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Refined model of incremental emplacement based on structural evidence from the granodioritic Newry igneous complex, Northern Ireland

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ABSTRACT

Although many intrusions are now known to have been incrementally emplaced, the mechanisms through which this takes place are generally poorly understood. The Newry igneous complex was incrementally emplaced within the Southern Uplands-Down-Longford terrane of Northern Ireland during late Caledonian sinistral transtension. This study uses a variety of new and existing data and techniques to provide a fuller and firmer understanding of incremental emplacement than has previously been available, addressing both deep-crustal processes and those operating within the emplacement site. Host-rock orientations suggest that some of the accommodation space for the Newry igneous complex was generated due to pull-apart tectonics operating within the Southern Uplands-Down-Longford terrane. Local host-rock deflections, concentric igneous foliations, and concentric linear anisotropy of magnetic susceptibility (AMS) fabrics show that inflation due to magma overpressure also generated significant space. Strong AMS fabrics close to the boundaries of some magma pulses in turn suggest that inflation was accomplished by injection of individual magma pulses and was thus incremental. The dome-like orientations of mineral foliations within plutons and the truncation of steep local host-rock tracts by the Newry igneous complex imply that the complex consists of four laccolithic bodies. On a larger scale, it is suggested that the deep-seated Argyll and Newry lineaments represent faults that allowed magma generated at depth to ascend to the crustal level of the Southern Uplands-Down-Longford tract boundaries. It is also inferred that sinistral movement along the Argyll and Newry lineaments may have produced the releasing bend within the Southern Uplands-Down-Longford terrane. Higher in the crust, reduced confining pressure resulted in tectonic opening along this releasing bend. This local stress field induced horizontal magma flow and emplacement of the Newry igneous complex as laccolithic bodies. This study suggests that simplistic emplacement models should largely be abandoned in favor of holistic models incorporating the multiple interdependent processes operating during magma ascent and emplacement.

INTRODUCTION

Emplacement refers to the way in which an igneous rock comes to be accommodated in its final crustal position (i.e., put in place; Pitcher, 1997). This is intimately connected to ascent, which is the process through which magma rises within the crust or uppermost mantle to reach its emplacement site (Jacques and Reavy, 1994). Since the nineteenth century, it has been recognized that emplacement requires inflow of magma into relocated crustal space (commonly referred to as "generated" space; Westropp, 1867), although the processes through which this occurs remain strongly debated (Hutton, 1988; Molyneux and Hutton, 2000; Petford et al., 2000; Stevenson et al., 2007a; Miles et al., 2016). A primary distinction is often made between magmatic (i.e., magma pressure–related) and tectonic controls on emplacement, although there may be a large amount of overlap between these influences (Hutton, 1988; Brun et al., 1990; Stevenson, 2009; de Saint Blanquat et al., 2011). Significant magma pressures typically lead to space generation through inflation (or ballooning) of an intrusion, which may produce high strains within the outer part of the intrusion and/or the adjacent host rocks (Cloos, 1925; Johnson and Pollard, 1973; Hutton, 1988; Cruden, 1990; Molyneux and Hutton, 2000; Yan et al., 2011). Tectonic controls on emplacement are often associated with shear zones or faults and thus can be derived through the study of regional structures (Hutton, 1982; Guineberteau et al., 1987; Brun et al., 1990; D'lemos et al., 1992; Petford et al., 2000; Rosenberg, 2004; Rabillard et al., 2014; McCarthy et al., 2015; Lancaster et al., 2017).

It is now recognized that many intrusions were emplaced incrementally via distinct magma pulses (Richey, 1927; Harry and Richey, 1963; Cook and Weir, 1980; Pitcher, 1997; Hecht and Vigneresse, 1999; Kryza et al., 2014; Anderson et al., 2016). Much of the compositional variation observed in such intrusions will not have been produced in situ and instead relates to processes operating within a source region or intermediate staging chamber (Pitcher, 1997; Coleman et al., 2004; Lipman, 2007; Miller, 2008; Farina et al., 2012; Anderson et al., 2016). The resulting intrusion will often display abrupt zone boundaries and relative compositional homogeneity within zones (Richey, 1927; Stevenson et al., 2007a; Anderson et al., 2016).

Several studies on granitic emplacement have utilized anisotropy of magnetic susceptibility (AMS) data (e.g., Tarling and Hrouda, 1993; Petford et al., 2000; Mamtani and Greiling, 2005; Stevenson et al., 2007a, 2007b, 2008; Wei et al., 2014; McCarthy et al., 2015; Morgan et al., 2017). This is because the technique can provide unique forms of structural data, revealing subtle or linear fabrics that are not apparent in the field, as well as providing quantitative fabric information (Owens, 1974; Jelinek, 1981; Stevenson et al., 2007a, 2007b). For this study, AMS data

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were combined with traditional structural field measurements of the Newry igneous complex in order to test the proposed model of incremental emplacement (Anderson et al., 2016) and investigate other influences on emplacement. The comprehensive data set allows new detail to be inferred about processes corresponding to intrusion of individual magma pulses.

GEOLOGICAL BACKGROUND

Regional Setting

The Newry igneous complex is situated within the late Caledonian Southern Uplands-Down-Longford terrane (Fig. 1; Meighan and Neeson, 1979; Neeson, 1984; GSNI, 1997; Cooper and Johnston, 2004a; Cooper et al., 2016; Anderson et al., 2016). This terrane extends across Britain and Ireland and consists of laterally continuous, steeply dipping, fault-bounded tracts predominantly composed of graywackes and shales that become younger to the north (Barnes et al., 1987). In the vicinity of the Newry igneous complex, the Southern Uplands-Down-Longford terrane is subdivided into the graywacke-dominated Hawick Group, and the Gala Group, in which there is a higher proportion of shale (Fig. 1). Many authors consider the Southern Uplands-Down-Longford terrane to represent an accretionary prism associated with closure of the Iapetus Ocean (McKerrow et al., 1977; Leggett et al., 1979, 1982; Needham and Knipe, 1986; Leggett, 1987; Anderson, 2004; Stone and Merriman, 2004; Waldron et al., 2008; Young and Donald, 2013). Although the Southern Uplands-Down-Longford terrane has previously been shown to have a regionally consistent trend, Beamish et al. (2010) used conductivity data to infer a localized strike swing in the vicinity of the Newry igneous complex (Fig. 1). Through late Caledonian sinistral transtension (Bluck, 1985; Soper and Woodcock, 1990, 2003; Soper et al., 1992; Dewey and Strachan, 2003; Brown et al., 2008), this strike swing may have resulted in pull-apart basin development, providing accommodation

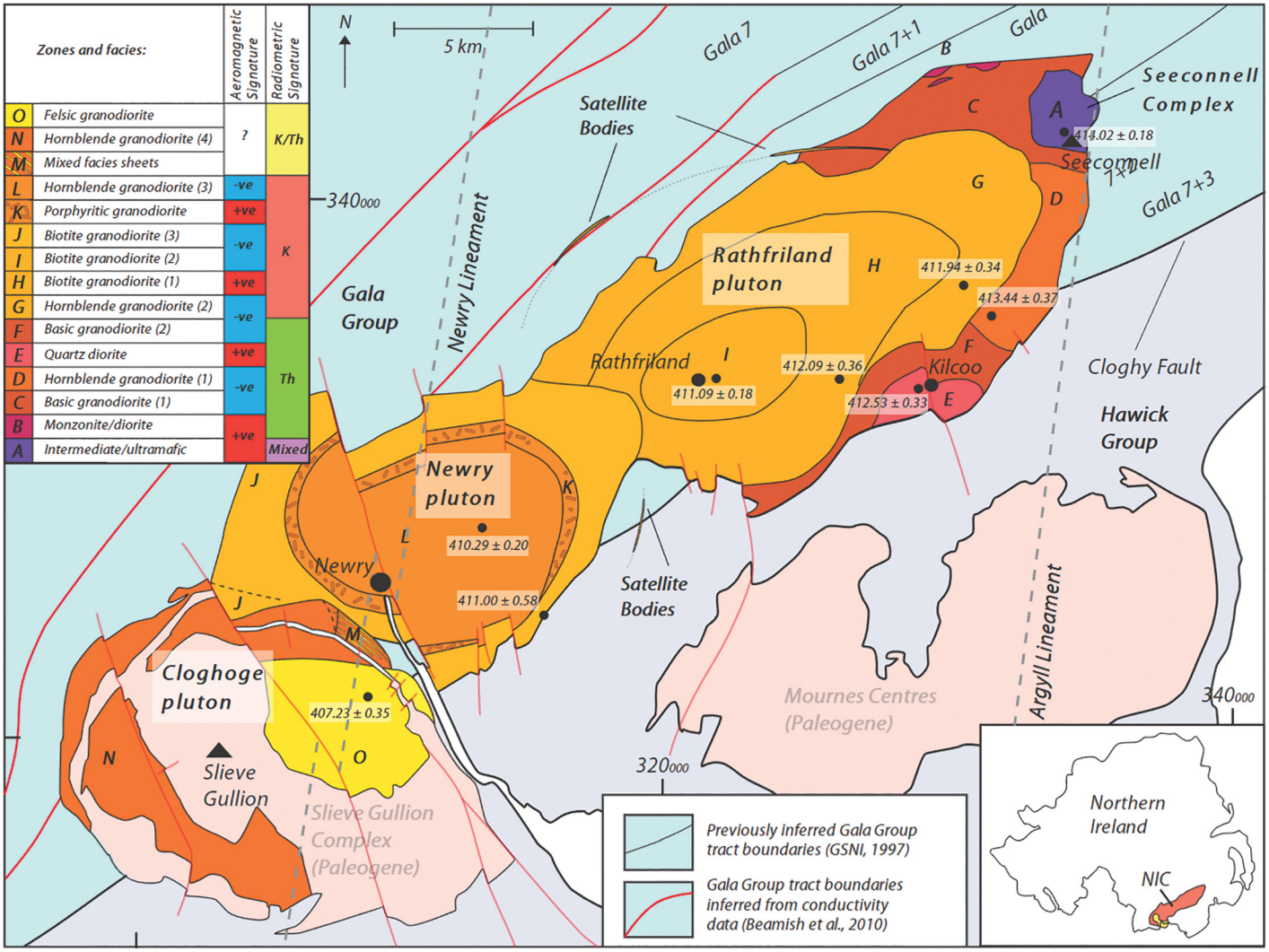


Figure 1. Geology of the Newry igneous complex (NIC) and its host rocks, including age determinations (in Ma) for the Newry igneous complex and recognized aeromagnetic/radiometric anomalies within the complex derived by Cooper et al. (2016); a newly mapped zonation of the Newry igneous complex (defined by zones A–O) derived by Anderson et al. (2016); and a simplification of the local host-rock structure, highlighting the modified Gala Group tract boundaries inferred by Beamish et al. (2010). The zonation includes the satellite bodies, which consist of fine-grained biotite/hornblende granodiorite. The positions of major grid lines (corresponding to sample grid references within Appendix 2 [see text footnote 1]) and the locations of key geographical features are also shown. Irish grid coordinate system.

space for emplacement of the igneous complex (Beamish et al., 2010).

Several deep-seated crustal lineaments are thought to have influenced ascent and emplacement of magma in the UK (Jacques and Reavy, 1994; Hutton and Alsop, 1996; Stevenson et al., 2006; Cooper et al., 2013). These lineaments are known primarily from geophysics (gravity and magnetic data) and are thought to trend approximately north-south over much of the UK to the north of the Iapetus suture. The origin of the lineaments is unclear, although they are proposed to represent pre-Caledonian faults (Jacques and Reavy, 1994; Hutton and Alsop, 1996; Cooper et al., 2013).

The lineaments are thought to have acted as conduits for magma ascent, with higher crustal structures such as shear zones controlling accommodation (e.g., Stevenson et al., 2006). For example, Jacques and Reavy (1994) presented a model where ascent of magma in SW Argyllshire was focused where NE-SW–trending Caledonian strike-slip structures related to Iapetus closure intersect older, presumably deeper, lineaments, which are orientated NW-SE. In Donegal, Hutton and Alsop (1996) have shown that construction of the Donegal Batholith was controlled by the interactions of the Donegal lineament and Main Donegal shear zone. More recently, McCarthy et al. (2015) have proposed an elegant model for the sequential construction of the Galway granite complex, involving a NNW-SSE fault system and the WNW-ESE Skird Rocks fault controlling ascent at different times.

The siting of the Newry igneous complex on two deep-crustal lineaments, termed the Argyll and Newry lineaments, has thus been considered as a potential influence on its emplacement (Cooper et al., 2013). In this study, we investigated this possibility further, developing a model whereby deep-crustal lineaments interact with known upper-crustal structures.

Newry Igneous Complex

The Newry igneous complex is composed of three plutons (Fig. 1), termed the Rathfriland (northeast), Newry (central), and Cloghoge (southwest) plutons (Cooper and Johnston, 2004a; Cooper et al., 2016; Anderson et al., 2016). These predominantly consist of granodiorite, although an exception occurs in the intermediate-ultramafic Seeconnell complex at the northeast margin of the Rathfriland pluton (Fig. 1; Inman et al., 2012; Cooper et al., 2016; Anderson et al., 2016). The Cloghoge pluton also hosts a number of Paleogene subvolcanic rocks, termed the Slieve Gullion complex (Fig. 1; Richey, 1927; Neeson, 1984; Cooper and Johnston, 2004b; Stevenson et al., 2008).

On the basis of compositional and geophysical characteristics, the Newry igneous complex is divided into 15 zones (zones A–O), which are inferred to represent sequentially emplaced magma pulses (Fig. 1; Anderson et al., 2016). The Seeconnell complex (zone A) is the oldest part of the Newry igneous complex, with zones becoming broadly younger to the southwest and toward the centers of individual plutons (Fig. 1; Cooper et al., 2016; Anderson et al., 2016). Sequentially emplaced zones tend to become broadly more felsic in composition, although this trend is reversed in zones F, K, and O (Fig. 1). This is interpreted to reflect a process of fractional crystallization interspersed with occasional mixing of more basic magma prior to final emplacement (Anderson et al., 2016).

The Seeconnell complex is crosscut by the main part of the Rathfriland pluton and consists of steeply dipping intermediate-ultramafic facies, principally composed of meladiorites, dioritic monzonites, and biotite pyroxenites (Reynolds, 1934, 1936; Meighan and Neeson, 1979; Neeson, 1984). These layers are generally coarse grained and in places show repetition along with sharp internal boundaries (Meighan and Neeson, 1979). Meighan and Neeson (1979) and Neeson (1984) suggested that these facies dominantly represent cumulates crystallized from magma injected from a staging site of intermediate composition. The steep dip of the layers suggests that these may have originated by side-wall crystallization within a magma chamber (Meighan and Neeson, 1979). The intermediate staging site supplying the Seeconnell complex may in turn have supplied the main Newry igneous complex as it continued to evolve (Meighan and Neeson, 1979; Anderson et al., 2016).

The outer contact of the Newry igneous complex is thought to be steep (Reynolds, 1934; Meighan and Neeson, 1979), which is consistent with known steep mineral foliation trends (Neeson, 1984). Two sets of satellite bodies are apparent to the north of the Rathfriland pluton and to the south of the Newry pluton, respectively (Fig. 1; Cooper et al., 2016). These crop out in several localities (represented by samples prefixed with "T" in Appendix 1)[1] as dikes 10–20 m in thickness, although they appear to be more extensive from Tellus Project aeromagnetic data (Cooper et al., 2016). Aeromagnetic data indicate that the satellite bodies are approximately concentric around zone H of the Rathfriland pluton and the outer Newry pluton, respectively (Cooper et al., 2016; Anderson et al., 2016).

[1]GSA Data Repository item 2017367, Appendixes 1–3, is available at http://www.geosociety.org/datarepository/2017 or by request to editing@geosociety.org.

METHODS

Structural Field Data

Structural data were collected from the Newry igneous complex and its host rocks and include a total of 181 mineral foliations and 158 host-rock bedding/cleavage measurements. Mineral foliations were defined by the planar alignment of biotite, hornblende, and plagioclase, which are virtually ubiquitous throughout the Newry igneous complex. Although linear alignment of these minerals occurs, this is rarely apparent in the field, whereas planar alignment is observed in most outcrops. Aligned minerals commonly show development of solid state textures to the extent that most of the measured foliations are suggested to have formed in a submagmatic or high-temperature solid state. However, determination of the state of these fabrics has proven to be highly subjective and is thus omitted here in favor of more quantitative approaches to igneous fabric understanding (i.e., AMS).

Both mineral foliations and host-rock measurements were obtained from known areas of exposure (Egan, 1872; Hull, 1881; Reynolds, 1934, 1943; Neeson, 1984), as well as through use of the Virtalis GeoVisionary Suite at the Geological Survey of Northern Ireland in Belfast. The latter provides three-dimensional (3-D) landscape visualization, allowing remote selection of appropriate sampling sites. The results were combined with 93 existing mineral foliation measurements collected by Neeson (1984).

AMS Data

AMS data were used in this study to assess the alignment and strength of magnetic fabrics, based on the original work of Owens (1974) and Jelinek (1981). Owens (1974) used AMS to define three principal magnetic susceptibility axes. These axes are orthogonal and represent the maximum (K_1), minimum (K_3), and intermediate (K_2) magnetic susceptibilities within a sample. The results can be illustrated as an ellipsoid with axes lengths and orientations representing the principal susceptibility values and directions, respectively (Fig. 2). This is termed the "magnetic susceptibility ellipsoid" (Owens, 1974; Stevenson et al., 2007a, 2007b).

Principal susceptibility values can be used to derive the following four parameters (see Owens, 1974; Stevenson et al., 2007a, 2007b):

$$\begin{aligned} K_{\text{mean}} &= \left(K_1 + K_2 + K_3\right)/3, \\ L &= \left(K_1 - K_2\right)/K_{\text{mean}}, \\ F &= \left(K_2 - K_3\right)/K_{\text{mean}}, \\ H &= L + F. \end{aligned} \quad (1)$$

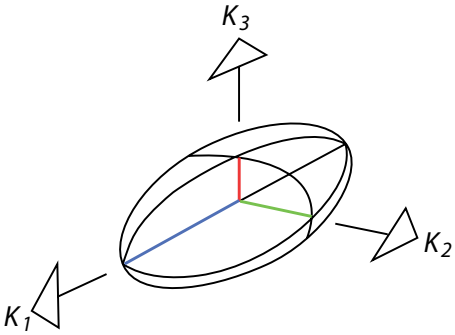


Figure 2. Theoretical magnetic susceptibility ellipsoid, showing orientations and relative magnitudes of the maximum (K_1), intermediate (K_2), and minimum (K_3) magnetic susceptibility axes (after Owens, 1974).

Of these, K_{mean} (or bulk susceptibility) is simply the mean value of the three magnetic susceptibilities for a sample. L is defined as the linear fabric strength, while F is defined as the planar fabric strength. H is the sum of L and F, representing the overall strength of the magnetic fabric (see Owens, 1974; Stevenson et al., 2007a, 2007b). Orientations of K_1, K_2, and K_3 can be plotted stereographically, including 95% confidence limits calculated by the method of Jelínek and Kropáček (1978).

The further parameters P_j and T_j, introduced by Jelinek (1981), respectively define the overall intensity and shape (disk-like vs. rod-like) of magnetic fabrics (also see Tarling and Hrouda, 1993; Borradaile and Jackson, 2010). These parameters are derived as follows:

$$P_j = \mathrm{Exp}\sqrt{\left\{2\left[\left(\eta_1-\eta\right)^2+\left(\eta_2-\eta\right)^2+\left(\eta_3-\eta\right)^2\right]\right\}},$$
$$T_j = \left(2\eta_2-\eta_1-\eta_3\right)/\left(\eta_1-\eta_3\right). \quad (2)$$

Here, η_1, η_2, and η_3 represent the natural logarithms of the principal susceptibilities, and η represents the natural logarithm of K_{mean}. The parameter P_j relates to overall fabric intensity, while T_j relates to fabric shape, whereby positive values represent disk-shaped (planar) fabrics, and negative values represent rod-shaped (linear) fabrics (Jelinek, 1981).

AMS samples were collected from a total of 113 locations from throughout the Newry igneous complex (sample locations are shown in Appendix 1 [see footnote 1]). These were obtained as relatively large (~15 × 15 × 15 cm) blocks, which were orientated prior to extraction (see Owens, 1984). At the University of Birmingham, subsamples (usually from 8 to 15) were obtained from each block. These were produced by extracting several drilled cores within the block, which were in turn sawn into smaller cylinders, each with a diameter and length of ~25 mm and 22 mm, respectively. A further measurement was also taken at this stage to relate the orientation of these subsamples to that of the original block in the field.

Subsamples were analyzed using an AGICO KLY-3S Kappabridge magnetic susceptibility meter. This allowed measurement of the magnetic susceptibility of each subsample in three different orientations, from which the three principal susceptibilities and the bulk susceptibility were derived.

Determination of AMS Causes

Minerals contributing to the magnetic fabric of rocks are variable, and, as a result, magnetic fabrics may not necessarily correspond to visible fabrics (Jover et al., 1989; Tarling and Hrouda, 1993; Borradaile and Jackson, 2004). The relationship of these fabrics in the Newry igneous complex was investigated through comparison of derived planar magnetic fabrics with mineral foliation data. Thermomagnetic analysis was also used to determine the magnetic fabric–carrying minerals for five samples. This technique involves measurement of magnetic susceptibility during heating and subsequent cooling of powdered samples (e.g., Akimoto, 1954; Henry et al., 2003; Petrovský and Kapička, 2006; Stevenson et al., 2007a, 2007b; Stevenson and Bennett, 2011; Fleming et al., 2013). Since magnetic minerals respond in particular ways to temperature changes, the results can be used to interpret magnetic mineralogy (Henry et al., 2003; Petrovský and Kapička, 2006). Samples were prepared through crushing at the Scottish Universities Research Centre (SUERC), in East Kilbride, Glasgow. These were then analyzed at the University of Birmingham using a CS-3 furnace apparatus, which functions in cooperation with an AGICO KLY-3S Kappabridge spinning magnetometer (see previous section). The furnace heats and subsequently cools powdered samples while the magnetometer records magnetic susceptibility at ~15 s intervals. Samples were heated from room temperature to a maximum of 700 °C, before being cooled back to room temperature over a duration of 3 to 4 h.

RESULTS

Host-Rock Bedding and Cleavage

Bedding and cleavage measurements in the vicinity of the Newry igneous complex are consistently subparallel (Fig. 3; see Appendix 2 for full list of results [see footnote 1]). This is consistent with previous work showing that these features display similar orientations throughout much of the Southern Upland-Down-Longford terrane (Barnes et al., 1987). Hence, S_1 cleavages and bedding can be used interchangeably to gauge regional strike direction.

At up to 1 km from the Newry igneous complex, bedding and cleavage generally strike parallel to the margins of the intrusion (Fig. 3). Hence, the strike of these structures does not appear to conform to the general ENE-WSW trend of the Southern Uplands-Down-Longford terrane. This relationship is clearly expressed at Dublin Road Bridge (J082241), which is close to both the Newry and Cloghoge plutons. Here, host-rock bedding and cleavage orientations curve around the two pluton margins, thus showing clear parallelism to these features, rather than to any terrane-wide trend (Fig. 3).

However, in locations that are more distal to the Newry igneous complex (greater than 1 km from its margin), bedding and cleavage often strike obliquely to the intrusion margins. These oblique measurements are consistent with the strike swing in the Southern Uplands-Down-Longford terrane derived from conductivity data by Beamish et al. (2010; see also Figs. 1 and 3 herein). This is particularly clear at Slieve Croob (J319454), Ballydoo Road (J166292), and Leode Road Quarry (J177280). The more distal (~1–5 km) measurements in the vicinity of Silverbridge (H972185) also follow the local strike swing, whereas the proximal measurements there (<1 km) parallel the Cloghoge pluton margin.

Proximal to the Rathfriland pluton (up to 1 km from its margin), bedding and cleavage dips are generally orientated steeply away from the intrusion (Fig. 3). Hence, these are parallel to known pluton margin trends in terms of dip as well as strike (Reynolds, 1934; Neeson, 1984). Some bedding and cleavage planes in the vicinity of the Newry and Cloghoge plutons dip toward the Newry igneous complex, although this dominantly occurs along the western margins of these plutons (Fig. 3). The more distal measurements (1–5 km from the Newry igneous complex margin) to the west of Silverbridge are consistently southward-dipping, regardless of the pluton boundary orientation, suggesting that this might represent the original host-rock trend prior to interference from the Newry igneous complex.

Host-rock orientations appear to be unaffected by the satellite bodies. This is most apparent in the vicinity of Leode Road Quarry (J177280), where a satellite body appears to crosscut host rocks without any deflection in the bedding of the latter.

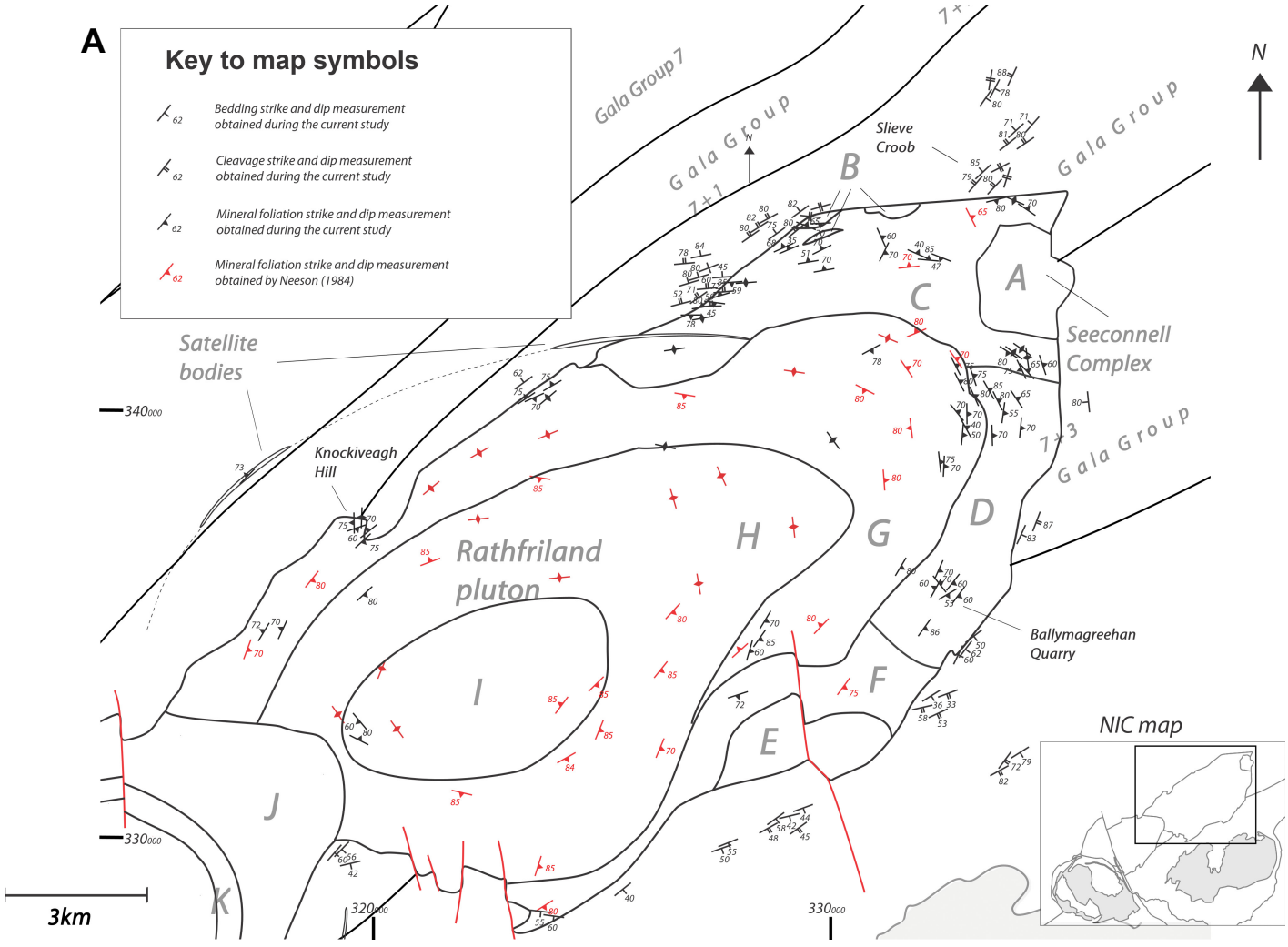


Figure 3 (*on this and following page*). Field structural data collected from the Newry igneous complex (NIC), satellite bodies, and host rocks. All data were collected during the current study, excluding the highlighted mineral foliations collected by Neeson (1984). (A) Data collected from the Rathfriland pluton and adjacent host rocks/satellite bodies.

Visible Mineral Foliations

Mineral foliations within the Newry igneous complex are predominantly steep (60°–90°), concentric, and outward-dipping (Fig. 3; see Appendix 2 for full list of results [see footnote 1]), consistent with previous work (Neeson, 1984). Exceptions include a small set of inward-dipping foliations in the outer part of the Rathfriland pluton, although these are almost exclusively very steep (80° or more) and follow a similar concentric trend to the outward-dipping foliations. Several significantly shallower (<30°) foliations are also present within the inner Newry pluton (Fig. 3).

Rarer obliquely trending mineral foliations occur at Cloghoge Upper Road Cutting (J079239), Ballymagreehan Quarry (J304355), and Knockiveagh Hill (J178376; Fig. 3). Measurements at Cloghoge Upper Road Cutting and Ballymagreehan Quarry were obtained from obliquely trending sheets (still thought to represent part of the Newry igneous complex; see Anderson et al., 2016), whereas those at Knockiveagh Hill appear to represent part of a much larger intrusion (i.e., zone G of the Rathfriland pluton).

AMS Fabrics

AMS fabrics in the Newry igneous complex typically show both planar and linear components, although these vary in terms of dominance. Within Figure 4A, strong planar (oblate) fabrics are often visually represented by samples that display proximal or overlapping 95% confidence limits for the maximum (K_1) and intermediate (K_2) susceptibility axes (e.g., samples R3B, N14, and C11F). Strong linear (prolate) fabrics are in turn represented by samples that show distinct maximum susceptibility axes (K_1), with the other axes being proximal or overlapping (e.g., samples R21, N24, and C6). Many samples exhibit small 95% confidence limits for all three susceptibility axes. This can occur where $K_1 > K_2 > K_3$, in which case the fabric is termed "triaxial," meaning it has neither a dominant planar nor dominant linear fabric component (e.g., samples R24, N20C, and C20; Owens, 1974). However, tight 95% confidence limits can also occur for oblate fabrics with a dominant K_1 value, and so caution is required when making interpretations from such plots alone. All planar and linear fabric components are derived and illustrated in Figure 4B. Orientations of K_1 and K_3 for each sample are stereographically plotted in Figure 5. Trends in L versus F and P_j versus T_j are in turn examined in Figures 6 and 7. Full

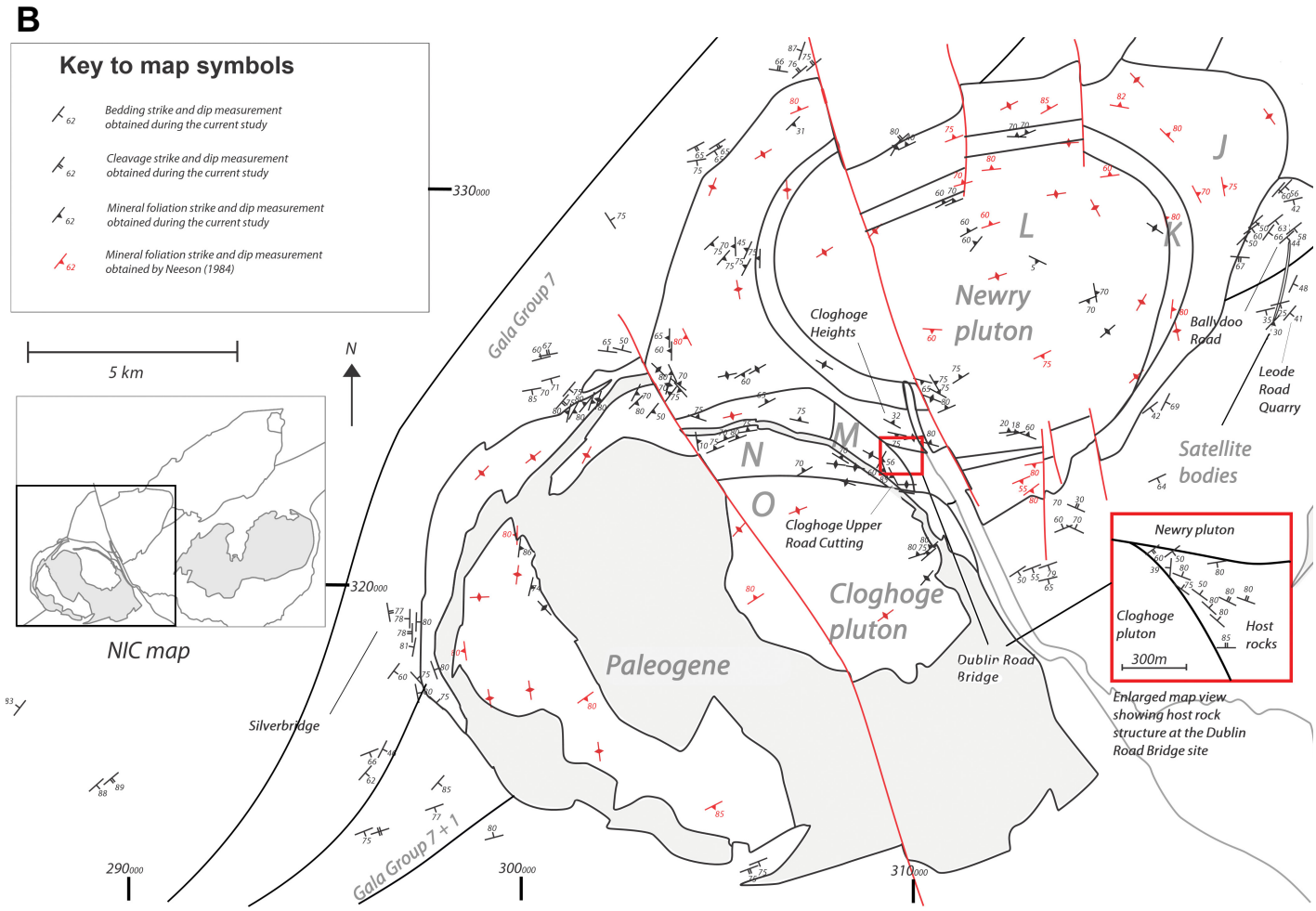


Figure 3 (*continued*). (B) Data collected from the Newry and Cloghoge plutons and adjacent host rocks/satellite bodies, and inset showing an enlarged map relating to the area of host rock between the southern Newry and Cloghoge pluton boundaries. See Figure 1 for zones and facies. Irish grid coordinate system.

AMS results for all samples are provided in Appendix 3 (see footnote 1), in which magnetic susceptibility values can be seen to range between ~10^{-4} and 10^{-2}.

Planar AMS Fabric Trends

Planar AMS fabrics within the Newry igneous complex are generally concentric and outward dipping (Figs. 4B and 5). Figure 5 shows that these fabrics are generally relatively steep (>50°) within the Rathfriland pluton and satellite bodies (for both areas, K_3 values predominantly plot within 40° of the perimeter of the stereonet, indicating that corresponding planar fabrics generally exceed 50° in steepness). Planar AMS fabrics show more variable steepness within the Newry and Cloghoge plutons (Fig. 5). Figure 4B reveals that these fabrics possibly shallow toward the center of the Newry pluton, whereas results for the Cloghoge pluton are more ambiguous.

Exceptions to the concentric planar AMS fabric trend are apparent within the eastern part of the Cloghoge pluton and the southwestern part of the Newry pluton, specifically at Fathom Mountain Railway Cutting (J077213), Cloghoge Roundabout (J080238), and Newry Railway Tunnel (J071266; Fig. 4B). Fabrics within these areas are variable and in some cases nearly perpendicular to pluton edges. Some of the anomalous fabrics at Cloghoge Roundabout are thought to correspond to the numerous variably orientated sheets that occur there (Anderson et al., 2016). However, the anomalous fabrics at Fathom Mountain Railway Cutting and Newry Railway Tunnel appear to correspond to main parts of the respective Cloghoge and Newry plutons.

Within the satellite bodies, planar AMS fabrics appear to be consistently contact-parallel (Fig. 4B). This is particularly clear from Doyles Road (J227418), where a localized deflection in contact orientation (to approximately north-south) corresponds to a similarly orientated AMS fabric.

Linear AMS Fabric Trends

Linear AMS fabrics also show a largely concentric trend and typically plunge at <45° (Figs. 4B and 5). Anomalous steeply plunging (>45°–90°) fabrics also occur, although these are mostly restricted to the Rathfriland pluton (Fig. 5). These steeper fabrics also appear to occur mainly at pluton margins, particularly within zones C and F of the Rathfriland pluton, as well as within areas along the Newry-Cloghoge pluton boundary (Fig. 4B).

Exceptions to the concentric linear AMS fabric trend occur throughout various parts of the Newry igneous complex, although they are clearest at Slievenalargy (J303345), Kilcoo (J278331), Newry Railway Tunnel (J071266), Clady Quarries (J090243), Cloghoge Round-

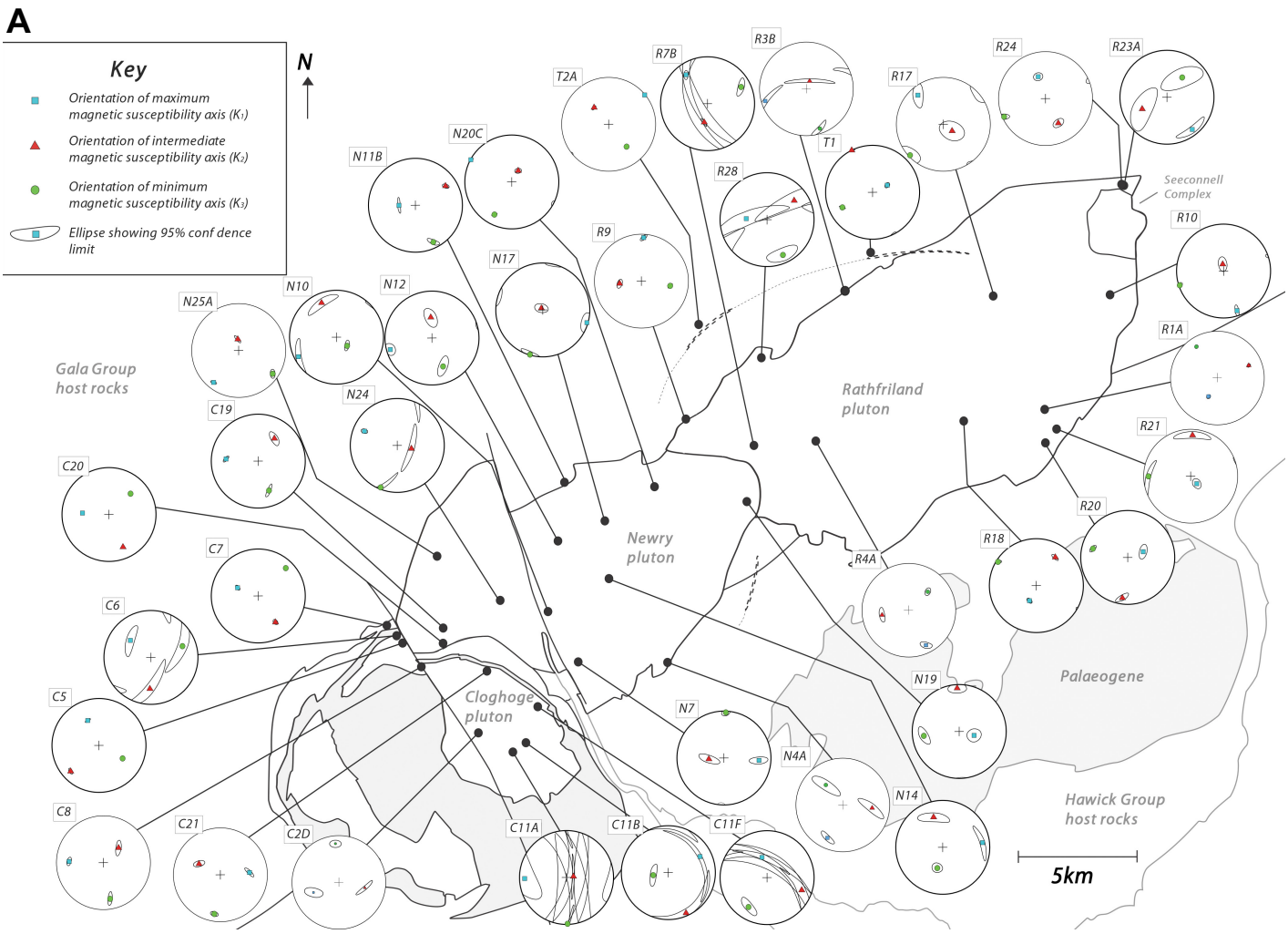


Figure 4 (*on this and following two pages*). (A) Stereographically plotted anisotropy of magnetic susceptibility (AMS) results for selected samples from the Newry igneous complex (NIC) and satellite bodies.

about (J080238), Fathom Mountain Railway Cutting (J077213), and Ballydoo Farm (a satellite body locality; J175284; Fig. 4B). In all of these areas, fabric trends are largely nearly perpendicular to the margins of the Newry igneous complex (or satellite bodies).

AMS Fabric Strength

A relatively weak correlation exists between linear and planar fabric strength (*L* and *F*) within the Newry igneous complex (Fig. 6). Anomalies to this trend include a number of samples that exhibit moderate *F* values (5%–10%) with very low *L* values (<2%), as well as several samples that show independently high values of either *L* or *F* (Fig. 6). Figure 7 illustrates that there are more planar than linear AMS fabrics within the Newry igneous complex as a whole (i.e., positive T_j values). This relationship is particularly clear within the Rathfriland pluton and satellite bodies, while fabric shapes within the Newry and Cloghoge plutons are more variable (Fig. 7). Fabric shape appears to show little relationship to intensity (P_j), although the strongest two fabrics encountered are clearly more planar (Fig. 7).

Mapping of *F* and *L* values shows that these parameters are variable throughout the Newry igneous complex, although patterns can be determined in particular areas (Fig. 6). High values of *F* and *L* occur close to the G-H zone boundary of the Rathfriland pluton and zone K of the Newry pluton, specifically at Cabra (J268353), St. Mary's Church (J248336), Curley Road (J151348), Newry Road (J137319), Goraghwood Quarry (J065321), and Greenan Lough (J111235). Most of the samples from these areas exhibit relatively high values of both parameters, although in a few examples, *F* is high while *L* is significantly lower. High values of both *F* and *L* are not encountered anywhere else within the Newry igneous complex other than in these areas.

Samples with relatively high *L* values and significantly lower *F* values occur within the southwestern Newry pluton and the northeastern Cloghoge pluton. These are observed clearly at Newry Railway Tunnel (J071266) and Cloghoge Roundabout (J080238; Fig. 6). The fabrics at these localities are also notably oblique to the concentric trend within the Newry igneous complex as a whole (see Fig. 6).

Causes of AMS

Correlation of AMS and Visible Fabrics

Visible foliations (Fig. 3) and planar AMS fabrics (Fig. 4B) show very similar orientations. This close relationship applies for both the concentric and oblique observed trends, with the

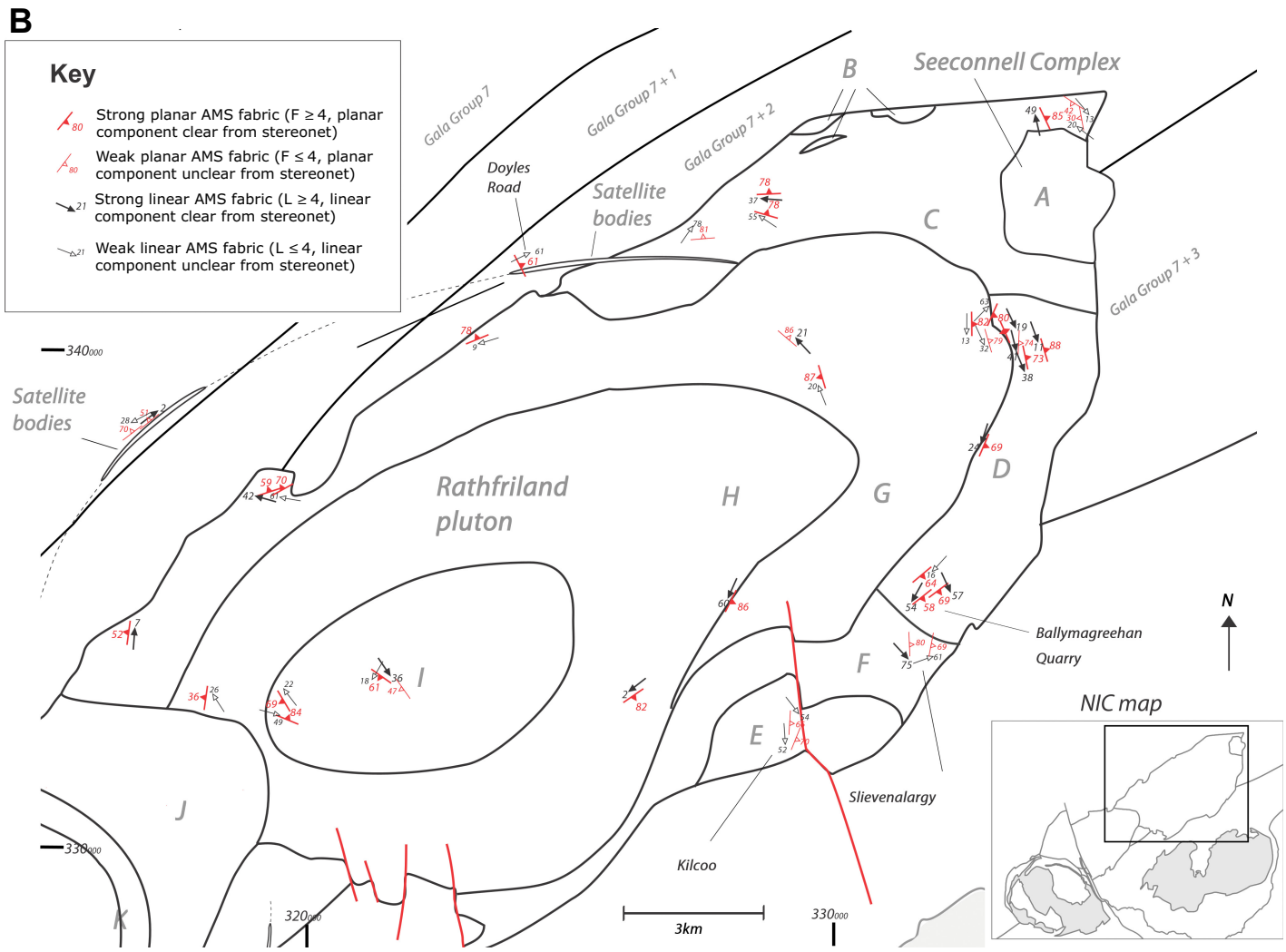


Figure 4 (*continued*). (B) Derived planar and linear AMS fabrics for the Rathfriland pluton and adjacent satellite bodies.

latter being observed at Ballymagreehan Quarry (J304355) and the northeastern part of the Cloghoge pluton. As a result, AMS results are considered to accurately reflect visible mineral foliations. The granitoids at Fathom Mountain Railway Cutting (J077213) display no visible fabrics, and so AMS data provide all fabric information for this area (Fig. 4B).

Thermomagnetic Analysis

Thermomagnetic data were obtained from five samples across four zones within the Newry igneous complex. These were zone I: biotite granodiorite from the Rathfriland pluton; zone L: hornblende granodiorite from the Newry pluton; zone M: sheeted biotite granodiorite from the Cloghoge pluton; and zone O: felsic granodiorite from the Cloghoge pluton (Fig. 8). Results from these samples are shown in Figure 8 and reveal the following four relationships:

Abrupt high-temperature magnetic susceptibility decrease. All analyzed samples showed a sharp, significant decline in magnetic susceptibility between ~570 °C and 600 °C (Fig. 8). In each case, this plots as a slightly curved line, with an inflection point at around 580 °C. The trend is indicative of a ferromagnetic (sensu lato) mineral, with the inflection point corresponding to the Curie temperature of this mineral (Petrovský and Kapička, 2006; Fabian et al., 2013). The Curie temperature of pure magnetite is 580 °C (Dunlop, 2006), and so this is thought to represent the dominant magnetic component in the analyzed samples.

Hopkinson Peak. Sample C3B showed a high-temperature rise in magnetic susceptibility during heating (Fig. 8). This occurred over a relatively wide temperature range, preceding a higher-temperature abrupt susceptibility decrease. The trend is consistent with the Hopkinson effect, whereby during heating, a magnetic susceptibility peak occurs immediately prior to the Curie point (Hopkinson, 1890; Dunlop, 1974). This can relate to either single-domain magnetic grains or large multidomain grains. Multidomain grains typically produce a narrower susceptibility peak than the one observed in sample C3B (Radhakrishnamurty and Likhite, 1970; Dunlop, 1974), although the data are very scattered, introducing uncertainty. Therefore, the magnetic mineralogy of sample C3B may consist of either single-domain or multidomain magnetite, whereas other samples are thought to be dominated by relatively small multidomain magnetite.

Midtemperature susceptibility peak. All samples showed peaks in magnetic susceptibility at ~200–300 °C during heating (Fig. 8). The rise in magnetic susceptibility leading up to this peak is best explained by the growth of new ferromagnetic minerals (such as magnetite and titanomagnetite) during heating (de Boer and

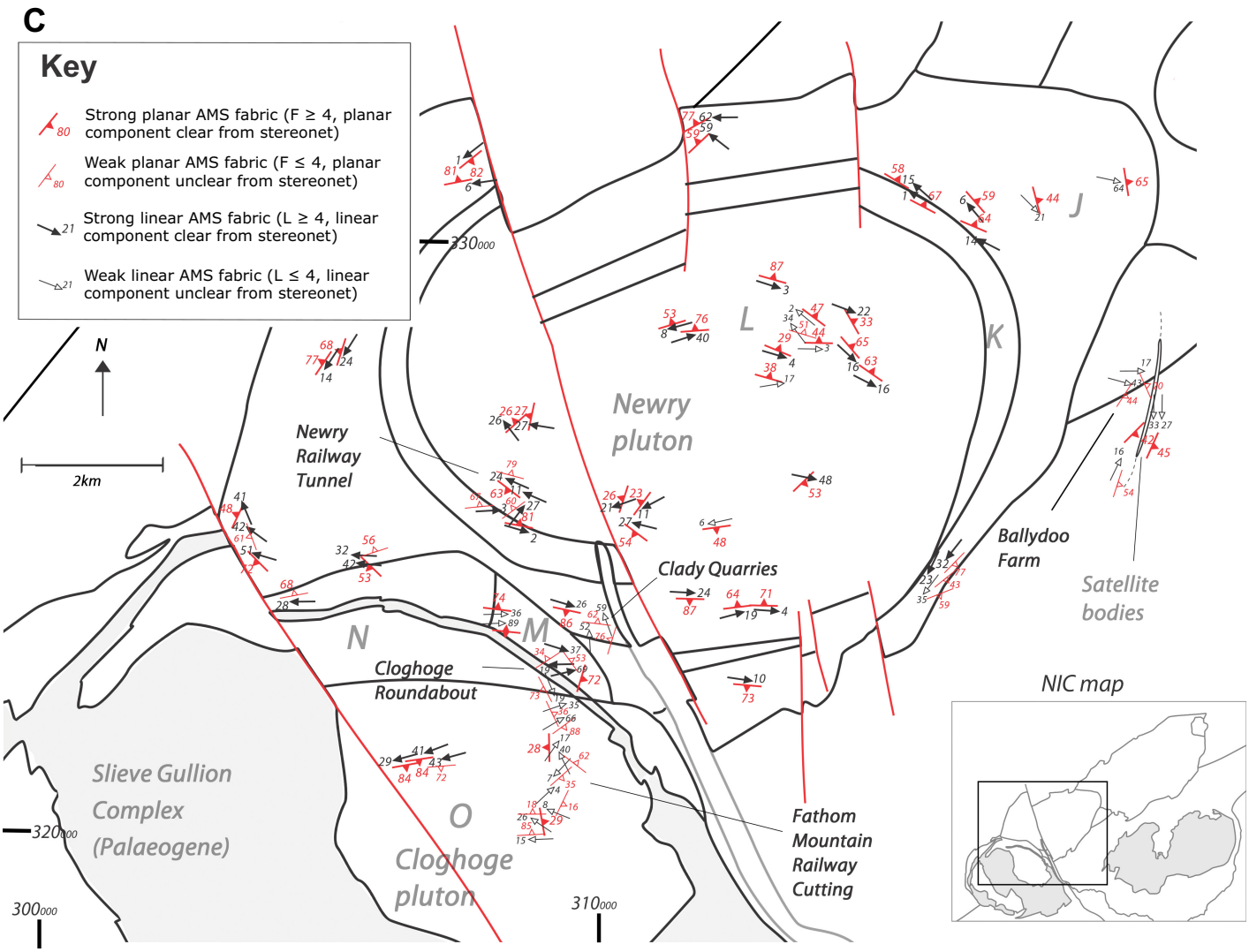


Figure 4 (*continued*). (C) Derived planar and linear AMS fabrics for the Newry and Cloghoge plutons and adjacent satellite bodies. See Figure 1 for zones and facies. Irish grid coordinate system.

Dekkers, 2001). The decline in susceptibility at higher temperatures can in turn be explained by a change from ilmenite with titanomagnetite (or magnetite) inclusions to homogeneous ilmenite with heating, since the latter will have lower magnetic susceptibility (Akimoto, 1954; Tarling and Hrouda, 1993; Hrouda et al., 1997). The decline in magnetic susceptibility associated with this process is relatively small, supporting the interpretation that stoichiometric magnetite represents the dominant magnetic component.

Variation between heating and cooling trends. During cooling, all analyzed samples showed lower susceptibilities (Fig. 8). This is thought to mainly result from rapid cooling under experimental conditions preventing exsolution of titanomagnetite (or magnetite) within ilmenite. Hence, the titanomagnetite/magnetite that was present at low temperatures prior to heating of the samples is not regained during cooling, resulting in a relatively flat cooling trend (Akimoto, 1954; Tarling and Hrouda, 1993; Hrouda et al., 1997). Some susceptibility reduction on cooling may also be due to oxidation of biotite and hornblende (which are almost ubiquitous throughout the Newry igneous complex; see Anderson et al., 2016) during heating, meaning that these no longer contribute to the magnetic susceptibility as the sample is cooled (Böhnel et al., 2002).

The results suggest that magnetite is the dominant magnetic fabric–carrying mineral throughout the Newry igneous complex, together with possible minor amounts of titanomagnetite, biotite, and hornblende. The magnetite is thought to mostly consist of multidomain grains, although in some areas (i.e., the eastern Cloghoge pluton), single-domain grains may also be present.

DISCUSSION

Tectonic Generation of Space

Orientations of host-rock bedding and cleavage support the work of Beamish et al. (2010), indicating a strike swing within the Gala Group of the Southern Uplands-Down-Longford terrane in the vicinity of the Newry igneous complex (Figs. 1, 2, and 4). During late Caledonian sinistral transtension (Bluck, 1985; Soper and Woodcock, 1990, 2003; Soper et al., 1992; Dewey and Strachan, 2003; Brown et al., 2008), this strike swing would have led to the development of pull-apart space within the crust. This space is likely to have developed along the faults separating tracts of the Gala Group. Figure 9 shows that the fault separating Gala Group tracts 7 + 2 and 7 + 3 can be

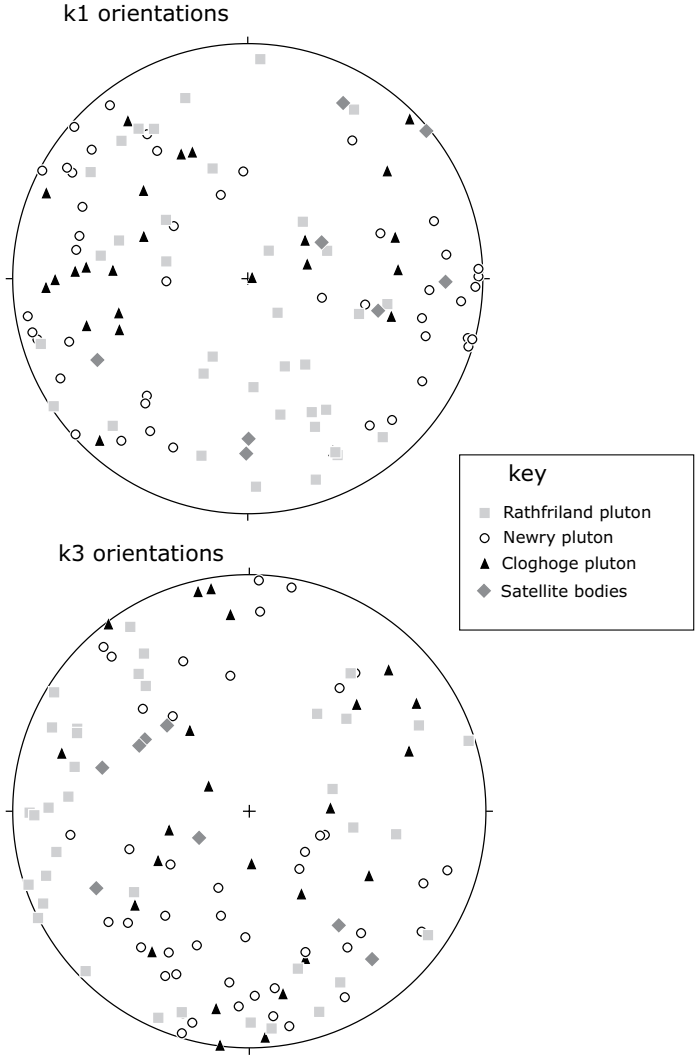


Figure 5. Stereographically projected orientations of K_1 (upper stereonet) and K_3 (lower stereonet) values obtained from anisotropy of magnetic susceptibility (AMS) analysis. Results from the three plutons of the Newry igneous complex and the satellite bodies are distinguished.

extrapolated directly through the Seeconnell complex and the central Rathfriland pluton, suggesting that tectonic space for these bodies was generated along this fault. The fault separating Gala Group tracts 7 + 1 and 7 + 2 can in turn be extrapolated through the central Newry and Cloghoge plutons, suggesting that tectonic space for these bodies was generated by opening along this second fault.

Emplacement of the satellite bodies associated with the Newry igneous complex (Fig. 2) may also have been tectonically facilitated. However, since these bodies are situated at oblique angles to local host-rock tracts (Cooper et al., 2016; Anderson et al., 2016), they are not thought to have intruded along particular faulted tract boundaries in the way that the main part of the Newry igneous complex may initially have been. Instead, the satellite bodies may represent magma that infilled concentric fractures associated with pull-apart tectonics, i.e., a form of ring dikes (Fig. 10; e.g., Mann et al., 1983; Smith, 2004).

Magma Overpressure Causing Inflation of the Newry Igneous Complex

Evidence for inflation of the Newry igneous complex due to magma overpressure is provided from both the host rocks and the complex itself. The parallelism of bedding and cleavage to the Newry igneous complex margins within proximal host rocks suggests that these rocks were deformed and deflected through inflation of the Newry igneous complex, which is consistent with high magma pressure (Fig. 4; e.g., Johnson and Pollard, 1973; Hutton, 1988; Molyneux and Hutton, 2000). The fact that bedding and cleavage in more distal host rocks occupy an independent trend (i.e., associated with the inferred strike swing) indicates that the influence of inflation on host-rock deformation diminishes with distance from the Newry igneous complex, as has been observed in other studies (e.g., Pitcher, 1997; Molyneux and Hutton, 2000; Stevenson et al., 2007a).

The general concentric trend of visible mineral foliations within each pluton of the Newry igneous complex is also consistent with high magma pressure (Fig. 4). This trend also supports inflation from a central part of each pluton, which is in turn consistent with the zonation of the Newry igneous complex whereby individual plutons are younger closer to the center (Anderson et al., 2016).

Exceptions to the concentric mineral foliation trend within the eastern Cloghoge and southern Rathfriland plutons are accounted for by the fact that the granitoids in these areas are thought to represent obliquely orientated (NE-SW–trending) sheets comprising part of zone M of the Newry igneous complex. It is considered that the fabrics within these areas reflect intrusion of the sheets, with any later overprint from inflation being insufficient to reorientate the resulting oblique trend. The inferred contact-parallel nature of fabrics within these sheets is supported by AMS results from the satellite bodies, which reveal contact-parallel magnetic foliations.

Alternatively, the oblique mineral foliations at Knockiveagh Hill (J178376) within the main Rathfriland pluton (Fig. 4) are considered to reflect the anomalous pluton margin trend in this area. It is proposed that flattening of a magma mush against this variably orientated part of the pluton margin would have produced fabrics that are similarly variably orientated, thus accounting for the oblique examples.

The predominantly shallowly to moderately dipping, concentric linear AMS fabrics are suggested to represent stretching associated with inflation of the Newry igneous complex. Since linear AMS fabric strength and planar AMS fabric strength (L and F) are correlated (Fig. 6), this inflation is also inferred to have been due to magma overpressure. The implied orientation of stretching is variable, although the dominance of shallower fabrics suggests that this may have been more pronounced in the horizontal plane (e.g., Brun et al., 1990). However, this interpretation may simply reflect level of exposure within the complex rather than processes operating for entire plutons.

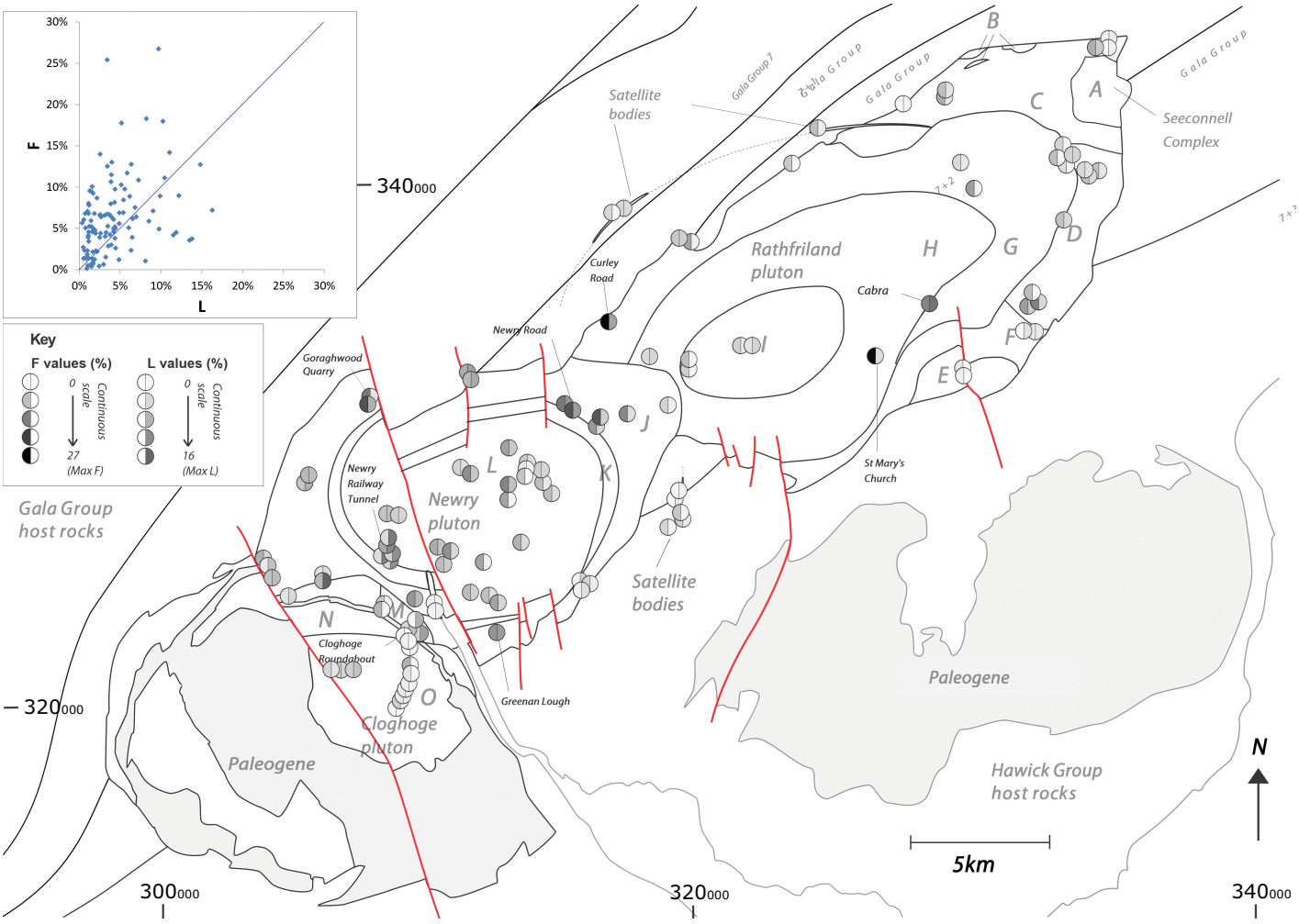


Figure 6. Anisotropy of magnetic susceptibility (AMS) fabric strengths (planar = *F*, linear = *L*) within the Newry igneous complex and satellite bodies. *F* and *L* are mapped as well as plotted against each other in the inset graph. See Figure 1 for zones and facies. Irish grid coordinate system.

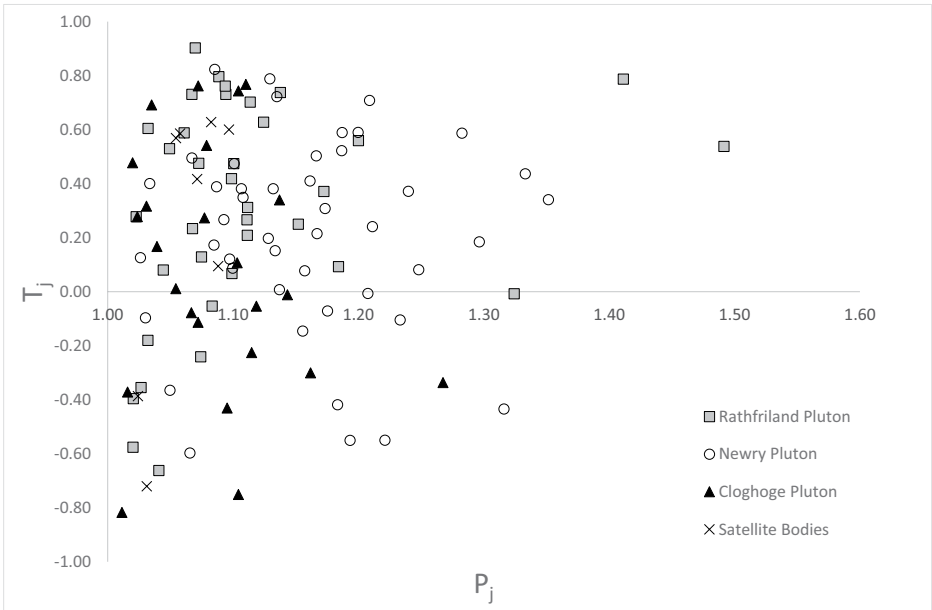


Figure 7. Plot of anisotropy of magnetic susceptibility (AMS) fabric parameters T_j and P_j (Jelinek, 1981) for the main parts of the Newry igneous complex. T_j represents overall fabric intensity, and P_j represents fabric shape (positive values: disk-like; negative values: rod-like).

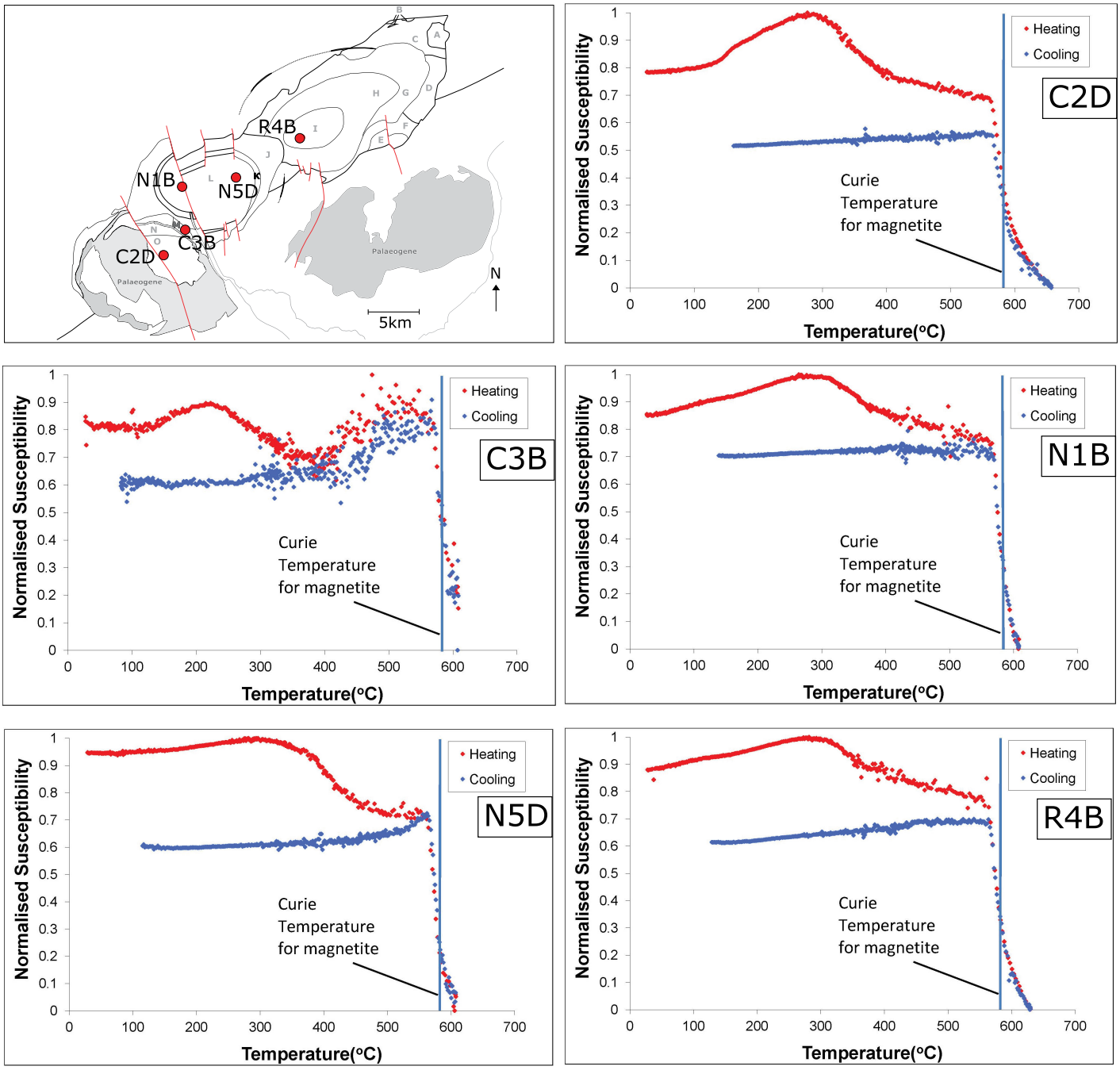


Figure 8. Thermomagnetic results, showing changes in magnetic susceptibility during heating and subsequent cooling for five samples from the Newry igneous complex. Sample locations are shown on the inset map (see Fig. 1 for zones and facies). Irish grid coordinate system.

Inflation of Individual Magma Pulses within the Newry Igneous Complex

The AMS results provide evidence that inflation of plutons within the Newry igneous complex occurred largely due to magma overpressure within individual magma pulses. The significantly high AMS fabric strengths close to the G-H zone boundary of the Rathfriland pluton and zone K of the Newry pluton (Fig. 7) suggest that these areas, in particular, were affected by this. It is proposed that the two magma pulses associated with these strong fabrics are represented by zone H of the Rathfriland pluton and zone L of the Newry pluton (Fig. 7). It is suggested that magma overpressure within both of these zones deformed the adjacent outer parts of their respective plutons, which would have exhibited more viscous rheologies due to the time intervals involved in emplacement (Anderson et al., 2016).

The exclusively high *L* values within samples at the western margin of zone L are also thought to reflect magma pressure. It is considered that in this area, stretching occurred along the flattening plane within the magma mush during inflation, producing fabrics that are dominated by a linear component. The proximity of these samples to

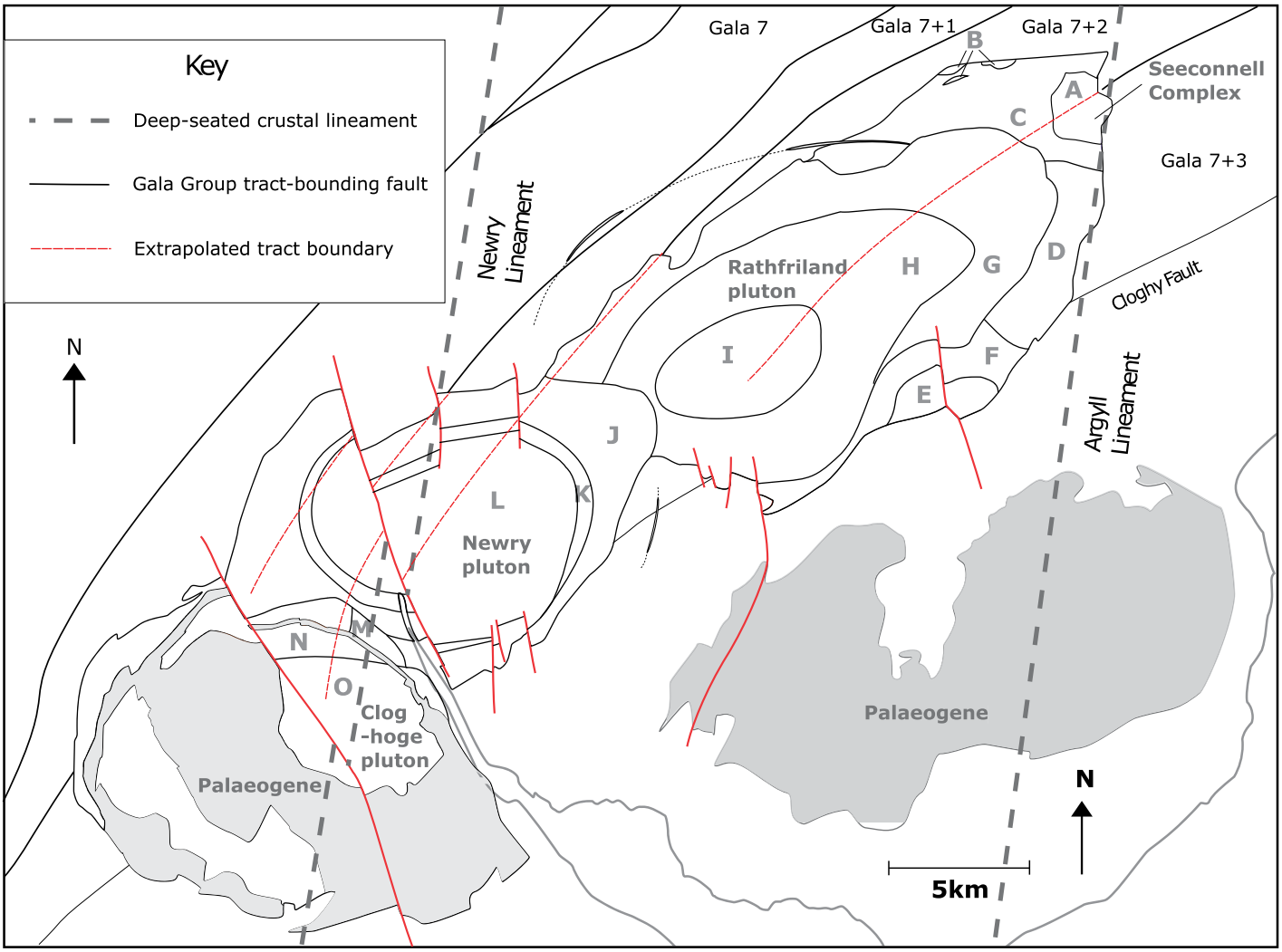


Figure 9. Gala Group tract boundaries and deep-seated crustal lineaments in the vicinity of the Newry igneous complex. Tract boundaries are extrapolated through the Newry igneous complex (after Beamish et al., 2010; Cooper et al., 2013). See Figure 1 for zones and facies.

the adjacent zone K, which likely represented a solid crystal framework at this time (Anderson et al., 2016), may have facilitated this process. The similar exclusively high *L* values within the sheets of the northeastern Cloghoge pluton may in turn relate to the same process.

Laccolithic Morphology of the Newry Igneous Complex

Mineral foliations within the Newry igneous complex can be used to infer pluton geometries, since these features are interpreted to reflect outward-directed magma pressure. Within individual plutons, mineral foliations are dominantly outward-dipping and are shallower within pluton centers than at their edges. This suggests that plutons are broadly dome-shaped and thus can be described as laccoliths.

The crosscutting of steeply dipping host-rock tracts by the Newry igneous complex in turn suggests that the complex encroached laterally into the host rocks. This again suggests that plutons of the Newry igneous complex exhibit laccolithic morphologies. Plutons would have initially crosscut their host rocks in the horizontal plane, before inflation brought the intrusion boundaries into near-parallelism with host-rock structures. The crosscutting of host-rocks tracts by the Newry igneous complex also precludes emplacement through in situ inflation of an inclined, bedding-parallel ascent zone.

Together, this evidence strongly suggests that each of the three main plutons of the Newry igneous complex represents a separate laccolithic body. The Seeconnell complex is known to have intruded separately (Anderson et al., 2016), although the overall geometry of this body is less clear. Due to its close relationship with the main part of the Newry igneous complex, the Seeconnell complex is tentatively thought to also represent a laccolithic body.

Emplacement in a Wider Context

Figure 9 shows that the two Gala Group tract boundaries associated with tectonic space generation (Gala 7 + 2/7 + 3 and Gala 7 + 1/7 + 2) appear to intersect the Argyll and Newry lineaments, respectively. Furthermore, these hypothesized intersections occur in significant areas of the Newry igneous complex, namely, the Seeconnell complex and along a line joining the Newry and Cloghoge pluton centers. These hypothesized intersections thus occur in the oldest part of the Newry igneous complex and in the centers of two of its plutons. Therefore, they

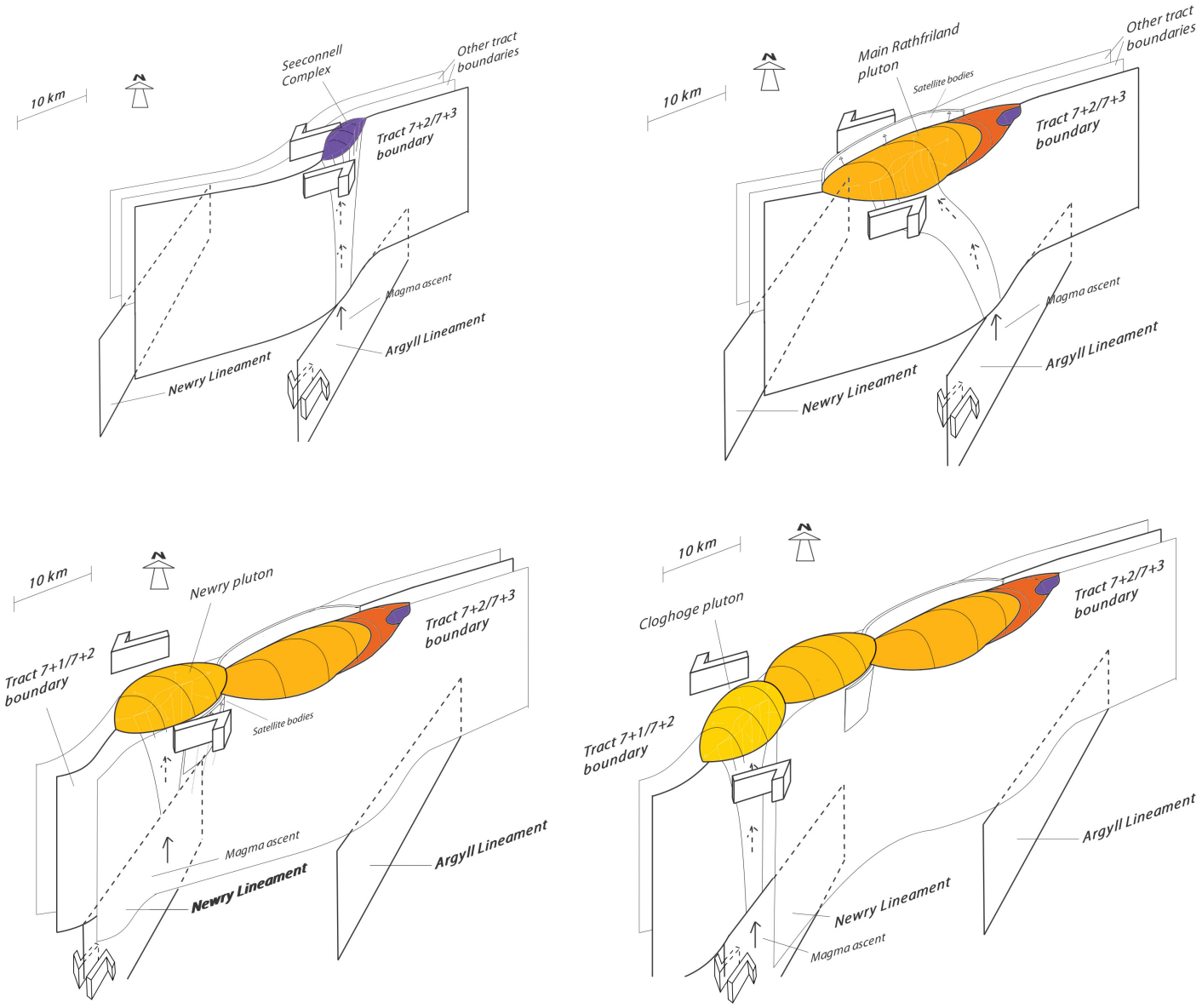


Figure 10. Schematic emplacement history of the Newry igneous complex and its satellite bodies, showing the interaction between deep-seated lineaments and Gala Group tract boundaries within the crust.

likely represent sites where magma would have first entered the emplacement site of the Newry igneous complex before expanding outward during subsequent intrusion.

Since the Argyll and Newry lineaments represent deep-seated structures (Cooper et al., 2013), it is proposed that these faults facilitated the ascent of magma from depth (Fig. 10). Where these faults intersected Gala Group tract boundaries, magma would have been able to ascend further, ultimately supplying the Newry igneous complex (Fig. 10; e.g., Jacques and Reavy, 1994; Stevenson et al., 2006). The magma supplying the Newry igneous complex is considered to have originated from the upper mantle, before occupying a staging site and attaining intermediate composition (Meighan and Neeson, 1979; Meighan et al., 2003). The intersection of deep-seated lineaments with tract boundaries higher in the crust would have allowed such transcrustal ascent of magma, although the crustal level of the staging site is unclear. The intersection between the Newry lineament and the Gala 7 + 2/7 + 3 boundary is also located close to the center of the Paleogene Slieve Gullion complex (Fig. 9; Cooper et al., 2013), suggesting that the magma supply for this intrusion may have been controlled by the same crustal structures as parts of the Newry igneous complex.

The only major site of intrusion within the Newry igneous complex that does not correspond to one of these lineaments is the central Rathfriland pluton, although this is located on the extrapolated Gala 7 + 2/7 + 3 boundary (Fig. 9). It is suggested that magma supplying the central Rathfriland pluton migrated southwestward along the Gala 7 + 2/7 + 3 boundary from the point at which this boundary intersects the Argyll lineament (Fig. 10). This may have been due to the accommodation space associated with initial tectonic opening (leading to the Seeconnell complex) being filled.

U-Pb data (Cooper et al., 2016) suggest that the Newry igneous complex gets younger to

the SW, with its oldest part being the Seeconnell complex. Therefore, it is proposed that the intersection between the Argyll lineament and the Gala 7 + 2/7 + 3 tract boundary, which occurs directly beneath the Seeconnell complex, provided the initial ascent route for magma supplying the Newry igneous complex. This led to emplacement of the Seeconnell complex at ca. 414 Ma, followed by the main Rathfriland pluton from 413 to 411 Ma (Fig. 10). The intersection between the Newry lineament and Gala 7 + 1/7 + 2 tract boundary subsequently facilitated ascent, leading to the emplacement of the Newry pluton from 411 to 410 Ma and the Cloghoge pluton until 407 Ma (Fig. 10).

We hypothesize that sinistral shear along the Argyll and Newry lineaments during late Caledonian deformation produced the tension-releasing bend within the Gala Group (Fig. 10). Higher in the crust, reduced confining pressure would in turn have allowed tectonic opening along this releasing bend. It is proposed that this local stress field induced horizontal magma flow, leading to lateral encroachment of the host rocks by magma and ultimately the formation of laccolithic bodies (Fig. 10).

CONCLUSIONS

The following four conclusions are drawn from the current study:

(1) This work supports the proposal by Beamish et al. (2010) that intrusion of the Newry igneous complex was facilitated by pull-apart tectonics. Furthermore, we suggest that accommodation space for the Newry igneous complex was produced by development of at least four separate pull-apart basins. These occurred along tract boundaries of the Gala Group within the Southern Uplands-Down-Longford terrane, due to the existence of a releasing bend during late Caledonian sinistral transtension. Opening along the Gala Group 7 + 2/7 + 3 tract boundary led to emplacement of the Seeconnell complex and the main Rathfriland pluton, with subsequent opening along the 7 + 1/7 + 2 tract boundary leading to emplacement of the Newry and Cloghoge plutons.

(2) Inflation of the Newry igneous complex due to magma overpressure also generated significant space. Much of this inflation was likely accomplished by a small number of individual magma pulses. Zone H of the Rathfriland pluton and zone L of the Newry pluton are thought to represent such key pulses, although others may also exist.

(3) The Newry igneous complex likely represents four laccolithic bodies, namely, the Seeconnell complex, main Rathfriland pluton, Newry pluton, and Cloghoge pluton. These crosscut the steeply dipping local host rocks.

(4) Interaction between deep-seated lineaments and Gala Group tract boundaries may have controlled the siting of the Newry igneous complex. Magma ascending within deep-seated lineaments would have been able to ascend further where these intersected the upper-crustal tract boundaries. Magma ascending from the intersection between the Argyll lineament and the Gala Group 7 + 2/7 + 3 tract boundary may have supplied the Seeconnell complex, before laterally migrating to supply the main Rathfriland pluton. Magma ascending from the near-parallel intersection between the Newry lineament and the Gala Group 7 + 1/7 + 2 tract boundary may have subsequently supplied the Newry and Cloghoge plutons. The latter intersection also underlies the Paleogene Slieve Gullion complex, and so siting of this intrusion may have been controlled by the same crustal structures as parts of the Newry igneous complex. It is possible that movement along deep-seated lineaments may have resulted in the bend within the Southern Uplands-Down-Longford terrane that yielded tectonic space for intrusion of the Newry igneous complex. Late Caledonian sinistral shear along the Argyll and Newry lineaments may have produced the observed releasing bend of the Gala Group within the Southern Uplands-Down-Longford terrane. Higher in the crust, reduced confining pressure may have resulted in tectonic opening along this releasing bend. This local stress field would have induced horizontal magma flow, so that previously steeply ascending magma encroached laterally to form laccolithic bodies.

Altogether, these findings suggest that emplacement of igneous complexes may be facilitated by many interdependent processes operating during magma ascent and at the final emplacement site. Therefore, simplistic emplacement models should largely be abandoned in favor of holistic models incorporating multiple processes.

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REFERENCES CITED

Akimoto, S.I., 1954, Thermo-magnetic study of ferromagnetic minerals contained in igneous rocks: Journal of Geomagnetism and Geoelectricity, v. 6, p. 1–14, https://doi.org/10.5636/jgg.6.1.

Anderson, P.E., Cooper, M.R., Stevenson, C.T., Hastie, A.R., Hoggett, M., Inman, J., Meighan, I.G., Hurley, C., Reavy, R.J., and Ellam, R.M., 2016, Zonation of the Newry Igneous complex, Northern Ireland, based on geochemical and geophysical data: Lithos, v. 260, p. 95–106, https://doi.org/10.1016/j.lithos.2016.05.009.

Anderson, T.B., 2004, Southern Uplands-Down-Longford terrane, *in* Mitchell, W., ed., The Geology of Northern Ireland: Our Natural Foundation: Belfast, Geological Survey of Northern Ireland, p. 41–60.

Barnes, R.P., Anderson, T.B., and McCurry, J.A., 1987, Along-strike variation in the stratigraphical and structural profile of the Southern Uplands central belt in Galloway and Down: Journal of the Geological Society [London], v. 144, p. 807–816, https://doi.org/10.1144/gsjgs.144.5.0807.

Beamish, D., Kimbell, G.S., Stone, P., and Anderson, T.B., 2010, Regional conductivity data used to reassess early Palaeozoic structure in the Northern Ireland sector of the Southern Uplands–Down–Longford terrane: Journal of the Geological Society [London], v. 167, p. 649–657, https://doi.org/10.1144/0016-76492009-122.

Bluck, B.J., 1985, The Scottish paratectonic Caledonides: Scottish Journal of Geology, v. 21, p. 437–464, https://doi.org/10.1144jg21040437.

Böhnel, H., McIntosh, G., and Sherwood, G., 2002, A parameter characterising the irreversibility of thermomagnetic curves: Physics and Chemistry of the Earth, Parts A/B/C, v. 27, p. 1305–1309.

Borradaile, G.J., and Jackson, M., 2004, Anisotropy of magnetic susceptibility (AMS): Magnetic petrofabrics of deformed rocks, *in* Martín-Hernández, F., Lüneberg, C.M., Aubourg, C., and Jackson, M., eds., Magnetic Fabric: Methods and Applications: Geological Society, London, Special Publication 238, p. 299–360, https://doi.org/10.1144/GSL.SP.2004.238.01.18.

Borradaile, G.J., and Jackson, M., 2010, Structural geology, petrofabrics and magnetic fabrics (AMS, AARM, AIRM): Journal of Structural Geology, v. 32, p. 1519–1551, https://doi.org/10.1016/j.jsg.2009.09.006.

Brown, P.E., Ryan, P.D., Soper, N.J., and Woodcock, N.H., 2008, The Newer Granite problem revisited: A transtensional origin for the Early Devonian trans-suture suite: Geological Magazine, v. 145, p. 235–256, https://doi.org/10.1017/S0016756807004219.

Brun, J.P., Gapais, D., Cogné, J.P., Ledru, P., and Vigneresse, J.L., 1990, The Flamanville Granite (northwest France): An unequivocal example of a syntectonically expanding pluton: Geological Journal, v. 25, p. 271–286, https://doi.org/10.1002/gj.3350250310.

Cloos, H., 1925, Einfurhrung in die tectonische Behandlung magmatischer Erscheinungen: Part 1: Das Riesengebirge in Shlesien: Berlin, Gebrüder Borntraeger Verlagsbuchhandlung, 194 p.

Coleman, D.S., Gray, W., and Glazner, A.F., 2004, Rethinking the emplacement and evolution of zoned plutons: Geochronologic evidence for incremental assembly of the Tuolumne intrusive suite, California: Geology, v. 32, p. 433–436, https://doi.org/10.1130/G20220.1.

Cook, D.R., and Weir, J.A., 1980, The stratigraphical setting of the Cairnsmore of Fleet Pluton, Galloway: Scottish Journal of Geology, v. 16, p. 125–141, https://doi.org/10.1144jg16020125.

Cooper, M., and Johnston, T., 2004a, Late Palaeozoic intrusives, *in* Mitchell, W., ed., The Geology of Northern Ireland: Our Natural Foundation: Belfast, Geological Survey of Northern Ireland, p. 61–68.

Cooper, M., and Johnston, T., 2004b, Palaeogene intrusive igneous rocks, *in* Mitchell, W., ed., The Geology of Northern Ireland: Our Natural Foundation: Belfast, Geological Survey of Northern Ireland, p. 179–198.

Cooper, M., Crowley, Q., Hollis, S., Noble, S., and Henney, P., 2013, A U-Pb age for the late Caledonian Sperrin Mountains minor intrusions suite in the north of Ireland: Timing of slab break-off in the Grampian terrane and the significance of deep-seated, crustal lineaments: Journal of the Geological Society [London], v. 170, p. 603–614, https://doi.org/10.1144/jgs2012-098.

Cooper, M., Anderson, P., Condon, D., Stevenson, C., Ellam, R., Meighan, I., and Crowley, Q., 2016, Shape and intrusion history of the Late Caledonian, Newry Igne-

ous Complex, Northern Ireland, *in* Young, M.E., ed., Unearthed: impacts of the Tellus Surveys of the North of Ireland: Dublin, Royal Irish Academy, p. 145–156, https://doi.org/10.3318/978-1-908996-88-6.

Cruden, A.R., 1990, Flow and fabric development during the diapiric rise of magma: The Journal of Geology, v. 98, p. 681–698, https://doi.org/10.1086/629433.

de Boer, C.B., and Dekkers, M.J., 2001, Unusual thermomagnetic behaviour of haematites: Neoformation of a highly magnetic spinel phase on heating in air: Geophysical Journal International, v. 144, p. 481–494, https://doi.org/10.1046/j.0956-540X.2000.01333.x.

de Saint Blanquat, M., Horsman, E., Habert, G., Morgan, S., Vanderhaeghe, O., Law, R., and Tikoff, B., 2011, Multiscale magmatic cyclicity, duration of pluton construction, and the paradoxical relationship between tectonism and plutonism in continental arcs: Tectonophysics, v. 500, p. 20–33, https://doi.org/10.1016/j.tecto.2009.12.009.

Dewey, J.F., and Strachan, R.A., 2003, Changing Silurian–Devonian relative plate motion in the Caledonides: Sinistral transpression to sinistral transtension: Journal of the Geological Society [London], v. 160, p. 219–229, https://doi.org/10.1144/0016-764902-085.

D'lemos, R.S., Brown, M., and Strachan, R.A., 1992, Granite magma generation, ascent and emplacement within a transpressional orogen: Journal of the Geological Society [London], v. 149, p. 487–490, https://doi.org/10.1144/gsjgs.149.4.0487.

Dunlop, D.J., 1974, Thermal enhancement of magnetic susceptibility: Journal of Geophysics (Zeitschrift fur Geophysik), v. 40, p. 439–451.

Dunlop, D.J., 2006, Inverse thermoremanent magnetization: Journal of Geophysical Research–Solid Earth, v. 111, B12S02, https://doi.org/10.1029/2006JB004572.

Egan, F.W., and Baily, W.H., 1872, Explanatory Memoir to Sheet 48: Dublin, Geological Survey of Ireland.

Fabian, K., Shcherbakov, V.P., and McEnroe, S.A., 2013, Measuring the Curie temperature: Geochemistry Geophysics Geosystems, v. 14, p. 947–961, https://doi.org/10.1029/2012GC004440.

Farina, F., Stevens, G., and Villaros, A., 2012, Multi-batch, incremental assembly of a dynamic magma chamber: The case of the Peninsula pluton granite (Cape Granite Suite, South Africa): Mineralogy and Petrology, v. 106, p. 193–216, https://doi.org/10.100700710-012-0224-8.

Fleming, E.J., Stevenson, C.T., and Petronis, M.S., 2013, New insights into the deformation of a middle Pleistocene glaciotectonised sequence in Norfolk, England, through magnetic and structural analysis: Proceedings of the Geologists' Association, v. 124, p. 834–854.

Geological Survey of Northern Ireland (GSNI), 1997, Geological Map of Northern Ireland, Solid Geology (2nd ed.): Belfast, Geological Survey of Northern Ireland, scale 1:250 000.

Guineberteau, B., Bouchez, J.L., and Vigneresse, J.L., 1987, The Mortagne granite pluton (France) emplaced by pull-apart along a shear zone: Structural and gravimetric arguments and regional implication: Geological Society of America Bulletin, v. 99, p. 763–770, https://doi.org/10.1130/0016-7606(1987)99<763:TMGPFE>2.0.CO;2.

Harry, W.T., and Richey, J.E., 1963, Magmatic pulses in the emplacement of plutons: Geological Journal, v. 3, p. 254–268, https://doi.org/10.1002/gj.3350030204.

Hecht, L., and Vigneresse, J.L., 1999, A multidisciplinary approach combining geochemical, gravity and structural data: Implications for pluton emplacement and zonation, *in* Castro, A., Fernández, C., and Vigneresse, J.L., eds., Understanding Granites: Integrating New and Classical Techniques: Geological Society, London, Special Publication 168, p. 95–110, https://doi.org/10.1144/GSL.SP.1999.168.01.07.

Henry, B., Jordanova, D., Jordanova, N., Souque, C., and Robion, P., 2003, Anisotropy of magnetic susceptibility of heated rocks: Tectonophysics, v. 366, p. 241–258, https://doi.org/10.1016/S0040-1951(03)00099-4.

Hopkinson, J., 1890, Magnetic properties of alloys of nickel and iron: Proceedings of the Royal Society of London, v. 48, p. 1–13, https://doi.org/10.1098/rspl.1890.0001.

Hrouda, F., Jelínek, V., and Zapletal, K., 1997, Refined technique for susceptibility resolution into ferromagnetic and paramagnetic components based on susceptibility temperature-variation measurement: Geophysical Journal International, v. 129, p. 715–719, https://doi.org/10.1111/j.1365-246X.1997.tb04506.x.

Hull, E., 1881, Explanatory Memoir to Sheets 60, 61 and Part of 71: Dublin, Geological Survey of Ireland, 56 p.

Hutton, D.H.W., 1982, A tectonic model for the emplacement of the Main Donegal Granite, NW Ireland: Journal of the Geological Society [London], v. 139, p. 615–631, https://doi.org/10.1144/gsjgs.139.5.0615.

Hutton, D.H.W., 1988, Granite emplacement mechanisms and tectonic controls: Inferences from deformation studies: Transactions of the Royal Society of Edinburgh–Earth Sciences, v. 79, p. 245–255, https://doi.org/10.1017/S0263593300014255.

Hutton, D.H.W., and Alsop, G.I., 1996, The Caledonian strike-swing and associated lineaments in NW Ireland and adjacent areas: Sedimentation, deformation and igneous intrusion patterns: Journal of the Geological Society [London], v. 153, p. 345–360, https://doi.org/10.1144/gsjgs.153.3.0345.

Inman, J., Anderson, P., Cooper, M., Condon, D., Crowley, Q., Meighan, I., and Stevenson, C., 2012, New insights into the emplacement of the Seeconnell complex within the Newry igneous complex, Northern Ireland [abs.], *in* 55th Irish Geological Research Meeting & Lithosphere Workshop.

Jacques, J.M., and Reavy, R.J., 1994, Caledonian plutonism and major lineaments in the SW Scottish Highlands: Journal of the Geological Society [London], v. 151, p. 955–969, https://doi.org/10.1144/gsjgs.151.6.0955.

Jelinek, V., 1981, Characterization of the magnetic fabric of rocks: Tectonophysics, v. 79, p. T63–T67, https://doi.org/10.1016/0040-1951(81)90110-4.

Jelínek, V., and Kropáček, V., 1978, Statistical processing of anisotropy of magnetic susceptibility measured on groups of specimens: Studia Geophysica et Geodaetica, v. 22, p. 50–62, https://doi.org/10.1007/BF01613632.

Johnson, A.M., and Pollard, D.D., 1973, Mechanics of growth of some laccolithic intrusions in the Henry Mountains, Utah: I. Field observations, Gilbert's model, physical properties and flow of the magma: Tectonophysics, v. 18, p. 261–309, https://doi.org/10.1016/0040-1951(73)90050-4.

Jover, O., Rochette, P., Lorand, J.P., Maeder, M., and Bouchez, J.L., 1989, Magnetic mineralogy of some granites from the French Massif Central: Origin of their low-field susceptibility: Physics of the Earth and Planetary Interiors, v. 55, p. 79–92, https://doi.org/10.1016/0031-9201(89)90235-5.

Kryza, R., Schaltegger, U., Oberc-Dziedzic, T., Pin, C., and Ovtcharova, M., 2014, Geochronology of a composite granitoid pluton: A high-precision ID-TIMS U-Pb zircon study of the Variscan Karkonosze Granite (SW Poland): International Journal of Earth Sciences, v. 103, p. 683–696, https://doi.org/10.100700531-013-0995-0.

Lancaster, P.J., Strachan, R.A., Bullen, D., Fowler, M., Jaramillo, M., and Saldarriaga, A.M., 2017, U-Pb zircon geochronology and geodynamic significance of 'Newer Granite' plutons in Shetland, northernmost Scottish Caledonides: Journal of the Geological Society [London], v. 174, p. 486–497, https://doi.org/10.1144/jgs2016-106.

Leggett, J.K., 1987, The Southern Uplands as an accretionary prism: The importance of analogues in reconstructing palaeogeography: Journal of the Geological Society [London], v. 144, p. 737–751, https://doi.org/10.1144/gsjgs.144.5.0737.

Leggett, J.K., McKerrow, W.T., and Eales, M.H., 1979, The Southern Uplands of Scotland: A lower Palaeozoic accretionary prism: Journal of the Geological Society [London], v. 136, p. 755–770, https://doi.org/10.1144/gsjgs.136.6.0755.

Leggett, J.K., McKerrow, W.S., and Casey, D.M., 1982, The anatomy of a Lower Palaeozoic accretionary forearc: The Southern Uplands of Scotland, *in* Leggett, J.K., Trench-Forearc Geology: Sedimentation and Tectonics on Modern and Ancient Active Plate Margins: Geological Society, London, Special Publication 10, p. 495–520, https://doi.org/10.1144/GSL.SP.1982.010.01.33.

Lipman, P.W., 2007, Incremental assembly and prolonged consolidation of Cordilleran magma chambers: Evidence from the Southern Rocky Mountain volcanic field: Geosphere, v. 3, p. 42–70, https://doi.org/10.1130/GES00061.1.

Mamtani, M.A., and Greiling, R.O., 2005, Granite emplacement and its relation with regional deformation in the Aravalli Mountain Belt (India)—Inferences from magnetic fabric: Journal of Structural Geology, v. 27, p. 2008–2029, https://doi.org/10.1016/j.jsg.2005.06.004.

Mann, P., Hempton, M.R., Bradley, D.C., and Burke, K., 1983, Development of pull-apart basins: The Journal of Geology, v. 91, p. 529–554, https://doi.org/10.1086/628803.

McCarthy, W., Reavy, R.J., Stevenson, C.T., and Petronis, M.S., 2015, Late Caledonian transpression and the structural controls on pluton construction; new insights from the Omey pluton, western Ireland: Earth and Environmental Science Transactions of the Royal Society of Edinburgh, v. 106, p. 11–28, https://doi.org/10.1017/S1755691015000201.

McKerrow, W.S., Leggett, J.K., and Eales, M.H., 1977, Imbricate thrust model of the Southern Uplands of Scotland: Nature, v. 267, p. 237–239, https://doi.org/10.1038/267237a0.

Meighan, I., and Neeson, J., 1979, The Newry igneous complex, County Down, *in* Harris, A.L., Holland, C.H., and Leake, B.E., eds., The Caledonides of the British Isles—Reviewed: Geological Society, London, Special Publication 8, p. 717–722, https://doi.org/10.1144/GSL.SP.1979.008.01.87.

Meighan, I.G., Hamilton, M.A., Gamble, J.A., Ellam, R.M., and Cooper, M.R., 2003, The Caledonian Newry complex, NE Ireland: New U-Pb ages, a subsurface extension and magmatic epidote, *in* Joint Meeting: Geological Society of America–Northeastern Section–Atlantic Geoscience Society, p. 79.

Miles, A.J., Woodcock, N.J., and Hawkesworth, C.J., 2016, Tectonic controls on post-subduction granite genesis and emplacement: The late Caledonian suite of Britain and Ireland: Gondwana Research, v. 39, p. 250–260, https://doi.org/10.1016/j.gr.2016.02.006.

Miller, J.S., 2008, Assembling a pluton…one increment at a time: Geology, v. 36, p. 511–512, https://doi.org/10.1130/focus062008.1.

Molyneux, S.J., and Hutton, D.H.W., 2000, Evidence for significant granite space creation by the ballooning mechanism: The example of the Ardara pluton, Ireland: Geological Society of America Bulletin, v. 112, p. 1543–1558, https://doi.org/10.1130/0016-7606(2000)112<1543:EFSGSC>2.0.CO;2.

Morgan, S., Jones, R., Conner, J., Student, J., Schaner, M., Horsman, E., and de Saint Blanquat, M., 2017, Magma sheets defined with magnetic susceptibility in the Maiden Creek sill, Henry Mountains, Utah, USA: Geology, v. 45, p. 599–602, https://doi.org/10.1130/G38932.1.

Needham, D.T., and Knipe, R.J., 1986, Accretion-and collision-related deformation in the Southern Uplands accretionary wedge, southwestern Scotland: Geology, v. 14, p. 303–306, https://doi.org/10.1130/0091-7613(1986)14<303:AACDIT>2.0.CO;2.

Neeson, J., 1984, The Geology and Geochemistry of the Newry Igneous Complex, Northern Ireland [Ph.D. thesis]: Belfast, Northern Ireland, Queen's University.

Owens, W.H., 1974, Mathematical model studies on factors affecting the magnetic anisotropy of deformed rocks: Tectonophysics, v. 24, p. 115–131, https://doi.org/10.1016/0040-1951(74)90133-4.

Petford, N., Cruden, A.R., McCaffrey, K.J.W., and Vigneresse, J.L., 2000, Granite magma formation, transport and emplacement in the Earth's crust: Nature, v. 408, p. 669–673, https://doi.org/10.1038/35047000.

Petrovský, E., and Kapička, A., 2006, On determination of the Curie point from thermomagnetic curves: Journal of Geophysical Research–Solid Earth, v. 111, no. B12, B12S27, https://doi.org/10.1029/2006JB004507.

Pitcher, W.S., 1997, The Nature and Origin of Granite: London, Springer Science & Business Media, 387 p., https://doi.org/10.1007/978-94-011-5832-9.

Rabillard, A., Jolivet, L., Arbaret, L., Laurent, V., Bessiere, E., and Menant, A., 2014, Granitoids and extensional shear zones in the Aegean Sea (Greece), interactions

during metamorphic core complexes formation: European Geosciences Union General Assembly Conference Abstracts, v. 16, p. 5146.

Radhakrishnamurty, C., and Likhite, S.D., 1970, Relation between thermal variation of low field susceptibility and magnetic hysteresis of basalts: Earth and Planetary Science Letters, v. 9, p. 294–298, https://doi.org/10.1016/0012-821X(70)90040-3.

Reynolds, D.L., 1934, The eastern end of the Newry igneous complex: Quarterly Journal of the Geological Society [London], v. 90, p. 585–636, https://doi.org/10.1144/GSL.JGS.1934.090.01-04.20.

Reynolds, D.L., 1936, The two monzonitic series of the Newry complex: Geological Magazine, v. 73, p. 337–364, https://doi.org/10.1017/S001675680009395X.

Reynolds, D.L., 1943, The south-western end of the Newry igneous complex. A contribution towards the petrogenesis of the granodiorites: Quarterly Journal of the Geological Society [London], v. 99, p. 205–246, https://doi.org/10.1144/GSL.JGS.1943.099.01-04.13.

Richey, J., 1927, Structural relations of the Mournes Granites (Northern Ireland): Quarterly Journal of the Geological Society [London], v. 83, p. 653, https://doi.org/10.1144/GSL.JGS.1927.083.01-05.27.

Rosenberg, C.L., 2004, Shear zones and magma ascent: A model based on a review of the Tertiary magmatism in the Alps: Tectonics, v. 23, TC3002, https://doi.org/10.1029/2003TC001526.

Smith, J.V., 2004, Determining the size and shape of blocks from linear sampling for geotechnical rock mass classification and assessment: Journal of Structural Geology, v. 26, p. 1317–1339, https://doi.org/10.1016/j.jsg.2003.11.019.

Soper, N.T., and Woodcock, N.H., 1990, Silurian collision and sediment dispersal patterns in southern Britain: Geological Magazine, v. 127, p. 527–542, https://doi.org/10.1017/S0016756800015430.

Soper, N.J., and Woodcock, N.H., 2003, The lost Lower Old Red Sandstone of England and Wales: A record of post-Iapetan flexure or Early Devonian transtension?: Geological Magazine, v. 140, p. 627–647, https://doi.org/10.1017/S0016756803008380.

Soper, N.J., Strachan, R.A., Holdsworth, R.E., Gayer, R.A., and Greiling, R.O., 1992, Sinistral transpression and the Silurian closure of Iapetus: Journal of the Geological Society [London], v. 149, p. 871–880, https://doi.org/10.1144/gsjgs.149.6.0871.

Stevenson, C., 2009, The relationship between forceful and passive emplacement: The interplay between tectonic strain and magma supply in the Rosses granitic complex, NW Ireland: Journal of Structural Geology, v. 31, p. 270–287, https://doi.org/10.1016/j.jsg.2008.11.009.

Stevenson, C., and Bennett, N., 2011, The emplacement of the Palaeogene Mourne granite centres, Northern Ireland: New results from the western Mourne centre: Journal of the Geological Society [London], v. 168, p. 831–836, https://doi.org/10.1144/0016-76492010-123.

Stevenson, C., Hutton, D.H., and Price, A.R., 2006, The Trawenagh Bay Granite and a new model for the emplacement of the Donegal Batholith: Transactions of the Royal Society of Edinburgh–Earth Sciences, v. 97, p. 455–477, https://doi.org/10.1017/S0263593300001565.

Stevenson, C., Owens, W.H., Hutton, D.H., Hood, D.N., and Meighan, I.G., 2007a, Laccolithic, as opposed to cauldron subsidence, emplacement of the Eastern Mourne pluton, N. Ireland: Evidence from anisotropy of magnetic susceptibility: Journal of the Geological Society [London], v. 164, p. 99–110, https://doi.org/10.1144/0016076492006-008.

Stevenson, C., Owens, W.H., and Hutton, D.H., 2007b, Flow lobes in granite: The determination of magma flow direction in the Trawenagh Bay Granite, northwestern Ireland, using anisotropy of magnetic susceptibility: Geological Society of America Bulletin, v. 119, p. 1368–1386, https://doi.org/10.1130/B25970.1.

Stevenson, C., O'Driscoll, B., Holohan, E.P., Couchman, R., Reavy, R.J., and Andrews, G.D., 2008, The structure, fabrics and AMS of the Slieve Gullion ring-complex, Northern Ireland: Testing the ring-dyke emplacement model, *in* Thomson, K., and Petford, N., eds., Structure and Emplacement of High-Level Magmatic Systems: Geological Society, London, Special Publication 302, p. 159–184, https://doi.org/10.1144/SP302.12.

Stone, P., and Merriman, R.J., 2004, Basin thermal history favours an accretionary origin for the Southern Uplands terrane, Scottish Caledonides: Journal of the Geological Society [London], v. 161, p. 829–836, https://doi.org/10.1144/0016-764903-170.

Tarling, D., and Hrouda, F., eds., 1993, Magnetic Anisotropy of Rocks: London, Springer Science & Business Media, 221 p.

Waldron, J.W., Floyd, J.D., Simonetti, A., and Heaman, L.M., 2008, Ancient Laurentian detrital zircon in the closing Iapetus Ocean, Southern Uplands terrane, Scotland: Geology, v. 36, p. 527–530, https://doi.org/10.1130/G24763A.1.

Wei, W., Chen, Y., Faure, M., Shi, Y.H., Martelet, G., Hou, Q.L., Lin, W., Le Breton, N., and Wang, Q.C., 2014, A multidisciplinary study on the emplacement mechanism of the Qingyang–Jiuhua Massif in southeast China and its tectonic bearings. Part I: Structural geology, AMS and paleomagnetism: Journal of Asian Earth Sciences, v. 86, p. 76–93, https://doi.org/10.1016/j.jseaes.2013.06.003.

Westropp, W.H.S., 1867, The origin of granite: Geological Magazine, v. 4, no. 41, p. 522–525, https://doi.org/10.1017/S001675680020890X.

Yan, D.P., Zhou, M.F., Zhao, D., Li, J.W., Wang, G.H., Wang, C.L., and Qi, L., 2011, Origin, ascent and oblique emplacement of magmas in a thickened crust: An example from the Cretaceous Fangshan adakitic pluton, Beijing: Lithos, v. 123, p. 102–120, https://doi.org/10.1016/j.lithos.2010.11.015.

Young, M.E., and Donald, A.W., 2013, A Guide to the Tellus Data: Belfast, Geological Survey of Northern Ireland, available at http://nora.nerc.ac.uk/509171/ (last accessed 23 May 2017).

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