shelves, controlled at least in part by faulting, persisted through the Dinantian. Intermediate to basic volcanic rocks were erupted at several centres, mainly in the south of the country.

Near the end of the Dinantian, carbonate production diminished and there was an influx of moderately immature siliciclastic sediments which formed the great majority of Namurian and Westphalian rocks.

The main (late Carboniferous-early Permian) Hercynian deformation gave rise to E- to NE-trending, generally upright folds in the south, with an associated cleavage. North of the Munster Basin patterns of folding are more varied, and cleavage is more sporadically developed. In areas where the Caledonian basement is largely composed of sedimentary rocks there is a pattern of dextral shear zones following the Caledonian strike and sinistral shears at a high angle to it. This pattern breaks down in areas where the Caledonian basement contains more rigid rocks such as granite plutons or volcanic complexes.

Mineralization in the pre-Devonian rocks of Ireland

There has been a wide range of exploration programmes in the pre-Devonian rocks of Ireland. The following targets have been of particular importance in recent years:

1. Stratiform deposits (Ba, Pb, Zn) in the Dalradian metasediments, with particular emphasis on the Easdale and Crinan sub-groups where stratigraphic sequences reflect sedimentation in a basin and horst regime comparable to that inferred for the Aberfeldy deposits of Perthshire in Scotland.
2. Gold-bearing quartz veins in immature arc-derived greywackes of the Crinan subgroup in county Tyrone.
3. Copper, lead and zinc associated with the Lower Ordovician volcanic arc which extends from south County Mayo, through Charlestown to County Tyrone.
4. Copper, lead and zinc mineralization associated with rhyolitic volcanism in the Ordovician volcanic arc of SE Ireland.
5. Gold-bearing vein structures of the Longford-Down Inlier, particularly associated with shear zones.

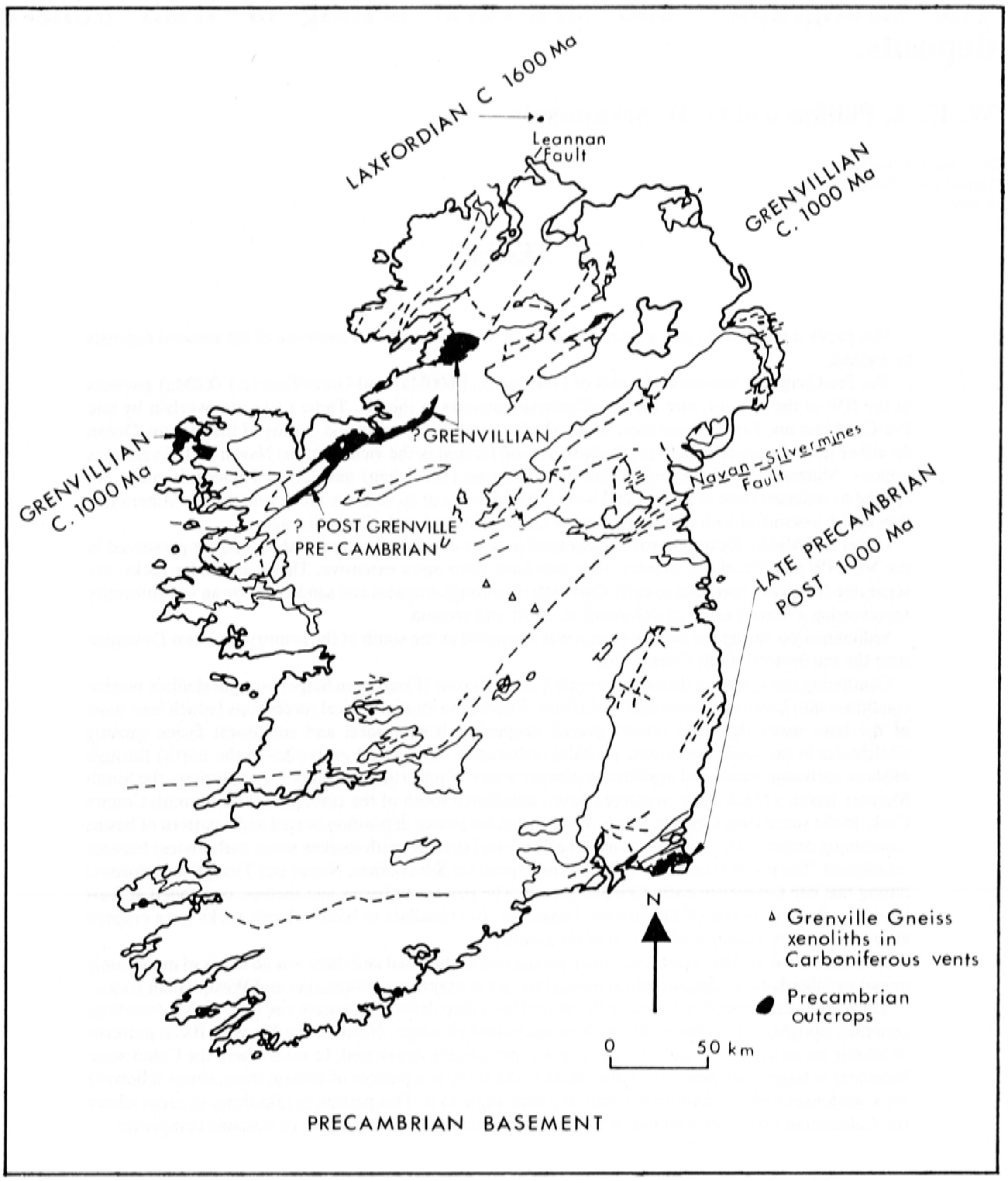


Figure 1. The distribution of Pre-Cambrian outcrops in Ireland.

6. A wide range of mineralization (Pb, Zn, Cu, Mo, Li, Be, U) associated with Caledonian granites (c. 400Ma) in Leinster, Connemara and Donegal.

7. Deposits of asbestos, talc and magnesite associated with ultrabasic intrusions in the Dalradian rocks of Connemara and in the pre-Dalradian (?) rocks of the Ox Mountains Inlier.

Detailed accounts of many of these targets and deposits are given elsewhere in this volume. The purpose of the next section of this paper is to give a brief and well illustrated introduction to the stratigraphic and structural framework of the pre-Devonian rocks of Ireland.

The Pre-Cambrian and Lower Palaeozoic geological framework of Ireland

The Caledonian orogeny, which affected the whole of Ireland between the late Silurian and middle Devonian, records the collision of the North American and European plates after the closing of the Iapetus Ocean. The collision suture zone is thought to extend across central Ireland,

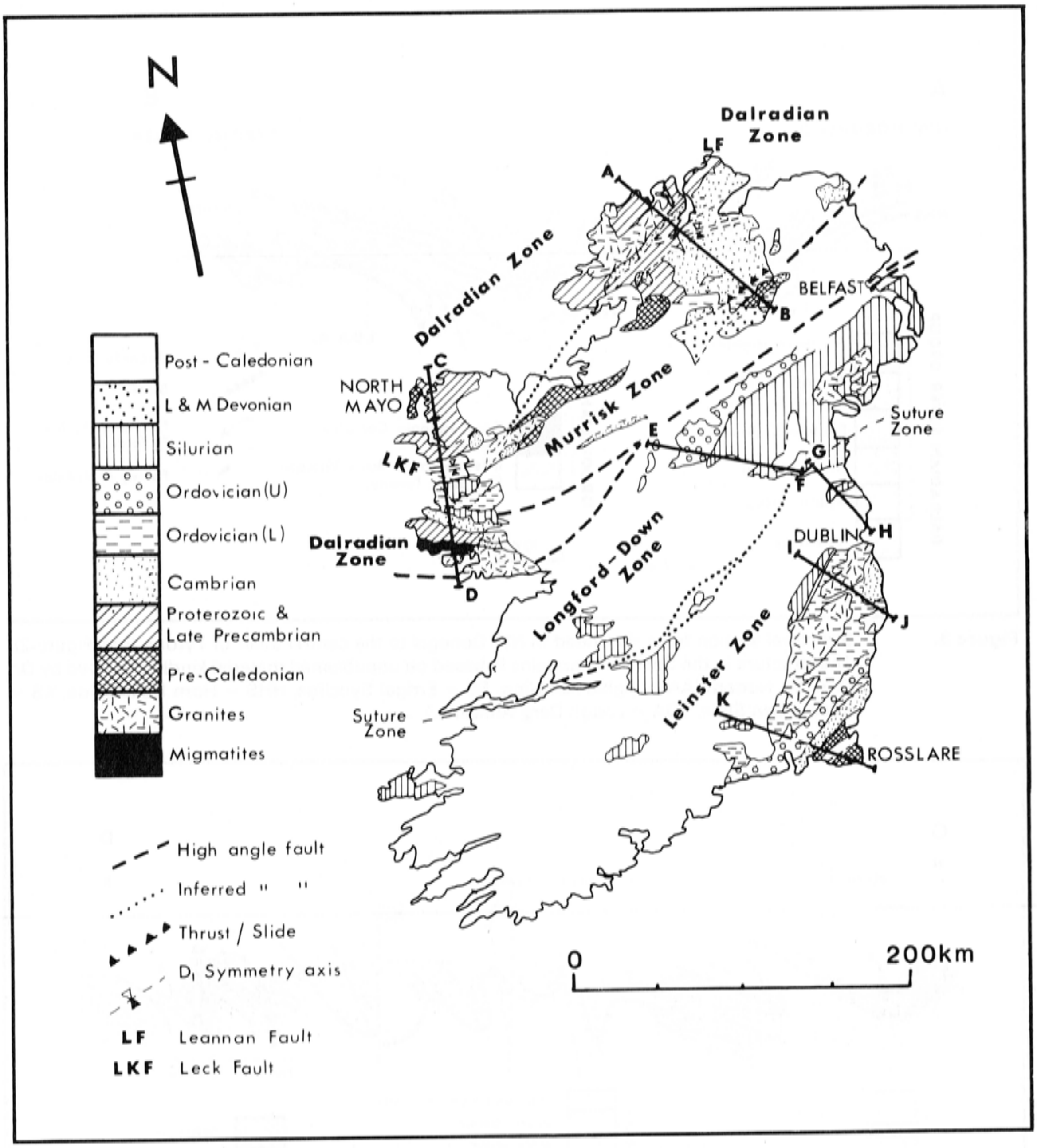


Figure 2. Simplified geological map of the Caledonide Orogen in Ireland showing the lines of sections for Figures 3 to 6.

passing through the vicinities of Navan and Silvermines (Phillips et al., 1979). The suture divides Ireland into two crustal blocks (NW Ireland and SE Ireland) which have quite different geological histories prior to the Silurian, when they were close enough to share comparable sedimentation. The main structural elements are shown in Figures 1-6.

NW Ireland

The Dalradian Supergroup, consisting of up to 17km of clastic and pelitic sediments deposited in an ensialic basin north of Iapetus during the period c. 800-530Ma (Anderton, 1982) lies in the northern part of this block within the Dalradian Zone. The distribution of stratigraphic units within the Dalradian is shown in Figures 7 and 8. A possible tectonic evolution of the Dalradian basin is shown in Figure 9. These sediments were deformed into refolded thrusts and nappes, with up to amphibolite facies metamorphism, during the Grampian orogeny of late Cambrian - early Ordovician age (Phillips, 1981). Pre-Caledonian amphibolite facies gneisses occur within this orogen at Inishtrahull (Laxfordian, c. 1 700Ma) and in N Mayo (Grenville, c. 1000Ma) (Van Breemen et al., 1978). The Dalradian basin in Ireland must have been situated in the vicinity of the

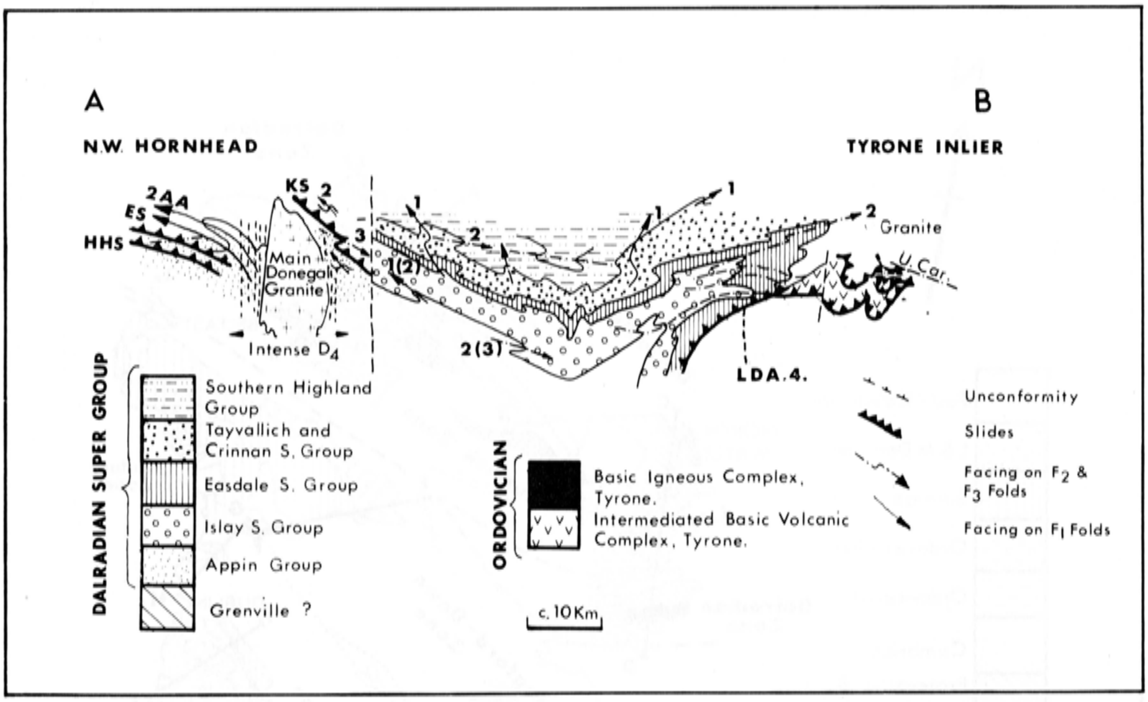


Figure 3. Structural section from Hornhead in NW Donegal to the central inlier of Tyrone (see Figure 2). The structure in the Sperrin Mountains is based on unpublished material kindly provided by Dr. D. H. W. Hutton. (AA = Aghla Anticline, ES = Errigal Syncline, HHS = Horn Head Slide, KS = Knockateen Slide, LDA = Lough Derg Anticline.)

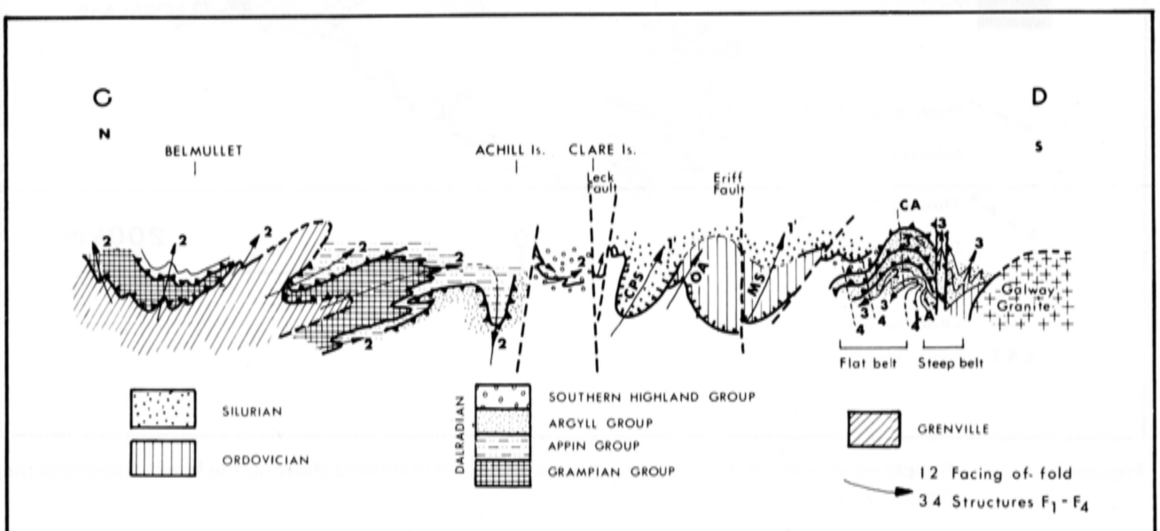


Figure 4. Structural section from N Mayo to Connemara (see Figure 2). Structural symbols as for Figure 3. (CA = Connemara Antiform, CPS = Croagh Patrick Syncline, LA = Lissoughter Anticline, MS = Mweelrea Syncline, OA = Oughty Anticline.)

Grenville Front. The considerable crustal thickening which arose from the Grampian orogeny resulted in the Dalradian Zone acting as a positive area for the rest of the Lower Palaeozoic. Caledonian plate collision further south generated a series of NE-trending sinistral shear zones during the early Devonian. The largest transcurrent displacement seems to have been about 160km along the Leck-Leannan Fault system. This branch of the Great Glen Fault of Scotland has displaced the Dalradian rocks of North Mayo from the latitude of central Donegal (Phillips and Holland, 1981).

South of the Grampian orogen of the Dalradian Zone lies a quite distinct tectonic zone, the Murrisk Zone, which is a continuation of the Midland Valley of Scotland. Pre-Caledonian basement, consisting of granulite and amphibolite facies metasediments, crops out in the NE Ox Mountains and in the Lough Derg Inlier (Phillips et al., 1975). These rocks are either of Grenville or younger Pre-

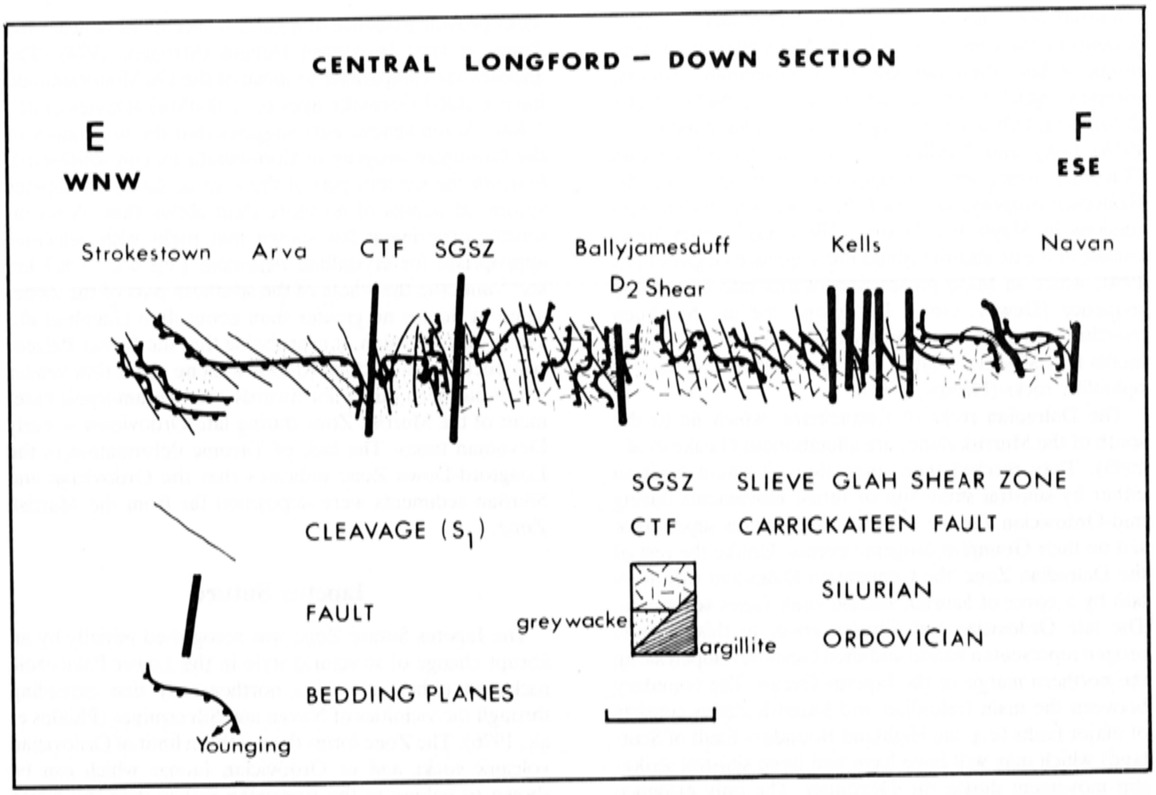


Figure 5. Structural section across the Longford-Down Zone from Strokestown to Navan (see Figure 2). (CTF = Carrickateen Fault, SGSZ = Slieve Glah Shear Zone.)

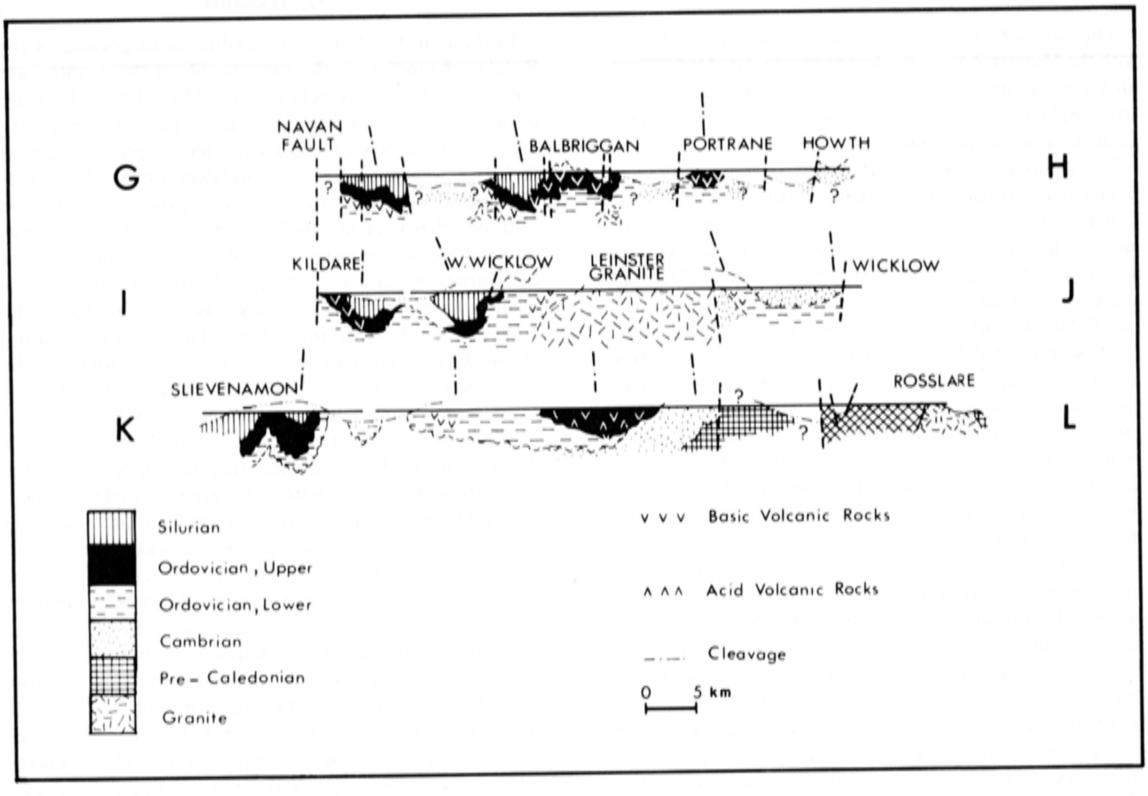


Figure 6. Structural sections from Navan to Rosslare (see Figure 2).

Cambrian age. The amphibolite-greenschist facies metasediments of the central and SW Ox Mountains either represent a late Pre-Cambrian or a Grampian orogenic complex, which has been reworked at greenschist facies during a mid-Ordovician orogenic event (Pankhurst et al., 1976; Long and Yardley, 1979). This mid-Ordovician (Taconic) event, which is significantly younger than the Grampian orogeny, deformed the Lower Ordovician successions in Mayo and Tyrone. These Ordovician rocks consist of a calc-alkaline island arc sequence (Ryan et al., 1980) which in Mayo passes northwards into a turbidite sequence (Dewey, 1963). In Tyrone the arc has been overthrust from the south by a slice of basement metasediments (Ox Mountains type) and by a higher level slice of ophiolitic rocks (Phillips, 1981).

The Dalradian rocks of Connemara, which lie to the south of the Murrisk Zone, are allocthonous (Leake et al., 1983). They reached their anomalous southern position either by sinistral strike slip or thrust movements during mid-Ordovician Taconic deformation which is superimposed on their Grampian orogenic events. Unlike the rest of the Dalradian Zone, the Connemara Dalradian was overlain by a cover of Silurian marine shelf facies sediments. The late Ordovician and Silurian cover to this Taconic orogen represents a littoral and shelf facies developed along the northern margin of the Iapetus Ocean. The boundary between the main Dalradian and Murrisk Zones consists of major faults (e.g. the Highland Boundary Fault of Scotland) which may well have have had large sinistral strike-slip movement during the Devonian. The only evidence that the two zones could have been adjacent to each other prior to the Devonian comes from the inferred southern source of metamorphic and granitic clasts in the upper Dalradian (Southern Highland Group) greywackes. If the metasediments of the central and SW Ox Mountains can be shown to be Dalradian, then this would support juxtaposition of the zones in late Pre-Cambrian times.

The northern boundary of the Connemara Dalradian with the Murrisk Zone is marked by major, late Ordovician, high angle faults which probably have a considerable sinistral displacement; Caledonian reactivation involved significant reverse faulting here.

The southern boundary of the Murrisk Zone (E of Connemara) is obscured by younger rocks. The Longford-Down Zone to the south contains a succession of cherts and black shales with local basaltic volcanic rocks which are followed by greywackes (Leggett et al., 1979). The succession, which spans the interval between Llanvirn and late Wenlock - early Ludlow, is exposed in a series of strike-fault-bounded blocks. Within each block the succession generally youngs to the NW; however, on a regional scale the oldest rocks are found in the NW where Ordovician greywackes dominate the Northern Belt. In the Central Belt, to the SE, Silurian greywackes dominate, with small inliers of Upper Ordovician black shales. This structural pattern requires a dominant component of southerly directed overthrusting on strike faults. The simplest interpretation of these rocks is that they represent pelagic sediments from the floor of the Iapetus Ocean which have been covered by turbidites derived from the North American plate. Northerly subduction of Iapetus lithosphere has then caused sequential northwards thrusting of these rocks, during late Ordovician and Silurian times, to produce an accretive prism which, here, lies allocthonously on the edge of the North American plate. There is growing evidence that strike slip movements have also been important in this Zone. Xenoliths of gneiss in overlying Dinantian volcanic rocks provide evidence of a gneissic basement beneath the Zone, at least in central Ireland (Strogen, 1974). The gneisses are comparable to those of the Ox Mountains and have yielded Grenville ages (c. 1 000Ma) (Davies et al., 1984). Aeromagnetic data suggests that the migmatites of the Grampian orogeny in Connemara extend southwards beneath the western part of the zone as far as the Iapetus suture, at depths of no more than about 4km. A recent seismic experiment has shown that rocks with velocities appropriate for crystalline basement (Vp 6.2 — 6.3 km sec^{-1} underlie the whole of the southern part of the Zone, again at depths no greater than about 4km (Jacob et al., 1985). In conclusion, it is probable that the Lower Palaeozoic rocks of the Longford-Down Zone are a thin veneer which has been thrust northwards over metamorphic basement of the Murrisk Zone during late Ordovician — early Devonian times. The lack of Taconic deformation in the Longford-Down Zone indicates that the Ordovician and Silurian sediments were depositied far from the Murrisk Zone.

Iapetus Suture

The Iapetus Suture Zone was recognised initially by an abrupt change of structural style in the Lower Palaeozoic rocks on either side of a northeasterly line extending through the vicinities of Navan and Silvermines (Phillips et al., 1976). The Zone forms the northern limit of Ordovician volcanic rocks and of Ordovician faunas which can be shown to belong to the European rather than the North American plate. Aeromagnetic and Pb-isotope data have been interpreted to provide evidence for a major change in crustal composition across this Zone (Kennan et al., 1979; see also O'Keeffe, this vol., and Caulfield et al., this vol.).

SE Ireland

In the Leinster Zone, amphibolite facies gneisses of the Rosslare Complex, in the extreme SE of the country, are older than 540Ma (Winchester and Max, 1982). They are covered unconformably by unmetamorphosed Arenig sediments. To the NW of this area, which represents part of the Irish Sea landmass of Cambrian times, the Lower Palaeozoic succession extends from Lower Cambrian to Ludlow (Brück et al., 1979). Lower Ordovician faunas (graptolites, brachiopods and trilobites) are indicative of the European plate assemblages. There is a minor unconformity within the Middle Ordovician (pre-Caradoc) in the eastern part of the Leinster Zone. Here, a major feature of the Ordovician and Silurian rocks as a whole is the development of a volcanic arc centred to the SE of a sedimentary fore-arc basin (Stillman and Williams, 1978). In the northern part of the Zone, isolated volcanic islands (basic - intermediate tholeiitic magmas) developed in the Llanvirn and Caradoc within an area of shale sedimentation. During the late Ordovician and Silurian these rocks became covered by fore-arc basin greywackes which spread northwards with time from the main volcanic arc to the south. Arc volcanism is most extensive in a belt extending from Arklow to Waterford and westwards probably to the Dingle peninsula. This volcanic activity started in the Llanvirn and ended in the Caradoc in the east but continued until the late Wenlock in the west. Initially, large shield volcanoes produced a mixture of tholeiitic and calc-alkaline basalts and andesites. After a hiatus, marked by an unconformity in the east, and then by deposition of Llandeilo limestones with shelly faunas, renewed fracturing and basin

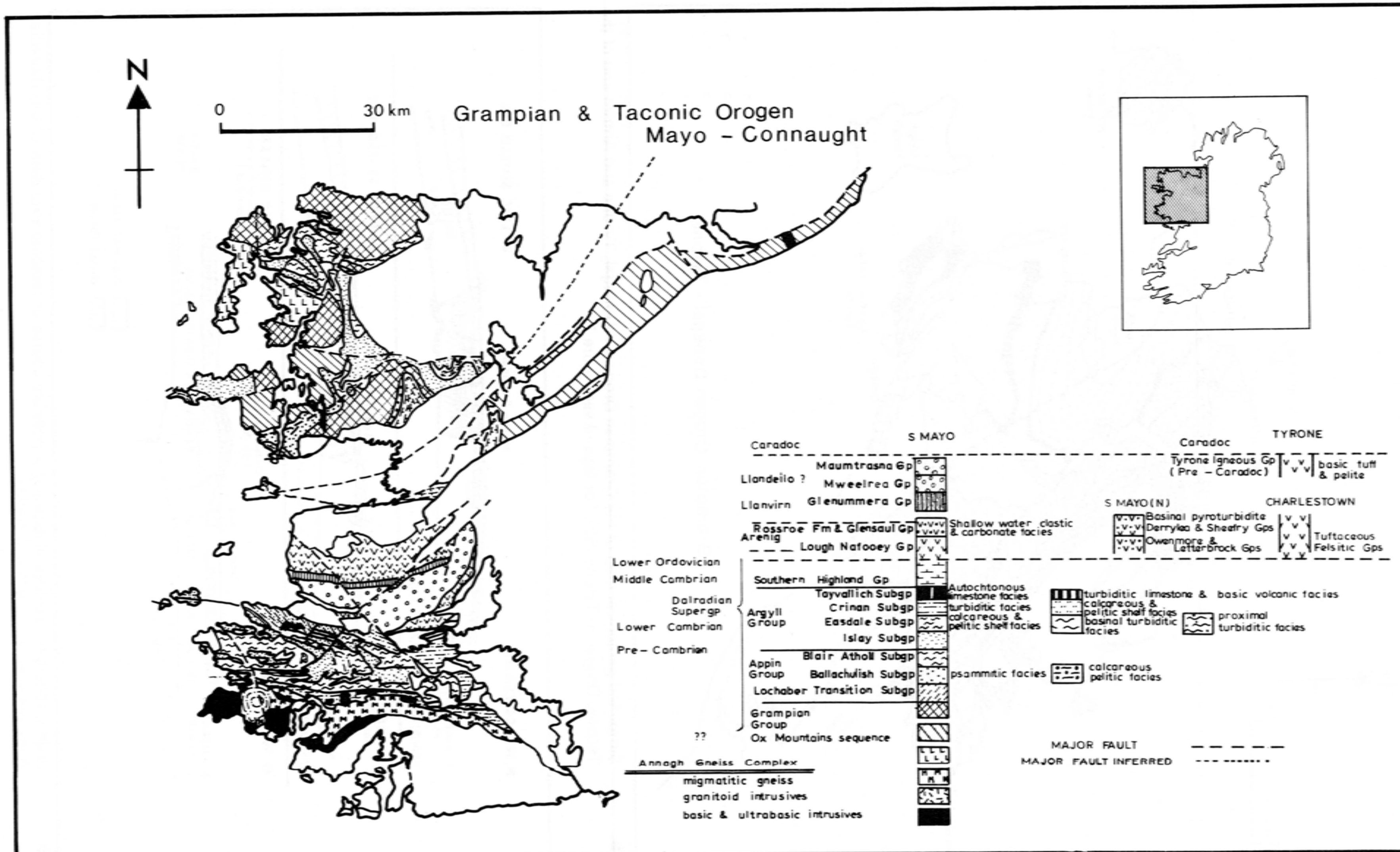


Figure 7. Simplified geological map and stratigraphic sequences of the Grampian and Taconic Orogens in Counties Galway, Mayo and Sligo.

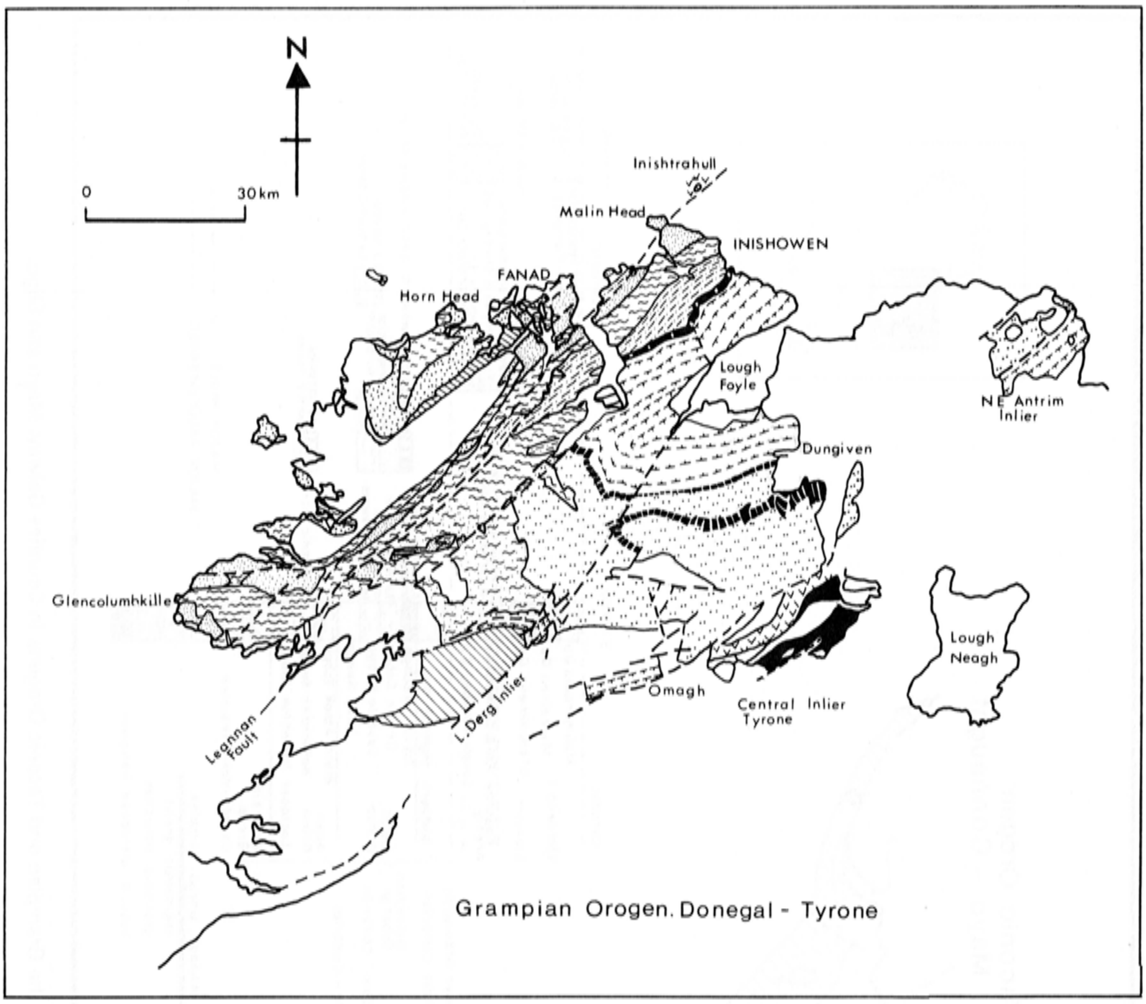


Figure 8. Simplified geological map of the Grampian Orogen of Donegal, Tyrone and Antrim and of the Taconic Orogen in Tyrone (SE). For legend see Figure 7.

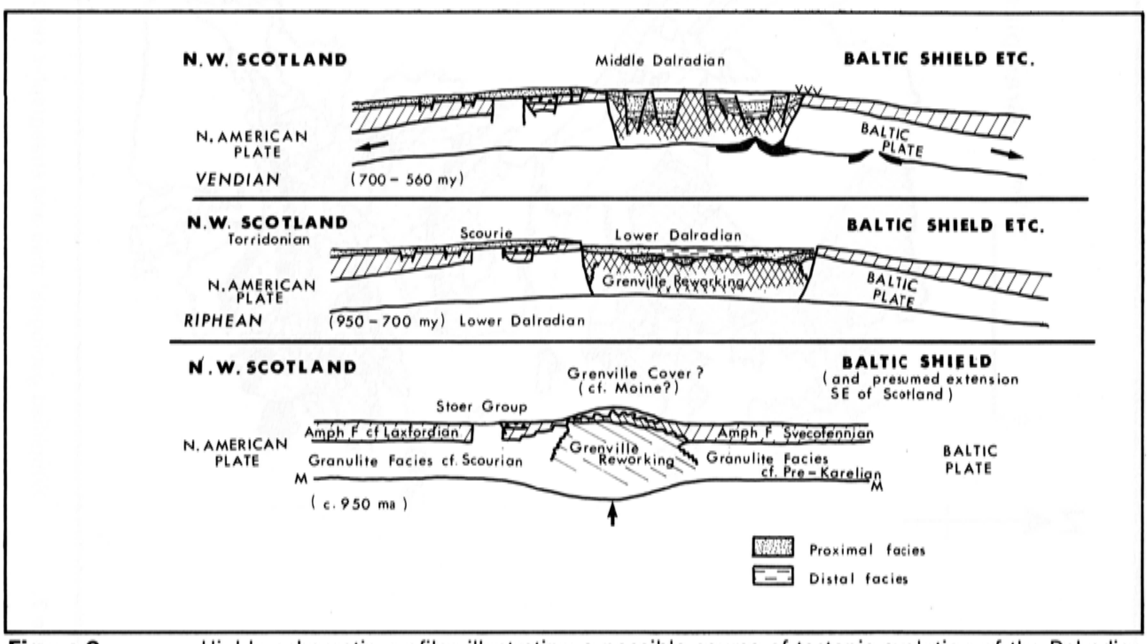


Figure 9. Highly schematic profiles illustrating a possible course of tectonic evolution of the Dalradian Zone between about 950 and 560Ma.

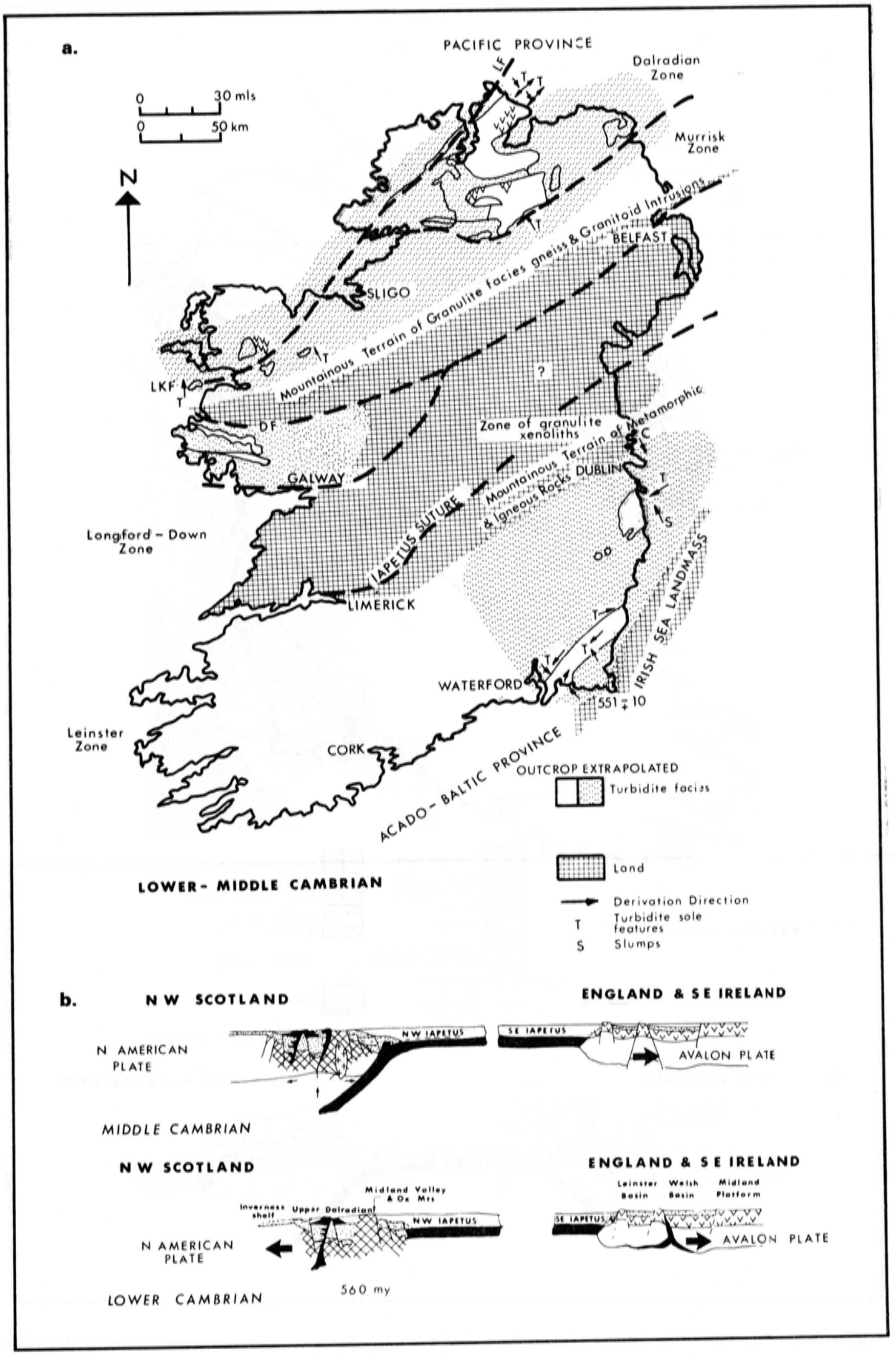


Figure 10. **a.** Map showing the outcrop, facies and palaeogeographic environments of Lower-Middle Cambrian rocks in Ireland. No attempt has been made to allow for post-depositional tectonic movements. (LF = Leannan Fault, LKF = Leck Fault, DF = Doon Rock Fault.)
b. Highly schematic profiles illustrating a possible course of tectonic evolution of Britain and Ireland during the Lower and Middle Cambrian. No allowance has been made for later strike slip movements. Symbols as for Figure 9.

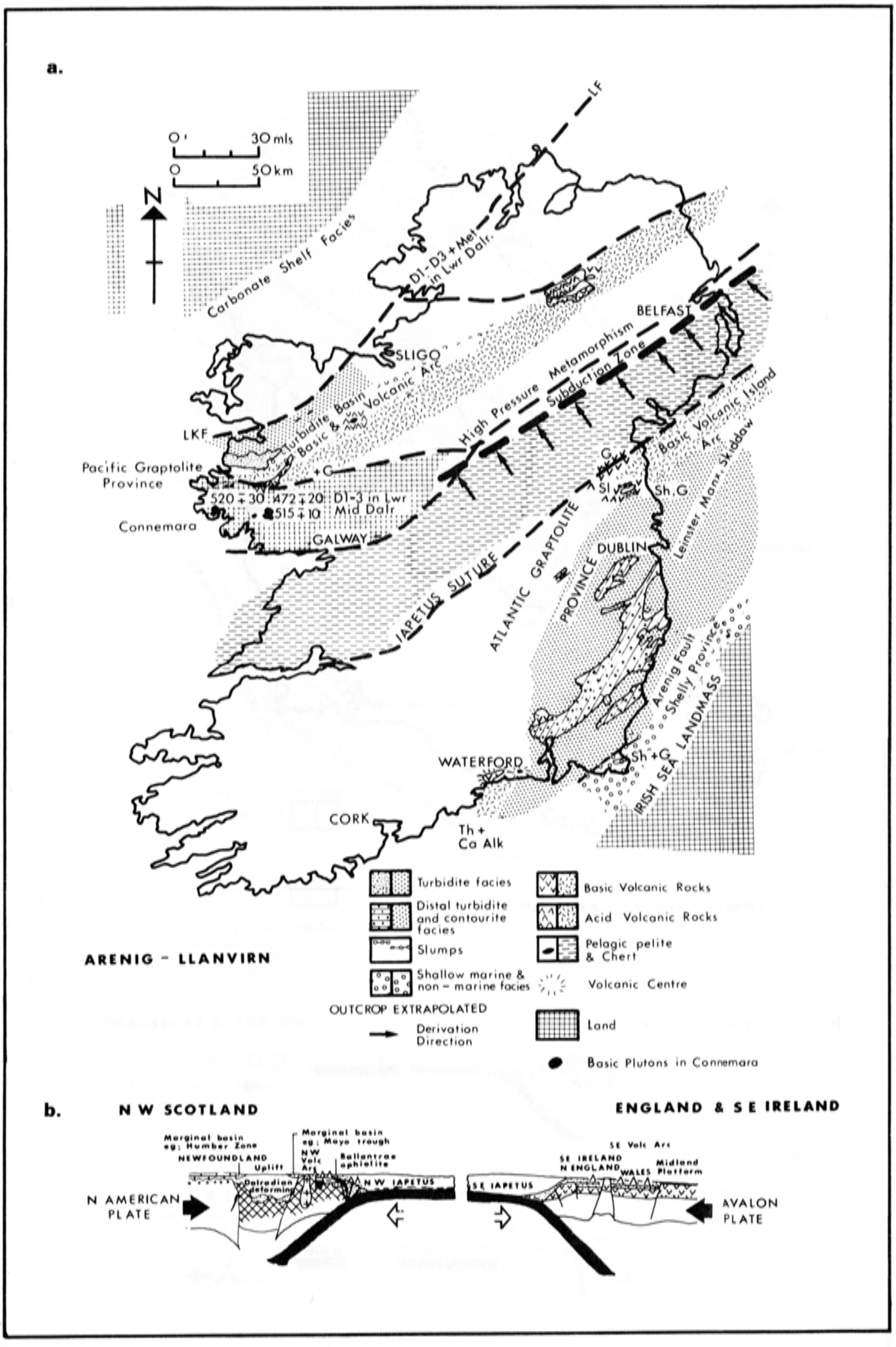


Figure 11. **a.** Map showing the outcrop, facies and palaeogeographic environments of early Ordovician (Arenig-Llanvirn) rocks in Ireland. The effects of later tectonic movements are ignored. (Ca Alk = calcalkaline volcanism, G = Graptolite faunas, Sh = Shelly faunas, Th = tholeiitic volcanism. Other symbols as in Figure 10a.)

b. Schematic profile illustrating a possible tectonic model for the Caledonide Orogen in the vicinity of Ireland, during Arenig and Llanvirn times. Subsequent strike slip movements have been ignored. Symbols as for Figure 9.

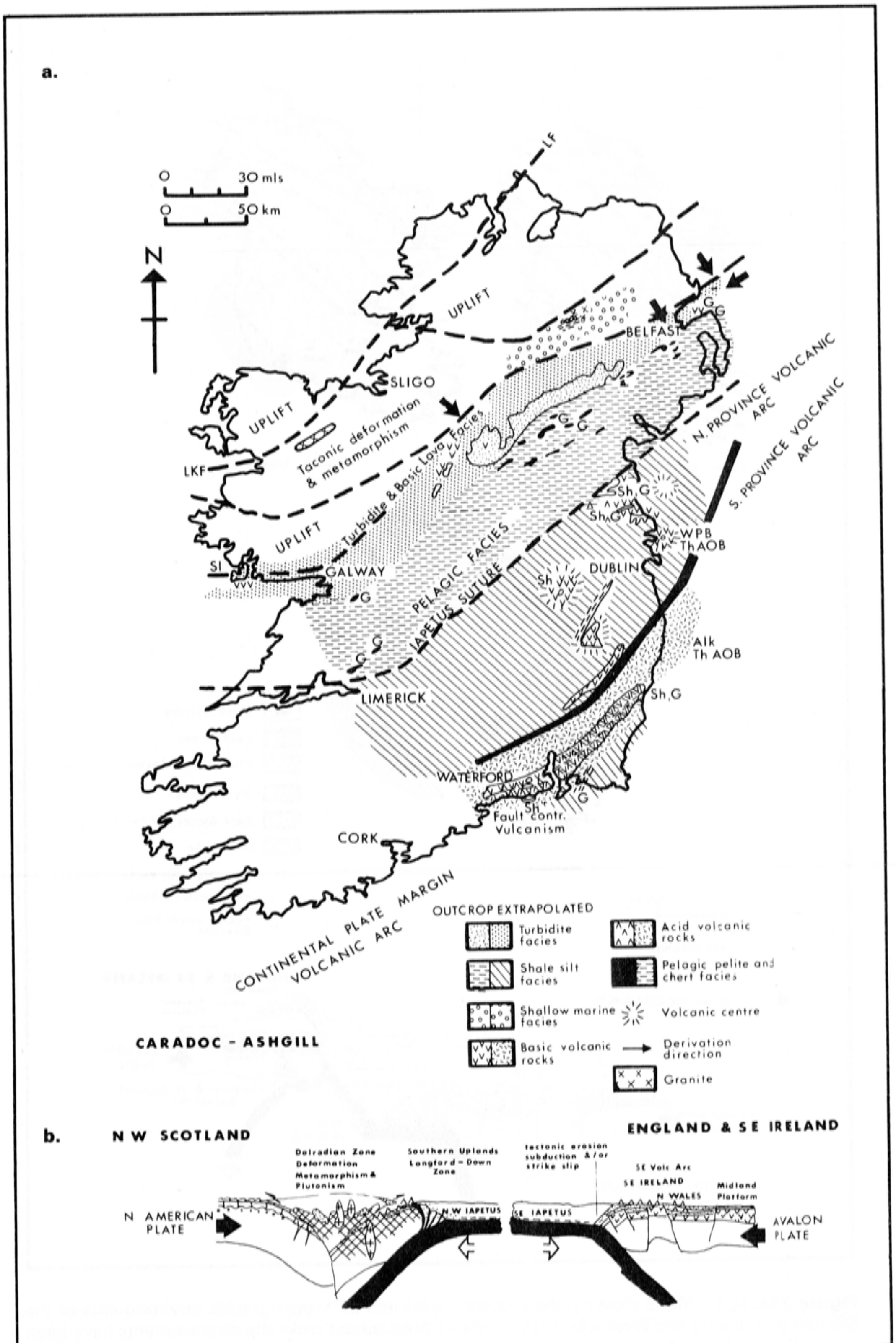


Figure 12. **a.** Map showing the outcrop, facies and palaeogeographic environments of late Ordovician (Caradoc and Ashgill) rocks in Ireland. (Alk = alkaline basalts, Th AOB = tholeiitic and alkaline olivine basalts, WPB = within-plate basalts.)

b. Schematic profile illustrating a possible tectonic model for the Caledonide Orogen in the vicinity of Ireland during the late Ordovician (Caradoc-Ashgill). Subsequent strike slip movements have been ignored. Symbols as for Figure 9.

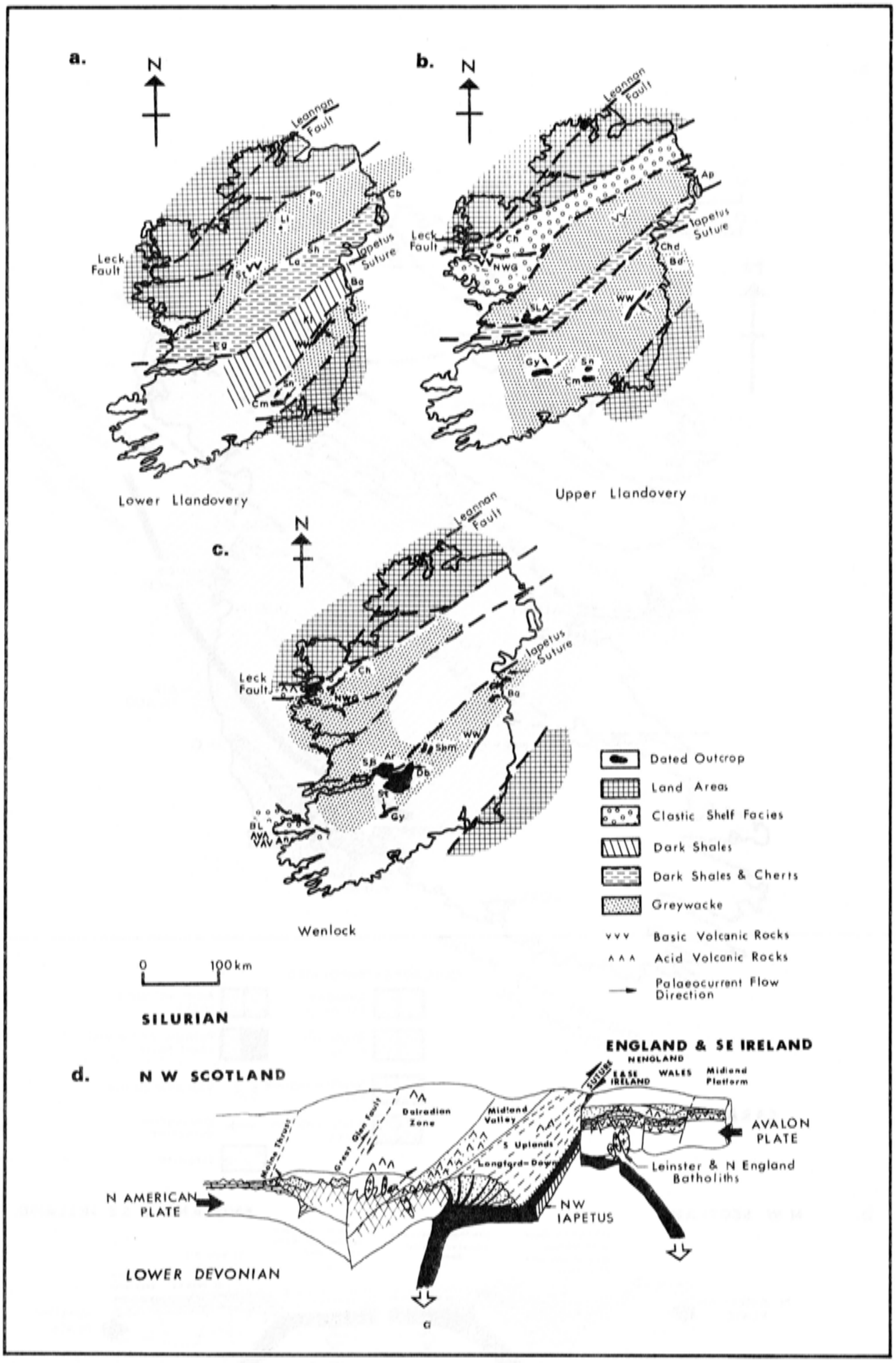


Figure 13a, b, c. Maps showing the outcrop, facies and palaeogeographic environments of the Silurian (Llandovery and Wenlock) rocks in Ireland. Subsequent strike slip displacements have been ignored. Localities:—Ap = Ards peninsula, An = Anascaul, Ar = Arragh Mountains, Ba = Balbriggan, Bl =Ballyferriter, Cb = Coal Pit Bay, Ch = Charlestown, Chd = Clogherhead, Cm = Comeragh Mountains, Db = Devilsbit Mountains, Gy = Galty Mountains, Kl = Kildare, La = Lough Acannon, Li = Lisbellaw, NWG = NW County Galway, Po = Pomeroy, SB = Slieve Bernagh, Sbm = Slieve Bloom Mountains, Sh = Shercock, SLA = Slieve Aughty, Sn = Slievenamon, St = Strokestown, Tg =Tomgraney, WW = W Wicklow. **d.** Schematic block diagram showing a possible tectonic model for the Caledonide Orogen in the vicinity of Ireland during early Devonian time.

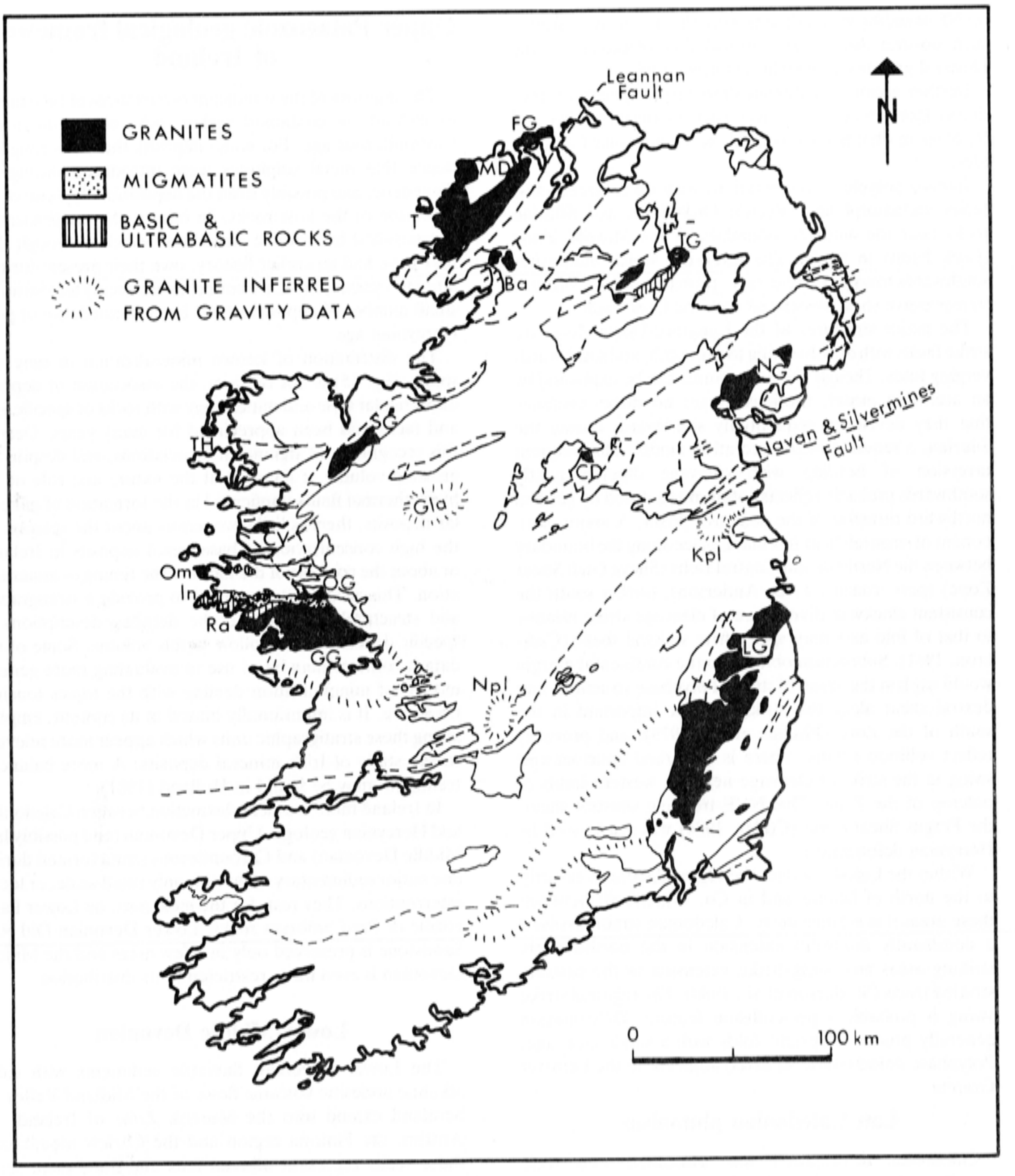


Figure 14. Location of late Caledonian plutons (c. 400Ma) and Grampian (late Cambrian-early Ordovician c. 510Ma) plutons in Ireland. Grampian plutons: migmatites and basic-ultrabasic plutons in Connemara. Taconic plutons: OG = Oughterard Granite, SG = Slieve Gamph Granodiorite, TG = Tyrone Granites (in part). Caledonian granitoid plutons: Ba = Barnesmore Granite, CD =Crossdoney Granodiorite, CV = Corvock Granite, FG = Fanad Granite, GG = Galway Granite, Gla = Glenamaddy pluton, In = Inish Granite, Kpl = Kentstown pluton, LG =Leinster Granite, MD = Main Donegal Granite, NG = Newry Granodiorite, Npl = Nenagh pluton, Om = Omey Granite, Ra = Roundstone Granite, T = Thorr Granodiorite, TG =Tyrone Granites (in part).

subsidence continued. This was accompanied by abundant calc-alkaline basaltic, andesitic and rhyolitic eruptions with intrusion of rhyolitic sheets. Subsequently a series of more alkaline intrusions were emplaced (Stillman, 1982). A possible interpretation of the evolution of the Irish Caledonides is outlined in Figures 10 to 13.

Late Caledonian deformation

In late Silurian - Middle Devonian times, the whole of Ireland was affected by Caledonian deformation caused by collision between the North American and European plates. In the NW of the country, sinistral displacements on NE-trending wrench faults were the dominant features; such sinistral shear-zones controlled emplacement of the Donegal granites (c. 400Ma) (Hutton, 1980).

Further south, Caledonian deformation generally produced more ductile structures such as upright folds and cleavage in what has been called the Paratectonic Caledonides.

Intense polyphase deformation, with up to greenschist facies metamorphism, affected Ordovician and Silurian rocks near the northern boundary of the Murrisk Zone (Leck Fault) in Mayo. The intensity, which diminishes southwards towards Connemara, probably reflects sinistral transpressive shear associated with the Leck Fault.

The major structures of the Longford-Down Zone are strike faults with overthrusting to the south, and southwards verging folds. Though these structures can be explained by an accretion model, there is as yet no direct evidence that they developed sequentially southwards during the Silurian, a requisite of the accretion model. The frequent inversion of bedding with cleavage dipping gently southwards probably reflects rotation generated by general northward thrusting of the accretive prism. A major component of sinistral shear has taken place along the boundary between the Northern and Central Belts (Slieve Glah Shear Zone) (pers. comm., T. B. Anderson); further south the consistent clockwise divergence of cleavage strike relative to that of fold axes may also reflect sinistral shear (Cameron, 1981). Subduction oblique to the continental margin would explain this sense of shear. Polyphase structures and dextral shear along the strike become important in the south of the Zone (Phillips et al., 1979), and probably reflect collision strains. There is a marked anticlockwise swing in the strike of cleavage near the western limits of outcrop of the Zone. This NNE-trending sinistral shear, the Fergus Shear Zone (Coller, 1984) was reactivated by Hercynian deformation.

Within the Leinster Zone, the regional strike is easterly to the north of Dublin and in Co. Waterford; between these areas it is northeasterly. Caledonian strain involved a dominantly down-dip extension in the northeasterly striking areas and along-strike extension in the easterly striking tracts (Sanderson et al., 1980). The regional strike swing is probably a pre-collision feature. Deformation generally produced upright folds with a single cleavage. Polyphase deformation occurred adjacent to the Leinster Granite.

Late Caledonian plutonism

Caledonian deformation was associated with wide spread emplacement of granitoid plutons (Fig. 14) at about 400Ma (Leake, 1978; Kennan, 1979; Plant, this vol.). The granitoid complexes of Leinster and Galway lie close to older (Ordovician) volcanic arcs and may have inherited feeder systems from the arcs. The main granites of Donegal were emplaced during sinistral shear and dilation on a northeasterly trending shear zone system.

The generally low initial $^{87}Sr/^{86}Sr$ ratios of these plutons has been used to argue a major input of mantle-derived magma (Halliday et al., 1979). Comparison of the composition of the granodiorites of the Longford-Down Zone (porphyry copper "I" type granites) with the more potassium-rich Galway granites, shows the sort of magma variation to be expected above a northwards dipping subduction system.

Gravity data over central Ireland reveals the presence of many negative anomalies which are possibly granitoids of Caledonian age. In several cases these anomalies correlate with areas of shelf facies sedimentation during the Visean.

Upper Palaeozoic geological framework of Ireland

The majority of the significant occurrences of base metals in Ireland are contained within rocks of Devonian and Carboniferous age. For some deposits there is strong evidence that metal sulphides were introduced during the diagenetic, and possibly even the depositional, phase of the evolution of the host rocks. In others, the mineralization is controlled by tectonic structures, which, although they may have had an earlier history, owe their present form to late Hercynian (late Carboniferous-Permian) tectonism. A small number of deposits, it has been claimed, are of post-Hercynian age.

The distribution of known mineralization in time and space (Fig. 15) is not random; the association of deposits of particular style and mineralogy with rocks of specific ages and facies has been appreciated for many years. Despite this recognition of significant associations, and despite the growing volume of data about the nature and role of the hydrothermal fluids implicated in the formation of particular deposits, there is little concensus about the reasons for the high concentration of base metal deposits in Ireland, or about the controls of the loci and the timing of mineralization. This account is presented to provide a stratigraphic and structural backdrop to the detailed descriptions of specific deposits which follow in this volume. Some of the data it contains may be of use in evaluating more general models of mineralization dealing with the topics touched on above. It is intentionally biased in its content, emphasizing those stratigraphic units which appear more relevant to the study of Irish mineral deposits. A more balanced treatment may be found in Holland (1981).

In Ireland there is a clear distinction between Caledonian and Hercynian geology. Upper Devonian (and possibly late Middle Devonian) and Carboniferous strata formed during one major sedimentary cycle with only small-scale, or local, interruptions. They rest, for the most part, on Lower Palaeozoic or Pre-Cambrian rocks. Lower Devonian Old Red Sandstone is preserved only in a few areas and the Middle Devonian is even more restricted in its distribution.

Lower-Middle Devonian

The Lower Devonian fluviatile sediments with calc-alkaline andesitic volcanic flows of the Midland Valley of Scotland extend into the Murrisk Zone of Ireland. In Antrim, the Fintona region and the Curlew mountains, these rocks represent alluvial fans and flood-plain sediments laid down in fault-controlled small basins. These basins probably represent pull-apart areas controlled by sinistral shear on ENE - trending faults. Lower and Middle Devonian rocks are seen in the SW Ox Mountains near Castlebar. This is another intermontaine basin probably formed in the same way on the Leck-Leannan fault system. An angular unconformity separates these Devonian rocks from the Dinantian in the Murrisk Zone.

Late Devonian

The earliest part of the late Devonian to Carboniferous succession is confined to the Munster Basin (Fig. 16), which has been described in several publications, the latest and most comprehensive of which is by Graham (1983). The basin trends ENE and in its axial zone it accommodates more than 6km of Old Red Sandstone facies rocks. Although the isopachytes are mostly based on minimum

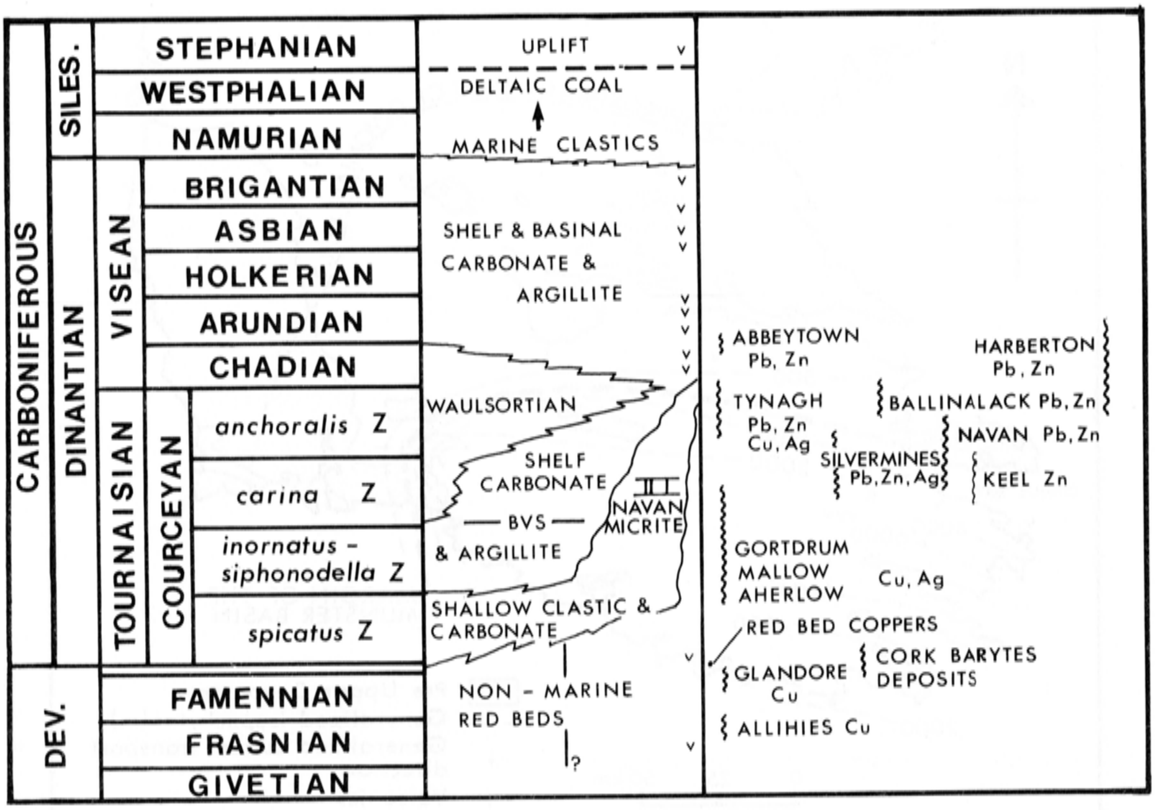


Figure 15. Outline late Devonian and Carboniferous stratigraphy of Ireland and distribution of important metal deposits in terms of the age of their host rocks. V in the middle column represents volcanics, and BVS the horizon of the Ballyvergin Shale Formation.

thicknesses (since pre-Devonian rocks are not exposed except along the northern margin) limited gravity data supports the interpretation of the basin as a half graben formed by down-to-the-south movement across the northern boundary faults. The greater part of the sedimentary fill consists of grey, green and red mudrock and sandstone, which is generally medium- or fine-grained. Coarse pebbly sandstone and conglomerate occur in the lower part of the succession around the northern margin, particularly in the east where thick formations of pebble and cobble conglomerate have been interpreted as the deposits of local alluvial fans. Transport of sediment was generally to the south, with more westerly flow in the east of the basin. Graham (1983) has suggested that the bulk of the Old Red Sandstone was deposited as fans developed at the termination of river systems which transported sediment from the metamorphic (Dalradian) higher ground far to the north.

In latest Devonian times, the palaeogeography and the patterns of subsidence changed significantly. The 'fall line' of the Old Red Sandstone crossed the northern and eastern margins of the Munster Basin and migrated into the Midlands. Although biostratigraphical correlations are poor, there is some evidence that subsidence of the basin relative to areas to the north was very much less than earlier in the Devonian. A new region of rapid subsidence, the South Munster Basin (Fig. 17) developed in the south. In that region also, there was a striking change in palaeogeography during latest Devonian times; the red-bed succession was replaced by a formation of grey-green sandstone, interlreted as having been deposited on a coastal plain; this, in turn, was covered by sandstone and mudrock of shallow marine origin.

Although the evolution of the Munster Basin has now been established, at least in outline, there is very little information about the mechanisms involved in its development or about the factors responsible for its location. Its northern margin, at least in the west, is probably a fault zone with an important earlier history. On the north side of Dingle Bay, coarse conglomerates with a southerly provenance (Horne, 1975) are made up of metamorphic, presumed Pre-Cambrian, clasts. They may have been shed from the southern (basinward) edge of a tilted fault-block at the margin of the Basin. Their clearly local origin implies significant fault movement prior to the late Devonian, as the late Devonian north of the Basin margin rests on rocks of late Silurian or early Devonian age. Whether the Basin developed in response to strike-slip movement along the northern marginal faults or purely as a result of regional extension is not known. Whatever mechanism was involved, it is likely that the initial rapid subsidence was accompanied by relatively high levels of heat flow (Sanderson, 1984). Evidence for high heat flow, at least locally, is provided by the occurrences of volcanic rocks low in the stratigraphic section close to the northern margin of the Basin (Fig. 17). Most of these are small volumes of basic flows, pyroclastics and intrusives (Penney, 1978), but in the mountains SE of Killarney there are thick developments of rhyolite and acid pyroclastics, whose eruption was accompanied by movement of faults parallel to the Basin margin (Avison, 1984).

Devonian rocks of the Munster Basin are the hosts to

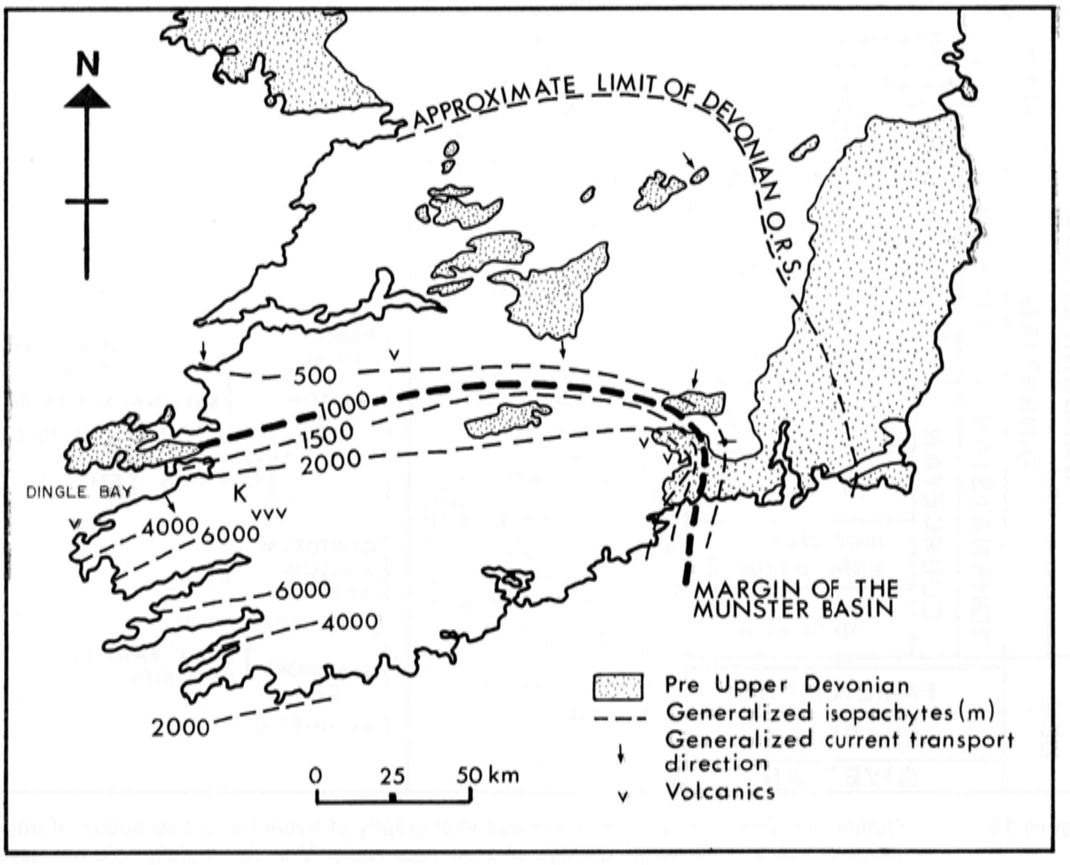


Figure 16. Generalized late Devonian palaeogeography and isopachytes. K = Killarney. Light stipple in this and later figures represents pre-late Devonian and post-Carboniferous rocks.

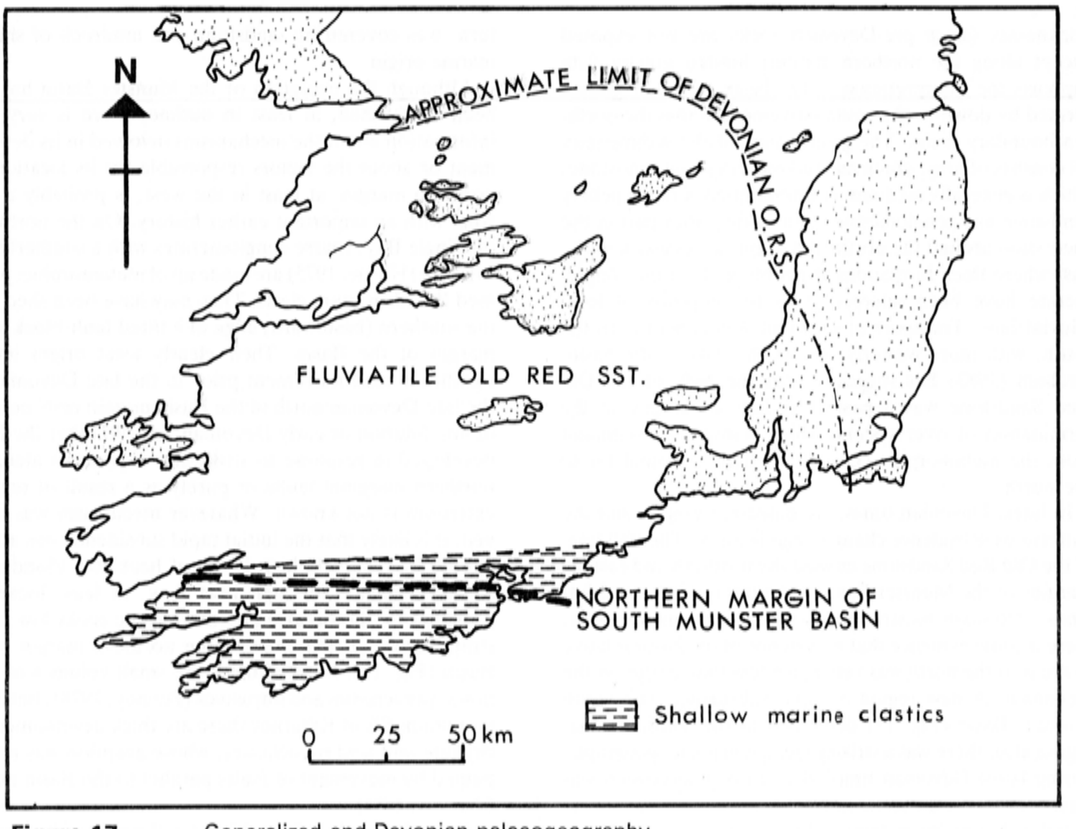


Figure 17. Generalized end-Devonian palaeogeography.

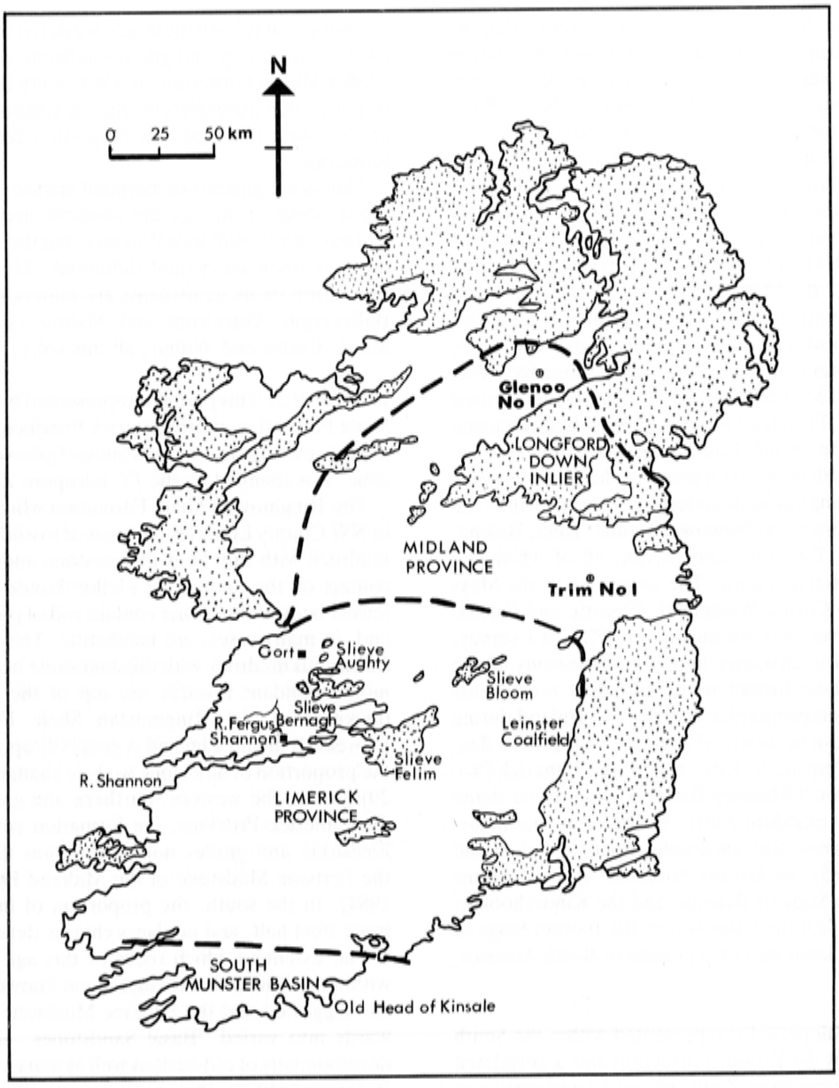


Figure 18. Regional divisions of Ireland during the Courceyan and location of some places named in the text.

several different kinds of metal and barite deposits (Reilly, this vol.). Most of the deposits clearly were formed in post-Devonian times, but one category, stratabound 'red-bed coppers', were introduced during the accumulational phase of the Basin's history. They occur in the upper part of the red-bed succession and in the lower part of the overlying grey and green sandstones of regressive coastal plain origin. One can speculate that formational waters, with their chemistry and temperature reflecting an origin in the deeper part of the Basin, may have been involved in the introduction of the copper sulphides.

Carboniferous

Dinantian and Namurian rocks are well represented in Ireland; the Westphalian is restricted to a few outliers, most of which contain only early Westphalian strata, as a result of extensive Mesozoic and Tertiary denudation. Significant metal deposits are restricted to host rocks of Dinantian age, more specifically to early and mid-Dinantian carbonates and shales, which are the main focus of the following account. The stages proposed by George et al. (1976) provide a framework (Fig. 15) in which to discuss the evolution of the palaeogeography of Ireland during the Dinantian.

Courceyan Stage

At a very general level, Courceyan stratigraphy can be described by reference to three standard successions representative of three major geological provinces (Fig. 18). The first province, the South Munster Basin, is characterized by carbonate-poor successions, such as that displayed at the Old Head of Kinsale, County Cork. Although it is possible that the Basin contains shale-hosted sulphides, no significant deposit has been discovered to date. A more detailed discussion of the stratigraphy than is attempted here can be found in Naylor et al. (1983). The second province extends from the northern margin of the South Munster Basin into the Midlands. It has been named the Limerick Province by Philcox (1984). Its standard succession, developed in the area south of the Shannon Estuary, initially described by Shephard-Thorn (1963), is found, with only modest variations, throughout the region. It can be applied to the host rocks of the Ballyvergin, Mallow, Aherlow, Gortdrum, Courtbrown, Silvermines and Tynagh deposits, all of which are described later in this volume. The third province, the Midlands, extends to the northern limit of late Courceyan marine deposition and contains very much more geographically variable stratigraphical successions which are unified by the presence of shallow-water micrite, commonly with bird's eye structures. In detail, this region can be divided into a number of different sub-areas (see Philcox, 1984), but for present purposes it is treated as a single unit, the Midlands Province. The section at Ballinalack, County Westmeath (Jones and Brand, this vol.) is fairly typical of the succession in the north Midlands; the general pattern of the stratigraphic sequence here, but not the detailed lithostratigraphy, can be recognized throughout the Province. Philcox (1984) has discussed regional variation of the Courceyan succession and has proposed correlations between many of the areas in which exploration drilling has been undertaken; these include the deposits and prospects at Newtown Cashel, Keel, Ballinalack, Oldcastle, Tatestown and Navan, all of which are discussed later in this volume. The succession in the Moyvoughly area of County Westmeath (Poustie and Kucha, this vol.), however, was not included in Philcox's survey. It is transitional in character between successions of the Midlands and those further south, but does not include micrite. The palaeogeographic evolution of Ireland during the Courceyan can be analyzed in terms of five time divisions which correspond to rock units in the Limerick Province and the South Munster Basin. These can be dated in terms of four conodont zones, the *spicatus, inornatus-Siphonodella, carina* and *anchoralis* Zones (Varker and Sevastopulo, 1985); the first two zones are age equivalents of the Hastarian Stage of Belgium and the Kinderhook of North America, and the latter two of the Ivorian Stage of Belgium and the lower part of the Osage of North America.

Division 1. This period is represented within the South Munster Basin by the Kinsale Formation and is correlated with the *spicatus* conodont Zone and the *VI* and early part of the *PC* miospore Zone (Clayton et al., 1978). During this period the sea transgressed northwards from the South Munster Basin across the Limerick Province and into the southern and eastern parts of the Midlands (Fig. 19). Within the South Munster Basin, the initial stage of the transgression was accompanied by the deposition of a widespread dark mudrock unit, the Castle Slate Member, which formed in a shallow offshore environment. The remainder of the very thick Kinsale Formation consists of sandstone and mudrock deposited above wave base. In the Limerick Province the equivalent rocks are varied, but can be described in a general way in terms of three successions. In the south and east the earliest Carboniferous rocks are fluviatile red-beds. The oldest marine deposits are grey and green sandstone with subsidiary dark mudrock; they are overlain by a varied succession of calcareous sandstone, well-washed sandy carbonate, (including, in some places, oolite) and mudrock. A typical development of these facies occurs at Gortdrum (Steed, this vol.) where the succession is capped by a widespread unit of laminated mudrock and sandstone with dessication cracks. In a limited area between Dungarvan and Cork Harbour, there is a transition between the Limerick Province and the South Munster Basin successions; there, the Castle Slate Member succeeds latest Devonian shallow marine sandstone and mudrock, but the top of the succession consists mostly of shallow water limestone. In the northern and western parts of the Limerick Province, grey and green sandstone and mudrock, the Mellon House Formation of NW County Limerick, overlies red-beds of Carboniferous age; in contrast to the regions to the south and east, the succession contains very little limestone.

Thin developments of marginal marine sandstone overlying red-beds of this age are probably present in the south and east of the Midlands Province, but their northern extent has not been accurately delimited. The Mellon House Formation or its equivalents are mineralized at Aherlow, Ballyvergin, Gortdrum and Mallow (Romer; Andrew; Steed; Carter and Wilbur; all this vol.).

Division 2. This period is represented by the Ringmoylan Shale Formation in the Limerick Province and corresponds almost exactly to the *inornatus-Siphonodella* conodont zone. It is spanned by the *PC* miospore Zone.

The Ringmoylan Shale Formation whose type section is in NW County Limerick, consists of fossiliferous calcareous mudrock with thin beds of limestone and rests with sharp contact on the underlying Mellon House Formation. The lowest beds of limestone contain rolled phosphate nodules and, in many cases, are haematitic. They are overlain by calcareous mudrock with thin limestone beds which become more abundant towards the top of the Formation. The thickness of the Ringmoylan Shale Formation varies between 10m and 40m and is generally approximately 20m; the proportion of limestone to shale changes markedly (Fig. 20). Along the western, northern and eastern margins of the Limerick Province, the formation contains very little limestone and grades northwards into the lower part of the Ferbane Mudstone of the Midland Province (Philcox, 1984). In the south, the proportion of limestone rises to more than half, and in places chert is developed.

The extent to which rocks of this age are represented within the Midlands Province is not known. Philcox (1984) has suggested that the Ferbane Mudstone may pass northwards into varied "Basal Sandstones" that include thin developments of red-beds as well as marginal marine facies. It seems unlikely that open marine deposits occur anywhere, except, perhaps, in the south and east.

Equivalent rocks in the east of the South Munster Basin comprise more than 80m of dark, slighly calcareous mudrock of the Courtmacsherry Formation; in the west of the Basin, some 250m of mudrock are interspersed with beds of limestone and with common phosphate nodules; the contact with the underlying sandstone of the Kinsale Formation is sharp.

The Ringmoylan Shale Formation hosts much of the mineralization of the Aherlow, Ballyvergin, Gortdrum and Mallow deposits.

In summary, the early part of the Courceyan (*spicatus* and *inornatus-Siphonodella* Zones) can be analyzed in terms of two trangressions. The earlier resulted in the movement of the strandline to the western, northern and eastern limits of the Limerick Province and possibly beyond, and led to the development of a shallow water shelf with thin accumulations of carbonate and clastic sand, and a thick succession of shallow water sand and mud in the South Munster Basin. Towards the end of this episode, sediment accumulation outpaced subsidence and tidal flats developed across the northern parts of the shelf. A second transgression pushed the strandline a little further north and east; a zone of inshore clastic sand and mud gave way southwards to an extensive muddy inner shelf and a more carbonate-rich outer shelf. Subsidence in the South Muns-

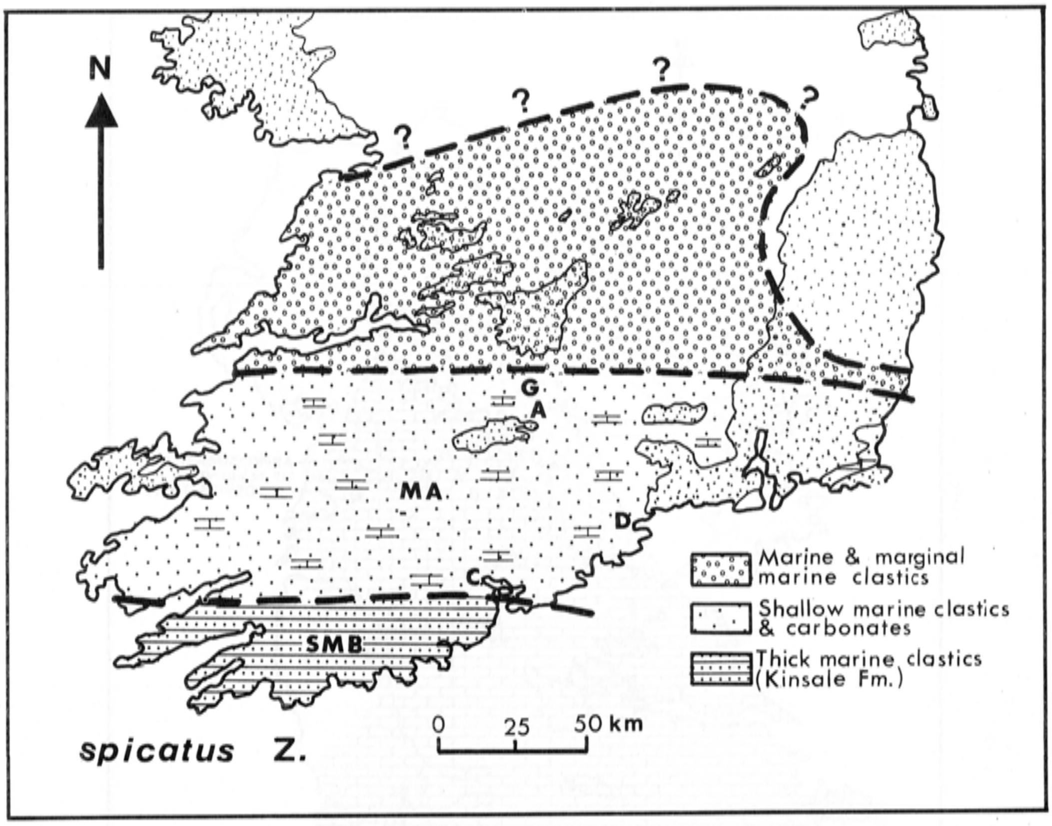


Figure 19. Generalized palaeogeography of the S of Ireland in late *spicatus* Zone times. A = Aherlow; C = Cork; D = Dungarvan; G = Gortdrum; MA = Mallow deposit; SMB = South Munster Basin.

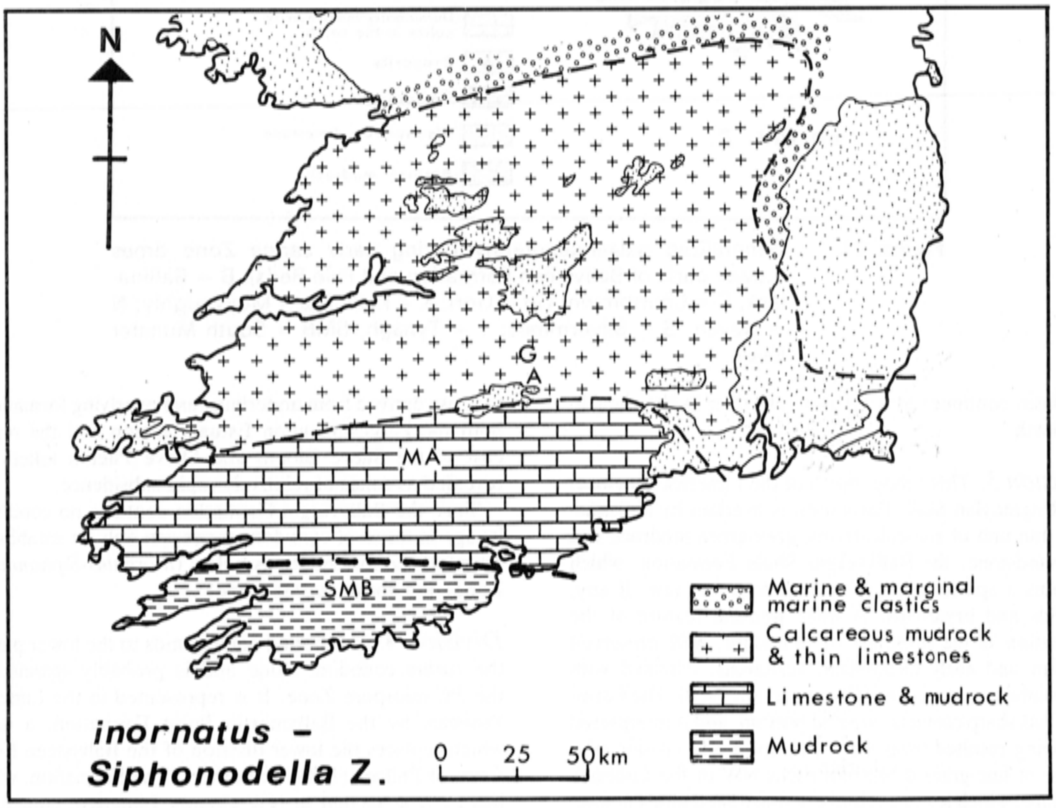


Figure 20. Generalized palaeogeography of the S of Ireland in late *inornatus — Siphonodella* Zone times. A = Aherlow; G = Gortdrum; MA = Mallow deposit; SMB = South Munster Basin.

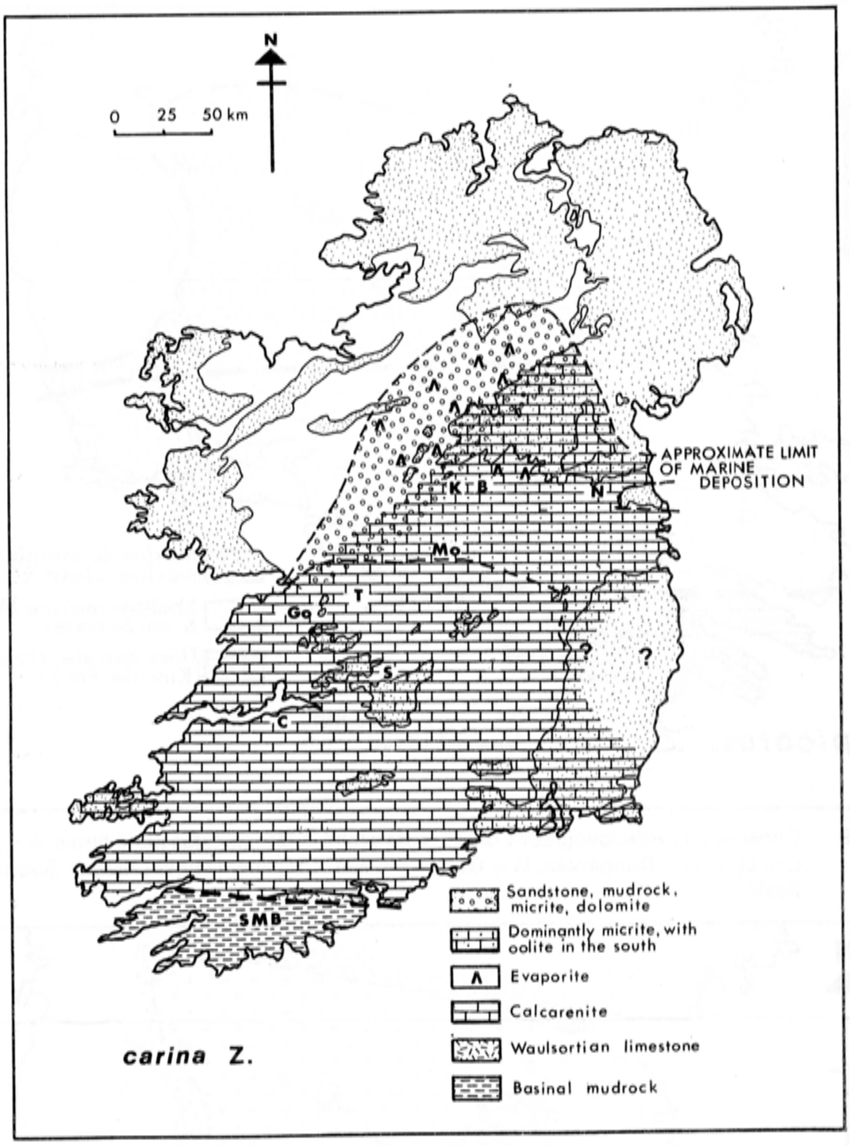


Figure 21. Generalized palaeogeography during early *carina* Zone times (Lower parts of Ballysteen Formation and Pale Beds). B = Ballinalack; C = Courtbrown; Go = Gort; K = Keel; Mo = Moyvoughly; N = Navan; S = Silvermines; T = Tynagh; SMB = South Munster Basin.

ter Basin continued at a greater rate than in the shelf to the north.

Division 3. Throughout much of the Limerick Province, the Ringmoylan Shale Formation is overlain by a distinctive, thin unit of non-calcareous, grey-green mudrock and fine sandstone, the Ballyvergin Shale Formation, which contains a sparse fauna of brachiopods but few, if any, crinoids and bryozoans. A most unusual feature of the Formation is the presence of abundant, well preserved Silurian and early Ordovician acritarchs, admixed with Carboniferous miospores (Clayton et al., 1980). The Formation has sharp contacts, top and bottom, and is interpreted as having resulted from the rapid uplift and erosion of a region of fine-grained Silurian rocks NW of the Limerick Province, which led to a relatively short-lived influx of fine-grained sediment across the shallow marine shelf of the time. Isopachytes for the formation reveal a pattern similar to those derived from underlying and overlying formations; both the Fergus-Shannon Estuary region and the region east of the Slieve Bloom and Slieve Phelim inliers are revealed as zones of relatively rapid subsidence.

Since the Ballyvergin Formation contains no condonts, its age in terms of conodont zones can only be established by reference to formations below (*inornatus-Siphonodella* Zone) and above (*carina* Zone).

Division 4. This period corresponds to the lower part of the *carina* conodont Zone and is probably spanned by the *PC* miospore Zone. It is represented in the Limerick Province by the Ballymartin Point Formation, a name which replaces the lower division of the Ballysteen Limestone of Philcox (1984) and others. The Formation, which has its type section in NW County Limerick, consists of open marine, argillaceous limestone and shale, typically 30-50m thick, and is, in general, more argillite-rich toward the western, eastern and northern margins of the Limerick Province and more limestone-rich to the south. As indicated by Philcox (1983, Fig. 5) it is thought to pass into marine mudstone (the Ferbane Mudstone) and sandstone in the southern part of the Midlands Province. Correlations elsewhere in the Midlands Province are tenuous but open marine conditions may have extended as far north as Navan (where the Muddy Limestone may be a correlative); the northern and western parts of the Province were probably covered by marginal marine sand and mud at this time.

Division 5. This period is probably far longer than the preceding four as it includes much of the *carina* Zone together with the *anchoralis* Zone. It equates with most, if not all, of the *CM* miospore Zone. In the Limerick Province it corresponds to the span of the Ballysteen Limestone Formation and part of the over-lying Waulsortian Limestone. The Ballysteen Limestone and its correlatives in the Midlands Province are described first (Fig. 21), followed by the Waulsortian Limestone.

Within the Limerick Province, the Ballymartin Point Formation is succeeded by the Ballysteen Limestone Formation (middle and upper divisions of the Ballysteen Limestone of earlier literature). The Formation consists of a lower unit dominated by skeletal packstone and an upper unit dominated by argillite. Its thickness varies considerably, partly as a result of differences in subsidence from place to place and partly because the upper boundary is markedly diachronous. Typical thickness range from > 300m present at Tynagh to < 100m found in the extremely condensed succession at Gort, County Galway. The lower boundary of the Formation is sharp and has been shown to be isochronous, being close to the appearance of the conodont *Pseudopolygnathus multistriatus* in many sections. The abrupt reduction in argillite at this horizon possibly reflects a regional transgression which would have reduced the input of clastic sediment to the shelf for a short period of time or, alternatively, marks a regional shallowing, with higher energy conditions across the shelf. The lower part of the Formation undoubtedly formed in relatively shallow water, because a widespread, thin unit of well-washed, carbonate grainstone, close above the base (the Fine Calcarenite Marker of Philcox, 1984; Fig. 4) is oolitic in several places. The upward increase in argillite through the Formation and the reduction in grain size and bioclastic content may reflect deposition in steadily deepening environments as subsidence of the shelf outpaced the accumulation of sediment. Within the Limerick Province, the Ballysteen Formation is surprisingly consistent in its character, and varies, for the most part, in its content of argillite and in the presence or absence of chert which is particularly common near the top of the Formation in some areas. However, in the south the Formation is substantially more carbonate-rich than further north, and in the area east of Slieve Bloom and Slieve Phelim it contains thick developments of oolite (see representative logs in Philcox, 1984; Fig. 4). The top of the Formation lies close to the base of the *anchoralis* Zone in NW County Limerick but is well within the *anchoralis* Zone further to the NE.

The Ballysteen Formation hosts mineralization in the Limerick Province and contains significant amounts of metals at Gortdrum, Courtbrown, Silvermines and Tynagh.

Within the Midlands Province, successions equivalent in age to the Ballysteen Formation are varied, both vertically and laterally, as is well illustrated by Philcox (1984). However, a general pattern, common to much of the Province, can be established. At the base are units of micrite, which commonly show fenestral fabric, vadose cement and other features indicating deposition and early diagenesis in peritidal environments. They are succeeded by varied carbonate and clastic sandstones and argillite which, together with the micrite, have been grouped into the Pale Beds and overlying Shaly Pales in the Navan area (Ashton et al., this vol.) Throughout the Midlands there is a well-marked boundary between these generally sand-rich units and overlying argillaceous bioclastic limestone and shale, which contain only small amounts of clastic sand. Biostratigraphic correlations between the Ballysteen Limestone and these Midland facies are imprecise, but it is clear that the micrite unit is equivalent to a section of the lower, limestone-dominant, part of the Ballysteen Formation. Whether the base of the micrite is approximately isochronous across the Midlands, and whether it correlates with the base of the Ballysteen Formation, requires further investigation; but the limited evidence available to date does not rule out either hypothesis. The Shaly Pales of the Navan area are equivalent to part of the upper shale-rich part of the Ballysteen Formation in County Limerick.

The regional variation within the Pale Beds and Shaly Pales of the Midlands is too great to allow more than an outline here. Much more detail is available in the logs illustrated in Philcox (1984). However, certain aspects of the facies distribution are worth emphasizing. First, the sequences become generally much sandier from south to north and from east to west, and the proportion of open marine carbonate becomes smaller in the same direction. Philcox (1984, Fig. 1) has drawn attention to this by showing the distribution of a prominent sandstone (the Upper Sandstone) at the top of the Pale Beds which occurs widely in the north Midlands west of Navan. The same point can be illustrated by comparing the high sandstone contents of sequences north and west of the Longford Down inlier with those to the south, and contrasting the latter with Pale Beds equivalents in the Dublin region which are essentially free of clastic sand. It is clear that the main source of clastic sediment lay to the north and west.

Second, the pattern of distribution of evaporites in a general way follows that of the sandstone; cumulative thicknesses of evaporite of more than a metre are restricted to the north Midlands, and to the areas west of Navan and to the NW of the Longford Down Inlier. The evaporites are all sulphate and are associated with shallow-water clastic sandstone, micrite and dolomicrite. No evaporites are known from the southern and eastern parts of the Midlands Province.

Third, the transition from the Pale Beds sequences of the Midlands into the Ballysteen Formation of the Limerick Province involves the southward feathering out of sandstone, the thinning of micrites and their replacement by carbonate sand, including oolite.

The Pale Beds are the most important hosts to mineralization of the Midlands Province since they contain the orebodies at Navan and carry most of the sulphides in the other mineral deposits with the exception of Ballinalack.

Throughout the Limerick Province and much of the Midlands Province, the Ballysteen Formation and lateral correlatives are overlain by the Waulsortian Limestone, a distinctive association of facies often referred to as "reef" limestone. The Waulsortian has its *locus typicus* in the Dinant Syncline, Belgium and is also found in England, Wales and the U.S.A. However, nowhere else in the world is it as thick or as laterally extensive as it is in Ireland (Sevastopulo, 1982). It is made up of an aggregate of banks,

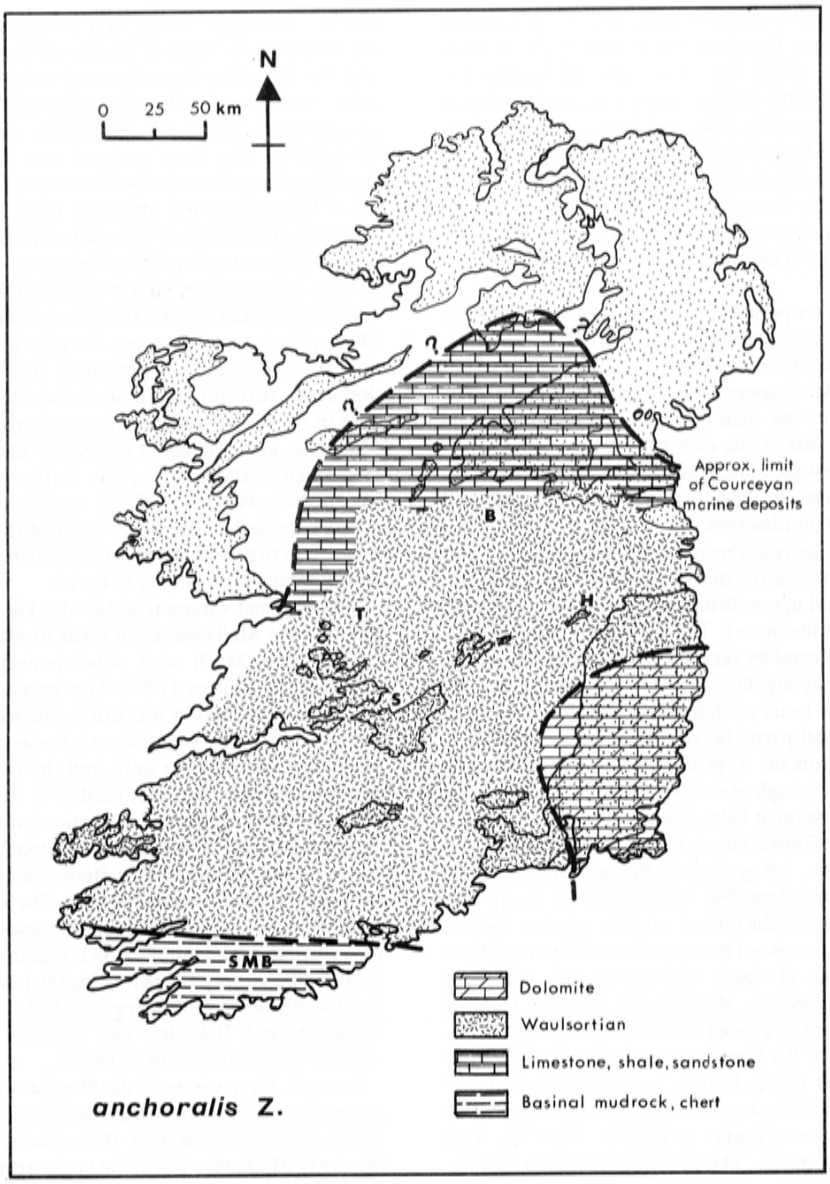


Figure 22. Generalized palaeogeography during late *anchoralis* Zone times. B = Ballinalack; H = Harberton Bridge; S = Silvermines; T = Tynagh; SMB = South Munster Basin.

which include mound-like and sheet-like forms that had original depositional dips on their flanks of up to 40°. The bank limestone in most places is pale to medium grey in colour, very pure and fine-grained, and usually is a wackestone or packstone. A common limestone type is wackestone containing large patches of sparry carbonate cements. These fill original voids which in many cases formed more than 50% of the sediment. The initial porosity was reduced very rapidly by the deposition of internal sediment and the precipitation of marine fibrous (probably high magnesium calcite) cement, now seen as radiaxial fibrous calcite. The early cementation probably produced the rigidity necessary to sustain the high depositional dips.

The Waulsortian first developed in a narrow zone just north of the South Munster Basin in the early part of the *carina* Zone, approximately at the horizon of the base of the Ballysteen Limestone (Fig. 21). In the late part of the *carina* Zone it spread into other areas, reaching the Shannon estuary approximately at the base of the *anchoralis* Zone and areas further east slightly later. It arrived in the Midlands Province later in the *anchoralis* Zone (Fig. 22). In many areas the Waulsortian persisted into the Chadian, but it had become extinct almost everywhere by the beginning of the Arundian.

The depth of water under which Waulsortian limestone formed has been the subject of several recent discussions. Lees et al. (1977) concluded that in Belgium the stratigraphically early developments (*carina* Zone) formed in relatively deep water, perhaps more than 200m deep, but that the later parts (Chadian) were deposited in shallower water. Miller and Grayson (1982) suggested that Waulsortian banks first developed on the deeper parts of carbonate ramps and moved up slope through time. In Ireland, there is good evidence that the Waulsortian was part of a sequence which records progressive deepening (seen, for instance, in the change from the shallow-water lower part of the

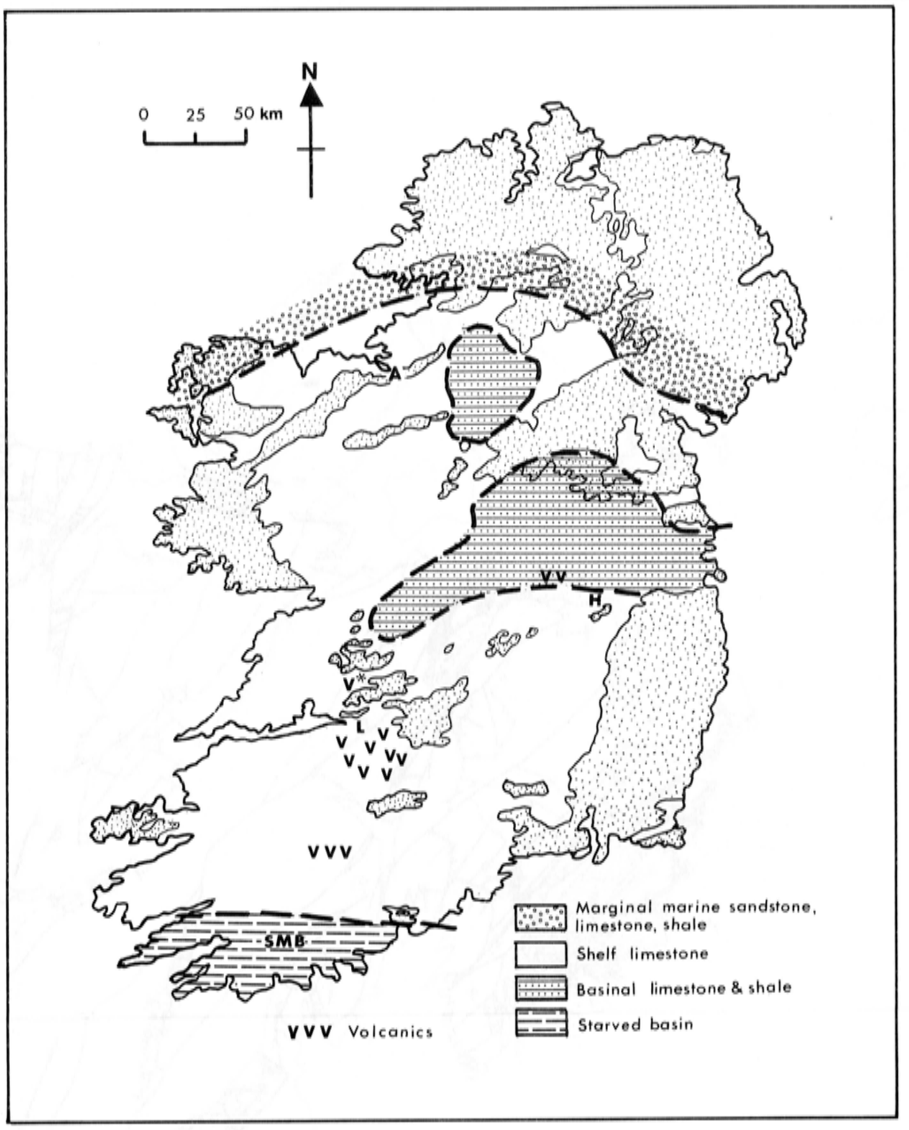


Figure 23. Generalized Chadian and Arundian palaeogeography. V* represents the location of Brigantian-aged volcanics. A = Abbeytown; H = Harberton Bridge; L = Limerick.

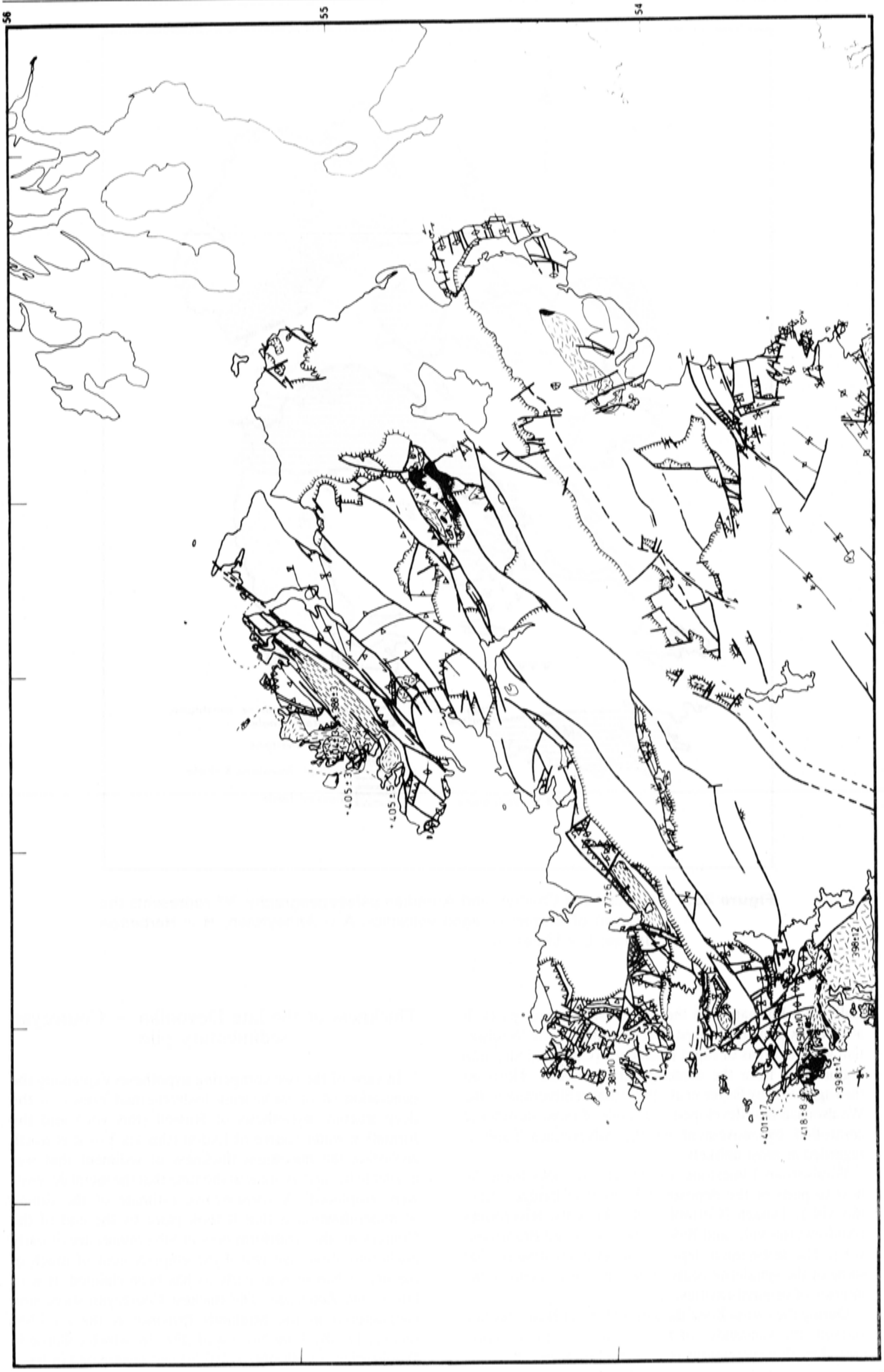
Ballysteen Formation to the deeper-water upper part). It also seems that the earliest developments of the Waulsortian were in areas of rapid subsidence (Cork and Shannon regions) far from the contemporary shoreline. However the suggestion by Boyce et al. (1983) that at Silvermines, the Waulsortian first developed as a result of rapid subsidence controlled by movement on the Silvermines Fault is regarded as most unlikely.

Waulsortian Limestone and associated rocks form the host to parts of the deposits at Harberton Bridge (Emo, this vol.), Tynagh (Clifford et al., this vol), Silvermines (Andrew, this vol.) and Ballinalack (Jones and Brand, this vol.). The last-named deposit is most interesting in that some of the sphalerite coats marine fibrous cements in the interior of original cavities.

During the *carina* Zone the South Munster Basin became starved; the remainder of the Dinantian there is represented by thin successions of dark mud rock and chert.

Thickness of the late Devonian — Courceyan sedimentary pile

In view of the two competing hypotheses explaining the generation of metal-bearing hydrothermal brines — the deep fracture hypothesis of Russell (this vol.) and the formation water source of Lydon (this vol.) — it is worth recording the maximum thickness of sediment that was available in various areas at the time that the metal deposits were emplaced. A conservative estimate of the timing of mineralization is that it took place by the end of the Courceyan; the stratiform ores at Silvermines are of early *anchoralis* Zone age and if the emplacement of much of the ore at Navan is as early as has been claimed, it is of late *carina* Zone age. The thickest Courceyan succession encountered in the Midlands Province is the c.1,770m recorded in the Trim No. 1 well (Fig. 18) which collared in Waulsortian (cf. Sheridan, 1972a) and terminated in basal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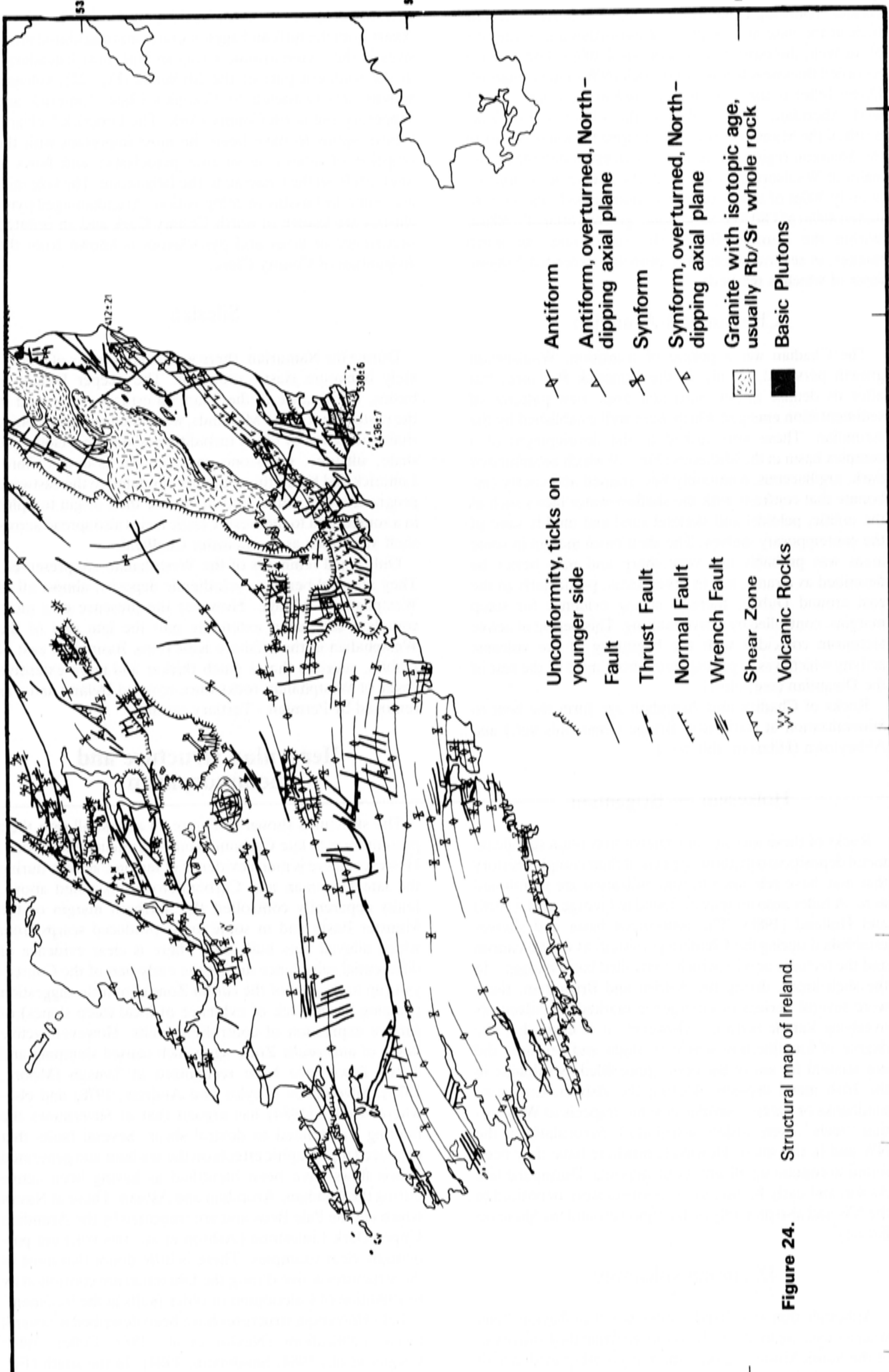

Figure 24. Structural map of Ireland.

clastics. Allowing an additional 150m for clastics and red beds at the base and 180m for Waulsortian above the top of the well, the estimated thickness is 2,100m. The greatest recorded thickness in equivalent rocks NW of the Longford-Down Inlier is the c. 600m reported in the Glenoo No.1 well (Sheridan, 1972b). Within the Limerick Province, north of the Munster Basin, the greatest thickness occurs in the Shannon region where there is an estimated maximum 800m of Waulsortian (some of it of Chadian age), approximately 300m of sub-Waulsortian marine beds and an estimated 400m of Old Red Sandstone, giving a total of 1,500m. Within the Munster Basin, the successions are much thicker; in several places they probably exceeded 7 000m, most of which is red-beds.

Chadian and Arundian

The Chadian was a period of transition; Waulsortian growth persisted, mainly in the Limerick Province, but after its demise in any particular area, new patterns of sedimentation emerged which were well established by the Arundian. These were linked to the development of a complex basin in the Midlands (Fig. 23) which accumulated dark, argillaceous, commonly fine-grained and cherty carbonate that contrasts with the shallow-water facies such as the oolitic, peloidal and skeletal sand and muddy sand of the contemporary shelves. The shelf/basin margin in some areas was probably not very sharp and may better be described as a ramp; but in other areas, particularly in the east around Dublin, there is strong evidence for steep margins, controlled by active faulting. This period of active tectonism coincided with the beginning of the volcanic activity which was to persist throughout most of the rest of the Dinantian (see below).

Rocks of Chadian and Arundian age form the host to mineralization at Harberton Bridge (Emo, this vol.) and Abbeytown (Hitzman, this vol.).

Holkerian — Brigantian

Rocks of these ages are not known to contain significant metal deposits so only those aspects of their complex history that may have relevance to mineralization are mentioned here. A fuller account may be found in George et al. (1976) and Holland (1981). The pattern of basin and shelves established during the Chadian persisted, as did volcanism and the tectonic activity which controlled basin margins. In the shelf areas, during the Asbian and Brigantian, there were several periods of emergence marked by palaeoșols overlying karstic surfaces. However, it is clear that the degree of karstification was very slight and certainly did not account for any of the open space filled by sulphide in the Irish metal deposits. During the Asbian, carbonate mudbanks or "reefs", similar in some respects to Waulsortian "reefs", were widely distributed, particularly in the NW and in the south. However, nowhere have they been found to contain significant metal deposits. During the late Asbian and early Brigantian, evaporites were deposited in the NW and also probably in the region around the Shannon Estuary.

Dinantian volcanism

Although thin clay bands, interpreted as having been volcanic ash, are moderately common within the Courceyan of the South Munster Basin, there is no other evidence of volcanism in Ireland until the Chadian. From then until the Brigantian, there was considerable, but localized, activity. Apart from the tuffs and agglomerates and associated intrusives in the region around Croghan Hill, near Edenderry, in the southern part of the Midlands (Fig. 22), volcanic activity was restricted to Counties Clare, Limerick and Tipperary and north County Cork. The Limerick Volcanic Centre seems to have been the most important with the eruption of mainly submarine pyroclastics and flows at intervals from the Chadian to the Brigantian. The volcanics are generally basaltic in composition. Arundian-aged pyroclastics are known in north County Cork and an isolated occurrence of lavas and pyroclastics is known from the Brigantian of County Clare.

Silesian

During the Namurian, there was a major influx of moderately immature clastic sediment. The deeper Dinantian basins, for instance in the Shannon estuary region and in the eastern part of the Midlands, were filled by basinal black shale succeeded by sandy turbidites and deltaic cyclothemic shale, siltstone, sandstone and coal. In Counties Clare, Limerick and Kerry this sequence is related to the eastward progradation of deltas that must owe their origin to uplift in a source area to the west. Clastic facies also spread across shelf areas such as the Leinster Coalfield.

Only small remnants of the Westphalian are preserved. They are coal-bearing cyclothemic deposits, almost all of Westphalian "A" age. However the presence of a more complete succession extending into the late part of the Westphalian in the offshore Kish Bank Basin, just east of Dublin, suggests that a much thicker and more extensive cover of Westphalian rocks once covered Ireland and was removed by Permian - Tertiary erosion.

Hercynian structure and metamorphism

The structures shown in Figure 24 almost all owe their present form to late Carboniferous - Permian deformation. However, there is much evidence of tectonic activity during the late Devonian and Carboniferous. As noted above, faults apparently controlled the northern margin of the Munster Basin and in some areas produced scarps from which alluvial fans built out. There is clear evidence of differential subsidence during the early part of the Courceyan (up to the end of the *carina* Zone) but little suggestion (judging by the lack of evidence of local steep slopes) of surface expression of controlling faults. However, active faults of *anchoralis* Zone age which caused slumping and debris flows have been recognized at Tynagh (Moore, 1975), Silvermines (Taylor and Andrew, 1978) and elsewhere. Coller (1984) has argued that at Silvermines the faulting was related to dextral shear. Several faults that produced topographic effects on the sea floor and generated debris flows have been identified as having been active during the Chadian, Arundian and Asbian. Those at Navan which cut the Pale Beds and are truncated by the Arundian Upper Dark Limestone (Ashton et al., this vol.) are particularly clear examples. There is little doubt that most of the structures active during the Dinantian are controlled by reactivation of Caledonian or older faults in the basement.

Late Hercynian structures have been described in several recent publications (Naylor et al., 1983; Coller, 1984; Cooper et al., 1984; Sanderson, 1984). In the south (Fig. 24), large scale, mostly upright folds trend ENE and are accompanied by pervasive cleavage. There is considerable debate as to whether the deformation in the south is thin-skinned (Cooper et al., 1984) or thick-skinned; (see Sanderson, 1984, who has argued for thick-skinned deformation involving transpression with the development of dextral shear). This southern zone is cut by a conspicuous, E-trending fault system between Dingle Bay and Mallow, that locally involves southwardly dipping thrusts. On most structural maps this fault system has been extended eastwards to Dungarvan and has been labelled the Hercynian (or Variscan) "Front". It does not mark an abrupt change of tectonic style, but north of it the strain decreases and becomes more heterogenous, cleavage becomes less pervasive, and fold and fault trends become more varied. Coller (1984) has shown how the structural pattern in Central Ireland is strongly controlled by basement structures and is the result of a transpressional regime which led to the development of dextral, NE-trending brittle and ductile shear zones and NE-trending open folds. To the north and west of the Longford-Down Inlier, the structural style is one of tilted blocks bounded by NE-trending faults, many of which are clearly reactivated Caledonian structures.

Little has been published on the metamorphic grade of Late Palaeozoic rocks in Ireland. Studies in progress using determinations of vitrinite reflectance, the colour alteration of conodonts and spores, and the crystallinity of clay minerals allow some preliminary remarks to be made. To the north and west of the Longford-Down Inlier, variable, but generally low, levels of organic metamorphism are the norm. The conodont Colour Alteration Index (CAI) (Epstein et al., 1977) is generally 2-3 (60-200°C). Similar values are commonplace in the north Midlands, but from around the Slieve Aughty, Slieve Bernagh and Slieve Phelim inliers southwards, the CAI values are usually 4 or 5. Epstein et al. (1977) correlated CAI 5 with temperatures of more than 300°C and CAI 4 with 190°-300°C. Other evidence suggests that these temperature values are too high, but data from vitrinite reflectance confirm the anthracite grade of coals in the Leinster coalfields (Niall Haughey, pers. comm.) and support the suggestion that most of the south of Ireland has experienced temperatures in excess of 200°C.

Post-Hercynian

The record of onshore Permian and Mesozoic sedimentation is limited to the NE of the country and to small grabens at Kingscourt and Wexford. The late Cretaceous high stand of sea level may have flooded a much wider area. During the Tertiary, there was extensive eruption of flood basalts in the NE, followed by sedimentation in the non-marine basin around Lough Neagh. Intrusion of basic dykes occurred over a wide area of the northern part of the country. Elsewhere the Tertiary appears to have been a time of erosion and the only sedimentary deposits are in solution cavities. During the Quaternary, ice sheets covered Ireland and their sedimentary products now cover much of the country.

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Discussion

ADRIAN BOYCE (Scottish Universities Reactor Centre) made the following comments:

The authors suggest that the Silvermines Fault System (SFS) was a dextral transcurrent shear, and that the Zn+Pb+Ba deposits were formed in the coeval terminal dilation zone of this shear system. Their model is said to account for permissive intrusion of a basement granite (the "Nenagh Pluton") into the putative dilation zone, as indicated by a gravity anomaly in the region (relatively weak compared to other granites in Ireland).

A number of points need to be raised in criticism of this thesis. Virtually all of the evidence compatible with dextral motion is found in Lower Palaeozoic rocks, e.g. the apparent change in structural style across the Fault. As regards the Dinantian succession (including the Old Red Sandstone of the area), Rhoden (1958) found no evidence of transcurrent movement, although the fault pattern itself was comparable with a dextral shear system. More up-to-date evidence reveals very minor transcurrent movement in the area (of the order of metres rather than tens of metres). In stark contrast to this is the compelling and obvious data illustrating considerable normal motion of the fault system (Boyce et al., 1983). The thickening of Mid- to Upper-Courceyan sequences across the Fault, the need for rapid seafloor subsidence to achieve palaeo-ecologically necessary depths preceding and during the Waulsortian Mudbank development, and the spectacular syndepositional debris flow breccias, all testify to major extension.

Given that a granite was permitted to intrude in the Nenagh/Silvermines area, it is likely to be of Newer Granite age, viz. 400Ma. This would confine the period of transcurrent tension to sometime preceding this date, not to 40Ma later during the Dinantian mineralizing episode. The significance, therefore, of the suspected granite to terminal dilation of Dinantian age is negligible.

Since the evidence for dextral motion, and possible associated terminal dilation, rests almost exclusively on Caledonian phenomena, and since the Fault System posesses a typical Caledonoid strike, it seems reasonable to deduce that the SFS is Caledonian in origin. Many authors have made a similar deduction, and Max et al. (1983), in their regional interpretation of Irish magnetic anomaly patterns, stress the importance of the reactivation of Caledonian structures to faults in the cover rocks. The SFS shows no significant pattern of transpression or transtension during the Dinantian, akin to that illustrated for other demonstrably transcurrent regimes, e.g. the Najd Fault System of Saudi Arabia (Moore, 1979). The Lower Carboniferous stress field appears to have been dominantly extensional at Silvermines, with a minor accommodating dextral component, even away from the apparent terminal dilation zone, where strike-slip displacement should be more pronounced.

As to the Nenagh Pluton, the presence of isostatic-ally buoyant upper crustal granites in the crust has a profound effect upon the patterns of sedimentation. Bott (1967) and Bott et al. (1984) have convincingly linked areas of long-term, major attenuation (and even erosion) of Carboniferous sedimentary successions with the mainly buried, upper crustal granites of northern England. No such clear attenuation is noted around the Nenagh area; indeed, rather than reflecting underlying buoyancy, the sediments clearly reflect underlying subsidence (see above).

Furthermore, no direct evidence of such a granite exists in the rocks; for example, no granite dykes have been found. On the contrary, the available evidence points, if not to the total absence of the granite, then to its irrelevance to the Dinantian mineralizing episode. This is illustrated by Samson's (1983) and Samson and Russell's (1983) comprehensive fluid inclusion and stable isotope studies, which clearly refute the active presence of a granite at depth below the Silvermines deposits.

The question of the relation of transcurrent faulting and granite intrusion to Irish Dinantian mineralization is very important in terms of exploration. I would urge the authors, (a) to consider whether major extension rather than transcurrence controlled faulting during the Lower Carboniferous in Ireland (possibly by reactivation of Caledonian transcurrent fault systems), and (b) to re-evaluate their evidence for the "Nenagh Pluton" in terms of known Dinantian sedimentology and mineralization.

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REPLY:

Most of Dr. Boyce's critical contribution is based on a misunderstanding of the conclusions reached by Adrian Phillips, David Coller and colleagues from their work on the structural controls of mineralization in the Silvermines area. (Phillips et al., 1982; Coller, 1984; Coller et al., 1985). Our detailed underground and surface structural mapping at Silvermines, when correlated with the stratigraphic, ore texture and metal zonation data provided by Mr. S. Taylor of Mogul of Ireland Ltd., showed a coherent pattern. The pattern fits elegantly into a model of a dilation zone formed during mineralization at the eastern termination of the Silvermines Fault. Dextral shear along the main E-trending Fault at this time generated WNW dextral-normal faults in the dilation zone which acted as ore feeder structures; it also generated NE-trending folds which controlled the alignment and positions of Waulsortian mudbanks. We also consluded that the easterly trending dextral shear was a reactivation of a basement Caledonian fault (part of the Caledonian collision suture zone) but movement was obstructed by the presence of a Caledonian granitoid pluton emplaced on the basement fault system. The following evidence was used to support the presence of such a buried Caledonian pluton:

1. A major Bouguer gravity low to the east and NE of Silvermines which can be modelled as a granite at a depth of about 3km within the Lower Palaeozoic basement.

2. A pattern of strike swings of Caledonian cleavage in inliers adjacent to the anomaly, showing a tangential strike around the gravity low, and the development of a shelf facies in the Visean limestones in the area of the gravity low and of basinal facies away from it (Brück, 1982).

3. The correlation between the area of the gravity low and low values of strain in the limestone.

The last two factors suggest that the "Nenagh Pluton" acted as a positive rigid block during the Carboniferous, in the same way as the North Pennines block acted in northern England.

Dr. Boyce also expresses the widespread miscon-ception that normal faulting is incompatible with wrench faulting. Numerous studies have shown that apparent and true normal displacements are essential features of wrench faults with bends terminations or *en echelon* patterns. There is, indeed, clear evidence of normal, sinistral, dextral, oblique-slip and thrust faulting at Silvermines. The overall pattern can be explained in terms of an E-trending dextral shear during mineralization, followed by an E-trending dextral transpressive shear during later Hercynian deformation. We agree that there is no evidence for large transcurrent movement at Silvermines. The important point to stress is that the termination of even small transcurrent shear zones must generate dilatant structures which can act as channels for concentrating the escape of mineralizing fluids.

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