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MICROSCOPIC CORDIERITE IN FUSED TORRIDONIAN ARKOSE

P. J. WYLLIE*

The Pennsylvania State University, University Park, Pa.

ABSTRACT

Progressive thermal metamorphism of Torridonian arkose by a picrite sill in Soay (Hebrides) has culminated in extensive fusion. Microlites of cordierite were precipitated from the liquid as colorless, six-sided prisms (maximum dimension 0.06 mm.) with abundant magnetite inclusions. Refractive indices of the cordierite lie between 1.529 and 1.541, and (−) 2V is small. The cordierite is frequently twinned on (110), and rare cruciform twins are also present. The latter have (021) or (101) as the probable twin plane. Only (110) and (130) have been reported previously as cordierite twin planes. The distortion index, Δ (degree of distortion from hexagonal symmetry, measured by *x*-ray powder diffraction), is 0.08. From independent evidence, the maximum P_{H_2O} was 430 kg/cm², and the minimum temperature interval of cordierite crystallization was 1025° C. to 935° C. If P_{H_2O} were less than 430 kg/cm², the estimated crystallization temperatures would be higher. A useful temperature scale may be established by: (1) correlation of the structural state of cordierite with estimated temperature and pressure of water vapor in buchites, and (2) extension of hydrothermal studies on synthetic cordierites. Both approaches are required because the crystallization history of cordierite may affect its structural state. It is probable that the crystallization histories of cordierites in most buchites followed similar patterns.

INTRODUCTION

Progressive thermal metamorphism of Torridonian arkose by a small picrite sill in Soay (the Hebrides) has culminated in extensive fusion. From the liquid in the fused sediment have crystallized microlites of magnetite, hypersthene, tridymite (now inverted to quartz) and cordierite.* The greatest development of the microlites occurs in black, obsidian-like xenoliths enclosed by the picrite, and it is here that their forms may be readily distinguished. The properties of the cordierite agree with those of the microscopic cordierites which characteristically occur in fused shales and sandstones. Detailed descriptions of such crystals have been presented by Hussack (1883), Prohaska (1885), Zirkel (1891), Harker (1904) and Venkatesh (1952). Records of their occurrence in buchites are too numerous to list. The cordierite in the Soay buchite exhibits cruciform twinning, which has not been reported previously for cordierite.

It has been discovered recently that minerals with cordierite composition exist in several structural modifications (Miyashiro *et al.* 1955). Just

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Contribution No. 58-70, The Pennsylvania State University, College of Mineral Industries, Department of Geophysics and Geochemistry, University Park, Pennsylvania.

* A complete account of the metamorphism and fusion will be presented elsewhere.

* Now at School of Chemistry, University of Leeds, Leeds, England.

as the structural state of feldspars may give some indication of their temperature of formation, so the structural state of minerals with cordierite composition in fused sediments permit an estimate of the temperature of intrusion of the igneous body causing the fusion.

Optical Properties

The glassy matrix of the fused xenoliths contains minute, colorless, six-sided prisms of cordierite, which constitute a maximum of seven modal per cent of the rocks. Simple prisms are commonly developed (Fig. 1*b*), but parallel growth of somewhat elongated crystals may produce "stepped" edges to the prismatic faces (Fig. 1*c*); in cross section, such crystals appear as overlapping hexagons (Fig. 1*b*). Some crystals are clear while their central parts contain inclusions of dusty magnetite which are arranged parallel to the length of the crystals and which appear as cores in cross sections (Fig. 1*b* and 1*c*). Similar inclusions of spinel or iron ore are common in microscopic cordierites (Prohaska, 1885, Zirkel, 1891, Venkatesh, 1952). In the glass surrounding many cordierite crystals there are cracks either approximately perpendicular to the crystal edges (Fig. 1*c*), or following approximately the crystal boundaries (Fig. 1*b*, cf. Zirkel, 1891). The cracks probably developed during cooling by contraction of the glass away from the cordierite.

Even with very fine crushing it was impossible to obtain crystals free from glass and it could be determined only that the refractive indices of the corderite lie between 1.529 and 1.541 (±0.003). All prismatic sections have straight extinction and most are length fast. The few which are length slow probably represent very short prisms with the diameter of the basal pinacoid greater than the length of the prism faces (Prohaska, 1885, Zirkel, 1891). Pseudohexagonal sections are almost isotropic but sector twinning is visible in many sections. The twinning can be seen more clearly if the mineral is viewed in sodium light with a retardation plate inserted. There are six triangular sectors with opposite pairs in optical continuity, and the slow vibration direction is perpendicular to the prism face in each sector. The twin plane and composition plane is therefore (110) (Venkatesh, 1952). The optic axial plane is perpendicular to the prism face in each sector and the optic orientation of the twinned crystals is that illustrated in Winchell and Winchell (1951, figure 364). Attempts to measure 2V on the universal stage were unsuccessful but since basal sections are almost isotropic, (−)2V must be small.

At least one crystal in a fused xenolith has the shape of a cruciform twin. The insertion of a one wave length retardation plate renders the twin units clearly visible (Fig. 1*e*). Two other crystals were found which appeared similar (Fig. 1*b*), but they were too small for details to be dis-

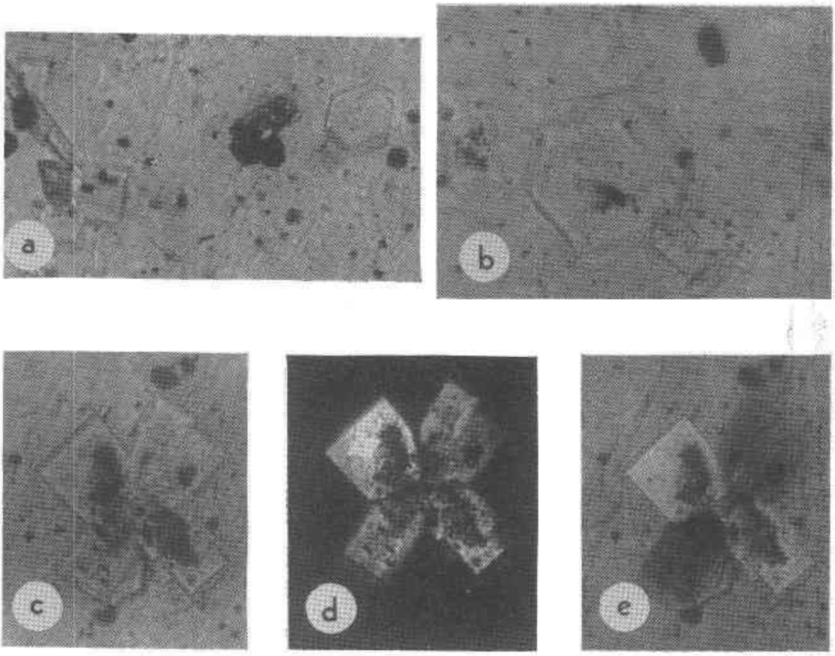

FIG. 1. Thin sections of buchite enclosed by picrite (×400). The groundmass of glass contains microlites of cordierite, hypersthene and magnetite. (*a*) Plain light; sections through six-sided prisms of cordierite; also present are accicular hypersthene and equant magnetite. (*b*) Plain light; six-sided cross-section of a large cordierite prism, partially surrounded by a crack in the glass. To the left is a small six-sided prism, with magnetite inclusions, lying completely within the thickness of the section. In the upper right corner is a poorly defined cruciform twin. (*c*) Plain light; cruciform twin of corderite with abundant magnetite inclusions. The "stepped" edges to prismatic faces result from parallel growth along the 'c' axis. In the glass surrounding the crystal there are small cracks perpendicular to the crystal edges. (*d*) The same as (c), with nicols crossed. The prisms are approximately 45° from extinction. (*e*) The same as (d) with a one wave-length retardation plate inserted in the 45° position. This demonstrates the different optical orientations of the twin units. The probable twin plane is either (021) or (101).

tinguished. On the universal stage, the approximate positions of two optic symmetry planes, both containing the '*c*' axis, were determined for each twin unit. It could not be ascertained which of these was the optic axial plane because no optic axes were located. From stereographic projection of the data the most probable twin plane is either (021) or (101), depending upon which of the optic symmetry planes is the optic axial plane. These are twin planes which have not been reported previously for cordierite. According to Winchell and Winchell (1951) and Venkatesh (1954), twinning in cordierite is exclusively confined to the (110) and

(130) planes, and twinning on (130), as well as (110), produces sector twinning in basal sections. In recent hydrothermal experiments on the fusion of shales (Wyllie and Tuttle, 1958) it was found that cordierite which grew in the fused charges invariably contained a small proportion of crystals exhibiting cruciform twins similar to those illustrated in Fig. 1. Careful search in buchites will probably reveal other examples and perhaps some can be found which will permit more accurate crystallographic measurements.

STRUCTURAL STATE

Miyashiro and others (1955, 1957) have recently discovered that crystals of cordierite composition exist in at least three structural modifications—indialite, high cordierite, and low cordierite. The new high temperature hexagonal mineral, indialite, was found among cordierites developed in sediments fused by burning coal seams (the cordierite was described by Venkatesh 1952, 1954). Apparently all gradations exist between hexagonal indialite and orthorhombic cordierite through distortion of the hexagonal lattice, and the distortion is probably caused by ordering of Si and Al atoms. Although the thermal relations existing among the polymorphs have been investigated, much experimental work remains to be completed.

The degree of distortion of the hexagonal lattice in cordierites can be measured easily on an x-ray powder diffraction pattern, and an angle representing the difference in 2θ between two peaks (Cu$K\alpha$ radiation) was called the distortion index, Δ, by Miyashiro (1957). For hexagonal indialite there is only one peak and the distortion index Δ is 0. For the most distorted cordierites Δ reaches 0.3. Δ was measured for the cordierite in the Soay buchite; the cordierite was not separated from glass and other minerals in the specimen, and Δ was determined from x-ray powder diffraction patterns of composite samples. Cordierite amounts to only seven modal per cent of the specimen, but satisfactory peaks were obtained in the required region. Diffraction patterns were recorded for several different samples. In most patterns the two peaks were not clearly resolved, but in others two peaks were obtained, and a value of $\Delta = 0.08$ was measured. This indicates that the symmetry of the cordierite is nearly hexagonal (this is confirmed by its small 2V).

The structural state of minerals with cordierite composition may yield information about their temperatures of crystallization. If equilibrium is maintained the least ordered forms would be expected from high temperature environments and the most ordered forms from low temperature environments. However, this simple picture is complicated by the fact that high and low forms may be distinguished regardless of the structural state. There is also another difficulty, namely that the structural state of cordierite will depend not only upon its temperature of crystallization, but also upon its crystallization history. Moreover, Miyashiro (1957) points out that many natural disordered cordierites have crystallized metastably at low temperatures.

Before we can infer growth conditions from measurements on natural cordierites, it is important that the structural state of cordierite be related under equilibrium conditions to varying temperatures and pressures of water vapor. Such studies are under way at the Geophysical Laboratory (personal communication from W. Schreyer). However, even when this work is completed, the distortion index of natural cordierites will not always be a satisfactory index of PT conditions, because (1) cordierite can crystallize in a metastable structural state, and (2) cordierite has so many structural holes that different environments may have a marked influence on the structural state in which it crystallizes. We cannot afford to neglect the crystallization history of such a mineral. For cordierites which have similar crystallization histories there is probably a simple correlation between temperature, pressure, and structural state. Most buchites contain cordierite and it is likely that their crystallization histories followed similar patterns: buchites are generally associated with hypabyssal intrusions, there is evidence that fusion proceeded in the presence of abundant water vapor, the cordierite crystallized from a liquid of granitic composition, rapid cooling is indicated by the preservation of glass and, finally, high cordierite always crystallizes in this environment. There remains to be considered the influence of compositional variation. According to Iijama (1956) there is no simple relation between the optical properties and the compositions of cordierite unless special attention is paid to structural relationships. Using Iijama's data, the cordierite in the Soay buchite appears to be rich in magnesium and poor in iron and manganese. Comparison of the mode and chemical analysis of a fused xenolith containing cordierite confirms that the corderite is magnesian because the amount of iron present is barely sufficient to account for the modal magnetite. It seems probable that the cordierite developed in buchites is generally rich in magnesia, except in the rare cases where the fused sediment is unusually rich in iron.

Measurements of the distortion index of cordierites from buchites may therefore provide a good indication of PT conditions, but care must be exercised in relating these measurements to equilibrium data obtained in laboratory experiments, because the two environments are very different. It is necessary first to obtain independent estimates of PT conditions in natural occurrences to provide a correlation between the laboratory and field measurements.

CONDITIONS OF FORMATION

For the Soay buchite an estimate of the temperature of the liquid from which the corderite crystallized is available (Wyllie, 1958). The compositions of the liquids present in the xenolith at the stages of maximum fusion and of quenching were calculated from chemical and modal analyses of a fused xenolith. Liquidus temperatures for these compositions were estimated from experimental data in the system albite-orthoclase-quartz-water for various pressures of water vapor (Tuttle and Bowen, 1958), and in this way, PT curves for the calculated liquid compositions were derived (AB and CD, Fig. 2). Since tridymite crystallized from the liquid, an upper pressure limit for the fusion was obtained from the intersection of the experimentally determined PT curve for the inversion of tridymite to quartz (in the presence of excess water vapor) with the curve CD. The range of PT conditions accompanying the cooling and crystallization of the liquid developed in the xenolith lies between the two PT curves AB and CD with temperatures between 1025° C. and 935° C. at a pressure of 430 kg./cm.^{2} of water vapor, and between 1310° C. and 1225° C. at atmospheric pressure. Without an independent estimate of pressure, no closer estimate of the temperature range can be made. Assuming that the total pressure equalled the pressure of water vapor (which is probable in this example), the upper pressure limit (AC) corresponds to a depth of about 1.7 km., and it is unlikely that the picrite sill was emplaced much higher in the crust than this.

The cordierite in the Soay buchite, with distortion index of 0.08, therefore crystallized within a PT range close to the line AC of Fig. 2. The equilibrium PT conditions determined hydrothermally which correspond to a distortion index of 0.08 may differ from the estimate derived in this section. But if several independent estimates of this sort can be made it may be possible to obtain a correction factor for cordierite *in this environment* which could be applied to the experimental data. If this proves feasible, we would have a simple method for estimating the temperature and pressure at the contacts of hypabyssal igneous intrusions when buchite is developed. An *x*-ray powder diffraction pattern of a crushed sample of the buchite, giving directly the distortion index of the cordierite, is the only measurement involved.

This data is presented as a first step toward the correlation of laboratory data with the properties of cordierite in buchites. Here we have an ultrabasic sill against which buchite has developed. The cordierite in the buchite has a distortion index of 0.08, and an independent estimate of PT conditions gives a crystallization range near to the line CD in Fig. 2. It is important that we check back and forth from rocks to experiments very

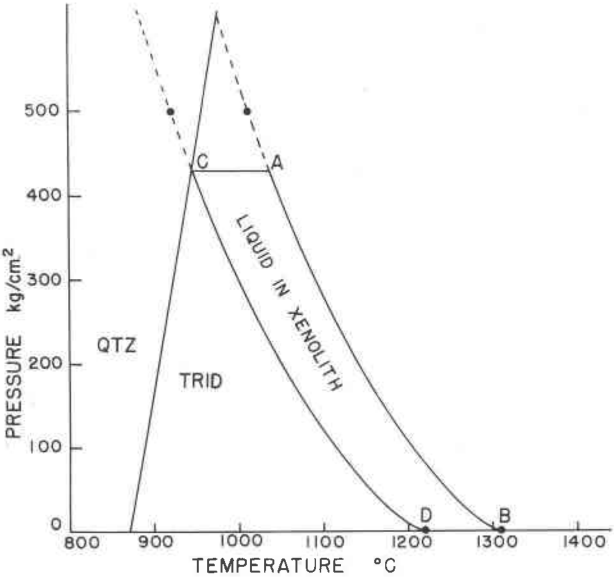

FIG. 2. Estimate of the PT conditions when the cordierite crystallized. The stage of maximum fusion of the xenolith is represented by the curve AB, and the condition when the liquid was quenched to a glass is represented by the curve CD. An upper pressure limit is given by the intersection of the quartz-tridymite inversion (in the presence of excess water vapor) with the curve CD. Cordierite crystallized from the liquid in the fused xenolith at PT conditions within the area ABCD, and probably close to the line CA.

frequently if we are to obtain full benefit from the increasing amount of controlled experimental data now becoming available.

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