Economic Geology
Vol. 65, 1970, pp. 579–582

Further Notes on the Deformation of Sulfides

J. E. Gill

Abstract

Results of recent triaxial compression experiments on sulfides, performed in the laboratories of the Technischen Hochschule Aachen (Siemes, 1967; Saynisch, 1967; Lang, 1968), show that galena, sphalerite and chalcopyrite can be made to flow plastically under ordinary laboratory temperatures if the confining pressure is above 300 bars for galena and above 1,000 bars for sphalerite and chalcopyrite. These results are used with those obtained from intrusion experiments at McGill University (see Gill, 1968) to arrive at a view of the behavior of each of these sulfides when stressed at various depths within the outer part of an average continental crust. This leads to a consideration of textural changes expectable as a result of mechanical deformation of sulfide orebodies including these minerals. The results would depend on the composition and texture of the original ore, and could differ markedly because of differences in confining pressure (depth), stress difference, strain rate or temperature.

SINCE publication of the article entitled "Experimental Deformation and Annealing of Sulfides and Interpretation of Ore Textures," I have received from the Institut für Mineralogie und Lagerstättenlehre of the Technischen Hochschule Aachen through the courtesy of Dr.-Ing. Heinrich Siemes the results of recent deformation experiments on polycrystalline galena, sphalerite and chalcopyrite at ordinary laboratory temperatures (Siemes, 1967; Saynisch, 1967; Lang, 1968). These were performed with triaxial compression equipment using confining pressures up to 5,000 bars and stressing to failure at strain rates of 0.3×10^{-3} sec^{-1} to 0.3×10^{-5} sec^{-1}. Some of the results of significance in relation to the interpretation of ore textures are shown graphically in Figure 1. The data chosen were obtained from tests on the purest material used in each set of tests.

Textures of all test specimens were investigated before and after deformation, and it was found that original textures were progressively superceded by others with marked lineation parallel to the axis of greatest pressure. X-ray studies showed that the crystallographic direction with this preferred position was [110] in all three minerals.

A few experiments on fine-grained pyrite from Rio Tinto failed to produce pervasive plastic flowage. Strengths ranged from 7,500 bars stress difference at 1,000 bars confining pressure to 15,000 to 17,000 bars at 5,000 bars confining pressure. Handin had previously reported ultimate strengths for pyrite from Utah at 24° C as 1,470 bars with no confining pressure and 5,000 bars with 490 bars confining pressure (Handin, 1965, p. 263).

Figure 2 was designed to represent average P-T conditions in continental crust and to relate results of the Aachen and McGill experiments to them. The depth scale is distorted slightly to preserve uniform pressure and temperature scales. Line e d m shows one estimate of average P-T in relation to depth below the earth's surface. Points a, b and c were obtained by projecting curves from intrusion experiments on galena as described in the paper referred to above (Gill, 1969, Fig. 8) to zero intrusion. Their positions are approximate, especially that of c, but the general position and shape of the curve must be about as shown. Its intersection with e d m, point d, marks the level in the crust below which intrusion into tubular openings 1.6 mm in diameter could occur.

At a depth of 1.25 km the confining pressure is 300 bars (o e in Fig. 2) and the temperature 25° C. From Figure 1 it is seen that plastic flow in galena starts where the stress difference exceeds 750 bars. This is plotted as e f in Figure 2. At the same temperature o k is the best estimate now possible of the applied pressure required for intrusion flow. It should be possible to work out a precise mathematical expression relating the stress difference required to initiate plastic flow in triaxial compression experiments to the applied pressure required to initiate plastic intrusion into openings of a specified size. This has not been done, but it seems clear that the stress difference required would be less at higher temperatures, so in Figure 3, line f g h has been drawn on the assumption that, at any given temperature, the stress difference required to produce flow in triaxial compression experiments is related to the applied pressure in the McGill intrusion experiments by a constant factor given by ef/ok = 0.4.

Figure 1 shows that the stress difference required to initiate plastic flow in galena also varies with the confining pressure. Line f i j in Figure 2 was

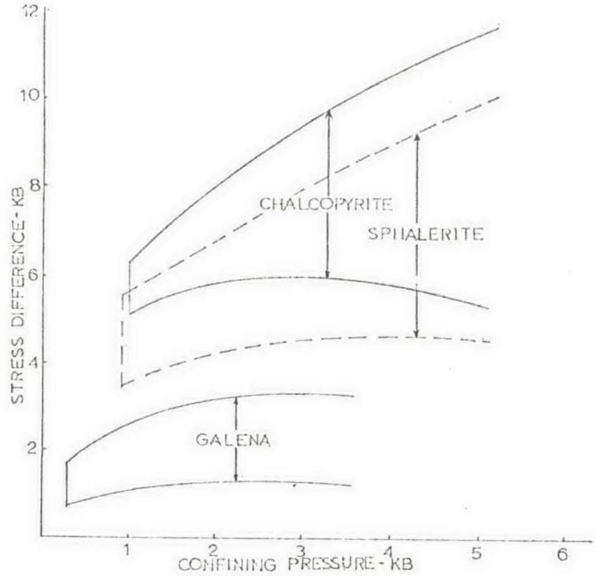

FIG. 1. Range of plastic flow for galena, sphalerite and chalcopyrite as determined by triaxial deformation experiments at laboratory temperature and at strain rates between 0.3×10^{-3} sec^{-1} and 0.3×10^{-5} sec^{-1}. Flow occurs only to the right of the vertical line connecting two curves for each of the three minerals. The lower curve gives the stress difference at which pervasive plastic flow commences. The upper curve gives the maximum stress difference sustained before rupture. Data from Siemes (1967), Saynisch (1967) and Lang (1968).

obtained by applying this correction. Thus at the depth marked by the line n d g i in Figure 2, n d represents the confining pressure and d i the approximate stress difference required to initiate plastic flow.

According to Siemes' data on galena, increase in stress difference at strain rates above 0.3×10^{-5} sec^{-1} would eventually produce rupture. At confining pressures higher than 300 bars a substantial amount of plastic flow would occur before rupture, the amount increasing with increase in confining pressure (see Fig. 1).

The line at 4.5 km depth in Figure 2 marks the level at which the confining pressure is approximately 1 kb and, therefore, the level below which sphalerite and chalcopyrite will flow plastically at 25° C (see Fig. 1). It appears probable that, because the temperature at this depth is 86° C or possibly higher, plastic flow may start at a shallower depth, but there is, at present, no precise information on this.

According to Saynisch, (1967) and Lang, (1968) the stress difference necessary to initiate plastic flow at 1 kb confining pressure and 25° C is around 3,500 bars for sphalerite and 5,000 bars for chalcopyrite. The higher temperature should also reduce these requirements.

All three sulfides would develop textures with dimensional and optical preferred orientation of grains as a result of plastic flow in the temperature range of Figure 2.

Figure 3 shows relations similar to those in Figure 2, but with a steeper temperature gradient, such as might result from batholithic intrusion. Data for galena are as before. Galena at a depth of 1.25 km (point d) should flow at a stress difference of less than 750 bars because the temperature is 100° C, under the conditions assumed. At 4/10 of the applied pressure for flow in the mullite tube experiments, it should start at around 560 bars stress difference (de). The relations at greater depth would be a vertically foreshortened version of those shown in Figure 2.

Points i, j and k in Figure 3 represent applied pressures and temperatures at which one might expect intrusion of chalcopyrite to start in mullite tube experiments similar to those conducted by Krishnamurthy (1967). Points a, b and c represent P-T conditions for recrystallization of chalcopyrite, as observed by him. Plastic flow into cracks should

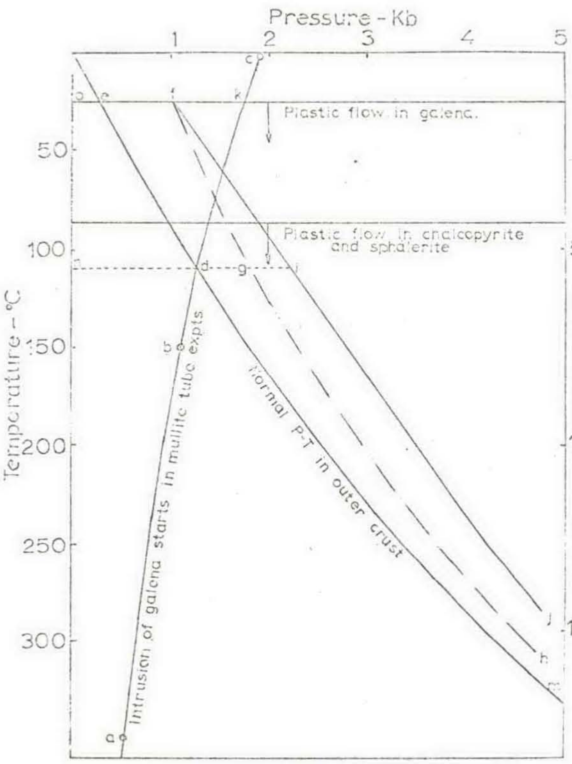

FIG. 2. Line e d m represents one view of P-T relation in the outer part of average continental crust. o e represents the confining pressure (300 bars) and e f the stress difference at 1.25 km depth, where galena should start to flow at 25° C. Line a b c marks the initiation of intrusion as deduced from the mullite tube experiments (by projection of curves in Fig. 8, Gill, 1969). The horizontal distance from e d m to f i j gives the stress difference required to produce flow at greater depths. The significance of line f g h is explained in the text. Data from Davies (1965), Siemes (1967), Saynisch (1967), Lang (1968).

occur below the depth marked by point k and recrystallization below the depth of point m.

The increased temperature should cause plastic flow of all three minerals to occur at depths shallower than those shown. At the present time there appears to be no quantitative information on this point. The stress differences required to initiate plastic flow at the minimum confining pressures required at 25° C are reduced at increased temperatures. This has been discussed for galena. Data are less satisfactory for chalcopyrite, but the trend of the curve for intrusion suggests that a relation between stress difference for plastic flow in triaxial compression and applied pressure in intrusion experiments may be similar. There is no experimental evidence bearing on this relation for sphalerite, but it appears to be reasonable to assume analogous behavior.

Information from Roberts (Gill, 1969) indicates that recrystallization does not occur in sphalerite as readily as in chalcopyrite.

Results obtained by H. C. Heard in his experiments on Yule Marble (1963) suggest that, at much lower strain rates, a steady state of deformation of galena, sphalerite or chalcopyrite could be attained at stress differences well below the maxima shown in Figure 1. At elevated temperatures the stress differences required would be still lower.

The curves shown for galena and chalcopyrite intrusion on Figure 3 are based on the results of experiments lasting only about 2½ hours each. R. L. Stanton and Helen Gorman (1968) have studied the textural results of heating natural polycrystalline sulfide ores in sealed, evacuated glass capsules for periods up to 90 days. They obtained clear evidence of grain boundary migration in galena, sphalerite and chalcopyrite and deduced, by projection of graphs, that this process could start in galena at around 20° C and in sphalerite at 60° C. No figure was obtained for chalcopyrite.

The minor adjustments studied by Stanton and Gorman could, if accompanied by persistent slow strain, result in substantial changes over long periods of time. They could not in themselves produce the textural effects of major plastic flow, nor could they replace an old, dimensionally oriented texture by a new mosaic of more or less equidimensional grains, as occurs with recrystallization.

The information now available indicates that if a mixture of galena, sphalerite, chalcopyrite and pyrite at a depth of 3 km in the continental crust were subjected to increasing stress, galena would flow at a stress difference of about 700 bars, continuing until the movement brought grains of stronger minerals into contact. If the strain rate were relatively high, galena could fail by rupture before this occurred.

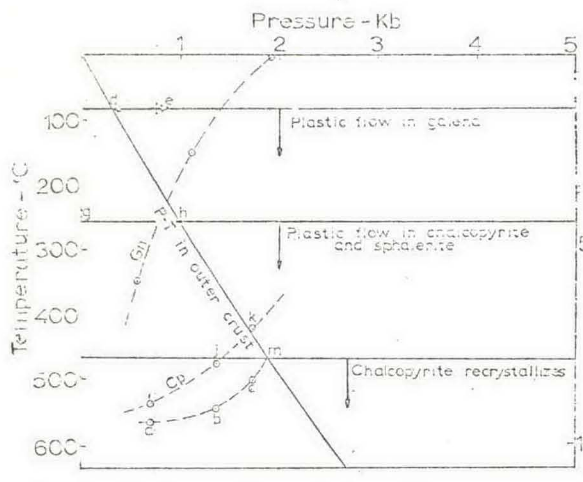

Fig. 3. Similar to Figure 2, but with a steeper temperature gradient. Data from intrusion experiments on chalcopyrite are added. Line i j k marks the beginning of appreciable plastic flow. Line a b c marks the start of recrystallization. The levels shown for the start of plastic flow may be adjusted upward when more experimental data are available. Data from Davies (1965), Krishnamurthy (1967), Siemes (1967), Saynisch (1967) and Lang (1968).

If the strain rate were very low, rupture of galena would probably not result. If the deformation of galena were to transfer the bulk of the load to sphalerite or chalcopyrite, they would fail by shearing at stress differences of around 600 bars, and galena could be forced into any openings created. If stress were then transferred to pyrite, rupture of pyrite would occur at a stress difference of around 6,000 bars. Galena and/or granulated sphalerite or chalcopyrite, or a mixture of these would be forced into the cracks or around fragments of pyrite.

At a depth greater than 5 km galena would flow first. At rapid strain rates it should shear at a stress difference of around 3 kilobars. If the rearrangement were to transfer the increasing load to sphalerite, this would start to flow at a stress difference of around 4 kilobars, and chalcopyrite would flow at about 5.5 kilobars. Either could move plastically to positions of reduced pressure created by complexities of transmission in such a mixture. At rapid strain rates sphalerite could shear at a stress difference of 6 to 6.5 kilobars, and chalcopyrite could shear at 7 to 7.5 kilobars. At low strain rates flow would continue until the stress build-up was transferred to pyrite. Continued increase in stress would ultimately cause rupture of pyrite. Galena, sphalerite and chalcopyrite should then penetrate rupture surfaces and flow around pyrite fragments. If the temperature were raised to 560° C, chalcopyrite would recrystallize to a mosaic texture and flow would be relatively rapid. In these circumstances the mobility of sphalerite and chalcopyrite may be in a reverse relationship to that at the start of flow because the few tests that have been made indicate that sphalerite recrystallizes only at temperatures well above 560° C.

McGill University,
Montreal, Canada,
January 28, 1970

REFERENCES

Davies, Raymond, 1965, Unpublished report, Department of Geological Sciences, McGill University, Montreal, Canada.

Gill, J. E., 1969, Experimental deformation and annealing of sulfides and interpretation of ore textures: Econ. Geol., v. 64, p. 500-508.

Handin, John, 1966, Strength and ductility. *In* Handbook of Physical Constants: Geol. Soc. America, Mem. 97.

Heard, H. C., 1963, Effect of large changes in strain rate on the experimental deformation of yule marble: Jour. Geol., v. 71, p. 162–195.

Krishnamurthy, P., 1967, Experimental deformation of sulphide ores: Unpublished M.Sc. Thesis, McGill University, Montreal, Canada.

Lang, Helmut, 1968, Stauchversuche mit polykristallinen Kupferkiesen und deren Ergebnisse unter besonderer Berücksichtigung der Gefügeregelung: Dr.-Ing. Dissertation Rheinisch-Westfälischen Technischen Hochschule Aachen.

Roberts, R. G., 1965, Notes on annealing experiments on pyrrhotite and sphalerite: Unpublished report, Department of Geological Sciences, McGill University, Montreal, Canada.

Saynisch, Hans J., 1967, Festigkeits- und Gefügeuntersuchungen an Zinkblenden: Dr.-Ing. Dissertation, Rheinisch-Westfälischen Technischen Hochschule, Aachen.

Siemes, Heinrich, 1967, Experimentelle Stauchverformung von polykristallinen Bleiglanzen: Facultät für Bergbau und Hüttenwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen.

Stanton, R. L., and Gorman, Helen, 1968, A phenomenological study of grain boundary migration in some common sulfides: Econ. Geol. v. 63, p. 907–923.