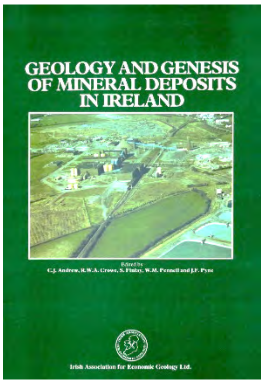

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To cite this article: Max, M.D. & Talbot, V. (1986) Molybdenum concentrations in the western end of the Galway Granite and their structural setting. *In:* Andrew, C.J., Crowe, R.W.A., Finlay, S., Pennell, W.M., and Pyne, J.F. '*Geology and Genesis of Mineral Deposits in Ireland*', Irish Association for Economic Geology, Dublin. 177-185. DOI:

To link to this article: https://

Molybdenum concentrations in the western end of the Galway Granite and their structural setting.

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Abstract

The c.400Ma Galway Granite is an E-W elongate, postkinematic pluton that is composed of a comagmatic series consisting of Carna, Errisbeg Townland, Murvey and Spiddal Granites, and some transitional varieties. The pluton is structurally complex in that the distinct varieties were intruded sequentially beginning with the Carna Granite and ending with the Murvey Granite, at least in the western end of the pluton.

Molybdenite and molybdenite-chalcopyrite concentrations have been investigated at Murvey and at Mace Head in the Carna Dome, at the western end of the Galway Granite. Molybdenite is largely structurally controlled along early quartz veins, but was probably an early segregation which would have pre-dated the hydrothermal activity seen throughout the Granite. Chalcopyrite is more widely disseminated in the host rock. ^{40}K radiometry at Mace Head showed that the sulphide concentrations and K-feldspar metasomatism were related, although not everywhere coincident, and almost certainly reflect a similar geochemical control.

Both the Murvey and Mace Head deposits are small, are exposed on the surface and die out rapidly downwards. They have the same vein-type of development even though they are developed both in the marginal, youngest granite type and in the oldest and most central granite types that are seen in the Carna Dome.

The Galway Granite appears to lie astride and near major structural discontinuities in the Connemara massif. Both its generation and emplacement as well as the apparent restriction of molybdenite concentrations to its western end may be due to movement along these major structures and the location of the different country-rock units.

Introduction

The Galway Granite is a composite, E-W elongate, granodiorite to leucogranite pluton that forms the northern margin to most of Galway Bay (Fig. 1) and occupies about 600km^2 along the southern side of the Connemara massif. The Granite was emplaced about 400Ma into high grade metamorphic (including Dalradian) and igneous rocks to the north, and into low grade metamorphic Lower Palaeozoic rocks to the south, in Lettermullan and Gorumna Islands and on the Skird Rocks (Leggo et al.,1966; Leggo and Pidgeon, 1970). Carboniferous rocks to the east and south mainly overlie the granite unconformably, but are locally in fault contact with it. Some work carried out through universities has been included during Geological Survey compilation and mapping between 1974 and 1976. Previous publications describe the emplacement of the western end of the Granite and details of the country rocks and the nearshore sea area (Max et al., 1975) and the Galway Granite as a whole (Max et al., 1978).

The granites are essentially comagmatic in that they comprise a semicontinuous igneous series which finally crystallized at approximately the same time (Fig. 2). Three main periods of magma injection involving the Carna (oldest), the Errisbeg Townland-Murvey series (youngest) and the Spiddal Granites have been recognized (Fig. 1). Whereas the main series between the Errisbeg Townland and Murvey Granites is continuous and probably results from fractionation (Leake, 1974), the types which may be transitional between the Errisbeg Townland and Carna, and the Errisbeg Townland and the Spiddal Granites appear to have been formed by reaction. All of the granites that have transitional contacts may also display locally sharp contacts suggesting continued movement within the pluton. No direct relations between the Carna and the Murvey Granites, or between the Spiddal and Carna or Murvey Granites were recognized. Dykes of Murvey Granite cut all the other Granites. In textural and petrological terms the Spiddal and Carna Granites are nearly identical granodiorites, but they are distinguished by their distinct ages of emplacement. The Errisbeg Townland Granites are most often foliated, and the Carna and Spiddal Granites have only a weak schistosity. The Murvey Granite is rarely foliated.

The structure of the granite batholith reflects the coalescing of discrete magma varieties (Fig. 3). There are two main granite domes, the Carna Dome and Galway-Kilkieran Dome, and a satellite, the Roundstone Dome. In addition the Spiddal Granite could be regarded as forming an internal "dome" and associated plugs. Only the Carna Dome is discussed here as the significant molybdenum occurrences are restricted to it. The Carna and Murvey Granites, along with a rim of Errisbeg Townland Granite, comprise the Carna Dome.

The Carna Granite is broadly divisible into K-feldspar-poor and K-feldspar-rich varieties. There is a range of composition and texture within the K-feldspathized Carna Granite (Fig. 2), and the ring structure suggested by Wright (1964) is often discontinuous and locally patchy. The K-feldspar-poor Carna Granite is generally a homogeneous, medium-grained, grey granodiorite with occasional plagioclase phenocrysts up to 2cm across. There are occasional

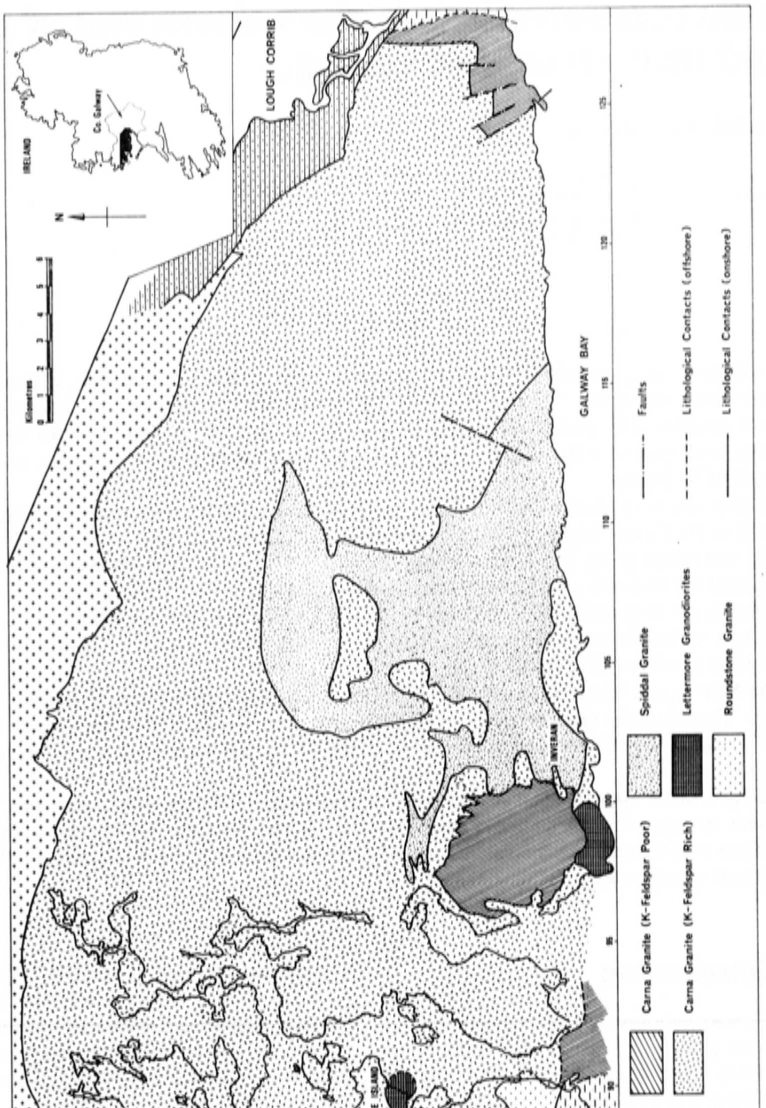

Figure 1. Map of Galway Granite after Max et al. (1978). Note restriction of the Mo occurrences to the far west.

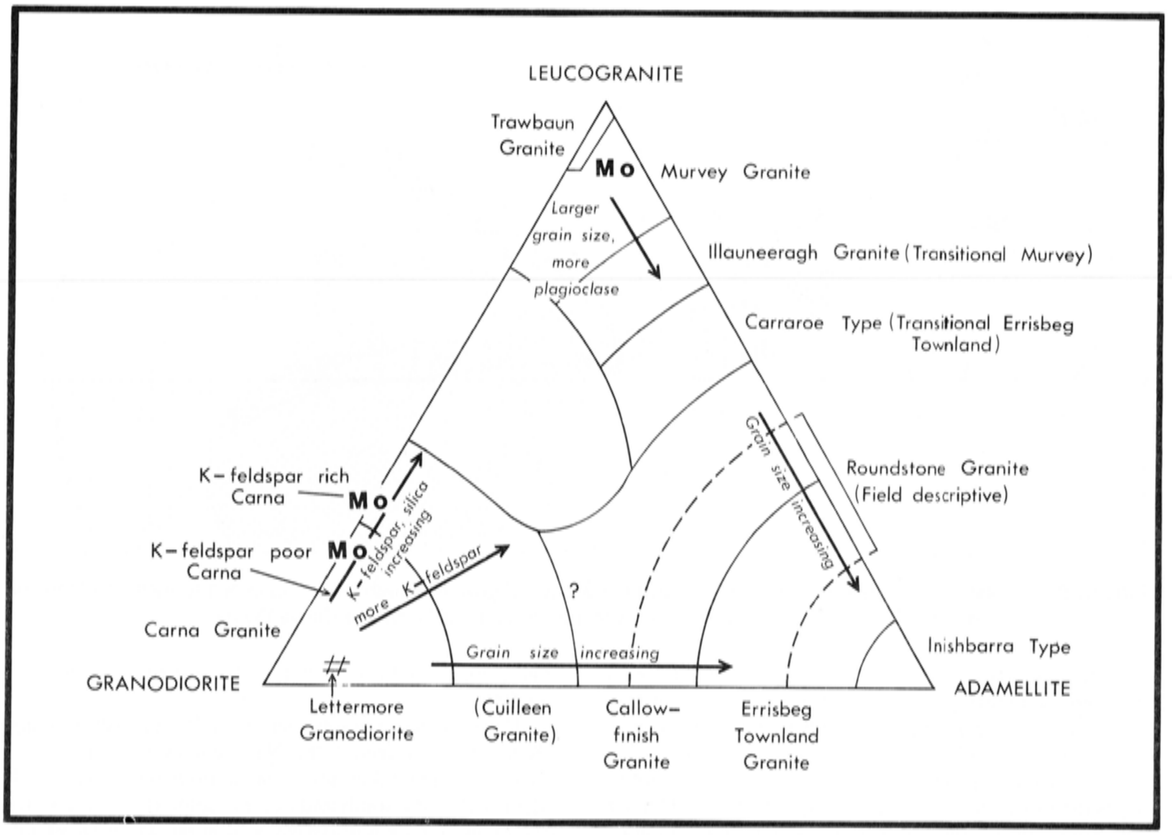

Figure 2. Diagram of Granite terminology. Note Mo occurrences are associated with both end-members of the finer grained varieties of granite.

megacrysts of K-feldspar. Northerly-striking, steeply-dipping biotite layering occurs intermittently throughout. Hornblende clots are sparse. The K-feldspar-rich Carna Granite groundmass is similar in appearance to the K-feldspar-poor type but is richer in K-feldspar, has a somewhat larger grain size and is generally pink. K-feldspar megacrysts are locally up to 2cm across and biotite and hornblende clots are more common. Usually contacts with the K-feldspar-poor type are gradational, but some are sharp. A molybdenite-rich zone occurs in both the K-feldspar-rich and K-feldspar-poor types towards the centre of the Dome.

The Murvey Granite is generally a fine-grained equigranular leucogranite (2-5mm) with only a few scattered megacrysts up to 10mm across. It is generally the most siliceous of the three main granite types and irregular zones are often pegmatitic or aplitic; xenoliths are rare. It exhibits bright pink weathering and is generally light red in colour with plagioclase not much in evidence. The more coarse-grained varieties (Fig. 2) are not seen in the Carna Dome. A molybdenite-rich zone occurs near the NW margin of the Dome (Figs. 1 and 3).

The Errisbeg Townland Granite is a coarse-grained two-feldspar adamellite which forms a rim to the Dome as well as the main body to the east. No molybdenite-rich zones have been recognized in this granite type to date.

Genesis of the Carna Dome

The more viscous Carna Granite appears to have formed first and could well have crystallized from the margins inwards, while the less viscous Errisbeg Townland Granite (Fig. 1) essentially crystallized from the interior towards the exterior by crystal settling. The Murvey Granite was probably derived from the Errisbeg Townland magma at a relatively late stage, and it appears to have chilled at the batholith margins more quickly than the older magmas.

Within the Carna Dome the relation between the K-feldspar-rich and K-feldspar-poor types is essentially injectional and metasomatic, and their distribution is circumcentric (Fig. 1). From the interior, near Mace Head, to the margin and contact with the Errisbeg Townland type, there is an alternation between K-feldspathized zones and the less altered, more grandioritic, K-feldspar-poor variety. However, the K-feldspar-poor zones nearest the margin often have relatively more K-feldspar than those near the central area of the Dome.

The alternating zones within the Carna Dome are, overall, gradational in K-feldspar and grain size toward the transitional contact with the Errisbeg Townland Granite rim. An intrusive mechanism that relates the presence of Errisbeg Townland magma on the rim of the Carna Dome to the zonal K-feldspathization of the Carna Granite seems likely. It could have been that as the first-formed Carna Granite began to settle and cool in the magma chamber, which had been marginally flooded with the younger Errisbeg Townland magma, "tensional" zones formed approximately parallel to the margins of the Carna Granite. These zones would have provided relatively low pressure areas into which fluids from the Errisbeg Townland magma would have percolated, forming the K-feldspathized zones (and some sulphide concentration). This would account not only for the arcuate structure, which represents a section through what were probably hemispherically shaped zones, but would also account for the general decrease of K-

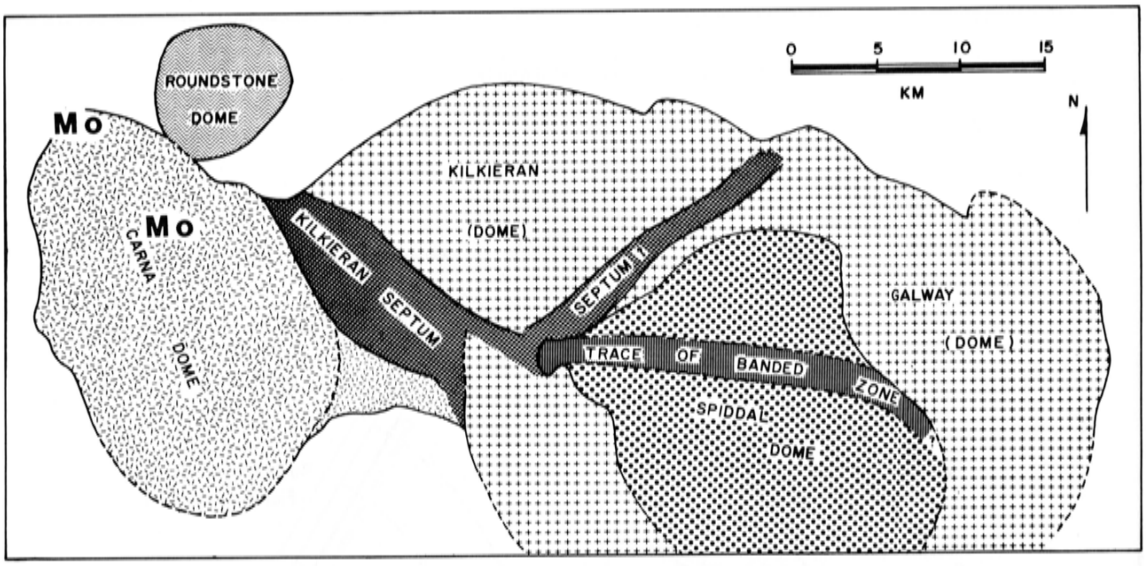

Figure 3. Structural diagram showing separate "domes" of granite which have coalesced to form the Galway Granite. Note Mo occurrences lie on the axis of elongation of the Carna Dome.

feldspar inwards away from the transitional contact with the rim of Errisbeg Townland Granite. An alternative mechanism for the development of the poorly defined zonal ring structure could be that such a low structural level is revealed within the Carna Dome that what is seen represents the root zone of a ring-dyke complex, which at higher structural levels would have had a more clearly defined expression. This would also be consistent with the cauldron subsidence model, as all of the sharper contacts observed dip towards the nearest margin of the granite.

The stoping and extensive crystallization history found in the older granites is not generally seen in the Murvey Granite, which has few xenoliths of country rock, and usually has sharp margins with the other granites, although there is often an increase in plagioclase near these contacts.

Late strain in the Granite

Sheet jointing commonly occurs throughout the granite, is generally low angle and undulating, and locally appears to have controlled the degree of blastesis.

Faulting in the area can generally be related to two major and several minor sets. There is an earlier, often curved, sometimes discontinuous, set of close-spaced faults which appears to be partially annealed by both matrix and megacrysts of the granites; this set probably represents late movement within the granite during the final stages of crystallization. These fault zones are mica-rich and it is likely that fluids migrated towards and along these zones as the granite cooled. Quartz veins with molybdenite films appear to have formed during this fault episode. The fault zones are often difficult to map on the ground but are prominent on the aerial photographs and generally trend within 30° of NE.

After the earliest faulting there followed a NW-trending set of faults which can be related in terms of orientation to other faults such as the Cleggan-Clifden-Murvey Fault in Western Connemara (Leake, 1974) and the Barna Faults in the eastern end (Coats and Wilson, 1971), which is probably the main southeastwards extension of the Oughterard Fault system. These faults are nearly vertical and have few secondary faults directly related to them; locally there appear to have been dextral movements in the order of 500m.

The youngest regional set of faults are SW-trending. Where these intersect the NW-trending set some strain was apparently taken up as the younger faults are usually deflected to the south and become somewhat less distinct. This can be seen particularly well in the Mace Head area where these faults usually have younger quartz veins developed in them. Younger faulting and jointing is common, but has not yet been related to a pluton-wide fault system.

Molybdenite occurrences

Two molybdenite occurrences have been studied in the Carna Dome. Although their host rock and structural position are quite different, the molybdenite (and associated chalcopyrite) appear to have been similarly emplaced.

Murvey

A concentration of molybdenite occurs near Murvey along the northwesternmost margin of the Galway Granite (Figs. 1 and 3). The area has a thin peat cover with little drift and there is abundant exposure. Two sets of joints are prominent, one lies about parallel to a NNW-trending porphyry dyke swarm, while the other is about parallel to the Granite margin. The molybdenite host rock is Murvey Granite. Occurrences of chalcopyrite have also been recorded but these are rare and are widely disseminated, in contrast to the molybdenite, which is concentrated.

The occurrence of molybdenite in this area appears to have been first recognised by Kinahan between 1871 and 1888 (Kinahan, 1889). A brief surface examination and the completion of 14 trial pits by Mr. A. Gassett in 1907 was not successful. In 1913, 22cwt (approx. 1 tonne) of ore of unknown grade was removed by G. G. Blackwell of Liverpool. H. J. Daly recommended in a 1917 report to the British Minister of Munitions that some expenditure in trial workings was justified as molybdenum had a strategic value during the First World War. During 1941-42 the Geological Survey of Ireland mapped the area in detail (25 inches to the mile), cleaned out the old workings and

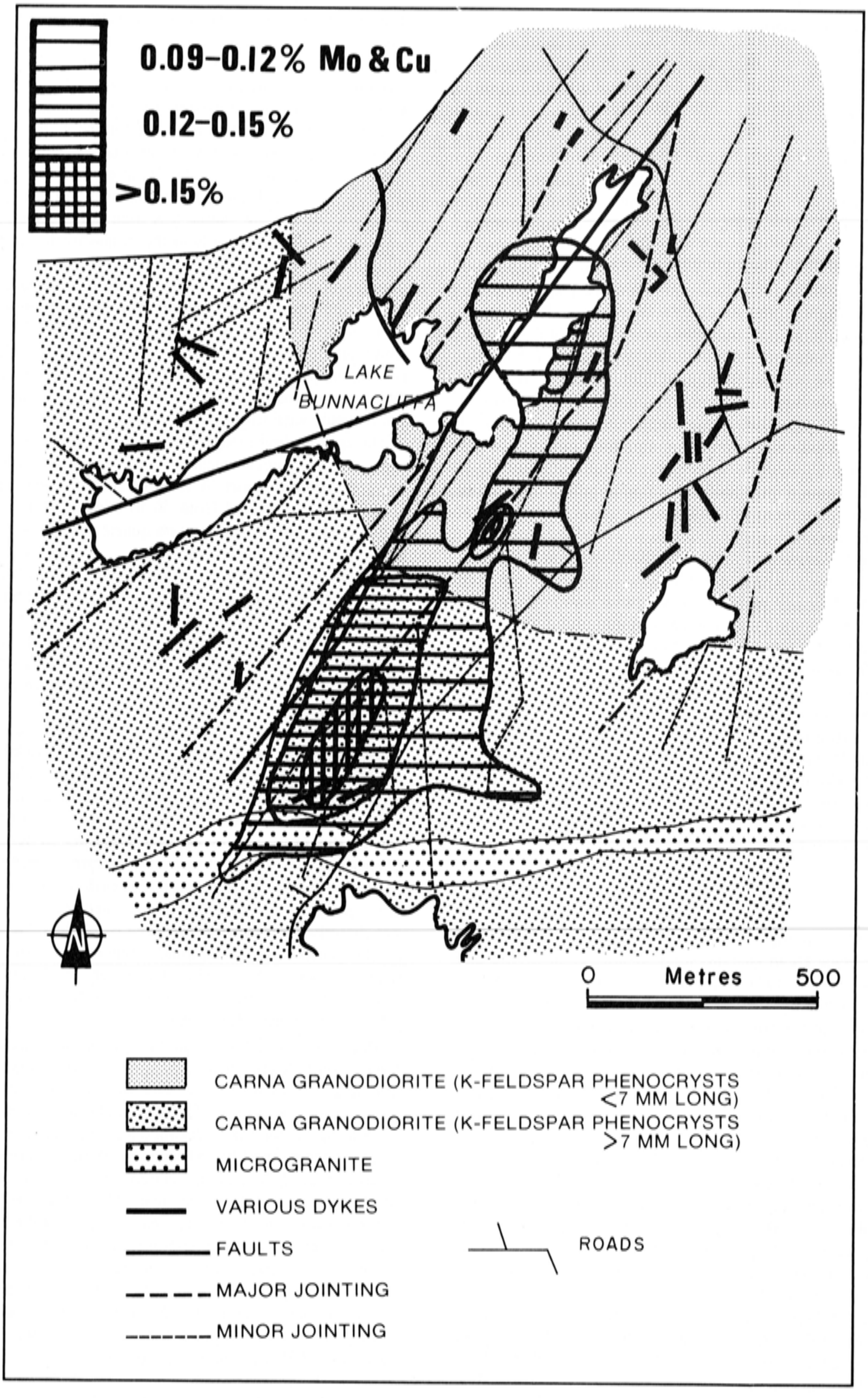

Figure 4. Detailed map of the Mace Head area with contoured total Cu-Mo values. Note extent of K-feldspar development.

considerably enlarged the principal working. As a result of this examination, the prospect was viewed as unfavourable for economic exploitation (Bishopp, 1943). A drilling programme in the mineralized area was carried out under the direction of M. V. O Brien and J. A. G. McCluskey (both of the Geological Survey) and consultant W. R. Jones in 1954 and 1955, and the prospects have been re-evaluated in recent years by exploration companies.

Molybdenite is common in a zone in the Granite about 530m long and parallel to the Granite margin. Scattered occurrences are present up to 500m further along the strike length of the deposit in each direction. Little or no molybdenite is found in the country rock schists, and none had been found more than 70m away from the contact. There is no continuity between these occurrences, which appear to follow sub-parallel fracture lines in the rim of the granite roughly parallel to the NNW trend of dykes and to some faulting and jointing. The molybdenite occurs in a vein quartz groundmass in the fractures, which are accompanied by a local (syn-mineralization?) alteration (kaolinization) of the granite to a yellow-green epidote-sausserite (Bishopp, 1943). This association of alteration in the granite and Cu-Mo mineralization is known to occur within the Galway Granite, but areas of kaolinization also occur without mineralization.

The deposit occupies a continuous area about 270m long by 16 to 65m, with one patch of virtually unmineralized granite. The mineralized zone is divided at the centre of its length by an 18m wide barren porphyry dyke which may post-date the mineralization. Vertical depth of mineralization in 24 boreholes varies from 2.5m to 18m. Molybdenum content is usually in the range 0.05% to 0.15% Mo. The occurrences of molybdenite die out downward and there is little indication of further molybdenite mineralization at depth. It has been calculated that there are 240 000t at 0.13% Mo in this small low grade deposit. More detailed reports and small scale maps of the Murvey deposit are housed in the Geological Survey of Ireland. Leake (1978) shows a good map of the area.

Mace Head

A NE-trending zone lying parallel to major faults (Fig. 4) at Mace Head contains molybdenite, chalcopyrite and pyrite (Talbot, 1973); the Mo is not directly related to the faults. While most of the chalcopyrite and pyrite traces are disseminated in the granodiorite, molybdenite is concentrated in the granodiorite in the vicinity of quartz veins where syn- to late-crystallization deformation is recorded by foliation and granulation of feldspars. The older quartz veins in these zones usually show deformation at their margins.

Molybdenite occurs as striated and unstriated smears on slickensides, as rosettes on partly recrystallized surfaces and on open joint planes. It is locally associated with pyrite and limonite at the margins of the older quartz veins. The occurrence of molybdenite is not directly related to the width of the older quartz veins, although most of the wider quartz veins are barren. Many of the older quartz veins associated with sulphides are cut and displaced by up to 3cm by joints which are commonly filled with sharply cross-cutting younger quartz veins. Molybdenite is absent from these younger quartz veins and associated younger mylonitic and brecciated zones, which are often annealed by the continued growth of silicate minerals. Late-stage K-feldspar metasomatism occurs in these zones as well as elsewhere in the granite and near the older vein sets.

It is likely that the segregation of MoS_2 from pyrite and chalcopyrite is due to its ability to sublimate at a much lower temperature than the melting point of other sulphides (Hollister, 1978; Westra and Keith, 1981). This would explain its migration and crystallization on the joint planes which developed along existing planes of weakness. Since none of the molybdenite is found within the younger quartz veins, it is likely that the hydrothermal activity continued after MoS_2 crystallization. The younger quartz veins are also associated with carbonates, fluorite and fine-grained muscovite/paragonite. Since less than 2.0% disseminated magnetite is present locally in the granodiorite, no strong magnetic anomalies occur. The interpretation of this phenomenon is that this area has been partly demagnetized by the introduction of sulphur-rich hydrothermal fluids of a reducing nature which, in the presence of sulphur, converted magnetite to pyrite; this replacement sequence is commonly seen in this section at Mace Head (Talbot, 1973). As a consequence, positive magnetic anomalies do not coincide with sulphide enrichment here.

The area around Lough Bunnacliffa was drilled as there were positive geochemical soil anomalies and observed outcrop mineralization. A total of 28 holes were drilled. Depth of holes varied from 30 to 80m and drilling was stopped when mineralization on quartz veins was not visually apparent for at least 4m.

The field and drill core evidence suggest that molybdenite enrichment post-dates the intrusion of microgranite and plagioclase porphyry dykes and pre-dates both the latest quartz veining and the youngest, but important, regional faulting. The mineralization dies out downwards and no deep trial hole was completed which might have proved a lower zone of sulphide mineralization.

A scintillation spectrometer with an appropriate filtering mechanism was used to detect potassium enrichment in the Mace Head area (Talbot and Max, 1984). The largest area of high scintillation counts corresponds to the K-feldspar enriched Carna Granite near the western boundary of the area, where copious amounts of K-feldspar phenocrysts often extend across the margins of quartz veins and aplite dykes. A small anomaly north of the lough may correspond to mapped K-feldspar enrichment, but does not directly corespond to the area of highest ^{40}K activity or the position of the sulphide deposit. Except for one slightly elongate 50cps closed contour, the microgranite dyke in the southern part of the area has values below 50cps (Talbot and Max, 1984).

Magnetics proved to be the best geophysical method for finding sulphides in the area (Talbot and Max, 1984) as the mineralized area was a magnetic low, but even so there is no absolute correlation. The survey showed the magnetic zone to be on the outer perimeter of the sulphide enrichment, and to be shallow. At Mace Head, potassium metasomatism, regarded as being related to a late fluid phase, is recognized in zones in the host granodiorite as well as along fracture and foliation zones. The central potassium alteration may also have been produced, however, by primary magmatic fluids. In this case mineralization may well also tend to occur at the migrating front of these magmatic fluids. The mineralization at Mace Head, however, is not coincident with the mapped boundary of the larger (metasomatic) K-feldspar megacrysts (Figs. 4 and 5), but where the zone of mineralization is coincident with the enriched K-feldspar the sulphide values appear to be enhanced.

Although molybdenite and chalcopyrite are often found in felsic muscovite-rich potassium-metasomatized granitoids (porphyries), they can also be found in more thoroughly

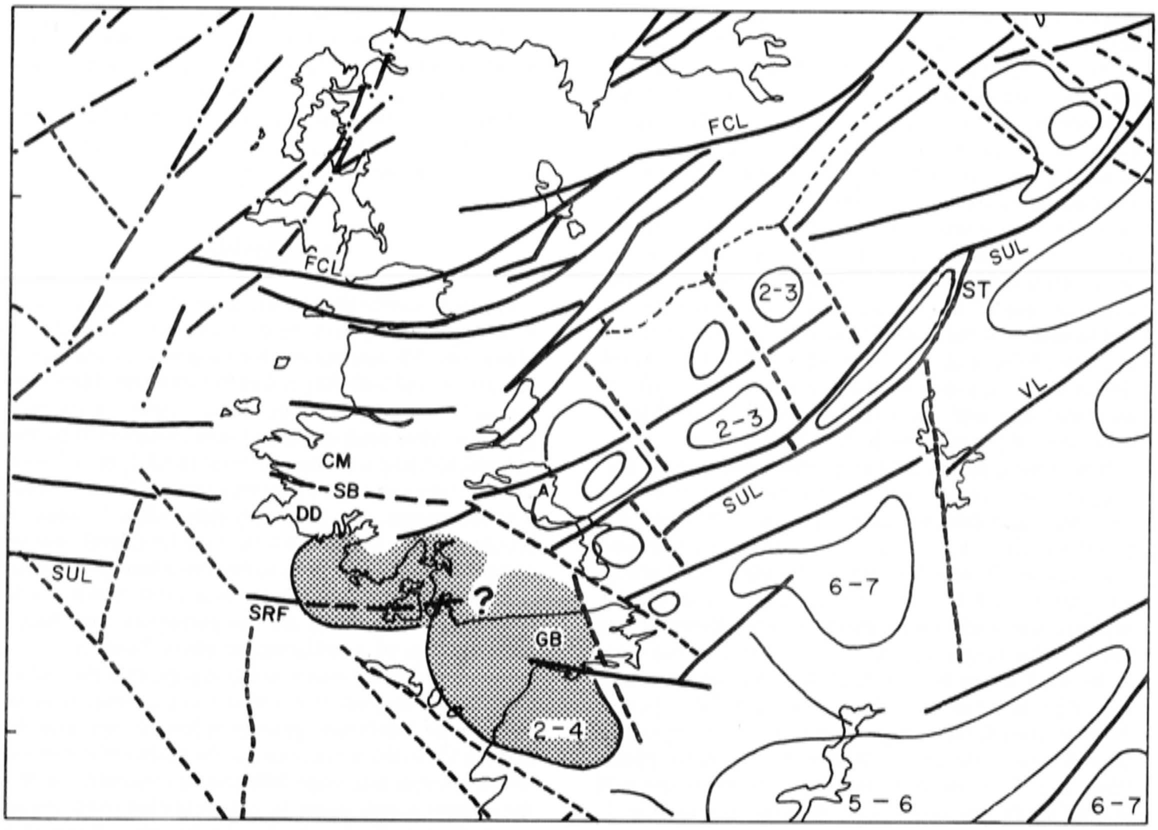

Figure 5. Regional magnetic structures in the west of Ireland. Solid lines, major linears; short dashed lines, transverse linears; dot-dash line, linears on faults reactivated during Mesozoic opening of the North Atlantic. CM, Connemara massif; FCL, Fair Head-Clew Bay line; GB, Galway Bay; GGF, Great Glen Fault; SB, Steep Belt; SRF, Skird Rocks Fault; ST, Strokestown; SUL, Southern Uplands Line; VL, Virginia Anomaly. Closed lines are magnetic bodies. Dashed line in Galway Granite shows probable eastwards extension of the Skird Rocks Fault after Max et al. (1975). The patterned area shows the exposed area of Galway Granite seen to the north of Galway Bay and its hidden southern continuation beneath Galway Bay and south of it.

crystalline and less altered granodiorites like that at Mace Head. ^{40}K enrichment and its consequent increased radioactivity, along with magnetics, could be used in the Carna Granite as a guide to identifying zones of the late stage alteration and, consequently, sulphide enrichment.

Other molybdenite occurrences in Connemara

Flakes of molybdenite have been observed in most of the granite bodies in Connemara as well as locally throughout the Galway Granite and in Dalradian rocks (Kinahan 1889). The main body of the Galway Granite, the Galway-Kilkieran Dome, has shows of sulphide mineralization, such as north of Rossaveel (Fig. 1) where molybdenite + galena + sphalerite occur in association with biotite bands in a dark facies of the Errisbeg Townland Granite.

Tectonic setting of the Galway Granite

It is likely that the concept of plate tectonics will be of value in mineral exploration by allowing more precise delineation of magmatic belts and tectonic settings which are favourable for particular types of mineralization and for specific paragenetic associations. The presence of certain mineral deposits and their known empirical relations with particular magmatic rock compositions in active plate margins has been used for many years as a guide to regional exploration. Applying the plate tectonic viewpoint in an annealed orogen such as the Caledonides, however, often causes confusion; this is partly due to the incomplete data base of plate tectonic parameters and the often speculative geological record. As all the major granites in Ireland in both the orthotectonic belts (Donegal and Galway Granites) and the Paratectonic belts (Leinster, Carlingford) were emplaced at about the same time from the same crustal source levels (O'Connor et al., 1982) and may have more chemical similarities than differences, reference to a plate tectonic model would involve the identification of a single zone of subduction and would necessarily place its one-time intersection with the earth's surface outside Ireland.

Although it is possible to relate the position of the major Irish granite batholiths to important structural and geophysical lines, structural elements within the Connemara massif do not exactly match geophysical elements. The well-defined Southern Uplands Line (Leggett et al., 1983), which coincides with a major magnetic linear, splays in the Strokestown area about 100km to the ENE of Connemara (Fig. 5) (Max et al., 1983). Two less well-defined linears then continue towards the southeastern side of the Connemara massif, one towards the Galway Granite, the other towards the eastern termination of the steep belt west of Lough Conn (A, Fig. 5) (Leake et al., 1981). Formation of the various structural elements in Connemara reflects a complex structural sequence: 1. Development of the steep belt occurred at or slightly after the c.500Ma peak of Grampian metamorphism. 2. Major thrusting of the Connemara Migmatites of the metamorphic massif over the rhyolitic volcanics and sediments in the Delaney Dome area (Fig. 5) immediately NW of Murvey during the Ordovician (?) (Leake et al., 1983). 3. The major faulting of the Ordovician South Connemara Group against the southern side of the metamorphic massif prior to the emplacement of the c.400Ma Galway Granite (Leggo et al., 1966; Max et al., 1975). It is likely that the splayed linears to the east of Connemara each mark the course of an active structural line with roots in the better defined major crustal boundary to the E of Strokestown.

How these structural lines have contributed to the generation and emplacement of the Galway Granite is uncertain, but both the Donegal Granite (Hutton, 1982) and the Leinster Granite (Cooper and Brück, 1983) were emplaced under the direct control of regional shearing. The Carlingford pluton in NE Ireland is elongate and lies near a major magnetic linear which is parallel to many faults which may have a shear component (Max et al., 1983). It therefore seems as if all the large Irish granites may be intimately related to shear belts as well as to faults and slides (Leake, 1978). Although the Galway Granite generally appears to be undeformed, there is a well defined east-trending planar fabric near its northern margin which becomes less well defined westwards, and rocks in the banded zone (Fig. 1) have extensively developed planar fabrics. Deformation in the subjacent country rocks could help to explain the long and complex sequence of injection.

The Galway Granite lies astride the Skird Rocks Fault (Fig. 5) separating metamorphic rocks of the Connemara Massif from Ordovician volcanics and sediments of the South Connemara Group to the south (Max and Ryan, 1975; Ryan et al., 1983). This Fault is probably a late expression of the westerly continuation of the Southern Uplands Line (Max et al., 1983) that is locally marked by major faulting in Britain and Ireland and may mark an annealed suture (Dewey, 1969). The Fault lies parallel to, and just south of, a major steeply dipping shear belt in the Connemara massif which is referred to as the "steep belt" (Leake et al., 1981), and is bounded by rocks of the Connemara Migmatite series and metasediments of uncertain affinity to the north in the Connemara massif, which are themselves allochthonous above the Mannin Thrust (Leake et al., 1983). Beneath the Mannin Thrust are rhyolitic volcanics and possibly volcanoclastic sediments; these are represented by the acid mylonites seen at the surface in a tectonic window in the area of the Delaney Dome (Leake et al., 1983). In 1983 a 230m drill core (which was terminated prior to reaching its target depth) was completed by the Geological Survey in an attempt to investigate below the mylonitic zone. In this, acid volcanics and sediments were found to contain pyrite and chalcopyrite which predate the mylonitization. As thrusting here preceded emplacement of the Galway Granite, greater account should be taken of the generation of the Galway Granite and its possible contamination by country rocks. The subjacent acid volcanics and low grade siliceous metasediments in the western end may have provided at least a local contaminant to the rising magma. The plane of the Mannin Thrust dips toward the Murvey and Mace Head areas, and may well once have underlain them, but the eastwards continuation of the subjacent overthrust volcanics and sediments is not known. Local contamination of the Galway Granite magma or of the late hydrothermal fluids within the granite by country rocks as well as a possibly heterogeneous, unseen lower crust may be in part the cause of restricted mineralization, but considerable geochemical work is necessary to investigate this possible relation.

Conclusions

The molybdenite concentrations at Murvey and at Mace Head appear to be associated with probably coeval faults of the same NE orientation; both deposits are exposed on the surface, and both die out rapidly with depth. Hydrothermal or late magmatic fluids in the vicinity of the faults appear to have been associated with alteration at Murvey and with K-feldspar blastesis at Mace Head. If both deposits formed at the same time, then the granite at Murvey, which is at the margin, was effectively fully "chilled" while the granite at Mace Head, at a lower structural level, was still somewhat ductile and open to extensive fluid percolation.

Although both deposits have been referred to as Cu-Mo porphyries, the granites are not porphyritic and there is no suggestion of a subjacent porphyry.There is also no evidence at present which would suggest that the Galway Granite was emplaced at a higher crustal level than any other of the Caledonian granites in Ireland. The late fluid and the Mo in the western end of the Galway Granite may not be a simple late-stage differentiate concentration from the original granite magmas; contamination of the magma or of the late fluids may be significantly influenced by country rocks.

The Galway Granite was emplaced during the late stages of major regional shearing in the earth's crust near the southern margin of the Dalradian miogeocline to the north of the Lower Palaeozoic Iapetus Ocean. The Galway Granite magma and the magmas of the other crustal Caledonian granites in Ireland appear to have many similarities, and it is possible that specific mineral deposits, by which these granites can be distinguished, are due to local tectonic controls as well as to the nature of the different country rocks.

Acknowledgements

Thanks to P. Ryan. Published with the permission of the Director of the Geological Survey of Ireland.

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