Laccolithic, as opposed to cauldron subsidence, emplacement of the Eastern Mourne pluton, N. Ireland: evidence from anisotropy of magnetic susceptibility

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Abstract: The structural evolution and emplacement of the Eastern Mourne pluton was investigated using anisotropy of magnetic susceptibility (AMS) measurements (carried out on 112 oriented block samples) and structural data from the host rocks. From these new data cauldron subsidence, as the emplacement mechanism, is disputed and evidence for an alternative, laccolithic style model involving inflation is presented. This includes deflection and uplift of host-rock bedding close to contacts and the magnetic fabric pattern, which has a gentle dome geometry, even close to contacts. The magnetic lineations usually plunge down-dip near the external margins but otherwise have a general SSW–NNE trend that diverges northward. This suggests a northward-directed inflow direction. The model for the emplacement of the Eastern Mourne pluton is a laterally fed laccolith, emplaced south to north. The eastern margin is interpreted as a faulted contact facilitating the inflation of an asymmetrical ‘breached’ laccolith.

Cauldron subsidence is essentially the subterranean or plutonic version of caldera collapse (Clough et al. 1909; Cole et al. 2005). It involves the sinking of a large block of country rock, facilitated by concentric (or ring-shaped), steeply outward-dipping fractures or faults, into a magma chamber, to be replaced by magma from that chamber (Clough et al. 1909; Anderson 1936; Hills 1963; Hall 1996, pp. 75–83). Ring-dyke emplacement is the initial stage, in which magma intrudes along the ring faults to enclose or partially enclose the central block, resulting in a ring-shaped or annular intrusion with steeply outward-dipping contacts (Richey 1932; Richey & Thomas 1932; Anderson 1936).

The principal feature of cauldron subsidence is that the pluton contacts are steeply dipping and the roof is flat (the pluton is said to be ‘stock-like’ or has a ‘bell-jar’ geometry). In addition, the contacts crosscut the host-rock structure (i.e. they are discordant), signifying brittle deformation. In this way, cauldron subsidence is a passive emplacement mechanism in the classic sense, where passive upwelling of magma will fill the space previously occupied by the subsided block. The main problem, however, is that unlike surface calderas, the central block is rarely identified in the plutonic version. The space required for emplacement has therefore not been fully accounted for.

The biotite (± amphibole) syenogranites of the Mourne Igneous Province (Fig. 1), are where the currently accepted model for subterranean cauldron subsidence used worldwide (e.g. Pitcher 1953; Turner 1963; Ike 1983; Bussell & Pitcher 1985; Johnson et al. 2002) was first developed, based on field evidence (Richey 1928, 1932; Richey & Thomas 1930, 1932; Anderson 1936; Pitcher 1953; Harry & Richey 1963; Hills 1963). The work by Richey (1928) on the Mourne granites was completed in tandem with that by Richey & Thomas (1930) on Ardnamurchan. This model, inspired by the original work of Clough et al. (1909) and Bailey et al. (1924) on Glen Coe and Mull, respectively, and the dynamics of this style of emplace-
The Eastern Mourne pluton was later used by Harry & Richey (1963) as an example of ‘pulses’ of granite, which is currently a fundamental concept for emplacement studies in general (Pitcher 1997).

The original mapping by Richey (1928) essentially identified an asymmetrically zoned pluton with G1 occupying gently dipping roof and steeply dipping wall situations (Fig. 2a), and proposed that internal contacts reflected this geometry. Crucial to Richey’s model were: (1) roof and wall situations of the G1 unit, reflected in the geometry of the external boundaries and internal contacts; (2) inflow from the east with steep or vertical flow entering from the east side (Fig. 3). In addition to this, subsidence should result in an essentially reverse sense of shear on steeply dipping contacts, recording the downward motion of the central portions (Fig. 3).

Alternative models and recent revisions of the Eastern Mourne pluton

A recent revision of Richey’s mapping (Meighan 1978; Hood 1981; Meighan et al. 1984; see also Cooper & Johnston 2004, p. 183, and OSNI 1:25 000 Mourne map, 2004) has shown that the outcrops of G1 in the wall situations are actually mostly of G2 composition. These outcrops were reclassified as G2 Outer and contain a mafic variant, so the granite units of the Eastern Mourne pluton are G1, G2 Outer mafic facies, G2 Outer (normal portion), G2 Inner and G3 (Figs 2b and 4a). The fundamental evidence for cauldron subsidence in this classic case is thus undermined.

Hood (1981) discussed all the available models (Rohleder 1932; Walker 1975; see below) in addition to that of Richey (1928). Hood believed that G3 supported a laccolithic style of emplacement, but finally preferred cauldron subsidence because the G2 Outer and G2 Outer mafic units appeared to represent a partial ring-dyke and a stage in the development of the cauldron subsidence-related pluton. Despite the recent revisions, and in the absence of any alternative hypothesis that is consistent with the field relations, cauldron subsidence in the sense of Richey...
AMS OF THE EASTERN MOURNE PLUTON

Key

G1 ROOF
Malic Facies
Normal Portion
Coarse Portion
Fine-medium area
Fine-only area

G2 OUTER
Coarse Portion
Fine-medium area
Fine-only area

G2 INNER

Western Mourne centre granites
Contact dip not constrained but probably near vertical
Preferred alignment of feldspar phenocrysts
Strike and dip (dip value in degrees) of Silurian host rocks

Minor water body and river. Only a selection are shown. Those referred to in the text are named: BBR - Bloody Bridge River, CS - Crock Stream, GR - Glen River, AR - Annalong River.

Peak with height (m), Those referred to in the text are named: SD - Slieve Donard, SC - Slieve Commedagh, SB - Slieve Bearnaigh, SB1 - Slieve Binnian, BN1 - Binnian North Tor, SM - Slieve Muck, M - Millstone Mountain.

Reservoirs and Lakes: LS - Lough Shinnagh

Dip and dip direction of granitic contact
Dip direction of steep granitic contact: > 50°
Dip direction of gentle granitic contact: < 30°

Inferred internal pulse boundary

a) Line of Binnian Tunnel
b) Line of Mourne Aqueduct section
(after Robbie 1955), see figure 6.

Shortened
Flattened/Deflected
Undeformed
(1928) has remained the established mechanism for the Eastern Mourne pluton (see Cooper & Johnston 2004, p. 186).

The only two alternative models published for the Mourne Centres are those of Rohleder (1932) (discordant laccolith) and Walker (1975) (curved flange from the side of an acid diapir). Rohleder's model did not gain acceptance as it was not supported by tangible field evidence. The model of Walker (1975) was designed to explain all the British Palaeogene Igneous Province intrusive centres but, although more sophisticated than Rohleder's, did not satisfactorily explain the structure that Richey (1928) originally mapped. For example, Walker's model suggested that the granites could have been emplaced into a flange fracture (effectively a lateral tear or tension fracture) off the main mafic magma chamber (possibly associated with the older Carlingford Complex to the SW).

**Published gravity evidence**

Bouguer gravity evidence (Cook & Murphy 1952) shows that the main anomaly (and by inference the main mafic magma chambers) lay to the SW of the Mourne area between Slieve Gullion and Carlingford. Separate Bouguer gravity data for the north Irish Sea (Wright et al. 1971) showed a further anomaly, situated just off the coast directly south of the Eastern Mourne pluton, of a similar magnitude to the main anomaly described by Cook & Murphy (1952). Hood (1981) suggested that these two anomalies, identified from separate surveys, may represent a mass of basic material that extends beneath the two areas. This is supported by more recently published gravity data (Reay 2004, p. 233) that show a continuous Bouguer gravity anomaly, which extends from the Slieve Gullion–Carlingford area to offshore due south of the Eastern Mourne pluton, showing that the two separately identified anomalies are more or less continuous. If this represents a basic magma body, and given the genetic link between the Mourne granites and the basic rocks in this area (Hood 1981; Meighan et al. 1984), it would suggest that the Mourne granites were emplaced in a roughly north or NE direction, and perhaps lends further credence to the flange-type fracture mechanism of Walker (1975); in this case, off the north side of a basic magma chamber in the Carlingford–Southern Mourne area.

**Evidence for inflation of the Eastern Mourne pluton**

**Deformation of host rocks**

The host rocks of the Eastern Mourne pluton are greywacke and slate that are usually moderately to steeply SE-dipping elsewhere in County Down (Anderson & Cameron 1979). Apart from local contact hornfels, the granite has no obvious metamorphic aureole. The deformation of the host rocks is rather difficult to assess because of poor exposure, the nature of the lithology and the existence of previous multiple deformations (e.g. Anderson & Cameron 1979). The alternative models discussed above nevertheless claim there is up-doming around the pluton.

Bedding dips recorded by Hood (1981), T. B. Anderson (pers. comm.) and in this study indicate that the bedding of the host rock is deflected into parallelism with the margin of the pluton in the NE, east and south (Fig. 4a). The dip of bedding around the NW of the pluton also seems much more irregular, with bedding dipping both to the NW and SE, suggesting that there may be shortening and folding perpendicular to the contact (Fig. 4b).

The structure, fabrics and deformation of the granite

Two of the observations by Hood (1981) concerning the structure of the Eastern Mourne pluton are significant to this study and must be mentioned here. First, he described further major variations based on petrographical and geochemical differences within the main granites (see Hood 1981; Cooper & Johnston 2004, p. 183; OSNI 1:25 000 Mourne map, 2004; and Fig. 4a). One of these corresponds to the fine–coarse ‘pulse-type’ boundary in G2 described by Harry & Richey (1963). Hood (1981) also noticed that there was evidence for numerous internal, small-scale, minor variations, especially in G3. These minor variations were seen in G3 cores taken for the aborted Lough Shanagh pumped water storage scheme (Hood 1981, fig. 12) and observed by Robbie (1955) in the Binnian Tunnel, which passed through G3 and G2 Inner beneath Slieve Binnian. In many places Hood (1981) also observed internal, gently dipping contacts at the junction of both major and minor variants in the granites and this has been confirmed here (Fig. 5). The implications of all these observations is that each granite and major variant in each granite was constructed of a number of large- and small-scale pulses of magma, respectively.

Second, Hood (1981) revised the geometry of the G2–G3 contact beneath Slieve Binnian based on his remapping and observations from the Binnian Tunnel (completed in 1952; Robbie 1955). Robbie (1955) and Hood (1981) showed that the G2–G3 contact was more likely to be a gentle dome shape rather than Richey’s sharp roof-to-wall transition (Fig. 6).

In the G2 Outer unit close to the eastern contact, there are numerous but sparse dark veins of varying thickness (1–10 cm), which anastomose and bifurcate seemingly irregularly but are roughly contact-parallel. These structures occur with greater abundance (although still relatively sparsely) closer to external contacts mainly along the eastern margin and on Millstone Mt [grid ref. J 372 285] (see Fig. 4a). They are thin, discrete shear zones containing mainly cataclasite with some mylonite (Fig. 7a–c). The sense of shear, where it can be discerned, is pluton-side-up (Fig. 7a and d). These deformation bands are distinct from (although possibly structurally and temporally associated with) much paler veins of greisen and kaolinite that also occur in these areas (Nockolds 1939; McCormick et al. 1993). These latter veins do not show any obvious signs of deformation.

The dark deformation bands resemble the crush lines found in the Camlough Breccias (also veins of cataclasite) around the Slieve Gullion centre (Richey & Thomas 1932) and the flinty crush rock associated with the ring fault of Glen Coe (Clough et al. 1909). The discrete nature of the deformation (i.e. in narrow, centimetre-scale zones) associated with these structures suggests that the granite was still at a very high temperature when they occurred. The presence of ductile deformation of feldspars giving way to brittle cataclasism, observed in thin section (Fig. 7a and c), suggests that they formed as the granite cooled to below 500 °C (Gapais 1989), or the particle locking threshold of Vigneresse et al. (1996). Their regional insignificance shows that they are unlikely to be related to tectonic deformation. As there was no subsequent metamorphism, deformation or significant hydrothermal activity (other than the localized effect of the greisen veins mentioned above) in this area, this deformation is likely to be directly emplacement-related.

The granite of the Eastern Mourne pluton is almost completely lacking in any visible mineral alignment fabric, although a weak, roughly contact-parallel alignment of feldspars is present on horizontal outcrop surfaces close to the eastern margin (Fig. 4a). Not constrained in three dimensions, it does nevertheless suggest
the existence of a hitherto undetected fabric. Various techniques are now available to constrain in three dimensions such subtle or even ambiguous fabrics. AMS has been chosen in this case as it provides a means to quickly and accurately measure a quantifiable 3D anisotropy that can be easily related to the petrofabric or mineral alignment fabric (for further information and discussion about AMS as a fabric analysis tool with specific reference to igneous rocks, see King 1966; Owens & Bamford 1976; Borradaile 1987, 1988; Rochette 1987; Tarling & Hrouda 1993; Borradaile & Henry 1997; Bouchez 1997).

**Anisotropy of magnetic susceptibility (AMS)**

AMS describes the orientation of magnetic minerals: the ‘magnetic fabric’. The magnetic susceptibility tensor has six independent quantities, which may be represented as three principal susceptibility magnitudes, $K_1 \geq K_2 \geq K_3$, and a corresponding set of three orthogonal principal axis directions: it may be pictured as an ellipsoid. It is conventional to recast the three magnitude parameters in terms of three parameters, which together reflect the ‘size’, ‘shape’ and ‘strength’ (or ellipticity) of the ellipsoid. The three parameters adopted here (see Owens 1974) are:

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**Fig. 5.** (a) Photograph of a subtle internal boundary within G2 Inner. Locality is the Summit Tor of Slieve Bearnagh [J 313 279]. It should be noted that the subtle contacts dip gently north, as do the magnetic fabrics (plotted stereographically, also see Fig. 10b). (b) Close-up photograph of the area marked in (a), showing the sharp contrast in texture (contact highlighted with white arrows). (c) Field sketch of the North Tor of Slieve Binnian [J 319 245]. The sketch records subtle subhorizontal layers in the outcrop that are picked out by drusy lenses and pegmatite fringes. It should be noted here also that the attitude of these layers is parallel to the magnetic fabric (plotted stereographically, also see Fig. 10b).

**Fig. 6.** Revision of the G2–G3 contact of Richey (1928) beneath Slieve Binnian according to Robbie (1955), from data collected from the Binnian Tunnel. Taken from Hood (1981, fig. 27).
The magnetic lineation $L = (K_1 - K_2)/K_{\text{mean}}$ and foliation $F = (K_2 - K_3)/K_{\text{mean}}$ are defined. A plot of the magnetic lineation $L$ against the magnetic foliation $F$ (see Fig. 8) indicates graphically the shape of the ellipsoid: prolate ellipsoids lie near the $L$-axis and oblate ellipsoids near the $F$-axis, whereas triaxial ellipsoids occupy the centre ground. Although the three quantities $K_{\text{mean}}$, $L$, and $F$ are sufficient to define the magnitude parameters of the ellipsoid, it is convenient to define another parameter, $H = L + F = (K_1 - K_3)/K_{\text{mean}}$ to indicate the strength of the magnetic fabric.

To assess the AMS of the Eastern Mourne pluton, a suite of 112 samples, oriented by compass, was collected. (A map of the sample localities and AMS data from the Eastern Mourne pluton, plotted as discussed in the text, are available online at http://www.geolsoc.org.uk/SUP18253. A hard copy can be obtained from the Society Library.) From each block, 6–12 (typically 10) cylindrical sub-specimens of c. 1 cm$^3$ were drilled in the laboratory (Owens 1994) and measured on an AGICO KLY-3s Kappabridge. The sub-specimen results (normalized by $K_{\text{mean}}$) were averaged for each block (Jelinek 1978; Owens 2000a, b) to produce mean values of the AMS ellipsoid. The principal axis directions for each block sample (with the 95% confidence limits of each axis) are plotted stereographically (see the supplementary publication).

Susceptibility values (in SI system) from these samples are between $47 \times 10^{-6}$ and $10 \times 10^{-6}$. (A table of susceptibility data from the Eastern Mourne pluton are available online at http://www.geolsoc.org.uk/SUP18253. A hard copy can be obtained from the Society Library.) Microscopic and thermomagnetic analyses confirm that the susceptibility is predominantly carried by magnetite or titanomagnetite, and secondarily by biotite. The AMS represents normal fabrics controlled by the shape-preferred orientation of magnetite grains and, to a much lesser extent, by the crystallographic orientation of biotite.

A small degree of recent weathering cannot be avoided in intensive sampling based on oriented block samples in areas of
Magnetic fabric

The strength of anisotropy (H) is variable over the Eastern Mourne pluton: from 0.53%, indicating a very weak fabric, to 10.24%, indicating a strong fabric. The shape of the anisotropy is also variable. Figure 8 shows a plot of L against F (as discussed above) for all the Eastern Mourne pluton samples. Although most samples have relatively weak fabrics, the more strongly developed fabrics in G2 Inner and Outer tend towards oblate, with the more intense fabrics being formed in G2 Outer. Although the magnitude of strain cannot be reliably determined from this dominantly ferromagnetically controlled AMS data, the shape of the anisotropy does allude to the type of strain, suggesting progressively more flattening in the older units. This trend is not carried through to G2 mafic facies and G1, probably because of their differing mineralogy (potentially more magnetite).

There is another way of providing at least a rough visual indication of the shape and strength of the mean anisotropy of block-sampled data, which is relevant to the presentation of mapped data. This is illustrated in Figure 9 and is used on the map (Fig. 10a). Figure 9a is a conventional L–F plot of all the specimens in two block samples. Figure 9b is a stereographic plot of the specimen principal axes for each block sample. Figure 9c plots the sample mean directions, with calculated 95% confidence ellipses. The shape of the confidence ellipses provides a key to the shape of the mean ellipsoid. This follows because the size of the ellipse semi-axis in each principal plane varies inversely as the difference between the two principal susceptibilities in that plane. Thus, for example, an oblate fabric will have a small circular confidence ellipse around the minimum susceptibility, with the other two confidence ellipses elongated in the foliation plane (e.g. M13, Fig. 9c), whereas a triaxial fabric will have confidences ellipses around the maximum and minimum axes that are both elongated toward the intermediate axis. The confidence ellipse area around the intermediate axis then will be larger and more circular than the other two (e.g. M18, Fig. 9c) (Jelinek 1978; Owens 2000a, b). The overall size of the confidence ellipses for the mean principal axis directions for a sample, if based on a constant number of specimens, gives a relative indication of the strength or scatter of specimen anisotropies within the block; the larger the ellipse, the greater the scatter and the weaker the fabric.

The magnetic fabrics for the Eastern Mourne pluton are summarized on Figure 10b. The general pattern is of a roughly dome-shaped foliation with lineations that usually plunge down-dip near the margins but otherwise have a rough SW–NE trend, which is particularly evident in G2 Inner and G3. The lineation pattern then diverges northward and is otherwise radial in the older units (Fig. 10b). In more detail, the magnetic foliations approaching the G2 Inner–G2 Outer contact and G2 mafic facies in the eastern part of the pluton are slightly steeper than usual. The foliations then become less steep once again towards the external margin in G2 Outer. This may be due to some subsolidus deformation of the G2 Outer unit by the emplacement of the G2 Inner unit and possibly the G3 unit (discussed below). The significant point is that the fabrics are gently dipping right up to the external margins, even those that are steep, precluding passive vertical magma flow upwards along these steep contacts. We think that the gently dipping fabrics are due to upward-directed forces from a forceful emplacement.

Discussion

Two crucial tenets of the original cauldron subsidence model of Richey (1928) have been undermined: (1) the roof and wall geometry is no longer evident, as Richey's 'wall' G1 was revised by Meighan et al. (1984) as being G2 Outer; (2) the contacts (external and internal) are generally gentle rather than reflecting roof and wall orientations as proposed by Richey (1928). In addition, the fabric pattern identified in this study is difficult to relate to a subsidence model (sensu Richey 1928), and the linear component of the magnetic fabric (probably representing the inflow direction) is generally SSW–NNE trending. Therefore, cauldron subsidence is disputed as a satisfactory mechanism to explain fully the emplacement of this pluton. An alternative must be sought.

Over the last 25 years, the application of geophysical methods to studies of granite plutons (e.g. Vigneresse 1990) and deep seismic profiles of the lithosphere (e.g. Toppozada & Sanford 1976; Chmielowski et al. 1999; Zandt et al. 2003), have shown that the 3D geometry of plutons is generally tabular, with floors that are less deep than the lateral extent of the pluton (e.g. McCaffrey & Petford 1997; Cruden 1998; Petford & Clemens 2000; Vigneresse & Clemens 2000). It is now generally accepted that a pluton is constructed from the incremental thickening or inflation of an initially thinner sheet, by roof uplift (laccolith), floor down-drop (lopolith), a combination of these, or lateral

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**Fig. 9.** (a) Plot of magnetic lineation (L%) against magnetic foliation (F%) from block samples M13 and M18. (b, c) Stereographic projections of data for individual stations (block samples) M13 and M18. M13 is an example where the magnetic fabric is well defined and M18 is an example where the magnetic fabric is poorly defined but accepted with caution. (b) Plot of each specimen's principal axes. (c) Plot of mean principal axis direction. K (SI $\times 10^{-3}$) and H values for each sample are also shown.
expansion of a vertical intrusion (for further discussion, see Petford et al. 2000; Vigneresse 2004). Classic models such as diapirism and cauldron subsidence have been argued to be unsatisfactory in explaining all the geodynamic aspects of mid- to upper-crustal pluton emplacement, from the evolution of the magmas to the deformation of the crust associated with this emplacement (Vigneresse 2004). A laccolithic style emplacement model is entirely feasible for the Eastern Mourne pluton based on the evidence for inflation and inflow of magma presented here.

Inflation and up-doming

The country rocks around the Eastern Mourne pluton are demonstrably domed, even though these country rocks underwent multiple deformations during the Caledonian Orogeny (Anderson & Cameron 1979) and the strain associated with inflation of the Eastern Mourne pluton is therefore not easy to constrain. Before the emplacement of the pluton the country rocks were, from structural observations elsewhere in County Down, consistently steeply inclined to the SE (Anderson & Cameron 1979). Now around the NE, east and south of the pluton bedding is roughly concordant with the contacts, whereas in the NW the bedding is much more irregular, dipping both NW and SE (Fig. 4a).

The steep contacts between country rock and G1 on the NE sides of Slieve Commedagh and Slieve Donard may also be explained by up-doming. The current G1–country rock contacts dip c. 70–80° to the NE. The current G1–G2 Inner contacts on these mountains usually dip at 30° to the NE. If this latter contact had begun as a horizontal roof contact of an initially thin sheet, subsequent inflation and up-doming associated with laccolith emplacement would cause this contact to tilt and dip more steeply, in this case, to the NE. Consistent with this updoming,
the initial dip of the G1–country rock contact (pre-G2) would have been c. 40–50°, which is moderate rather than steep (Fig. 11a, i). This supports emplacement of G1 as a laccolith.

Some have argued that the volume discrepancy, which remains when strains around inflated plutons (measured in the outcrop plane) have been restored, can only be explained by movement of host-rock material downwards (Paterson & Fowler 1993; Vernon & Paterson 1993; Paterson & Vernon 1995). However, this argument does not take into account the up-doming of host-rock material, by inflation, if the pluton began as a thin horizontal sheet. Only an apparently small amount of strain in the horizontal (outcrop) plane is required to make the space, particularly if the inflation was not extreme. Following this, the gentle Mourne contacts (except the eastern contact) suggest that this is a relatively high aspect ratio pluton (still fairly thin), which might be expected, given that this granitic magma was probably of low viscosity. This is also supported by Bouguer gravity evidence, which reveals no significant negative anomaly over the Eastern Mourne pluton (Cook & Murphy 1952). Thus, the inflation of the Eastern Mourne pluton was not necessarily extreme and need not have caused large amounts of strain. In addition, the steep eastern margin is characterized by unusually high deformation, with shears and cataclasite veins mainly inside the granite. There are also numerous cataclasite veins and dominantly brittle disruption of the country rock structure immediately outside the granite. This deformation, together with the gently dipping magnetic foliations close to the margins, suggests that the margin represents a faulted contact, the sense of shear (where discerned) being pluton side up. In this way, the gently dipping foliations close to the steeply dipping external contacts in the east have been truncated by this deformation. Therefore, a proportion of inflation-related strain was taken up by displacement in the sense of a ‘breached laccolith’ or bysmalith (Corry 1988), producing an asymmetrical cross-section (Figs 10c and 11a). In this type of emplacement, accommodation space was created forcefully by uplift of the roof achieved by piston-like faulting as well as doming (Fig. 11b).

Alternatively, it may be that the inflation observed here could

Fig. 11. (a) Laccolithic inflation of the Eastern Mourne pluton. The host-rock structure is schematically represented with diagonal lines. (1) Emplacement of G1. (2) Emplacement of G2 Outer and mafic facies with incipient piston-like faulting accommodation. (3) Emplacement of G2 Inner with (i) the steepening of the G1–country rock contact on Slieve Commedagh and Slieve Donard (Fig. 4a), as a result of doming caused by laccolith-style emplacement of younger units (north–south section), and (ii) the shearing of G2 Outer mafic facies along the G2 Inner–G2 Outer boundary and continued piston-like faulting on the eastern margin. (4) Emplacement of G3. (b) Schematic diagram demonstrating the doming and faulting of an arbitrary layer just above the initial emplacement level. This demonstrates uplift of the roof achieved by a combination of doming in the west over Slieve Muck and piston-like faulting along the eastern margin.
Ardnamurchan (Brown & Bell 2006). Around the Northern Arran Granite (England 1990, 1992) and on Skye, were originally interpreted by Harker (1904, p. 127) as this resurgence. Uplift of the country rocks, as around the Eastern Mourne pluton, is also observed around other British Palaeogene Igneous Province central complexes. Uplift around these centres in NE Ireland (Slieve Gullion and Carlingford) was noted by Walker (1975). The granitoids of the Western Red Hills centre, Skye, were originally interpreted by Harker (1904, p. 127) as having been emplaced as subhorizontal sheets (laccoliths). More recently, Butler & Hutton (1994) described granite emplacement in Skye associated with doming. Uplift of the country rocks around a central complex is also seen on Rum (Emeleus 1997), around the Northern Arran Granite (England 1990, 1992) and on Ardnamurchan (Brown & Bell 2006).

**Origin and emplacement of G2 mafic facies**

The G2 Outer mafic facies is a mafic variant of G2 Outer. It crops out as a steeply oriented sheet of relatively mafic granite between G2 Inner and G2 Outer in the east with minor occurrences in the west. In the east, it has a sharp contact with G2 Inner and a rapidly gradational contact with G2 Outer, and it is grouped with G2 Outer because of these contact relationships (Figs 2b, 4a and 10b). Geochemically, the composition of the G2 Outer mafic facies is between that of G1 and G2 Outer, and it has been suggested that this may be a mafic cumulate that was fractionated from a parental magma to produce G2 Outer (normal portion) with a mafic variant, the G2 Outer mafic facies (Hood 1981; Meighan et al. 1984). The steep inclination of the contacts of the G2 Outer mafic facies led Hood (1981) to conclude that this was part of a ring-dyke.

The fabrics identified in the current study become gradually steeper approaching the sharp contact between G2 Inner and G2 Outer mafic facies (from subhorizontal in the centre to 30–50° near the contact), then become gradually less steep (to roughly 15–20°) from G2 Outer mafic facies into G2 Outer (normal portion) (Fig. 10). This may be explained by subsolidus shearing of the boundary between G2 Inner and G2 Outer, related to the accommodation of G2 Inner, resulting in steepening of this boundary and causing G2 Outer mafic facies to be dragged up from the floor of an initially horizontally zoned G2 Outer sheet (Fig. 11a, part 3 inset).

**Inflow direction**

The data presented above clearly show that the Eastern Mourne pluton was emplaced forcibly in the sense of a laccolith; however, there may be more than one way of interpreting how the magma infilled this pluton. Classically (according to Gilbert 1877) a laccolith is fed from a centrally located feeder conduit or dyke (e.g. the Papoose Flat pluton, de Saint-Blanquat et al. 2001). In the Eastern Mourne pluton, the linear component of the magnetic fabric, trending roughly SW–NE, may represent magma flow perpendicular to the NW–SE-trending, contemporaneous and consanguineous dyke swarm (Tomkieff & Marshall 1935; Akiman 1971; Hood 1981; Meighan et al. 1984), suggesting that some of these dykes acted as feeder dykes to the pluton. The general SW younging of successive units may be due to a southwestward shift of active feeder dykes (Fig. 12a, central feeder dyke model). However, a feeder dyke or collection of feeder dykes has not been identified for the Eastern Mourne pluton. Also, there are no steeply dipping fabrics in the central areas of the pluton to suggest a centrally located feeder or feeders.

Alternatively, the marked deflection and faulting of the host rocks in the east may indicate the region of maximum magma pressure and thus suggest that the pluton was fed from the east and NE via some sort of steeply outward inclined arcuate feeder. However, bearing in mind the progressively more aplitic nature of the magma involved (Hood 1981; Meighan et al. 1984) and thus lower emplacement temperature, this model would require that each successive pulse of magma would have to subvert its predecessors, travelling further and further to break through (Fig. 12b, arcuate feeder model). There is also no evidence of any steep feeder zones such as steeply dipping foliations, steeply plunging lineations or significant underlying gravity anomaly.

The preferred interpretation considers that the SW–NE-trending lineation diverges to the NE and is similar to the flow pattern observed using AMS and other means in other sheet-like intrusions (e.g. Petronis et al. 2004; Thomson & Hutton 2004; Horseman et al. 2005) and in lava flows (e.g. Canón-Tapia et al. 1995). This suggests that the magma infilled the pluton in the northeasterward direction and was fed from the SW (see Petronis et al. 2004) (Fig. 12c, breached laccolith model). This then implies that the source area was somewhere near the Carlingford and Slieve Gullion Complexes or SE of these. Gravity evidence supports this, as a major gravity anomaly extends from beneath the Slieve Gullion–Carlingford area to due south of the Eastern Mourne pluton (Cook & Murphy 1952; Wright et al. 1971; Reay 2004, p. 233). Although the current model argues for roof uplift rather than floor subsidence, the lateral emplacement model of Walker (1975) regains some credence.

**Conclusion**

AMS has revealed a gentle dome-shaped fabric pattern within the Eastern Mourne pluton. This fabric is subparallel to the gently dipping external contacts and parallels the internal contacts. The shape of the AMS fabrics of the most similar units (G2 Outer, G2 Inner and G3) show progressive flattening of earlier units, probably by the emplacement of younger units (Fig. 8).

Neither the gentle dip of the fabric, nor the gently domed form of the pluton, nor the SW–NE-directed emplacement is consistent with Richey’s cauldron subsidence model. The fabric pattern revealed here is explained by the inflation of an initially much thinner sheet. This is supported by evidence of up-doming of the host rocks. The inflation of this intrusion may have been facilitated by a fault-like contact along the eastern margin, which would explain the deformation found here and the steepness of the contact in this area. In a similar way, the steep attitude of the G2 Outer mafic facies may have been caused by steepening of the boundary between G2 Inner and G2 Outer by subsolidus shear and, by the same process, dragging of G2 Outer mafic facies from the floor of an initially horizontally zoned sheet.

A laccolithic emplacement is proposed for the Eastern Mourne pluton. Although there may be more than one interpretation of the inflow direction, the preferred model is a laccolith that was fed laterally from the SW, rather than from beneath or from the NE, and is supported by published gravity evidence. Given its status as a classic example of cauldron subsidence from the work of Richey (1928), the Eastern Mourne pluton provides a notable example where the inflation of an initially thin sheet provides a generally acceptable explanation for space creation. A crosscutting pluton...
Fig. 12. Alternative models (drawn schematically) to explain the inflow direction for the Eastern Mourne pluton. In each part: 1, G1; 2, G2 Outer (and G2 Outer mafic facies); 3, G2 Inner; 4, G3. (a) Central feeder dyke model. Infilling of a laccolith from a central feeder dyke. The dykes in this case trend NW–SE, perpendicular to the predominant lineation identified from AMS, consistent with the dominant trend of this dyke swarm. The active feeder(s) migrate SW with the general younging trend of the units of the pluton. (b) Arcuate feeder model. (i) Cross-section and (ii) plan view, showing the possible infilling from arcuate feeders located to the NE of the pluton. (c) The preferred breached laccolith model showing a lateral infilling diverging, and therefore flowing, in a northeastward direction. The pluton was infilled from the SE. (d) The final outcrop pattern and AMS fabric pattern are best explained by the NE-directed infilling model shown in (e).

does not necessarily require a large subsided block, if only minor inflation can be detected. Therefore, care must be taken when interpreting the emplacement of other central complexes worldwide, many of which owe their emplacement model to cauldron subsidence, developed primarily in the British Palaeogene Igneous Province centres by J. E. Richey and his coworkers.

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