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Sheared galena; textures and microstructures

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Abstract—Detailed microstructural and X-ray texture analyses have been carried out on five examples of galena ores which have been subjected to low temperature simple shear deformation. Dislocation glide and dislocation creep microstructures were found. Kinking of lattice planes is a significant deformation mechanism in all of the samples studied. Dynamic recrystallisation along kink and deformation bands and at core-mantle boundaries leads to a grain refinement from coarse 1–3 cm grains to 40–150 μm grain size. Strong crystallographic preferred orientations are found.

In one example from the Halkyn mine (North Wales), coarse-grained galena has undergone dynamic recrystallization into very fine-grained galena (4–10 μm) which has no preferred orientation. It is inferred that Coble Creep is the dominant deformation mechanism in this very fine-grained galena.

The deformation microstructures found in this study of naturally deformed galena are similar to those found in experimentally deformed single crystals of galena. The features in the naturally deformed material indicate low temperature deformation (100–200°C) and are consistent with the theoretical predications of Atkinson (1977).

INTRODUCTION

MANY small galena deposits occur as coarse-grained veins in faults. Post-depositional movement on the faults has commonly produced a fine-grained texture with a well developed foliation known as 'steel galena' or 'bleischweif'.

In this paper the results of a detailed microstructural study (McClay 1978) of coarse-grained galena ores subjected to simple shear deformation are briefly summarised. Detailed optical and scanning electron microscopic investigations have been carried out and supplemented by X-ray texture analyses of selected samples. The results are compared with those found by Siemes (1977) and Siemes & Spangenberg (1980) and with theoretical calculations of preferred orientations using the programmes of Lister (1974).

THE VEIN DEPOSITS

Five examples of sheared galena from Yerranderie, NSW; Braubach, W. Germany; Ruth Hope Mine, British Columbia; Pibram, Czechoslovakia, and from Halkyn, North Wales were studied.

The samples are from deformed vein deposits and are essentially monomineralic galena with only minor quantities (<10%) of gangue minerals and other sulphides (Table 1). The grain sizes vary from 1–2 cm down to 5–10 μm and all samples have a very strongly developed foliation and/or lineation. From the geology of the deposits and from the structures found in the samples themselves, it is possible to infer that the original galena was deposited as large (1–3 cm) grains in open fissures and faults (McClay 1978). The deposits have large undeformed grains at the margins of the veins and a progressive decrease in grain size is observed as the shear zone develops towards the central portion of the veins. Other minerals, e.g. pyrite and sphalerite remain large and undeformed or are fractured and brecciated. It is also possible to infer that these deposits have only undergone low temperature shear deformation (probably <200°C) late in their geological history (McClay 1978). Polygonal microstructures such as those produced by annealing (McClay 1978, Clark *et al.* 1977) are not observed. In this analysis, it seems reasonable to assume that the shearing plane is parallel to the vein walls, and in the more highly deformed samples the well developed grain fabric is dominantly parallel to the vein walls and hence the shearing plane (Siemes & Spangenberg 1980). In the following section, the macrostructures found in these examples of sheared galena are described.

GRAIN FABRICS

All of the five deposits exhibit a well developed grain fabric (Table 1). In the Pibram galena which appears to have undergone the least amount of shear, large lozenge-shaped galena grains (1000–1500 μm × 400–500 μm × 400 μm) have their long axes at 30–40° to the vein walls (i.e. shear plane). In the other deposits, of which the Yerranderie galena (Fig. 1) is typical, there is a progressive increase in the shape fabric with a concomitant decrease in grain size as the large (cm) grains at the margins undergo increasing deformation towards the centre of the sample. The shape fabric becomes strongly developed and the foliation curves into parallelism with the shear plane (Fig. 1). The grain fabrics for all examples are summarized in Table 1.

MICROSTRUCTURES

Polished sections and cleavage fragments were etched with the Brebrick & Scanlon (1957) etchant (details given in McClay 1977). On large polished slabs etching

Table 1. Summary of microstructures and textures of the sheared galena deposits

DEPOSIT	MINERALOGY MAJOR	MINERALOGY MINOR	GRAIN FABRIC	GALENA GRAIN SIZE INITIAL?	GALENA GRAIN SIZE RECRYSTAL-LIZED	MECHANISMS IDENTIFIED	CRYSTALLOGRAPHIC PREFERRED ORIENTATIONS	COMMENTS
PIBRAM Czechoslovakia	Galena	Tetrahedrite, pyrite, quartz, carbonates	Strong lozenge shaped fabric, grains with axes 30°-40° to vein walls	1-2cms	200-300μm polygonal where developed	Dislocation glide, kinking, microcracking	[001] poles at low angle to shear plane	Low temperature, low confining pressure, slight polygonisation
RUTH HOPE Slocan British Columbia	Galena	Tetrahedrite, sphalerite, calcite	Strong lineation, prolate grains up to 5:1 ratio, curving foliation mainly parallel to shear plane	2-5cms	70-150μm elongate 1.5-3:1 ratios	Glide, kinking, polygonisation, dynamic recrystallization	[110] towards lineation [001] symmetric about foliation plane, well developed	Low temperature, dynamic recrystallization
BRAUBACH West Germany	Galena	Boulangerite	Strongly developed foliation, weak lineation	?	50-150μm slightly prolate, parallel to lineation	Dislocation creep, kinking, dynamic recrystallization, slight grain growth	[001] parallel to foliation [110] towards lineation, well developed	Similar to Siemes (1977, 1979)
YERRANDERIE NSW Australia	Galena	Pyrite tetrahedrite, quartz, ankerite	Well developed foliation, curving into parallelism with shear plane	1-2cms	50-100μm prolate	Dislocation creep, kinking, dynamic recrystallisation	[001] towards foliation plane, [110] perpendicular to foliation, well developed	Possible flattening component
HALKYN North Wales	Galena	Sphalerite	Ultra fine grained, well developed foliation, large lozenge shaped grains	2-3cms	5-10μm equant polygonal grains	Initially dislocation creep and dynamic recrystallization, diffusional creep	No preferred orientation	Galena mylonite, very low deformation temperature (McClay 1978)

was achieved using 48% hydrobromic acid.

The brevity of this contribution prevents any detailed exposition of microstructures found in the five deposits. A number of representative photomicrographs are presented to illustrate the microstructures found in these ores (Fig. 2).

The sheared galena ores typically exhibit a well defined foliation of small new grains around lozenge shaped augen of old grains (Fig. 2A). The large grains are commonly traversed by kink bands and deformation bands which are sites for recrystallisation (Fig. 2B). In the areas of most intense deformation the foliation is outlined by bands of polygonal grains (Fig. 2C). Second phase particles (tetrahedrite and/or boulangerite) are concentrated at the grain boundaries and triple junctions. In other ores such as Yerranderie (Fig. 2D), the foliation is defined by bands of elongate grains of similar orientation. Augen grains show the development of subgrains with recrystallization at the margins (Fig. 2E). Recrystallization is concentrated along kink and deformation bands (Fig. 2F) and this may give rise to secondary foliation at a low angle to the shear plane.

Scanning electron microscope studies have been carried out on etched cleavage fragments from all deposits (McClay 1978). Sub-grain boundaries within kink bands are particularly well delineated (Fig. 2G). In the Halkyn ore, the recrystallized galena has an extremely small grain size (~5 μm). In this example, one of the recrystallization mechanisms is interpreted as sub-grain rotation in a core–mantle structure (Fig. 2H).

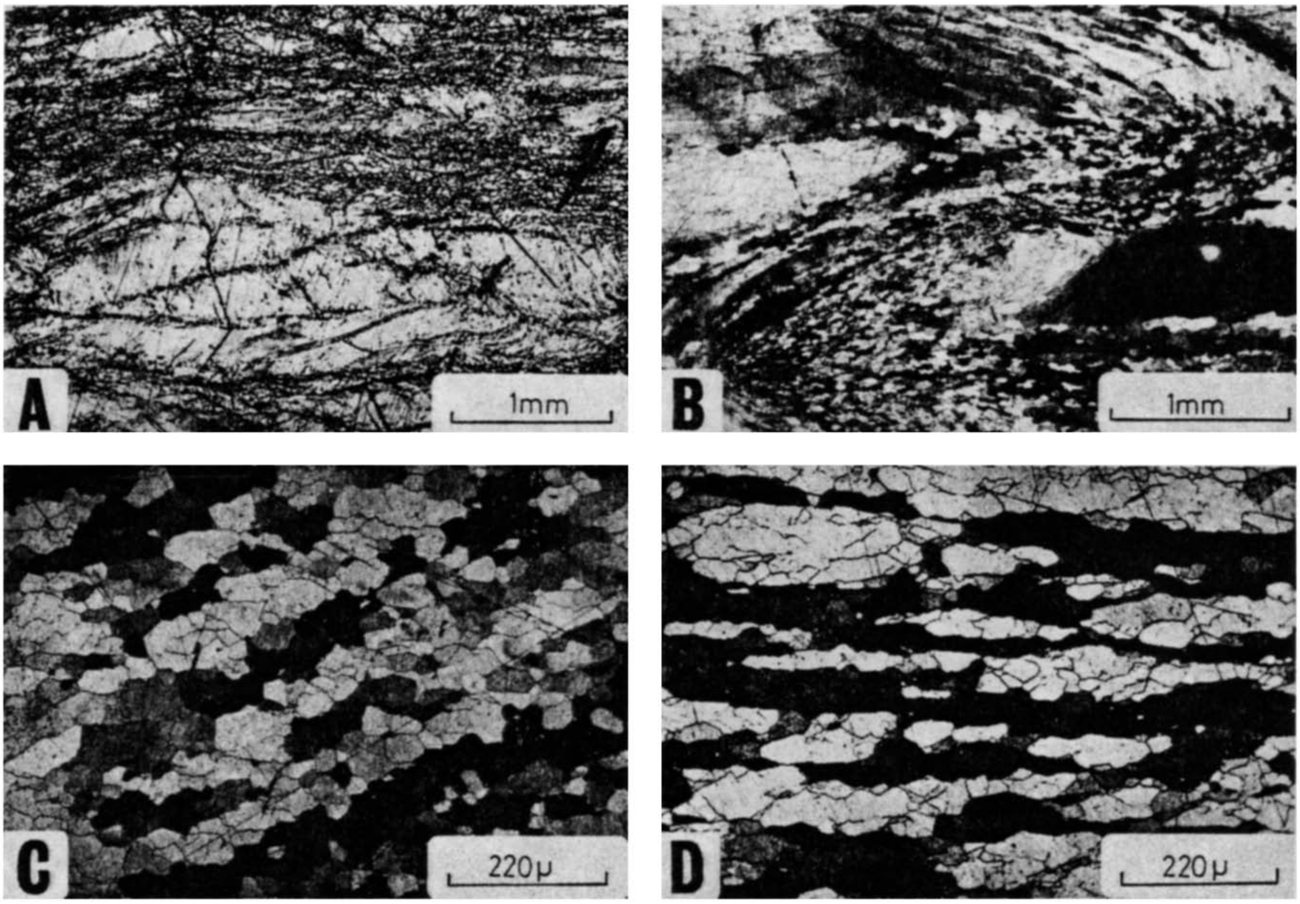
CRYSTALLOGRAPHIC PREFERRED ORIENTATIONS — TEXTURES

X-ray texture goniometry was carried out on samples from all five deposits and the results are summarized in Table 1. In all but the Halkyn ore, strong crystallographic preferred orientations had developed (Fig. 3). The pole figures for Yerranderie are similar to those for other deposits (except Halkyn) in that the peaks are strong and similar to single crystal configurations. More than one orientation component was found (discussed by Siemes & Spangenberg 1980). In general the [001] poles tend to lie in or towards the foliation plane (shear plane) and the [110] poles in the shear (lineation) direction. Preferred orientations in laminated galena are discussed more fully by Siemes (1980). Pole figures for Halkyn ores are shown in Fig. 4. These show no preferred orientation of the galena lattice planes. Computer simulations using a Taylor–Bishop–Hill model (Lister 1974) were made for simple shear in galena by Dr. G. Lister (personal communication). It is important to note that the computer simulations show only weak preferred orientations for large strains (McClay 1978).

DISCUSSION AND CONCLUSIONS

Galena has two principal slip systems, {100} <011> and {110} <1$\bar{1}$0>. At temperatures up to 300°C {100} <011> is the dominant system with the lower critical

Fig. 1. Photograph of an acetate peel of a sample of sheared galena from Yerranderie, NSW. The sense of shear is dextral. Note the curving foliation delineated by kink bands. Section cut normal to the foliation and parallel to the lineation (horizontal).



Figs. 2 (A) to (D) captions on p. 231.

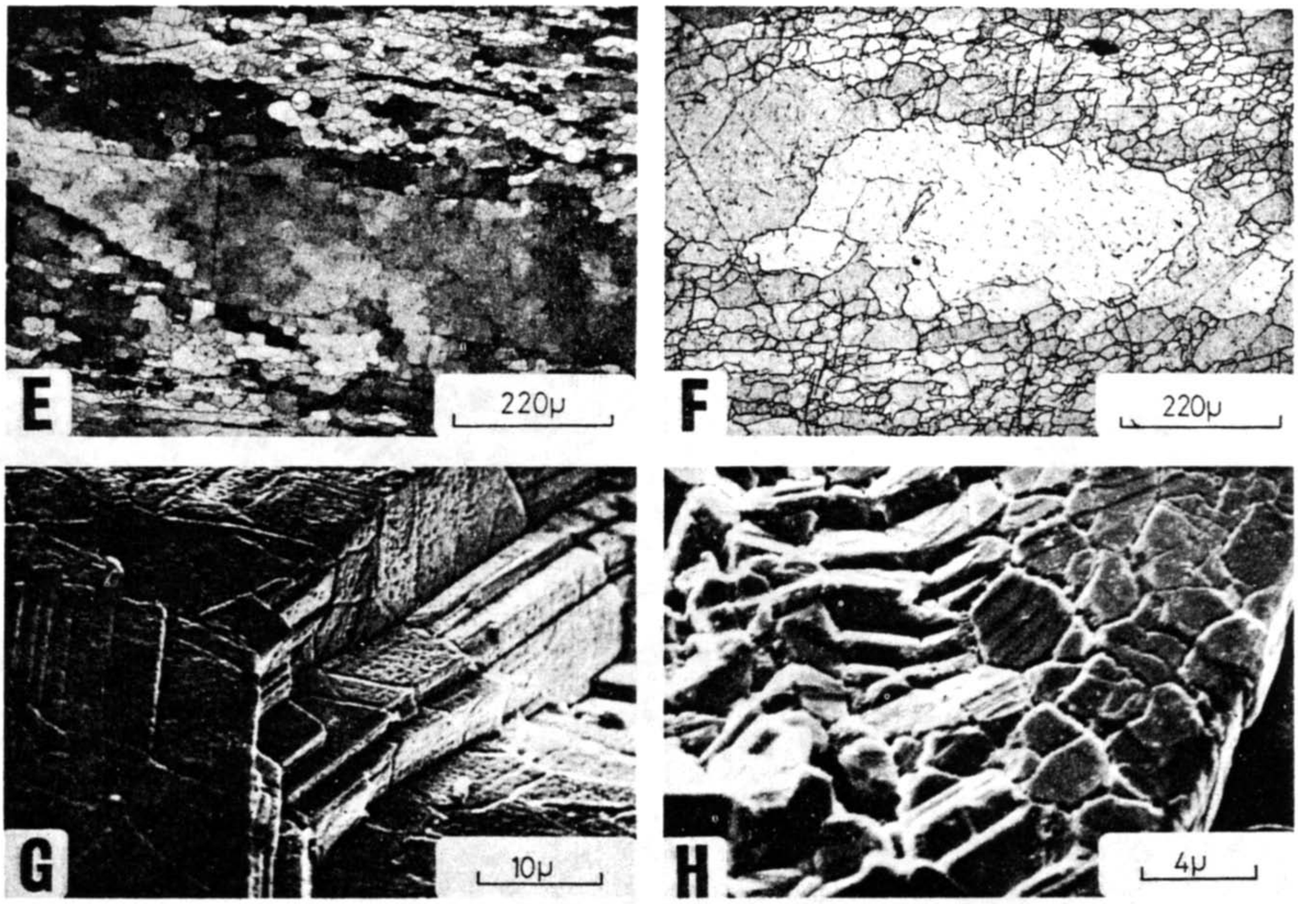


Fig. 2. Microstructures in sheared galena. (A) Lozenge-shaped old grain in Halkyn galena showing kinked cleavage traces. Note recrystallization along kinks and at grain boundaries to give very fine-grained strongly foliated matrix. The sense of shear is dextral. Etched polished section. (B) Recrystallization along kink and deformation bands with largely undeformed augen galena grains. The sense of shear is sinistral. Etched polished section, Ruth Hope mine. (C) Polygonal grains in banded structure in relict kink bands. The sense of shear is dextral. Braubach etched polished section. (D) Strong preferred orientation indicated by recrystallized grains along relict kink bands. The sense of shear is sinistral. Etched polished section, Yerranderie, NSW. (E) Augen structure of large old grain with subgrains surrounded by fine-grained recrystallized galena. The sense of shear is sinistral. Etched polished section, Yerranderie, NSW. (F) Dynamic recrystallization along kink bands. Section perpendicular to foliation and parallel to lineation. The sense of shear is sinistral. Yerranderie, NSW. (G) Etched cleavage fragment of Yerranderie galena showing kink band with elongate subgrains. Scanning electron micrograph. (H) Etched cleavage fragment of Halkyn galena showing progressive misorientation of subgrains in core-mantle structure. Note the very small recrystallized grain size.

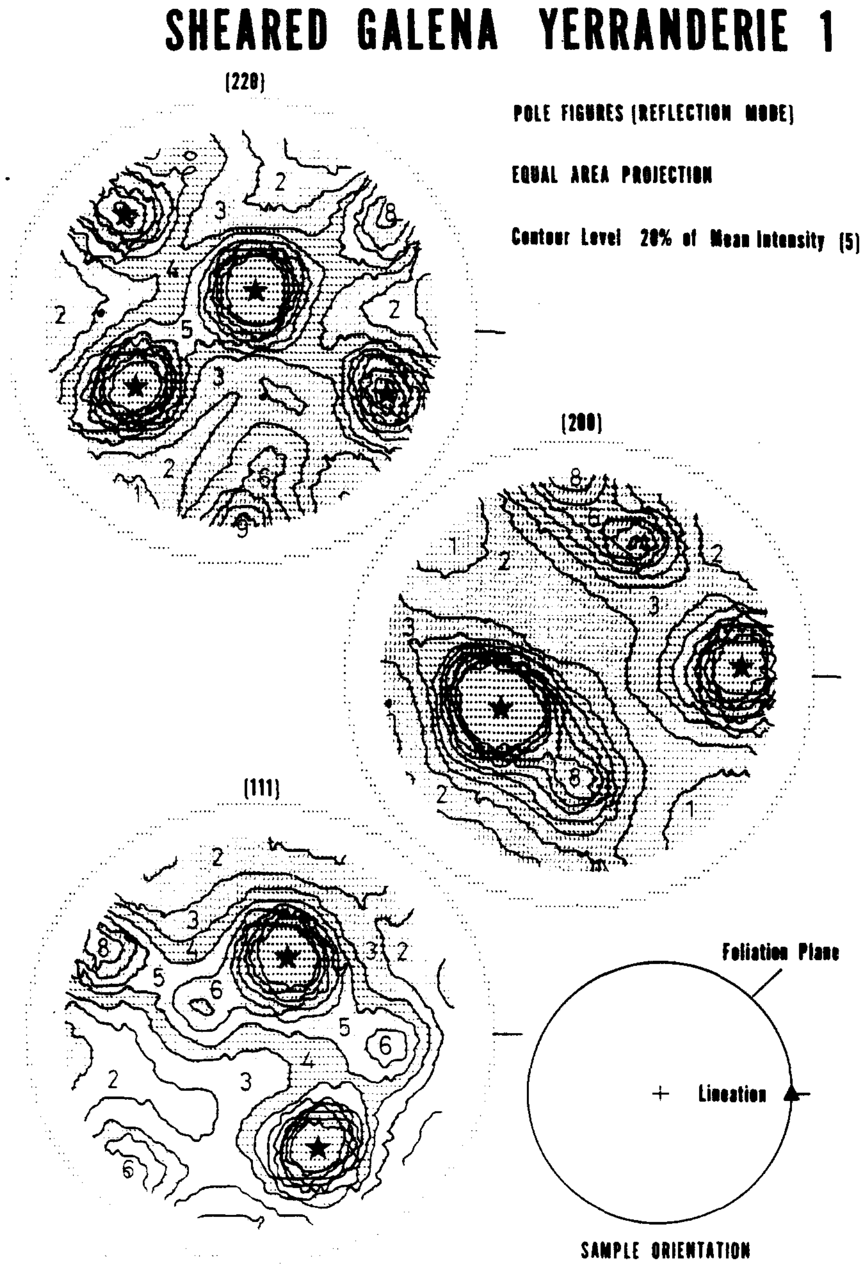


Fig. 3. Partial X-ray pole figures of Yerranderie galena. Contour levels are 20% of the mean intensity (5). Stars indicate maxima greater than 120% of the mean intensity.

resolved shear stress (McClay 1978). The slip features and kink bands observed in this study are consistent with {100} <011> being the dominant system. Dynamic recrystallization microstructures are found along kink bands, deformation bands and in core–mantle structures in a manner analogous to that described in quartz (White 1976). The strong preferred orientations found in four of the five ores indicate that dislocation creep and glide are the dominant deformation mechanisms during low temperature shearing of coarse-grained galena. These results are consistent with the theoretical predictions of Atkinson (1977).

In the Halkyn ore, the large relict old grains exhibit dislocation creep and glide structures (slip lines, kinking, dynamic recrystallization). Dynamic recrystallization in kink bands, deformation bands and at core–mantle boundaries, however, leads to a reduction in grain size from cm to 1 to 4–5 μm. The equant grain shapes, straight grain boundaries and lack of crystallographic preferred orientations permits one to infer that these small recrystallized grains are deformed principally by diffusional creep. From the theoretical work of Atkinson (1977) it is possible to demonstrate that such fine-grained galena would deform mainly by Coble Creep (grain boundary diffusion and grain boundary sliding) under geological strain rates (10^{-12}–10^{-14} s^{-1}).

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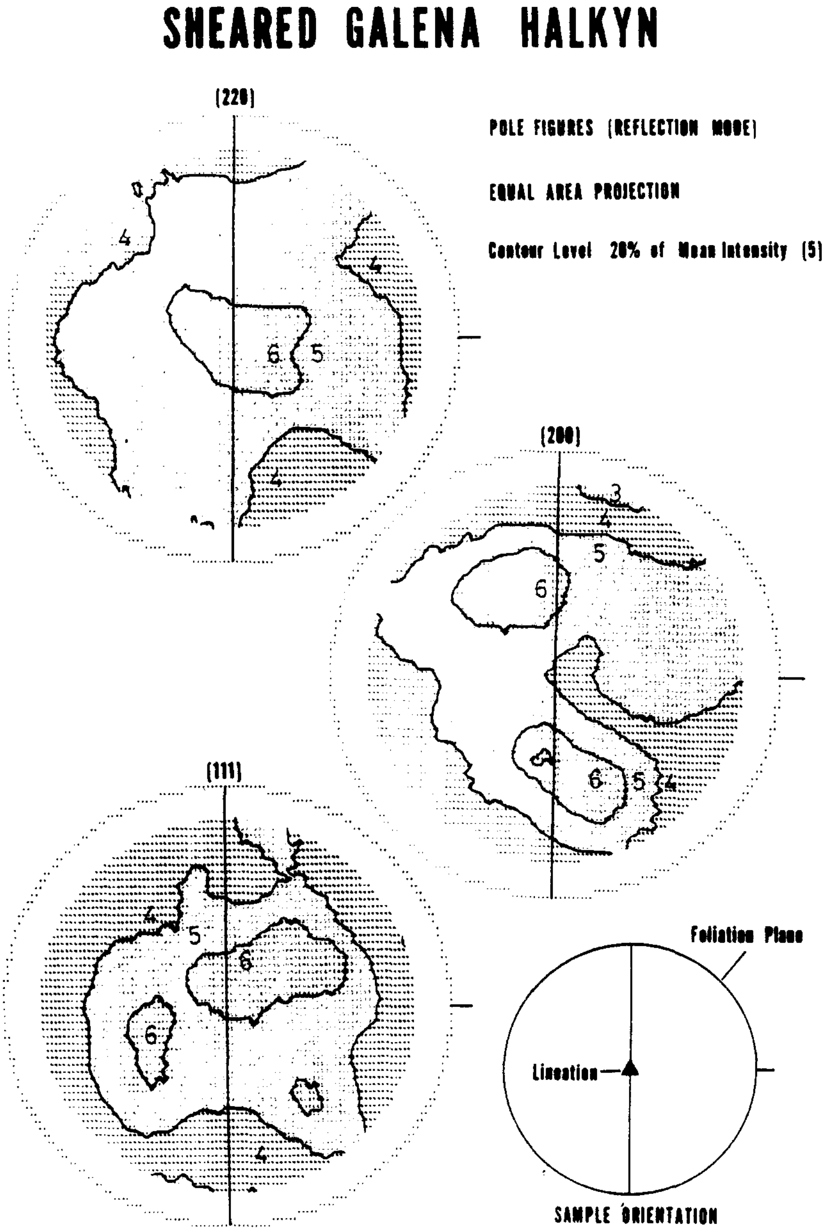

Fig. 4. Partial X-ray pole figures of Halkyn galena. Note the lack of preferred orientation. Contour levels as in Fig. 3.

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