

Grandidierite from a pelitic xenolith in the Haddo House complex, NE Scotland

R. K. HERD

Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8, Canada

B. F. WINDLEY

Department of Geology, The University, Leicester LE1 7RH, United Kingdom

AND

D. ACKERMANN

Mineralogisches Institut der Universität, D-2300 Kiel, Federal Republic of Germany

ABSTRACT. Grandidierite occurs in the outer margin of a biotite-rich pelitic xenolith in norite close to the contact of a tourmaline-bearing granite in the Haddo House norite-gabbro complex. The boron for the grandidierite was derived by metasomatism from the granite. The assemblage is (decreasing order): An_{55-51} plagioclase (65%), biotite (10%), spinel (10%), cordierite (5%), corundum (5%), ilmenite, grandidierite ($< 1\%$), rutile, sphene, zircon. X_{Mg} range is grandidierite (0.80-0.78) $>$ cordierite (0.78) $>$ biotite (c. 0.59) $>$ spinel (0.35-0.27). The grandidierite has little chemical variation: SiO_2 , 19.9-20.5%; Al_2O_3 , 51.3-51.9%. A compilation of all grandidierite analyses in the literature shows that the only substitutions are $Fe^{2+} \rightleftharpoons Mg$ and $Al \rightleftharpoons Fe^{3+}$, the X_{Mg} range being 0.98 to 0.19.

DURING his extensive studies of the Haddo House complex (see fig. 1) the late Professor H. H. Read (1931, 1935) discovered a blue mineral which he thought to be sapphirine. The sample and thin section were later lost. In his later years he encouraged two of us (RKH and BFW) to search for and rediscover the occurrence, which we did with the assistance of Professor J. V. Watson. Gribble (1968) extensively investigated cordierite-bearing rocks and xenoliths in the Haddo House area. He reported blue lazulite (in the absence of electron probe data) from the same area the two of us visited. However, the blue mineral which we found has proved on analysis to be grandidierite. This mineral has been recorded from the aureole of the Comrie diorite (Macpherson and Livingstone, 1981; Livingstone and Macpherson, 1983). The purpose of this paper is to present the first description of grandidierite in Britain from the Haddo House locality, and to present a compila-

tion of all published analyses of grandidierite in order to evaluate its compositional range.

The Haddo House complex is a Caledonian gabbro-norite body intruded into andalusite-cordierite pelitic schists, pebbly grits, and cordierite-biotite gneisses; it is located about 32 km north of Aberdeen in NE Scotland. The norite is characterized by abundant xenoliths of the country rocks, many of which contain corundum and spinel. The gabbros and norites are intruded by the Auchedly granite, which contains orthoclase and biotite, and tourmaline crystals up to 30 cm long. The grandidierite occurs in a pelitic xenolith in norite which itself forms a large xenolith in the granite. The locality is situated north-west of the Wood of Schivas at the northern end of the largest xenolith of norite that lies in the Auchedly granite seen on fig. 4 of Read (1935) and on fig. 2 of Gribble (1968). The 1 m \times 70 cm sized outcrop occurs in grass 50 m north-east of the road on the east side of the Ythan River [Gribble's (op. cit.) loc. 74 \times] (1:50,000 sheet 30, GR 898355). The next observable outcrop 30 m to the west is of the tourmaline-bearing granite. The xenolith is 30 \times 25 \times 10 cm in size and has a plagioclase-rich rim 5-10 mm wide. Such rims are common on the pelitic xenoliths, but they are widest here close to the granite contact. The norite matrix is also biotite-rich. The grandidierite occurs inside the plagioclase-rich rim, on the outer margin of the biotite-rich core of the xenolith.

Mineral assemblage and texture. The rim of the xenolith consists of plagioclase (c. 95% vol.), biotite, and ilmenite; the plagioclase is partially altered to fine-grained sericite. There is a transition zone about 2 mm thick in which the amount of biotite

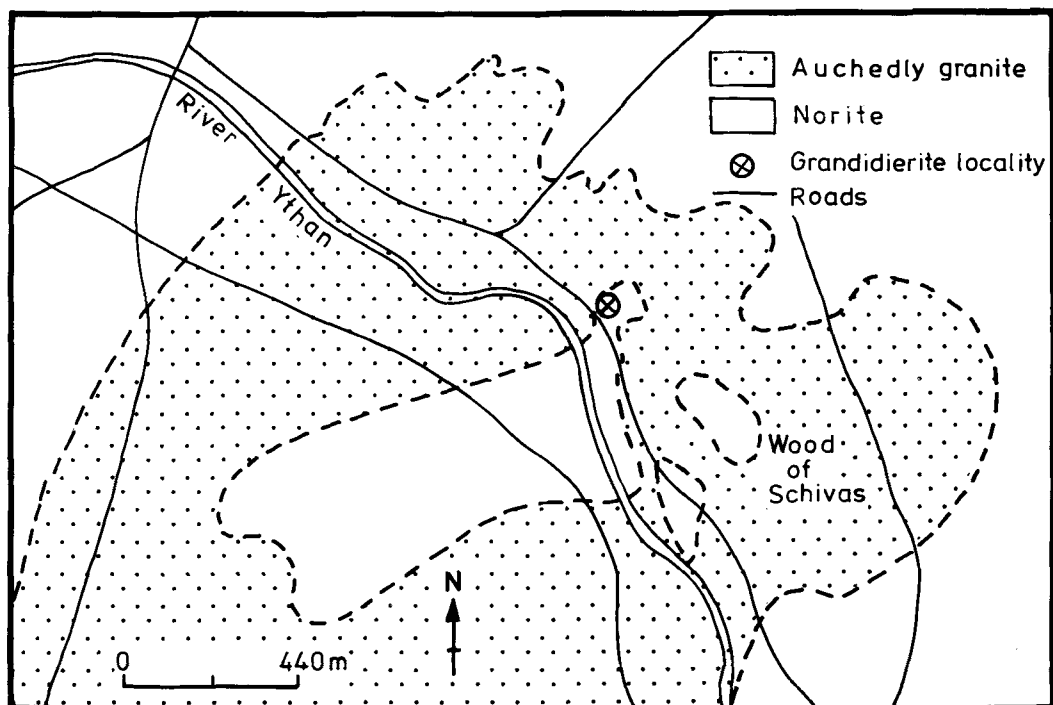


FIG. 1. Sketch map showing location in the Haddo House complex from fig. 4 of Read (1935).

increases and new spinel appears passing into the grandierite-bearing region at the margin of the core. Within another millimetre corundum and cordierite join these phases. The core of the xenolith is rich in biotite, spinel, corundum, and cordierite.

The grandierite-bearing core margin has the assemblage (decreasing abundance order): plagioclase (65% vol.), biotite (10%), spinel (10%), corundum (5%), cordierite (5%), ilmenite (< 1%), grandierite (< 1%), rutile, sphene, zircon. There is no preferred orientation of any of these phases. Biotites are widely and irregularly scattered, but the spinels and corundums are densely peppered throughout the plagioclase.

Plagioclase forms unaltered, usually unzoned subidioblastic grains ranging from 1 μm to 6 mm in length. Some large plagioclases contain myriads of minute needles less than 1 μm thick arranged in several orientated sets; these are too small for identification but we suspect they are rutiles. There is a second generation of rutile which occurs in the plagioclase as rare unorientated pale-yellow needles up to 100–200 μm thick and 1 mm long. Biotite (deep red) occurs as single grains up to 2 mm long and aggregates up to 2 mm across of smaller grains, which contain biotites, sphenes, and zircons with

radioactive haloes. Biotite and plagioclase have stable grain boundaries, and rarely biotite truncates plagioclase–plagioclase boundaries. Xenoblastic cordierite is patchily intergrown with plagioclase and biotite, with a similar grain size. It contains many fine inclusions, but lacks the rutile needles seen in plagioclase. Some inclusions show the typical yellowish haloes. The cordierite is virtually untwinned, in contrast to the feldspar. Spinel forms subidioblastic to xenoblastic granules up to 200 μm across which are deep green with no colour zoning. They contain some corundum but no opaque inclusions. They occur in plagioclase, cordierite, and biotite with stable grain contacts. Zoning in the plagioclase may occur next to spinel. Colourless corundum occurs in plagioclase and cordierite, and rarely in biotite and spinel. There are two generations. One forms rounded grains up to 100 μm across, the cores of which typically contain minute needles of an unidentified mineral which are arranged in crystallographic sets. The other generation forms angular grains up to 200 μm across which have no such needles, and rarely have biotite inclusions. There are xenoblastic ilmenite grains in plagioclase and biotite, and some late prehnite alteration of biotite.

Grandierite occurs in and between plagioclase,

biotite, and cordierite with sharp contacts as xenoblastic to subidioblastic elongate grains (fig. 2), some with well-formed prism faces. Some elongate grains lie parallel to the basal planes of biotite and some cross-cut biotite cleavages. Characteristically it is not in contact with spinel and corundum, but some grains contain inclusions of these phases.

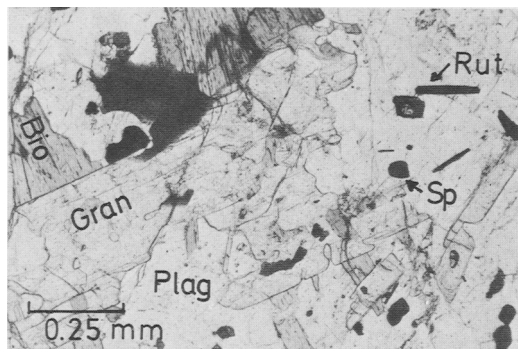


FIG. 2. Photomicrograph of grandidierite grain in plagioclase.

Some grains cutting biotite have biotite inclusions which are in optical continuity with the matrix biotite. Grains reach 1.2 mm in length and locally have a good cleavage parallel to prism faces. The grandidierite shows second order birefringence, is pleochroic from pale blue to colourless, and has parallel extinction. We conclude that grandidierite grew contemporaneously with biotite, cordierite, and plagioclase during the metamorphism; it has no reaction textures to indicate its growth history.

Mineral chemistry. Microprobe analyses were made with energy and wavelength dispersive equipment in Kiel and Leicester. Representative analyses are listed in Table I.

Plagioclases in the xenolith rim and core margin have no zoning but a notable difference in composition from *c.* An₆₅ in the grandidierite-free rim to An₅₅₋₅₀ in the grandidierite-bearing core margin. The K₂O content in the latter is 0.2 wt. % and in the former it ranges from 0.05 to 0.15 wt. %. Biotite is, like plagioclase, unzoned and has X_{Mg} [= Mg/(Mg + Fe)] of 0.56 in the rim and 0.59 in the core margin with some Al₂O₃ (17.6 wt. %). TiO₂ is high, varying from xenolith rim to core margin from 5.2 wt. % to 4.4 wt. % respectively. Cordierite is unzoned with an X_{Mg} of 0.78, and it is very close to its ideal formula. Spinel, occurring in the core, is a hercynite-rich aluminous type. It has no zoning and little compositional variation from grain to grain. The Cr₂O₃ content is 0.1 to 0.5 wt. %, MnO is *c.* 0.7 wt. % and the X_{Mg} [= Mg/(Mg + Fe + Mn)]

varies from 0.35 to 0.27. This X_{Mg} is calculated using 3 cations per formula and accordingly we get 0.1 Fe³⁺ per formula, in comparison with 1.91 for Al. All corundums show a remarkably constant Fe₂O₃ of *c.* 1.0 wt. %. Ilmenite follows the theoretical formula of FeTiO₃ but has a MnO content of 1.4 to 1.2 wt. % from rim to core. Grandidierite (25 point analyses on 7 grains) shows little chemical variation throughout the rock. Its X_{Mg} [= Mg/(Mg + Fe + Mn)] is 0.80 to 0.78 (*cf.* cordierite) and its MnO content is less than 0.1 wt. %. Some grain rims have a low Cr₂O₃ content of 0.1 wt. % in contrast to undetectable amounts in grain cores.

Discussion. The Haddo House grandidierite occurs in a pelitic xenolith in norite close to an intrusive tourmaline-bearing potassic granite. The spinel, corundum, cordierite, and biotite in the xenolith were reasonably derived by partial assimilation of the pelitic material by the norite—a common process in this complex (Read, 1931, 1935). Gribble (1968) gives a whole-rock analysis of his specimen 74X.

Because the plagioclase-rich rims on the xenoliths are widest near the granite contact, and because the norite is also biotite-rich next to the rims, we infer that the boron for the grandidierite was derived from the granite. Thus the grandidierite-bearing rock has a dual origin, derived from the pelitic rock by boron metasomatism.

The grandidierite is situated in An₅₀₋₅₅ plagioclase and biotite in association with spinel, corundum, and locally cordierite, and its X_{Mg} in relation to that of other minerals is as follows: grandidierite (0.80–0.78) > cordierite (*≈* 0.78) > biotite (*c.* 0.59) > spinel (0.35–0.27). It is known that grandidierite is a boron-bearing mineral from the analysis of Scoon in McKie (1965), and up to now this is the only analysis for boron in the literature. We follow the formula of (Mg_{0.9}Fe_{0.1})Al₃SiBO₉ of Stephenson and Moore (1968). From our analyses the TiO₂, CaO, Na₂O, and K₂O contents are less than 0.1%. On the basis of 30 oxygens we obtain a range of Si atoms per formula of 3.94 to 4.02, and for Al 11.85 to 11.94. The atomic number of Mg + Fe is always higher than the theoretical formula, with a range of 4.10 to 4.20. From these Al and MgFe values in relation to the theoretical formula we suggest there are appreciable amounts of Fe³⁺ in our grandidierite.

Since the first discovery by Lacroix (1922), there are now known to be about twenty-three grandidierite occurrences in the world. We have plotted all the analyses of grandidierite published in the literature, together with those of Haddo House, in MgO–Fe²⁺O–(Al,Fe³⁺)₂O₃ and (MgFe²⁺)O–Al,Fe³⁺)₂O₃–SiO₂ triangles (fig. 3). In determining the formula of grandidierite from

TABLE I. Representative (wavelength dispersive) microprobe analyses of minerals in grandierite-free rim and grandierite-bearing core-margin of the xenolith. Specimen number 68 RKH (\equiv 68 BW 112)

Mineral	Grandierite			Plagioclase			Biotite		Cordierite		Spinel		Ilmenite		Corundum	
Anal. ref. nos.	1	2	3	4	5	6	7	8	9	10	Rim† 11	Rim 12	Core 13	Rim 14	15‡	Rim 16‡
SiO ₂	20.60	20.29	20.49	51.63	54.03	54.60	36.36	33.90	49.01	49.10	—	—	—	—	—	—
TiO ₂	—	—	—	—	—	—	5.24	4.67	—	—	0.04	0.04	51.48	50.80	—	0.15
Al ₂ O ₃	51.80	50.29	50.80	30.45	28.77	27.79	13.70	17.60	33.33	33.52	57.11	58.56	—	—	99.1	98.7
Cr ₂ O ₃	—	—	—	—	—	—	0.19	0.03	—	—	0.21	0.19	0.10	0.06	0.07	0.08
FeO*	5.00	5.26	5.26	—	—	—	16.40	15.30	5.10	5.08	33.97	30.45	47.00	47.25	0.57§	0.80§
MnO	0.06	0.08	0.09	—	—	—	0.08	0.05	0.02	0.06	0.42	0.35	1.43	1.19	—	—
MgO	11.20	10.99	10.89	—	—	—	11.80	12.30	10.36	10.12	7.11	9.15	—	0.42	—	—
CaO	—	—	—	13.46	11.19	10.45	0.06	—	0.04	0.06	—	—	—	—	0.02	—
K ₂ O	—	—	—	—	0.21	0.16	9.21	9.20	—	—	—	—	—	—	—	—
Na ₂ O	—	—	—	3.70	5.00	5.59	0.10	0.45	0.18	0.18	—	—	—	—	—	—
Without B ₂ O ₃	88.66	86.91	87.53													
Anhydrous total				99.24	99.20	98.59	93.14	93.50	98.04	98.12	98.86	98.74	100.01	99.72	99.76	99.73
X _{Mg} = Mg/(Mg + Fe + Mn)	0.798	0.786	0.784				0.57	0.58	0.79	0.78	0.27	0.35				

* Total Fe as FeO.

† Spinel cores are full of inclusions.

‡ Anal. 15; ten-grain core without inclusion needles; anal. 16; eleven-, with needles.

§ Fe₂O₃.

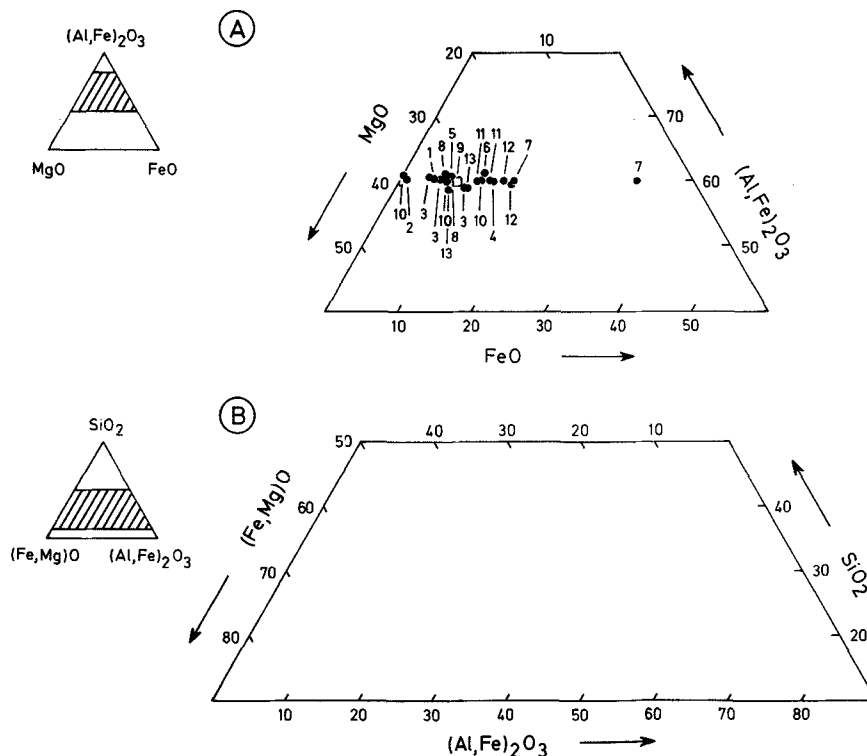


FIG. 3. Compilation of all grandidierite analyses (black circles) in the literature in (a) $\text{MgO}-\text{Fe}^{2+}\text{O}-(\text{Al,Fe}^{3+})_2\text{O}_3$ and (b) $(\text{MgFe}^{2+})\text{O}-(\text{Al,Fe}^{3+})_2\text{O}_3-\text{SiO}_2$ diagrams calculated on the basis of 20 cations. Open square is the region of the Haddo House grandidierites on the basis of twenty-five analyses. For discussion see text. Sources: 1. McKie (1965); 2. von Knorring *et al.* (1969); 3. Black (1970); 4. Anderson (1975); 5. de Roever and Keift (1976); 6. Krogh (1975); 7. Huijsmans *et al.* (1982); 8. Semroud *et al.* (1976); 9. Vrana (1979); 10. Seifert and Olesch (1977); 11. van Bergen (1980); 12. Haslam (1980); 13. Grew (1983).

electron microprobe analyses with respect to Fe^{2+} and Fe^{3+} we followed the method of Hamm and Vieten (1971) for clinopyroxenes and we made the calculations on the basis of 20 cations. The range of X_{Mg} values of 0.98 to 0.19 is shown in fig. 3a; most of the analyses are in the range 0.8 to 0.6. Thus the Haddo House grandidierite is close to the most magnesian known. Only two analyses of Fe^{3+} in grandidierites have been determined, both from Malagasy (Madagascar) (McKie, 1965; von Knorring *et al.*, 1969; FeO 2.87, Fe_2O_3 0.80; FeO 0.56, Fe_2O_3 0.49, respectively). From these analyses it can be inferred that the microprobe analyses of total FeO from the majority of grandidierites contain a significant amount of Fe_2O_3 . The experimental results of Olesch and Seifert (1976) suggest that there is a possibility that the FeO-free Mg-end-member of grandidierite may exist. The analyses plotted in $(\text{MgFe}^{2+})\text{O}-(\text{Al,Fe}^{3+})_2\text{O}_3-\text{SiO}_2$ space (fig. 3b) show that all grandidierites have a composi-

tion close to the ideal grandidierite formula of $2(\text{Mg,Fe}^{2+})\text{O}-3(\text{Al,Fe}^{3+})_2\text{O}_3-2\text{SiO}_2$. Grandidierite is thus seen to have the substitutions $\text{Mg} \rightleftharpoons \text{Fe}$ and $\text{Al} \rightleftharpoons \text{Fe}^{3+}$, but perhaps not the common substitution of $\text{MgSi} \rightleftharpoons \text{AlAl}$. In our discussion, we have neglected the important B content of this mineral because of the paucity of available analytical data.

The occurrence of the Haddo House grandidierite in a pelitic hornfelsed xenolith in a high-level gabbro-norite pluton near the roof of the Auchedly granite (Read, 1931, 1935) suggests formation at high temperature and low pressure. The lack of reaction intergrowths and of mineral zoning suggests that the assemblage has been annealed at a high temperature.

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