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# Origin of hydrous cordierite and isotopically light oxygen in granulite-facies rocks, Strangways Range, Central Australia

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ABSTRACT. The origin of hydrous cordierite from a granulite-facies terrain in the Strangways Range, Central Australia, reported by Wilson (1978) is reviewed. In the light of geochemical and microstructural evidence for a metasomatic episode which affected the terrain subsequent to the growth of the cordierites, it is contended that the hydrous character of the cordierites results from hydration of the cordierite at this time. Extraneous argon also recorded in these cordierites may either have been incorporated into the cordierites at this time or at a later stage in the history of the terrain due to partial loss of radiogenic argon from micas which grew during the metasomatic episode. Furthermore, in view of the history of these cordierites, oxygen isotope values for the cordierites reported by Wilson are likely to be anomalous, and the isotopically light oxygen in the host granulites recorded by Wilson and Baksi (1978) probably reflects exchange with the metasomatic fluids which permeated the terrain.

IN a paper published recently in this journal (Wilson, 1978), cordierites containing large quantities of water and argon were described from a granulite-facies terrain in the Strangways Range, Central Australia. Wilson interpreted the water and argon as primary, incorporated at the time of crystallization of the cordierite under granulite-facies metamorphic conditions, and implied that some of the water may be structurally bound. In addition, he presented oxygen isotope data for these cordierites, the first such values to be determined for cordierite. The described cordierites occur in granulite-facies rocks for which abnormally light oxygen isotope values have been reported (Wilson and Baksi, 1978), which these authors have tentatively attributed to 'high latitude Precambrian meteoric waters that were heated by non-igneous means in deep aquifers long before their granulite facies metamorphism'. The geochemical character of the cordierites and the oxygen isotopic values for their host rocks are important in that they are in conflict with experimental evidence for the behaviour of volatiles in cordierite (e.g. Shreyer and Yoder, 1961, 1964; Smith and Schreyer, 1962; Newton, 1972) and with previously published oxygen isotope data for high-grade metamorphic rocks (e.g. Wilson *et al.*, 1970; Wilson and Green, 1971; Bottinga and Javoy, 1975). The purpose of this paper is to present some of the findings of a detailed structural-geochemical-geochronological investigation of an area immediately adjacent to Wilson's cordierite localities (Allen, 1979*a*) which bears upon the origin of the hydrous and argon-rich character of the cordierite and the light oxygen isotope values of their host rocks. This work suggests that these phenomena are related and due to a semi-regional metasomatic episode which affected the terrain subsequent to growth of the cordierite.

*Metamorphic relations.* The Strangways Range forms part of the Arunta Block, a 150000 km$^2$ gneiss terrain occupying much of the southern part of the Northern Territory of Australia. The main metamorphic and tectonic character of the Arunta Block was developed during a Mid-Proterozoic orogenic episode dated at 1600-1800 Ma, whilst localized retrogression confined mainly within shear zones took place during the Mid-Palaeozoic Alice Springs Orogeny. Recent work (e.g. Marjoribanks and Black, 1974; Allen and Black, 1979; Allen, 1979*a*, *b*, in prep.) indicates the presence of further events and a somewhat more complex history for the Arunta Block.

The Arunta Block is composed of a series of tectonic slices each of distinct metamorphic, tectonic, and lithologic character, bounded by east-west shear zones and north-west-south-east faults. In the southern Strangways Range, such a tectonically bounded unit, the Utralanama Block, contains the two cordierite localities described by Wilson (1978). The present work is based on investigations in the area which extends between

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these two localities (Wilson, 1978, fig. 1, localities 1 and 2), containing abundant cordierite-bearing rocks identical to those described by Wilson. The Utralanama Block is in juxtaposition with an amphibolite-facies tectonic unit, the Ankala Block, across an east–west shear zone, the Harry Creek Deformed Zone, which passes 2 km to the south of Wilson's locality 1. Initiation of this shear zone brought the two tectonic units into their present juxtaposition (Allen and Black, 1979).

Prior to its movement into juxtaposition with the Ankala Block, the Utralanama Block underwent three granulite-facies recrystallization episodes. The first two recrystallizations are correlated with the Mid-Proterozoic regional metamorphism of the Arunta Block—the Arunta Orogeny (Allen, 1979*a*). The earlier event (M1) was responsible for development of the major mineralogical and microstructural characteristics of the various rock types of the Utralanama Block, whilst the second (M2) resulted in considerable fabric modification, but only minor mineralogical changes. The Arunta Orogeny was accompanied by partial melting of the Utralanama Block and upwards migration of minimum melt compositions, resulting in extreme depletion of K, Rb, and $H_2O$ from the terrain (Allen, 1979*b*). Development of garnet or orthopyroxene, instead of biotite, in the tonalitic partial melts which remained in the terrain, indicates very low $P_{H_2O}$ conditions (< 700 bars; cf. Luth, 1967). Fairly precise pressure conditions of 6–7 kbars are set for the Arunta Orogeny by the presence of cordierite–garnet–orthopyroxene assemblages in pelitic rocks, whilst assemblages in other rock types, together with the extreme depletion of the terrain, suggest temperatures of the order of 900 °C or more. The cordierites described by Wilson grew during M1. Ages of 1800 Ma and 1710 Ma are proposed for M1 and M2 respectively (Allen and Stubbs, in press).

The third granulite-facies recrystallization episode (M3) which affected the Utralanama Block was essentially of a metasomatic character. Fluids enriched in K, Rb, Ba, and $H_2O$ permeated quartzofeldspathic and pelitic rocks of the Utralanama Block and attacked Arunta Orogeny plagioclase, orthopyroxene, garnet, cordierite, and ilmenite, with resultant development of secondary alkali feldspar, biotite, aluminous anthophyllite, sillimanite, and quartz (Allen, 1979*b*, in prep.). However, except locally, mafic, calc-silicate, magnesian, and manganiferous rocks were unaffected by the metasomatic fluids. The metasomatic episode, which occurred under static conditions, appears to be related to the formation of the Wuluma Granite–Ingula Migmatite Complex, centred a few kilometres to the north-west of Wilson's cordierite localities (Allen, in prep.), and has been dated at 1440±60 Ma by the Rb/Sr method (Iyer *et al.*, 1976) and at 1450–1500 Ma by the $^{40}Ar/^{39}Ar$ step degassing method (Allen and Stubbs, in press).

Two types of metasomatic breakdown of cordierite are recognized (Allen, in prep.). The most obvious breakdown is manifested by the development of fibrous or vermicular 'colonial' intergrowths of aluminous anthophyllite, sillimanite, and quartz growing inwards from the cordierite grain boundaries (fig. 1). These intergrowths are ubiquitous but show different degrees of development. In some rocks they may completely pseudomorph the cordierite, whereas in others development may be minimal. Grain size is also variable and is only rarely sufficiently coarse to allow optical and electron-microprobe examination of the intergrowths.

The second cordierite breakdown reaction is less ubiquitous, but more significant microstructurally. Coarse intergrowths of ragged reddish-brown titaniferous biotite, vermiform aluminous anthophyllite, and fibrolitic sillimanite abut against and impinge into cordierite grains. The intergrowths do not form continuous growths round the margins of the cordierite, or attack all cordierite grains in a given rock. Development of these intergrowths

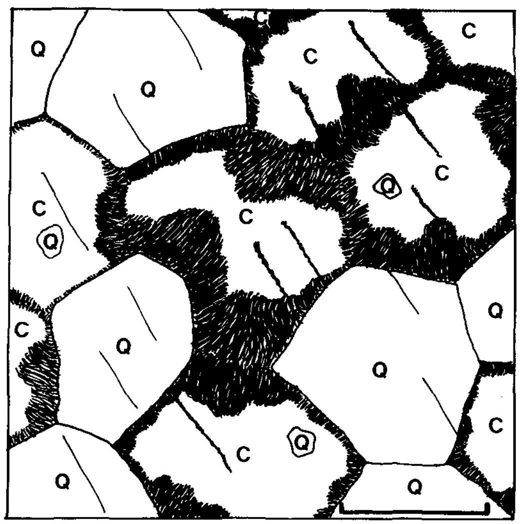


FIG. 1. Fibrous 'colonial' replacement intergrowths composed of aluminous anthophyllite, sillimanite, and quartz attacking cordierite in a quartz–cordierite–orthopyroxene biotite granuloblastic pelitic gneiss. The marginal development, lobate form, and growth of the intergrowths along pre-existing hair fractures in the cordierite suggests inwards growth of the intergrowths from the grain boundaries, in response to hydration of the cordierite during M3. C—cordierite, Q—quartz. Scale bar = 1 mm.

is also variable, as are the proportions of the constituents.

The two cordierite breakdown effects occur together and are considered to be contemporaneous, but representative of different types of reaction of the cordierite. The first breakdown type is essentially of an isochemical nature, apart from the addition of water, and reflects hydration of the cordierite by the metasomatic fluids. The second represents the reaction of cordierite and adjacent quartz in the presence of K-rich metasomatic fluids. The first of the above cordierite breakdown intergrowths has also been investigated by Vernon (1972), who also attributed them to hydration of the cordierite.

A possible reaction for formation of the 'colonial' intergrowths is:

anhydrous cordierite + water = aluminous anthophyllite + aluminosilicate + quartz

which has been verified by Green and Vernon (1974) during the course of an experimental investigation of the 'colonial' breakdown reaction using the natural reactants and products from Johannsen's Mine (Wilson's locality 1). On the basis of Green and Vernon's work, *P-T* conditions of 8.5–9.5 kb and 780–850 °C are postulated for M3 (Allen, in prep.).

*Origin of the hydrous cordierite.* In the light of the above evidence, there seems good reason to suspect that the large quantities of water quoted by Wilson (1978) in the cordierites (i.e. 1.09 % and 1.00 % $H_2O+$) may be of metasomatic origin, resulting from hydration of the cordierite during M3. Considerable experimental data on the behaviour of cordierite supports this contention. Large quantities of water (up to 1 mole per formula unit) can be accommodated in the six-membered ring channels parallel to the c-axis in cordierite (Smith and Shreyer, 1962; Shreyer and Yoder, 1964). Moreover, the quantity of water held in hydrous Mg-cordierite is controlled by the $P_{H_2O}$ prevailing during growth of the cordierite (Shreyer and Yoder, 1961, 1964). Furthermore, water in cordierite has been shown to be loosely bound and capable of being driven off by heating to a few hundred degrees and 1 atm, without affecting the cordierite structurally (Shreyer and Yoder, 1964). Thus, under the very low $P_{H_2O}$ conditions of the Arunta Orogeny, it is unlikely that the growing cordierite would absorb, far less retain, anything like the 1.09 % water recorded by Wilson. On the other hand, Newton (1972) has described experiments conducted at high pressures and temperatures (8 kb and 750 °C) which showed that addition of water to anhydrous cordierite brought about instantaneous hydration of the cordierite and its stabilization to pressures 3 kb higher than the anhydrous cordierite. It would therefore appear that hydration of cordierite during the M3 metasomatic episode is a more tenable origin for the water in the cordierite of the Strangways Range than the primary origin postulated by Wilson (1978). This conclusion accords well with the microstructural interpretations of Vernon (1972) and Allen (in prep.), that the 'colonial' intergrowths formed in response to hydration of the cordierite. That these intergrowths do not result from isochemical breakdown of originally hydrous cordierite is implied by their marginal development and inwards growth since, had the cordierite been originally hydrous, the breakdown products ought to have developed throughout the grains, not merely at the margins.

*Origin of the argon in the cordierite.* The extraneous argon in the same cordierites also appears to be related to the M3 metasomatic event. Wilson (1978) stated that the amount of $^{40}Ar$ in the cordierite ($15 \times 10^{-5}$ cm$^3$ STP/g) was about twenty times in excess of argon that would be generated by the 0.08 % $K_2O$ of the cordierite based on an age of 1460 Ma for the cordierite. However, as contended earlier, all the cordierite in the Utralanama Block grew during the M1 event which has been attributed with an age of 1800 Ma. On the other hand, the 1460 Ma age for the cordierite, postulated by Wilson, lies within the age range suggested for M3 (Allen and Stubbs, in press). Wilson's assignment of the 1460 Ma age to the cordierite is based on the $1440 \pm 60$ Ma total rock isochron ($1470 \pm 60$ Ma—recalculated using $\lambda\ ^{87}Rb = 1.42$) obtained from four phlogopite-bearing granulite-facies rocks from Johannsen's Mine (Iyer *et al.*, 1976). However, this isochron has an unusually high $^{87}Sr/^{86}Sr$ initial ratio (0.764) for granulite-facies rocks, which generally have very low initial ratios ($< 0.707$; Spooner and Fairbairn, 1970). Furthermore, a phlogopite-free mafic granulite dated by Iyer plotted well below the isochron close to the $^{87}Sr/^{86}Sr$ axis. The $^{87}Sr/^{85}Sr$ ratio for this rock (0.706) which is almost devoid of Rb (0.8 ppm; see Iyer *et al.*, 1976, Table 3) is consistent with normal granulite-facies values. This suggests that the mafic rock reflects material unaffected by the metasomatic event, whilst the $1440 \pm 60$ Ma isochron defined by the four phlogopite-bearing rocks represents the age of the metasomatic event. This argument is supported by geochemical evidence which indicates that the mafic rocks retain their depleted granulite-facies chemistry, whereas other rock types have had their chemistries modified by the metasomatic event (Allen, 1979*b*). It is thus contended that the phlogopite in the rocks dated by Iyer *et al.* (1976)

was deposited during M3, and indeed geochemical and microstructural evidence (Allen, in prep.) suggests that most if not all of the biotite in the Utralanama Block is of M3 metasomatic origin.

Two possible origins for the extraneous argon in the cordierite are thus proposed. The first is that it entered the cordierite structure at the same time as the water during the M3 metasomatic episode. In the absence of data it cannot be certain that argon was a component of the metasomatic fluids, but this is a distinct possibility. Alternatively the argon may have become incorporated in the cordierite at a later date, through escape from neighbouring M3 biotite grains during a subsequent retrogressive episode such as the Alice Springs Orogeny. Evidence supporting the latter origin are the younger $^{40}Ar/^{39}Ar$ step degassing ages obtained from M3 biotites by Allen and Stubbs (in press) and the 1389 Ma *K*-Ar age for a coarse phlogopite from one of the cordierite localities (D. C. Green quoted in Iyer *et al.*, 1976); these ages suggest loss of argon from biotites of the Utralanama Block subsequent to the M3 event.

*Oxygen isotopes.* In view of the above arguments, there is a strong possibility that the isotopically light oxygen in the granulite facies host rocks of the hydrous cordierites ($\delta\,^{18}O = 2.7\,\%$; Wilson and Baksi, 1978) is of metasomatic origin. It seems highly unlikely that permeation of these rocks by metasomatic fluids would leave oxygen isotopic values unaffected and so it is suggested that the anomalously light oxygen isotope values reported from this terrain (Wilson and Baksi, 1978) may result from exchange with the metasomatic fluids which permeated the terrain during M3. Furthermore, oxygen isotope values for the cordierites presented by Wilson ($\delta\,^{18}O = 1.97\text{–}3.11\,\%$), the first such values recorded for cordierite, also probably reflect exchange with the M3 metasomatic fluids and thus are likely to be anomalous. In fact the data presented by Wilson and Baksi (1978) tend to support this contention. Mafic rocks, which geochemical evidence indicates have not been affected by the metasomatic fluids (Allen, 1979*b*), give higher $^{18}O$ values ($\delta = 4.5\text{–}6\,\%$) than the more siliceous, quartzofeldspathic and pelitic rocks of the terrain. Furthermore, oxygen isotope temperature data derived from quartz-cordierite and quartz-phlogopite pairs (Wilson and Baksi, 1978) are identical (760° and 770° respectively), although Wilson and Baksi acknowledge that the phlogopite is of M3 origin. These temperatures are close to temperatures postulated for M3 ($\approx$ 800 °C; Allen, in prep.). Thus until alternative oxygen isotope data for cordierite become available, it should be noted that the values reported by Wilson (1978) are derived from cordierites which appear to have been hydrated subsequent to growth, and therefore are not normal anhydrous cordierites typical of regionally metamorphosed rocks.

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