Tectonic and kinematic evolution within mid-crustal orogenic root zones: a case study from the Caledonides of northwestern Ireland

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Abstract – The Slieve League Peninsula of northwest Ireland lies on the western limb of a major orogenic strike-swing in which regional foliation trends have deviated from the northeast–southwest trends typical of much of Scotland, to west–east orientations. Across-strike coastal exposures on the western tip of the peninsula through Neoproterozoic Dalradian metasediments enable a detailed examination and analysis of the structural evolution of a Caledonian orogenic root zone which has been previously correlated with the Loch Awe Syncline of southwest Scotland. Minor structural development may be evaluated in terms of regional strain profiles and overprinting relationships. Over much of the area, a composite, steep northeast–southwest-trending S2–S3 foliation containing a gently southwest-plunging quartz mineral elongation lineation is the dominant fabric at outcrop, and is associated with MP2 almandine–amphibolite facies metamorphism. F2 folds are isoclinal with curvilinear hinges and similar geometry. They typically plunge steeply towards the southwest and display variable (dextral) or north-directed vergence, whilst minor F3 fold hinges plunge moderately towards the southwest and typically verge (sinistrally) towards the south. Major, composite D1–D3 tectonic slides are developed in the Argyll Group. Structural and stratigraphic relationships indicate that D1 induced large-scale reversals in younging across tectonic slides, resulting in reversals in subsequent F2 and F3 facing patterns. Tectonic sliding is associated with an intensification of strain demonstrated by increasingly intrafolial and curvilinear folding, together with extensional crenulations, sheared quartz pods and metre-scale asymmetric boudinage of metadolerites, all of which indicate dextral (D2) and sinistral (D3) shear. After unfolding subsequent folds (F4), this corresponds to top-to-the-north (D2) and top-to-the-south (D3) translations. D4 results in regionally northwest-verging structures, with minor crenulations and the S4 cleavage transecting fold hinges in an anticlockwise sense, suggesting a dextral component of deformation. The detailed kinematic data indicate that the overall geometry of this western, deep-level arm of the root zone is not a product of the classic mushrooming fountain of nappes model, but rather major interference between consistent northerly directed D2 thrusting and a later phase of southeast-directed (D3) retrocharriage ('back-folding') which intensifies towards the south.

1. Introduction

The internal or metamorphic portions of orogenic belts are typically characterized by zones of intense fabric development associated with multiple folding, which may ultimately result in moderately to steeply inclined foliations and thrust sheets dipping downwards into root zones. The term 'root zone' has been simply defined as 'the region at the back of a thrust sheet which passes downwards into the earth's surface' (Ramsay & Huber, 1987, p. 522). Within such upright and broadly symmetrical major orogenic root zones, processes of strain localization and partitioning are frequently governed by pre-existing variability resulting from structural and stratigraphic heterogeneity. The concentration of deformation results in multiple overprinting associated with the generation of composite fabrics (e.g. Davis, 1995; Wennberg, 1996). Such foliations provide a detailed and intricate record of the tectonic evolution and structural relationships developed within the internal portions of orogenic belts.

The detailed analysis of the geometry, dynamics and kinematics of orogenic root zones thus has widespread implications for the study of mid-crustal deformation zones and mountain building processes in general. The Neoproterozoic–Cambrian Dalradian succession of Ireland and Scotland (see Harris *et al.* 1994 and Alsop *et al.* 2000 for reviews) provides a well-defined and readily discernible stratigraphic tool with which to unravel structural complexities arising from the Grampian Orogeny at ~470 Ma (Friedrich *et al.* 1999*a*,*b*; Flowerdew, 1999; Flowerdew *et al.* 2000; Oliver, in press; Alsop & Hutton, 1993*a*,*b*). This orogeny generated major fold-and-thrust nappes throughout the Irish and Scottish Caledonides, and it

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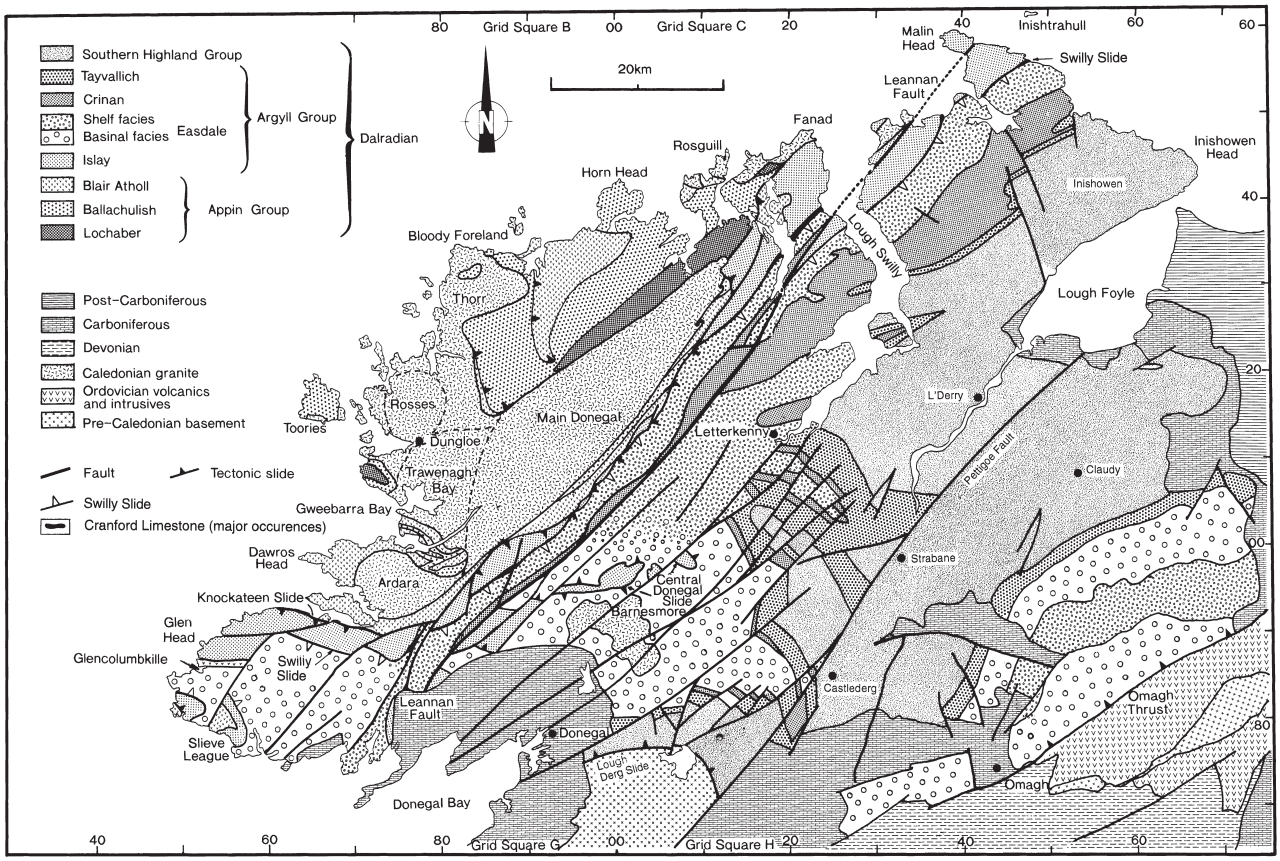


Figure 1. Simplified geological map of northwest Ireland showing Dalradian subgroups, facies changes and regional Caledonian strike-swing. Location of Slieve League Peninsula (Fig. 2) is labelled in the southwest of the map area.

is the resultant fold-and-thrust geometries developed within a mid-crustal root zone exposed in the Slieve League Peninsula of northwest Ireland which form the focus of the present work (Fig. 1).

Within the Dalradian of the southwest Highlands of Scotland, the major Loch Awe Syncline broadly separates southeast-dipping rocks in the northwest from northwest-dipping rocks to the southeast (Roberts, 1974; Roberts & Treagus, 1977, 1979). This upright, symmetrical synform also separates divergent major nappe translations towards the northwest (in the northwest) and the southeast (in the southeast). Fold nappes and thrusts therefore dip towards, and downwards into, the root zone, which may be traced towards the northeast into the Central Highlands where divergent nappe translations are considered coeval by some workers (e.g. Thomas, 1979, 1980). The relative importance and timing relationships of opposing translations on either flank of the root zone have been the subject of much debate (e.g. Coward, 1983; Nell, 1986; Treagus, 1987) and are discussed with reference to this particular case study (Section 5).

The western continuation of the southwest Highlands orogenic root zone may be traced into northwest Ireland as the Lough Foyle or Inishowen Syncline (Pitcher & Berger, 1972; Hutton & Alsop, 1996, 1997). The broadly synformal geometry similar to that described above in the Loch Awe area of Scotland undergoes a ~34 km sinistral displacement by the northeast–southwest-trending Leannan Fault System (Alsop, 1992*a*), and deeper structural levels are superbly exposed on the Slieve League Peninsula of western Donegal (Fig. 1). This area forms an ideal location in which to undertake a detailed examination of the tectonics and kinematics of the overall root zone as the geometry is not masked by the numerous metadolerite intrusions, Devonian lavas and granites which complicate the structure of the southwest Highlands. Furthermore, the overall geometry is clearly depicted by a complete across-strike structural section with a varied Dalradian succession providing excellent lithostratigraphic control.

The Slieve League Peninsula lies on the western limb of a major orogenic strike-swing in which regional foliation trends have deviated from the northeast–southwest trends typical of much of Scotland, to west–east orientations. This strike-swing is defined by magnetic and gravity data throughout the pre-Carboniferous rocks of Ireland (Max, Ryan & Inamdar, 1983; Readman, O'Reilly & Murphy, 1997) and is associated with sedimentary facies changes within the Dalradian (Alsop & Hutton, 1990), which suggest at least a Neoproterozoic origin. The trend of the Loch Awe/Lough Foyle Syncline appears to mirror

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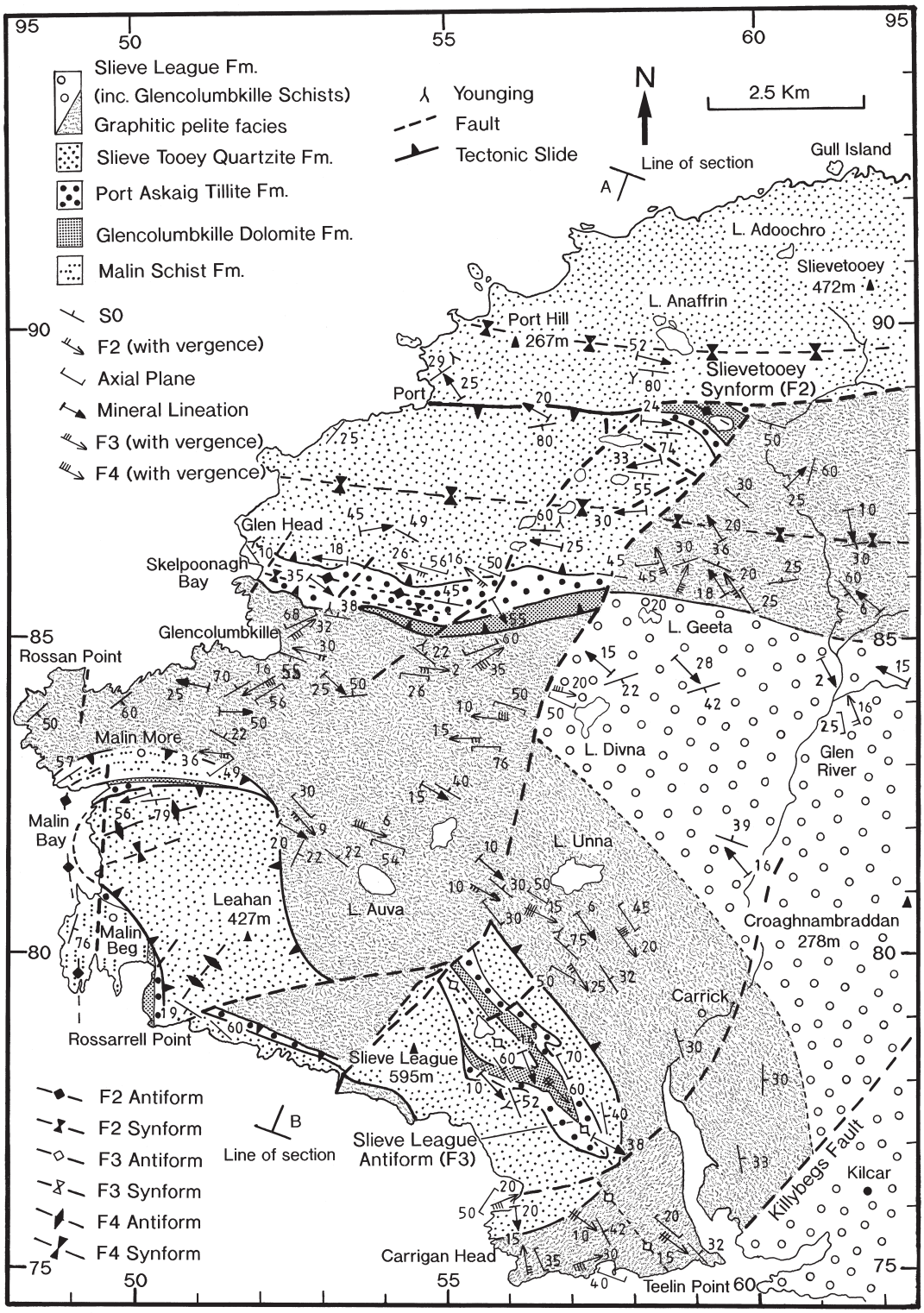


Figure 2. Simplified lithostratigraphic map showing the Dalradian of the western Slieve League Peninsula (see Fig. 1 for location). Note the general east–west trends and overall symmetric outcrop pattern with Slieve Tooey Quartzite Formation exposed on both the north and south coasts. Minor intrusions have been omitted. Detailed study area is positioned on the western tip of the peninsula (Malin Bay – see Fig. 4).

the regional strike-swing which is considered an original feature of the Laurentian margin, and which has strongly influenced subsequent Caledonian tectonics (Alsop & Hutton, 1993*a*; Hutton & Alsop, 1996).

The western tip of the Slieve League Peninsula contains excellent coastal exposures of Appin and Argyll Group Dalradian rocks which, apart from the original survey mapping of Hull, Kilroe & Mitchell (1891), a brief mention by Anderson (1954) and lithological mapping by Howarth (1971), have received little attention

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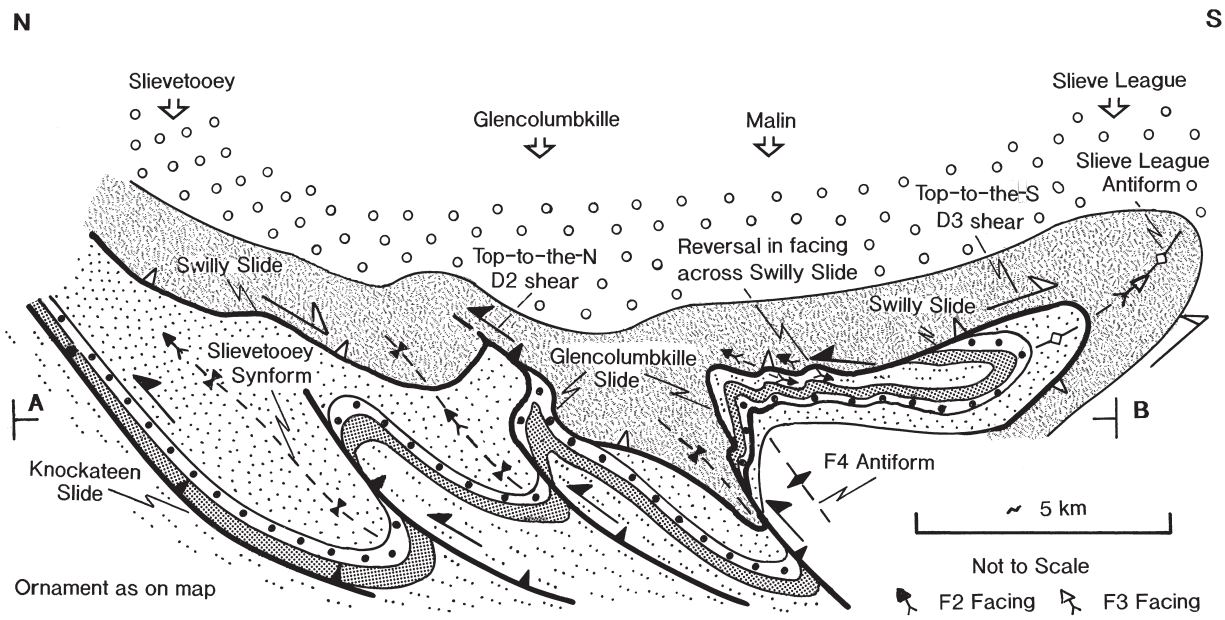


Figure 3. NNE–SSW-trending schematic cross-section across the western end of the Slieve League Peninsula illustrating major north-directed D2 tectonic slides and folds, and subsequent southerly directed D3 shear. Line of section (A–B) and key to lithological ornament are shown on Figure 2.

(Figs 1, 2). Johnston (1997) suggested a possible overall coherent model for the gross stratigraphic pattern associated with north-directed D2 ductile thrusting, which is broadly supported by the present study (Figs 2, 3). The geometry and age of the major structures developed within this small but critical area are investigated in this study, which provides a detailed examination and analysis of the deeper structural evolution of the root zone during Caledonian orogenesis. Details of revisions to the Dalradian stratigraphy are now presented prior to a description of structures and their implications.

2. Dalradian stratigraphy

The well-defined local stratigraphy has previously been described in great detail (Howarth, 1971; Pitcher & Berger, 1972; Johnston, 1995; Long, McConnell & Alsop, 1999) and will not be repeated here. However, major revisions to the established stratigraphy are presented below in order to provide the framework necessary for the structural investigation (Table 1). Within the Malin area of western Donegal (Fig. 2), Howarth, Kilburn & Leake, (1966) described a relatively complete Dalradian succession from the Glencolumbkille Schist Formation through to the Slieve Tooey Quartzite Formation. Recent mapping, however, suggests that the Glencolumbkille Schist Formation is representative of the younger Easdale Subgroup and may be further subdivided into graphitic pelite and psammitic members (Alsop, Bryson & Hutton, 1998), whilst the Malin Schist Formation crops out over a larger area than previously envisaged (see next section). Thus, a relatively complete but condensed (~400 m thickness) stratigraphic sequence is observed from the Malin Schist Formation, Skelpoonagh Bay Limestone Formation, Glen Head Schist Formation, Glencolumbkille Dolomite Formation, Port Askaig Tillite Formation to the overlying Slieve Tooey Quartzite Formation (Figs 2, 4; Table 1). The Appin Group stratigraphy is considered to form a tectonic sliver between the Slieve Tooey Quartzite Formation and the Glencolumbkille Schist Formation and is entirely bounded and isolated by tectonic slides (Figs 3, 4). The significant modifications to the stratigraphy outlined above are now described in further detail.

2.a. Malin Schist Formation

The Malin Schist Formation comprises thinly interbedded (< 5 cm), cross-laminated buff quartzites, together with psammitic bands (< 10 cm), grey biotite-rich semipelites and persistant grey, crystalline limestones best exposed around Malin Beg Tower [Irish Grid G 489796]. This interbanded unit is hitherto unrecognized in the Malin More area [G 500830] (Figs 2, 4) and was previously thought to represent the Easdale Subgroup (Pitcher & Berger, 1972; Geological Survey of Northern Ireland, 1977, 1997), or a correlative of the Glencolumbkille Pelite or Appin Group (Howarth, 1971; Johnston, 1997) (Table 1). The Malin Schist Formation has an overall strongly banded appearance and is here considered a correlative of the Loughros Formation and the graphitic pelites typically found beneath the overlying (Skelpoonagh Bay)

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Table 1. Summary of stratigraphic revision within the Dalradian of the Malin region

Howarth (1971), Pitcher & Berger (1972)	This study	Dalradian stratigraphy
Crockuna Schist	Glencolumbkille Schist Formation Tectonic slide	Easdale Subgroup (Argyll Group)
Slieve Tooey Quartzite Port Askaig Tillite	Slieve Tooey Quartzite Formation Port Askaig Tillite Formation	Islay Subgroup (Argyll Group)
Glencolumbkille Dolomite Glen Head Schist Skelpoonagh Bay Limestone	Glencolumbkille Dolomite Formation Glen Head Schist Formation Skelpoonagh Bay Limestone Formation	Blair Atholl Subgroup (Appin Group)
Glencolumbkille Pelite Malin Beg 'Group'	Malin Schist Formation	

The Glencolumbkille Pelites (correlated with the Appin Group by previous workers) are now considered to be in tectonic contact with the rest of the sequence and form part of the younger (Glencolumbkille Schist Formation) Easdale Subgroup (see text for further details).

limestone formations (Pitcher & Berger, 1972; Meneilly, 1982; Alsop & Hutton, 1990). An increase in the limestone element is typically marked by a concomitant reduction in the psammitic and quartzite component. The Malin Schist Formation passes upwards via a sedimentary transition into the Skelpoonagh Bay Limestone Formation of established stratigraphy, which consists of sacharoidal limestone and semipelite interbedded on a metre scale and is described in detail by Howarth, Kilburn & Leake (1966) and White & Hutton (1985). The Malin Schist Formation is thus considered to represent Appin Group, crops out over a larger area than previously realized, and is in tectonic contact with the Islay and Easdale subgroups (Figs 2, 3, 4) (see below).

2.b. Glencolumbkille Schist Formation

The predominantly graphitic pelites exposed west of the NNE–SSW-trending fault passing northwest of Slieve League [G 540790] (Fig. 2) were previously interpreted as representing Appin Group (Howarth, Kilburn & Leake, 1966; Howarth, 1971; Pitcher & Berger, 1972; Johnston, 1997) with Anderson (1954) recognizing the lithological similarity and correlating the pelites on either side of the fault. The Glencolumbkille Schist Formation is separated from the rest of the sequence by tectonic sliding (see Section 4) and is now considered to represent Easdale Subgroup of the Argyll Group (Alsop, Bryson & Hutton, 1998; Long, McConnell & Alsop, 1999). The formation may be subdivided into two interbanded members (Alsop, Bryson & Hutton, 1998), which are described in detail below.

2.b.1. Banded psammite member

This distinctly banded member crops out in cliff-top exposures immediately to the south of Rossan Point [G 481837] (Figs 2, 4). It consists of dark grey graphitic pelite and pale grey, medium-grained psammites (< 10 cm thick) interbanded with more massive quartzite units up to 25 cm thick. Psammites may become coarser grained in thicker beds and grade into the adjacent pelite units. This member, which lacks limestone units, passes via a sedimentary transition associated with a rapid increase in graphitic pelite and a concomitant reduction in psammite and quartzite into adjacent graphitic pelites.

2.b.2. Graphitic pelite member

This unit comprises monotonous, dull, black, weakly foliated graphitic pelites intercalated with subordinate grey, sacharoidal limestone and occasional thin (< 5 cm) psammite bands [G 489827]. Partially chloritized garnets are prominant, whilst in thin section the graphitic pelites comprise muscovite, biotite, quartz, sericitized oligocene, calcite and graphite, the latter comprising up to 5% of some specimens. Towards the margins of the member, prominantly striped light grey psammitic layers (< 5 cm thick) interbedded with thin, grey, biotite semipelite and graphitic pelite occur. This banded unit also contains occasional intercalated sacharoidal limestones and discontinuous quartzites.

The established Dalradian succession, incorporating the revisions and modifications described above, provides a stratigraphic framework for the analysis of Caledonian deformation. It is the detailed examination of the resulting structures in the critical Malin region of west Donegal lying within the main structural root zone which forms the subject of the subsequent section.

3. Structural evolution of the Malin region

Although no detailed structural studies have been undertaken in this critical area, a complicated polyphase history has long been suggested (Anderson, 1954). Johnston (1997) provides the only cohesive framework and broadly suggests that the dominant structures are northwest-vergent D2 thrust nappes,

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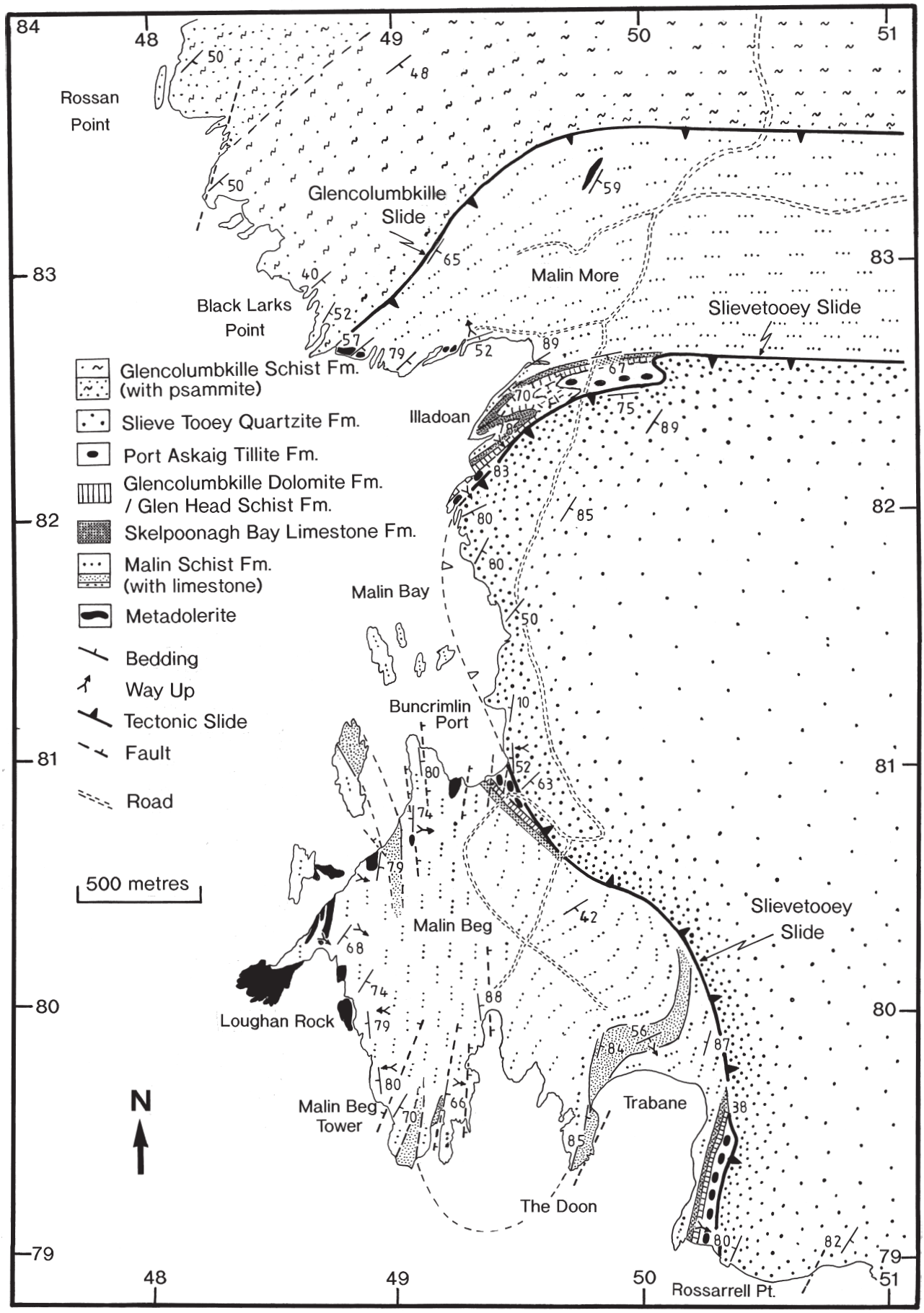


Figure 4. For legend see facing page.

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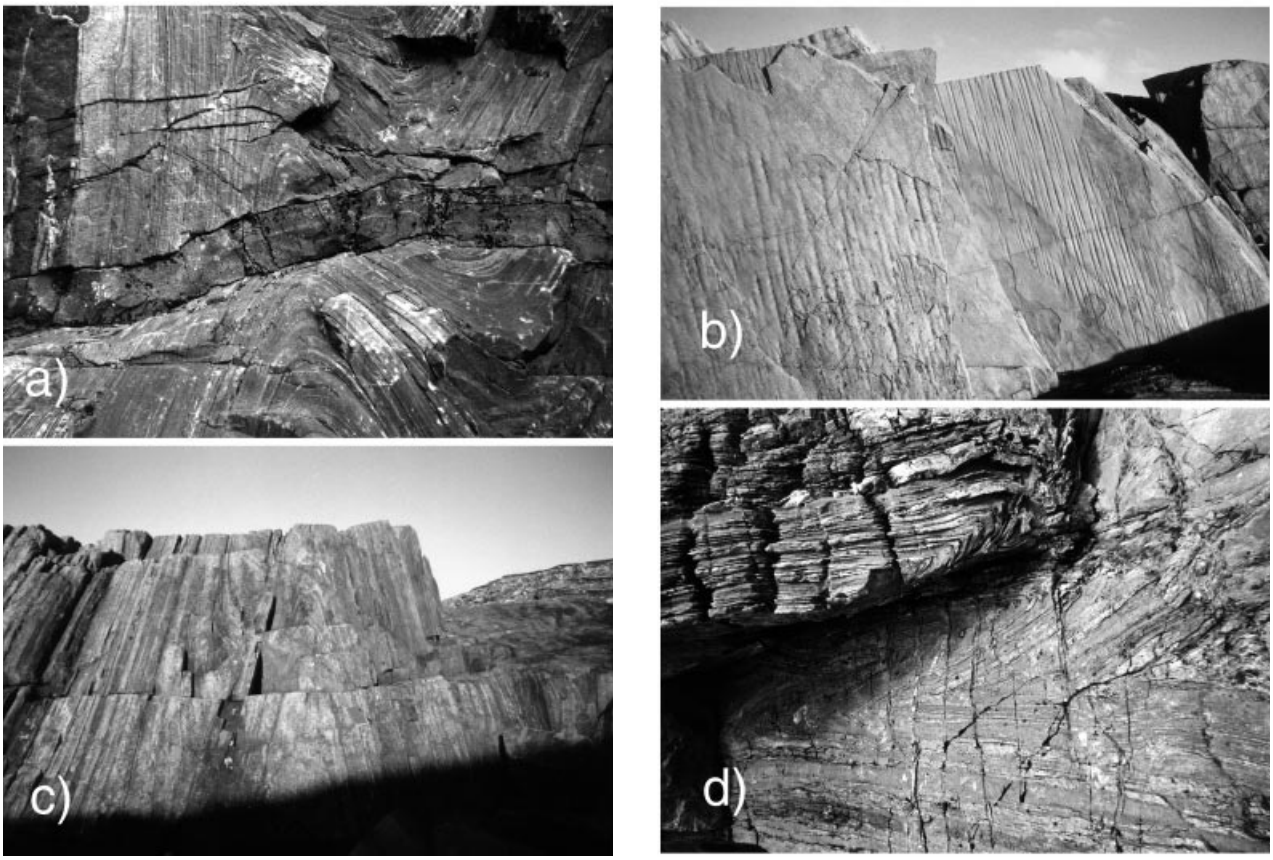


Figure 5. (a) Looking northeast at tight, upright F3 fold hinges developed within the Skelpoonagh Bay Limestone Formation and subsequently cross-cut by a post-tectonic lamprophyre. Refer to Figure 9 for more details. Field of view is ~2 m across. Illadoan Point, Malin More [G 4935 8235]. (b) View looking east at steeply south-plunging boudins developed within psammites on sub-vertical S2–S3 face. A quartz infill within the necks of boudins is observed at the top of the face. A moderately southwards-plunging mineral lineation is also clearly visible. Height of face ~5 m. Malin Schist Formation Malin Beg [G 4880 7990]. (c) View looking north of north–south-trending high-strain sub-vertical psammites of the Malin Schist Formation displaying isoclinal F2 fold pairs (foreground). 20 cm notebook for scale. Malin Beg [G 4885 7970]. (d) Looking northeast at tight, upright F2 dextral fold hinges developed within Skelpoonagh Bay Limestone Formation. Field of view ~2 m across. Illadoan Point, Malin More [G 4935 8235].

which is corroborated by this work (Fig. 3). Ductile deformation in the area may be broadly separated into four major phases (D1–D4) which result in the generation of folds and fabrics. Metadolerites appear to be deformed by both the S2 and S3 regional fabrics which are themselves locally folded by crenulations which may be traced into the regional S4 cleavage of the host rock. These relationships appear to indicate a pre-D2 age of metadolerite emplacement similar to that observed in Glencolumbkille immediately to the north (Alsop, Bryson & Hutton, 1998), but different to that observed elsewhere in Donegal at these stratigraphic levels (Hutton & Alsop, 1995). Peak metamorphic conditions in the area are associated with the growth of (subsequently chloritized) garnet porphyroblasts. These contain relict internal S2 cleavage alignment and are partially augened by S3, indicating a post-D2, pre-D3 (MP2) phase of metamorphism identical to that observed in Glencolumbkille (Alsop, Bryson & Hutton, 1998). Growth of 'late-stage' biotite porphyroblasts which overprint ductile (D4) fabrics is observed throughout the Malin and Glencolumbkille region (e.g. Howarth, Kilburn & Leake, 1966; Pitcher & Berger, 1972, p. 72).

Variably orientated, thin (typically < 1 m) hornblende–biotite lamprophyre sheets are observed to cut ductile D1–D4 deformation fabrics, indicating a post-tectonic age of intrusion (e.g. [G 49358235]) (Fig. 5a). Locally, the lamprophyres may be jointed [G 502795], or brecciated (e.g. [G 489827]) and associated with sulphide mineralization (e.g. [G 492818]). The similar relative timing relationships between deforma-

Figure 4. Simplified lithostratigraphic map showing the Dalradian of the Malin Bay area (see Fig. 2 for location). Minor intrusions (apart from metadolerites) are omitted for clarity. Note the tectonic nature of the Appin Group contacts (Malin Schist Formation–Port Askaig Tillite Formation).

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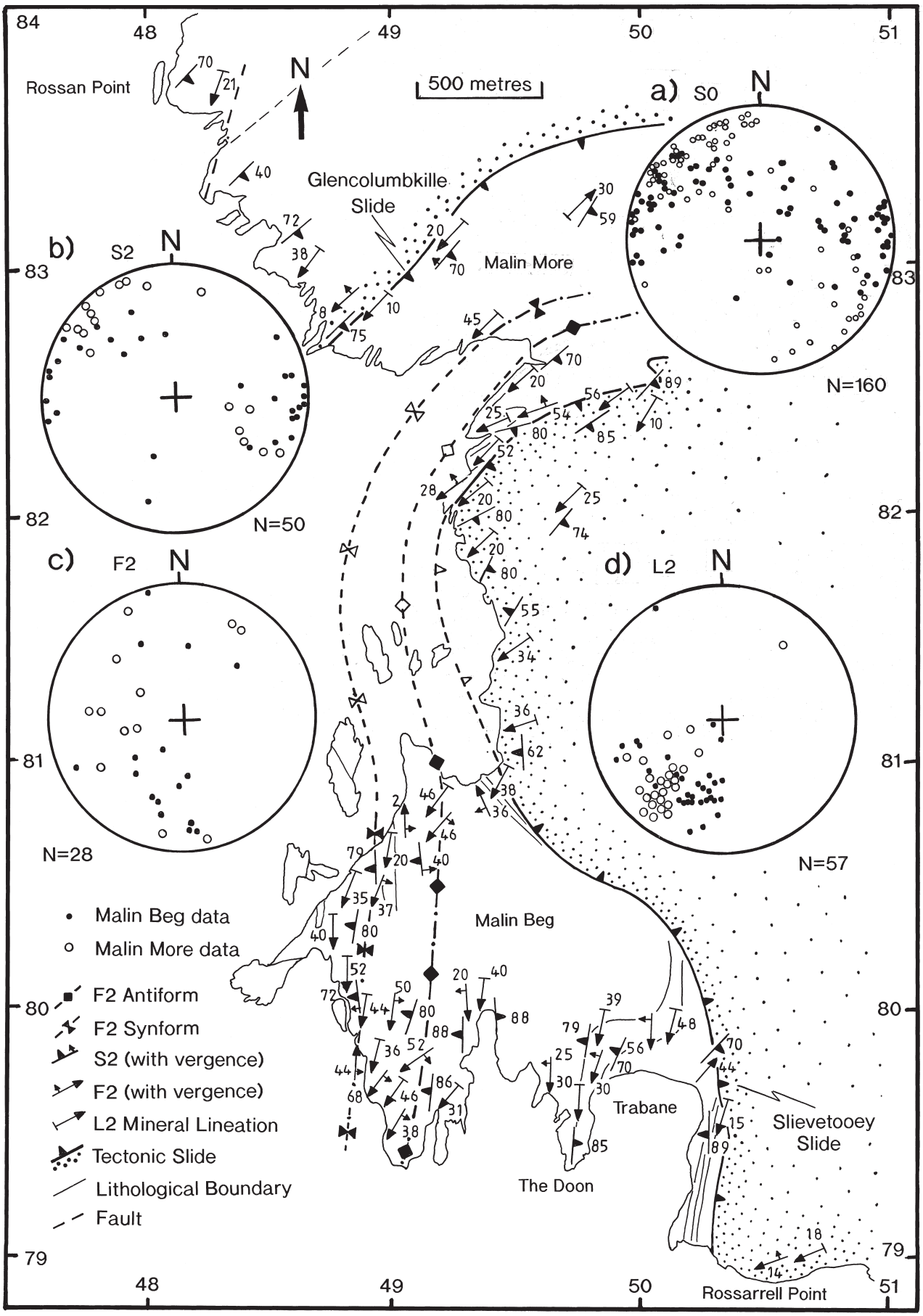


Figure 6. For legend see facing page.

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tion, metamorphism and igneous intrusion observed at Malin compared to elsewhere on the Slieve League Peninsula provide important constraints and strengthen the proposed regional correlation of deformation described in Section 5.

3.a. D1 structures

Evidence for early D1 minor structures has been largely destroyed by the intensity of subsequent deformation which results in fabric transposition. Over much of the Malin area, the dominant regional fabric observed at outcrop is axial planar to minor folds of bedding. The secondary nature of this regional (S2) cleavage is most clearly seen in thin sections from psammite bands within fold hinges, where it is defined by a closely spaced (< mm) alignment of mica-rich lithons separated by intervening quartz-rich lithons. Within pelites, the obvious pervasive S2 schistosity is (in thin section) an intense crenulation which is clearly folded around F3 fold hinges and recrenulated by the axial planar S3 cleavage (e.g. [G 493823]). The dominant regional cleavage thus clearly represents an S2 fabric, rather than a primary (S1) or slaty cleavage. We have observed no evidence of associated F1 folding or bedding cut across by S1, and the vergence and facing of D1 is thus indeterminable.

Whilst local reversals in D2 facing are not observed, stratigraphic relationships suggest that a major structural break associated with a reversal in the sense of younging (and hence facing) does occur across the Glencolumbkille Slide. This structure separates the largely right-way-up Glencolumbkille Schist Formation (Easdale Subgroup) in the hangingwall, from inverted Blair Atholl Subgroup (Malin Schist Formation, Glencolumbkille Dolomite Formation) and Islay Subgroup (Port Askaig Tillite Formation, Slieve Tooey Quartzite Formation) in the footwall to the slide (Figs 3, 4). Both tectonostratigraphic packages thus young in opposing directions away from the Glencolumbkille and Swilly slides, resulting in a reversal in the polarity of D2 and D3 structural facing on either margin of the slide (Fig. 3). Such a relationship is entirely consistent with observations on similar structures elsewhere on the Slieve League Peninsula (Alsop, Bryson & Hutton, 1998) and also in central Donegal (Alsop, 1992*b*) and suggests that a major F1 fold limb may have been transected by tectonic sliding (see Alsop, 1992*b*, 1994*a*,*b*) (see Section 5).

3.b. D2 structures

Structures generated during D2 represent the major phase of deformation recognized within the area and are associated with the development of tectonic slides (see Section 4), together with large-scale folds. Major F2 folds are tight-isoclinal, have wavelengths of 500 m and result in D3 and D4 facing reversals in Malin More and Malin Beg (Figs 4, 6, 7). The F2 fold package is bounded by the Glencolumbkille and Slievetooey slides and displays an overall dextral pattern of fold vergence, which after unfolding of subsequent F3 and F4 folding (see below) is consistent with original top-to-the-north F2 vergence.

As noted above, the main fabric observed at outcrop is considered to be S2, defined by a grain shape and alignment fabric of quartz, biotite, muscovite, chlorite and opaques in pelite. The intense (S2) crenulation cleavage, together with bedding (S0), is clearly folded around later F3 fold hinges and transected by the axial planar S3 cleavage (e.g. [G 493823]) (Fig. 8a). Within psammitic units, S2 is defined by a closely spaced (< mm) alignment of mica-rich lithons separated by intervening quartz-rich lithons, whilst in thick, relatively pure limestones, S2 may appear weak due to recrystallization. This schistose alignment of phyllosilicates and quartz grains typically maintains a slight obliquity to bedding (S0) within quartzite and psammitic units. Within pelitic horizons which have been pervasively deformed by D3 deformation, the S2 crenulation is transposed by an intense S3 crenulation cleavage resulting in a composite S2–S3 fabric. The orientation of S2 is governed by later F3 and F4 refolding, and typically trends northeast–southwest and is steeply southeast-dipping in the Malin More area, becoming north–south-trending and sub-vertical in Malin Beg (Figs 6, 7). In detail, S0 and S2 typically dip towards the east or southeast on F3 short limbs and are moderately west- or northwest-dipping on F3 long limbs (Fig. 6a,b).

S2 typically contains a mineral elongation lineation (L2), principally defined by quartz and mica and considered to represent the D2 stretching (X) direction. The L2 lineation is variably plunging towards the southwest in the Malin More area, and plunges moderately towards the south in the Malin Beg region (Figs 5b, 6d). L2 becomes noticeably more pronounced in areas of greater D2 strain adjacent to tectonic slides (see Section 4).

S2 is axial planar to minor (~1 m short limbs) F2 fold pairs of bedding and S1 which are most visible in the grey interbedded semipelites, quartzites and calcareous pelites of the Malin Schist Formation. F2 folds are typically isoclinal with similar geometries and curvilinear hinges, plunge steeply towards the south–southwest in the Malin Beg area and are more variable in Malin More (Figs 5c,d, 6c). The present orientation of F2 hinges is controlled by later F3 and

Figure 6. Simpified map of D2 structures in the Malin Bay area. Refer to Figure 4 for details of Dalradian lithologies. Inset stereonets (a–d) are equal area lower hemisphere projections of bedding and D2 structural data (poles to planar data). Note the more north–south trends of data from the Malin Beg subgroup area.

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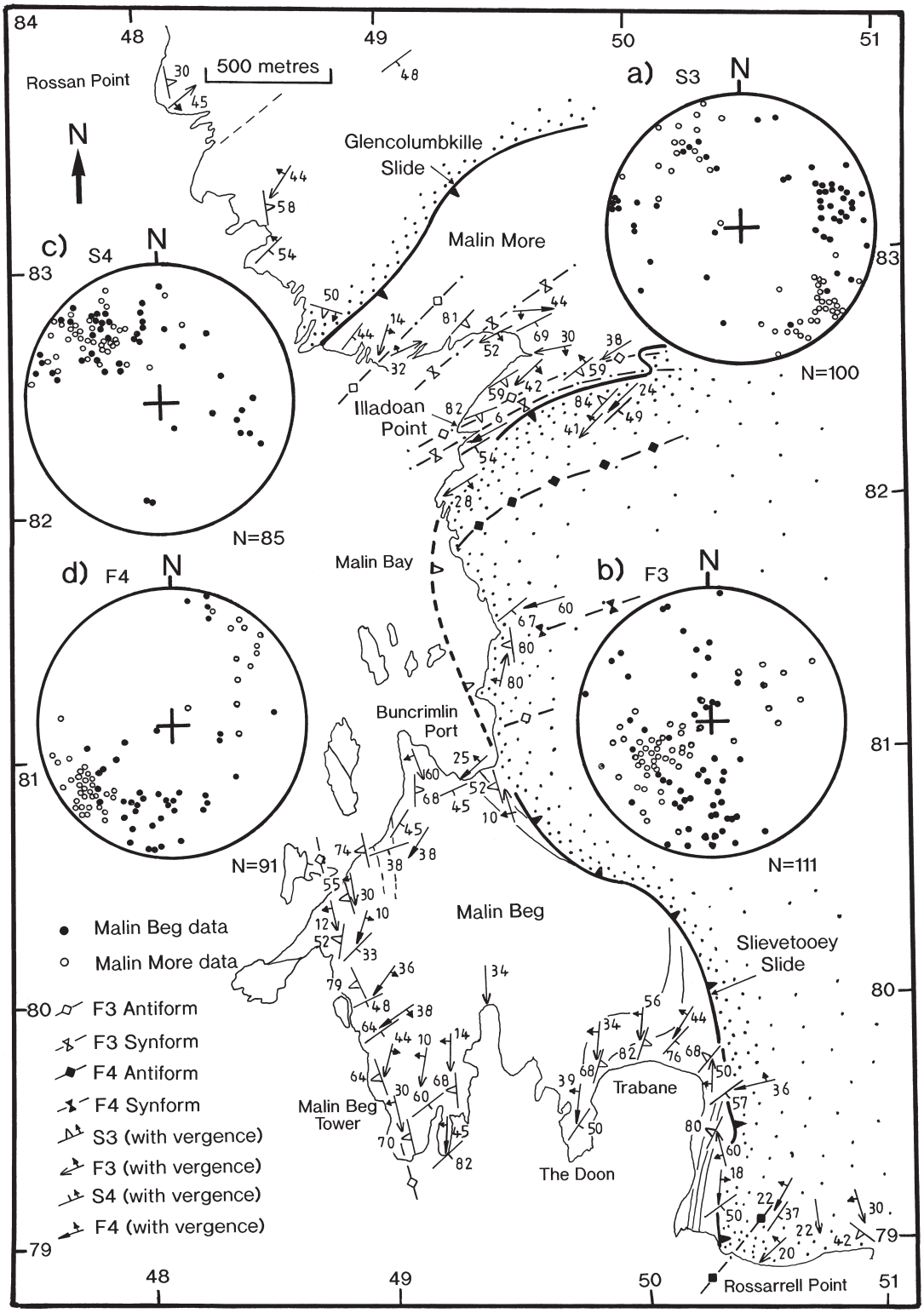


Figure 7. Simplified map of D3 and D4 structures in the Malin Bay area. Refer to Figure 4 for details of Dalradian lithologies. Inset stereonets (a–d) are equal area lower hemisphere projections of D3 and D4 structural data (poles to planar data). Note the more north–south trends of data from the Malin Beg subgroup area.

F4 refolding. Minor F2 fold pairs verge towards the associated major structures shown on Figure 6 and are obviously overprinted by the fine S3 crenulation cleavage. On sub-horizontal exposure surfaces, both sets of moderately to steeply plunging minor F2 and F3 fold pairs may display a similar sense of vergence, with earlier F2 folds being tightened by subsequent D3 deformation, making identification difficult. F2 and F3 minor folds may, however, be clearly separated on the short limbs of large sinistrally verging northeast-

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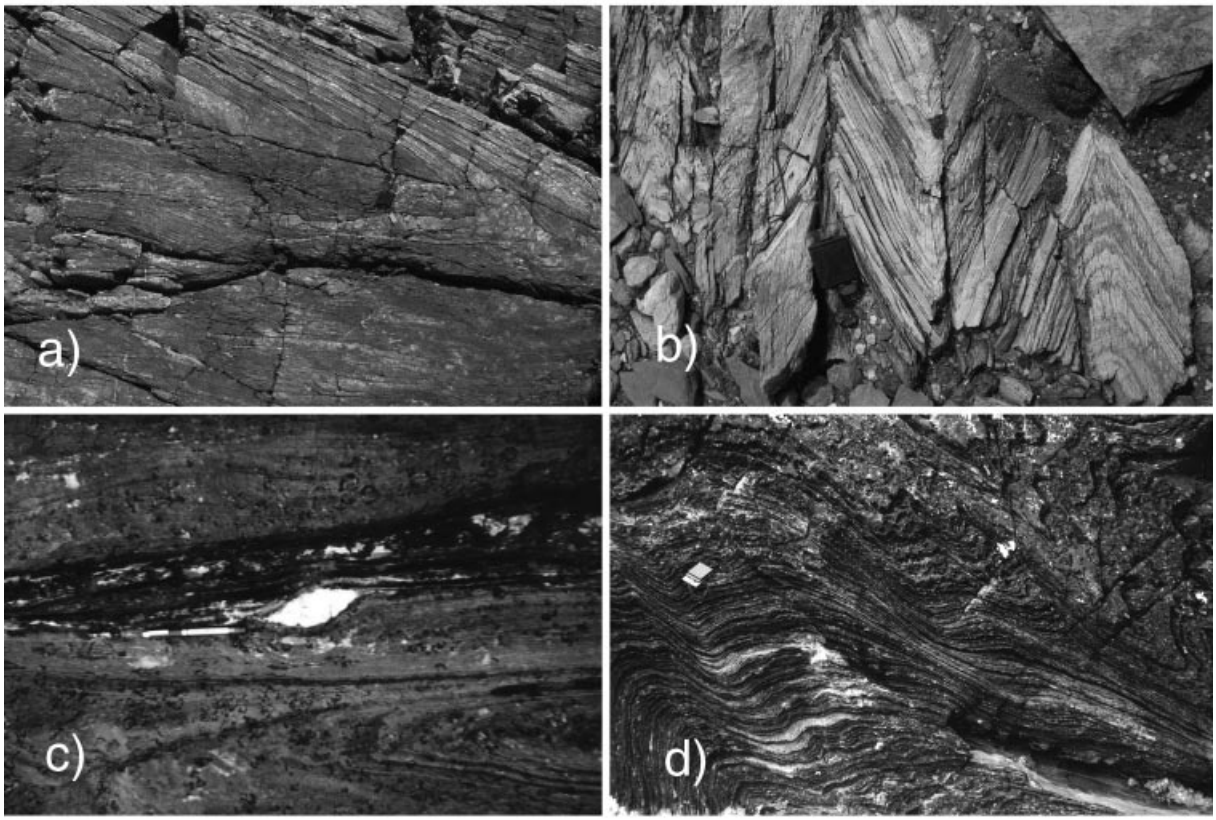


Figure 8. (a) Looking east at moderately northeast-plunging F3 fold pair. Psammitic member of the Glencolumbkille Schist Formation. Field of view ~4 m across. Rossan Point [G 4810 8370]. (b) Northeast–southwest-trending minor F4 hinges and intense southeast-dipping axial planar S4 cleavage. Psammitic member of the Glencolumbkille Schist Formation. 10 cm long compass for scale. Carickcall [G 4820 8330]. (c) Sheared quartz pod developed within Skelpoonagh Bay Limestone Formation indicating dextral (D2) shear. Plan view (northeast on right side of photograph). Pen is 13 cm long. Illadoan Point, Malin More [G 4935 8235]. (d) F2 folds developed within Skelpoonagh Bay Limestone Formation and displaying a component of dextral D2 shear on fold limbs. 10 cm long compass for scale. View looking southwest, Illadoan Point, Malin More [G 4935 8235].

facing F3 fold pairs, such as those exposed east of Illadoan Point [G 493823], where coaxial F2 and F3 folds display Type 3 'fish-hook' interference patterns and are readily distinguished by opposing vergence (e.g. [G 493823]) (Figs 7, 9a).

Cross-lamination, graded bedding and overall stratigraphic younging indicate that the F2 folds in Appin Group rocks adjacent to the Glencolumbkille Slide face sideways towards the south with an overall dextral vergence (Fig. 10). After unfolding F4 by rotating the regional, short steep limb up to the west–northwest, then D2 in the hangingwall of the Glencolumbkille Slide originally verged and faced towards the north–northeast (Fig. 11).

3.c. D3 structures

The present orientation of the major F2 isoclines and D2 structures described above is a consequence of subsequent refolding by F3 and F4 folds. The 500 m wavelength upright, F3 folds are typically gently to moderately plunging towards the southwest and are largely confined to the Malin Schist Formation bounded by D1–D3 tectonic sliding. Notably, however, major F3 folds are also developed within the Slieve Tooey Quartzite Formation in the footwall of the Slievetooey Slide, partially resulting in the strike-swing observed around Malin Bay which is exaggerated during D4 (Fig. 7). The F3 folds display overall sinistral vergence, (e.g. Illadoan Point [G 4935 8235]) (Fig. 4), which after restoration of F4 refolding (see above) indicates original top-to-the-south vergence (Fig. 11).

At outcrop scale, S2 is pervasively deformed and overprinted in pelitic horizons by an intense, finely spaced (0.1–0.2 mm wide) S3 crenulation cleavage associated with an alignment of opaque mineral grains, whilst in recrystallized limestone, S3 is typically marked by a planar schistosity. The overprinting relationships of S3 on S2 are most apparent in the hinges of mesoscopic F3 folds where the intensity of S3 increases, and also where the S3 crenulation is superimposed and transects earlier F2 fold pairs.

The S3 fabric is typically steep to sub-vertical and trends northeast–southwest in Malin More, and is north–south-trending and dips steeply to the west in

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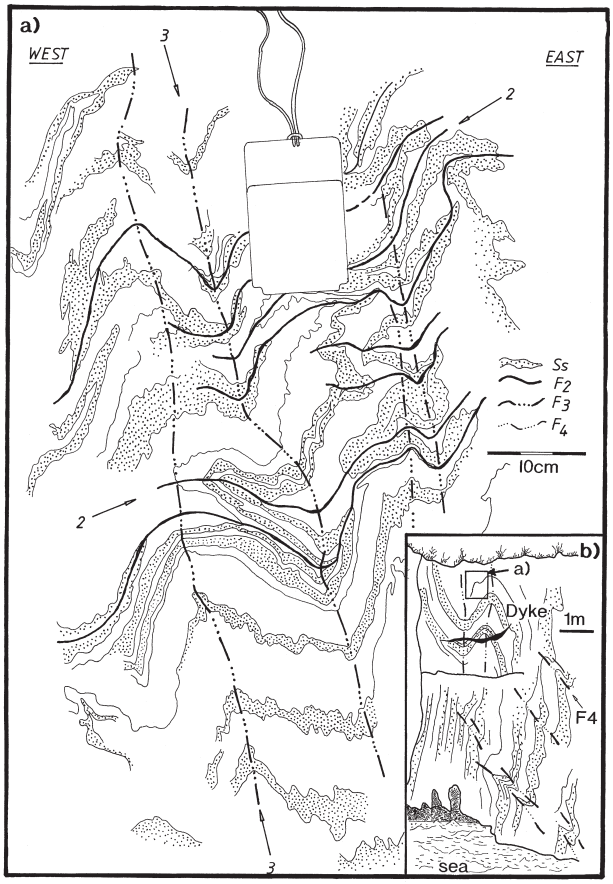


Figure 9. (a) Detailed field sketch showing Type 3 refolding relationships of F2 and F3 minor folds developed in the Skelpoonagh Bay Limestone Formation. Illadoan Point [G 4935 8235]. (b) shows the location of (a) and subsequent overprinting of F2 and F3 by locally southeast-verging F4 folds. This sketch also shows the location of the cross-cutting lamprophyre dyke illustrated in Figure 5a.

Malin Beg (Fig. 7a). The present orientation of S3 is considered a consequence of refolding by F4, together with some original variation due to refraction associated with lithological variability and D3 strain heterogeneity (see below). The fine S3 crenulation is axial planar to upright, minor F3 fold pairs which verge towards the associated major folds. F3 folds are typically close-tight with interlimb angles of ~24°, similar geometries and non-cylindrical curvilinear hinges, which typically plunge moderately to steeply towards the southwest in Malin More and towards the south in Malin Beg although orientations are more dispersed (Figs 7b, 8a). The tightness of minor F3 folding is extremely variable, and away from major F3 hinge zones interlimb angles are typically 100°–120°.

Mesoscopic F3 folding is highlighted by its development in the distinctive ~16 m thick Skelpoonagh Bay Limestone Formation, which is folded into a moderately southwest-plunging fold pair with a short (inverted) limb length of 100 m at Illadoan Point [G 493823] (Fig. 7). The major short limb of this F3 fold is associated with steeply plunging dextral northeast-verging minor F3 fold pairs. The short limbs of F3 folds are consistently thinned, with boudinage of bedding-parallel metadolerite sheets indicating layer-parallel extension (e.g. [G 493823]), resulting in the marked attenuation (to a thickness of ~10 m) of the Skelpoonagh Bay Limestone Formation.

Where D3 strain increases adjacent to tectonic slides, fabrics become composite (S2–S3) and the L2 mineral lineation becomes a compound L2–L3 lineation due to the coaxial nature of D2 and D3. A decrease in the interlimb angle is noted towards the mesoscopic hinge zones and especially the eastern synformal hinge adjacent to the Slievetooey Slide 100 m east of Illadoan Point. At this locality, F3 folds within quartzite beds become intrafolial with steeply dipping sheared limbs undergoing sinistral displacments of up to 1 m [G 494823]. With increasing strain, F3 fold hinges may become detached as observed near Malin Beg tower [G 488797], with the development of bedding-parallel boudinage associated with steeply southwest-plunging boudin necks. Although with increasing strain, fold axes typically rotate and become sub-parallel to the transport direction (see Alsop & Holdsworth, 1999, for a review), minor F3 fold hinges are occasionally observed to fold the L2 mineral elongation lineation (e.g. footwall of the Glencolumbkille Slide [G 49482828]).

Observations of younging (e.g. graded bedding), coupled with knowledge of the stratigraphic sequence within the Appin Group rocks, indicate that the dominant (sinistrally southwest-verging) F3 long limbs young towards the southeast whilst the short limbs young towards the north. Minor F3 fold hinges plunge moderately towards the southwest and typically face towards the east. Reversals in F3 facing are related to the existence of large-scale F2 isoclines. After unfolding F4 by rotating the regional, short steep limb up to the west, then D3 in the hangingwall of the Glencolumbkille Slide originally verged towards the south, whilst facing was predominantly towards the south although obviously controlled by its position relative to F2 hinges (Fig. 11).

3.d. D4 structures

An understanding of this late-phase of ductile–brittle deformation is crucial to the tectonic interpretation of the region as it controls the present disposition of the earlier D2–D3 structures (Fig. 11). Major northeast–southwest-trending F4 antiformal traces associated with reversals in D4 vergence are located at Rossarrell Point [G505790] and Malin Bay [G 492820] (Fig. 7). These F4 folds result in a reorientation of the earlier D2 and D3 structures such as the Slievetooey Slide from north–northeast-dipping,WNW–ESE-trending, as observed throughout much of the southern Slieve League Peninsula, to steeply dipping northeast–southwest or north–south trends in the Malin area

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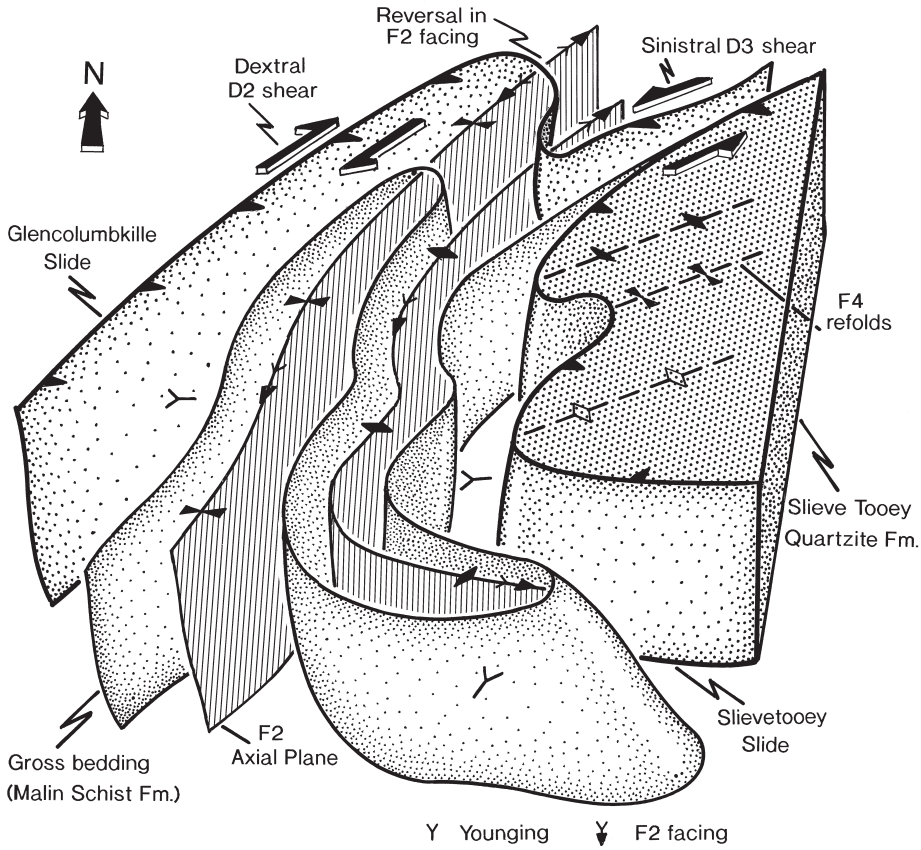


Figure 10. Schematic 3-D diagram illustrating the geometry of dextrally verging F2 folds within the Malin Schist Formation and subsequent refolding by sinistrally verging F3 and F4. Note the cut-out and excision by tectonic sliding, together with reversals in the polarity of F2 structural facing across the Glencolumbkille Slide.

(Figs 2, 7). Regional considerations and correlation with the Glencolumbkille area (Johnston, 1997; Alsop, Bryson & Hutton, 1998) indicate that the Malin region is on the short, steeply dipping limb of a major northwest-vergent D4 fold system associated with mesoscopic (hundreds of metres) short limbs (e.g. Rocky Point [G 491843]) (Figs 10, 11).

Within the Malin region, both the S2 and S3 fabrics are subsequently deformed by a zonal (1–3 mm) crenulation cleavage (S4) associated with minor folds of bedding and the earlier fabrics (Fig. 8b). This secondary S4 fabric is the most obvious crenulation over much of the area and clearly overprints minor F3 folds (e.g. [G 493823]). S4 intensifies into a discrete crenulation cleavage towards the Slievetooey Slide junction, where it is southeast-verging and transects F4 hinges in an anticlockwise sense (see Section 4). F4 folds may be associated with brittle deformation, resulting in the development of axial planar fractures and fault breccia up to 2 m thick (e.g. [G 487803]). Northeast–southwest-trending S4 crenulations typically dip moderately to steeply towards the southeast, although steep northwest-directed dips are also recorded in the Malin Beg area (Fig. 7c). S4 is axial planar to gently southwest-plunging F4 fold hinges which become gently south-plunging in the Malin Beg area (Fig. 7d). Minor F4 folds display a closed geometry and typically verge towards the southeast over much of the area and towards the asymmetric F4 antiforms at Rossarrell Point and Malin Bay, although regionally the F4 fold system is northwest-verging. Associated with F4 folding is a steeply south-plunging down-dip mineral lineation defined by pyrite which overprints the earlier L2 quartz mineral lineation [G 493800] and becomes more pronounced towards the hinge of the Rossarrell Point F4 Antiform (e.g. Trabane [G 499799]). This lineation is equivalent to the L4' lineation recorded in Glencolumbkille (Alsop, Bryson & Hutton, 1998), which is generated at a high angle to F4 hinges during D4 slip between competent lithologies.

Confirmation of the F2, F3, F4 refolding chronology is found in a prominant limestone band 150 m south of Illadoan Point where two stages of refolding are clearly developed. An irregular east–west-trending exposure surface reveals three interacting fold phases (Fig. 9a,b). An upright, tight fold pair with 1 m long short limbs (F3) coaxially refolds isoclinal, neutral-verging minor F2 folds. This interference pattern is subsequently refolded and transected by F4 folds and crenulations which are overturned towards the northwest.

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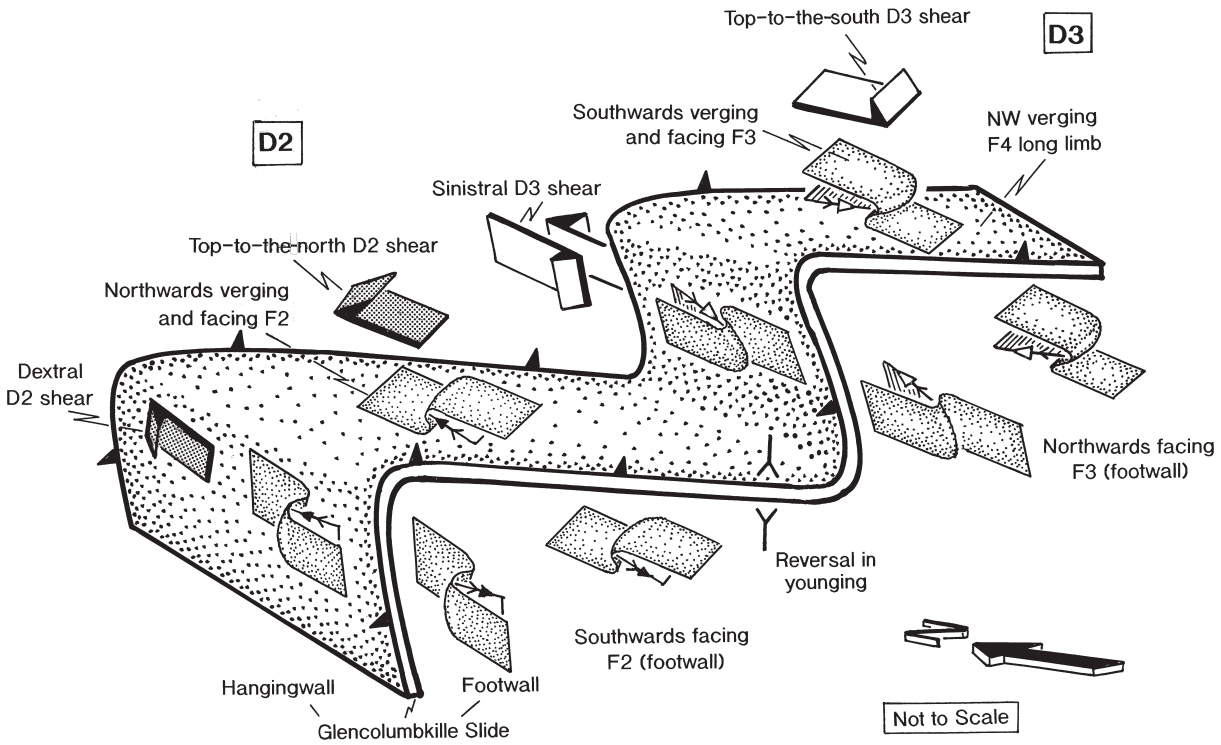


Figure 11. Schematic cartoon illustrating the geometry and kinematics of D2 and D3 structures and the effects of subsequent F4 refolding in the Malin Beg–Malin More area. The sketch demonstrates the effects of a reversal in younging across the Glencolumbkille Slide, and resulting reversals in F2 and F3 facing directions.

4. Tectonic slides

Tectonic slides are syn-metamorphic ductile dislocations marked by an intensification of regional deformation and frequently associated with distinct stratigraphic boundaries (see Hutton, 1979, 1981 for reviews). The major, composite D1–D3 Slievetooey and Glencolumbkille tectonic slides are developed at the base of the Argyll Group adjacent to the Malin Schist Formation (Appin Group) and are marked by an intensification of both D2 and D3 strain demonstrated by the increasingly intrafolial nature of minor folds, the hinges of which become non-cylindrical, and the development of a pronounced, gently southwest-plunging quartz-mica mineral elongation lineation (L2). The tectonic slides were active during D2 resulting in intense S2 fabrics, minor fold rotation, intrafolial F2 fold hinges and the development of centimetre-scale asymmetric quartz clasts indicating dextral (D2) shear (e.g. [G 493823]) (Fig. 8c, d). These tectonic slides were reactivated during D3 resulting in extensional crenulations, intense S3 fabrics, minor fold rotation, intra-folial F3 fold hinges, sheared quartz pods and metre-scale asymmetric boudinage of metadolerites all of which indicate sinistral (D3) translations (e.g. Illadoan Point [G 493823]). D2 and D3 deformation is considered coaxial, with the development of fold interference patterns and a composite L2–L3 mineral lineation (Figs 9, 10). S4 intensifies into a discrete crenulation cleavage towards the Slievetooey Slide junction, with minor crenulations and the S4 cleavage transecting fold hinges in an anticlockwise sense suggesting a dextral component of deformation. Thus, strain has been localized into tectonic slides bounding the Malin Schist Formation over a protracted tectonic history encompassing both dextral top-to-the-north (D2) and sinistral top-to-the-south (D3) components (Fig. 11).

4.a. Slievetooey Slide

The Slievetooey Slide is marked by 70 m of flaggy Slieve Tooey Quartzite Formation (e.g. [G498 822]) which in thin section is characterized by recrystallized quartz grains displaying limited undulose extinction and a strong phyllosilicate (muscovite) alignment. The slide contact displays a strong stretching lineation together with quartz veins < 1 m thick [G 493822] and sheared metre-scale pods of metadolerite [G 493820], and is marked by a distinct stratigraphic cut-out juxtaposing Glencolumbkille Dolomite and Port Askaig Tillite with Slieve Tooey Quartzite Formation. Where carbonates are juxtaposed along the tectonic slide, they are typically veined and brecciated on a millimetre scale [G 493820]. Dolomites are typically rubbly, producing a narrow gully parallel to the main fabric. The brecciated zone has sharp contacts with the well-foliated quartzite and contains angular fragments

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displaying disorientated fabrics and typically < 5 cm diameter [G 493822]. Within the highly deformed contact zone, deformation is focused and localized into narrow (15 cm wide) high-strain zones in which a pronounced L2 mineral lineation is developed [G 493822].

The slide has developed on the southwest-verging limb of the major F2 fold pair, but also cross-cuts F3 axial planes suggesting D3 reactivation (Figs 6, 10). This is supported by the intensification of S3 fabrics coupled with the increasingly curvilinear nature of F3 fold hinges (see Section 3.c). Intense D3 strains are observed adjacent to the slide east of Trabane, where an attenuated sequence of limestones and dolomites is observed together with increasingly platy Slieve Tooey Quartzite Formation (Figs 4, 7). Sinistral (D3) extensional crenulation cleavage is developed adjacent to the Slievetooey Slide (e.g. [G 500826]) and at Malin More (e.g. [G 493822]). Sheared quartz clasts up to 10 cm long indicate sinistral (D3) and dextral (D2) deformation across the Slievetooey Slide [G 493822]. Intense dextral F2 folding is developed in the Skelpoonagh Bay Limestone Formation [G 493822]. Dextral rotation of competent clasts within the Port Askaig Tillite Formation suggests intense D2 shear (e.g. Rossarrell Point [G 501791]) whilst sinistral D3 shear bands are developed along the same slide southwest of Buncrimlin Port [G 491807]. Asymmetric sinistral boudinage of metre-scale metadolerite pods is observed on the coastal outcrops [G 493822]. Anticlockwise transection of southeast-verging F4 fold hinges by the S4 cleavage, coupled with an intensification of S4 into a discrete crenulation cleavage, suggests continued reactivation during D4, possibly associated with dextral transpression (cf. Sanderson & Marchini, 1984) (e.g. [G 492820]). After unfolding of F4 deformation, dextral D2 shear equates to original top-to-the-north translation, whilst sinistral D3 shear relates to top-to-the-south deformation across the Slievetooey Slide (Figs 10, 11).

4.b. Glencolumbkille Slide

The Malin Schist Formation exposed to the southeast of the Glencolumbkille Slide [G 488828] is marked by increasingly platy and thinnly bedded quartzites and limestones. The Glencolumbkille Schist Formation to the northwest is dominated by graphitic pelites with thin grey psammites, and the slide contact between the two formations is sharp. On the well-exposed coastal sections, S2 and S3 fabrics clearly intensify towards the Glencolumbkille Slide (e.g. Portanagh [G 490825]) (Fig. 4). At the slide contact, steeply plunging, isoclinal F2 folds are typically dextral- (southeast)-verging, whilst sinistral (D3) shear bands are developed adjacent to the Glencolumbkille Slide (e.g. [G 481837]). This once again equates to original top-to-the-north D2 translation, and top-to-the-south D3 shear across the Glencolumbkille Slide (Figs 10, 11).

5. Regional tectonics and implications

The structural history of the Malin region described above will now be compared with the tectonic evolution of the Dalradian elsewhere in northwest Ireland to enable a structural framework to be developed. The implications of these findings will then be discussed with reference to models of orogenic root zones proposed for the Scottish Dalradian.

5.a. Kinematic evolution

The identification of a zone of high strain at the base of the Islay Subgroup (Slievetooey Slide) and the Easdale Subgroup (the Glencolumbkille Slide) are analogous to that observed in the Glencolumbkille region directly to the north (Alsop, Bryson & Hutton, 1998) (Figs 2, 3). This study provides further evidence for regional D1 dislocations at certain stratigraphic levels throughout the Dalradian of Donegal (Hutton & Alsop, 1995). Importantly, the Glencolumbkille Slide is at the same horizon as the Swilly Slide (Hutton & Alsop, 1997) and Central Donegal Slide (Alsop, 1992*b*, 1994*a*,*b*) observed elsewhere in Donegal (Fig. 1). Although the intensity of subsequent deformation has destroyed evidence of early minor folds and fabrics, a major reversal in stratigraphic younging is considered to occur across these structures including the Glencolumbkille Slide (Fig. 3). These tectonic slides are thought to be associated with significant D1 deformation in the Argyll and Southern Highland groups, which appears to intensify towards the south in an area marked by the regional Dalradian strike-swing and significant lateral facies variations. Initial (D1) deformation may thus be focused into areas of irregular original basin geometry (see Alsop, 1992*b*, 1994*a*,*b*; Hutton & Alsop, 1996). As the tectonic slides conceal reversals in structural facing, they are not considered a product of simple reactivation and inversion of extensional basin margin faults as suggested for elsewhere in the Dalradian by Soper & Anderton (1984).

D2 deformation is associated with north-directed thrusting as observed in the Glencolumbkille area (Alsop, Bryson & Hutton, 1998). In both the study area and the Glencolumbkille area, the age of thrusting is bracketed by the metamorphic peak (associated with garnet growth) which occurs directly after D2 (MP2) metamorphism. The geometry of ductile thrusting is inferred in Figure 3 where north-directed (D2) translations on tectonic slides are associated with northwards-verging F2 folding within intervening packages of rock. These observations are also consistent with northwest-directed regional (D2) ductile thrusting in the Dalradian of west and northwest Donegal (Hutton & Alsop, 1995, 1996, 1997; Jolley, 1996) and thus provide a coherent regional framework for deformation, although isotopic constraints on the age of thrusting in the Malin region are currently lacking (Figs 3, 11).

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Following north- and northwest-directed D2 ductile thrusting, both the study area and Glencolumbkille underwent intense southeast-directed D3 shear (Alsop, Bryson & Hutton, 1998). This deformation resulted in the reactivation of D2 ductile thrusts together with the formation of major southeast-facing fold nappes in the south of the Slieve League Peninsula (Figs 2, 3). The F3 Slieve League Antiform and Ballybofey Nappe of central Donegal and western Tyrone are considered to reflect the same (D3) deformation relating to gravity-driven flow off structural highs to the northwest (Alsop, 1994*b*). Deformation associated with southeast-directed shearing of the Ballybofey Nappe has recently been dated at ~470 Ma by Flowerdew *et al.* (2000), confirming the Grampian age of these major fold nappes. This southeast-directed shearing has thus been traced for ~120 km along strike from western Slieve League to the Sperrin Mountains (see Alsop & Hutton, 1993*a*,*b*, 1994), and is considered broadly equivalent to the southeast-directed translations observed in the southern Grampians of Scotland, although detailed correlations through the critical intervening ground must await further study. Significantly, major fold nappes, such as the Ballybofey Nappe of northwest Ireland, may thus represent one of the few places where both the upper and lower limbs of southeast-translated nappes are presently exposed, thus enabling complete structural traverses and strain gradients to be assessed (see Alsop, 1994*a*,*b*, 1996).

The present disposition of the D2 and D3 structures is controlled by subsequent northwest-vergent F4 folding which is developed on a large scale in both the study area and Glencolumbkille (Alsop, Bryson & Hutton, 1998) (Figs 3, 11). Dextral D4 shear is concentrated along existing tectonic slides, whilst to the north in the Glencolumbkille area, D4 shear is associated with sinistral transpressive deformation (Alsop, Bryson & Hutton, 1998). A major reversal in D4 shear sense is thus developed across the central part of the peninsula, with sinistral translation in the north and dextral in the south effectively extruding the central block towards the east from the possible hinge of the major strike-swing further to west in the present Atlantic. The geometry of the root zone may thus be partially controlled by tectonics associated with relatively late lateral extrusion and shearing.

5.b. Regional correlations and models of root zones

The term 'root zone', as defined by Ramsay & Huber (1987), is a purely descriptive geometrical term which has no implication concerning the generation and evolution of the root zone. Consequently, several different tectonic processes may generate root zones in different orogenic belts. The Pennine Nappes of the Swiss Alps comprise both oceanic and continental rocks which may be traced into adjacent vertical or subvertical root zones (e.g. Ring, 1992) which have undergone relatively late strike-slip deformation (e.g. Schmid, Zingg & Handy, 1987). The Proterozoic Irumide Belt of Zambia displays divergent thrusting associated with opposing facing directions centred about a central root zone marked by upright, upward-facing folds and rocks of possible oceanic affinity. In these instances root zones may thus conceal sutures, with widespread implications for the overall plate tectonic evolution. Root zones may be marked by divergent thrusting across them, which in the case of the the Irumide Belt, has been interpreted as a region of simple backthrusting centred about the root zone (e.g. Daly, 1986). Root zone geometries may also be the product of multiple folding where regional thrusts are simply rotated into more steeply dipping attitudes during subsequent deformation within 'cover' sequences (see below).

A number of models have been proposed to explain the apparent overall symmetry of recumbent nappes and tectonic slides diverging away from a central, upright root zone in the Dalradian of the southwest and central Grampian Highlands of Scotland. In the 'mushroom' model of Sturt (1961) and Thomas (1979, 1980), lateral compression results in a central root zone which separates northwest-facing and -verging D1 fold nappes in the northwest from coeval, but southeast-facing and -verging nappes to the southeast. Roberts & Treagus (1977, 1979) and Treagus (1987) prefer a model incorporating early, upright (D1) folds centred above the root zone, which fan outwards to produce a 'fountain of nappes' geometry during subsequent (D2) deformation associated with gravity collapse. D2 deformation in deeper levels was associated with top-to-the-northwest shear, whilst at higher levels D2 shear was directed towards the southeast (Nell, 1986; Treagus, 1987; Krabbendam *et al.* 1997). A recent model by Treagus (1999) suggests that D2 deformation is dominated by pure shear at deeper crustal levels, whilst higher levels display gravity-driven simple shear directed towards the southeast.

The control of original basin architecture on root zones in the Central Highlands which incorporate major, upright primary folds has been suggested by Robertson & Smith (1999). The overall setting of the Slieve League Peninsula in a major zone of lateral facies variation associated with a regional strike-swing (coupled with the noted facies variation in both the Appin and Argyll groups) suggests that such primary basinal controls may be significant factors in the location and structural evolution of root zones. Large-scale regional models in which dominant northwest-directed shearing leads to crustal thickening resulting in southeast-directed gravity-driven collapse have been suggested by Coward (1983) and Dewey & Shackleton (1984). These models do not necessitate 'root zones' to nappes and question the validity of such a hypothesis based on space problems between narrow root zones and large nappes (Shackleton, 1979; Coward, 1983).

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This study clearly documents north-directed D2 shear on both flanks of the synformal 'root zone' suggesting that a 'mushroom' model associated with coeval divergent nappe translations away from the central zone is inappropriate in northwestern Ireland. Similarly, south-directed regional D2 shear has not been observed, whilst south-directed D3 shear is constant across the area and locally reactivates earlier D2 structures. Our observations of precise timing relationships between north-directed D2 thrusting, followed by south-directed D3 shear associated with fold nappe translation, suggest that a model incorporating regional thrusting followed by southeast-directed gravity collapse is most appropriate.

6. Conclusions

The broad, upright synformal fold present on the Slieve League Peninsula has an across-strike width of 20 km, with Islay Quartzite defining both fold limbs and the Easdale Subgroup pelites preserved within the hinge (Fig. 3). The synform is east–west-trending in west Donegal and is considered equivalent to the structurally higher northeast–southwest-trending Lough Foyle/Loch Awe Syncline of northeast Donegal and the southwest Highlands of Scotland. The overall orientation and geometry therefore reflect the regional Caledonian strike-swing of western Ireland, indicating the strong control exerted by the pre-existing geometry of the Laurentian margin on Caledonian orogenesis. At the structural level analysed in western Slieve League, the early (D1) relationships are heavily overprinted by subsequent deformation. However, structural and stratigraphic relationships support a reversal in the polarity of D2 facing directions across major tectonic slides, indicating a significant D1 dislocation at the base of the Easdale Subgroup as observed elsewhere in Donegal.

Top-to-the-north (D2) thrusting is preserved consistently across the root zone indicating that there is no reversal in nappe translation across the root zone as envisaged in a mushrooming 'fountain of nappes' hypothesis (Sturt, 1961; Thomas, 1979, 1980). Top-to-the-southeast (D3) deformation becomes increasingly intense towards the south with the present overall synformal geometry reflecting the interplay and interference between these deformation phases. There is thus no reversal in D2 and D3 shear across the supposed root zone, and no direct evidence of pure shear-dominated deformation at greater structural depths as suggested by Treagus (1999) in the Central Highlands. Southeast-directed D3 shear may be interpreted as retrocharriage or 'back-folding' following the north-directed D2 crustal thickening associated with peak metamorphic conditions (e.g. Alsop, 1994*b*). This study clearly demonstrates that root zone geometries may thus be a product of large-scale fold interference generated during progressive and/or multiple phases of deformation within orogenic belts.

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