The emplacement of the Palaeogene Mourne Granite Centres, Northern Ireland: new results from the Western Mourne Centre

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Abstract: There is a basic assumption that the upper crustal point of magma emplacement overlies the point where magma was generated. This contribution discusses the concept of lateral magma movement in the upper crust based on the Mourne Granite Centres, Northern Ireland. We report anisotropy of magnetic susceptibility fabric data from the Western Mourne Centre that indicate SS to NNE inflow in this centre, parallel to the Eastern Centre. This suggests that these two centres share a common feeder zone outside the Mourne area c. 20 km to the south, coincident with a c. 50 mGal gravity anomaly that may be caused by an unexposed mafic pluton. The links between mafic and felsic magmas in this region, and the coincidence of the projected Mourne granite feeder zone and the possible buried mafic pluton lead to a model in which the Mourne granites were emplaced in a NNE direction as two gently dipping sheets from this unexposed mafic body. From this we develop a model that incorporates existing geophysics and known tectonic framework and involves an interconnected upper crustal network of Early Palaeogene igneous intrusion pathways fed from a common tectonically controlled, and probably long-lived, deeply penetrating feeder zone.

Supplementary material: Anisotropy of magnetic susceptibility data, thermomagnetic analyses and a thin section showing magnetite in biotite cleavage are available at http://www.geolsoc.org.uk/SUP18458.

Granite plutons are now widely accepted to be tabular in geometry and emplaced as an initially thin sheet that subsequently thickens (Cruden 1998; Petford et al. 2000). Multiple sheeting of granites into a tectonic shear zone occurs by essentially the same process but with vertical or steeply dipping sheets and an element of tectonic space creation (e.g. Hutton 1992, 1996; Mahan et al. 2003). Although the latter may also provide a crustal-scale ascent route for magma (Hutton & Alsop 1996; Stevenson et al. 2006), plutons that are not obviously associated with a deeply penetrating structure, although they require lateral magma flow at least locally during emplacement, are nearly always assumed to have been fed by subjacent transcrustal dykes (e.g. Petford et al. 1993). The ‘non-tectonically controlled’ alternative is that the pluton was emplaced either as a large buoyant mass (a diapir) through a combination of ductile flow and stoping of country rocks (Paterson & Fowler 1993, Paterson et al. 1996), or through the mainly brittle and passive wholesale subsidence of blocks of country rock (cauldron subsidence) nearer the surface (Cole et al. 2005), or a combination (e.g. Wang et al. 2000). In either context, crustal magma transfer is dominantly vertical and the ascent site is taken to be directly subjacent.

Here we focus on the upper crustal emplacement of the c. 56 Ma anorogenic Mourne Granite Centres, part of the British and Irish Palaeogene Igneous Province. Based on new anisotropy of magnetic susceptibility (AMS) data from the Western Centre that reveal subtle igneous fabrics (interpreted to record magma flow) we confirm the laccolithic emplacement recently proposed for the Eastern Centre (Stevenson et al. 2007b). The implications of our model are that the extent and distribution of Palaeogene granite in the subsurface in this region differ significantly from the accepted classic model involving cauldron subsidence.

Existing geophysical data help us to define the location of a feeder zone linking upper crustal magmatism to mid- or lower crustal levels. From this we can then begin to link magma emplacement with a crustal-scale magma transfer model that integrates the contemporaneous tectonic framework and considers control on intrusion and transport at different crustal levels, opportunities for magma–crust interaction and sources for contamination. This study demonstrates that determining the magma inflow sense and emplacement mechanism are fundamental elements in crustal-scale modelling of the distribution of igneous material.

Mourne Granites

The biotite (± amphibole) syenogranites of the Mourne Granite Centres, part of the British and Irish Palaeogene Igneous Province and the North Atlantic Large Igneous Province, were emplaced into Silurian age (Hawick Group) greywacke and slate at around 56 Ma at c. 1–2 km (Anderson & Cameron 1979; Hood 1981; Gamble et al. 1999; Fig. 1) and heralded the breakup of North America and Eurasia c. 55 Ma (Jolley & Bell 2002). The Mourne Granites are anorogenic and the granitic melt formed by fractionation of basalts derived from plume-driven mantle melting under intact continental lithosphere (Meighan et al. 1984; Kent & Fitton 2000) but, as has been shown for other British and Irish Palaeogene Igneous Province centres, may have had melt contributions from crustal contamination sources (e.g. Geldmacher et al. 2002; Troll et al. 2005).

Laccoliths as opposed to cauldron subsidence

The Eastern and Western Mourne Granite Centres, Northern Ireland, were the first published example of the ring-dyke cauldron subsidence model for granite emplacement (Richey
1928). Stevenson et al. (2007b) outlined the key criteria that Richey (1928) used to invoke cauldron subsidence in this plutonic complex *sensu* Clough et al. (1909). Revisions of Richey's (1928) original mapping in both centres (Emeleus 1955; Hood et al. 1981; Meighan et al. 1984) involved only minor modifications of Richey's original framework and the ring-dyke cauldron subsidence model persisted (for a summary see Cooper & Johnston 2004, pp. 182–187) until Stevenson et al. (2007b) revealed magmatic fabrics in the Eastern Mourne granite using anisotropy of magnetic susceptibility (AMS) measurements. The fabric pattern that Stevenson et al. (2007b) revealed did not provide any evidence of vertical magma flow consistent with a ring-dyke style feeder. Instead, AMS data revealed lateral magma flow directed NNE indicated by northward divergence of the AMS lineation pattern (see Petronis et al. 2004). Stevenson et al. (2007b) acknowledged, however, that the inflow may have alternatively been from the eastern (or northeastern) margin, possibly from an unexposed ring-dyke style feeder, or from subjacent dykes. The adjacent Western Mourne Granite Centre is part of the same granite suite (Gibson 1984; Gamble et al. 1999). With a fabric pattern revealed by this study that is similar to that of the Eastern Centre, the Western Centre results add further support to the conclusions of Stevenson et al. (2007b).

AMS can reveal the preferred orientation of paramagnetic minerals and the preferred orientation and/or distribution of ferromagnetic minerals (principally magnetite), which are often controlled by the silicate fabric. Thus, the orientation of the principal axes of the susceptibility ellipsoid can be used as a proxy for the orientation of mineral alignment fabrics and can be a powerful tool for constraining or defining very subtle fabrics in three dimensions (Tarling & Hrouda 1993).

**Western Mourne AMS fabrics**

AMS was measured on oriented blocks from 66 localities in the Western Mourne Centre on an AGICO KLY-3S kappabridge (Jelinek 1973) at the University of Birmingham. Each oriented block yielded between six and 12 subspecimens. Susceptibility values are $5.2 \times 10^{-2}$ to $1.7 \times 10^{-4}$ (average of $2.9 \times 10^{-4}$) in the S.I. system (consistent with Stevenson et al. 2007b). Anisotropies are around 5% (with $P_i$ c. 1.05 using parameters of Jelinek 1981). The shape of the fabrics are dominantly oblate (with $T_i$ c. 0.4, Jelinek 1981) and the lineation orientation is distinct at around 43% of the sampled sites (enough to deduce a pattern). Thermomagnetic analyses are consistent with Stevenson et al.'s (2007b) Eastern Mourne results where magnetite is present, and thin sections show that it is associated with biotite and occupies biotite cleavage planes. The AMS fabrics therefore reflect the biotite fabric and are an accurate measure of the petrofabric (see Stevenson et al. 2007a).

The AMS fabric pattern revealed in the Western Granite centre (Fig. 2) is remarkably similar to the pattern that Stevenson et al. (2007b) reported for the Eastern Centre. The magnetic foliation is dome shaped and concordant with gently dipping margins and internal contacts. The lineation pattern is generally SSW–NNE trending and diverges northward. The only exceptions are close to a roof pendant that partially separates the Eastern and Western Centres. Here the AMS fabrics are somewhat irregular, possibly recording some perturbation of the inflow by this roof pendant. This roof pendant could then be interpreted as a large-scale example of a stub or broken bridge structure commonly found in

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**Fig. 1.** (a) Location of the major intrusive centres, dyke swarms and extrusions of the British and Irish Palaeogene Igneous Province. Only the intrusive centres are labelled; SG, Slieve Gullion; C, Carlingford; M, Mourne; Ar, Arran; Mu, Mull; A, Ardnamurchan; R, Rum; S, Skye; K, St. Kilda; B, Blackstones. Iapetus suture is marked with a dashed line. (b) Palaeogene intrusive centres in the north of Ireland (after Cooper & Johnston 2004). 1, Western Mourne Centre; 2, Eastern Mourne Centre; 3, Carlingford Centre; 4, Slieve Gullion Centre. Dash-dot line, main faults; dashed line, national boundary.
sill complexes (Hutton 2009). The dominantly oblate fabrics are consistent with forceful emplacement and the NNE-divergent lineation pattern is parallel to that of the Eastern Mourne Centre. Therefore the NNE-directed sense of emplacement is supported for the Mourne Granite Centres.

Existing geophysical data

Our model for the Mourne Granites is two tabular (perhaps 2 km thick) gently dipping sheets of granite, emanating from an unexposed feeder somewhere to the south of the Mourne area. Previous attempts to model the subsurface geometry of the Mourne Granites have been based on cauldron subsidence stock-like bodies (Reay 2004, p. 245). The lack of a significant negative anomaly associated with the Mourne Granite Centres has been modelled by placing a body of denser mafic material beneath the stock of granite. Our new geological model for the Mourne Centres does not require the granite to be very thick and there is therefore no requirement for a lot of dense material directly beneath to cancel out a thick body of low-density granite. Therefore the slightly higher gravity anomaly in the Mourne region may be due to a relatively thin sheet of mafic material beneath a relatively thin sheet of low-density granite. Aeromagnetic data (Reay 2004) do not reveal significant anomalies associated with the Mourne centres or in the region south of the Mourne area. Published gravity data (Reay 2004) show a large positive anomaly of up to 50 mGal, elongate in plan view, which extends from the Slieve Gullion area to the postulated feeder region south of the Mourne Granites (Fig. 3).

For other nearby Palaeogene centres, the strong magnetic signal combined with the positive gravity anomalies suggests the presence of relatively shallow mafic rocks. The lack of a significant magnetic signature south of the Mournes but a large gravity anomaly indicates the presence of either a deeper mafic body (assuming it is magnetic) or a mafic body of a slightly different age (different magnetization) in the region.

Lithospheric structure

The tectonic framework of the region was created during the c. 400 Ma collision between Laurentia and Avalonia and is dominated by NE–SW Caledenoid structures, which include major terrane bounding faults and the dominant country rock strike. The area in question is situated between 30 and 40 km north of the suture in the Southern Uplands–Down–Longford terrane and consists of medium- to fine-grained clastic sediments. The BIRPS survey in the early 1980s (Brewer et al. 1983; Soper et al. 1992) revealed a northward dipping (c. 20°) reflectivity boundary interpreted to represent the Iapetus Suture between the weakly reflective Southern Uplands–Down–Longford terrane to the north and the highly reflective Lake District–Lakesman accretionary terrane to the south, which consists of similar clastic sediments but also Ordovician volcanic rocks and intrusions (Murphy et al. 1991; Stone & Kimbell 1995). The Southern Uplands–Down–Longford terrane has a maximum thickness at the Southern Uplands Fault, tapering southward to zero where the Iapetus Suture crops out, thus defining a wedge. There is no
known older basement separating the Southern Uplands–Down–
Longford and Lake District–Lakesman Palaeozoic accretionary
terranes from mantle lithosphere at the 30 km deep Moho
(Brewer et al. 1983; Soper et al. 1992).

Subsidiary lineaments that trend SSW–NNE and SE–NW are
also recognized in other areas of the NW Scottish and Irish
Caledonides with an acknowledged control on the ascent and
emplacement of mainly mid-crustal Caledonian plutons (Watson
1984; Jacques & Reavy 1994; Hutton & Alsop 1996; Stevenson
et al. 2006). Close to the Mourne area, the SE–NW-trending
Newry Fault may be part of this system.

Discussion

Non-subjacent feeder

The parallel NNE-directed magma flow trajectories for the
Eastern and now the Western Mourne Granites indicate a
common feeder to the south of the Mourne area (Fig. 2b). Although gravity data are consistent with the presumably
shallower floor of the granite, they also suggest that there is a
large dense unexposed and relatively deep body in the region
south of the Mourne Granites. Given the cogenetic links between
mafic and felsic igneous rocks in this region (Gamble et al.
1999), we propose that this anomaly represents an unexposed
mafic (or at least composite) intrusion that fed magma to the
Mourne area and acted as a deeply penetrating feeder linking
upper crustal magmatism to the lower crust or at least mid-crust.
The extension of this anomaly WNW provides a potential
geophysical link to the other Palaeogene igneous complexes of
Slieve Gullion and Carlingford.

Controls on ascent and emplacement of magma

The feeder zone that we propose for the Mourne Granites is
roughly 10–20 km north of the Iapetus Suture, which is c. 7 km
deep at this point. The existing gravity and magnetic data suggest
(without detailed modelling) that this feeder zone may be
represented by a mafic or composite body at least 2–3 km deep,
giving a roughly 5 km thick zone from our feeder site to the
Iapetus Suture plane. Assuming roughly 1–2 km (no more than
3 km) denudation since the Palaeogene (e.g. Green et al. 2000),
the point at which our ascent route meets the Iapetus Suture was
10–15 km deep in the Palaeogene. This would have been close to
(or slightly above) brittle–ductile transition depth.

Implications for petrogenesis and magmatic evolution

The sense of magma flow that our new and recent AMS data
have identified for the Mourne Granite Centres points toward a
geophysical anomaly that we propose represents the feeder zone
that links the Mourne granites to the mid- or lower crust. This
feeder zone lies roughly 10–20 km to the south of the Mourne
area and brings the magma pathway closer to the north-dipping
Iapetus Suture. The position of the feeder zone, however,
provides only a few kilometres of Southern Uplands–Down–
Longford terrane crust above 25 km of Lake District–Lakesman
terrane crust. Our model suggests that the Ordovician calc-
alkaline intrusions that dominate the Lake District–Lakesman
terrane would have played a role in primary contamination of
ascending Palaeogene magma and that Southern Uplands–
Down–Longford terrane contamination would have occurred
second in the upper crust during ponding above the brittle–
ductile transition zone.

The coincidence of the Iapetus Suture, the brittle–ductile
transition and the Newry Fault focused magma ponding, creating
an upper crustal magma reservoir roughly 10–15 km deep close
to or just above the contemporaneous brittle–ductile transition.
Given the distribution of geophysical anomalies in the area, other
Palaeogene centres including Carlingford and Slieve Gullion may
have shared a similar pathway. We cannot say whether they were
actually fed from the same chamber, but there is at least now a
conceivable physical link.

Implications for British and Irish Palaeogene Igneous
Province tectonomagmatism

The emplacement model deduced from AMS data has led to a
crustal-scale ascent–emplacement model that was controlled by
lithospheric structures. This framework channelled magma from
the lower crust or mantle and focused accumulation in an upper
crustal reservoir that fed a series of shallow plutons and volcanic
centres (Fig. 4). This framework inevitably required tectonic
reactivation of appropriate structures to aid delivery and ponding of magma.

The Iapetus Suture extends northeastward across southern Scotland and southwestward across central Ireland. NE–SW-trending structures dominate the structure of the Southern Uplands—Down—Longford terrane, so if the NW–SE-trending Nevy Fault controlled the Northern Irish Palaeogene magmaism, the reactivation of NW–SE- and SSW–NNE-trending lower crustal structures or lineaments played a significant role in the ascent of Palaeogene magma. The intersection of these structures with NE–SW Caledonide structures (sensu Jacques & Reavy 1994) must have provided ascent routes.

Conclusion

The Western Mourne Granite was emplaced as a NNE-directed laccolith in parallel with Stevenson et al.’s (2007b) Eastern Centre laccolith. This magma flow direction is traced back to a large positive gravity anomaly that is suggested to represent the upper crustal magma reservoir for the Mourne Granite Centres and may provide a physical link indicating common magma pathways with other Palaeogene centres in the area. This study also provides a new model for the subsurface distribution of Palaeogene granites in this region.

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