Inclusions in the apatites of some igneous rocks.

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In a recent paper by Dr. W. F. Fleet and Dr. F. Smithson[1] attention was drawn to the occurrence of dark apatites and apatites with dark cores of inclusions in certain sediments of the Midlands of England, and it was pointed out that the only other definite occurrences known of these peculiar apatite grains in either igneous or sedimentary rocks appeared to be restricted to the Old Red Sandstone of the Cardiff area,[2] the 'newer' granites of Jersey,[3] and the Leinster granite.[4] These writers also expressed the hope 'that any future observation of such grains may be recorded with a view to tracing the source of the detrital grains of Welsh and English rocks'. Dr. W. Mackie has since recorded[5] dark cores in the apatite of the 'Benrinnes grey granite (Ruthrie), in some of the apatites of Loch Moy granite, Ross of Mull, Noesting (Shetland), some of the central Grampian rocks and all or nearly all the Galloway granites'. The object of these notes is to record further occurrences of dark apatite and apatites with dark cores, at the same time making some observations on the nature of the inclusions.

Part I. Apatite in the granites of Normandy, Brittany, and Jersey (by A. W. Groves).

Barfleur granite, Normandy.—The inclusions form a solid rod-like core with sharply defined straight margins running down the centre of the crystal parallel to the prism faces. The core usually terminates

[1] W. F. Fleet and F. Smithson, Geol. Mag. London, 1928, vol. 65, pp. 6–8.
[2] A. Heard and R. Davies, Quart. Journ. Geol. Soc. London, 1924, vol. 80, p. 501.
[3] A. W. Groves, Geol. Mag. London, 1927, vol. 64, pp. 244, 249.
[4] W. J. Sollas, Trans. Roy. Irish Acad., 1891, vol. 29, pp. 434–5; F. Smithson, Geol. Mag. London, 1928, vol. 65, pp. 14, 19.
[5] W. Mackie, Trans. Edinburgh Geol. Soc., 1928, vol. 12, p. 28.

with rounded or frayed ends before reaching the end of the crystal, and the length of the core is very variable. Some of the cores are practically opaque while others transmit light and show marked absorption parallel to their length, the colour range being from greenish-grey to nearly black. The majority of the apatite grains in the specimens examined from this granite mass contained dark central cores. Some rare cases have been observed where the core shows crystalline outline corresponding to that of the enclosing apatite crystal; basal sections of apatite have in several instances shown six-sided cores. One case has been noted from Port de Landemer in which an apatite crystal consisted of a black almost opaque core, surrounded by a sharply defined zone of grey apatite, and this in turn surrounded by clear apatite. The grey zone clearly displayed the same crystal forms as the external ones, while the opaque zone at the centre also showed the same forms.

Flamanville granite, Normandy.—Occasional inclusions of a greenish-brown colour and others almost opaque occur, but cores are much less common than in the Barfleur granite.

Jersey.—The presence of apatite with dark central rod-like inclusions in the 'newer' granites of Jersey has already been recorded by the writer (loc. cit.). With low magnification the cores appear almost opaque. Using a magnification of 500 diameters and a strong light, the central cores are seen to be generally of greenish-brown or greenish-grey tint. Sometimes there is a marked absorption of light parallel to the length of the core. In a few favourable cases it has been noted that the core has a fairly high birefringence and has positive sign of elongation like those recorded by Smithson from the Leinster granite, but none of the purple shades occurring in the Leinster granite are found in Jersey.

A weathered granite pebble, extracted from the Rozel conglomerate of the north-east of Jersey, when crushed yielded a suite of heavy minerals among which apatite crystals with central cores of opaque foreign matter were common. Other types of granite pebbles in this conglomerate do not yield apatite with cores.

Chausey Islands, Normandy.—Apatite grains with central cores of inclusions of variable character are common in two specimens of granite from these islands.

Brittany.—The belt of porphyritic pink granites, designated by the French Geological Survey as 'granite porphyroïde de l'Aber Ildut', running from Trégastel through Pleumeur, Carantec, St. Pol de Léon, l'Aber Ildut, and Île Melon (near Brest), is throughout characterized by abundant apatite containing cores of many types. The following main types are to be distinguished:

(*a*) Nearly opaque rod-like masses. (Figs. 5 and 6.)

(*b*) A central zone, sometimes rather ill-defined, pleochroic from light-grey to greenish-grey or brown and suggestive of finely dispersed chlorite or green biotite. (Fig 3.)

(*c*) A central strip, generally of rectangular shape, consisting of what appears under moderate magnification to be a zone of transverse fibres. Under high magnification the 'fibres' are seen to be segregations of dark foreign matter along parting planes parallel to the basal plane. This type generally shows little pleochroism.

(*d*) A rectangular or irregular strip pleochroic from grey to a bluish or purplish tint and having the same other optical properties as the rest of the crystal. Central voids often occur in the grey area. (Fig. 2.)

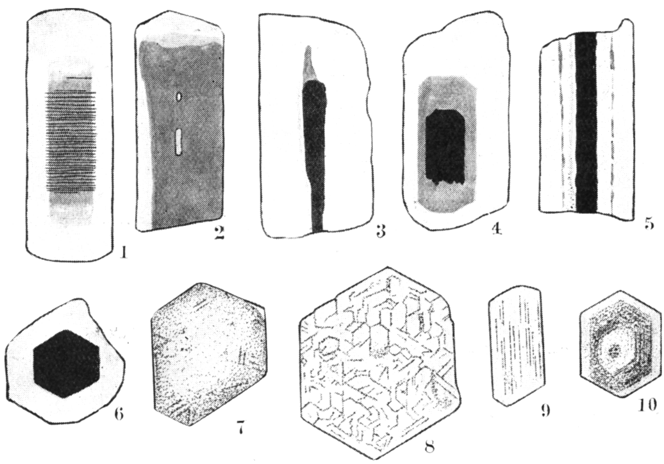
(*e*) Another type of core is frequently observed consisting of the characters of types (*c*) and (*d*). The pleochroism of this type is generally marked. (Fig. 1.)

In all cases where pleochroism is visible the absorption for ϵ is greater than for ω.

Gault Clay.—A sample of Gault Clay from about two miles east of Dorking, Surrey, yielded large grains of apatite two of which contained finely developed central cores of deep greenish-brown. The cores are non-pleochroic, sharply defined, and measure 0·1 mm. in width.

Thanet Sand.—A single grain of apatite with a central core of non-pleochroic opaque matter has been noted from the Thanet Sand of Ewell, Surrey.

General Remarks.—Attempts to determine the nature of the inclusions in the examples just described have yielded little evidence in grains of types (*a*), (*c*), (*d*), and (*e*). Despite the different colours, the writer is of the opinion that the nature of the inclusions in most of the types other than type (*b*) are similar, and that the different degrees and ranges of pleochroism produced are dependent on the size and arrangement of the fine particles of foreign matter. Those of type (*b*) which show a greenish-brown colour, maximum absorption parallel to length, strong birefringence, and positive sign of elongation are suggestive of biotite, but the number of grains showing all these characters is relatively small. In other cases in type (*b*) the greenish-brown colour is accompanied by no indications of birefringence, and chlorite is suggested as a probability. One broken grain has been noted in which a core of type (*b*) protruded through the end owing to fracturing away of the surrounding apatite. The core was green, fairly broad and flattened, and could be definitely identified as



FIGS. 1–10. Apatite crystals with inclusions, from: 1, Trégastel, Brittany; 2, St. Pol de Léon, Brittany; 3, Flamanville; 4, Port de Landemer, near Barfleur; 5, La Pulente, Jersey; 6, St. Pol de Léon; 7, Surville Manor, Jersey; 8 and 9, Bonne Nuit Bay, Jersey; 10, Pors-Even, north Brittany. Figs. 6, 7, 8, and 10 are of transverse sections, the others longitudinal. Magnification: Figs. 1–6 ×100, 7–10 ×200.

green biotite. In yet other cases the core consists of opaque discrete particles, and quite commonly is a rod of opaque matter (type (*a*)). A few apatite grains have been noted with a central void or gas inclusion in place of a core. Sometimes the central void is partly filled with opaque particles of foreign matter.

For the zoning of the Dartmoor zircons Dr. A. Brammall has suggested the following as a possible mechanism. The growth of a crystal of X from its solution creates a two-way migration of molecules: (1) An inward diffusion of the constituents of X towards the centre of crystallization; and (2) An outward diffusion and repulsion of substances not required by X. Alien substances thus repelled tend to become temporarily concentrated in a very narrow fluid zone around the margin of the crystal X, and for one of these substances, say Y, the concentration may reach the labile state with the result that a cloud of crystalline Y particles may suddenly arise. As the precipitation of Y particles would automatically raise the concentration of X in the zone of precipitation, growth of X, suddenly accelerated, might overstep the Y particles and enclose them in a definite growth zone. This process, repeated rhythmically, would explain the zoning of the Dartmoor zircons by ilmenite dust.

Such a theory would explain the presence of biotite and chlorite as inclusions in apatite—minerals which generally crystallize after apatite. The cores of inclusions could then be explained as apatite charged with inclusions forming the dark core, a sudden change of physical conditions causing the rest of the crystal growth to be clear and devoid of inclusions. The grey areas described may be due to zoning on a sub-microscopic scale, the reflection and transmission of light from such small particles giving rise to colour effects simulating pleochroism. A zoned crystal such as that of fig. 4 would represent two well-defined changes in the physical conditions; fig. 10 is a comparable case to that of the zoned zircons; while in fig. 5 the outer thin zone of inclusions would indicate a temporary return to conditions favourable for the formation of inclusions.

The regular arrangement of inclusions in chiastolite is known to be due to the fact that the particles consisting of carbon in the solid state exert no osmotic pressure and are consequently passive to the forces exerted by the growth of the crystal. The plates of foreign matter parallel to the basal plane in the cores of types (*c*) and (*e*) (fig. 1) seem to be more readily explained by some such theory as that generally held for chiastolite. The same remark also applies to crystals of the type of fig. 8.

There are numerous references in text-books[1] to apatite crystals with inclusions and showing pleochroism. In all the cases of pleochroic apatite examined by the writer the pleochroism is seen under high magnification to be confined to the core of inclusions; with magnifications of less than about 50 diameters the whole grain often has the appearance of being pleochroic.

I wish to thank Prof. W. W. Watts and Dr. A. Brammall for critically reading the manuscript of these notes.

[1] J. P. Iddings, Rock Minerals, 2nd edit., 1911, p. 524; E. Weinschenk, Petrographic Methods, New York, 1912, p. 237; F. H. Hatch and A. K. Wells, Text-book of Petrology, 1926, vol. 1, pp. 114–15.

Part II. Apatite in the volcanic rocks of Jersey and Brittany (by A. E. Mourant).

A study of the volcanic rocks, presumed to be pre-Cambrian, of Jersey and north Brittany has brought to light a number of instances of apatite with inclusions and apparently pleochroic.

Jersey.—The Jersey examples all occur in andesites, and the apatites of nearly all the normal andesites show at least traces of inclusions. All the andesites examined, however, from the contact-metamorphic aureole of the 'newer' granite show apatites entirely free from the characteristic inclusions, though they are of the same size and shape as those in the unaltered andesite.

Longitudinal sections show innumerable dark fibres arranged in lines parallel to the length of the crystal. The larger fibres show visible pleochroism, being practically opaque to light vibrating parallel to their length, and dark brown for the perpendicular vibration. The fibres occasionally show visible double refraction which must therefore be very high. In one case it appears that they have positive elongation. Elongated cavities can be detected in addition to normal fibres in a few crystals. A few large negative crystals contain irregularly arranged partly chloritized biotite.

In transverse sections the crystals show the inclusions in lines about one inclusion deep, forming an irregular network approximating, in some cases very closely, to a lattice-work of lines parallel to the traces of the prism faces. The lines seldom, if ever, cross one another.

Oblique and longitudinal sections show that the pattern is remarkably constant from end to end of the crystal. The terminations of the crystals are frequently irregular as though broken. In such cases the inclusions run unaffected to the end. Where pyramid faces are present a short, ill-defined terminal zone is generally clear. Inclusions are occasionally crowded (generally individually parallel to the prism edges) along surfaces parallel to the basal planes and along irregular surfaces resembling cracks.

The lattice structure is best seen in the apatite of andesite from the top of the slope south of the west end of Bonne Nuit Bay (figs. 8 and 9). At Surville Manor the chief characteristic is a marked crowding of the inclusions towards the crystal margins (fig. 7).

Two somewhat unusual types of apatite occur with others in a section of much weathered andesite, probably ash, from near Highfield, St. Saviour. One type contains numbers of opaque plates parallel to the basal plane of the crystal. Only two such crystals are present, and it is impossible to determine the optical characters or the finer details of structure. This type is perhaps the same as type (*c*) above and, like it, shows no pleochroism. The other variety in the same micro-section is also represented solely by two crystals. These are colourless for the ordinary ray and quite uniformly pale reddish-brown for the extraordinary. Both crystals occur in very rusty parts of the slide and there is a strong suggestion that the colour is due to iron introduced during weathering. This is the only case in which the apatite itself definitely appears coloured.

Brittany.—In north Brittany the inclusions are apparently of the same nature as that common in Jersey but are sometimes sub-microscopic. As the fibres get smaller and smaller the host takes on an appearance of pleochroism and colour change becomes more conspicuous, with ϵ pure dark grey and ω pale brown, as would be expected from the comminution of the larger fibres. This effect is hardly seen in the Jersey examples. Another marked difference is in the arrangement of the fibres in zones parallel to the crystal faces. The longitudinal arrangement is unchanged.

At Pors-Even in a somewhat basic variety of the 'porphyre pétro-siliceux' the apatites generally show traces of a core of rather coarse inclusions followed by finer matter collected in, but not entirely confined to, very sharp zones of growth of which nine were counted in one crystal (fig. 10). A flow-breccia of similar composition at Les Heaux contains many small apatites with pleochroic cores in which many of the inclusions are sub-microscopic. A few crystals have larger inclusions more widely distributed and showing definite traces of the lattice arrangement.

North of Pors-Even, in the 'orthophyre de Tréguier' most of the apatites are water-clear, but a few show strong pleochroism, while inclusions are only indistinctly seen with the highest power. One or two dark zones are visible with traces of a much finer zoning. The external layer is always clear.

The 'albitophyre de Pors-Hir' at L'Arcouest contains apatites with inclusions confined to a relatively small core, probably with a clear centre. The inclusions are mostly sub-microscopic. The depth of darkening is moderate. One example shows a rather indefinite central core in which separate inclusions are just visible. This is separated by a clear zone from a sheath showing crystal outline in which separate bodies cannot be seen. The exterior of the crystal is clear.

The apatites of this rock as a whole greatly resemble those described above from the granite.

The nature of the inclusions is probably identical in all the examples described from the volcanic and hypabyssal rocks of Jersey and north Brittany, but they are best examined in those of Jersey. Haematite and manganite are suggested as possibilities. The absence of signs of a platy habit and of pleochroism in transverse sections is, however, against the former, while the pleochroism is almost too strong for the latter.

I wish to thank Prof. W. J. Sollas for his helpful criticism during the preparation of this paper.