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The Trawenagh Bay Granite and a new model for the emplacement of the Donegal Batholith

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ABSTRACT: The Trawenagh Bay Granite (TBG) is shown to be a tabular pluton with gently inclined contacts that, from anisotropy of magnetic susceptibility (AMS) studies, was emplaced as a series of flow lobes whose geometries indicate that it flowed horizontally towards the W out of late stage adjacent steeply inclined monzogranite sheets of the Main Donegal Granite (MDG). We thus confirm in detail the central broad idea of the Pitcher & Read (1959) model that the Main Donegal Granite fed the Trawenagh Bay Granite. Early TBG flow lobes cut and are cut by deformation associated with the sinistral shear zone in which the MDG lies, thus demonstrating synchronicity of shearing and magmatism. The TBG magma leaked out of the shear zone and emplaced into undeformed country rocks and was probably guided by shear zone splays that die out along its northern and southern margins. At a late stage in the development of MDG, the splays developed from the NNE-trending SW boundary of the shear zone and caused a gap in this structure through which TBG magma was channelled out of the MDG. A review is presented of the last twenty-five years of published and unpublished work on the batholith, showing that the MDG shear zone was a long-lived structure almost certainly in existence before the emplacement of that body, and that four of the contiguous granitiods (Thorr, Ardara, and Rosses, as well as Trawenagh Bay) were all sourced within the shear zone. A new model is presented for the development of the batholith. The pre-existing crustal structure was a deep-seated N12°E fault in the basement to the Dalradian wall rocks of the granites, that was coupled to up to six other more minor WNW–ESE basement faults in the W. A NE–SW-trending sinistral shear zone was initiated at the end of the Caledonian orogeny, as calc-alkaline and deep-seated appinites were generated in the area. This shearing activated the pre-existing structures at the current crustal level, and the N12°E structure acted as a continental transform fault which allowed the dilation needed to facilitate the wedging space requirements of the MDG and the other units in the shear zone, as well as transferring regional sinistral shear through the system. The Thorr and Ardara plutons were emplaced first into the shear zone and then those magmas leaked out into the adjacent wall rocks: one to form a large laccolith, the other to form a balloon. Steep early MDG complex sheets (granodiorites and tonalities) were emplaced in the shear zone between the Thorr and Ardara emplacement sites. Dilation continued until late stage extensive monzogranite sheets were intruded in the NW and SE of the pluton. One of these probably leaked material westward to form the Rosses laccolith and southwestwards to form the TBG in the final stages of shear zone movement.

KEY WORDS: ascent and emplacement, granite emplacement, laccolith, Main Donegal Granite, pluton definition, shear zone

The Donegal Batholith is a well known and well studied late Caledonian batholith (Pitcher & Berger 1972), the constituent plutons of which were intruded penecontemporaneously at around 400 Ma (Pitcher & Berger 1972; O'Connor *et al.* 1982) (Fig. 1). The good exposure of this batholith, afforded by coastal sections and glacial pavements, reveals complexity on scales of centimetres to kilometres and has provided several key granite emplacement studies: Pitcher (1953a, b, 1970); Pitcher & Read (1959); Pitcher & Berger (1972); Holder (1979); Hutton (1982); Molyneux & Hutton (2000).

The first major concerted research effort on the Donegal granites was begun in 1947 by workers from Imperial College London, lead by H. H. Read and W. S. Pitcher and was based on the 6 inch = 1 mile mapping scale (1: 10 580). The findings of this were summarised in Pitcher & Berger (1972) together with a new 1 inch to 1 mile (1:63 360) map of both the granites and their envelope rocks. This work was one of the first that described an entire granite batholith on such a large scale and it is still regarded as iconic. The main conclusion was that a variety of emplacement mechanisms, both forceful and passive, could operate at essentially the same time and at the same level in the crust. Another significant outcome of this work was in the description of examples of subtle zonation and internal granite contacts (e.g. Pitcher 1953a, b; Whitten 1957; Pitcher & Read 1959).

Hutton (1982) brought a new phase of structurally based granite emplacement research to the Donegal Batholith with the discovery that the Main Donegal Granite lay in a major regional tectonic shear zone. According to Hutton's model, a displacement gradient along this shear zone not only caused dilation of the zone to allow the space needed for the Main Granite, but also created varying stresses in the wall rocks of the zone which controlled the emplacement of the other plutons of the batholith. The present contribution is the culmination of the latest phase of this emplacement research on the Donegal Batholith, bringing together the significant findings of several theses on other plutons of the batholith since 1982, including McErlean (1993), Molyneux (1997), Price (1997) and Stevenson (2004), and key studies and overviews including Hutton (1982), Hutton & Alsop (1996), Price & Pitcher (1999), Molyneux & Hutton (2000), Hutton & Seigesmund (2001) and Pitcher & Hutton (2004). First an

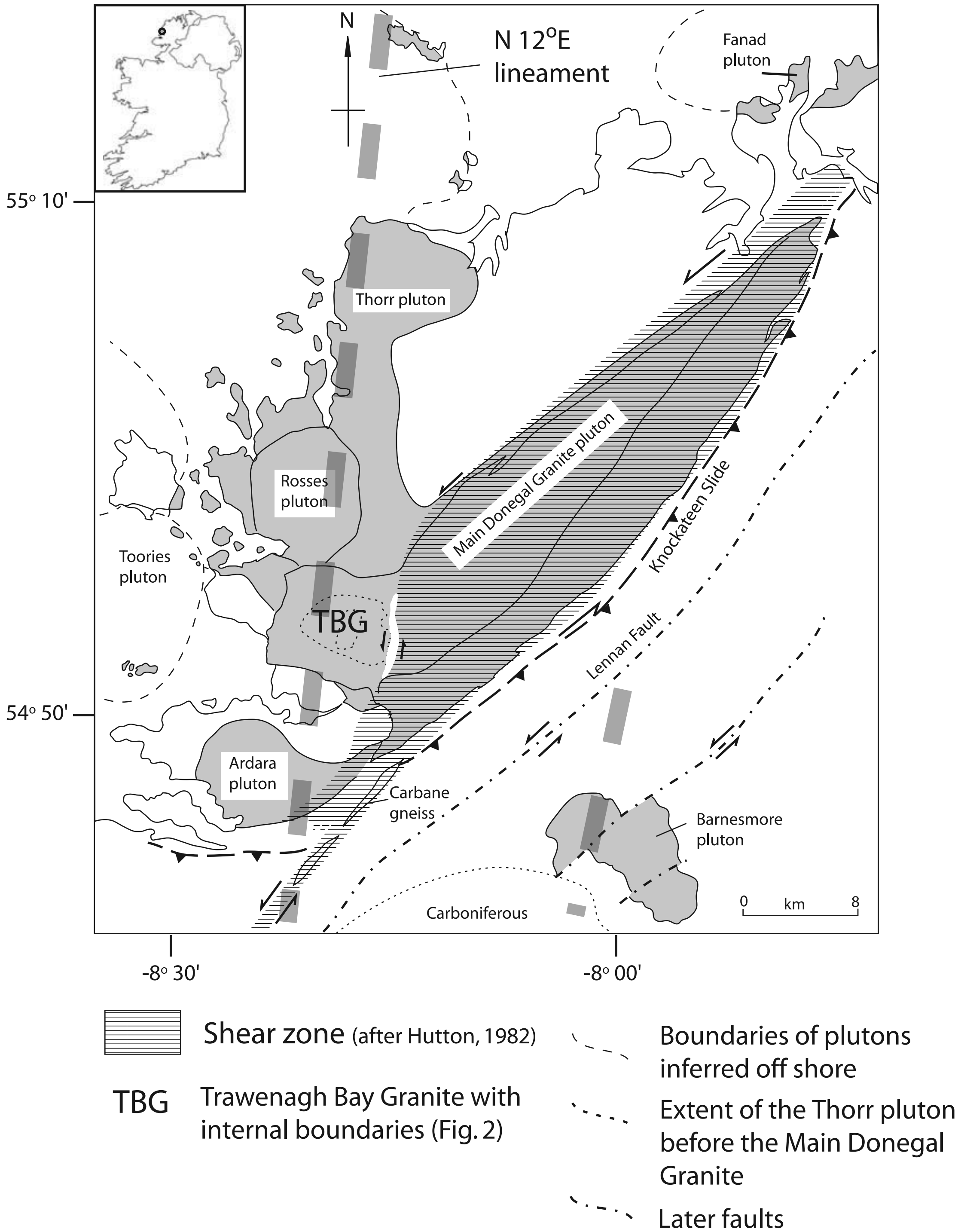


Figure 1 The Donegal Granites, the Main Donegal Granite shear zone and the N°12E lineament.

emplacement model is proposed for the Trawenagh Bay Granite (the 'enigma' of Pitcher & Berger 1972) based on the findings of Stevenson (2004) and Stevenson *et al.* (in press); then added to this a summary of the findings of the post-Hutton (1982) emplacement research on the Donegal Batholith; and a new model for the emplacement of the batholith is presented.

1. The emplacement of the Trawenagh Bay Granite

The Trawenagh Bay Granite, first described by Gindy (1953), has been regarded by Pitcher & Read (1959), Pitcher & Berger (1972) and Price & Pitcher (1999) as the most problematic pluton in the Donegal Batholith, both in terms of its emplacement mechanism and in its relationship with the much larger Main Donegal Granite (MDG) which it adjoins along its eastern contact. The Main Donegal Granite is renowned as an early described example (Read 1958; Pitcher & Read 1959, 1960) of a pluton elongate parallel to the regional strike, composed of steeply inclined NE–SW trending granite sheets, separated by trains of similarly elongated country rock xenoliths which root into roof septa; all intensely coplanarly deformed, with an associated gently plunging mineral stretching lineation.

Pitcher & Read (1959) and Pitcher & Berger (1972) showed that the northwestern petrological facies of the MDG was very similar to the TBG. Price (1997, and see below) and Price &

Pitcher (1999) confirmed this, linking the late monzogranite sheets with the TBG units. Thus, the TBG apparently forms a continuous lobe of the MDG, yet, in contrast to the MDG the TBG exhibits: (1) many cross-cutting contacts oblique to the regional strike; (2) relative homogeneity in composition; (3) a paucity of internal structure, including visible sheeting, fabrics, and banding; and (4) a paucity of septa, trains of xenoliths or any other inclusions. The ambiguity of the relationship between the two is compounded by their contact/transition becoming obscured by later deformation and a lack of critical exposures. The boundary is fundamentally of a structural, rather than a petrological nature, although Pitcher & Read (1959) believed that a screen of pegmatites represented this contact. This conflict of petrological similarities yet structural differences in these intrusions has not yet been accounted for in anything other than vague and generalised terms (Pitcher & Read 1959; Hutton 1982).

1.1. Previous emplacement theories for the Trawenagh Bay Granite and current understanding

Initially, the TBG, because of its lack of internal structure and cross cutting nature, was considered to have been emplaced by a passive mechanism, involving piecemeal stoping (Pitcher & Read 1959; Pitcher & Berger 1972). For Read (1958) and Pitcher & Read (1959), the identification of the steep NE–SW foliation in the adjoining MDG as a magmatic flow fabric and the SW splaying of the country rock xenolith zones ‘raft trains’ indicated a NE to SW flow of MDG magma as it disrupted the country rock roof septa. The central tenet of their model was that MDG *fed* TBG by lateral flow.

In later times, recognising that the fabric in MDG was predominantly of a high temperature solid state type, Pitcher & Berger (1972) were less than enthusiastic about the flow model, and instead emphasised that the deformation in the pluton was imposed by simple regional squeezing (pure shear) of the cooling body. The sheeting mechanism and significance of the raft trains as disrupted roof septa were still upheld and the MDG pluton was regarded memorably as ‘a plexus of coalescing granite sheets’.

Hutton (1982) showed that the MDG lay in a sinistral shear zone of regional extent whose western edge defined the contact with the weakly deformed TBG. In this model, the TBG represents the final stage of the construction of the MDG when magma was emplaced into the weakly deformed wall of the shear zone. The TBG emplacement was facilitated by a locally N–S tensional domain created about the bowed flank of the shear zone. Later contributions (Hutton 1992) emphasised that the sheeted emplacement of the MDG was a feature shared by many other ‘shear zone’ granites worldwide.

The re-examination of the TBG by Price & Pitcher (1999), which reported the unpublished mapping of W. S. Pitcher (see also Price 1997; Fig. 2), made a significant contribution to the understanding of this body. The major breakthrough was the discovery of subtle internal contacts in a body previously regarded as largely homogeneous with only minor aplitic variants (Fig. 3). This observation led to a more sophisticated interpretation of the geometry of the TBG as an inclined, sheeted body (see Price & Pitcher 1999). Although now recognised as sheeted, the gently inclined or subhorizontal geometry of TBG is in stark contrast to the vertically orientated sheets of the adjoining MDG. Price & Pitcher (1999) saw this as a reason to consider the emplacement of the TBG as a separate body from that of the MDG but of the same magma type. They suggested that the TBG was emplaced from the north into the wall of a major magma-filled shear zone during the final stages of the shear zone development (cf. Hutton 1982).

From anisotropy of magnetic susceptibility (AMS) derived magnetic fabrics, Stevenson *et al.* (in press) have identified structural flow lobes in the TBG. From the consistent westward closure of these lobes and their consistent long axis orientations, these primary flow features indicated that the TBG magma flowed from east to west, i.e. from within the shear zone and the MDG (Fig. 4a). This has not only provided the first clear picture of viscous and pulsed magma emplacement, unambiguously indicating flow direction, but also proof that the TBG represents magma that was displaced from the MDG as Read (1958) and Pitcher & Read (1959) so clearly envisaged.

The confirmation that the MDG fed the TBG now allows a direct appraisal of the emplacement of the TBG. Following the conclusions of Stevenson *et al.* (in press), one can address the structure of the TBG and relate this to the development of the MDG (magma filled) shear zone. In particular, it allows us to focus on the conundrum of how the weakly deformed and cross cutting nature of the TBG can occur apparently contemporaneously with the structurally concordant MDG and its intense ductile deformation.

1.2. Fabrics and deformation

For what follows, it is necessary to make a nomenclature distinction between the different shear zone elements that are associated with the MDG and TBG. The NE–SW elongated MDG is contained within a major NE–SW trending shear zone, which extends beyond the pluton particularly to the north. This major feature will be referred to as ‘the MDG shear zone’ (Fig. 1). Although deformation is pervasive and fabrics are steep and trending NE–SW in the MDG, the strains increase markedly at the boundaries of the pluton and the fabrics are typically of a high temperature solid-state type. On the NW and SE margins of the pluton these high strain fabrics are parallel to the main NE–SW trending fabric seen in the interior regions. Hutton (1982) reported however that at the SW end of the pluton the marginal high strain zone turned south and ran *continuously* in a NNE–SSW orientation oblique to the main NE–SW fabrics in the MDG. This high strain zone separates MDG from TBG, and it and others like it are the subject of what follows. Where a distinction needs to be made, this latter structure will be referred to as ‘the TBG/MDG marginal shear zone or TBG/MDG boundary shear zone’ or words to that effect.

The distribution of solid- and magmatic-state deformation fabrics in the Trawenagh Bay Granite is shown in Figure 4b. The eastern margin of the granite is characterised by the boundary shear zone which displays a strong mylonitic fabric with a moderately to well developed composite S–C fabric (Fig. 5). Price (1997) describes deformed and extensively recrystallised feldspar and quartz grains that indicate subsolidus deformation here between 450–500 °C (Gapais 1989).

The zone may be divided into two areas. The first in the NE of the TBG is the area from Meenatotan to Meenderryherk (Fig. 6), where the E–W trending TBG–Thorr pluton contact swings to a NE–SW trend and becomes the MDG–Thorr pluton contact. The second is in the E of the TBG from Galwollie Hill to north of Croaghleconnel Hill, covering most of the contact zone between the TBG and MDG (Fig. 7).

In the Meenatotan to Meenderryherk area, a pervasive solid-state fabric is observed in all granite types. This fabric consists of a planar mineral fabric and two conjugate shear fabrics (sinistral and dextral) which form discrete centimetre-scale shear bands (Fig. 6a, b). These fabrics are hereafter referred to as S_1, S_s and S_d respectively. There is also a moderately developed lineation (L) in S_1. In the NE extremity of this area, the fabric is dominated by S_s, which trends NNE

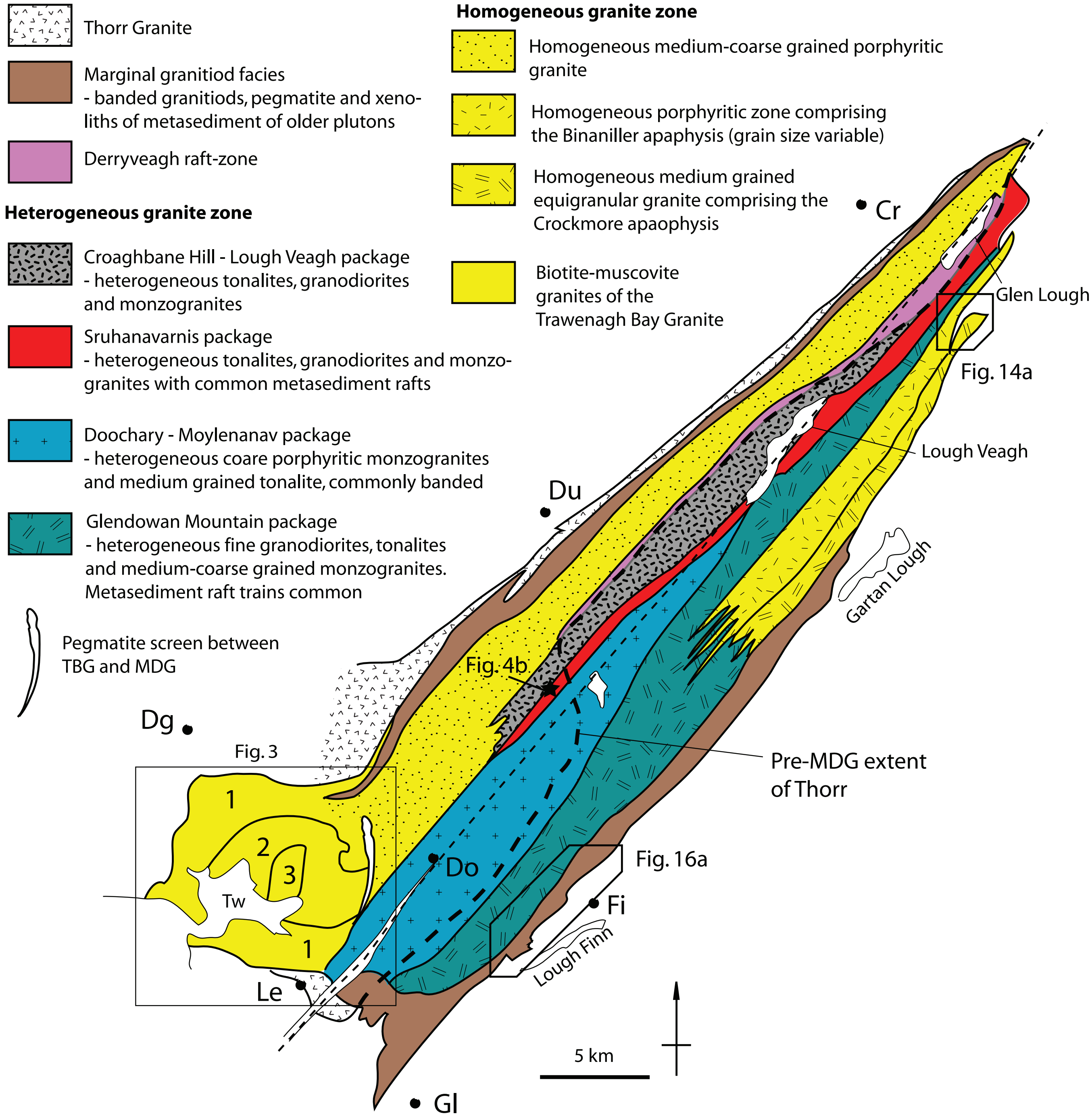


Figure 2 The internal units of the Main Donegal Granite from Price (1997), and the Trawenagh Bay Granite (TBG) after Price & Pitcher (1999). Abbreviations: (Dg) Dungloe; (Du) Dunlewy; (Cr) Creeslough; (Le) Lettermacaward; (Gl) Glenties; (Fi) Fintown; (Do) Doochary; 1, 2, 3=TBG G1, G2, G3 respectively.

and dips steeply W. S_1 is contact parallel and S_d is usually subsidiary to the others but evident nonetheless. S_d trends NE and dips moderately to steeply NW. L plunges SSW.

The preponderance of S_s, i.e. sinistral shear, is consistent with deformation that may be associated with the NW margin of the MDG sinistral strike slip shear zone and agrees with Hutton's (1982) observations. However, proceeding SW, S_d becomes more prominent and the fabric strikes E–W, following the contact. Along the E–W trending TBG–Thorr pluton contact, S_s and S_d are roughly equal and the deformation is coaxial (Fig. 6a, c). Thus, moving from the MDG to the TBG, the non-coaxial, sinistral dominated fabric evidently loses ground to coaxial deformation (Fig. 6c).

This deformation is also restricted in extent on either side of the TBG/MDG–Thorr contacts, rapidly dying out moving north, to the south and into the TBG. To the south the solid-state deformation, as it weakens, can be seen to overprint an earlier magmatic-state fabric in the TBG. It seems that the (solid state) MDG shear zone of Hutton (1982), rather than swinging from NE–SW to NNE–SSW along the TBG–MDG contact, diverts westwards and dies or tips out along the TBG/Thorr contact. (Fig. 6c).

In the second area, from Galwollie to Croaghleconnel, a similar composite solid-state fabric is once again encountered (Fig. 7a, b). Here S_1 is apparent, trends NNE–SSW in the east of the area and is steeply dipping or subvertical. Moving west, S_1 swings to a more NE–SW trend and dips steeply northwest. Continuing west, S_1 gives way gradually to a magmatic-state mineral alignment, which trends NE–SW. S_s is most obvious in the south of the area, dying out gradually until it is completely

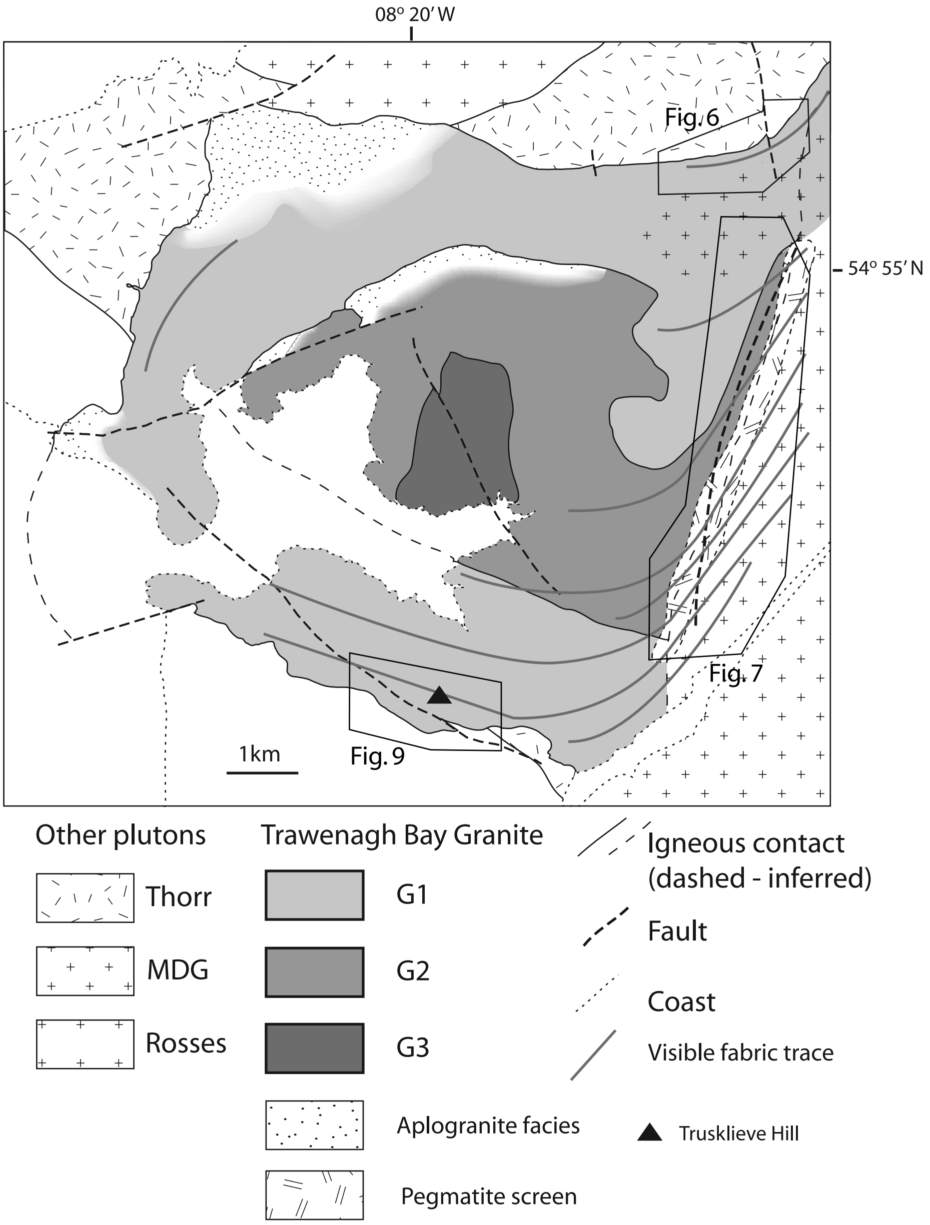


Figure 3 The Trawenagh Bay Granite after Price & Pitcher (1999) and Stevenson *et al.* (2007).

absent a few hundred metres north of Croaghleconnel Hill. S_d is everywhere either absent or weakly developed, trending E–W. L plunges ~45° consistently SW. This deformation is consistent with the observations of Hutton (1982) and Price (1997), except that the NNE–SSW solid-state high strain shear zone, described by Hutton (1982), is not continuous (Fig. 7c) and there is a gap here (in TBG G1) between Meenatotan and Croaghleconnell occupied only by NE–SW trending magmatic state fabrics (Fig. 8).

Similar solid-state deformation is also observed in places along the southern contact of the Trawenagh Bay Granite, particularly at the foot of Truskliev Hill (Fig. 9), where shear bands (both sinistral and dextral) are also visible in outcrop. The orientation of (antithetic) S_d describes bulk sinistral shear parallel to the gently N dipping southern contact of the Trawenagh Bay Granite. Additionally, three main 0·5–1 m-thick aplite sheets dipping WNW may be tension gashes in a crystallising magma, supporting a sinistral sense along this southern contact. Microscopically, here, feldspar grains are not as extensively deformed (remaining rigid relative to quartz), indicating deformation at ~500°C (Gapais 1989).

The rest of the Trawenagh Bay Granite shows almost no visible fabric and (except for subtle fabrics defined by AMS) the granite appears undeformed. The relatively restricted solid-state deformation dies out rapidly in central portions and any weak fabric is defined by the alignment of plagioclase and biotite phenocrysts. Microscopically, plagioclase is the main phenocryst phase (An_{18-24} after Price 1997) occurring as 3–15 mm-long elongate laths. Quartz and alkali feldspar occur interstitially; alkali feldspar sometimes as microcline. Quartz occasionally exhibits undulose extinction and closer to the eastern margin quartz subgrains are developed. Biotite occurs throughout the TBG, occasionally slightly kinked close to the eastern margin. Therefore, according to Paterson *et al.* (1989), any fabrics in the greater proportion of the TBG formed by magmatic to submagmatic flow (>500°C after Gapais 1989). Accordingly, the visible fabrics of the TBG represent the deformation of a crystallising magma up to a crystal content of around 70–80% (Vigneresse *et al.* 1996).

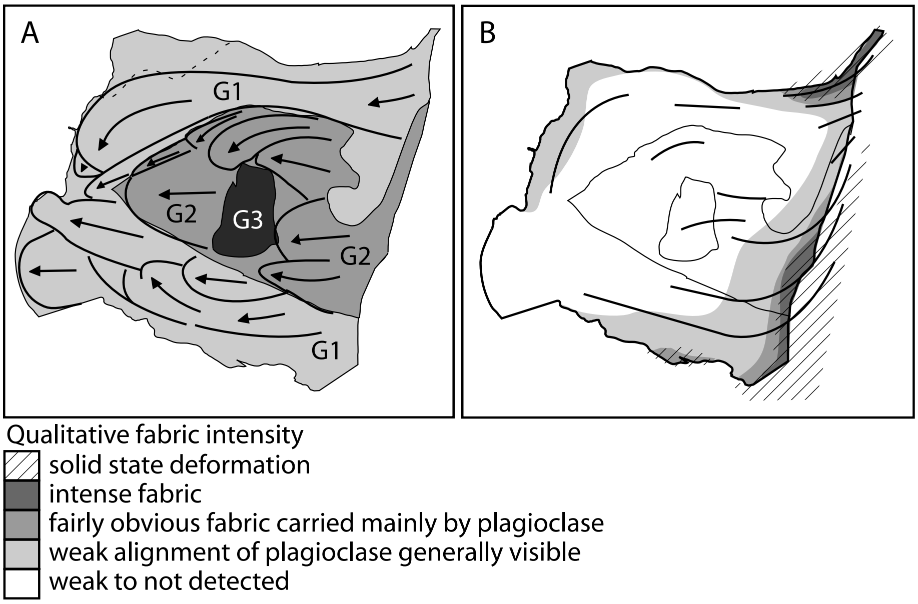


Figure 4 (a) Flow lobes and flow directions within the TBG taken from Stevenson *et al.* (2007). (b) Distribution and intensity of visible fabrics in the TBG. Fabric intensities are determined qualitatively. Solid black lines represent the orientation of the fabric trace on horizontal outcrops.

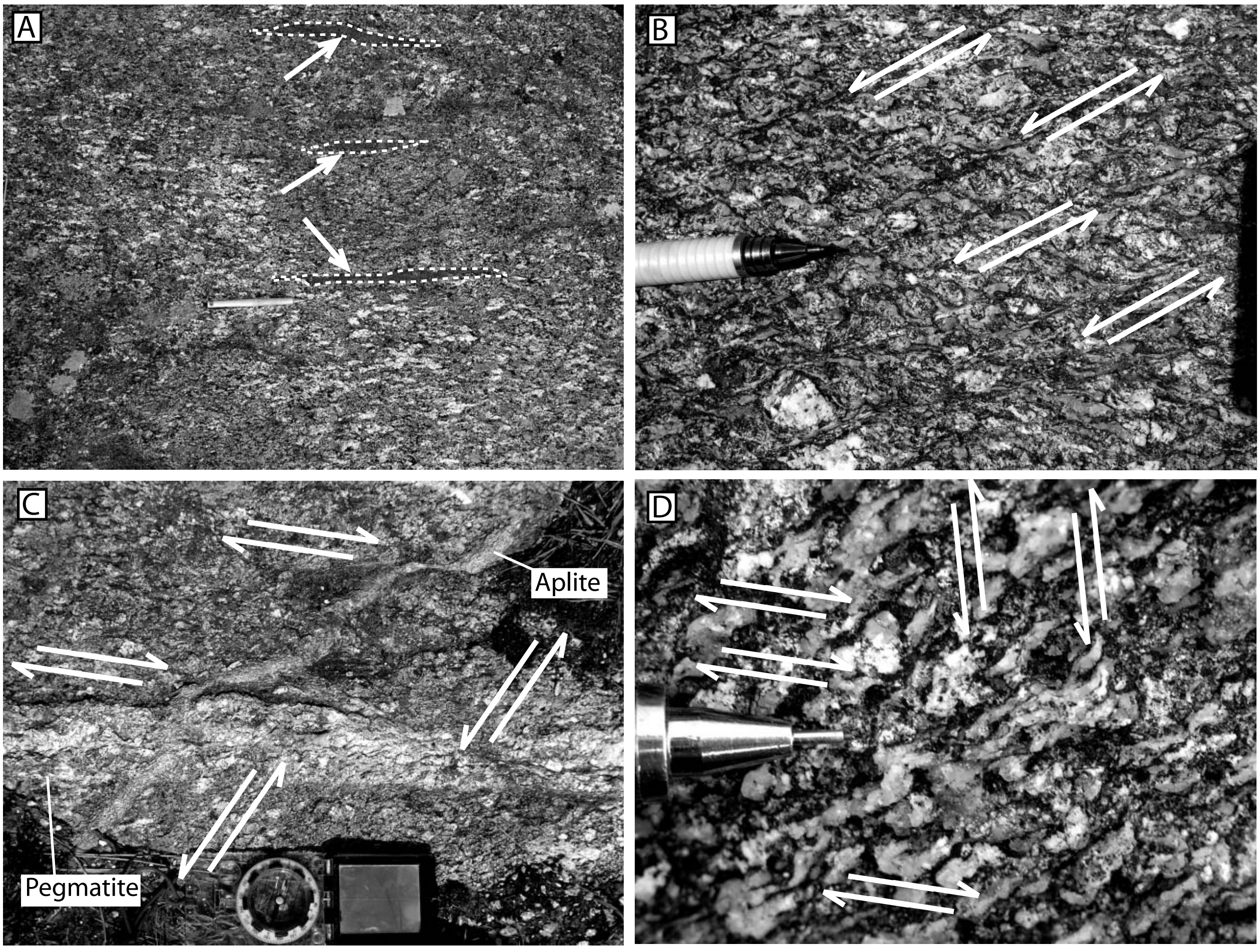


Figure 5 Field photographs showing examples of deformation at the northern and eastern margins of the TBG associated with the Main Donegal Granite shear zone: (a) Deformed mafic enclaves in porphyritic monzogranite flattened parallel to an intense fabric carried mainly by plagioclase phenocrysts. The pencil (for scale) is oriented roughly E–W; (b) Submylonitic MDG monzogranite close to the TBG–MDG contact. This mylonitic fabric is dominated by sinistral shear; (c) Protomylonitic monzogranite of the TBG–MDG transition in the NE of the TBG. A small late aplite vein is cut by dextral shears whilst the outcrop is pervasively affected by sinistral shear, most clearly demonstrated by a fairly well developed sinistral S–C fabric in the earlier pegmatite dyke. Note that the pegmatite is also slightly sinistrally offset about the small aplite vein. The compass (for scale) is oriented ENE–WSW; (d) Less intensely deformed monzogranite of the TBG where dextral and sinistral shears are roughly equally developed.

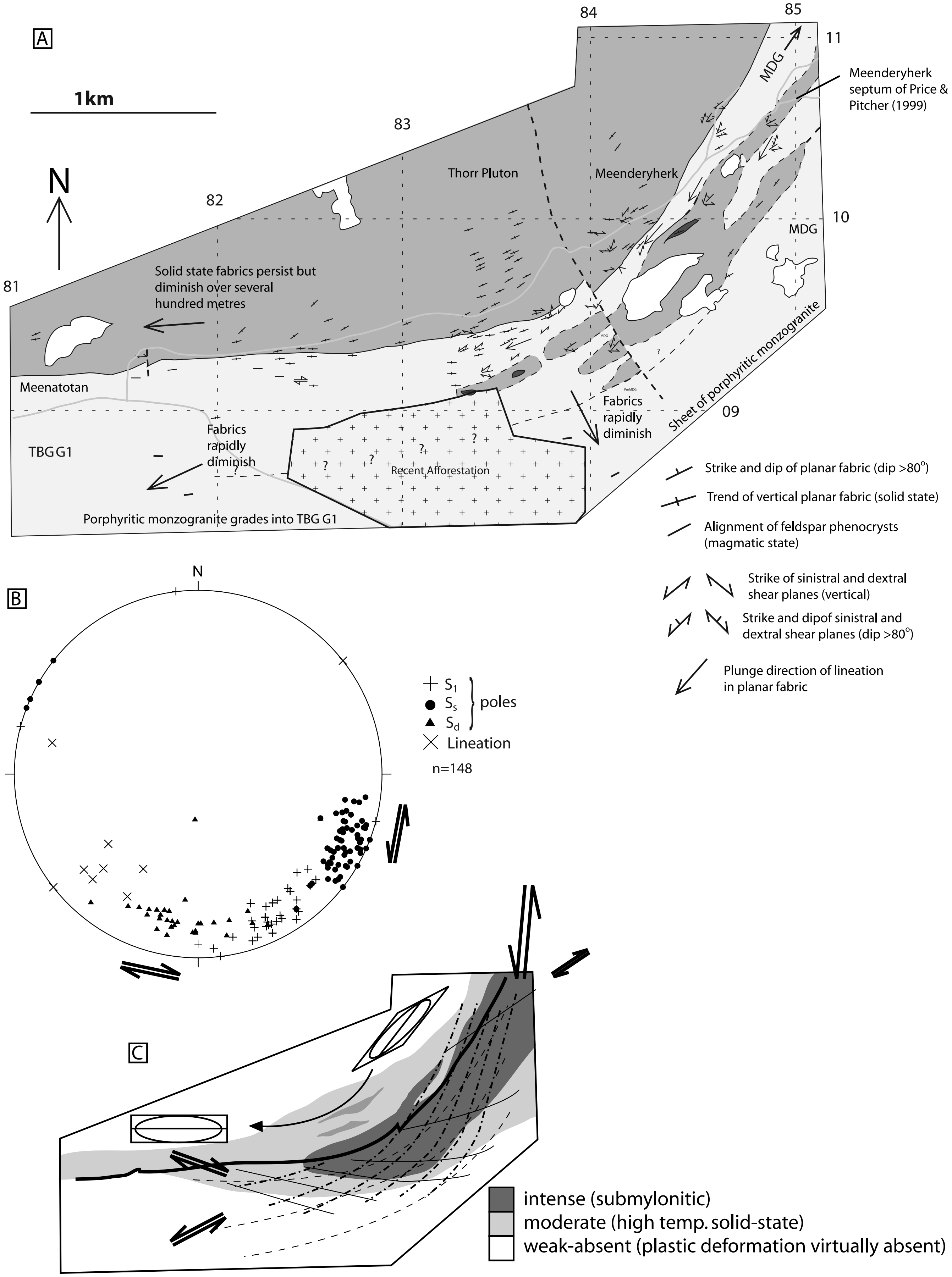


Figure 6 (a) Map of the Meenatotan–Meenderyherk area. (b) Equal area lower hemisphere stereonets of lineations and poles to all planar fabrics. (c) Summary sketch map of the fabric distribution and intensity in the Meenatotan–Meenderyherk area. Key represents the intensity of solid-state fabrics.

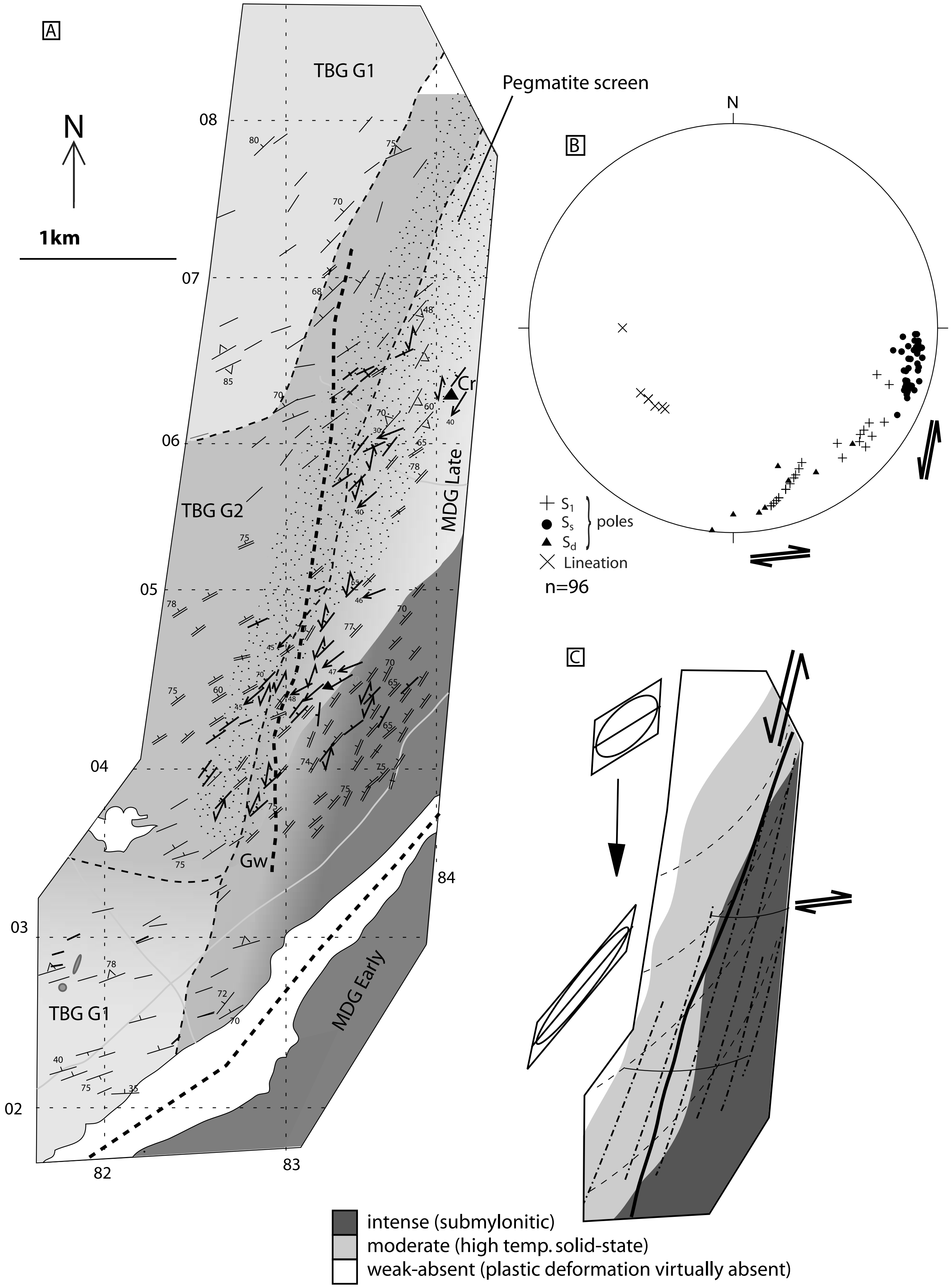


Figure 7 (a) Map of the Galwollie Hill–Croaghelconnell Hill area; (Cr) Croaghelconnell Hill, (Gw) Galwollie. (b) Equal area lower hemisphere stereonets of lineations and poles to all planar fabrics. (c) Summary sketch map (as in Fig. 6) of the fabric distribution and intensity in the Meenatotan–Meenderyherk area.

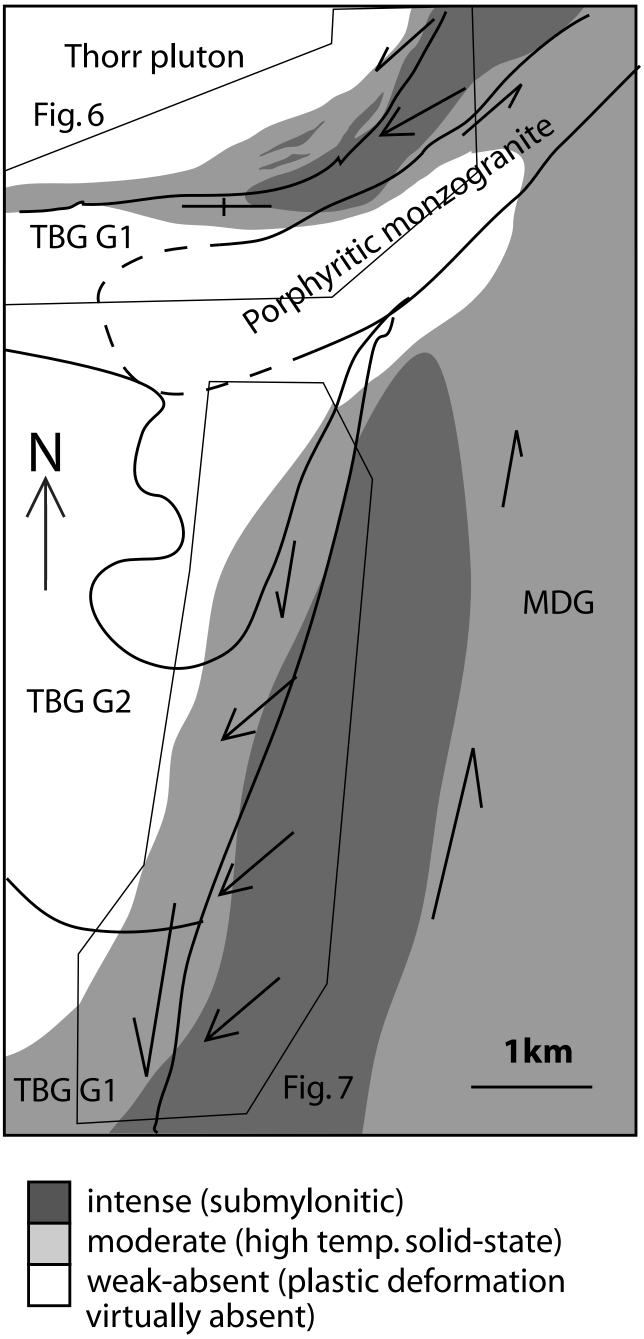


Figure 8 Summary of Figures 6 and 7 showing the distribution of solid-state fabrics in the eastern margin of the TBG.

1.3. Deformation of the country rocks and discordant to concordant TBG contacts

In contrast to the concordant MDG, the TBG cross cuts its surrounding country rock, which includes the Thorr Pluton, the G1 unit and minor intrusions of the Rosses Complex and a succession of Lower Dalradian metasediments and metadolerites. As described above, the TBG northern contact is concordant with the MDG shear zone fabrics in the NE corner. As these fabrics diminish towards the west, the TBG contact becomes gently north-dipping. The trend of the contact is still roughly parallel with the strike of the weak, steeply north-dipping fabrics in the Thorr and Rosses plutons, which, although of magmatic-state, have been attributed to MDG shear zone related deformation (Hutton 1982).

Stevenson (2004) described fabrics and deformation in the Thorr pluton due west of the northern contact of the TBG on the shore of Dungloe Bay in the vicinity of Toberkeen (B 752 107) that are conspicuously of higher strain than surrounding granites (Fig. 10a, b). These fabrics are cut by later microgranite sheets of the Rosses complex, which capture and rotate xenoliths of Thorr granodiorite (Fig. 10c). The microgranite sheets are then affected by a later high temperature solid-state deformation that imposes a steep E–W fabric and discrete metre-scale shear zones (Fig 10a, c, d, e). It is suggested that these Thorr fabrics represent an extension of an early phase of the MDG shear zone that begins to follow the northern contact of the TBG in Meenatotan. The high temperature solid-state deformation is coeval with later stages of the MDG shear zone.

The western contact of the TBG cuts across structures, including major pre-granite folds in metasediment and E–W trending fabrics and structures in the Thorr pluton, the latter associated with the E–W-trending MDG shear zone related fabrics parallel to the northern contact. The southern contact of the TBG is parallel with WNW–ESE-stretching lineation (consistent with MDG shear zone related deformation according to Meneilly 1982). The foliation associated with this stretching lineation is however steeply dipping, whereas the TBG contact dips gently N. Thus the TBG is completely concordant to country rock fabrics adjoining the MDG, then as these fabrics diminish moving away from the shear zone, the TBG northern contact becomes gently dipping while the strike remains parallel to stretching. Then finally, the western contact is completely cross cutting (Fig. 11).

Previously unreported in Lettermacaward is a high temperature solid-state shear zone affecting the country rocks, trending roughly parallel to the strike of southern contact of the TBG, lying roughly 1 km from this contact. Marked by intense stretching lineations in a ~5–20 m wide zone, this shear zone creates a sinistral offset in the metasediment and metadolerite boundaries and of the earlier Mulnamin Anticline in Lettermacaward (Fig. 12) (see Meneilly 1982 for details of the Mulnamin Anticline). These shear zone fabrics are continuous with MDG shear zone-related fabrics in the Thorr pluton.

1.4. Internal variation and relative timing of emplacement

Price & Pitcher (1999) reported three internal units within the TBG: G1 – biotite monzogrante; G2 – biotite-muscovite monzogranite; and G3 – aplitic biotite-muscovite microgranite. These were identified principally from subtle discontinuous gently dipping contacts, often indicated by the presence of hanging wall aplites and pegmatites. These units gave the TBG a roughly concentric and normally zoned outcrop pattern (Fig. 3).

Mainly from crosscutting relationships on Galwollie Hill (grid ref. G 830 038), Price (1997) and Price & Pitcher (1999) concluded that the TBG was emplaced after the MDG. However, considering the multiply sheeted nature of both of these plutons, only the observation that the MDG early facies was emplaced before the TBG G1 can be confirmed here. We report that xenoliths of MDG early facies (tonalite and diorite) occur in the TBG G2 in the southeastern region close to Galwollie Hill, as do xenoliths of TBG G1. Further to the N only sheets of aplitic monzogranite (TBG G3 or G2) can be seen to cross cut normal (aphyric) and porphyritic monzogranite (TBG G1 or MDG later facies), perpetuating the ambiguity in timing between later MDG and early TBG (Fig. 11).

The flow lobes described by Stevenson *et al.* (in press) from AMS measurements define smaller scale divisions within the TBG (see Fig. 4a). The flow lobes by and large seem to be deformed or cut by the NNE–SSW MDG shear zone, but the northern contact of the TBG (and the northern most flow lobe) seems to be controlled by the NE–SW MDG shear zone. In the

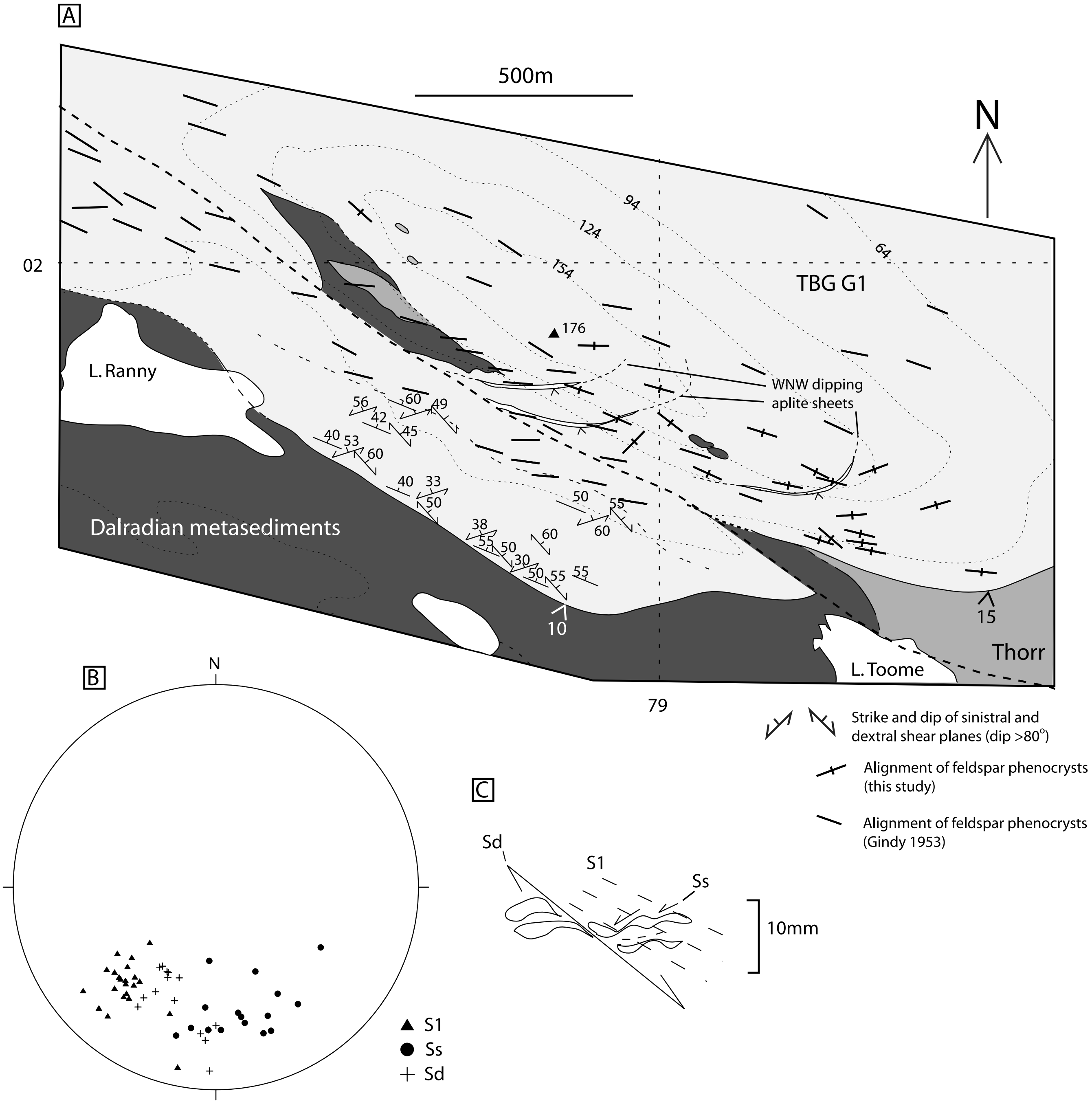


Figure 9 (a) Map of the Trusklieve Hill area (contours and summit height in metres). (b) Equal area lower hemisphere stereonet of poles to planar fabrics. (c) Sketch (taken from a field sketch) demonstrating the relationship between the main planar fabric (S_1) and sinistral (S_s) and dextral (S_d) shear planes.

NE of the TBG, in the gap in the NNE trending marginal solid state shear zone, a sheet of porphyritic monzogranite extends continuously into the TBG from a package of similar porphyritic monzogranite in the MDG (Fig. 8). This sheet corresponds to one of the flow lobes of Stevenson *et al.* (in press) and rapidly dissipates or grades into the TBG G1. It seems to represent MDG magma ‘spilling’ across the gap in the MDG shear zone from MDG into TBG.

1.5. The development of fabrics and the timing of emplacement

The development of magmatic- and solid-state fabrics in the TBG and MDG associated with the MDG shear zone suggests that the shearing was synchronous with, and continued after, crystallisation of these plutons (Hutton 1982). Other workers have disputed the timing of the MDG shear zone and magma emplacement, discounting magmatic deformation as shear zone related and contending that the shear zone must be later than any magma emplacement (Vernon & Paterson 1993; Paterson & Vernon 1995).

Price (1997) reported highly deformed xenoliths of Thorr granodiorite in the MDG, which are disoriented with respect to each other. In addition to this, in the Meenatotan to Meenderryherk area (Fig. 6), the Thorr pluton exhibits intense high temperature solid-state mylonitic fabrics consistent with a sinistral shear zone, and is cut by TBG/MDG granite of visibly lower strain, proving that this deformation commenced before, or at latest during the emplacement of, the MDG. The flow lobes described by Stevenson *et al.* (in press) were guided initially (at least in their exit from the MDG) by the E–W-trending shear zones in Meenatotan and Lettermacaward. These shear zones therefore formed relatively early, although high temperature solid-sate deformation evidently continued post emplacement, probably concentrated along granite contacts. The NNE–SSW trending shear zone in the Galwollie–Croaghelconell area deforms and deflects the fabrics that are continuous with the flow lobes (it effectively deflects the tails of the lobes) and was therefore formed after the emplacement of the TBG. The NNE–SSW trending shear zone formed during the later stages of the magma-shear zone system probably guided by an underlying structure and helping to define a boundary between the TBG and MDG (we will return to the evidence for this underlying structure below, see section 2.1.1).

1.6. The emplacement of the TBG

Price & Pitcher (1999) showed that the TBG was a three unit centred pluton which dipped north but had a steep western contact. This shape, together with the concentric nature, suggested a broadly laccolithic structure. Strong deformation in this pluton is concentrated around its northern, southern and eastern margins and is only weakly deformed internally. These observations are in marked contrast to the adjoining MDG, with which TBG shares a major magmatic facies comprising steeply inclined NE–SW trending sheets and pervasive intense coplanar fabrics. Stevenson *et al.* (in press) have shown that the TBG contains flow lobes which are orientated E–W and consistently close towards the west. This indicates that flow into the TBG was from the east and from within the shear zone. Additionally, the earliest and major unit of TBG (G1) can be traced, as the root of a major flow lobe, directly into a major MDG monzogranite sheet. The TBG therefore represents MDG magma that has flowed out of the shear zone and into the adjacent relatively undeformed wall rocks. These findings confirm the central tenet of the model of Pitcher & Read (1959): that the Trawenagh Bay granite magma was fed by flow out of the Main Donegal Granite.

The presence of high temperature solid-state shear zones has been described along the northern and near the southern margin of the TBG, which deform both the pluton and its country rocks. We regard these as splays from the NNE–SSW part of the MDG shear zone. As they die out from east to west, so we go from the concordance (see Fig. 6) that is so much a characteristic of the MDG to the complete discordance achieved at the western contact of the TBG (cf. Fig. 3). It is suspected that these high temperature solid-state shear zones originated much earlier in the emplacement of TBG and it is suggested that the initial exit of TBG magma from the MDG shear zone was guided by these splays. As will be seen in the overall model, it is likely that TBG emplacement commenced when the splays developed from the NNE–SSW high strain zone that defines the western edge of MDG: the edge that was to become the MDG/TBG ‘contact’. As the westward splays developed from this NNE–SSW shear zone, a gap (Meenatotan to Croaghleconnell), formed within it through which, at the current exposure level, TBG G1 magma flowed westwards out of the shear zone and the parent body (Fig 13).

The internal structure of TBG G2 is very similar to that of G1 and it is likely to have been emplaced in a similar manner; however whilst there is no *direct* petrological analogue of TBG G2 in the MDG (at least from the existing geochemical work of Price 1997) and G2 appears to truncate against the latter at a pegmatite screen along the NNE–SSW shear zone, we suspect that G2 is strongly genetically connected with the widespread MDG monzogranite facies (see below), but perhaps not directly at the current exposure level. Likewise with the small volume TBG G3; Stevenson *et al.* (in press) failed to find a consistent magnetic fabric in this unit and concluded that this was probably the roof, or laccolithic cupola, of the third sheet.

2. A new model for the emplacement of the Donegal Batholith

2.1. A summary of new findings since 1982

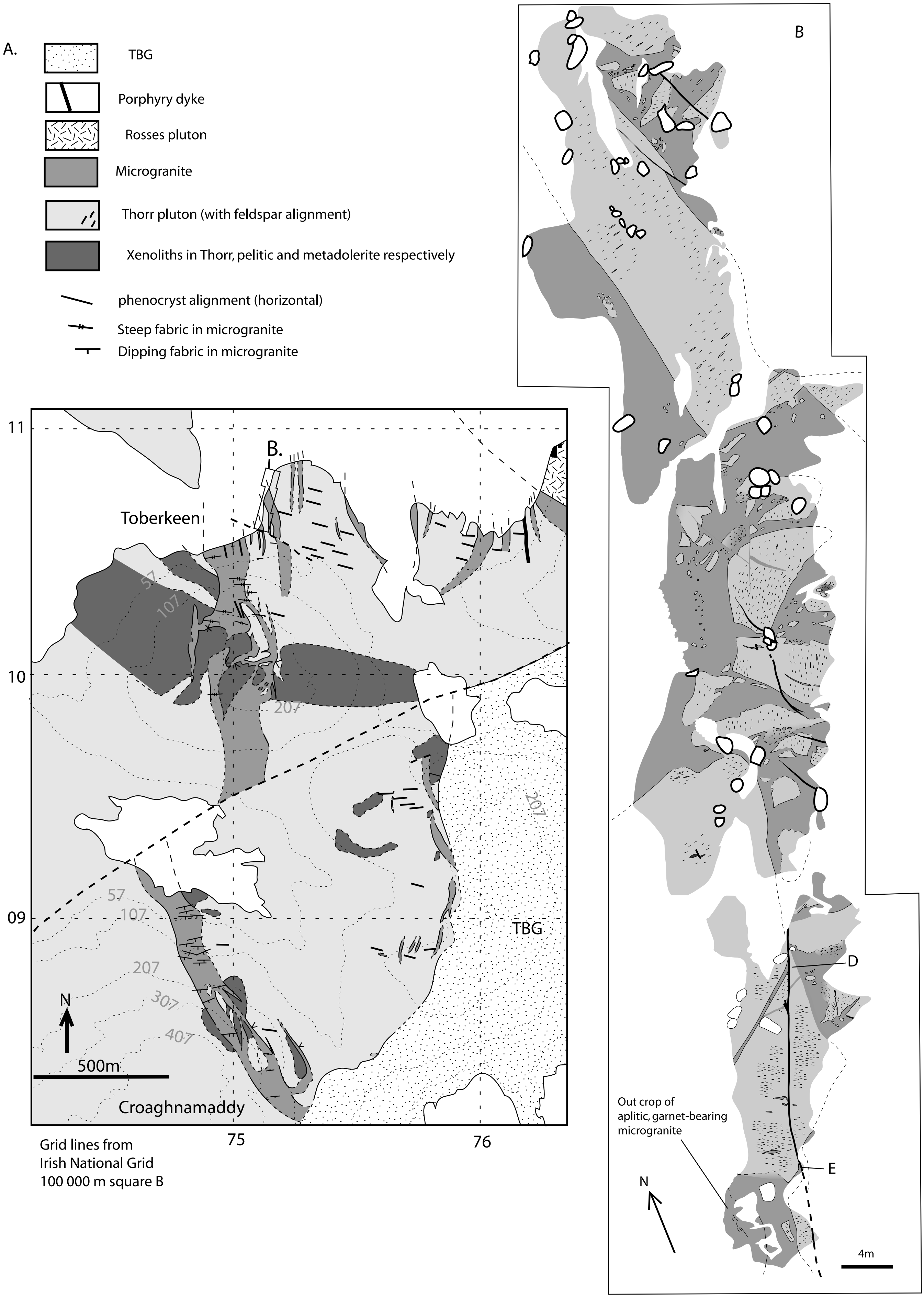
In addition to the findings discussed in relation to the TBG, the key contributions to emplacement research on the Donegal Batholith since Hutton (1982) are as follows:

2.1.1. The Major N12°E lineament. Accurate determination of the displacement on late Caledonian sinistral faults in Donegal and restoration of this displacement showed that six out of the eight Donegal granites form a N12°E alignment (Fig. 1) (Hutton & Alsop 1996). Most of the mantle-derived appinite suite (Pitcher & Berger 1972) associated with the Ardara pluton is located along this as well. This alignment of granite plutons and the appinite suite also coincides with a major strike swing and facies changes in the Dalradian sediments; a feature that is the Irish expression of the Newfoundland–Labrador promontory separated from the latter by the opening of the N Atlantic. Hutton & Alsop (1996) considered that this lineament was the upper crustal expression of a deep fault in the pre-Dalradian basement that separated originally differently oriented Laurentian shelf segments; perhaps originally a transform fault. This ‘bend’ affected Dalradian sedimentation patterns, Caledonian deformation patterns and the axial deep fault provided a siting mechanism for the Caledonian plutons.

2.1.2. Detailed mapping of the Main Donegal Granite. Price (1997) (see Fig. 2) mapped parts of the MDG at various scales from 1:101000 to 1:100 and extracted considerable detail from exceptionally well exposed glacial pavements (e.g. Fig. 14). A general emplacement sequence, repeated throughout the pluton, is of four main intrusion phases (ignoring late stage microgranite, aplite and pegmatite veins): (1) early fine grained granodiorites; (2) tonalite; (3) later coarser grained granodiorite; and finally, (4) voluminous monzogranites. Pitcher & Read (1959) first proposed the steeply inclined sheeted nature of the pluton, with the original country rocks displaced by sheet dilation and now preserved as raft trains. Remapping of the critical NE sector (e.g. Fig. 14) confirms the origin of the raft trains as sheet separators, traced into country rock septa in the gently northeastern plunging roof and thence into the country rock stratigraphy itself. Moving SW in the pluton, the raft trains splay apart as the pluton widens, consistent with the idea of progressive wedging apart of the country rocks and increased magmatic dilation in that direction.

Price (1997) recorded considerably more complexity within the pluton than had hitherto been appreciated. Seven major subdivisions of sheeting (‘packages’) were described that can be broadly divided into two types; early heterogeneous sheets and later homogeneous sheets (see Fig. 2). The heterogeneous sheets usually contain all of the four petrological types and are typically very complicated, with the phases frequently intruding on sub-metre scales. On a very broad scale however, the heterogeneous sheets occupy central, medial parts of the pluton, whereas the later homogeneous (monzogranite) sheets occur on the NW and SE sides adjacent to the country rocks. Price (1997) saw the evolution of the centrally located sheets as the progressive intrusion of early dykes into country rock and older units of the Donegal Batholith. Subsequent intrusion of tonalities, further granodiorites (mainly as numerous small scale intrusions) and then the larger monzogranite sheets caused dilation of the entire body with time (Fig. 15).

2.1.3. The Thorr Pluton. McErlean (1992) showed that the early syn-magmatic foliation of this granite (in areas away from the strong deformation associated with the MDG) was


A.
TBG
Porphyry dyke
Rosses pluton
Microgranite
Thorr pluton (with feldspar alignment)
Xenoliths in Thorr, pelitic and metadolerite respectively
phenocryst alignment (horizontal)
Steep fabric in microgranite
Dipping fabric in microgranite
11
10
09
75
76
B.
Toberkeen
57
107
207
307
407
TBG
N
500m
Croaghnamaddy
Grid lines from
Irish National Grid
100 000 m square B
B
D
E
Out crop of
aplitic, garnet-bearing
microgranite
N
4m

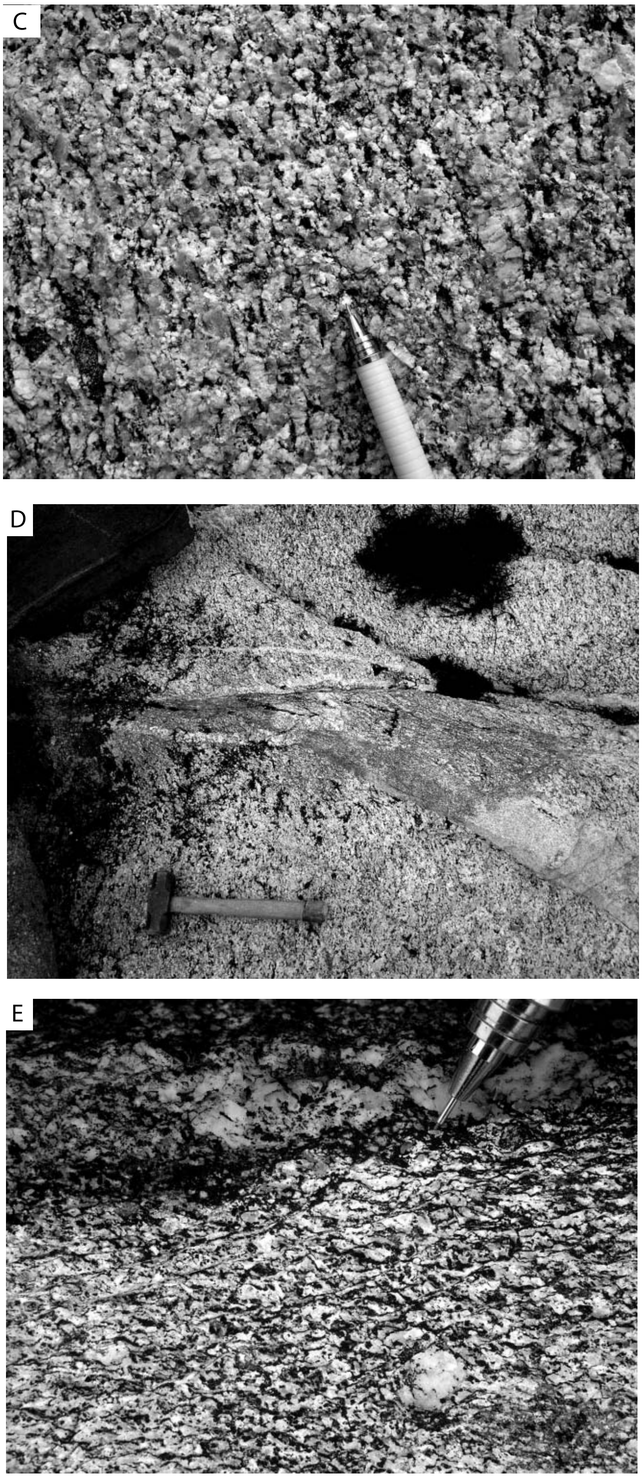


Figure 10 (a) Map of the area directly to the NW of the TBG in the vicinity of Toberkeen (see Fig. 1). Gridlines from the Irish National Grid square B. (b) Detailed map (location indicated in part a) of a microgranite sheet intruding Thorr tonalite and rotating this fabric. Location of photos in parts (d) and (e) are indicated. (c) Field photograph of typical fabric seen in Thorr granodiorite and tonalite outcrops. (d) & (e) Field photographs demonstrating that the microgranite sheeting is then affected by late high temperature solid-state deformation.

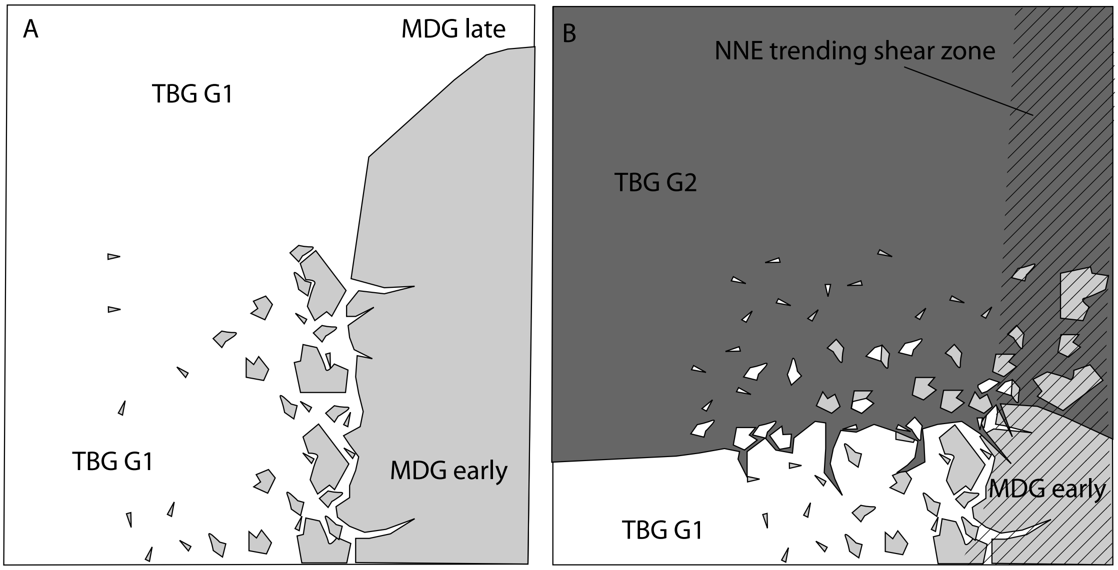
associated with low strains and sinistral shear on northerly trends with a shallow plunging transport lineation. Many of the contacts of the pluton, are also associated with well developed (although quantitatively low) sinistral shear; this is particularly the case with the north trending eastern contact in which the sinistral deformation is on northerly trends. In addition we note that Whitten (1957) had recorded that there are several major E–W-trending zones of strong (cataclastic-crystal plastic) deformation that cut and deflect the magmatic state fabric in a sinistral sense in the northern part of the pluton.

Pitcher & Read (1959) and Pitcher & Berger (1972) first noted and subsequently discussed the sheet of the Thorr pluton that extends along the NW margin of the MDG and the significant volume of Thorr granite xenoliths that occur within the MDG to the SE of this. They referred to this collective grouping of Thorr granite material in MDG as the 'Thorr prolongation'. Hutton & Alsop (1996) and Price (1997) reconstructed the geometry and extent of all Thorr material within the MDG (see Fig. 2). Running the entire length of the MDG shear zone, this prolongation has uniformly much higher strains than surrounding MDG lithologies. The present authors interpret this to mean that this material has been in the shear zone for a longer period than the MDG, thus implying that the shear zone initiated before emplacement of MDG units. The step on the original southern margin of the Thorr prolongation may indicate that it initiated as a pull apart in the MDG shear zone (Price 1997). It is also worth noting that the largest volumes of early granodiorite and tonalite bodies in the MDG are located next to this Thorr feature: consistent with the idea that a further pull-apart on this step initiated the intrusion of the MDG.

2.1.4. The Carbane Gneiss. This small enigmatic intrusion, first described by Grenville Cole (1902), occurs on the S side of the MDG as a series of slivers along a NNE trending fault that displaces the early Knockateen Slide by about 8 km (see Fig. 1). The gneiss has long been regarded as belonging to the Thorr pluton, even though it appears to be entirely separated from the Thorr prolongation in the MDG. It is intensely deformed by sinistral high temperature solid-state deformation. The fault that it lies along can be traced to the contact of the MDG where, although it brecciates the granite, it does not displace it (Price 1997). Thus the Carbane Gneiss, as part of early Thorr material, occupies a narrow shear zone that entirely predates the shear zone deformation of MDG age. Although untested geochemically, this is consistent with the Thorr–MDG-shear zone timings noted in the previous paragraph.

2.1.5. The Ardara Pluton. This pluton, which has attracted worldwide attention in the debate on ballooning versus diapirism in granite emplacement, was remapped by Molyneux (1997) following the earlier work of Akaad (1954) and Holder (1979) (see Molyneux & Hutton 2000). Of regional tectonic significance was the discovery of a NE–SW-trending sinistral shear zone along the southern boundary of the pluton. Fabric studies of Molyneux & Hutton (2000) revealed that although much of the sinistral strain in this zone occurred as the granite cooled past its solidus, there was also evidence of magmatic state sinistral shear, implying that the shear zone was active during emplacement. This shear zone increases in strain to the NE, crosscuts the NNE-trending shear zone that separates the TBG and MDG and runs into the NE–SW-trending high strain edge on the SE side of the MDG (see Fig. 1). This continuation into the MDG shear zone led Molyneux & Hutton (2000) and Hutton & Siegesmund (2001) to propose that the Ardara pluton magmas were injected up (ascended) along the shear zone and then bled off into the southerly inclined country rocks to the north forming a tongue or proto sill. This initial intrusion subsequently inflated as a balloon in that location.

Price (1997), in his detailed mapping along the SE side of the MDG, has confirmed the observations of Cheeseman (1956 in Price 1997 and Pitcher & Berger 1972)) and Pitcher & Berger (1972) that xenoliths of Ardara pluton G1 (the porphyitic



Stage 1 - emplacement of TBG G1/MDG late

Stage 2 - emplacement of TBG G2

Figure 11 Diagram (not to scale) representing the development of the observed relationship between TBG G2, TBG G1, MDG late and MDG early (see Fig. 7). (a) The initial stage when TBG G1 (continuous with the MDG early facies) intrudes and stopes the MDG early facies. (b) The second stage is when TBG G2 intrudes and stopes both. These are then affected by the NNE trending shear zone (see sections1.5 and 2.2.1).

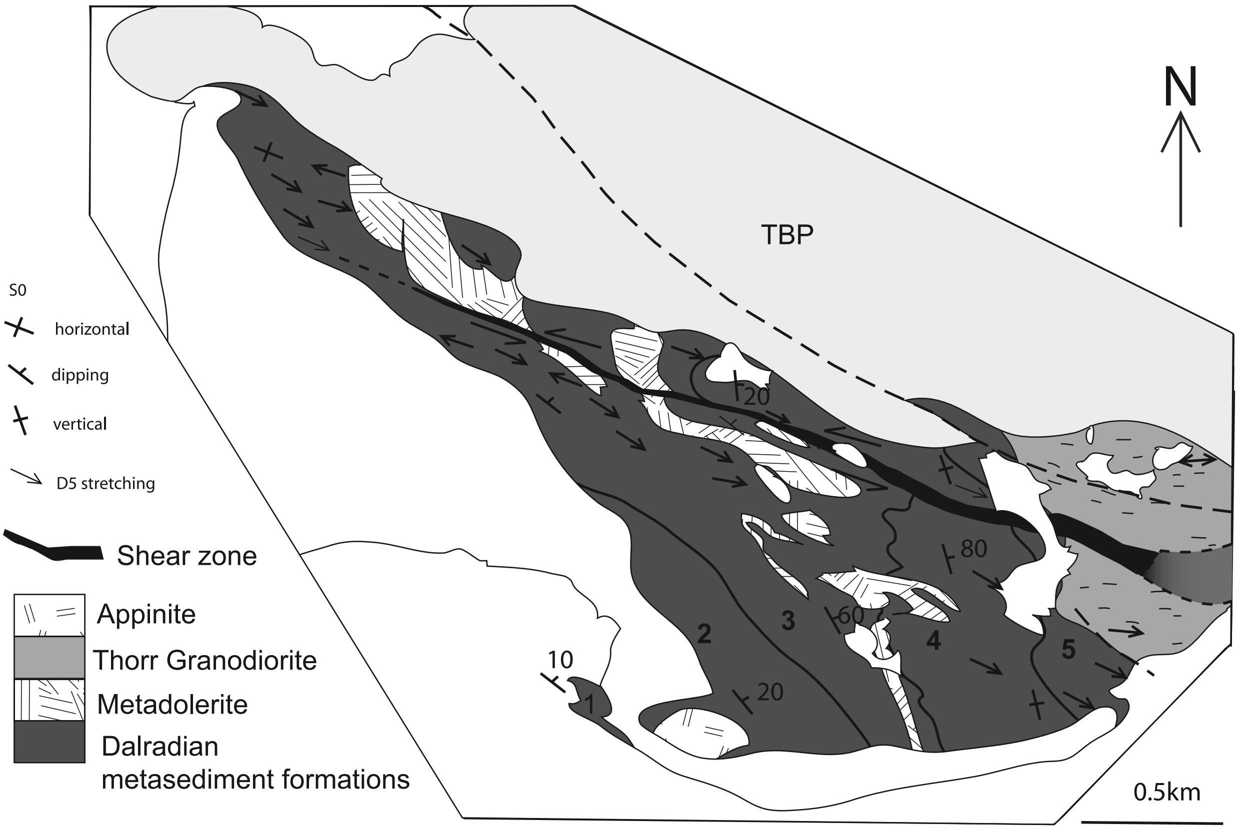


Figure 12 Map of the Lettermacaward area showing a summary of the bedding structure of the Dalradian metasediment formations including D5 stretching lineations (1=Ards Quartzite; 2=Sessiagh–Clonmass Formation; 3=Lower Falcarragh Pelite; 4=Falcarragh Limestone; 5=Upper Falcarragh Pelite). Shear zone related fabrics in the Thorr Granodiorite and the extent of the Lettermacaward shear zone are shown.

tonalite–quartz diorite) occur within the MDG along its southern margin directly along strike from the tail of the Ardara pluton as far as Carbat Gap, a distance of ~13 km (Fig. 16). Importantly, Price observed that the state of strain in these xenoliths is far higher than in the surrounding MDG material. Price also discovered a 100 m section of the tonalite in contact with pelitic country rocks: thus, an original (pre MDG) intrusive contact is preserved in that location. In one locality, Ardara G1, although exhibiting strong sinistral shear zone related fabrics, cross cuts a shear zone fabric (late F_6 folds) in the pelitic country rocks (grid ref. B 930 187 after Price 1997). These observations are taken to mean that the tail of the Ardara pluton was in part an original feature, emplaced into an active shear zone, which continued its movement right

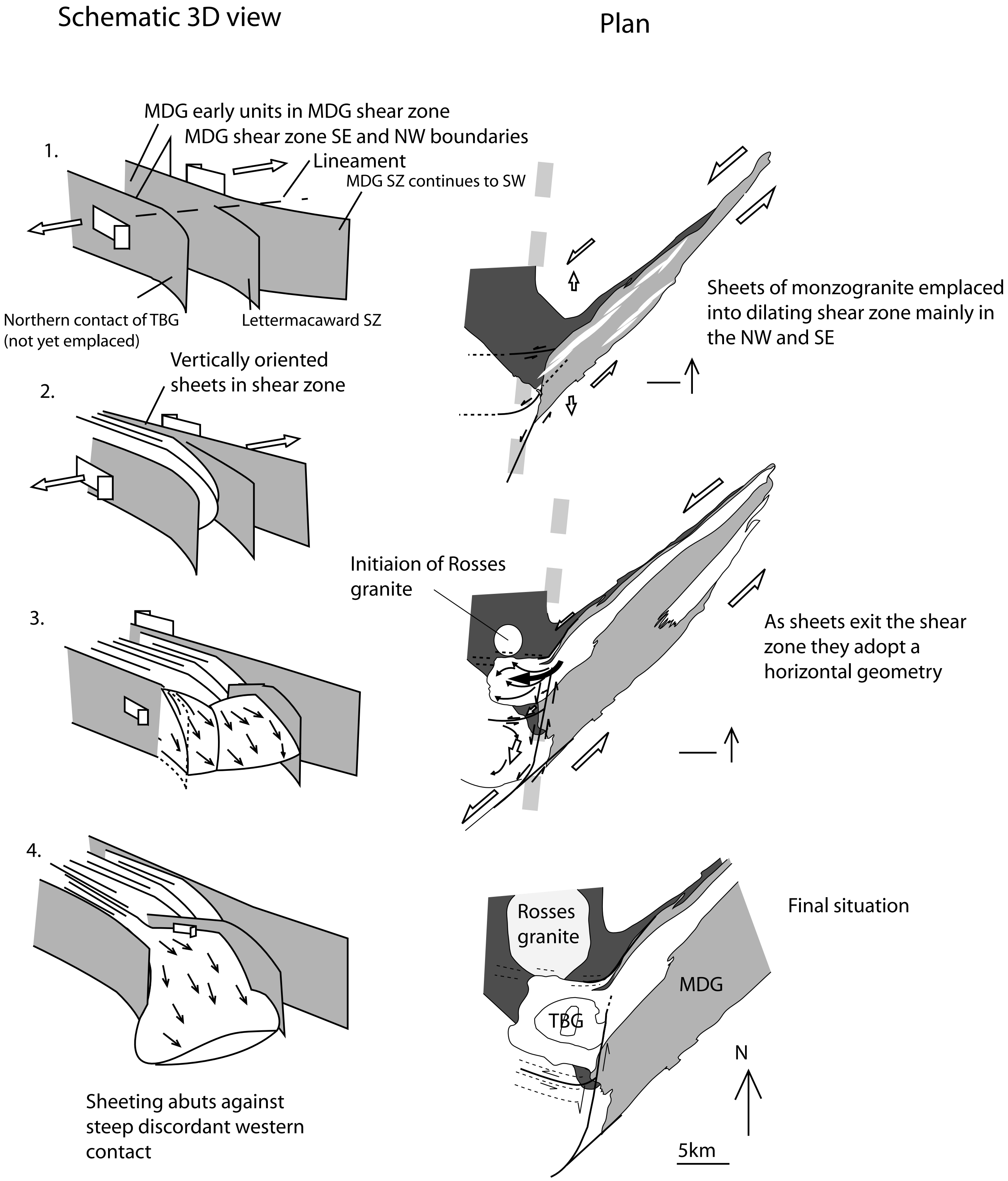


Figure 13 The emplacement of the Trawenagh Bay Granite. Stage 1: early units of the MDG emplaced within the main NE trending shear zone, minor splays propagate west of the N 12° E lineament; Stage 2: sheets of later MDG units initially guided by these splays exit the main shear zone; Stage 3: as magma migrates further from the shear zone and the sheets amalgamate, the emerging TBG adopts a horizontal geometry, and shearing has switched to the NNE trending boundary between the TBG and MDG and propagates south to north; Stage 4: the final situation, the TBG thickens as a further sheet – G2 – is emplaced and it abuts against a steep western contact.

through to the end of the shear zone movements that accompanied the youngest granite of the MDG. Thus once again a pluton (in this case the Ardara) has occupied the shear zone before significant volumes of MDG material were emplaced into it.

2.1.6. The Rosses Pluton. Stevenson (2004), using AMS measurements, discovered a fabric in the Rosses pluton that had a contact parallel planar component (in agreement with microscopic fabrics observed by Pitcher 1953a) with a linear component disposed E–W (Fig. 17a). Likening this E–W trend

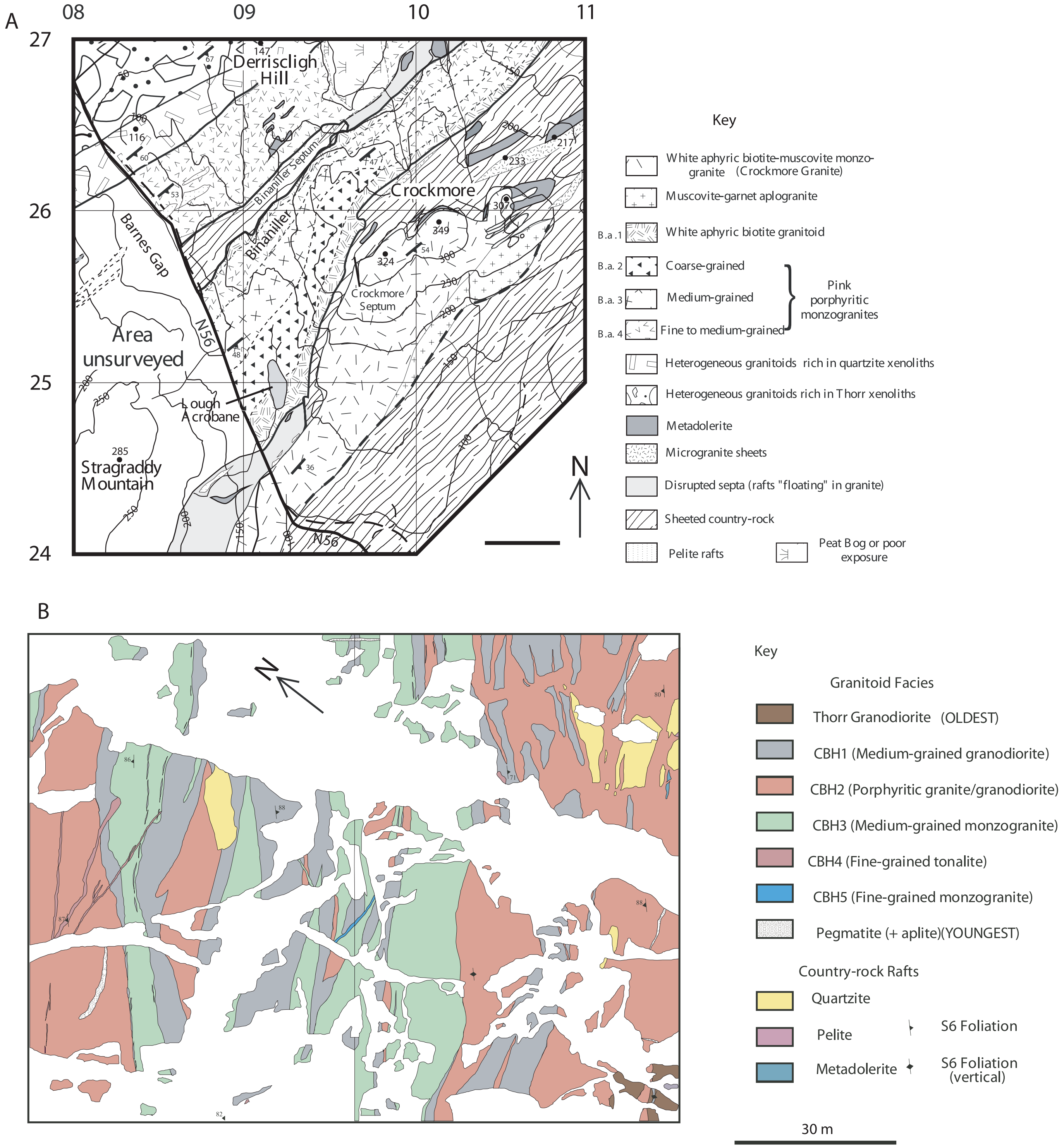


Figure 14 Examples of the various scales of sheeting in the MDG from Price (1997) (see Fig. 2): (a) Granite sheets and country rock septa in the vicinity of Crockmore in the NE of the pluton. Grid lines from the Irish National Grid square G; (b) Detailed mapping of small-scale sheeting on Crobane Hill.

to the dominantly E–W fabric of the TBG that represented E to W inflow (Stevenson 2004; Stevenson *et al.* in press; and present paper), Stevenson (2004) inferred the same inflow direction for the Rosses pluton.

Lateral inflow is inconsistent with the cauldron subsidence emplacement mechanism of Pitcher (1953a). Therefore, Stevenson (2004) preferred a laccolithic style emplacement. With this E to W emplacement direction, we can now tentatively connect the Rosses pluton to the MDG and, given the similarity of the monzogranites in the MDG, TBG and Rosses plutons, suggest a similar shear zone origin with a connecting feeder from the MDG westwards below the present surface, beneath the Thorr–Crovehy area, rising up into the Rosses laccolith (Fig. 17b).

2.2. Discussion

In summary, the key findings and outcomes from emplacement research in the Donegal Batholith since Hutton (1982) include: (1) the detection of a N12°E lineament (Hutton & Alsop 1996); (2) a detailed mapping of the MDG (Price 1997); (3) the interpretation of Thorr and Ardara granite material existing in the shear zone before the MDG was emplaced (Price 1997); (4) multiple shear zones associated with the Adrara, Thorr and TBG plutons (McErlean 1992; Molyneux & Hutton 2000;

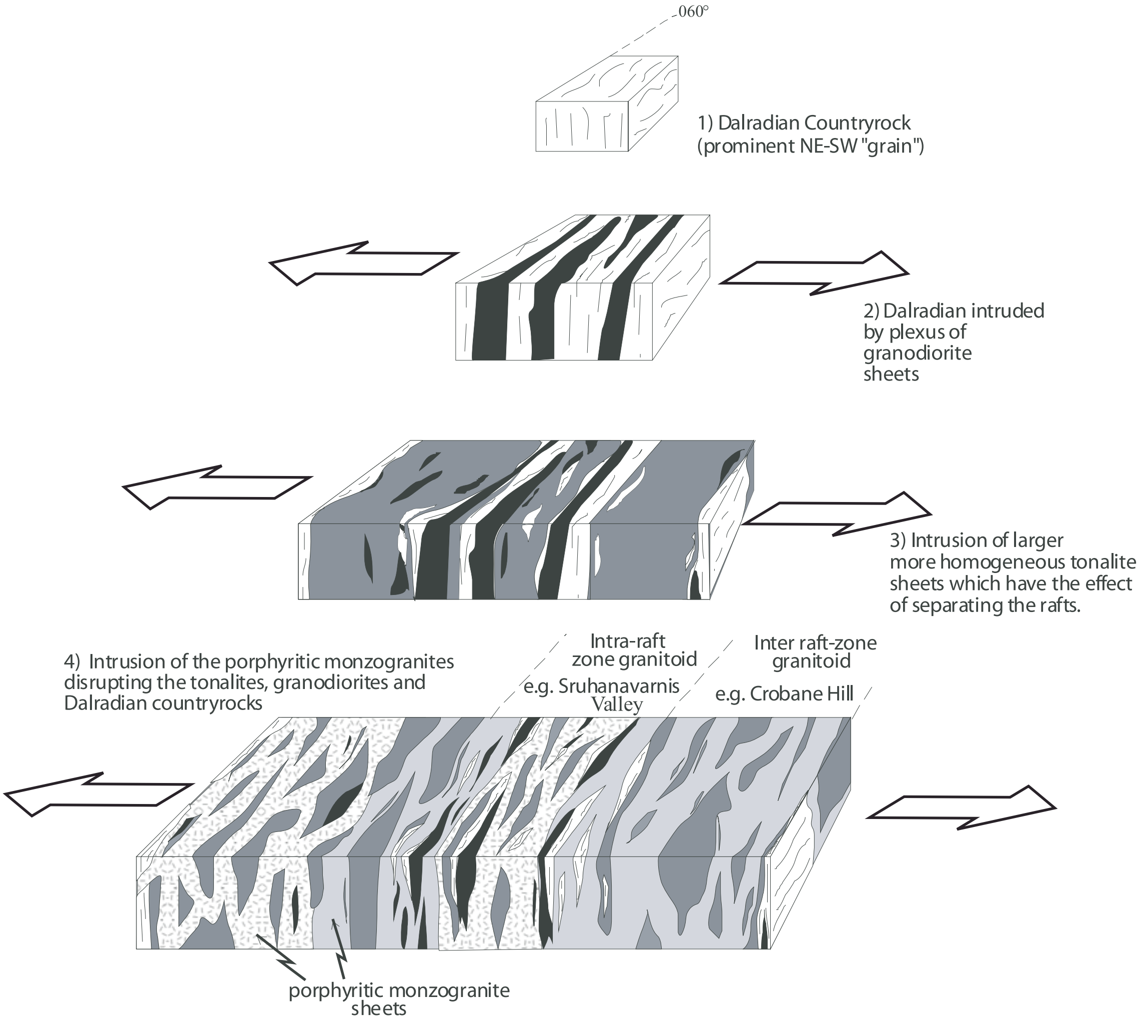


Figure 15 The evolution of sheeting in the MDG (not to scale) after Price (1997), showing the sequence of intrusion and dilation of the shear zone. The widening or dilation of the MDG shear zone proceeds with initially with intrusion of a plexus of granodiorite sheets parallel with (controlled by) the prominent NE fabric in the Dalradian country rocks (stage 1 and 2). This is followed by the intrusion of larger homogeneous tonalite sheets (stage 3). The final stage is the intrusion of porphyritic monzogranites disrupting the tonalities, granodiorites and country rock rafts (stage 4).

Stevenson 2004; present paper); (5) the nature and timing of deformation associated with the emplacement of the Carbane Gneiss (Price 1997); and (6) the east to west flow directions for the TBG and the Rosses pluton (Stevenson 2004; Stevenson *et al.* in press).

2.2.1. Mutiple shear zones. In the first part of this paper it has been shown that the northern and southern boundaries of the TBG are occupied by two relatively narrow, steeply inclined shear zones that trend WNW–ESE (see section 1.3, Figs 6, 7, 9, 10). These shear zones link into the broad MDG shear zone to the east and both continued movement after the pluton had started to crystallise, consistent with them being of regional tectonic rather than purely granite-related strain.

The southern edge of the MDG shear zone is continuous with the high strain contact of the Ardara pluton, i.e. there is a strand of the MDG shear zone along the Ardara's southern contact. This shear zone is tentatively extended to the west of Ardara at Loughros More, where moderately high strain shear zone folds have been discovered in the northern part of that peninsula (see Fig. 16b). Therefore, a further strand of the MDG shear zone swings from NE to WNW–ESE. This WNW–ESE orientation of shear zones west of the Ardara granite and along the northern and southern boundaries of the TBG is linked to the late stage gneissic/cataclastic fabric zones in the northern part of the Thorr pluton which cause sinistral deflection of the Thorr magmatic-state fabric.

Thus, there are at least five smaller shear zones west of the N12°E lineament and the main larger shear zone to the east (Fig. 18). It has been suggested (Hutton & Alsop 1996) that the N12°E lineament is the upper crustal expression of a deep fault that originated in the basement prior to Dalradian deposition. Here this interpretation is extended to the WNW–ESE trending shear zones that occur west of the lineament, that are attributed to deep-seated WNW–ESE faults in the Dalradian basement. This orientation of lineaments was first recognised in the British and Irish Caledonides by Watson (1982). During the late Caledonian, it is contended that regional NE–SW sinistral shearing activated this old system (N12°E and WNW–ESE) of deep faults that fundamentally determined the local siting of plutons and the deformation that affected them. This will be developed in detail in the final model.

2.2.2. The Main Donegal Granite shear zone Data collected since 1982 show that this was a long-lived shear zone, almost certainly in existence before the intrusion of the MDG itself. Price's (1997) work has confirmed the sheeting mechanism of Pitcher & Read (1959) and we reemphasise that the shear zone, in accumulating magma, wedged apart, i.e. it dilated. It is also emphasised that the splaying of the raft trains

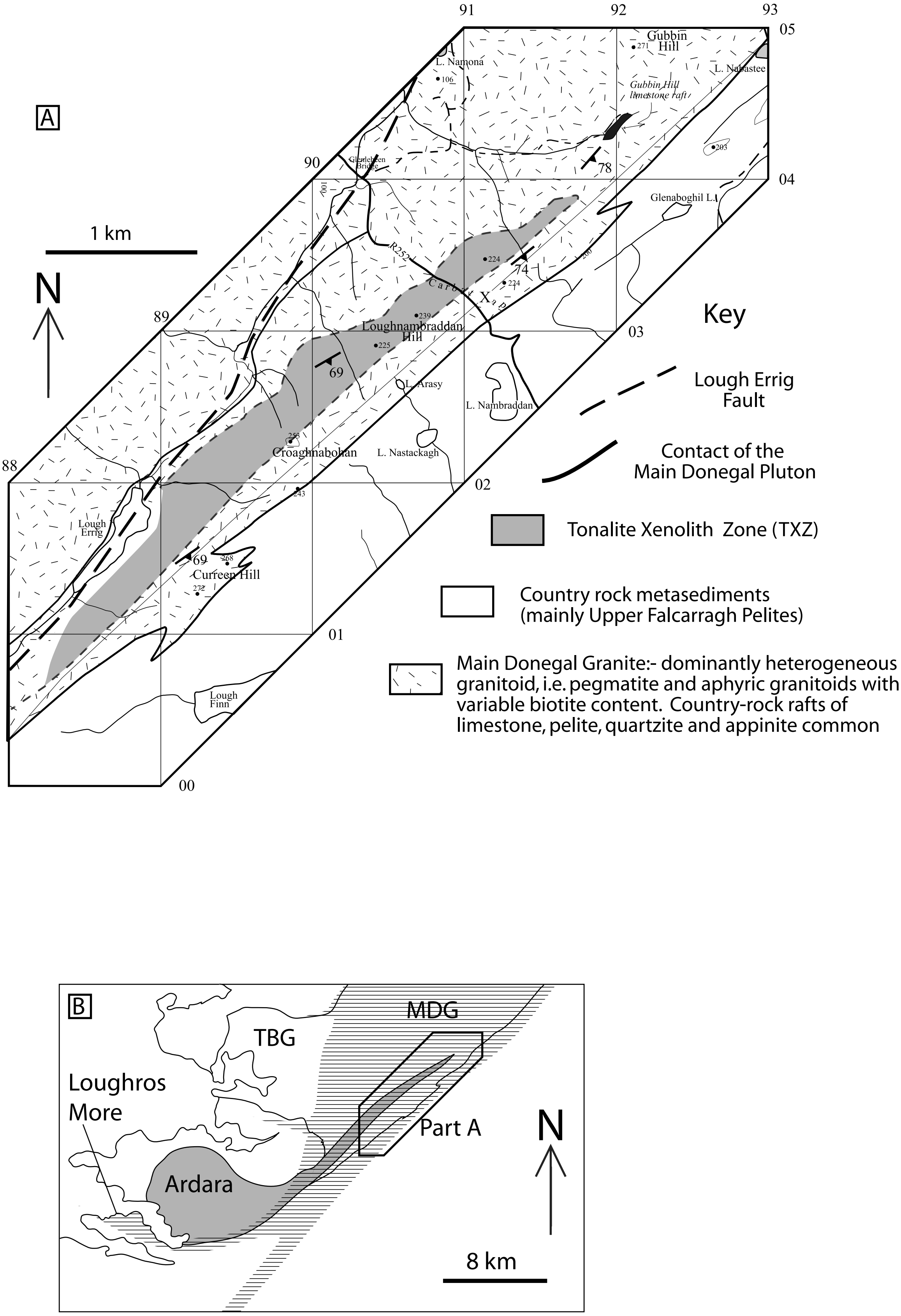


Figure 16 (a) A map of the area west of Fintown (see Fig. 2), a zone of tonalite xenoliths that are likely of the Ardara pluton, suggest that parts of this pluton were emplaced into the main shear zone at an early stage. Grid lines taken from the Irish National Grid square G. (b) Sketch map demonstrating the implication of part (a) for the pre-MDG extent of the Ardara pluton. The extent of the shear zone along the southern boundary of the Ardara pluton to Loughros More is also shown.

towards the SW means that the amount of dilation increases in that direction and that this dilation is abruptly terminated along the NNE–SSW trending contact with the TBG.

In the Hutton (1982) model, the maximum amount of sinistral shear (displacement) in the shear zone was estimated to be ~20 km (Hutton 1982). No new data are available to test

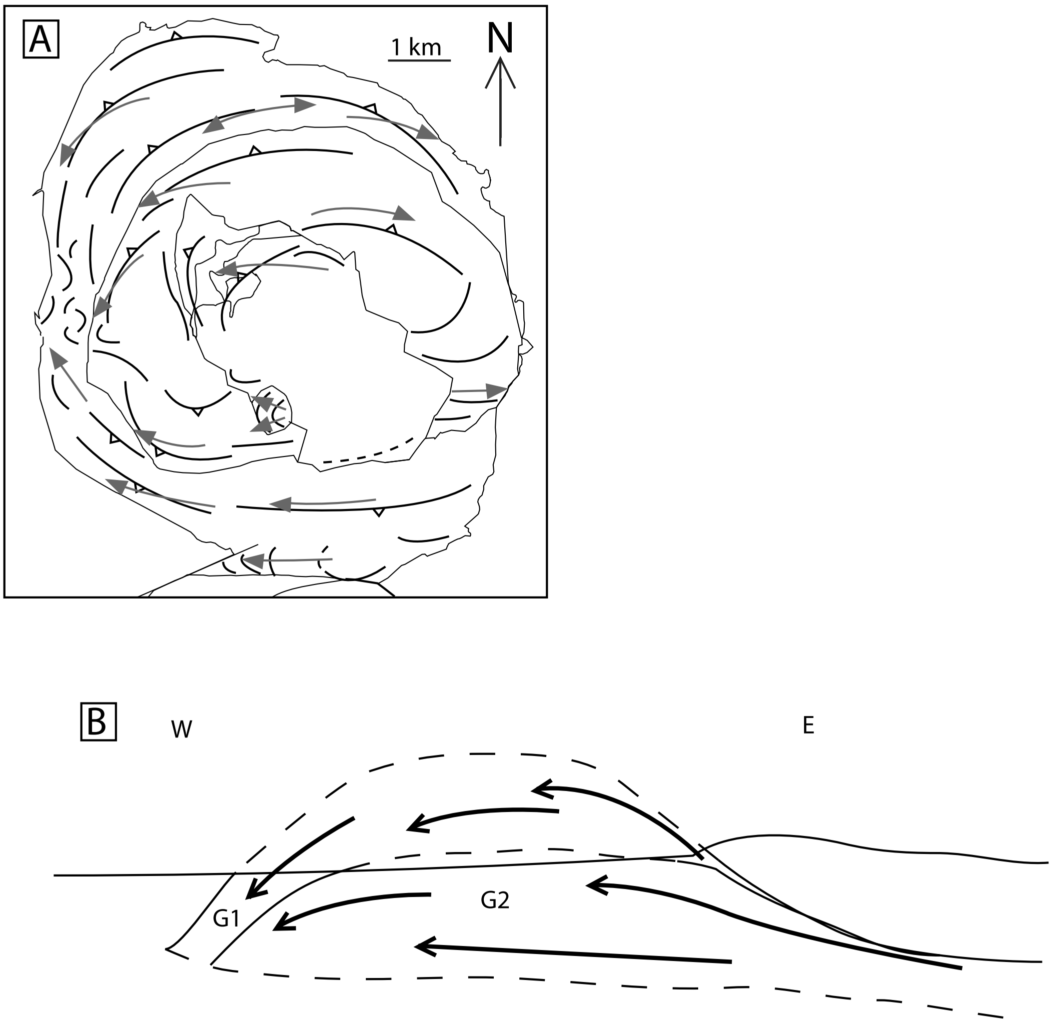


Figure 17 (a) Interpretation of AMS fabrics in the Rosses pluton taken from Stevenson (2004). Shown is a summary of the orientations; strike of foliations with a barb indicating the dip (generally <40°), there is no barb when the dip is steep or near vertical; lineations generally plunge gently, directions indicated with grey arrows. (b) Sketch cross section illustrating the lateral emplacement (magma inflow) of the Rosses pluton (G1 and G2 only).

this, as the shear zone is parallel to the strike of the Dalradian stratigraphy and clear oblique offset markers are not available. However, the same lithologies (e.g. the Falcarragh Pelite) occur on both margins of the shear zone. Very large displacements (>100 km) must be ruled out by this relationship and the approximate contiguity of the pre-granite strike swing across the granite outcrop must keep the displacement estimates close to the original approximation.

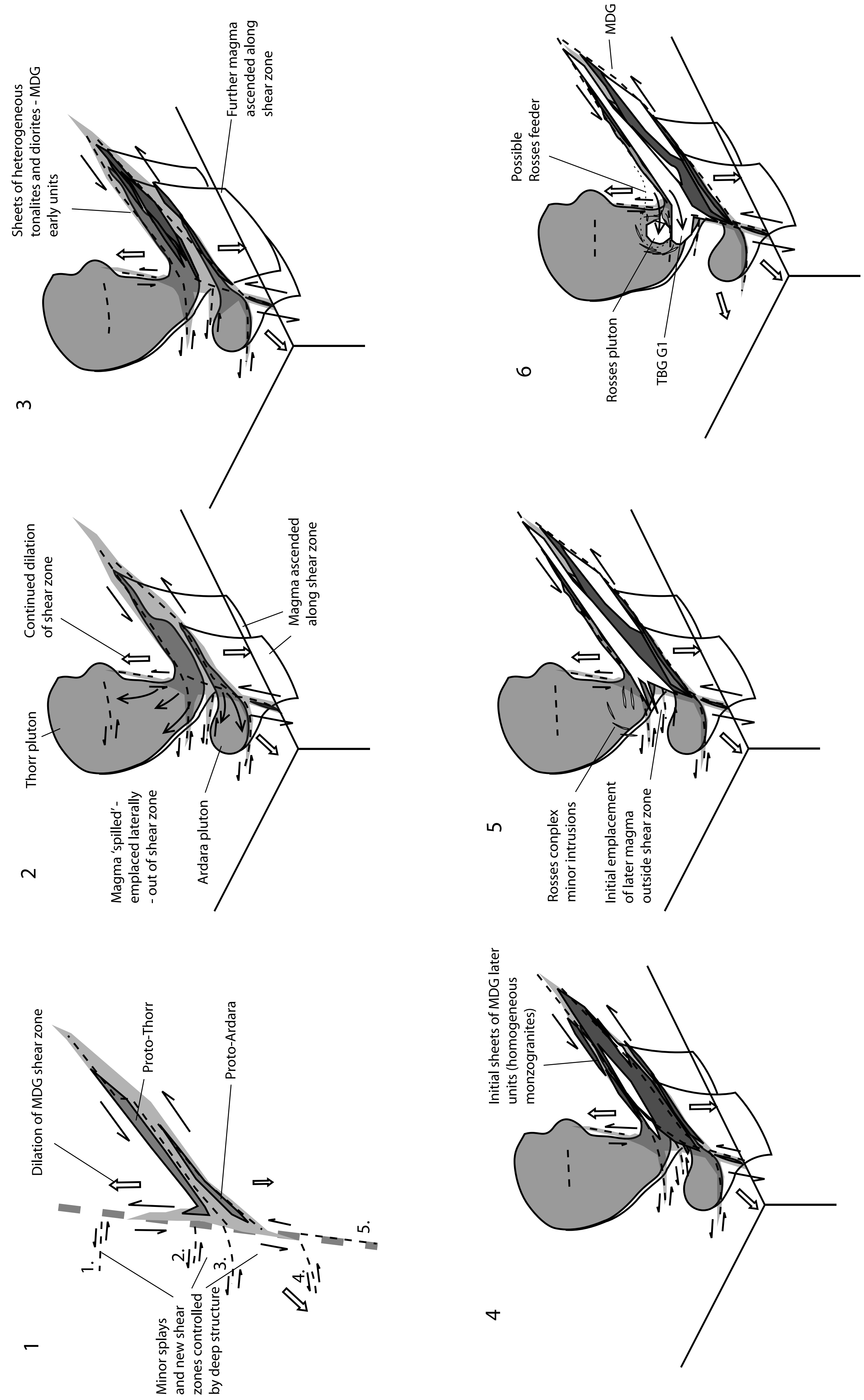
Hutton's (1982) model also had the dilating crack opening by outward bowing of the northern margin under sinistral shear. This idea was driven by the need to accommodate a decrease in displacement from ~20 km in the NE to <5 km on the NNE-trending shear zone which emerges from the south side of MDG in south Donegal. Hutton (1982) did not appreciate at that time that several other smaller shear zones existed at the western end of the MDG shear zone. Thus, the present authors' new data allow the large sinistral displacement at the NE end to be accommodated within the five newly recognised shear zones in the west. This removes the need for an outward bowing of the northern contact.

It is suggested that the shear zone dilated, facilitated by movement along the intense NNE–SSW-trending shear zone that separates the TBG and the MDG. This is essentially a type of transform fault, controlled by the N12°E lineament, along which additional sinistral shear was transferred as the individual sheets were emplaced (Fig. 18).

2.3. Emplacement of the Donegal Batholith

It has been shown that three, and possibly four, of the Donegal granites have prolongations of significant amounts of material within the MDG. By inference, the east to west flow direction discovered by the TBG study (Stevenson *et al.* in press and present work) suggests that their magma source lay in the shear zone. Magma that flowed out of this dilating shear zone, across the lineament, ultimately adopted a new geometry. Once free from the smaller shear zones (local tectonic structures), this geometry was one of subhorizontal sheets, possibly guided by gently dipping country rock bedding and cleavage planes. This emplacement style is most clearly seen in the Ardara pluton (Hutton & Seigesmund 2001) and Trawenagh Bay Granite (present paper), whose magmas appear to have followed original gently north/NW and south dipping anisotropies respectively.

In the present new model for the emplacement of the Donegal Batholith, a propagating shear zone intersects a highly oblique deep crustal fault. Magma ascending along this shear zone was accommodated passively by dilation of the shear zone against the old fault, which acted like an oceanic transform fault, with the amount of dilation increasing towards the transform. The magma in general migrated sideways/subhorizontally out of the shear zone across the upper crustal expression of this fault and into the wall rocks,


1
Dilation of MDG shear zone
Proto-Thorr
Proto-Ardara
1.
2.
3.
4.
5.
Minor splays and new shear zones controlled by deep structure
2
Thorr pluton
Continued dilation of shear zone
Magma ascended along shear zone
Magma 'spilled'- emplaced laterally - out of shear zone
Ardara pluton
3
Sheets of heterogeneous tonalites and diorites - MDG early units
Further magma ascended along shear zone
4
Initial sheets of MDG later units (homogeneous monzogranites)
5
Rosses conplex minor intrusions
Initial emplacement of later magma outside shear zone
6
Possible Rosses feeder
MDG
Rosses pluton
TBG G1

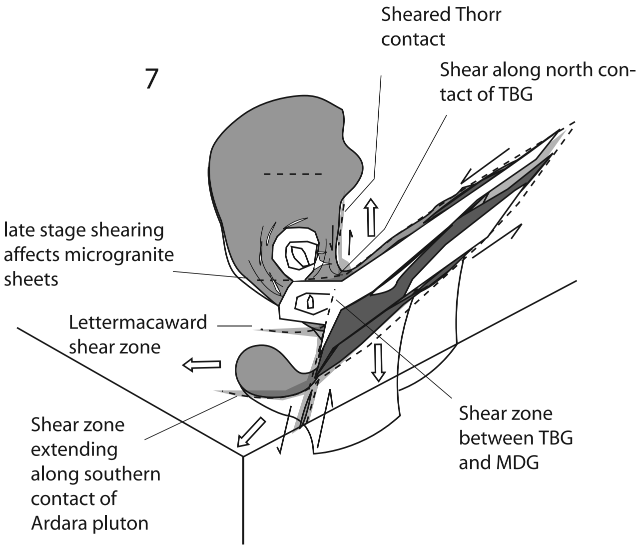


Figure 18 New model for the emplacement of the Donegal Granite Batholith (see text for details); also bear in mind the timing overlap in stages: (Stage 1) the orientation of the main NE trending shear zone, the N12°E lineament and the five minor splays west of the lineament (1=northern of Thorr; 2=future northern contact of TBG; 3=Lettermacaward; 4=future southern contact of Ardara; 5=future location of Carbane gneiss), early material (proto Ardara and Thorr) is emplaced in the main shear zone; (Stage 2) magma exits the main shear zone across the lineament (probably initially as vertical sheets) westward and NW to form the Thorr and Ardara plutons (see text points 2 and 3); (Stage 3) the early units of the MDG are emplaced (early tonalities and diorites) in the main shear zone; (Stage 4) later homogeneous monzogranites emplaced in the main shear zone; (Stage 5) initial emplacement of monzograniteic material outside the main shear zone (proto TBG and Rosses microgranites); (Stage 6) continued development of Rosses and TBG emplacement; (Stage 7) final situation, emplacement of youngest members of the TBG and Rosses, switching of shearing to a NNE shear zone along the boundary of the TBG and MDG.

guided by smaller shear zones that were themselves possibly controlled by deep crustal structures. This process happened repeatedly and each episode created material within the shear zone and a pluton outside it. In detail this model is as follows (see Fig. 18):

1. Thickened, granite generating lithosphere, containing an old, deep NNE-trending fault (possibly a transform fault) and other old, deep WNW-trending faults comes under regional NE–SW sinistral shear and intersect with a major NE trending shear zone during late Caledonian orogenesis (Fig. 18, stage 1).
2. The Thorr and Ardara plutons are the earliest plutons, but cannot (yet) be placed in the intrusion sequence. Following Pitcher & Berger (1972), the earliest granite is the Thorr pluton, which was emplaced initially within the MDG shear zone. The shear zone begins to dilate (to accommodate this magma) controlled by the developing NNE lineament acting as a transform fault with variable displacement. Dilation is accompanied by bulk sinistral shear, which deforms the crystallising body of magma. Early in this episode, magma exited the dilating shear zone, as sheets (cf. Fig. 13), across the lineament and is emplaced west and NW into the gently inclined bedding and early regional deformation cleavages of Dalradian host rocks (see Hutton 1981) to form what we suggest was a large laccolithic sheet – the Thorr pluton. Movement on the transform fault induces weak sinstral shear in the eastern part of the Thorr pluton and particularly along its north trending eastern contact. Some magma is also emplaced southward along the minor NNE shear zone extending SW of the lineament to form the Carbane Gneiss (Fig. 18, stage 2).
3. The Ardara pluton has a similar mode of emplacement where magma is initially emplaced into the dilating shear zone. This magma is emplaced near the extreme southern end of the dilating shear zone, where again magma leaks across the transform and this time balloons instead of becoming laterally extensive. Why the Ardara pluton emplacement was so much more forceful is not fully understood. It may have been emplaced into a shear zone tip that was in compression (cf. Hutton 1982). Ardara emplacement was also preceded and accompanied by minor appinite intrusions that cluster about the crossover point of the major MDG shear zone and the NNE lineament, implying that this crossover was a deeply penetrating ascent route (Hutton & Alsop 1996) (Fig. 18, stage 2).
4. Throughout the events surrounding Thorr and Ardara pluton emplacement, continued regional sinistral shearing caused deformation in the major MDG shear zone and the early magma emplacements, and may also have initiated WNW shear zones west of the lineament (for example at Toberkeen near Dungloe, see above), and a shear zone along the southern margin of the Ardara pluton that extends out to the WNW (Fig. 18, ongoing).
5. Contemporaneously with (or very soon after) Thorr and Ardara emplacement, the early units of the MDG were emplaced into the dilating shear zone in the medial zone (Price 1997), between the already in place tails of Thorr and Ardara, as deformation continued in the surrounding shear zones. The initial MDG magmas possibly exploited a step on the southern contact of the Thorr prolongation as a magmatic pull-apart (Fig. 18, stage 3).
6. From crosscutting relationships, the Rosses pluton is next in sequence. Although there is no direct (geochemical) evidence for Rosses magma in the MDG shear zone, there is considerable petrological similarity between the monzogranites of Rosses, TBG and MDG. It is thus suggested that Rosses material also migrated out of the MDG shear zone, but below the current surface and formed a domed laccolith inside the Thorr pluton (Fig 18, stages 5 and 6).
7. Shortly afterwards (or even overlapping with) the Rosses emplacement, but when the Thorr was fully crystallised and capable of taking up solid-state deformation along its margins (seen on its eastern margin) and on WNW shear zones, monzogranite magma was emplaced into the NW and SE margins of the MDG shear zone in significant volumes and migrated westward again across the transform forming the TBG (see also Fig. 13). The northern and southern boundaries of the TBG were controlled initially by two of the WNW shear zones, one preserved in Lettermacaward (see Fig. 9) (although this shear zone is not in contact with the TBG at the current surface) and one now partially remaining along the northern boundary of the TBG as a continuous splay of the main MDG shear zone (see Fig. 10). The gap in the NNE–SSW high strain shear zone that nominally separates the TBG and MDG plutons, and within which TBG G1 magma apparently flowed from one pluton to the other, may have been created by the switching of shearing from the NNE–SSW-trending main strand into the westerly splays that define the northern and southern edges of TBG. With the cessation of magmatic emplacement, deformation persisted along the shear zones and splays, imparting the high temperature solid-state fabrics that are so typical of the marginal facies of the Main Donegal Granite and surrounding rocks. This continuing post-emplacement deformation is consistent with the idea

that regional tectonic deformation fundamentally controlled the magmatic evolution and emplacement of the batholith (Hutton 1982) (Fig. 18, stages 6 and 7).

The Fanad, Barnesmore and Toories plutons have not been discussed here. It is possible that there is another lineament affecting the MDG shear zone at the extreme NE causing Fanad emplacement (J. Reavy pers. comm. 2004). As for the Toories and Barnesmore plutons, lack of exposure and the distal position of both with respect to the MDG shear zone-lineament system, make their emplacement with respect to the MDG shear zone system difficult to assess.

Our studies indicate that the Main Donegal Granite, as historically named (Pitcher & Read 1959), contains magma from at least three, and probably four, other bodies. Pitcher (1997, p. 231) offers a generally acceptable definition of a pluton as "A largish body of the order of 1–200km^2 in outcrop, built from one or more pulses of magma yet clearly circumscribed by its country rock envelope", and a batholith as "an array of such plutons". This definition of pluton is reasonably acceptable for everything in the Donegal batholith except the Main Donegal Granite since it seems contradictory to have plutons within a pluton. In terms of this classic definition of a pluton the Main Donegal Granite proper only constitutes the material within it that does not occur outside of the shear zone, i.e. the early granodiorites and tonalities.

Leaking shear zones appear to create problems for conventional views of what constitutes a pluton. However, considering that shear zones provide pathways or ascent routes for magma from the lower crust to the upper crust (Jaques & Reavy 1996), here we appear to have a prime example of ascent (vertical) giving way to emplacement (horizontal) and a mechanism of how this happened.

2.4. Some concluding remarks

The model presented in this paper attempts to draw together all the available information regarding the emplacement of the Donegal Batholith. However, although it is acknowledged that the model is far from complete, the value in this approach is that it poses several important questions as well as reiterating long-standing problems.

The first relates to the relative timing of emplacement of the constituent plutons. This has remained enigmatic, as not all of the plutons have direct crosscutting relationships. Furthermore, radiometric dates have so far been unable to distinguish the absolute emplacement ages of individual plutons and the units within them (Halliday *et al.* 1980; Siegesmund & Becker 2000; O'Connor *et al.* 1982). The present model makes the reasonable assumption that the timing of emplacement of the constituent plutons is very close and individual plutons are likely to overlap significantly. Age dating of the deformational history of these plutons may provide an important test of this new model.

Secondly, one of the primary conclusions of Pitcher & Berger (1972) was that the constituent plutons of the batholith were emplaced at the same level in the crust. Our model is based on this premise. However, this idea has never been quantitatively tested using P–T determinations and such a study could provide a strong test of our model, as it assumes no major erosion has occurred in the intervals between each intrusive event. Also of interest would be timescales derived from age dating (cf. Condon *et al.* 2004) in connection with P–T conditions, i.e. the dynamic P–T conditions associated with emplacement of the batholith.

Finally, the present authors would like to draw attention to some remarkable comments that were once made about the Trawenagh Bay and Main Donegal Granites. In the discussion of Pitcher & Read's (1959) paper, which took place after its reading at the Geological Society's old lecture room in Burlington House on the 5th of June 1957, Charles Fallows Tozer, one of Pitcher and Read's Donegal granite mapping team, commented, "*If the granite was moving horizontally, where was it coming from and where was it going? Also what was the full nature of the granite relationships in the Trawenagh Bay area?*" He then continued (with "considerable irony", W. S. Pitcher pers. comm. 2000). "*The mental picture obtained of this area was the fantastic one of a huge sink hole with a torrent of Main Granite magma pouring down one side and the Trawenagh Bay magma welling up the other . . .*" In terms of the interpretation advanced in this paper some 50 years later, the authors would give this assessment about "eight out of ten" and remind the reader of the remarkable intuitions and perspicacity of W. S. Pitcher and H. H. Read, as well as the enchantment of Read's "magic boots" (Pitcher & Berger 1972, preface).

3. Dedication

We would like to dedicate this paper to the memory of the late Wally Pitcher. Although DHWH and WSP came from different research backgrounds and cultures and their early dealings were somewhat vexed, enthusiasm for the Donegal granite eventually prevailed. WSP encouraged and involved DHWH with important people in the science and especially with his circum-Pacific granite group; the contacts thus made did much to launch the younger man's career and for this he will be forever grateful. Wally solidly and enthusiastically supported and encouraged what he called "the structural approach" through six Donegal Granite PhDs at Durham and Birmingham, the last being Stevenson's. He even, in his mid 70s, mapped in the field with Price, and astonished the young, fit student with his ability, not only to decipher the subtle differences between virtually identical TBG facies, but also with his ability at barbed wire fence hopping. He knew, as I think we have eventually understood, there is something very odd and probably very important about the Main Donegal and Trawenagh Bay Granites and was utterly fascinated with them.

In his last years we were welcomed visitors at Fletcher Close on the Wirral where we discussed Donegal granite and enjoyed Wally and Stella's wonderful hospitality. Wally loved Donegal and its people and we were privileged to have accompanied him and Stella on his last trip to the county in 2002. Our lives have been immeasurably enriched by knowing this most gentle of men.

4. References

Akaad, M. K. 1954. The Ardara granitic diapir of County Donegal, Ireland. *Journal of the Geological Society, London* **112**, 263–88.

Cole, G. 1902. On the composite gneisses in Boylagh, west Donegal. *Proceedings of the Royal Irish Academy* **24B**, 203–30.

Condon, D. J., Bowring, S. A., Pitcher, W. S. & Hutton, D. H. W. 2004. Rates and tempo of granitic magmatism: a U–Pb geochronological investigation of the Donegal Batholith (Ireland). *Geological Society of America, Abstracts with Programs* **36**, 406.

Gapais, D. 1989. Shear structures within deformed granites: Mechanical and thermal indicators. *Geology* **17**, 1144–7.

Gindy, A. R. 1953. The plutonic history of the district around Trawenagh Bay, County Donegal. *Journal of the Geological Society, London* **108**, 377–411.

Halliday, A. N., Aftalion, M. & Leake, B. E. 1980. A revised age for the Donegal Granites. *Nature* **284**, 542–3.

Holder, M. 1979. An emplacement mechanism for post tectonic granites and its implications for their geochemical features. *In* Atherton, M. & Tarney, J. (eds) *Origins of Granite Batholiths: Geochemical Evidence*, 116–28. Nantwich: Shiva Publishing Ltd.

Hutton, D. 1981. The Main Donegal Granite – Lateral Wedging in a Syn-Magmatic Shear Zone. *Journal of Structural Geology* **3** (1), 93.

Hutton, D. H. W. 1982. A tectonic model for the emplacement of the Main Donegal Granite, NW Ireland. *Journal of the Geological Society, London* **139**, 615–31.

Hutton, D. H. W. 1992. Granite Sheeted Complexes – Evidence for the Dyking Ascent Mechanism. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 377–82.

Hutton, D. H. W. & 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* **153**, 345–60.

Hutton, D. H. W. & Siegesmund, S. 2001. The Ardara Granite: Reinflating the Balloon hypothesis. *Zeitschrift der Deuchen Geologischen Gesellschaft* **152**, 309–23.

Jacques, J. M. & Reavy, R. J. 1996. Caledonian Plutonism and Major Lineaments in the Sw Scottish Highlands. *Journal of the Geological Society, London* **151**, 955–69.

McErlean, M. A. 1992. A new shear criterion for rocks deformed in the magmatic state: examples from the Thorr Granite, Co. Donegal. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 494.

McErlean, M. A. 1993. *Granitoid emplacement and deformation: a case study of the Thorr pluton, Ireland, with contrasting examples from Scotland.* Unpublished PhD Thesis, University of Durham, UK.

Meneilly, A. W. 1982. Regional structure and syntectonic intrusion in the Gweebarra Bay area, County Donegal, Ireland. *Journal of the Geological Society, London* **139**, 633–46.

Molyneux, S. J. 1997. *Processes of granite emplacement: NW Ireland and Brazil.* Unpublished PhD Thesis, University of Durham, UK.

Molyneux, S. J. & 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* **112** (10), 1543–58.

O'Connor, P. J., Long, C. B., Keenan, P. S., Halliday, A. N., Max, M. D. & Roddick, J. C. 1982. Rb–Sr isochron study of the Thorr and Main Donegal Granites, Ireland. *Geological Journal* **17**, 279–95.

Paterson, S. R., Vernon, R. H. & Tobisch, O. T. 1989. A review of criteria for the identification of magmatic and tectonic foliations in granitoids. *Journal of Structural Geology* **11**(3), 349–63.

Paterson, S. R. & Vernon, R. H. 1995. Bursting the Bubble of Ballooning Plutons – a Return to Nested Diapirs Emplaced by Multiple Processes. *Geological Society of America Bulletin* **107** (11), 1356–80.

Pitcher, W. S. 1953a. The Rosses granitic ring complex, County Donegal. *Proceedings of the Geologists' Association* **64**, 153–82.

Pitcher, W. S. 1953b. The migmatitic Older Granodiorite of the Thorr district, Co. Donegal. *Quarterly Journal of the Geological Society of London* **108** (for 1952), 413–60.

Pitcher, W. S. 1970. Ghost stratigraphy in intrusive granites: a review. *In* Newall, G. & Rast, N. (eds) *Mechanisms of Igneous Intrusion. Geological Journal Special Issue* **2**, 141–56. Liverpool: Seel House Press.

Pitcher, W. S. 1997. *The nature and origin of granite*, 2nd edition. London: Chapman and Hall.

Pitcher, W. S. & Berger, A. R. 1972. *The Geology of Donegal, a study of granite emplacement and unroofing.* London: Wiley Interscience.

Pitcher, W. S. & Hutton, D. H. W. 2004. *A Master Class Guide to the Granites of Donegal.* The Dublin: Geological Survey of Ireland.

Pitcher, W. S. & Read, H. H. 1959. The Main Donegal Granite. *Quarterly Journal of the Geological Society of London* **64**, 259–305.

Pitcher, W. S. & Read, H. H. 1960. The aureole of the Main Donegal Granite. *Quarterly Journal of the Geological Society of London* **66,** 1–36.

Price, A. R. 1997. *Multiple sheeting as a mechanism of pluton construction: The Main Donegal Granite, NW. Ireland.* Unpublished PhD Thesis, University of Durham, UK.

Price, A. R. & Pitcher, W. S. 1999. The Trawenagh Bay granite: a multipulse, inclined sheet in the flank of a synplutonic shear zone. *Irish Journal of Earth Science* **17**, 51–60.

Read, H. H. 1958. Donegal granite. *Science in Progress* **182**, 225–40.

Siegesmund, S. & Becker, J. K. 2000. Emplacement of the Ardara pluton (Ireland): new constraints from magnetic fabrics, rock fabrics and age dating. *International Journal of Earth Sciences* **89**, 307–27.

Stevenson, C. T. E. 2004. *Magma Flow and Granite emplacement in Contrasting Tectonic Environments using Anisotropy of Magnetic Susceptibility.* Unpublished PhD Thesis, University of Birmingham, UK.

Stevenson, C. T. E., Owens, W. H. & Hutton, D. H. W. 2007. Flow lobes in granite: the determination of magma flow direction in the Trawenagh Bay Granite, N. W. Ireland, using anisotropy of magnetic susceptibility. *Geological Society of America Bulletin* **119**(11–12), 1368–86.

Vernon, R. H. & Paterson, S. R. 1993. The Ardara pluton, Ireland: deflating an expanded intrusion. *Lithos* **31**, 17–32.

Vigneresse, J. L. 1995. Control of Granite Emplacement by Regional Deformation. *Tectonophysics* **249**, 173–86.

Vigneresse, J. L., Barbey, P. & Cuney, M. 1996. Rheological transitions during partial melting and crystallization with application to felsic magma segregation and transfer. *Journal of Petrology* **37**, 1579–600.

Watson, J. 1982. The ending of the Caledonian orogeny in Scotland. *Journal of the Geological Society, London* **141**, 193–214.

Whitten, E. H. T. 1957. The Gola granite (County Donegal) and its regional setting. *Proceedings of the Royal Irish Academy* **58B**, 245–92.

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