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TEXTURES AND GENESIS OF LEAD-ZINC ORES FROM NARLARLA WEST KIMBERLEY REGION, WESTERN AUSTRALIA

by

D.C. Gellatly

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SUMMARY

The origin of the lead-zinc ores of the Narlarla Mine, situated in a Devonian limestone reef complex in the West Kimberley Division, Western Australia, has been disputed. An early suggestion of a syngenetic origin has been superseded by theories of epigenetic mineralization, with the lead mineralization introduced in solution from a source either in the underlying Precambrian or from the nearby Jurassic(?) leucite lamproites. The macrosopic structures of the low-grade sulphide-dolomite ores, which include bedding, cross-bedding, graded-bedding, and flame structures, provide strong evidence for syngenetic sedimentary origin for the sulphides but do not preclude post-depositional movement of the ores. The massive sulphide ores exhibit well developed colloform textures. The Narlarla deposits are similar to other strata-bound lead-zinc deposits, especially to those of Pine Point and southeast Missouri. The ores and associated fine-grained dolomite appear to be foreign to their present environment of coarse-grained calcarenite. Emplacement by slumping or by mudflow intrusion from nearby in the Devonian rocks is suggested as a possible alternative to deposition of the sulphides <u>in situ</u>.

PREFACE

Because of loss of the original set of plates for this Record, delays have inevitably occurred in its production. The upsurge in exploration interest which it was intended to stimulate has already commenced, and about 150 mineral claims for lead and zinc were staked during 1971 over areas of Devonian rocks in the northern part of the Canning Basin.

It is now 7 years since mining operations ceased at Narlarla, and the excavated material from which the specimens described here were obtained has weathered rapidly. As a result of this, further specimens of the bedded dolomite-sphalerite ores are not now obtainable and the descriptions and plates contained in this record assume greater importance.

INTRODUCTION

The Narlarla lead-zinc deposits near Napier Downs in the West Kimberley Division of Western Australia have been known since 1901 (Woodward, 1907). Two orebodies, both discovered from surface outcrop, were situated in a Devonian limestone reef complex. Little is known about the smaller of the two, the No. 1 deposit, which consisted mainly of secondary lead and zinc minerals, and which was worked out before the area was geologically mapped. The No. 2 deposit has yielded about 11 000 tons of ore to date and has been largely worked out.

Specimens described in this report were collected at the suggestion of Dr J.A. McDonald, of CSIRO, in 1967 during a programme of regional mapping of the adjacent Precambrian rocks jointly by the Bureau of Mineral Resources and the Geological Survey of Western Australia. The object of this report is to document the small-scale sedimentary structures and microscopic textures of the ores, and to suggest a theory of deposition and emplacement which could assist appreciably in further prospecting. These notes are a contribution to a more comprehensive study of the Narlarla ores being carried out in conjunction with Dr McDonald.

PREVIOUS WORK

The deposits were examined briefly by Woodward (1907), Finucane & Jones (1939), and Prider (1941). They were drilled under option by The Zinc Corporation in 1952, but results did not prove extensions to the known mineralization and no development was undertaken. The near-surface ore was mined out in 1964-65 by Devonian Proprietary Limited, and operations then abandoned. All that remains is a narrow vertical shoot of ore at the southwestern end of the No. 2 orebody. The resulting open cut is now partly filled with water and no ore is visible <u>in situ</u>. During operations in 1964 the workings were visited by Halligan (1965), by Jeppe (map in Halligan, 1965), and by Hutton (1965), who carried out a detailed geochemical survey in the immediate vicinity of the orebodies.

The enclosing Devonian reef complex was mapped between 1948 and 1952 by Guppy and others (Guppy et al., 1958) and from 1956 to 1962 by Playford & Lowry (1966), and the adjacent underlying Precambrian in 1966-67 by Gellatly et al. (1968).

Finucane & Jones (1939), in view of the lack of post-Devonian igneous rocks in the area (the leucite lamproites were not then known), suggested that the ores were formed by deposition from waters of meteoric origin, but did not elaborate on this statement. Halligan (1965) and Playford & Lowry (1966) have interpreted Finucane & Jones' statement as a suggestion of a syngenetic origin, but this was not stated and probably not envisaged. Prider (1941), on the other hand, suggested a possible connexion between the sulphide mineralization and the leucite lamproite igneous activity of Mount North. Halligan (1965) has suggested that the sulphides have been derived from the Precambrian and have been redeposited by migrating groundwater.

PRESENT STUDY

The site of the No. 2 orebody is at present a water-filled open-cut and material <u>in situ</u> could be neither sampled nor observed. All the material described here was collected from the waste dump near the mine. As representative a collection as possible was made, but emphasis was placed on specimens containing appreciable amounts of both carbonates and sulphides, since it seemed likely that these would provide more information on the genesis of the ore than would specimens of the ore itself (almost entirely sulphides) or of the carbonates. The material collected has been examined in detail in hand specimen, thin section, polished section, and polished thin section. Thin sections were stained and then covered with a solution of alizarin red dye in $N/_{15}$ HCl. This enabled calcite (stained pink) and dolomite (unstained) to be reliably distinguished. Some of the minerals, particularly the sphalerite, and carbonates that have locally replaced the sulphides, are being analysed with an electron microprobe by Dr McDonald and results will be reported elsewhere.

GENERAL GEOLOGY

Field Occurrence

The Narlarla lead-zinc deposits are enclosed in a west-northwest trending Devonian limestone reef complex on the northern margin of the Canning Basin, close to the unconformable contact with the underlying Precambrian (Fig. 1). The reef complex in this area - the Napier Range - has been divided into reef facies (Windjana Limestone) back-reef facies (Pillara Limestone) and fore-reef and inter-reef facies (Napier Formation) (Playford & Lowry, 1966). The reef consists of massive algal limestone and dolomite; it is backed by well-bedded flat-lying or gently dipping biostromal limestone (back-reef), and fronted by steeply dipping well-bedded calcarenite and limestone breccia (fore-reef). The lead-zinc deposits occur in the fore-reef facies limestones that dip southwestwards and westwards at 20°-30°.

Although only minor developments of reef limestone are found in the Napier Range near Narlarla, the moderately steep depositional dips suggest that the reef probably lay immediately to the northeast, close to the present outcrops of fore-reef material. The back-reef facies is absent in the vicinity of the deposits.

The fore-reef limestones around the lead-zinc deposits consist of flaggy to blocky, thin to thick-bedded, buff to pale grey and interbedded red-brown, medium to coarse-grained calcarenite and calcirudite. This coarse-grained red-brown material contrasts strongly with the pale grey-green fine-grained dolomite with which the sulphides are associated. The calcarenite contains small specks of sphalerite, not only around the deposits but also as far away as Carpenter Gap, some 40 km to the southeast. Within the inter-reef facies near the deposits there are several small masses of reef limestone that have been interpreted by Guppy et al. (1958) as bioherms, and by Playford & Lowry (1966) as fallen blocks of reef limestone. Evaporites have been noted in the reef complex in Copley Valley to the southeast (Playford & Lowry 1966) but have not been found around Narlarla.

In the vicinity of the deposits there is an abrupt change in strike in the limestones forming a southwest-plunging antiform. Most of the dips in the fore-reef and inter-reef facies are thought to be depositional, and this structure is probably primary rather than tectonic. The main (No. 2) deposit lies close to the axis of this structure and the No. 1 deposit a short distance to the northwest (Fig. 2). It is considered that this structure may have contributed to localization of the ore deposits.

Several faults, most of them with an east-west trend, cut the Devonian limestones within less than a kilometre of the deposits. One northeast-trending fault passes close to the No. 2 deposit, and small east-west-trending faults were noted within it by Halligan (1965). The displacement of most of these faults is small and the nature of the displacement unknown. The largest fault in the vicinity cuts the reef complex about 600 m south of the mine and appears to have a dextral transcurrent displacement: this suggests post-Devonian reactivation of the Precambrian transcurrent fault system of the West Kimberley.

Petrography of the Limestones

Limestones from the fore-reef deposits of the Napier Formation in the vicinity of Narlarla are typically coarse-grained, fragmental, dolomite-free, biogenic calcarenite and pebbly calcirudite. They contain ooliths and ostracods and fragments of bryozoans, brachiopods, and of calcarenite up to 1 cm, in an inequigranular matrix of coarse-grained clear crystalline calcite, and up to 10% of sub-rounded detrital grains of quartz, plagioclase, K-feldspar, biotite, muscovite, and zircon, and rare opaques.

The dolomites are pale grey-green, and consist principally of small (0.04 mm) scattered rhombohedral dolomite grains forming about 80% to 85% of the rock and interstitial pale grey-green to brown clay minerals. Small scattered grains of quartz, plagioclase, K-feldspar, green and brown biotite, chlorite, galena, and sphalerite together constitute about 5% of the rock. No calcite was detected. The dolomitic rocks have been termed 'micrite' by Hutton (1965), but the usage is at variance with the original definition of the term.

There is a distinct difference in grainsize and texture between the limestone and dolomite. No replaced rock or fossil fragments have been found in the dolomite and there is a distinct difference in the quartz and feldspar grains present - those in the limestone being larger and more poorly sorted than those in the dolomite. This indicates that the dolomite formed as a primary rock, or else originated as a separate fine-grained carbonate rock that underwent diagenetic replacement, rather than as a replacement product of the calcarenite, which is coarse-grained.

Specimens containing 1.5 cm to 2 cm bands of fragmental limestone alternating with sinuous 2 mm bands of pale grey-green dolomite have been observed. A specimen of one of these has been examined in an attempt to determine the genetic relationships between the two rock types. The calcitic bands are coarse-grained and fragmental, and are essentially identical with the calcarenite described above. The thin dolomitic bands, however, are finer-grained, have smaller quartz grains, and carry a few small grains of galena and sphalerite - minerals which have not been recorded from the limestone. One example of a small tongue of fine-grained dolomite intruding a calcarenite layer has been noted, but the extent of the movement of dolomite implied by this is uncertain.

Other Base Metal Occurrences

Apart from the Narlarla deposits, no base-metal occurrences of sufficient size to warrant mining operations have been found in the Devonian rocks of the Kimberley area. However, numerous small occurrences have been found which indicate that the mineralization is not confined to the immediate vicinity of Narlarla, but occurs at least in minor amounts over a strike length of more than 200 km. All known base-metal occurrences in Devonian rocks of the West Kimberley region are listed in Table 1. In addition, minor showings of galena have been noted in a limestone reef complex of Devonian age in the Bonaparte Gulf Basin some 450 km to the northeast of Narlarla.

TABLE 1

MINERAL OCCURRENCES IN DEVONIAN ROCK OF THE WEST KIMBERLEY REGION

Minerals	Locality	Latitude/ Longitude	Reference
Sphalerite, galena, pyrite, marcasite, chalcopyrite, bornite, malachite, azurite, cerussite smithsonite, hydrozincite	Narlarla	17°16'S/ 124°43'E	Finucane & Jones (1939), Prider (1941): Halligan (1965), this work.
Galena (?), sphalerite(?)	Carpenter Gap	?	Finucane & Jones (1939).
Galena	"Near Pillara Spring"	?	Matheson & Guppy (1949).
Limonitic gossan	" "	?	Playford & Lowry (1966).
"Lead minerals"	Fossil Downs	?	Harms (1959).
Limonitic gossan (1% Zn)*	Oscar Range	17°54'S/ 125°16'E	Derrick & Gellatly (1971).
Galena	BMR No. 2 (Laurel Downs)	18°07'S/ 125°20'E	Henderson, Condon, & Bastian (1963).
Native copper	Bugle Gap	?	E.C. Druce (pers. comm.)

* Occurs in sandstone close to Devonian limestone. The age of the sandstone is uncertain.

THE NO. 2 OREBODY

The No. 2 orebody was an irregular lens slightly over 30 m long, about 20 m wide, and around 7 m thick on the average. The lower and upper contacts were apparently conformable, but the southern contact appears to have been discordant and partly fault-controlled. The immediately surrounding fore-reef limestone dips to south-southwest and west at 16° to 25°. The western end of the deposit coincides approximately with the position of the antiform axis mentioned above. A plan and sections of the deposit are shown in Figure 3.

The deposit consisted essentially of massive sulphide ore overlain by an oxidized zone consisting mainly of secondary lead and zinc minerals. The primary ore contains discrete 1 mm to 2 mm grains of galena set in a matrix of irregularly shaped, partly spheroidal grains of dark grey sub-metallic sphalerite. Small irregular druses, some filled with pale grey-green dolomite, are common and give the ore a cellular appearance. The sulphide content of this ore is generally around 80%. In addition there is a wide range of low-grade ores with a pale grey-green fine-grained dolomite gangue. The sulphides in these low-grade ores occur variously as thick irregular colloform bands (sphalerite and minor galena) (Figs 8a, 8b, 10a), as thin beds of fine-grained crystalline sphalerite (Figs 5a, 5b, 6a, 7a, 7b), and as disseminated grains of sphalerite and minor galena (Figs 6b, 5a, 5b, 6a, 7a). In almost all specimens where colloform and laminated sphalerite are present, the laminated sphalerite forms a border zone to the colloform zone and separates it from the dolomite (e.g. Fig. 10a). Examples of colloform sphalerite in direct contact with dolomite, however, are also found (e.g. Figs 4c, 8b). Evidence of slumping, brecciation, and development of flame structures are common. These macroscopic textural features are outlined below.

Since the specimens described were not observed in situ, the exact significance in terms of deposition and emplacement of the ore is necessarily uncertain and their interpretation subjective.

Primary Structures in the Ores

Most of the ore extracted was a massive sulphide ore consisting almost entirely of galena and sphalerite with little or no gangue. Macroscopically these are mainly structureless, but microscopically they show well developed spheroidal and colloform textures.

The low-grade ores, in which the sulphides are associated with a dolomite gangue, show a great variety of structures, many of them clearly sedimentary. These include bedding lamination (Figs 5, 6, 7, 8a, 10a), graded beddings (Figs 6a, 6b, 12, 13), small-scale cross-bedding (Figs 4b, 6a, 7a), and small-scale unconformities (5b, 7a). In addition, many compaction and deformation features are present, including flame structures (Figs 7b, 8b, 9b), fracturing, disruption of sphalerite laminae (e.g., Figs 5a, 6b, 9b), and irregular intrusion of laminated and colloform sulphides by dolomite and small scale intraformational recumbent folding (Figs 5a, 9b). Erosional truncation of laminated sphalerite-bearing dolomite is present in some specimens (Figs 5b, 7a).

Parallel laminations range from those that are asymmetrical (vertically) and consist of intimate mixtures of carbonate and sulphide grains and are obviously sedimentary, and possibly due to varying conditions of carbonate and sulphide precipitation, to those that consist entirely of colloform sulphides and show symmetrical development of alternating laminae, e.g. of pyrite and sphalerite, and are probably of colloidal origin. The sedimentary laminations mostly maintain their parallel structure upwards (apart from localized disturbances due to flame structure intrusions) whereas the parallel laminations of the colloform type generally pass upwards into lobate or spheroidal colloform nodules 0.5 to 1 cm across. Small, 1 mm spheroidal grains of grey sphalerite have been noted on the upper surface of some sulphide laminae.

Small-scale cross-bedding is outlined by laminations of sphalerite alternating with laminae of fine-grained dolomite. Individual cross-laminations are 2 to 3 mm thick and sets are up to 2 cm thick. Sets generally have a planar base and a planar erosional top. Foreset laminae are straight or gently concave.

Two types of compositional graded bedding are present. The first type is thought to be of the normal gravitational detrital variety and shows a slight concentration of heavy sulphide grains towards the base of 1 cm thick layers (Fig. 6b). The sulphide grains are mainly large (ca 0.5 cm) and include at least four different types occurring in intimate association, as well as scattered grains of galena. The second type consists of thin 1 to 3 mm graded laminae which commonly show the reverse relationship, i.e. they have a fine-grained dolomitic basal part grading upwards to a sphalerite-rich top (Figs 5b, 7b). Only two types of sphalerite are present; one consistently borders the other and locally increases in proportion towards the top of the layer (Figs 13a, b).

Macroscopic Replacement Textures

Evidence of minor replacement and recrystallization is apparent in hand specimen but is a comparatively insignificant feature in many specimens; e.g., trains of galena crystals up to 2 mm across are concentrated along certain bedding laminations in fine-grained sphalerite. The galena crystals are mostly elongate and have grown normal to the lamina and downwards into the underlying fine-grained sphalerite. Also, scattered galena crystals are apparent in some of the sedimentary layers where they appear to have developed through complete recrystallization of the layer. Small irregular patches of pyrite, mostly conforming to bedding, locally replace both carbonates and sulphides (Fig. 7a).

Thin transgressive veinlets of galena occur within the fine-grained laminated sphalerite but terminate at the boundary of the underlying and overlying dolomite, and have apparently been derived through redistribution of galena previously associated with the laminated sedimentary sphalerites. There is no evidence that such replacement has been affected by material brought into the rock.

Microscopic Textures

(a) Bedded sulphide-dolomite ores. Typical specimens of two distinct types of bedded dolomite-sphalerite from specimens 67.16.0406 (Fig. 5b) and 67.16.0431 (Fig. 6b) have been examined by means of thin sections, and typical specimens of massive granular and disseminated granular bedded sphalerite have been examined by polished sections from specimen 67.16.0434 (Fig. 10).

The bedded sphalerite in the lower part of 67.16.0406 (Fig. 5b) differs from that in the upper part. In the lower part, thin (1 to 2 mm) layers of sphalerite-rich material containing minor fine-grained dolomite and detrital quartz alternate with layers of micrite consisting of dolomite, quartz, and minor biotite and clay. The sphalerite layers show graded bedding: the upwards sequence (established from facings indicated by cross-laminations and by flame-structures) is from a sphalerite-poor base to a sphalerite-rich top (Fig. 12; 13a, b). In many of the sphalerite laminae the individual grains show bipartite zoning from a dark, apparently iron-rich core to a light coloured margin; this zoning gives the grains a 'frog-spawn' appearance (Fig. 13b, c, d). Locally these zoned grains are overgrown by narrow colloform bands (Fig. 13d). Most of the grains are irregular and subrounded, but well zoned euhedral grains are present locally.

In many of the laminae there is a tendency for the light-coloured outer layer of the sphalerite grains to become more abundant upwards and for these overgrowths to merge near the tops of the layers. Essentially only the two types of sphalerites are present in these thin graded layers and the light coloured variety is consistently an overgrowth on the dark. The consistency of the two sphalerite types and of their mutual relationships in these laminae suggests precipitation of the sphalerite in situ.

By contrast the upper part of specimen 67.16.0406 (Fig. 5b) and the non-colloform parts of 67.16.0431 (Fig. 6b) contain randomly mixed assemblages of several different types of sphalerite showing different types of zoning and indicating differing crystallization histories. Some of the more distinctive types of sphalerite present are as follows:

1. Unzoned small dark brown turbid grains showing radial growth lines.
2. Unzoned pale grey-brown mottled grains.
3. Small 'frog-spawn' grains with dark brown opaque centres, and a pale grey-brown or yellow-brown translucent outer zone.
4. Large 'frog-spawn' grains with a small pale grey-brown centre, broad dark brown opaque zone grading to an orange-brown outer margin, followed by a narrow pale grey-brown translucent outer zone. These differ from the normal frog-spawn grains mainly in size and in the presence of a translucent core.
5. Grains showing fourfold concentric zoning as follows: (a) turbid grey centre; (b) pale brown translucent zone; (c) sharply defined deep orange-brown translucent zone; and (d) pale grey-brown translucent border zone.
6. Grains showing zoning similar to 5 but without the translucent border zone, and some without grey centres.
7. Grains showing four-fold zoning as follows: (a) translucent pink centres with well developed crystal form; (b) translucent pale yellow zone grading out to an orange-brown zone which in turn grades into (c), a dark brown opaque zone, and (d) a narrow pale yellow-brown outer zone (Fig. 14a).
8. Spheroidal grains up to 1.5 mm showing both radial growth lines and concentric zoning (Fig. 14b) as follows: (a) dark brown translucent centre; (b) dark brown opaque zone; (c) deep yellow-brown translucent zone grading outwards to an opaque brown margin.

This assemblage of assorted types of sphalerite is associated with small scattered grains and cleavage flakes of galena. It is characteristic of parts of specimens shown in Figs 5b and 6b and is considered to be a detrital assemblage.

Thin layers of granular sphalerite from specimen 67.16.0434 (areas 1 and 4 of Fig. 10b) have been examined in reflected light. These granular layers occur both above and below the central colloform zone. The textures of the granular zones above and below are similar, but that above the colloform zone is much thinner and consists mainly of disseminated grains, whereas the lower layer is more massive (Fig. 16a, b).

In the lower (massive) granular zone (mg, Fig. 10) the individual layers range from 1 mm to 5 mm in thickness and are separated by thin laminae of carbonate and of pyrite. The sphalerite grains, which are about 0.1 mm across, coalesce and the interstices are occupied variously by carbonate, pyrite, or carbonaceous matter (Fig. 18a). The upper part of this granular zone contains small scattered grains of galena. These basal granular layers grade upwards into a layer showing regular colloform banding (rc, Fig. 10) and are separated from this colloform layer by only a thin selvedge (ca 1 mm) of fine-grained carbonate and pyrite.

The upper disseminated granular zone (dg) consists of scattered grains of sphalerite in a dolomite matrix. The sphalerite grains are surrounded by minute scattered granules of pyrite (Figs 16b, c), which also forms a thin discontinuous selvedge between the granular zone and the adjacent colloform zone and completely encloses sphalerite grains locally (Fig. 16c).

(b) Massive sulphide ores. These are more complex mineralogically and texturally than the sulphide-dolomite ores. They consist of approximately equal amounts of sphalerite and galena, and minor wurtzite, marcasite, carbonaceous material, chalcopyrite, chalcocite, covellite, and bornite. Analyses show a silver content of around 4 oz per ton (115 g/tonne), but no silver minerals have been identified so far. The textures are essentially botryoidal and spheroidal. Colloform banding is common.

Sphalerite, which is dark brown and opaque except in very thin sections, occurs almost entirely as botryoidal growths. Galena occurs largely in the interstices between the sphalerite structures, but also locally forms spheroidal and skeletal nuclei within them.

Wurtzite forms narrow, light brown bands within sphalerite and is identifiable only in polished thin section by its birefringence. Marcasite grows in interstices between sphalerite grains and commonly forms overgrowths on galena. Chalcopyrite locally forms nuclei within colloform sphalerite. Chalcocite and covellite, which are commonly intergrown and occur in close association with carbonaceous inclusions, form nuclei within colloform sphalerite and are also found as small inclusions surrounding galena nuclei. Bornite occurs as rare isolated grains at the interface between colloform sphalerite and the surrounding galena.

Unidentified carbonaceous material, which is abundant throughout the massive sulphide ores, occurs as small disseminated inclusions which generally show zonal arrangement and commonly occur in sphalerite immediately surrounding spheroidal cores of galena (e.g. Figs 19c, d). This material is soft and smears readily during polishing. A specimen of the massive sulphide ore has been examined by J. Saxby of CSIRO (pers. comm.) who was unable to isolate any carbonaceous material, and thus its identity must remain in doubt.

Two types of massive sulphide ore are present. The most common type contains approximately equal amounts of sphalerite and galena, together with minor amounts of copper minerals, and has irregular botryoidal texture and shows colloform banding. This type forms the central zone of specimen 67.16.0434 (Fig. 10). The other type occurs as 1 cm to 2 cm-thick regular bands of colloform sphalerite* with minor concentric bands and radial inclusions of galena (rc zones of Fig. 10) and generally separates the botryoidal ore from the enclosing granular sphalerite and dolomite.

The regular colloform (rc) layers of specimen 67.16.0434 show well developed concentric banding (Fig. 17 c, d) which is better developed in the right hand regular colloform layer (areas 3 and 4 of Fig. 10b) than the left. In the left layer regular banding is commonly imperceptible in polished section, but irregular developments of carbonaceous inclusions (Fig. 17b) and of fine sphalerite-carbonate intergrowths (Fig. 17) locally outline irregular ill defined banding. Both right and left colloform zones contain typical radial inclusions of galena (Figs 16d, 17) considered to be infillings of syneresis cracks. In these colloform zones galena and sphalerite occur also as discontinuous concentric bands, some of which are sharply truncated against bands of carbonate which has apparently replaced sphalerite (Fig. 17c) and galena (Fig. 18a, c). This carbonate is at least partly smithsonite (J.A. McDonald, pers. comm.). In the right colloform zone the concentric banding is outlined by well-defined bands of minute carbonaceous inclusions (Fig. 17c, d).

The central zone of specimen 67.16.0434 consists essentially of sphalerite, galena, marcasite, and carbonate, and exhibits irregular colloform, botryoidal, and spheroidal textures (Fig. 18c, d, Fig. 19a, b). The botryoidal masses consist mainly of sphalerite with spheroidal cores of galena surrounded by borders of ?carbonaceous inclusions. These galena spheroids have commonly coalesced to form irregular shapes. Unlike the regular colloform bands that border this zone the irregular colloform sphalerite has well developed pyramidal crystal terminations where it abuts on to interstitial carbonate. Evidence of brecciation of the botryoidal zone and infilling of the fractures by carbonate has been noted locally (Fig. 18b).

This botryoidal zone is similar in texture to the massive sulphide ore which made up most of the deposit. Some additional textural and mineralogical features have been noted from other specimens of the massive ore. The spheroidal cores of the botryoidal masses consist of varied assemblages of galena, sphalerite, and copper minerals listed below.

Through examination of thin polished sections of the massive sulphide ores it has been possible to gain a more complete knowledge of the mineral composition of the cores in relation to the colloform overgrowths (Figs 22, 23, 24). Whereas viewed in reflected light alone the composition of the cores and some of the concentric structure can be observed, by using both transmitted and reflected light on the one specimen the full sequence of concentric layers is apparent as is also the radial growth structure of both the spheroids and the regular colloform layers.

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* The term "schalenblende" has been used previously for zinc sulphides (sphalerite with or without wurtzite) showing textures of this type (e.g. Edwards 1954). The use of "sphalerite" and "wurtzite" (where applicable is preferred here to that of "schalenblende".

The spheroids and other botryoidal forms in the massive sulphide ore consist essentially of a core or nucleus of variable composition and an outer zone of colloform sphalerite and wurtzite. The following assemblages have been found forming the nuclei:

(1) galena, with or without abundant minute inclusions of sphalerite (e.g. Fig. 19c);

(2) sphalerite, with minor inclusions of disseminated galena and carbonaceous material (e.g. Fig. 22a);

(3) sphalerite and skeletal galena (e.g. Figs 20c, 24c);

(4) chalcopyrite, and minor sphalerite and carbonaceous inclusions (e.g. Fig. 24a);

(5) chalcopyrite and galena, with zones of carbonaceous inclusions (Fig. 19a);

(6) chalcocite and covellite, and minor disseminated galena, sphalerite, and carbonaceous inclusions (Fig. 23a);

(7) carbonaceous material and minor sphalerite and chalcocite (Fig. 22c).

The areas surrounding these nuclei consist almost entirely of sphalerite with carbonaceous inclusions, and wurtzite. The carbonaceous inclusions locally outline concentric banding (Fig. 19c), but in most examples concentric colloform banding is discernible only in polished thin sections through the variations in the texture of sphalerite and through the presence of thin wurtzite layers (Figs 22, 23, 24). Sphalerite forming part of the nuclei, or immediately surrounding the nuclei, is generally opaque, and is surrounded by a thin layer of pale brown translucent microcrystalline wurtzite. This in turn is surrounded by a sphalerite layer which has radiating crystal structure and well developed pyramid terminations. A further layer(s) of opaque sphalerite and of wurtzite are generally present before the interface with interstitial coarsely crystalline galena is reached. It is noteworthy that in each example studied the layer of radiating sphalerite occurs only as an overgrowth on a thin layer of wurtzite.

Etching of colloform sphalerite from Narlarla, in addition to the evidence from polished thin sections noted above, indicates that it consists of innumerable minute elongate radial crystals (Fig. 21d), a feature which has been considered by Roedder (1968) to indicate origin through direct crystallization from a supersaturated solution resulting in abundant crystal nucleation, rather than from crystallization of a sulphide gel. Other evidence relevant to this problem is provided by the lozenge-shaped inclusions of galena in sphalerite shown in Figs 17c, d. These are considered by Roedder to be indicative of differences in relative rates of crystallization between inclusion and host, and thus evidence for crystallization from solution.

COMPARISON WITH OTHER LEAD-ZINC DEPOSITS

The Narlarla lead-zinc deposits may be compared with certain other conformable deposits of these metals ('Mississippi Valley type deposits'), particularly with those of McArthur River (N.T., Australia), Pine Point (Canada), Tynagh (Ireland), and the Tri-state, Southeast Missouri, and Upper Mississippi Valley in central USA. All are associated with limestone-dolomite sequences, and in particular the Pine Point, Tynagh, and Southeast Missouri deposits are associated with limestone reefs, which appear to have influenced localization of the ores; in the other areas, however, the presence of faults appears to have been the dominant factor controlling the location of the ore deposits.

McArthur River

Stratiform zinc-lead ores of the H.Y.C. deposits in the McArthur River area have been described by Croxford (1968) and their stratigraphy and depositional environment have been described in detail by Brown (1969).

The McArthur River ores consist of extremely fine-grained laminated sphalerite and galena occurring in association with lenses of coarse breccia in a sequence of dolarenite, shale and potash-rich tuff. The lead-zinc deposits apparently formed in water over 60 m deep in a basin environment offshore from a series of barrier islands backed by lagoons and supratidal areas with evaporites.

There are close similarities in sedimentary structures, especially bedding laminations and graded-bedding, between the Narlarla ores and those of McArthur River, which are stratiform and considered to be of sedimentary origin. Slump breccias in the McArthur River Deposits contain clasts more angular than those in the Narlarla ores, which appear to have undergone movement in a plastic state, but elsewhere in the Napier Range angular blocks of reef limestone have fallen into fore-reef deposits.

If the line of barrier islands postulated by Brown (1969) for the McArthur River area can be considered to have formed a barrier similar to that of the limestone reefs in the Narlarla area, then deposits of the base-metal sulphides in the Kimberley region would be expected in the basin facies, or near the outer margin of the fore-reef facies rather than in the part close to the reef.

Pine Point

The lead-zinc deposits of Pine Point (Campbell, 1966) occur within dolomitic limestone reefs. The distribution of reefs and of mineralized rocks in general follows the trend of a major fault of Precambrian age, but both reefs, fold axes, and orebodies are oblique to the fault.

Textures in the ores (Roedder, 1968) are similar to those of Narlarla. They are partly colloform, with finely banded concentrically zoned sphalerite surrounded and locally replaced by coarsely crystalline galena. Pyrobitumen in the ores is considered to have assisted precipitation of the metals from ore-bearing fluids, but the source of these is uncertain.

Tynagh

At Tynagh (Derry et al., 1965) the lead-zinc ores occur in reef-facies limestone where it interfingers with muddy limestone. A volcanic ash bed occurs in the muddy limestone at approximately the same horizon as the reef. The primary sulphides, like those of Narlarla and Pine Point, have colloform banded and concentric structures, and are associated with masses and veins of coarser sulphides.

Southeast Missouri

A close similarity appears to have existed between the depositional environment of Narlarla deposits and those of the southeast Missouri lead-zinc district in that the limestones of both areas are characterized by the presence of reef, fore-reef and back-reef facies.

In the Southeast Missouri district (Snyder & Gerdemann 1968) bar-reef structures with a trend normal to the shoreline were major sites for ore deposition. Mineralization is also found where sands and conglomerates pinch out over buried granite domes. The bar reefs are reported as up to 15000 ft long and 1000 ft broad, and exhibit 'arch' structures due to interfingering of carbonate sand with grey shaley carbonates. Mineralization occurs at major bedding plane contacts. Over the crests of the bars the lower parts of the reefs are mineralized, and along the flanks of the reefs mineralization occurs in breccias at horizons of major contacts.

Tri-state and Upper Mississippi Valley

There are also similarities between Narlarla and the 'Tri-state' (Brockie et al. 1968) and Upper Mississippi Valley (Heyl, 1968) types of mineralization, though the similarities are not as pronounced as with Southeast Missouri and Pine Point.

The Tri-state and Upper Mississippi Valley deposits occur in limestone-dolomite-shale-sandstone-chert sequences but in both areas limestone reefs are absent. In both areas the orebodies are found in dolomite. In the Tri-state ores the mineralized dolomite is jasper-bearing and mineralization is absent where the dolomite is associated with shale, whereas in the Upper Mississippi Valley the ores are associated with dolomites with thin shale partings and are generally capped by thick impermeable shale. The ores occur in large flat-lying breccia zones (Tri-state) and in fault and joint fractures, irregular breccia fillings and bedded replacements of wall rocks (Mississippi Valley).

In both these districts the mineralization is considered to be epigenetic and to post-date deposition of the host rocks.

Red Sea

Muds rich in Cu, Zn, Pb, and Fe and associated with very saline hot brines have recently been discovered at the bottom of the Red Sea (Degens & Ross, 1969). The metals are being precipitated from the brines, which are thought to have originated through leaching of evaporites in on-shore areas by meteoric waters with possible additions of sulphur and metal-bearing solutions from volcanic sources on the sea floor. This provides a possible model for the formation of syngenetic sedimentary ore deposits. Although the sulphur in the main brine pool of the Red Sea - the Atlantis II Deep - is considered on isotopic evidence to be of volcanic origin the proportions and concentrations of dissolved metals in the brines are similar to those of salt dome brines in non-volcanic areas (Craig, 1969) and thus volcanicity is not a necessary factor in the formation of metal-rich brines or of syngenetic sedimentary metal deposits which may have formed from them.

There are some similarities between the Red Sea deposits and those of Narlarla which are worthy of comment. The principal similarity in environment is the presence in both areas of evaporites. In the Kimberley region evaporites are not extensive but may have been more extensive in coastal deposits now removed by erosion.

The Red Sea sediments consist partly of gels. This could have a parallel in the probable colloidal origin of the colloform ores of Narlarla.

The 'frog-spawn' sphalerite grains with dark iron-rich centres apparently have similarities with the marmatite (ZnFeS) grains from the Red Sea muds which have a high iron content in their cores (up to 27%) and a lower iron content in crystal margins (Stevens & Wittkopp, 1969).

DISCUSSION

Age and Isotopic Ratios

Isotopic ratios for a specimen of galena from Narlarla have been determined by Farquhar (Russell & Allan, 1957). The values obtained are as follows: Pb^{206}/Pb^{204} = 20.06, Pb^{207}/Pb^{204} = 16.30, Pb^{208}/Pb^{204} = 41.82. These values are anomalous in that they lie appreciably above the lead growth curve, whereas Stanton and Russell (1959) have shown that leads from conformable (as opposed to vein type) deposits generally lie on or very close to the growth-curve.

On the basis of a comment on these results by Farquhar that the sample was enriched by lead extracted from granitic basement rocks, Halligan (1965) has suggested derivation from pre-existing mineralization in the Lamboo Complex, and that the remobilization was probably due to migrating groundwater.

Determinative methods, however, have improved considerably since these isotopic determinations were carried out, and nothing is known as yet about the isotopic composition of leads from the Lamboo Complex itself. In view of these factors the suggestion of derivation of lead from the Precambrian must be regarded as unsubstantiated. Also this possible source has no bearing on the time or method of concentration, deposition, and emplacement, which are considered here to be more important aspects of the genesis of the deposits.

Significance of Small-scale Structures

Separate modes of origin are envisaged for the two types of compositional graded-bedding between sulphide and carbonate components of these rocks.

In the first type the sulphides are associated locally with dolomitic pebble conglomerate and appear to have been transported as detrital grains. Sphalerite grains show variable graining and constitute an assemblage in which individual grains have had different crystallization histories. Because of their greater density the sulphides have been concentrated preferentially in the basal part of the layer, which has a sharp lower bounding surface, and which grades upwards into a more carbonate-rich part.

In the second type, the thin graded laminae with sphalerite-rich upper parts, only two types of sphalerite are present and there is no irregular mixing of these that might suggest detrital deposition. Wherever possible this type of graded-bedding has been examined in relation to other indicators of upward sequence, such as grainsize variations within the carbonate and sulphide phases separately, truncated cross-laminations, scour-and-fill structures, and flame structures. In most examples the sphalerite is concentrated mainly in the upper part of the layer. The gradation results at least partly from an increase in the relative development and local coalescence of the outer (lighter coloured) parts of the 'frog-spawn' type sphalerite grains. This suggests that the grading is due to variations in conditions of deposition <u>in situ</u>, and it is envisaged that these sphalerite-rich laminae have been deposited either at or very close to the sediment-water interface.

Development of flame structures, i.e. fracturing and intrusion of sulphide layers by fine-grained dolomite, must have taken place shortly after deposition while the sediment still contained sufficient pore space water to flow readily. Thus the intruded material, which includes both bedded and massive colloform textured ore, must be either syngenetic, or at the latest, diagenetic.

Similarly the evidence of erosional truncation of laminated sphalerite-bearing dolomitic micrite infers deposition of sphalerite in the sediment prior to erosion and deposition of the overlying sediment.

Evidence of graded-bedding and cross-bedding involving the sulphide and the mixed sphalerite assemblages of such specimens indicates that much of the sulphide was precipitated either during or before sedimentation and these grains are clearly syngenetic relative to the enclosing dolomite. It is possible that this applies to all the sulphides in the deposit (although there may have been some deposition within the topmost few centimetres of sediment and minor subsequent solution and redeposition to give sulphide veinlets (e.g. 67-12-13)).

Despite the evidence for syngenetic and possibly diagenetic deposition of the sulphides, the ores and their associated dolomite constitute a <u>non-stratiform</u> (see Fig. 3) (but <u>strata-bound</u>) deposit and it is difficult to explain their presence within the fore-reef environment with its steep depositional dips.

The sulphides and associated dolomite were presumably deposited in a reducing environment, but the red-brown colour of much of the bedded inter-reef calcarenite suggest oxidizing conditions. Thus the environment of deposition of the sulphides and the associated dolomite differ from that of the enclosing calcarenite, and suggests that the dolomite and sulphides forming the orebodies were probably not deposited in their present position.

<u>Deposition</u>

The sulphides considered to have been deposited on, or very close to, the sea floor through chemical precipitation as sulphide-rich muds similar to those forming at the present day in the Red Sea. Evidence for deposition of this type is strongest for the discrete grains of sphalerite forming the stratified sphalerite/dolomite ores. The mixed sphalerite assemblages found in parts of these rocks indicates penecontemporaneous deposition and erosion and redeposition of the sulphides. The fact that these sphalerites are discrete crystals rather than colloform masses has a parallel in the formation of sphalerite crystals rather than gels in the recent sediments of the Red Sea (Stevens & Witko, 1969).

The deposition of sulphides either as crystals or as gels within the top few centimetres of the sedimentary sequence rather than at the sediment-water interface is considered to be a possible mode of origin, specially for the colloform material, which because of mutually opposing senses of depositional growth (Fig. 10) cannot have formed on the sea floor.

Deposition of base metal sulphides within the topmost layers of the sediment through migration of metal and sulphide ions through unconsolidated fine-grained quartz, dolomite, limestone, andesitic tuff, and carbonaceous and iron-rich shale has recently been demonstrated experimentally by Lambert & Bubela (1970). The sulphides formed thin monomineralic layers and in certain of the experiments spheroids of galena were produced which simulate closely those found in the irregular colloform zone of specimen 67.16.0434 (Fig. 10) from Narlarla. Similar experiments by Temple & Le Roux (1964), which resulted in migration of sulphide and metal ions into an agar gel where sulphides were formed, possibly provide an even closer parallel to the conditions necessary for the production of continuous regular colloform layers.

Roedder (1968) has recently questioned the colloidal origin of colloform textures on the ground that colloform-banded masses consist of innumerable minute elongate crystals which have grown normal to the banding, and suggested that colloform banding has resulted from abundant crystal nucleation from supersaturated solution. Evidence from the Narlarla ores confirm Roedder's observations that colloform sphalerite consists of minute radiating crystals. The interpretation suggested by Roedder, however, does not apparently take into account the fact that most sulphides are precipitated initially as gels and develop crystal structure later; and also cannot account satisfactorily for the two types of sphalerite - granular and colloform - found at Narlarla.

The opposing directions of growth of the regular colloform bands (e.g. Fig. 10) and the differences in texture between the two bands apparently preclude formation of them both by deposition on the sea floor and by deposition from metal-bearing solutions migrating laterally within permeable beds. Downwards diffusion of metal-bearing solutions into a gelatinous hydrocarbon and sulphur-rich hydroxide mud, however, could provide a satisfactory depositional model.

Source of Metals

The source of metals in the Narlarla deposits is unknown, but the anomalous lead isotope ratios are apparently consistent with derivation from the Precambrian of the region either through weathering or by circulation of meteoric groundwater. Evidence for volcanic activity in the Devonian is confined to two rather doubtful age determinations (Bennett & Gellatly, 1970), and volcanicity probably played no direct part in derivation of the metals.

The metals may have been concentrated mainly through formation and leaching of evaporite deposits in shallow-water back-reef areas, but possibly also in the soft parts of marine organisms, some of which at the present day are very effective accumulators of base metals, especially of zinc (Boyle & Lynch, 1968).

Emplacement

The sulphides and the associated fine-grained dolomites are essentially foreign to their present environment in coarse-grained red-bed calcarenite (although thin partings of sulphide-free dolomite are known from within the sequence). In addition the orebody cuts across the bedding of the enclosing limestone. Halligan (1965) has suggested localization and control by faulting, but neither direct block faulting of the orebody into place nor control of ore-bearing solutions by faults can explain adequately the irregular shape of the orebody (including its thin underground extensions), the sedimentary structures observed within the ore, and the evidence of disruption of sedimentary banding by intrusion of fine-grained dolomite.

It is unlikely that highly oxidizing (red-bed) and highly reducing (sulphide-depositing) conditions coexisted side by side in the fore-reef deposits. Thus, as an alternative to deposition of these in situ, it is suggested that the sulphides could have been emplaced into the fore-reef beds after deposition.

It appears that the sulphides and associated dolomite are intimately related and, if emplaced, must have been emplaced together. The orebody could have been emplaced either through slumping, or through intrusion of a mass of sulphide-rich carbonate mud. Direct evidence is lacking, since no sulphides are now exposed. However, the narrow tail of sulphides extending downwards from the orebody (Fig. 3) suggests that emplacement by upward intrusion of a mixed sulphide carbonate mud would agree with the evidence available. Such a mechanism of emplacement would be similar to that of the present-day mud-lumps of the Mississippi Delta (Fisk, 1961) and also similar to the intrusive lenses of calcareous sandy mud in the Lower Limestone and the Radar Member of the Permian Reef Complex of the Guadaloupe Mountains, U.S.A. (Newell et al., 1953). If such intrusion of mineralized dolerite has taken place at Narlarla, it could have been derived from underlying sulphide-bearing back-reef beds. The amount of movement need not have been great.

CONCLUSIONS

Two distinct types of lead-zinc ores are found at Narlarla, both of which show banding. These may be referred to as bedded granular and colloform ores. The granular material consists of individual crystals which have locally coalesced during growth to form monomineralic bands, whereas the gross structure of the colloform material is typical of 'schalenblende' from many localities (e.g. Roedder, 1968; Edwards, 1954), but it mostly lacks fine laminations, e.g. such as those from Pine Point and Aachen-Moresnet. Layers of granular sphalerite have undergone intraformational erosion. Both granular and colloform layers have suffered brittle fracture and have been intruded by 'flame-structures' of unconsolidated sediment, indicating that deposition of the sulphides antedated consolidation of the host dolomite. In addition, the colloform material has locally been deformed plastically, a feature which suggests that it was deposited as a gel and that the earliest post-depositional movements took place before the gel crystallized. Most of the movement however took place after consolidation of the colloform sulphide material but before consolidation of the dolomite.

Most of the sulphide was probably deposited in a reducing environment on the sea floor, either at or immediately below the sediment water interface. Since sedimentary reworking of the granular sulphide but not of the colloform sulphide, has been noted the granular sulphide was probably deposited at the sediment/water interface, and the colloform material as a colloid within the sediment, possibly within pre-existing gels such as form the present-day muds of the Atlantis II Deep of the Red Sea.

This concept of deposition both on the sea floor and within the topmost layers of sediment is in agreement with experimental evidence and is similar to that suggested by Freidrich (1964), who suggests all transitions between epigenetic and syngenetic sedimentary deposits through formation of epigenetic deposits in rocks of the ocean floor and escape of some solution upwards into the ocean to be precipitated to form syngenetic deposits. The concept put forward here for the Narlarla deposits differs slightly from this in that it envisages syngenetic and diagenetic (rather than epigenetic) deposition with metals deposited within the sediment being deposited as a result of downward rather than upward movement of the metal ions.

The oxidizing environment of the fore-feef facies of the limestone reef complex with its steep depositional dips in an unusual setting for such a deposit. It could have formed in situ as an isolated pocket, but it seems more likely, in view of the obvious preconsolidational deformation of the ore, that it could have been emplaced either through gravitational sliding or slumping, or alternatively could have been squeezed in as a mud-flow intrusion from below.

In their lithological setting - associated with dolomitic mud in a limestone reef complex - the Narlarla lead-zinc ores show similarities with those from many other areas which are major producers of these metals. In view of these similarities, and the widespread occurrence of minor base-metal occurrences in the area, recognition of the essentially syngenetic nature of the ores indicates that the Devonian rocks of this region are prospective for further base-metal discoveries and warrant systematic exploration.

ACKNOWLEDGEMENTS

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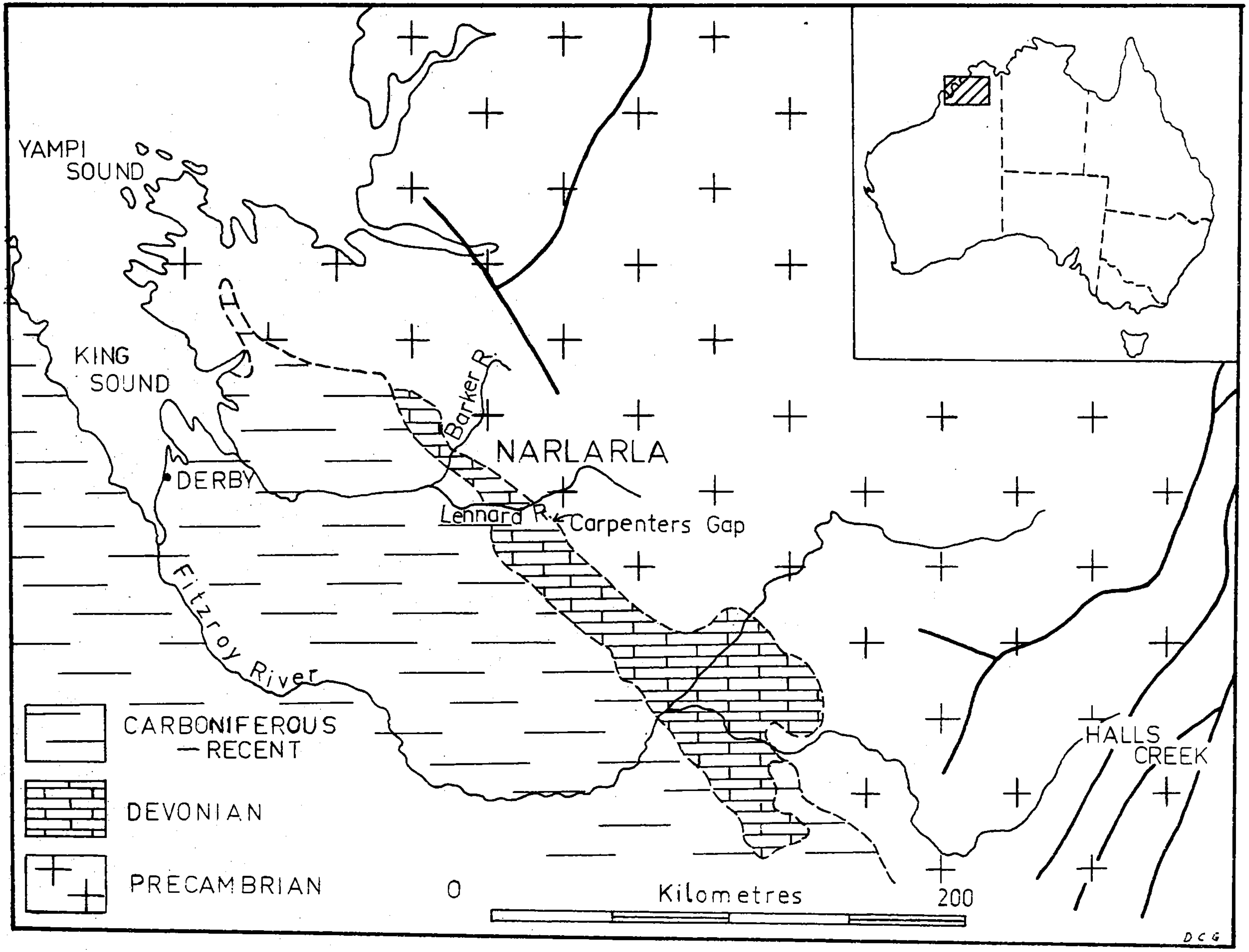

Fig.1. Locality Map.

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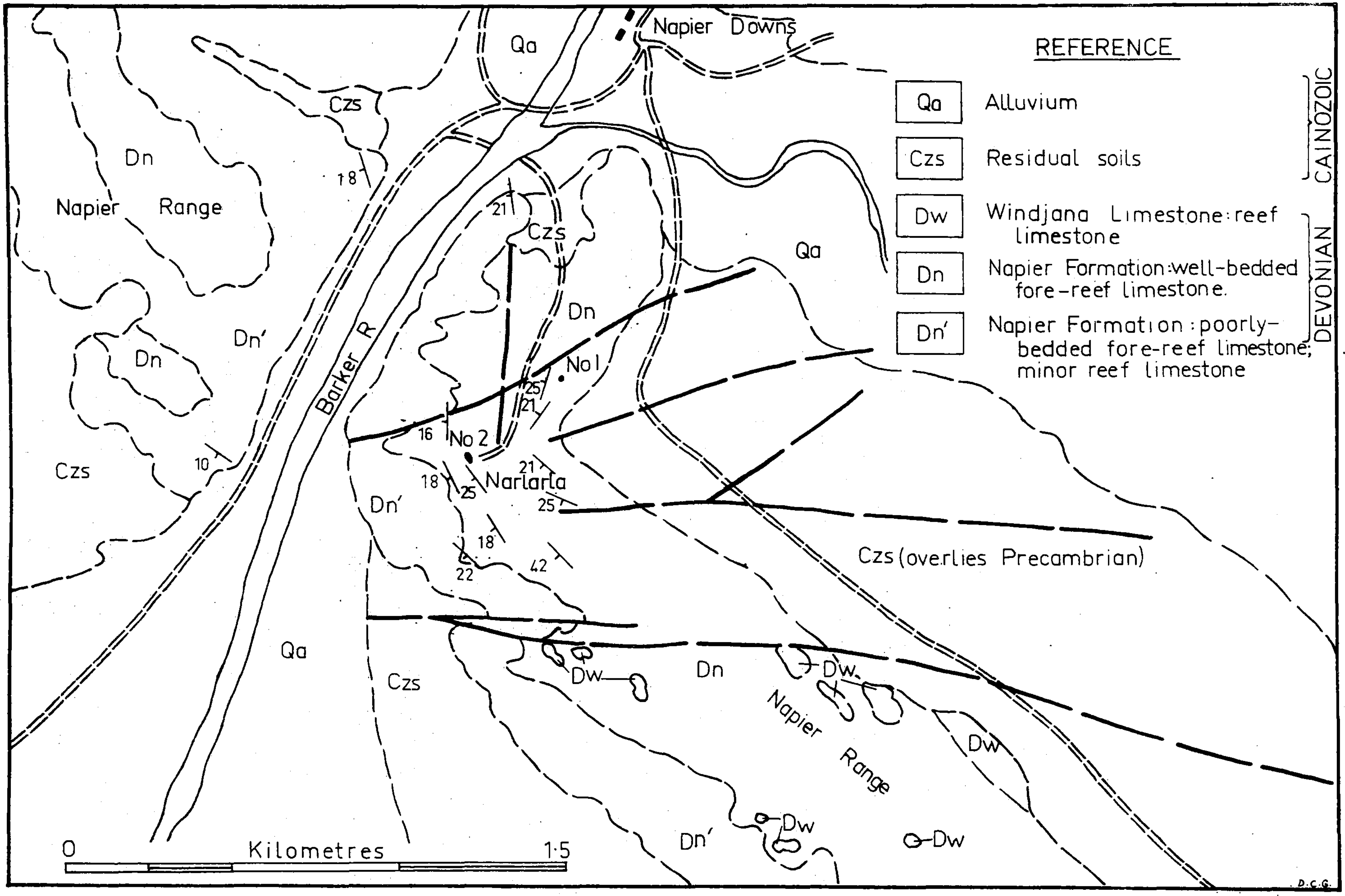

Fig. 2 Geological map of Narlarla area.

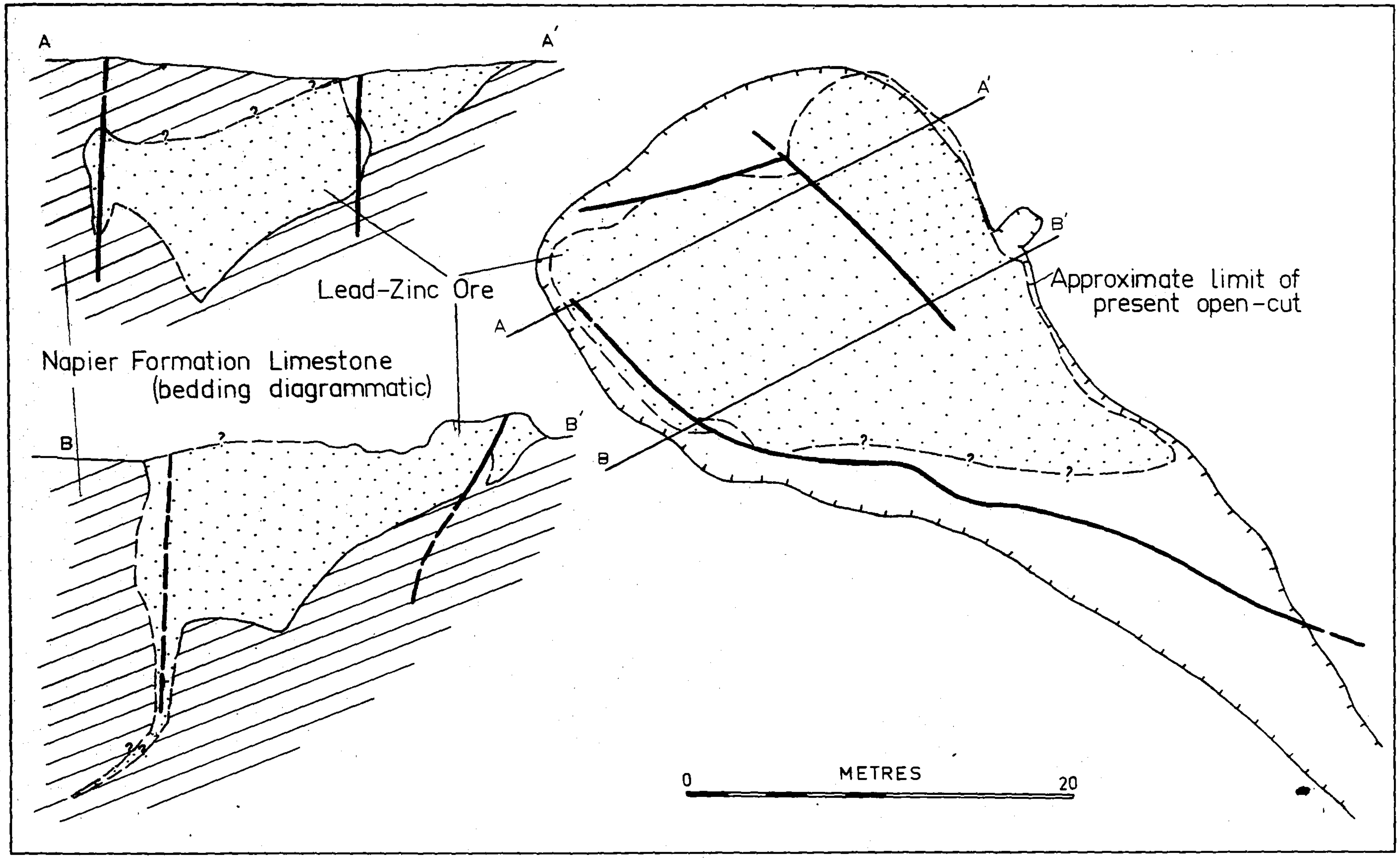

Figure. 3. Generalised plan and sections of Narlarla No. 2 ore body (after Halligan 1965)

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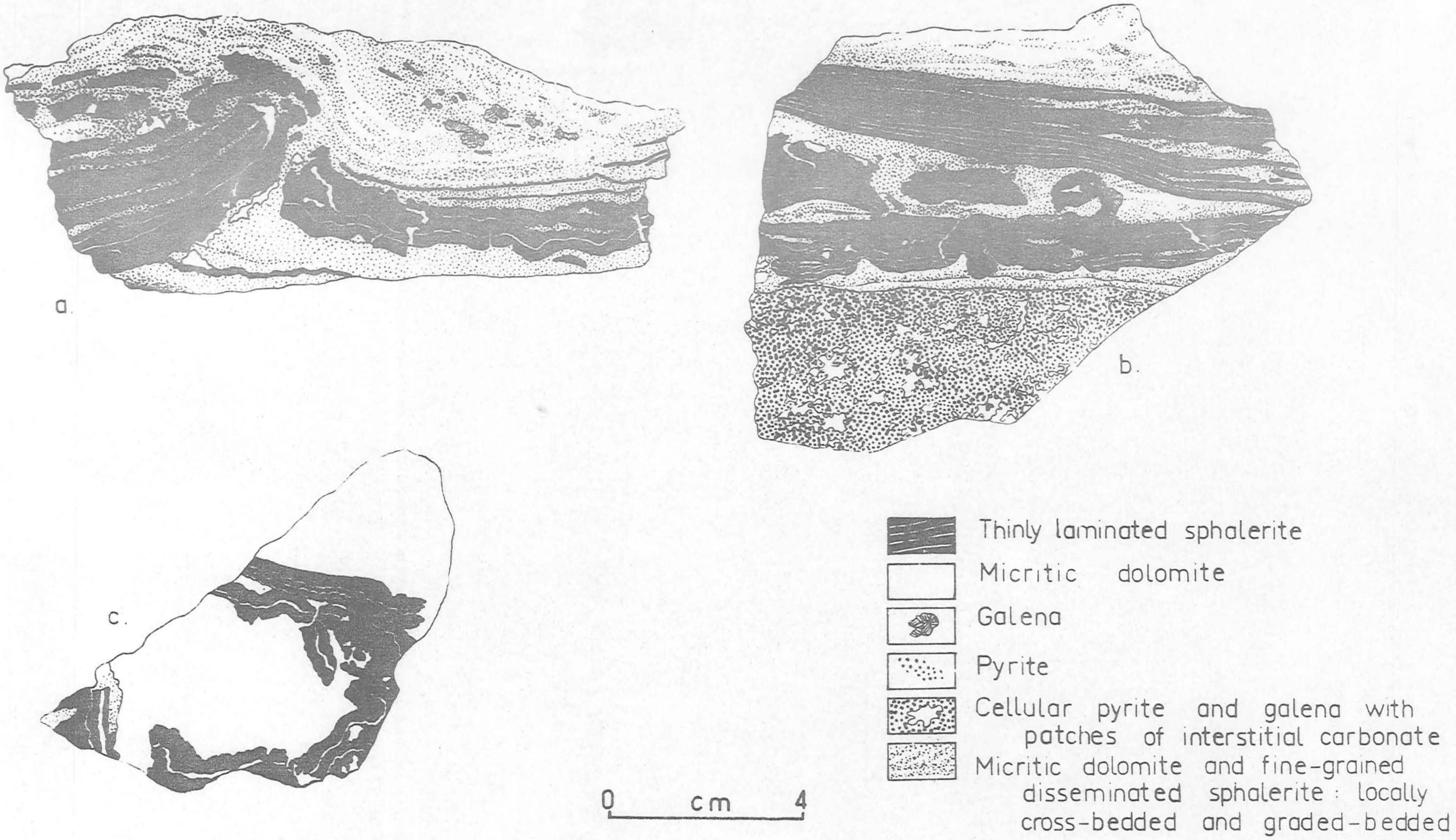

Fig. 4. Textures of some Narlarla zinc ores.

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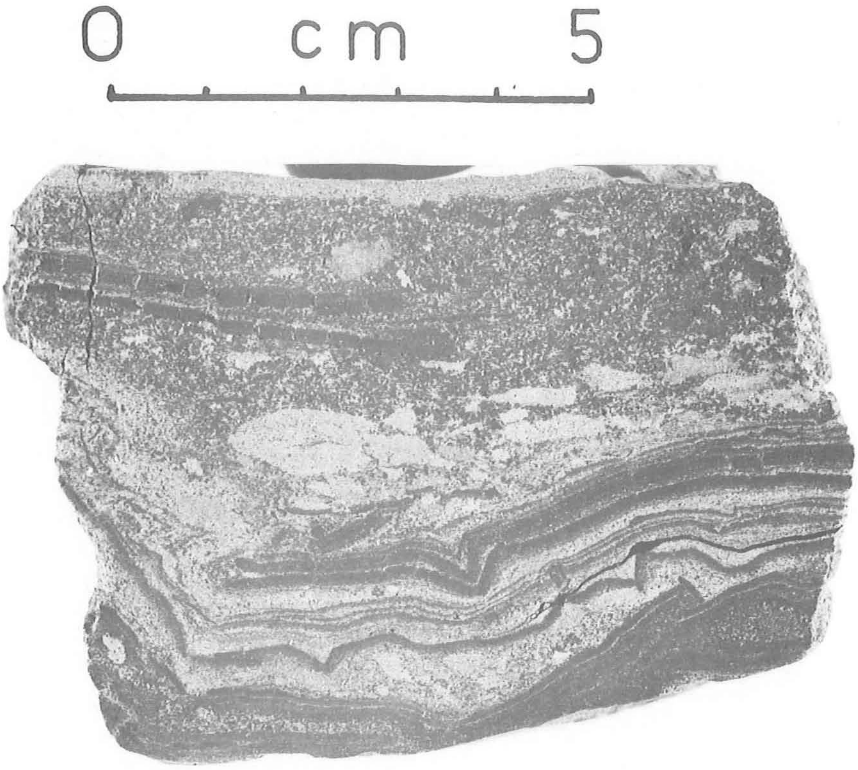


Fig. 5(a) Thin sphalerite-dolomite laminations overlain by dolomitic mud-pellet conglomerate and a detrital mixed sulphide assemblage. Grading of small-scale sphalerite-dolomite layers is towards a sphalerite-rich top. Uppermost of lower sphalerite beds have been truncated prior to deposition of conglomerate. Underlying laminations are continuous. Specimen 67.16.0406 Neg GA1281

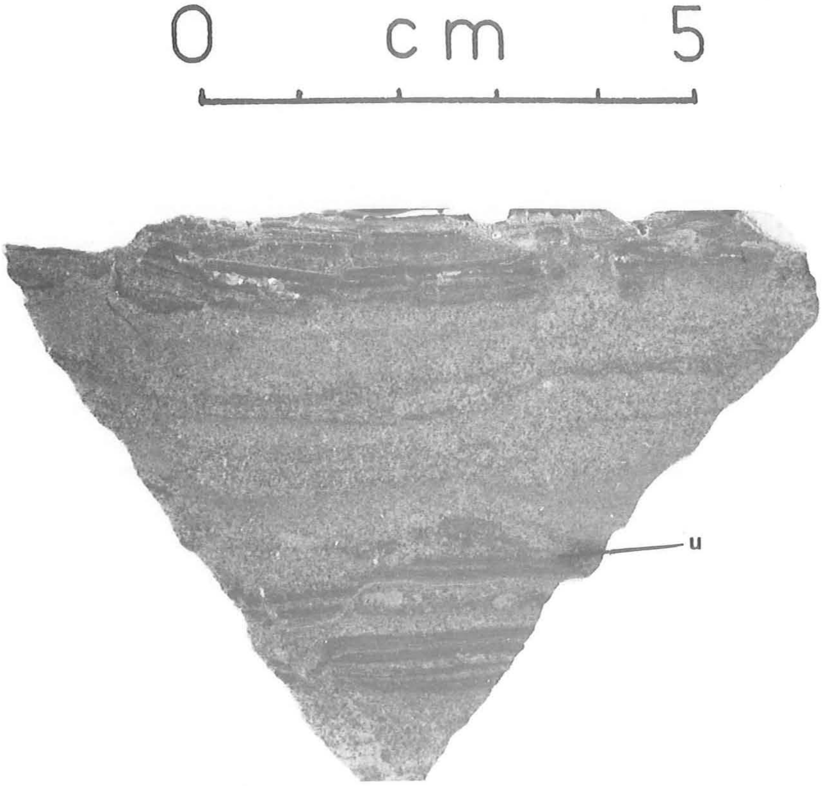


Fig. 5(b) Bedded sphalerite-bearing fine-grained dolomitic micrite with thin sphalerite layers. Sphalerite layers have been fractured and disrupted : dolomite has flowed and formed flame-structures intruding sphalerite. Sphalerite layers at top grade down into more carbonate-rich basal parts. Note erosional unconformity (u) at top of lower sphalerite-rich zone. Specimen 67.16.0436 Neg GA1286

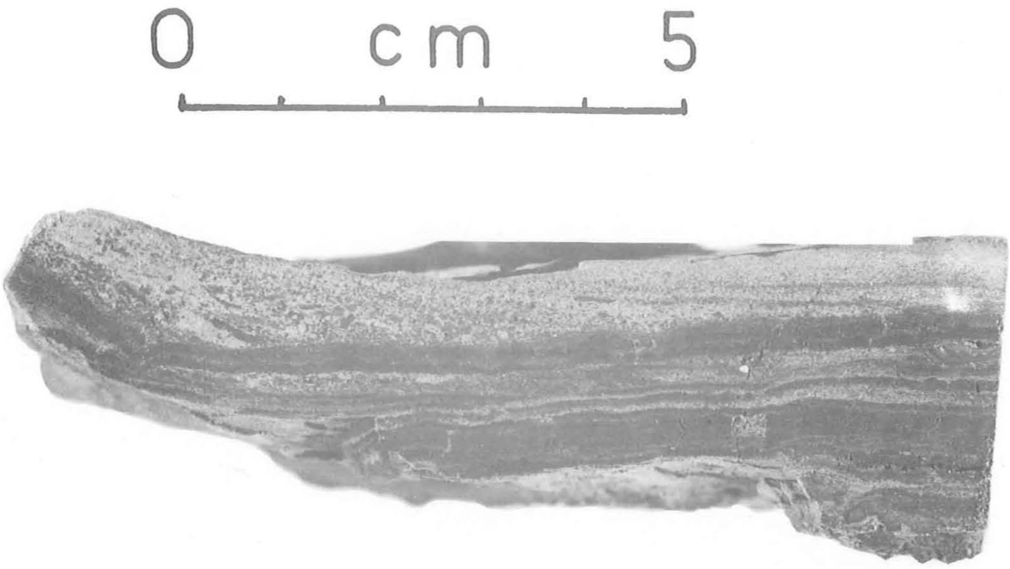


Fig. 6(a) Laminated sphalerite showing small-scale compositional graded bedding of sphalerite-dolomite layers with sphalerite-rich tops, overlain by cross-laminated sulphide-bearing dolomite zone. The cross-laminated material shows grainsize graded bedding grading upwards (left to right) from coarse-grained to fine-grained. Specimen 67.16.0420. Neg. GA1274.

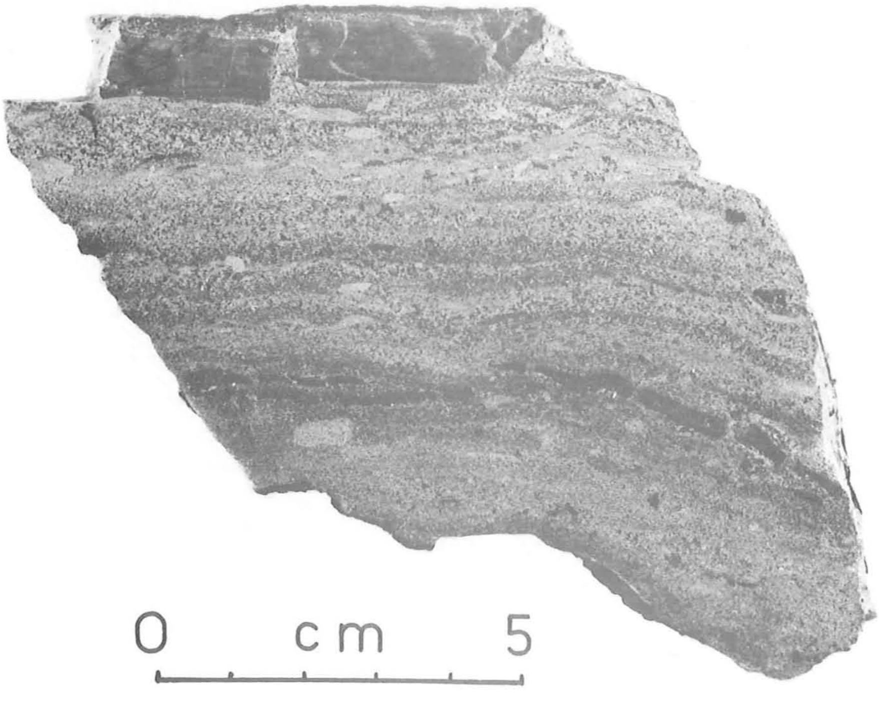


Fig. 6(b) Banded sulphide-bearing, pebbly dolomite. "Pebbles" of fine-grained dolomite and massive dolomite are lenticular and have probably been derived through erosion (due to slumping?) of unconsolidated sediment. The sulphide bearing beds are graded from a sharply bounded base, rich in assorted detrital sphalerite grains, to a carbon-rich top. Way-up which is indicated by graded bedding agrees with that indicated by intrusion of dolomite into fractures in massive sphalerite. Specimen 67.16.0431. Neg. GA1282.

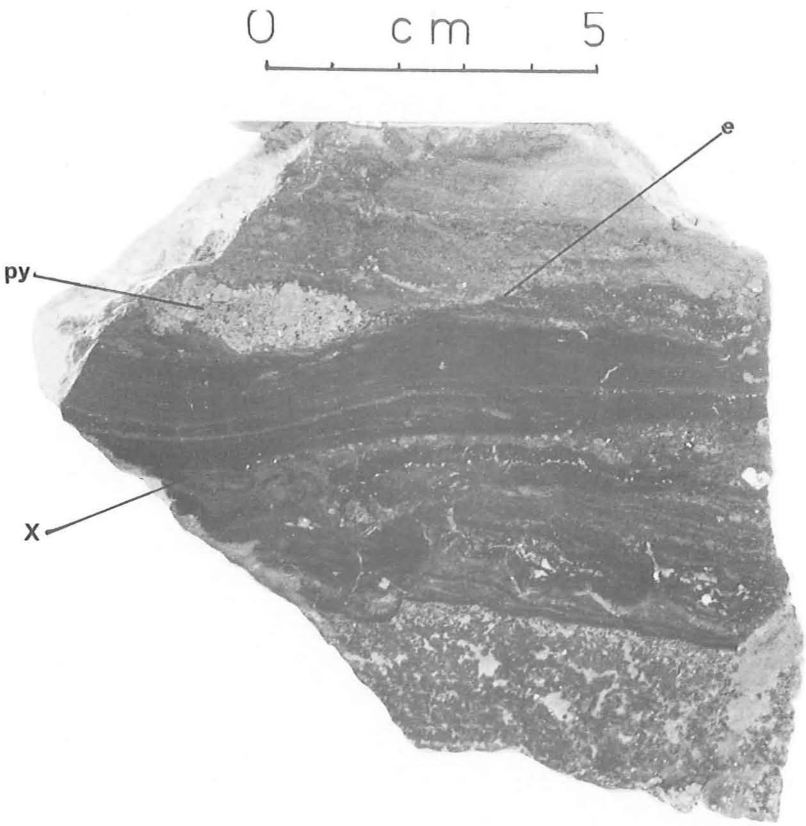


__Fig. 7(a)__ Moss-type growth structures of galena, sphalerite and pyrite with carbonate in interstices. Immediately overlying beds grade from sphalerite-rich base to carbonate-rich top. Carbonate-rich layer in centre shows truncated cross laminations (x). Topmost sphalerite laminations show erosional truncations. (e) Large pyrite nodule (py) contains 0.5 mm spherical grains of sphalerite. Specimen 67.16.0413. Neg. GA1287.

__Fig. 7(b)__ Parallel sedimentary laminations. Shows well developed replacement of sphalerite band by pyrite (py). Way up is uncertain; flow from flame structure probably indicates the specimen is right way up. If so small scale sphalerite-carbonate layers have a sphalerite-rich base. Specimen 67.16.0405. Neg. GA1272.

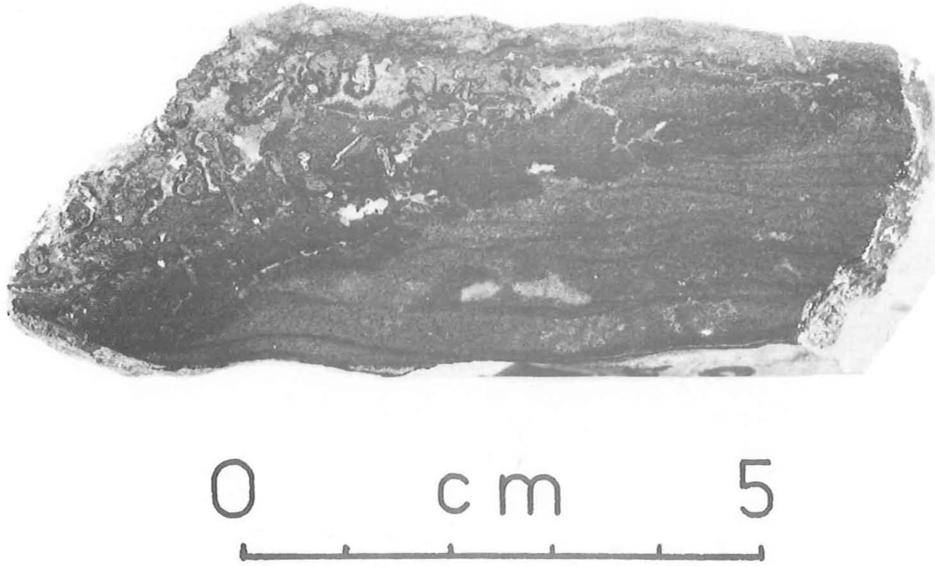


Fig. 8(a) Colloform sphalerite and galena at base, overlain by fine-grained massive sphalerite, which in turn is overlain discordant by fine-grained dolomite with thin partings of sphalerite. Note elongate form of some colloform structures. Specimen 67.16.0432. Neg. GA1280.

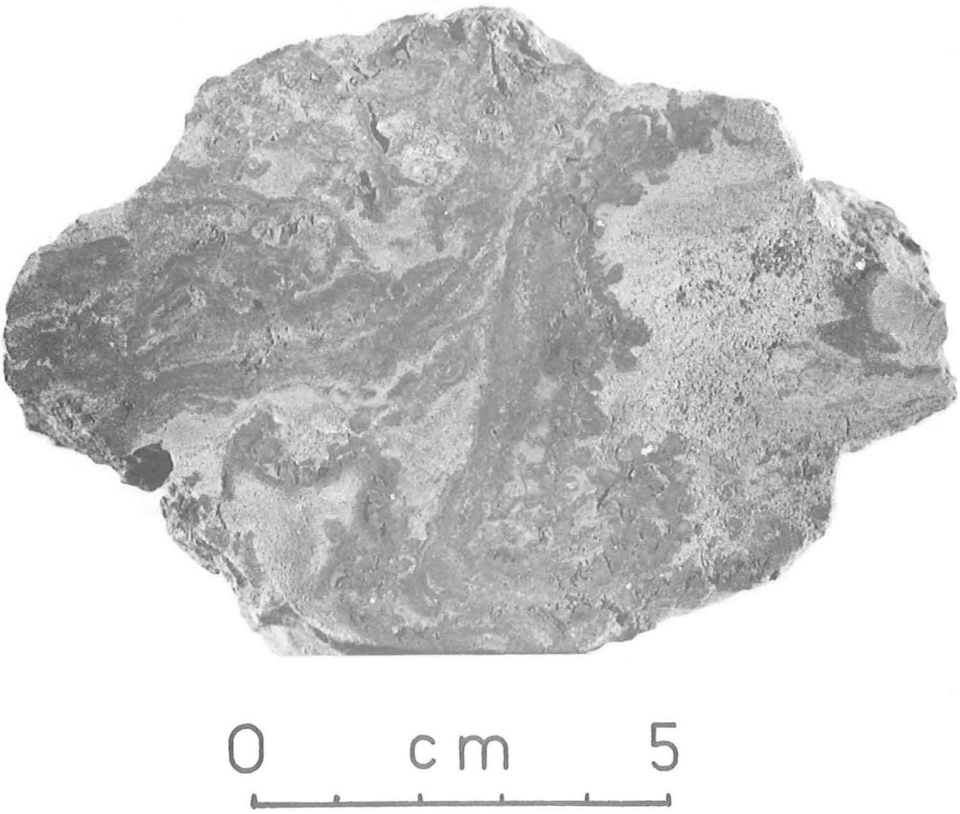


Fig. 8(b) Intensely contorted slumped bands of colloform sphalerite and galena with interstitial sulphide-bearing dolomite. Colloform sulphide bands have deformed plastically (lower left) during incipient flame structure development. Specimen 67.16.0433. Neg. GA1271.

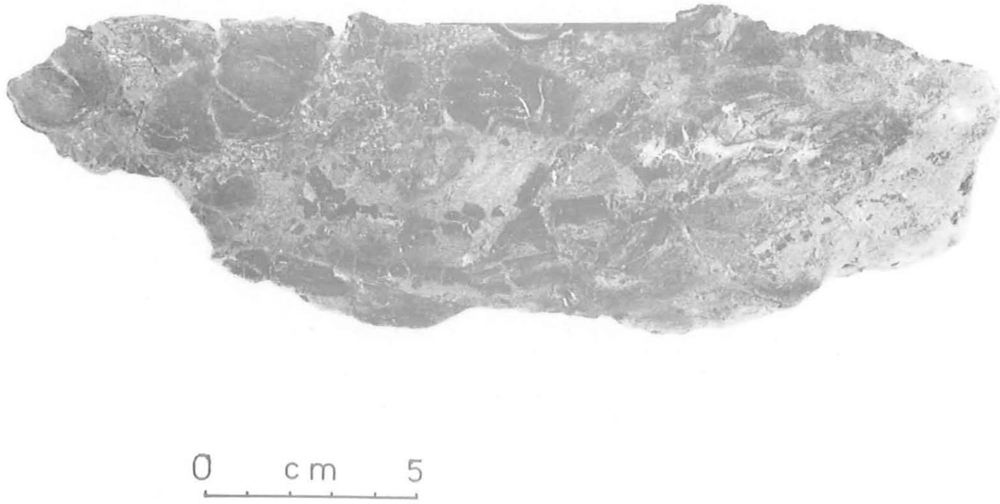


Fig. 9(a). Intensely brecciated laminated and colloform sulphides. More massive sulphide layers have fractured but sulphide-bearing dolomite has flowed readily and has infilled fractures. Specimen 67.16.0416. Neg. GA1276.

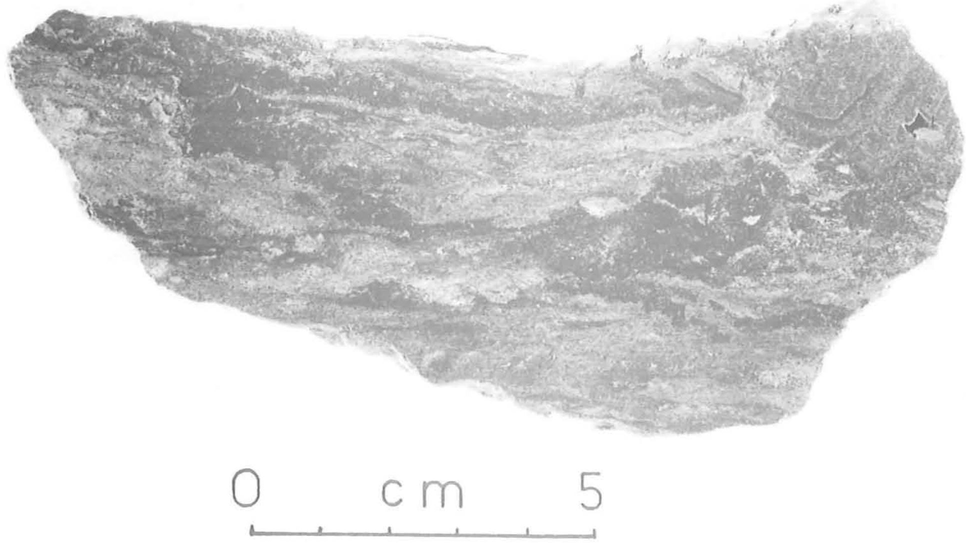


Fig. 9(b) Intraformational recumbent slump-type folds. Carbonates near top edge are coarse and contain 1 mm quartz grains, but elsewhere are fine-grained. Massive sulphide layers (top right) have fractured but dolomite and granular sphalerite have flowed and have locally erupted through massive sulphide layers. Specimen 67.16.0417. Neg. GA1285.

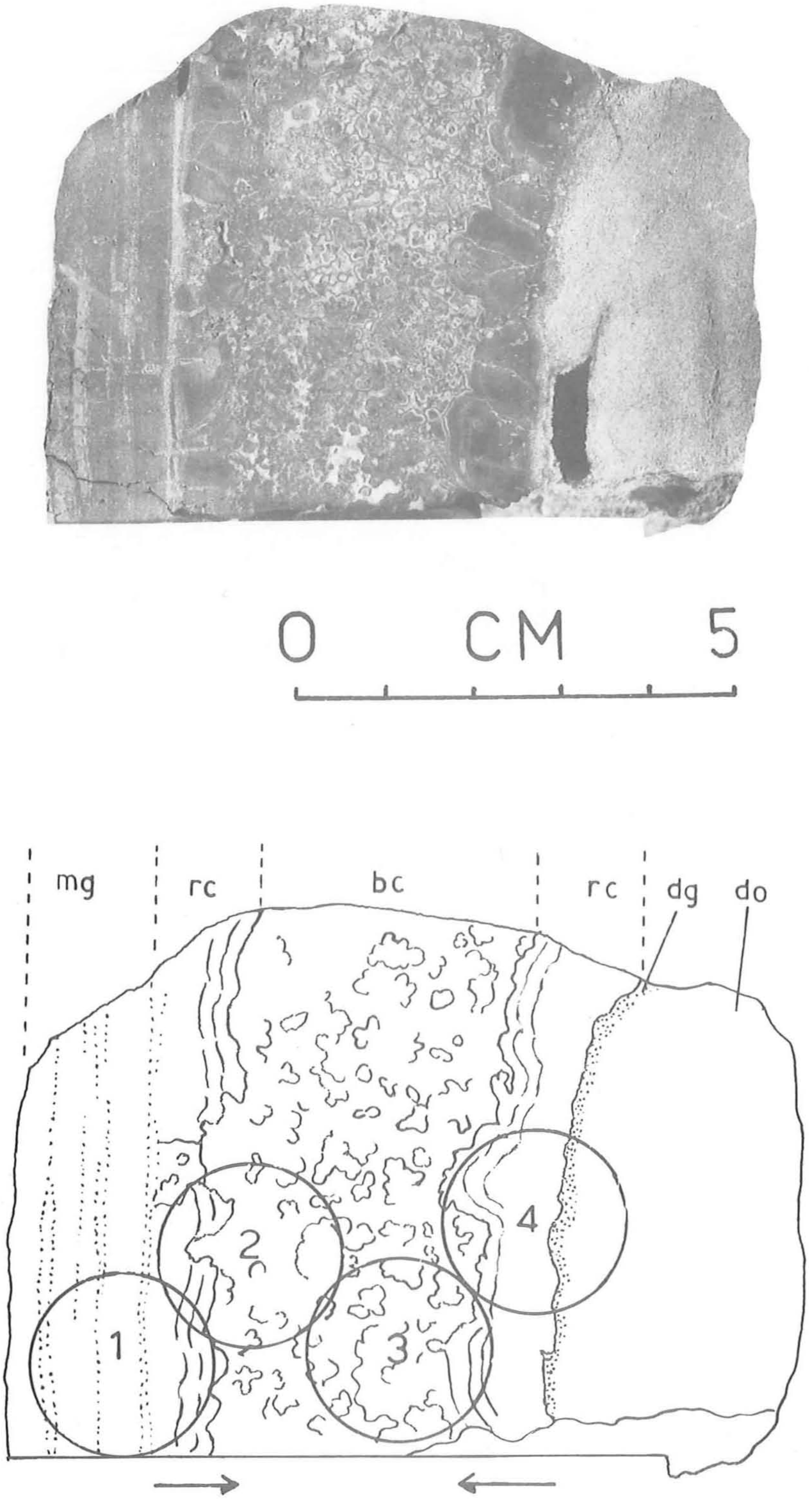


Fig. 10 Relationship of colloform sphalerite to bedded sphalerite : central zone of irregular betryoidal and colloform sphalerite and galena (bc) bounded by zones of regular colloform sphalerite (rc) and zones of massive granular bedded sphalerite (mg), disseminated granular sphalerite (dg) and dolomite. Arrows show growth directions of colloform layers. Circles 1, 2, 3, 4, show locations of polished sections referred to in descriptions of microscopic textures. Area 1 - specimen 68.16.0354/1; area 2 - specimen 68.16.0354/2; area 3 - specimen 68.16.0354/3; area 4 - specimen 68.16.0354/4. (Specimen 67.16.0434. Neg. GA1279).

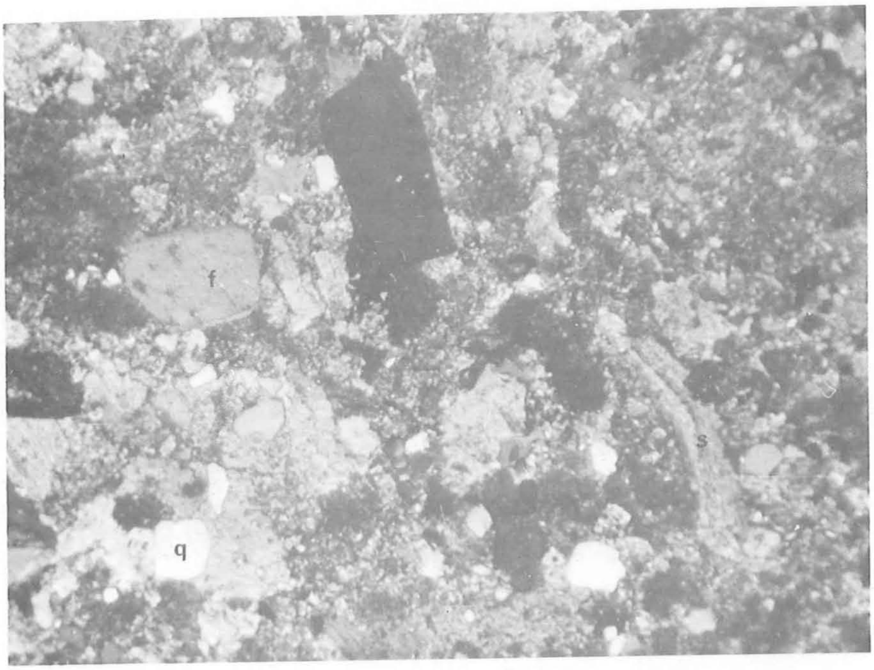


Fig. 11(a) Coarse-grained calc-arenite, from fore-reef facies, Napier Formation, Narlarla. Shows detrital grains of quartz (q) and feldspar, and shell fragments (s) in a coarse-grained calcitic matrix. x50 Crossed polarizers. (Specimen 68.16.0349. Neg. M1085/17).

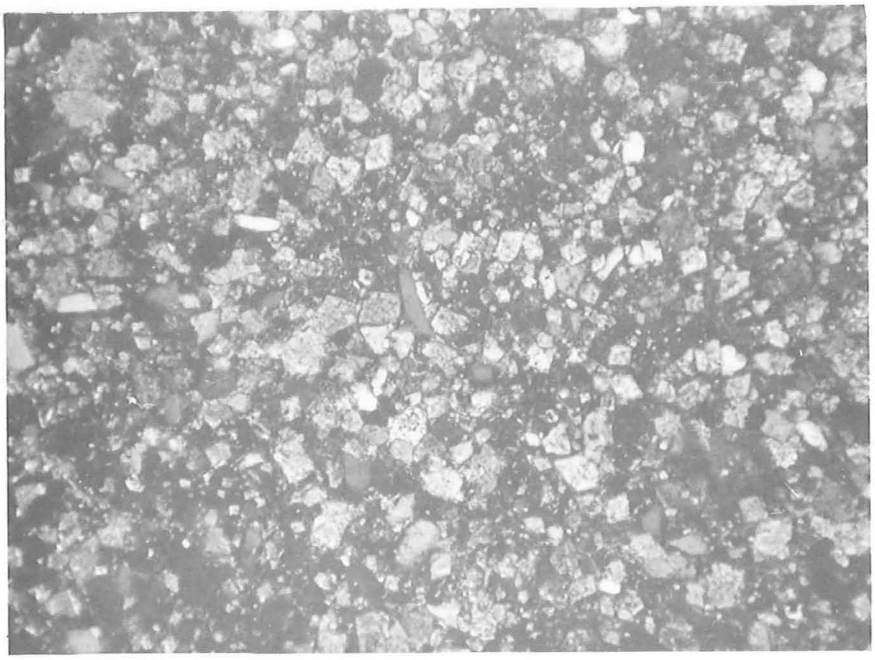


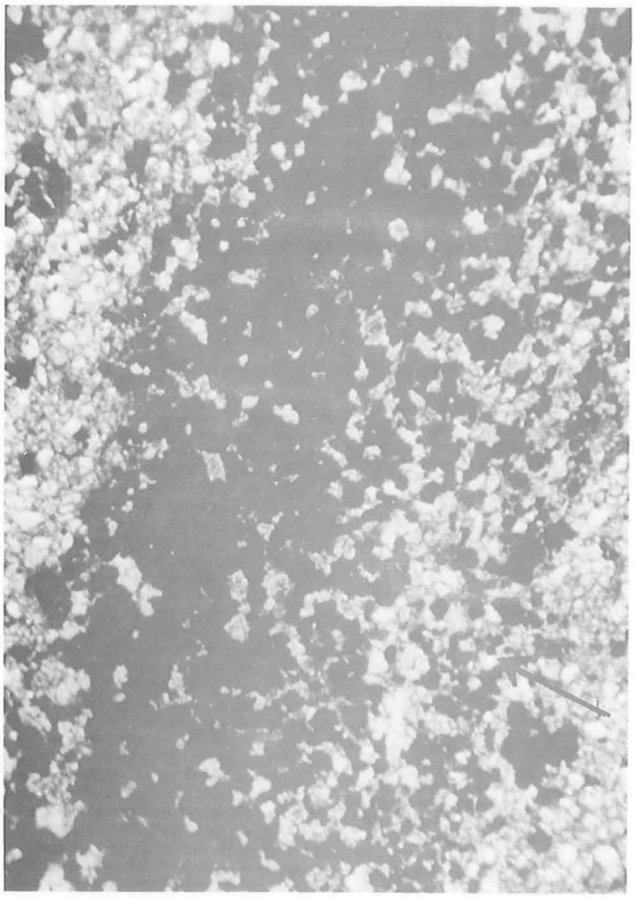
Fig. 11(b) Fine grained dolomitic micrite - host rock for Narlarla lead-zinc ores. Consists of euhedral dolomite rhombs and small scattered detrital quartz grains, and interstitial green chlorite. x75 Crossed polarizers. (Specimen 68.16.0352. Neg. M1085/19).

FIGURE 12

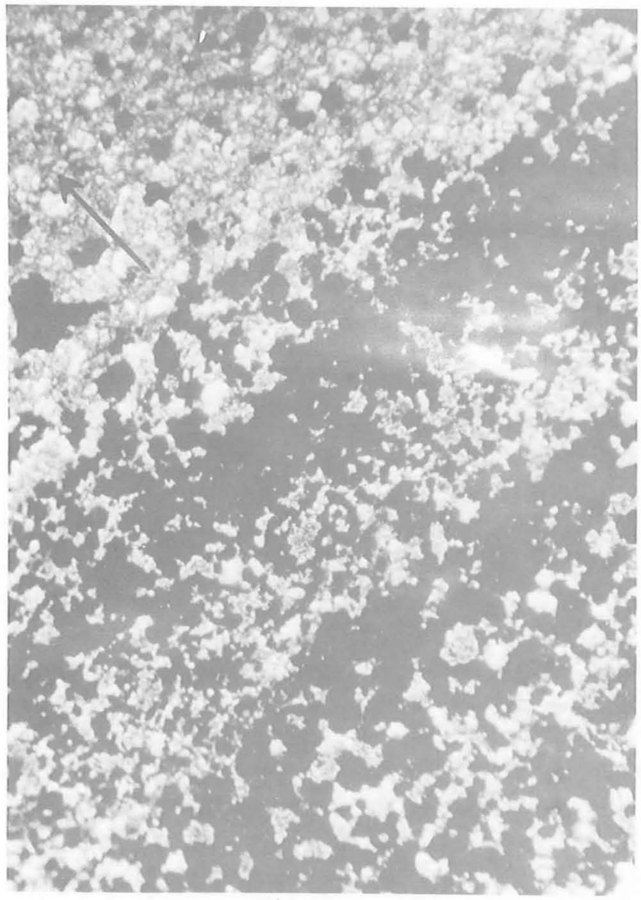
Fig.12(a) Graded sphalerite layer in fine-grained dolomite. Clear grains are detrital quartz. Arrow indicates way up of bedding. X45 Plane polarized light (Specimen 68.16.0353. Neg. M834/22).

Fig.12(b) (c) Repetitive graded sphalerite layers in fine-grained dolomite. Topmost parts of layers locally consist almost entirely of granular sphalerite. Arrows indicate way up of bedding. Plane polarized light. X45 (Specimen 68.16.0353. Negs M834/24, 25).

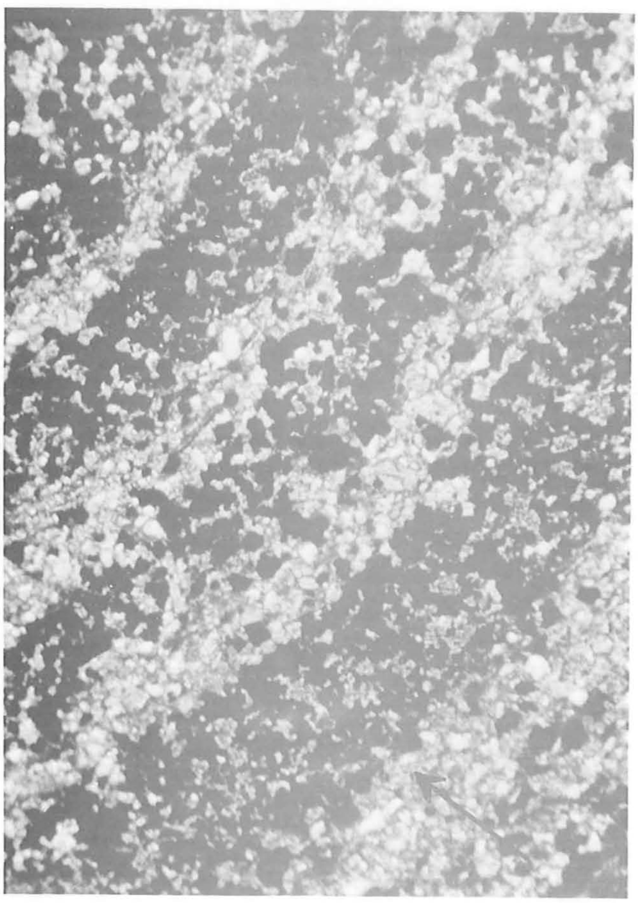
Fig.12(d) Graded sphalerite layer in dolomite. Sphalerites at top of layer (way up indicated by arrow) have coalesced to form a mono-mineralic layer. Individual sphalerite grains are zoned. X75. Plane polarized light (Specimen 68.16.0353. Neg. M834/30).



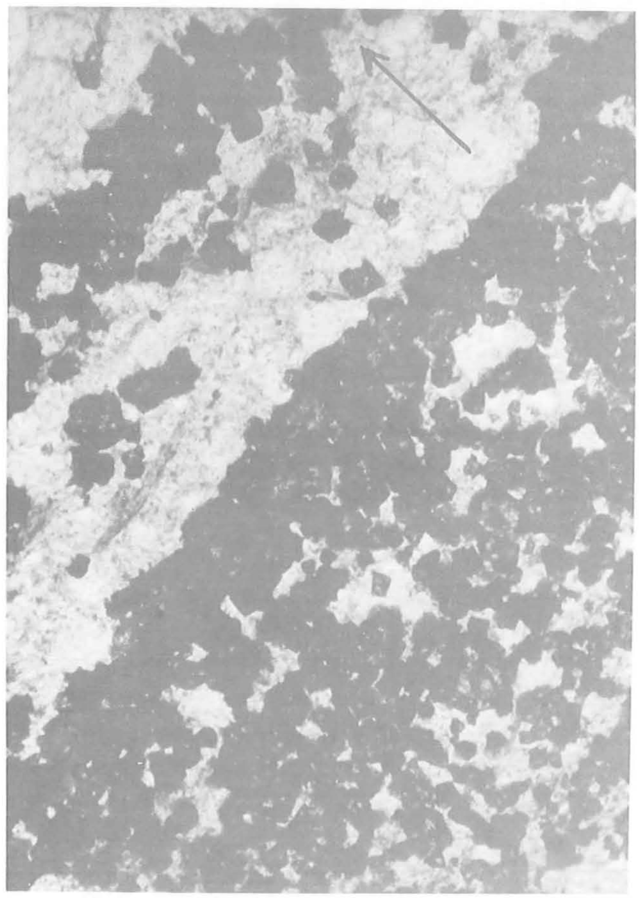
a



b



c



d

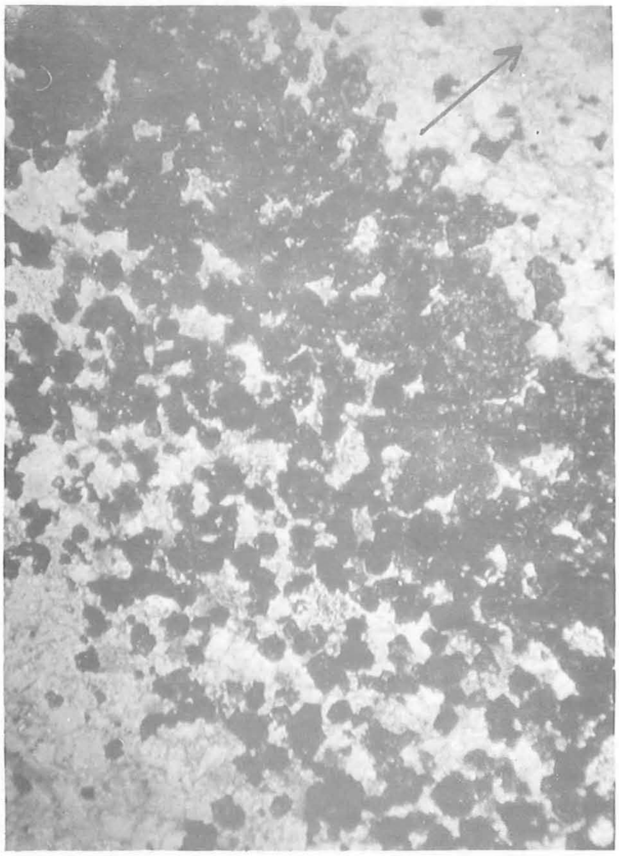
FIGURE 12

FIGURE 13

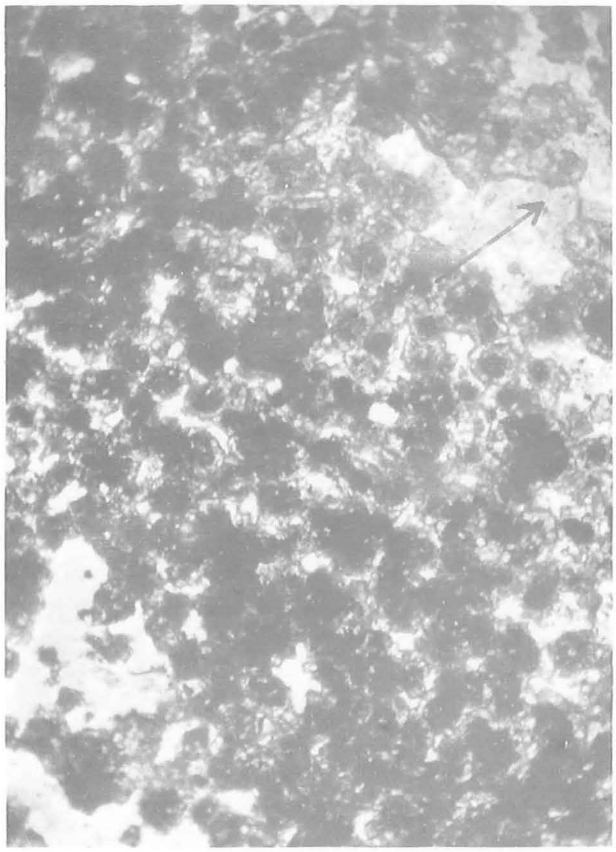
Fig.13(a) Graded sphalerite layer in fine-grained dolomite. Sphalerite becomes paler in colour upwards in the layer (way up indicated by arrow). X75. Plane polarized light. (Specimen 68.16.0353 Neg. 1085/1)

Fig. 13(b), (c) Graded layers of 'frog-spawn' sphalerite in dolomite. Sphalerite grains have dark brown opaque centres and pale yellow-brown marginal zones which become more abundant towards the uppermost parts of the layers. X125 Plane polarized light. (Specimen 68.16.0383. Negs 1085/3,5).

Fig.13(d) 'Frog-spawn' sphalerite grains overlain by a continuous band of colloform sphalerite which in turn is followed by galena (g). X300 Plane polarized light (Specimen 68.16.0353 Neg. 834/36).



a



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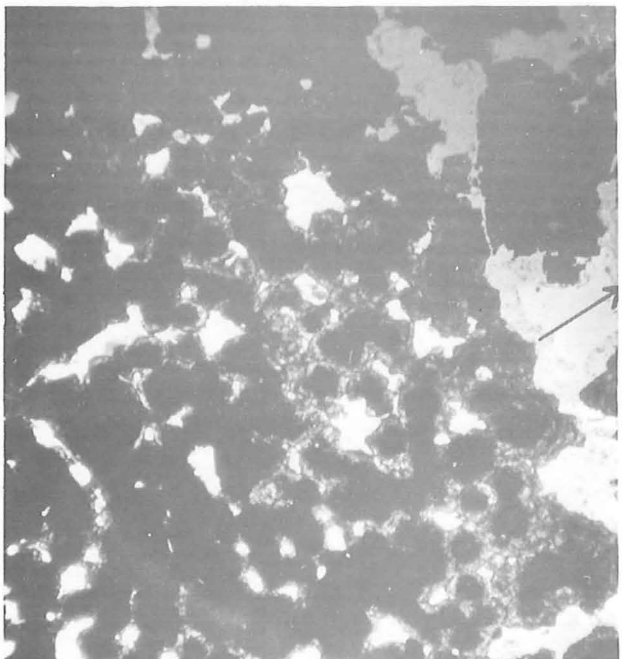
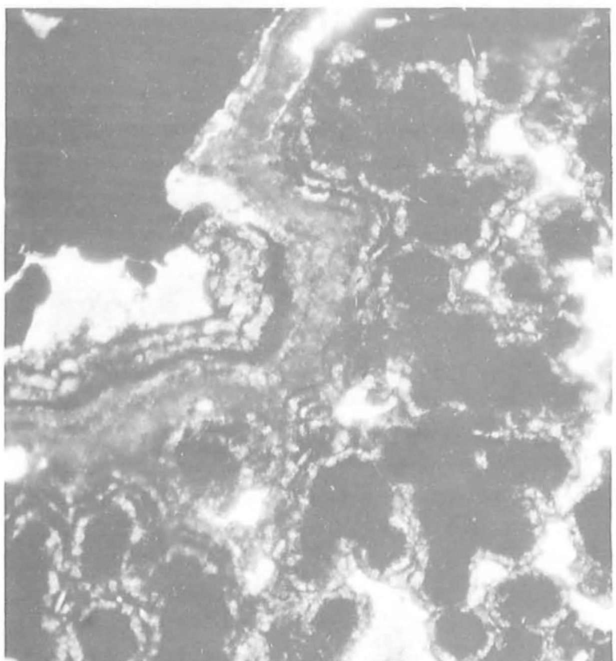


c



d

FIGURE 13

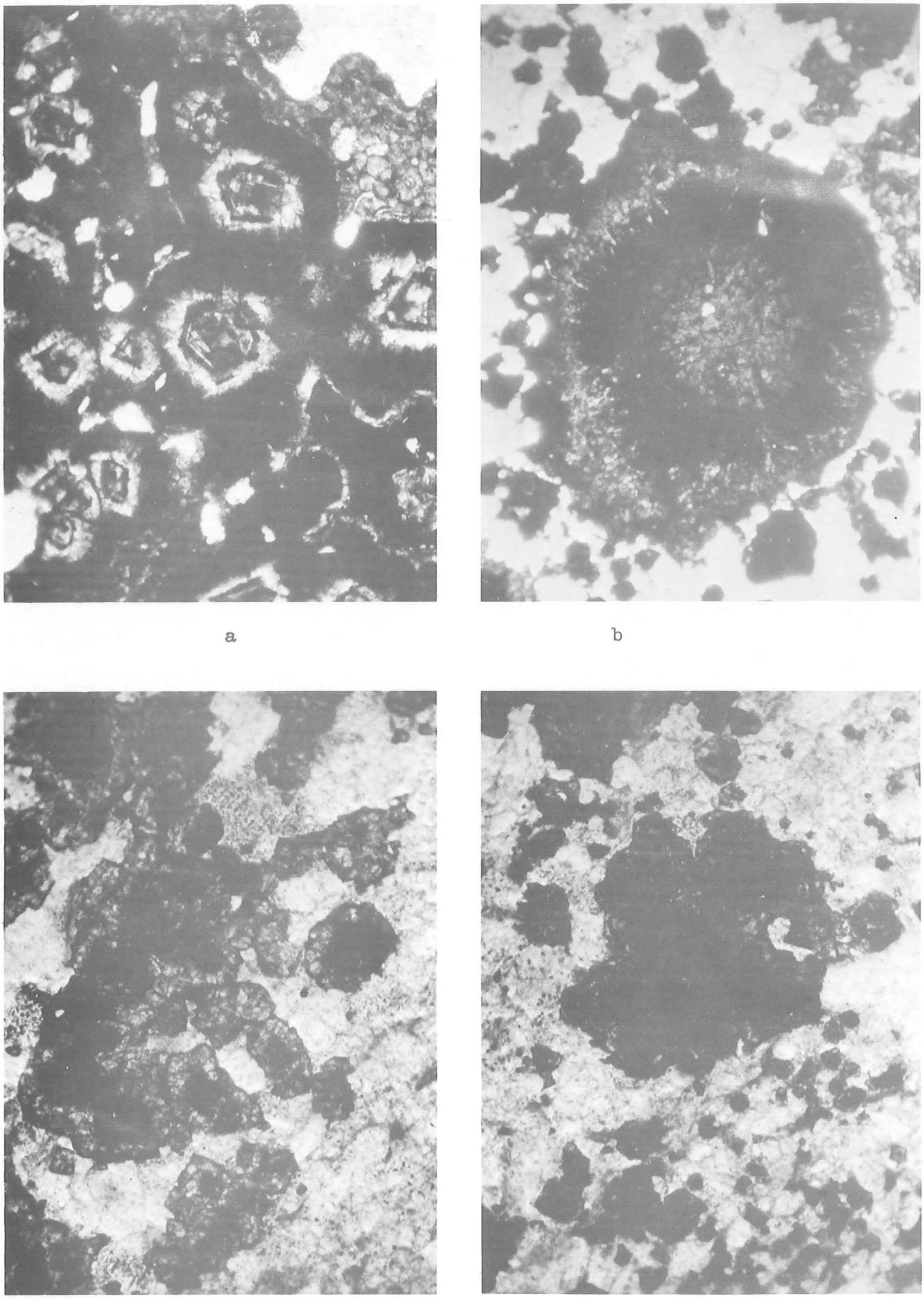
FIGURE 14

Fig.14(a) Zoned sphalerite: pink euhedral crystal cores surrounded by a pale yellow-brown zone grading outwards into orange-brown and dark brown opaque marginal zones: these zoned crystals are surrounded (lower left) by a narrow selvedge of fine-grained pale grey-brown sphalerite x 75. Plane polarized light. (Specimen 68.16.0353, Neg. M834/37).

Fig.14(b) Spherical zoned grains of sphalerite: shows concentric zoning in various tones of dark brown. Outer zone shows radial growth structure X75. Plane polarized light (Specimen 68.16.0353 Neg. 1085/23).

Fig.14(c) Zoned 'frogspawn-type' sphalerite grains consisting of dark brown and pink cores surrounded by pale yellow-brown margins. X75. Plane polarized light. (Specimen 68.16.0353 Neg. 834/32).

Fig.14(d) Large composite zoned sphalerite grain with dark brown opaque centre and alternating narrow dark-brown and pale-yellow brown marginal zones X75. Plane polarized light. (Specimen 68.16.0353 Neg. 834/31).



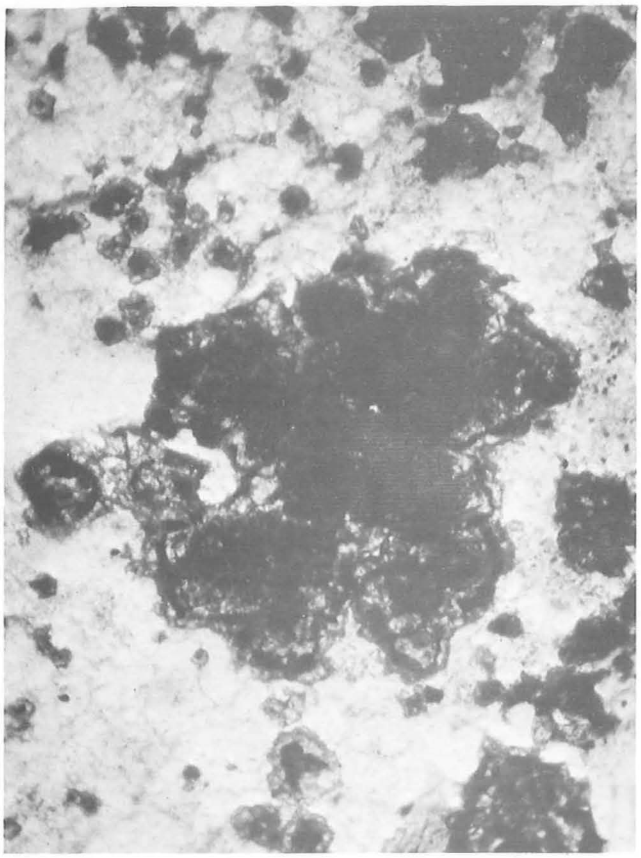
a b c d

FIGURE 14

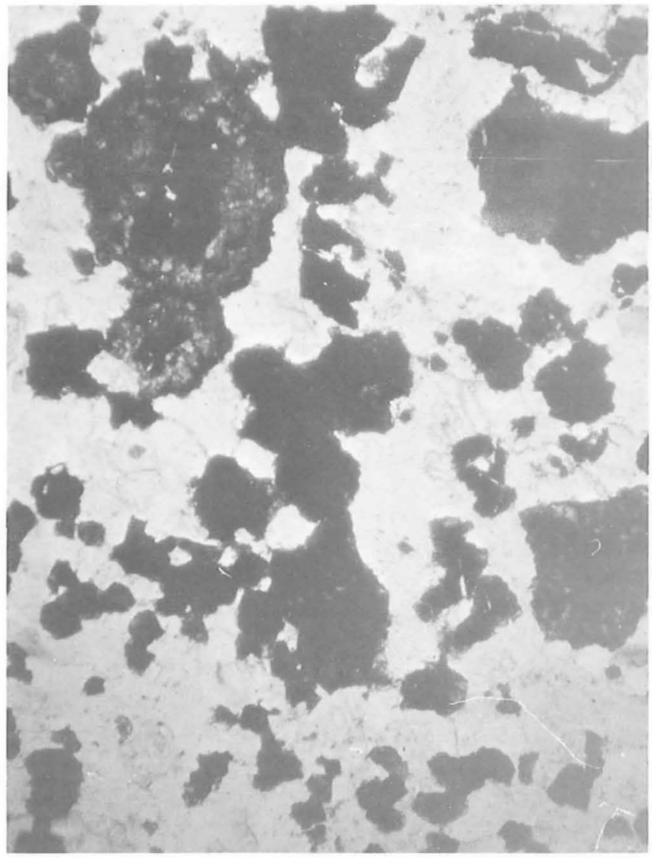
FIGURE 15

Fig.15(a) Large composite zoned sphalerite grain with translucent amber brown central zone grading out to dark brown opaque zone followed by further narrow amber-brown which darkens outwards. Small surrounding sphalerite grains are opaque. Matrix is dolomite X75. Plane polarized light. (Specimen 68.10.0354).

Fig.15(b, c, d) Mixed sphalerite assemblages. Adjacent grains show differing types of zoning. They are mostly (1) completely opaque (2) have opaque centres and translucent margins, and (3) translucent centres and opaque margins X75. Plane polarized light. (Specimen 68.16.035(b), Negs M1085/10, 12, 13).



a



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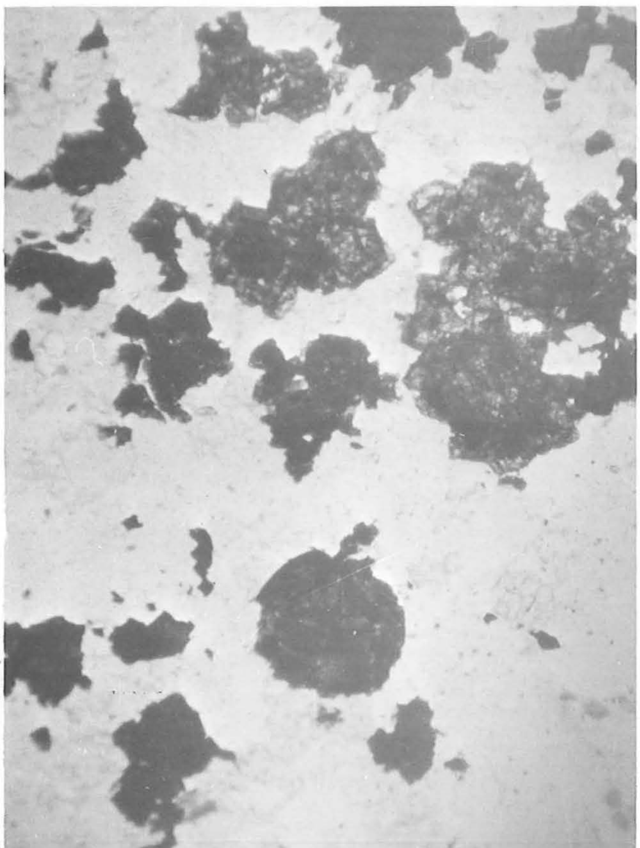
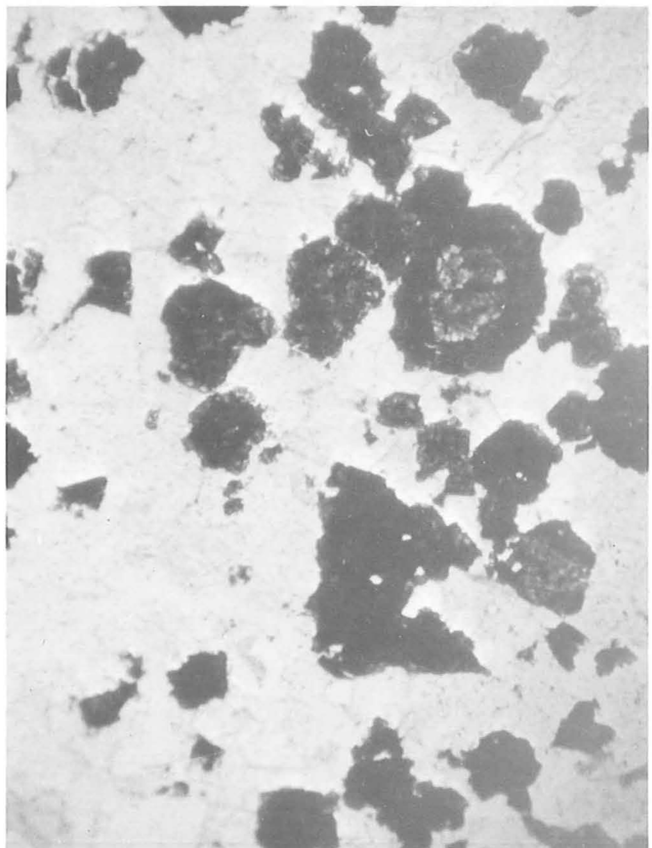


c



d

FIGURE 15

FIGURE 16

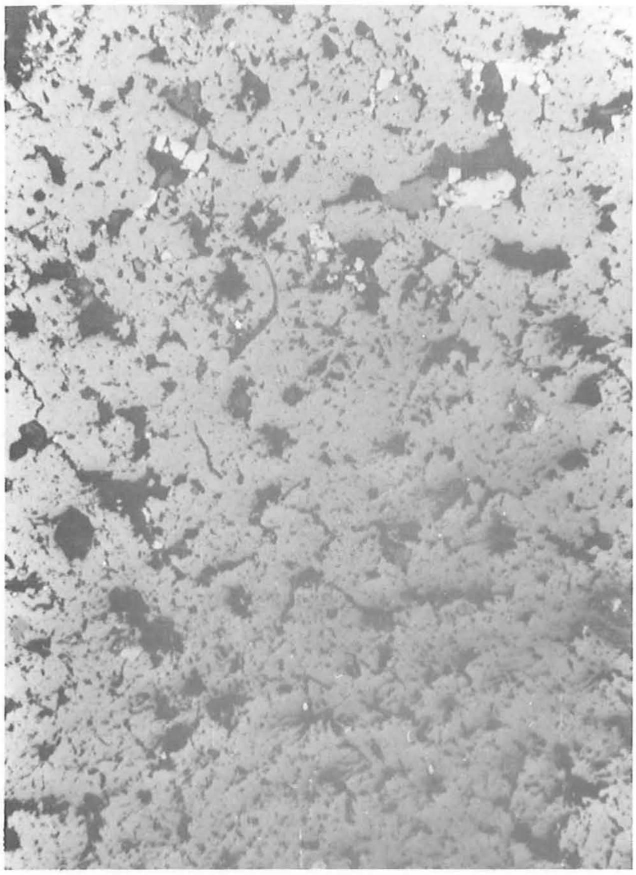
Fig.16(a) Granular sphalerite with included carbonaceous material (black) and traces of pyrite. Area 1 of Fig. 10. Reflected light. X125. (Specimen 68.16.0354/1 Neg. M1086/5).

Fig.16(b) Granular sphalerite (light grey) with interstitial dolomite (mid-grey) and minute pyrite grains (white). Area 1 of Fig. 10. Reflected light. X125. (Specimen 68.16.0354/1. Neg. M1086/6).

Fig.16(c) Granular sphalerite (mid-grey) partly enclosed by pyrite (white) with interstitial dolomite (dark grey). Area 4 of Fig.10. Reflected light. X125. (Specimen 68.16.0354/4. Neg. M1086/18).

Fig.16(d) Radial, spindle shaped inclusions of galena in sphalerite. Area 2 of Fig. 10. Reflected light. X125. (Specimen 68.16.0354/2. Neg. M1086/7).

d - dolomite   s - sphalerite   py - pyrite



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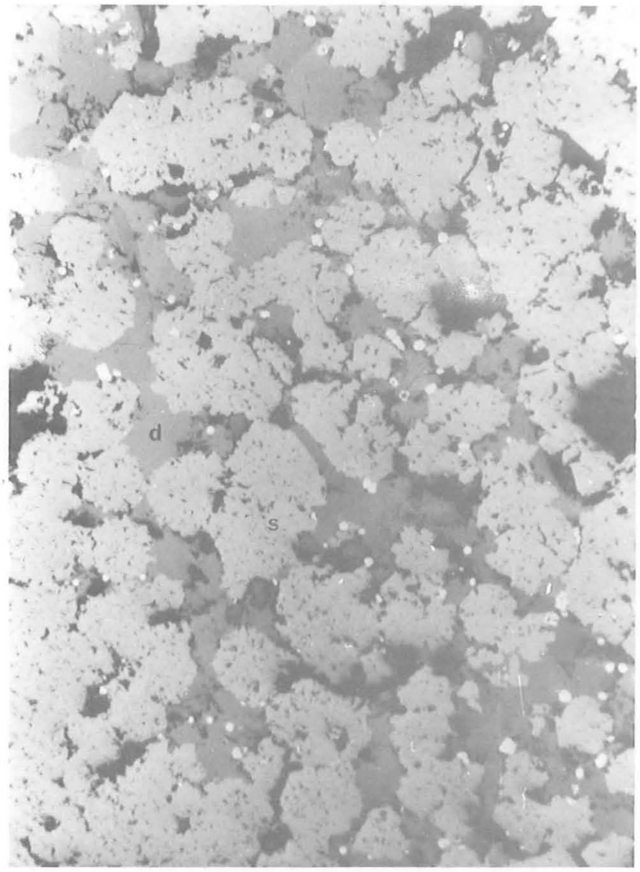

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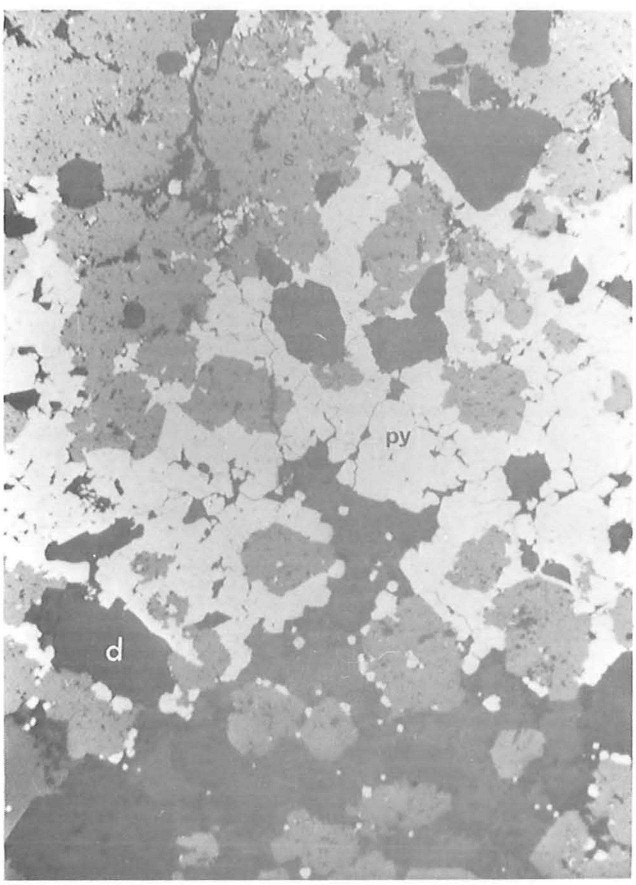

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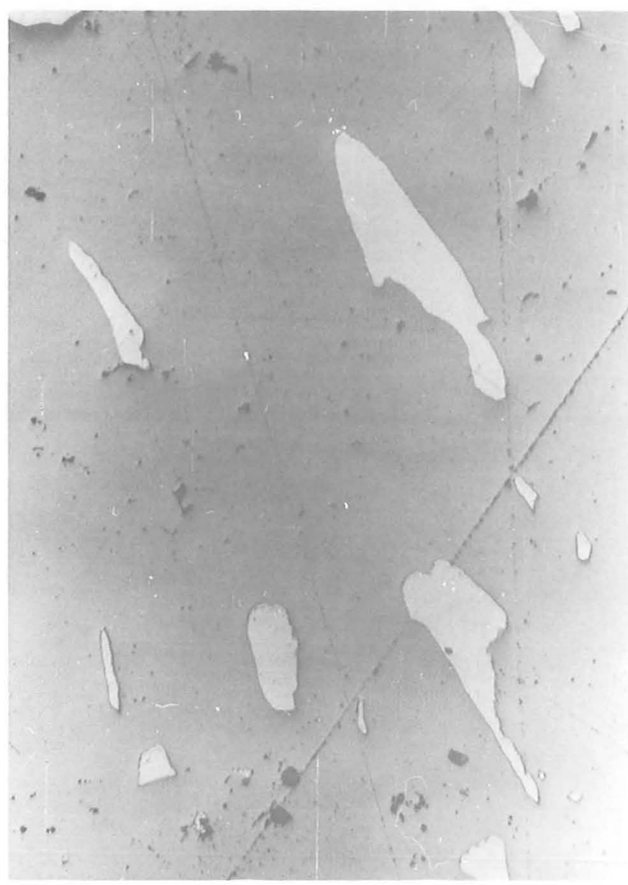


d

FIGURE 16

FIGURE 17

Fig.17(a) Galena spindles in finely intergrown sphalerite and carbonate; separated from sphalerite (top right) by a narrow border of colloform galena. Reflected light X125. Area 1 of Fig. 10. (Specimen 68.16.0354/1. Neg. M1086/8).

Fig.17(b) Layer of massive sphalerite containing fine radiating growths of carbonaceous material. Reflected light. X125. Area of Fig. 10. (Specimen 68.16.0354/1 Neg. M1086/9).

Fig.17(c) Colloform sphalerite containing concentric layers and radial spindles of galena. Individual layers of both sphalerite and galena are replaced locally by carbonate. Area 3 of Fig. 10. Reflected light X125. (Specimen 68.16.0354/3. Neg. M1086/27).

Fig.17(d) Colloform sphalerite containing radial inclusions of galena. Layering of sphalerite is outlined by minute carbonaceous inclusions. Note widening and narrowing of galena spindles. Area 3 of Fig.10. Reflected light X50. (Specimen 68.16.0354/3, Neg. M1086/19).

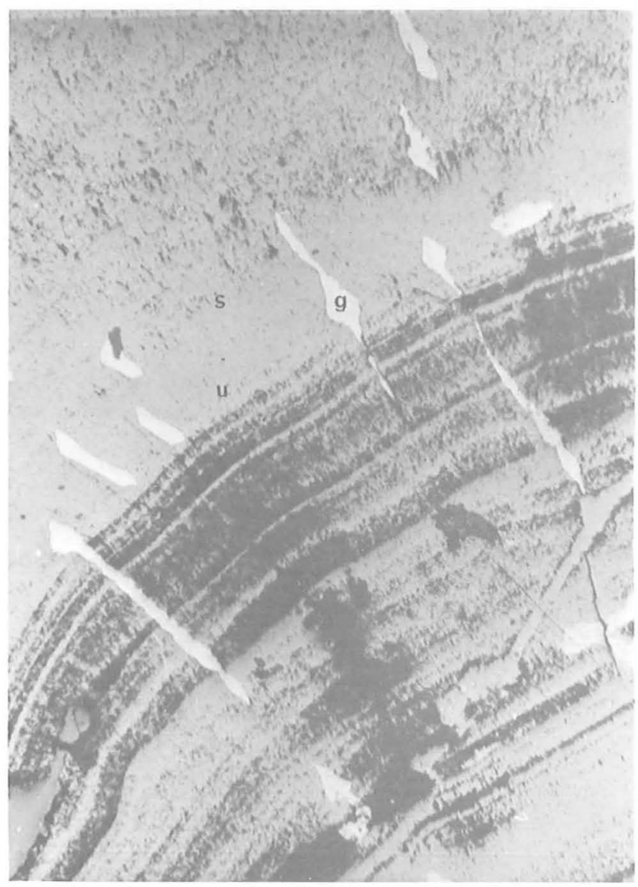
c - carbonate g - galena s - sphalerite

u - unidentified carbonaceous material

a

b

c



d

FIGURE 17

FIGURE 18

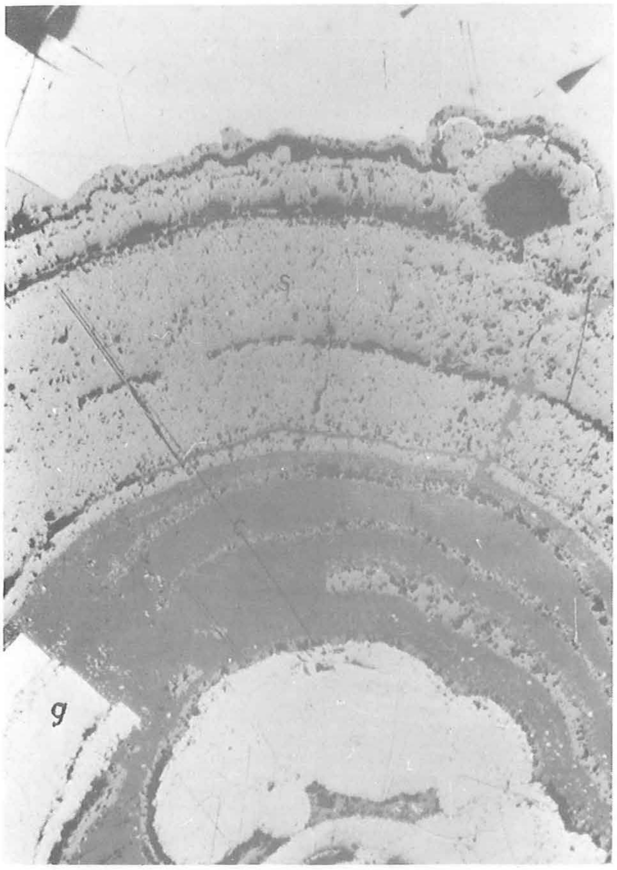
Fig.18(a) Colloform sphalerite surrounding a core of galena. A major part of a broad galena layer has been replaced by carbonate (c). Area 2 of Fig. 10. Reflected light. X125. (Specimen 68.16.0354/2. Neg. M1086/16).

Fig.18(b) Brecciated sphalerite. Carbonate fills fractures. Area 3 of Fig. 10. Reflected light. X125. (Specimen 68.16.0354/3. Neg. M1086/22).

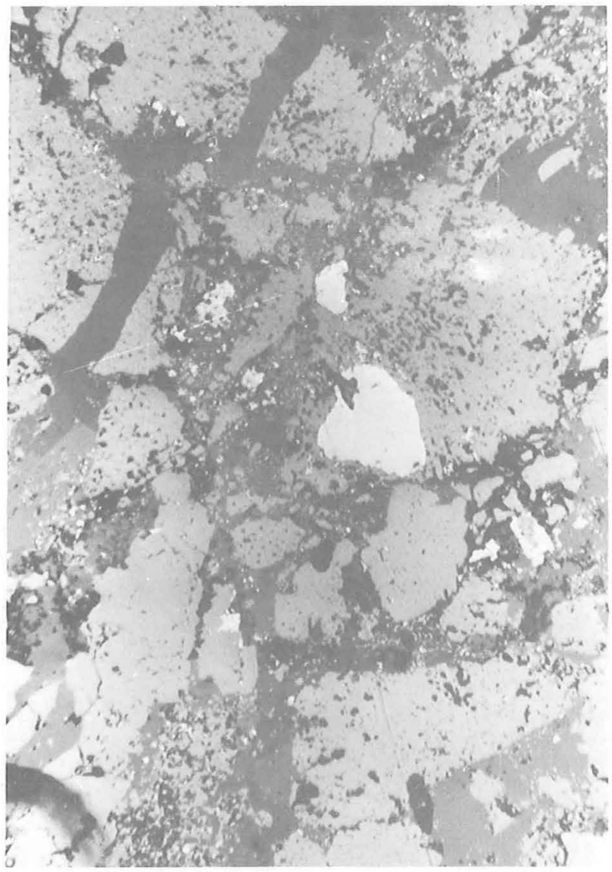
Fig.18(c) Spheroids of galena and associated carbonaceous material (lower left) surrounded by colloform layers of galena and sphalerite. Area 3 of Fig. 10. Reflected light. X125. (Specimen 68.16.0354/3. Neg. M1086/22).

Fig.18(d) Spheroids of galena surrounded by a border of carbonaceous material, and enclosed in sphalerite. Area 3 of Fig. 10. Reflected light X125. (Specimen 68.16.0354/3 Neg. M1086/14).

c - carbonate   g- galena   s - sphalerite
u - unidentified carbonaceous material



a



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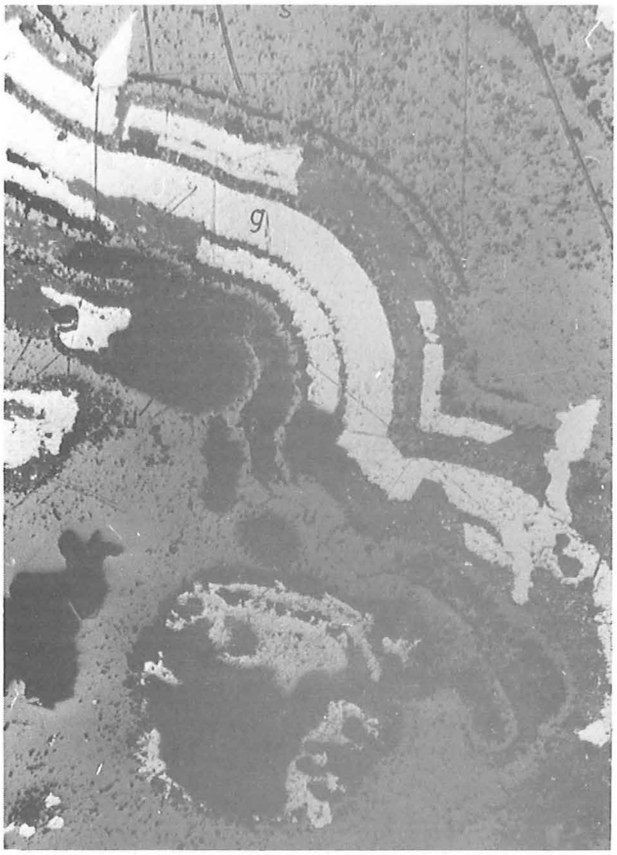
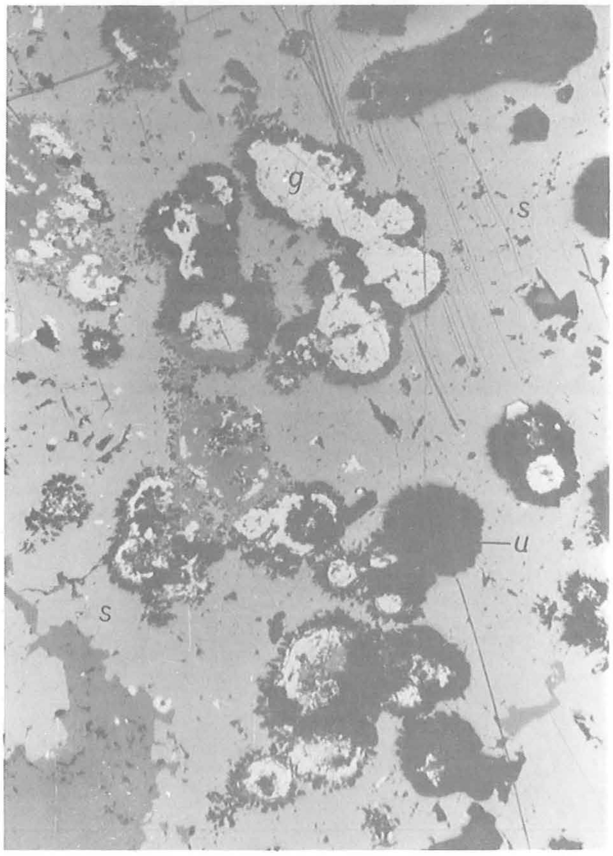


c



d

FIGURE 18

FIGURE 19

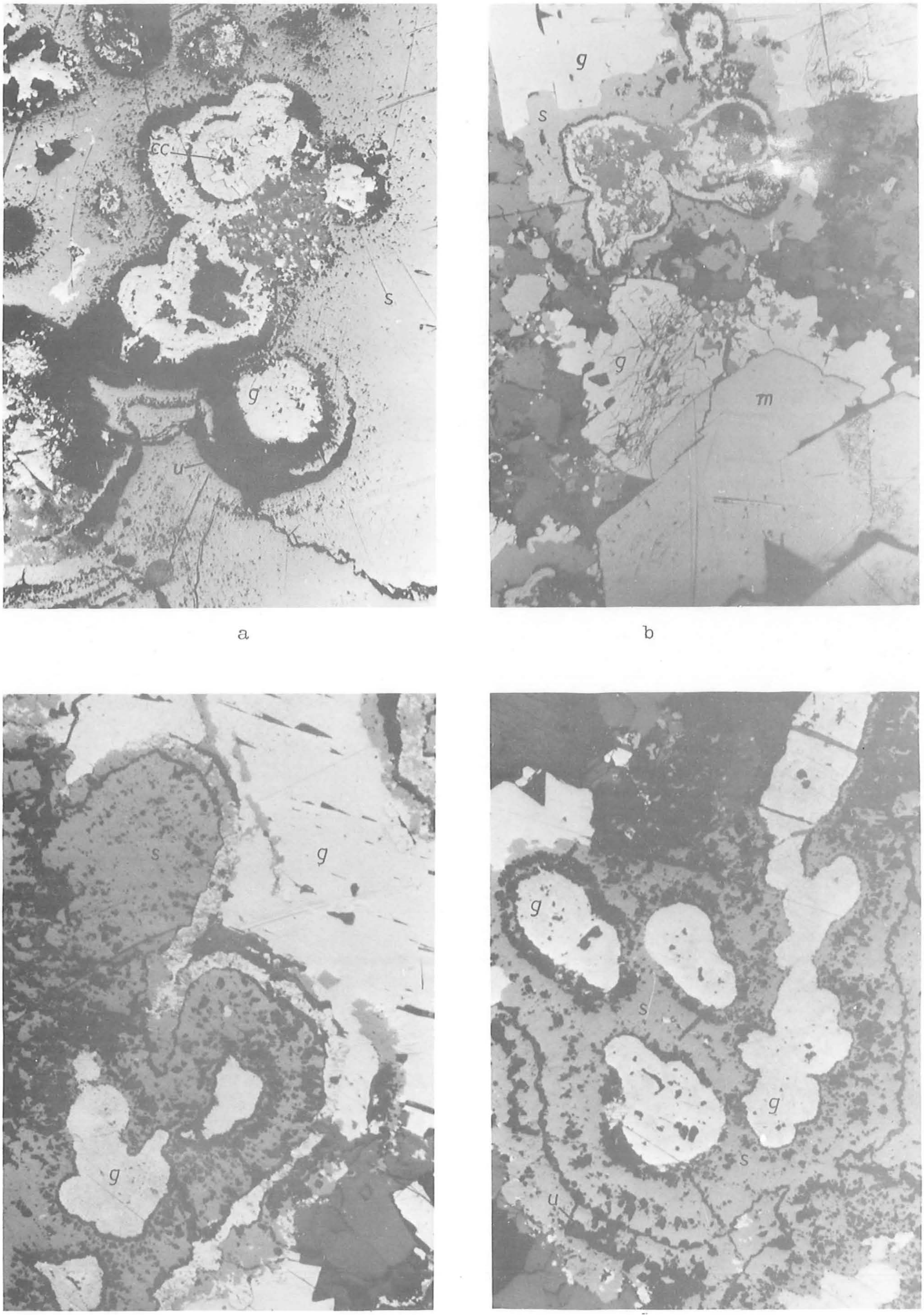
Fig.19(a) Galena spheroids surrounded by a zone of carbonaceous material and enclosed in sphalerite. Some spheroids have cores of chalcocite. Reflected light. X125. (Specimen 68.16.0354/2. Neg. M1086/10).

Fig.19(b) Galena spheroids, partly replaced by carbonate and surrounded by sphalerite. Large galena crystal (lower right) is overgrown by marcasite. Reflected light. X125. (Specimen 68.16.0354/2. Neg. M1086/15).

Fig.19(c, d) Irregular colloform structures: galena cores enclosed by sphalerite with concentric bands of carbonaceous inclusions: sphalerite surrounded (19d) by a narrow zone of intergrown galena and sphalerite. This in turn is surrounded by coarsely crystalline galena. Reflected light X50. (Specimen 67.16.0395 Neg. M1088/1, 3).

c - carbonate cc - chalcocite g - galena m - marcasite

s - sphalerite u - unidentified carbonaceous material



a b

c d

FIGURE 19

FIGURE 20

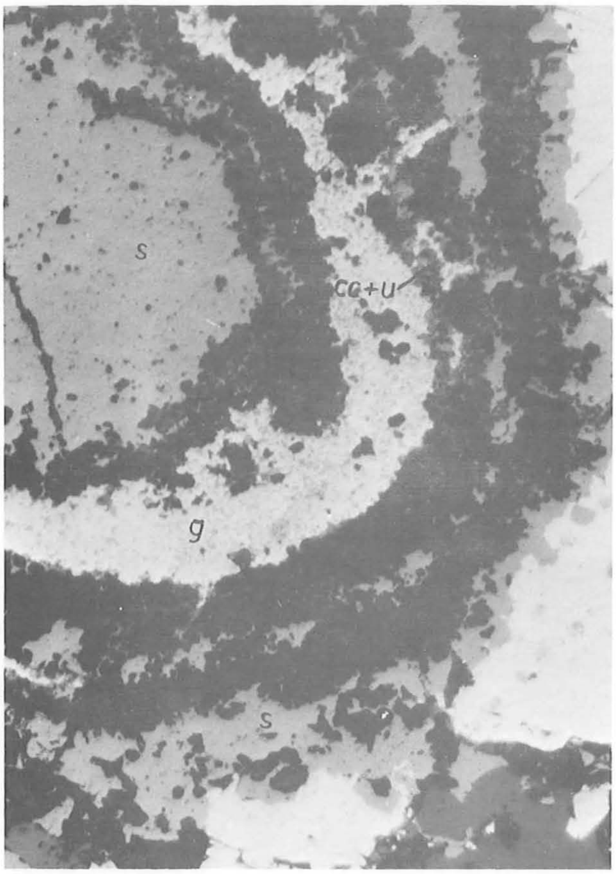
Fig.20(a) Concentric zoning of colloform structure showing successive zones of: sphalerite with peripheral carbonaceous inclusions; galena containing minute inclusions of sphalerite; sphalerite with carbonaceous inclusions and minor chalcocite; galena. Reflected light. X125. (Specimen 67.16.0395. Neg. M1088/5).

Fig.20(b) Colloform sphalerite with carbonaceous inclusions partially replaced by veinlet of galena. Reflected light. X50. (Specimen 67.16.0395. Neg. M1088/7A).

Fig.20(c,d) Skeletal galena in colloform sphalerite. Reflected light. X33. (c) cross section of elongate sphalerite lobe, (d) elongate section sphalerite lobe. (Photographs by J.A. McDonald).

cc - chalcocite g - galena s - sphalerite

u - unidentified carbonaceous material



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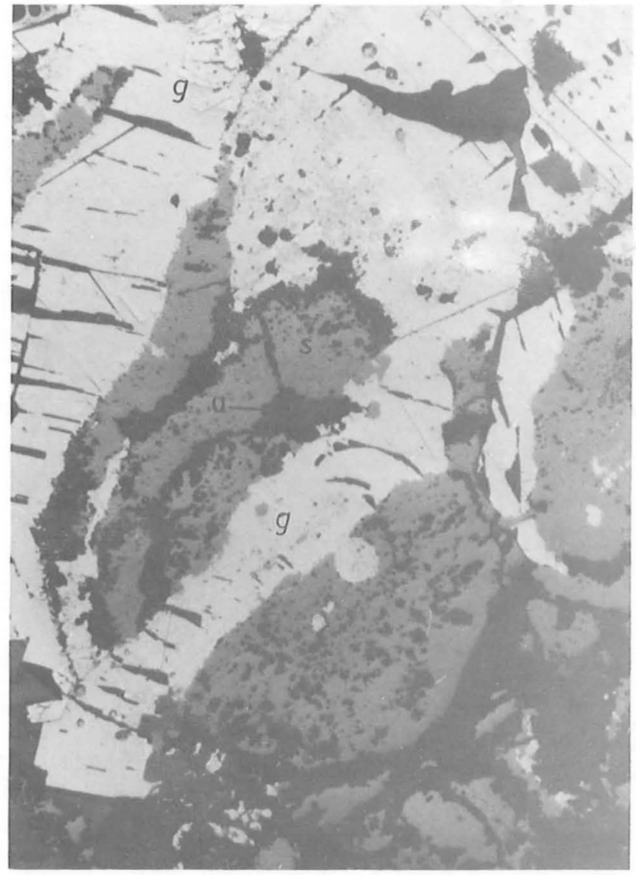

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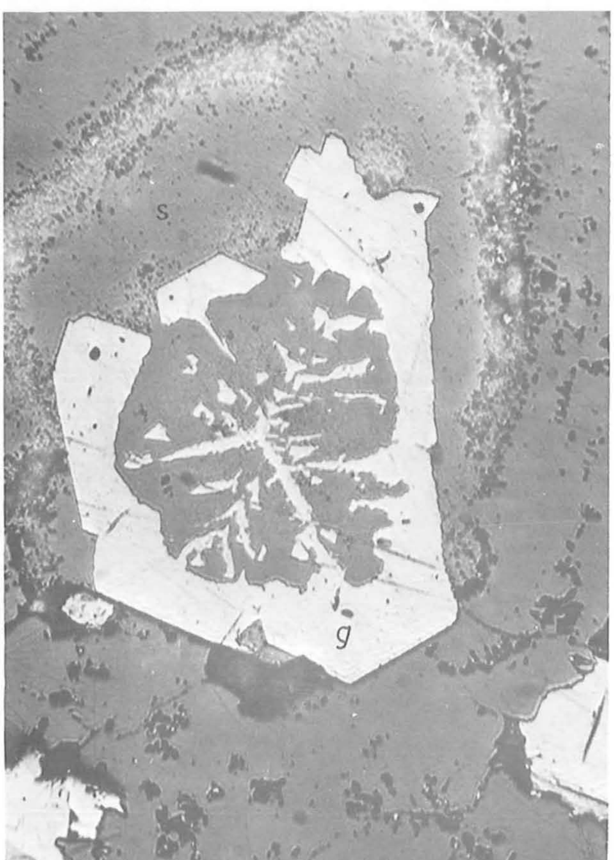


c

d

FIGURE 20

FIGURE 21

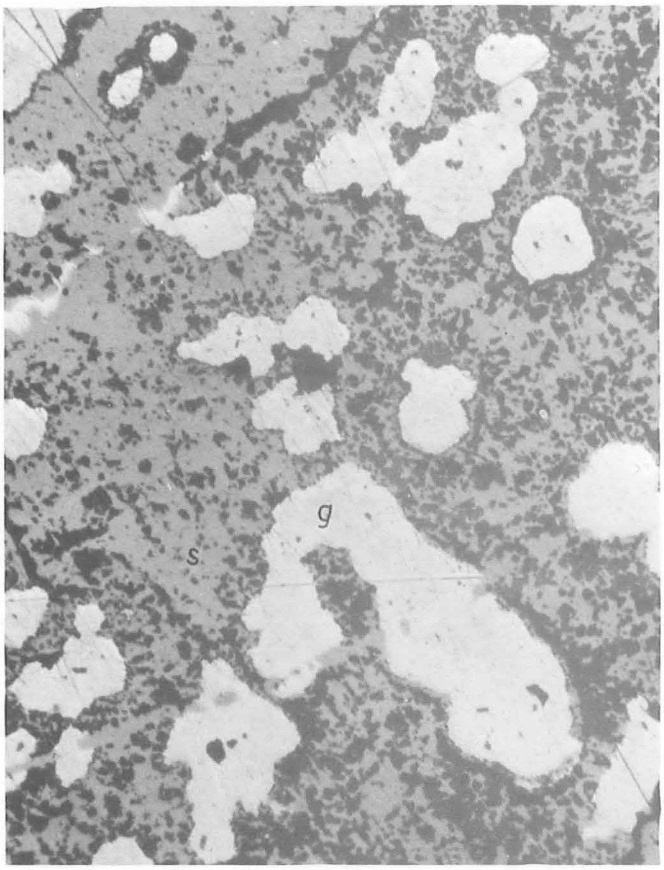
Fig.21(a) Irregular botryoidal and spheroidal galena enclosed in sphalerite with carbonaceous inclusions. Reflected light. X50. (Specimen 67.16.0395. Neg. M1088/3).

Fig.21(b) Colloform banding in sphalerite developed around galena spheroids enclosed in sphalerite. Plane polarized transmitted light. X50. (Specimen 67.16.03 Neg. 1086/25).

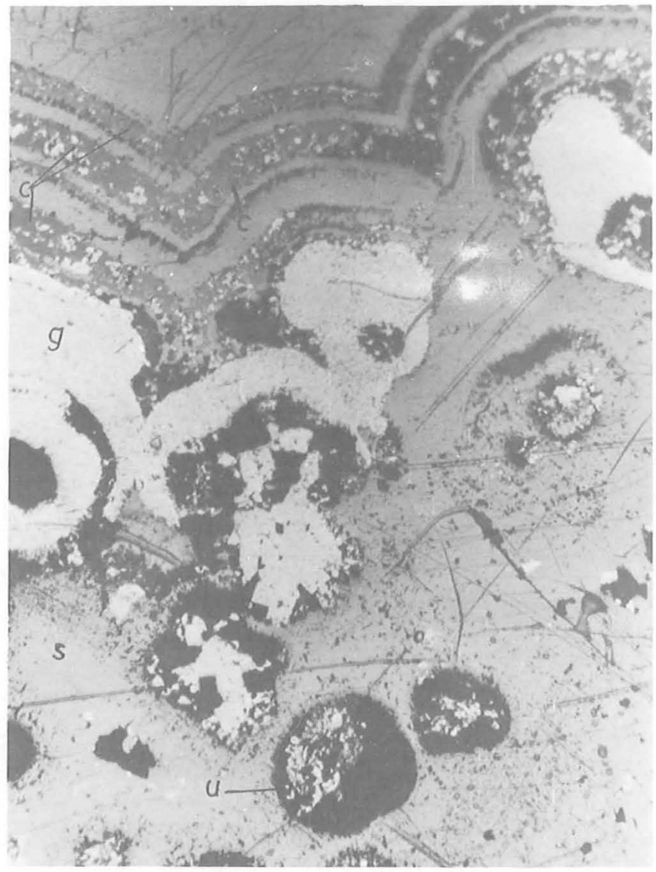
Fig.21(c) Radiating crystal structure of banded colloform sphalerite. Surface etched. Reflected light. X550. (Photograph by J.A. McDonald).

c - carbonate g - galena s - sphalerite

u - unidentified carbonaceous material



a



b

c

FIGURE 21

FIGURE 22

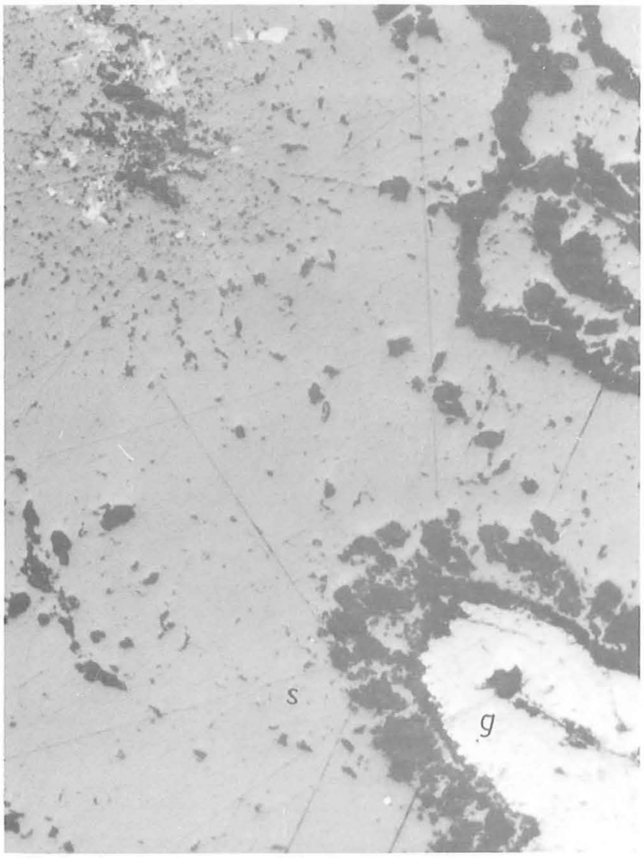
Fig.22 (a,b) Colloform sphalerite and wurtzite surrounding central core of galena (upper left), and sphalerite plus minor galena and carbonaceous material (lower right). Reflected light (a), and plane polarized transmitted light (b). Identical fields of view. (Polished thin section of specimens 67.16.0395, Negs M1132/9, 10).

Fig.22(c,d) Colloform sphalerite and wurtzite surrounding central cores of carbonaceous material plus minor sphalerite and chalcocite (centre) and sphalerite with traces of galena (upper left). Outer translucent sphalerite zone has well-formed pyramid terminations. Reflected light (d). Identical fields of view (Polished thin section of specimen 67.16.0395. Negs M1132/4, 5).

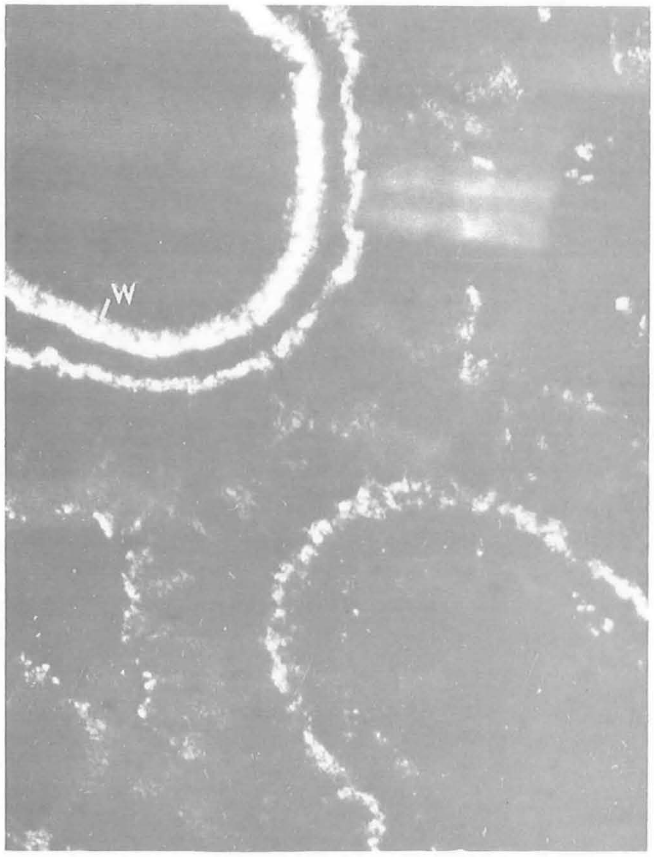
cc - chalcocite g - galena s - sphalerite

u - unidentified carbonaceous material w - wurtzite

FIGURE 22



a



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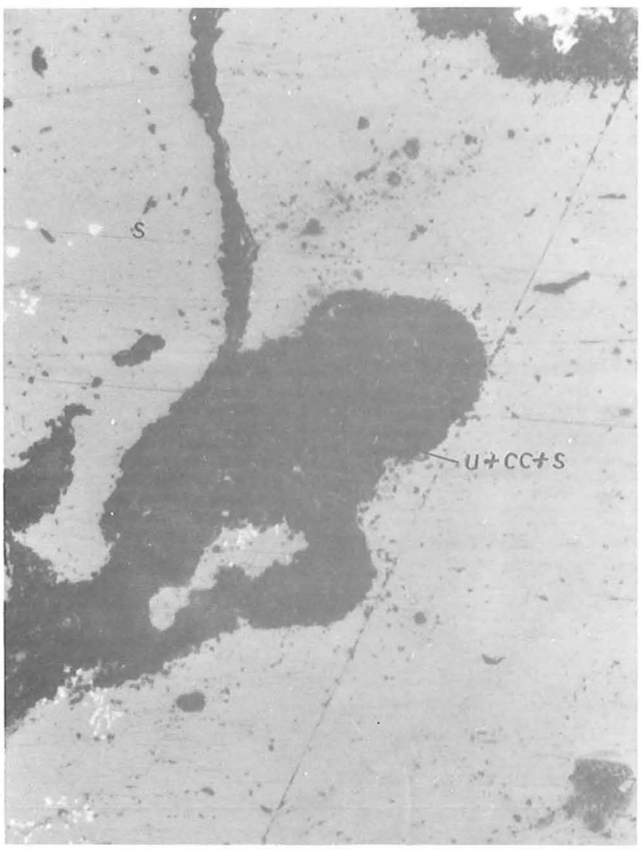


c

d

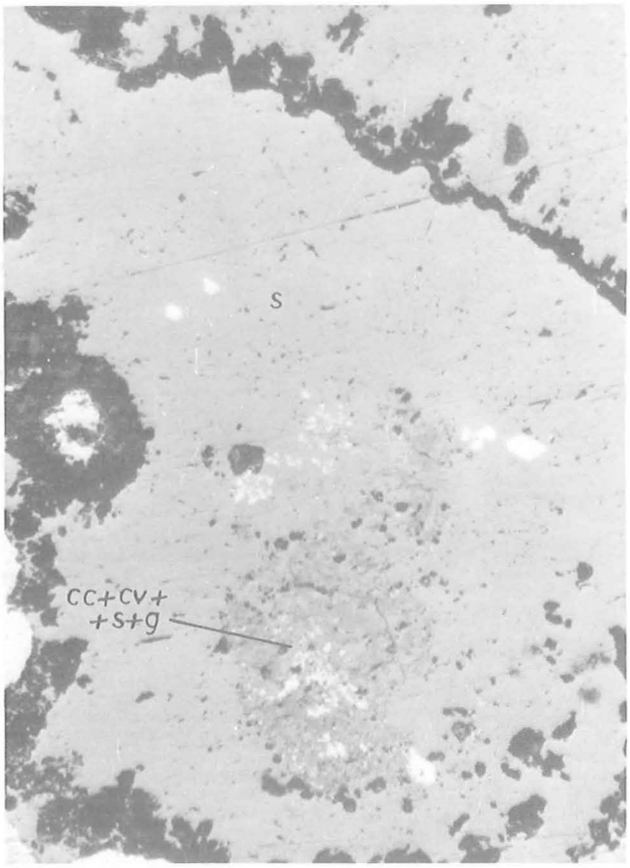
FIGURE 23

Figs.23(a,b) Colloform sphalerite and wurtzite surrounding central cores of chalcocite, covellite, galena and sphalerite (centre); galena, chalcocite and carbonaceous material (upper left). Reflected light (a) and plane polarized transmitted light (b). Identical fields of view. (Polished thin sections of specimen 67.16.0395. Negs M1132/2, 3).

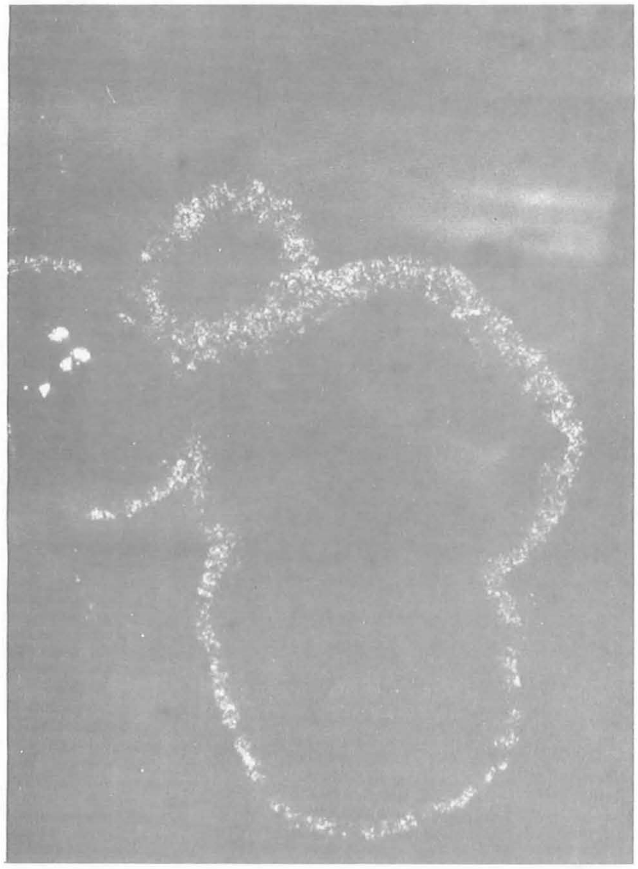
Figs.23(c,d) Colloform sphalerite and wurtzite surrounding an irregular botryoidal core of galena, chalcocite, carbonate and minor carbonaceous material. Carbonaceous material shows streaking due to imperfect polishing. Outer zone of translucent sphalerite shows well-formed pyramid terminations. Reflected light (c) and plane polarized transmitted light (d). Identical fields of view. (Polished thin section of specimen 67.16.0395. Negs M1132/14, 15).

cc - chalcocite   cv - covellite   g - galena   s - sphalerite

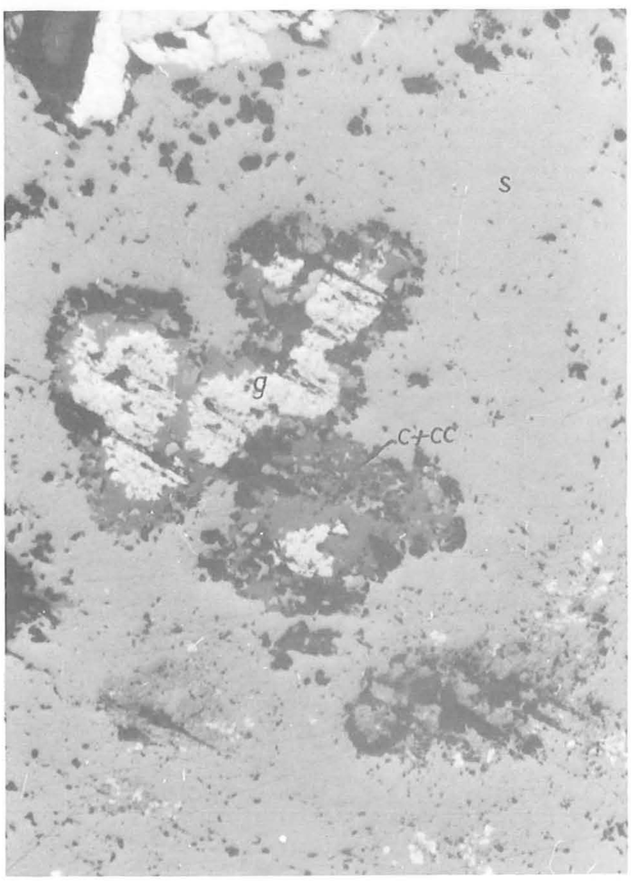
u - unidentified carbonaceous material   w - wurtzite



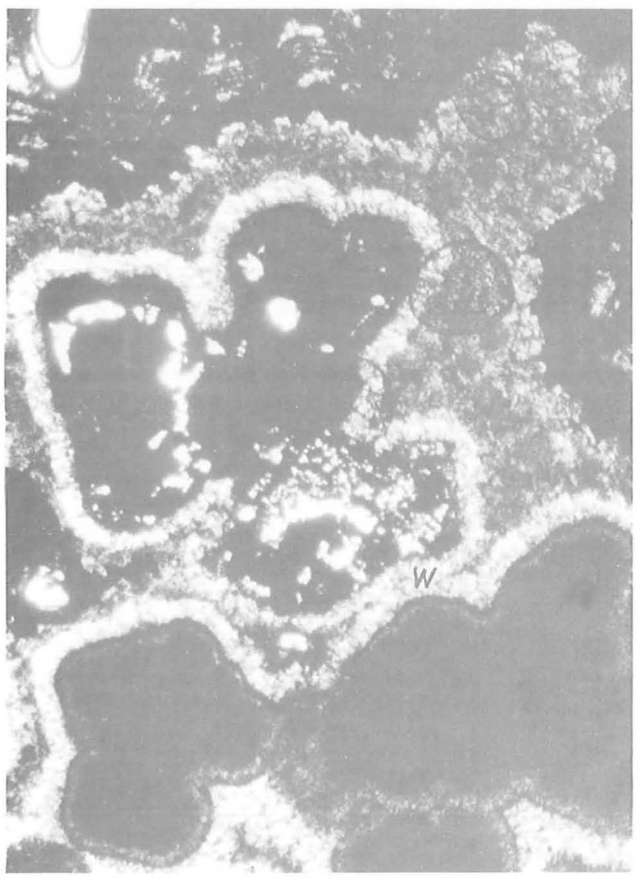
a



b



c



d

FIGURE 23

FIGURE 24

Figs.24(a,b) Colloform sphalerite and wurtzite surrounding central cores of chalcopyrite, and chalcocite and covellite. Reflected light (a). Plane polarized transmitted light (b). Identical fields of view. (Polished thin section of specimen 67.16.0395 Negs M1132/7, 8).

Figs.24.(c,d) Colloform sphalerite and wurtzite surrounding central cores of sphalerite and skeletal galena. Sphalerite shows complex zoning. Reflected light (c). Plane polarized transmitted light (d). Identical fields of view. (Polished thin section of specimen 67.16.0395. Negs M1132/11, 12).

cc - chalcocite   cpy - chalcopyrite   cv - covellite

g - galena   s - sphalerite   w - wurtzite

u - unidentified carbonaceous material

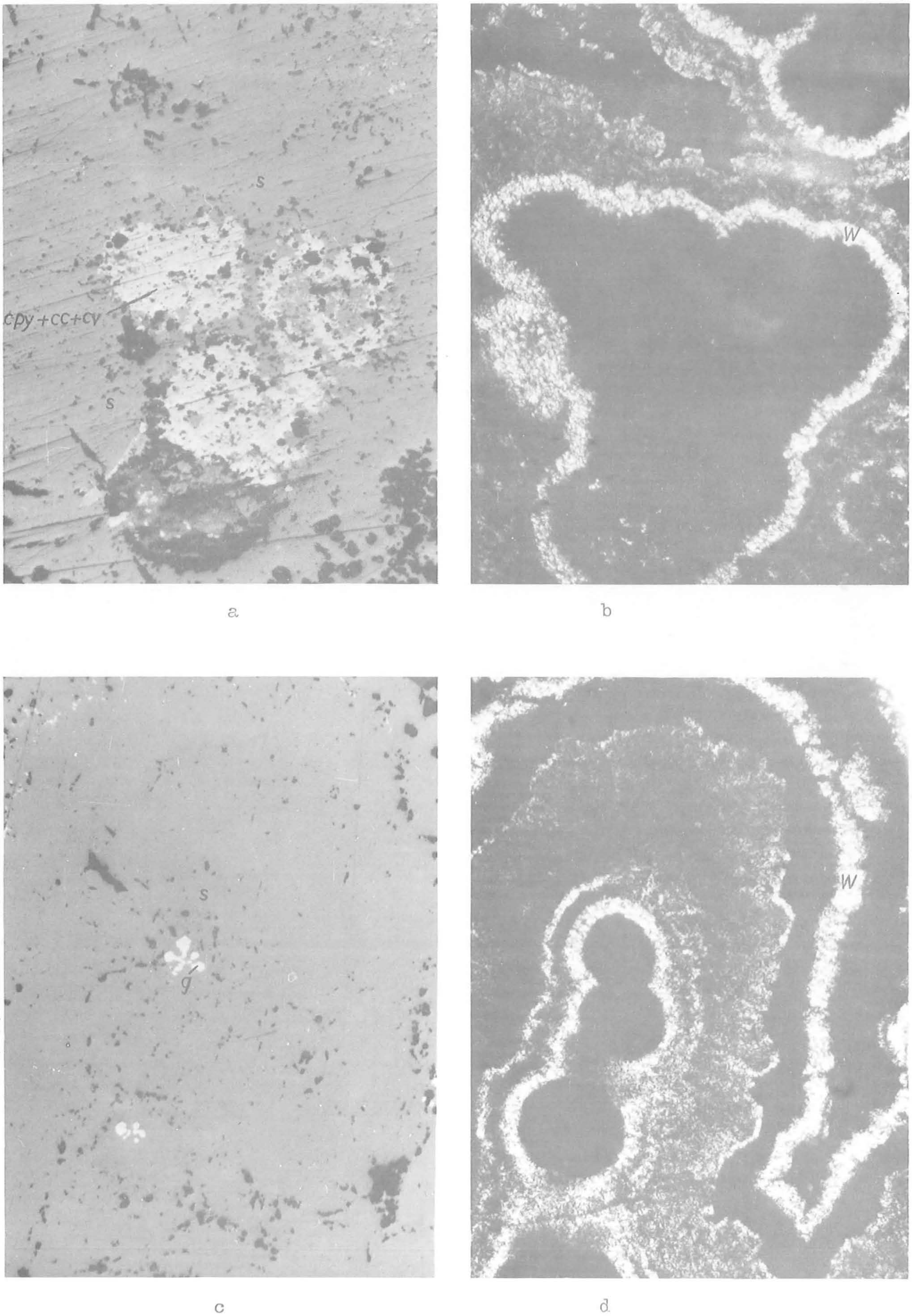


FIGURE 24