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Extensional geometries as a result of regional scale thrusting: tectonic slides of the Dunlewy–NW Donegal area, Ireland

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Abstract—The synmetamorphic ductile dislocations, known in the British Caledonian literature as 'Tectonic Slides', pose a classical structural problem. That is, despite being associated with synchronous contractional folds and cleavages the low angle dislocations have the effect, in many celebrated cases, of juxtaposing younger over older rocks: a geometry normally associated with extensional rather than contractional deformation. Recent models have attempted to demonstrate that this is the result of thrust reactivation of original, sedimentary, extensional growth faults.

The Appin Group Dalradian metasediments of the complex and small Dunlewy area of NW Donegal, Ireland, contain the following geometric elements: (a) an early strike-swing-related stratigraphic facies change; (b) a major inter-deformational dolerite sheet; (c) major regional recumbent folds and slides; (d) major structures related to the 400 Ma sinistral Main Donegal Granite shear zone. This solution to the structural geometry reveals that the early mid-crustal (~11 km depth) D_2 Ardsbeg–Dunlewy Slide is a thrust to the northwest. Its hangingwall contains rocks two-thirds of which are younger than the rocks of the footwall, together with major recumbent folds, coeval with the underlying thrust, which face downwards into the thrust in the direction of transport. Rather than thrust reactivation of an original extensional growth fault, we find that both stratigraphic and structural constraints are satisfied by a double thrusting model, with fault-bend folding onto an upper ramp of an earlier formed but penecontemporaneous and kinematically linked major fold pair.

This solution to the geology also allows us to recognize that the regional (pre-granite) structure of the Dalradian of NW Donegal is a series of major D_2 synmetamorphic thrust bounded nappes possibly involving up to 250 km of northwesterly overthrusting.

INTRODUCTION

Tectonic slides (Bailey 1910, for a review see Hutton 1979a) are ductile faults coeval with major folds and fabrics that are generated in polyphase mid- to lower crustal deformational domains. Although occurring within broad ductile shear zones they are typically sharp stratigraphical discontinuities associated with the gradual low-angle cut-out of the rocks on either side. Bailey originally recognized that slides can have older over younger 'thrust' geometries, as well as younger over older 'lag' geometries, and that the latter were difficult to explain in terms of contractional tectonics (Bailey 1938). More recently, Soper & Anderton (1984) and Anderton (1985, 1988) have proposed that the more common lag-type, apparently extensional, geometries, are the result of contractional (thrusting) along old sedimentary growth fault planes. This hypothesis, although criticized for its lack of structural considerations and absence of strong supporting data by Roberts & Treagus (1990), remains the only general model for these unusual stratigraphic and structural relationships. Most recently, Glover (1993) has proposed that the major Fort William Slide in the SW Scottish Highlands is not a tectonic feature at all, but rather an intra-Dalradian unconformity.

In order to address the general problem, the complex Caledonian structures developed in the Dalradian rocks around the village of Dunlewy, to the northwest of the Main Donegal Granite, in NW Ireland have been examined (Figs. 1 & 2). This small (~20 km^2) area, which has been the subject of extensive earlier work (Nolan, in Hull *et al.* 1891, Rickard 1962, 1963, 1971), contains: (a) a major stratigraphical facies variation in the Dalradian sediments; (b) early slide and fold relationships; (c) a major cross-cutting inter-deformational dolerite sheet; and (d) structures associated with the early Devonian Main Donegal Granite Shear Zone (Hutton 1982). The regional (D_2) metamorphic paragenesis in pelitic rocks is biotite grade within the greenschist facies. During the emplacement of the Main Donegal Granite and the development of associated structures, pressure remained equivalent to an overburden of ~11 km (Pitcher & Berger 1972). Such is the importance of this area in deciphering the origin and nature of tectonic slides, that we present below, in necessary detail, the field observations, structural and stratigraphic analysis that allow the early fold and slide relationships to be

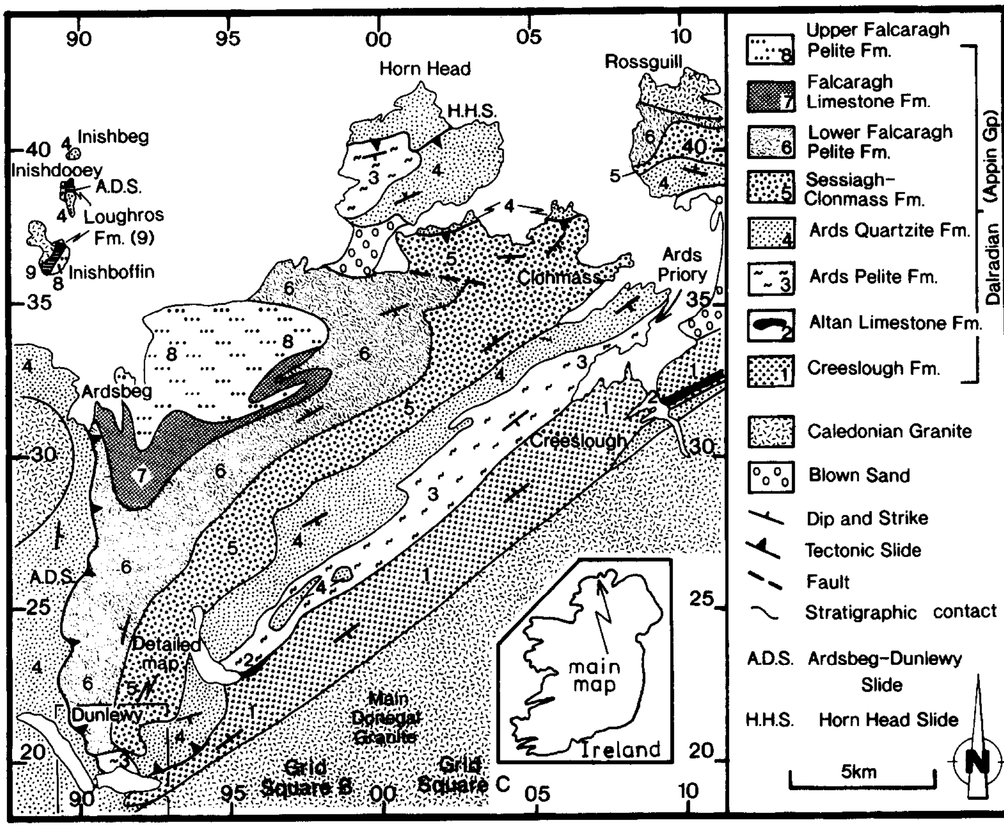

Fig. 1. Location map and general geology of the Dalradian rocks of NW Donegal (modified from Pitcher & Berger 1972, Hutton 1982). Lithological symbols and numbers are used in subsequent figures. Area of detailed mapping shown in Fig. 2 is indicated in outline.

unravelled from the other major events in the geological history.

STRATIGRAPHIC FRAMEWORK

The late Precambrian (Appin Group) Dalradian stratigraphy of NW Donegal has been extensively described and discussed elsewhere (Pitcher & Berger 1972, Hutton 1982b). The sequence and its Scottish equivalent is shown in Table 1, together with a basic description of the units involved. All contacts, as demonstrated either here or elsewhere in Donegal, are stratigraphic and usually transitional. Whilst accepting the main sequence of Creeslough Formation, (oldest), Altan Limestone, Ards Pelite, (Ards Transition member), Ards Quartzite, Sessiagh Clonmass Formation, Lower Falcarragh Pelite, Falcarragh Limestone, Upper Falcarragh Pelite, Loughros Formation (youngest), some additional locally important units are recognized. A thin limestone (member) is seen within the Creeslough Formation in Dunlewy and is correlated with the Duntally Limestone of McCall (1954) in an adjacent area. A further thin and impersistent limestone occurs within the Ards Pelite and is here named the Dunlewy Limestone (member). McCall's (1954) division of the Sessiagh–Clonmass Formation into three limestone members separated by two quartzites is difficult to sustain in this area (see Rickard 1962) and elsewhere (Pitcher & Berger 1972). A simpler sequence is preferred involving a lower dolomitic limestone member (the Clonmass Limestone) transitional with the Ards Quartzite, a succeeding thinly bedded quartzite often with pelitic and calcareous pelite intercalations (the Sessiagh Quartzite) and an upper dolomitic limestone [the Port Limestone (member)] transitional with the overlying Lower Falcarragh Pelites. (See also Rickard 1962.)

STRUCTURAL FRAMEWORK

The rocks of NW Donegal have been affected by a protracted sequence of deformational episodes (see Hutton 1982b) of which only two produce major structures. Within the established deformation sequence these are numbered D_2 and D_6 (Fig. 3). D_2 structures are regional and Caledonian in nature and associated with gently inclined cleavages, recumbent folds and slides. We refer to this in what follows as *Main phase structures*. D_6 is localized around the Main Donegal Granite and is considered (Hutton 1982a) to be part of a major transcurrent shear zone with steep fabrics and upright folds. We refer to this in the sequel as *shear zone structures*. Before proceeding to describe these regional structures we deal briefly with the details of the minor structural chronology.

The first deformational event to affect these rocks is only rarely preserved because of overprinting and transposition processes. S_1 is a fabric subparallel to bedding and major structures are absent. The main phase cleavage (S_2) is a pervasive schistosity which only in mesoscopic F_2 fold hinges is identifiable as a crenulating cleavage. Generally S_2 dips gently towards the north-northwest and south-southeast (Fig. 4b), and is associated with a well developed mineral stretching lineation (Fig. 4e) which is generally northwest–southeast but swings to east–west within the area. Minor F_2 folds and bedding/cleavage intersections are shallow plunging and

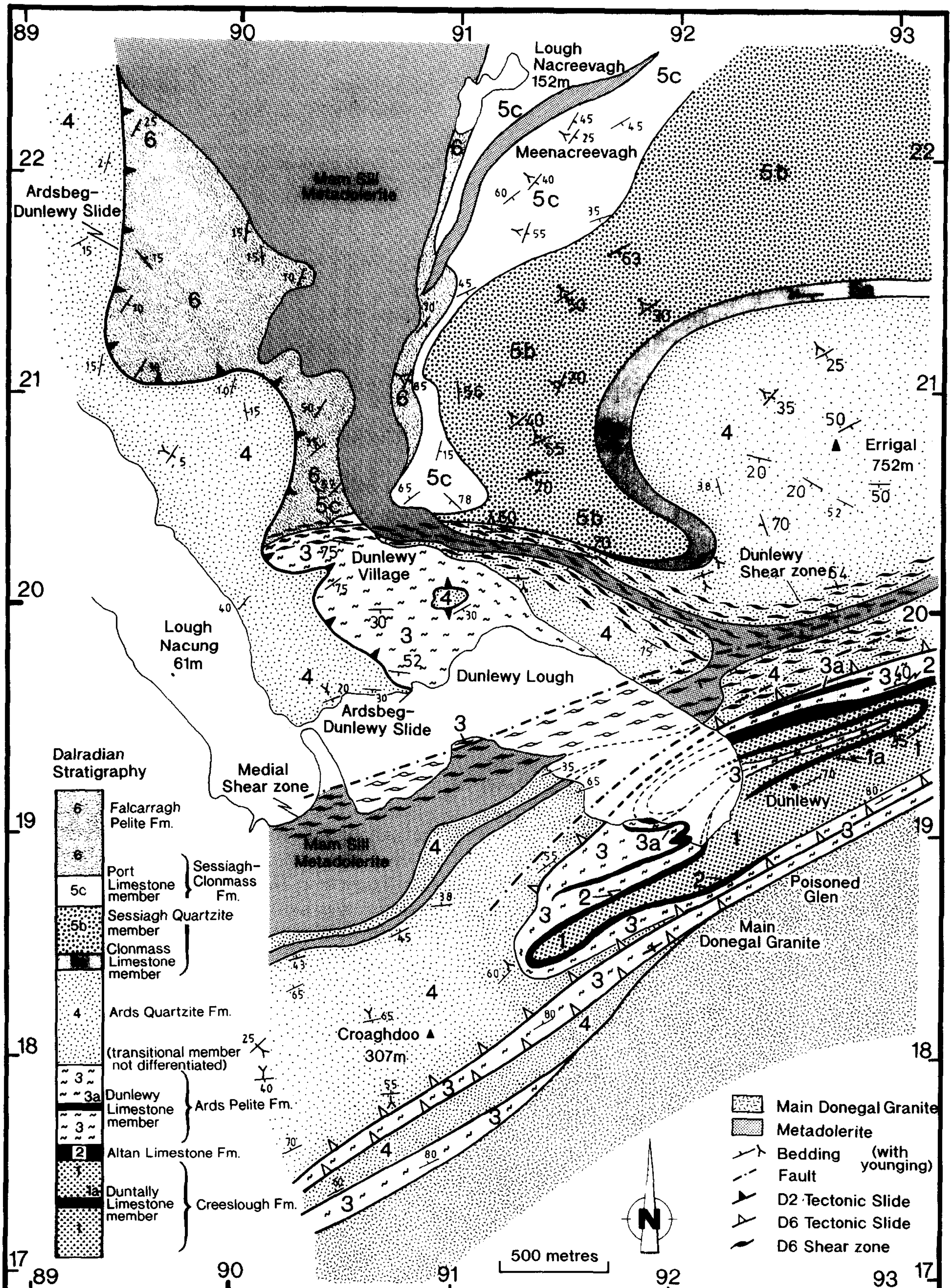

Fig. 2. Solid geology of the Dunlewy area together with slides and shear zones.

Table 1. Stratigraphic and lithological summary of the Dalradian sequence in NW Donegal and Scottish equivalents.

NW Donegal–Creeslough (Pitcher & Berger 1972)		Ballachulish–Appin (Harris & Pitcher 1975)	Dalradian subgroups (Harris & Pitcher 1975)
7 Falcarrach Limestone	(grey and blue limestone)	Lismore Limestone	
6 Lower Falcarragh Pelite	(black graphitic pelites)	Cuil Bay Slates	—
5 Sessiagh–Clonmass Formation	[members—Port Dolomotic Limestone (5c), Sessiagh Banded Quartzite (5b), Clonmass Dolomite Limestone (5a)]	Appin Phyllite and Limestone	
9 Loughros Formation	(impure quartzite and banded pelite)	—	
8 Upper Falcarragh Pelite	(graphitic pelites with silt bands)	—	Blair Atholl
4 Ards Quartzite	(well bedded and massive quartzites)	Appin Quartzite	Ballachulish
3 Ards Pelite	(black graphitic pelites and thin limestones, including the Dunlewy Limestone (member 3a))	Ballachulish Slate	
2 Altan Limestone	(grey and creamy limestone)	Ballachulish Limestone	—
1 Creeslough Formation	(pale grey calc-pelites and limestones, including the Duntally Limestone (member 1a))	Leven Schists	Lochaber

variable in orientation with modes between northeast–southwest and east–west (Fig. 4f). The facing of F_2 structures is towards the northwest and major slides and recumbent folds of this (main phase) age are well developed.

Subsequent to the formation of the regional foliation (S_2) and lineation (L_2), several sets of overprinting secondary folds and fabrics can be distinguished. These structures are directly related to the continued development of main phase structures during protracted regional deformation. The main regional fabric is sporadically cut by a gently northwest- and west-dipping crenulation cleavage (S_3) (Fig. 4d), which, because of its low angle to bedding and the earlier fabrics produces a wide variety of orientations of its intersection lineation and minor F_3 fold axes (Fig. 4d). D_3 structures generally verge south-southeast, southeast and east. A larger (kilometer scale) monoformal F_3 ESE-vergent fold has been mapped in the townland of Meenacreevagh. Small biotite porphyroblasts overprinting S_2 and crenulated by S_3 indicate that the peak of regional metamorphism occurred in the D_2–D_3 interval as seen elsewhere in NW Donegal (Hutton 1982b). In the area of the Sessiagh–Clonmass Formation to the west of the Errigal Mountain, these early gently inclined cleavages are cross-cut by steep, generally N–S-trending cleavages, one with E-dips and W-vergence (S_4), and another less common W-dipping and E-vergent (S_5) (Fig. 4h). Major structures of this age are not seen.

Shear zone structures are represented by a steeply inclined E–W-trending crenulation cleavage (S_6) which intensifies southwards into a NE–SW-trending schistosity (Fig. 4c) and associated gently plunging fold axes (Fig. 4g) and co-linear mineral stretching lineation (Fig. 4e). Within the syn-kinematic aureole of the granite the S_6 shear zone schistosity transposes all previous cleavages. Subsequent deformation within the shear zone produced a series of overprinting secondary structures. The most important of these are conjugate extensional crenulation cleavages (D_8) of which the more common north-northeast–south-southwest set has sinistral extensional offsets related to the overall sinistral character of the major shear zone (see Hutton 1982b). Having briefly described the complete deformational history we move now to a more detailed examination of the regionally significant 'Main Phase' (D_2) and 'Shear Zone' (D_6) structures.

REGIONAL STRUCTURE

The Main Donegal Granite Shear Zone Structures (D_6)

On the southeast side of Dunlewy Lough an originally right-way-up sequence of Ards Quartzite Formation (intruded by a metadolerite), underlain by Ards Pelite Formation, Altan Limestone Member and the Creeslough Formation together with a number of other discontinuous limestones are folded into a gently SW-plunging steeply NW-inclined, upward facing major F_6 antiform which contains a number of subsidiary hinges (Figs. 2 and 3). To the south of this major antiform, the Ards Quartzite Formation/Ards Transition Member pair are repeated by two D_6 tectonic slides associated with mylonite zones. The northernmost of these cuts out a second-order F_6 synform, together with the Ards Quartzite Formation/Ards Pelite Formation boundary in the hangingwall, and ultimately juxtaposes two separate units of the Ards Transition Member.

Whilst pervasive D_6 strains generally diminish northwards this pattern is heterogeneous. Thus in the metadolerite immediately south of Dunlewy Lough, the N-dipping S_6 intensifies irregularly northwards and the metadolerite is inferred to be in D_6 tectonic contact with the Ards Pelite Formation to the north. To the immediate north of the lough, however, D_6 strains are much lower and so a zone of high D_6 strain is inferred to run along the middle of the lough. This zone is seen along strike to the east where it intersects the Ards Quartzite Formation/Ards Pelite Formation boundary south of Errigal Mountain, resulting in tectonic sliding along this contact. This 'Medial Shear Zone' also separates N-dipping bedding, S_2 and S_6, and SE-vergent F_6 in the south from S-dipping S_2 and S_6, and NW-vergent F_6 in the north, and the shear zone is therefore coincident with a major F_6 synform hinge (Figs. 2, 3, 5 and 6).

D_6 strains intensify northwards again within and particularly along the southern boundary of the WNW-striking outcrop of Ards Quartzite west of Errigal. Approaching this zone from the south (Fig. 3), gently S-dipping S_2 is folded about gentle to open N-vergent F_6 fold pairs with wavelengths of 10–20 m. Within about 50 m of the Ards Quartzite Formation contact, S_2 steepens to a uniform dip of about 40° south before, further north, being transposed entirely by the near vertical or steeply S-dipping S_6 cleavage and its associated gently plunging mineral lineation. As D_6 strains diminish on the north side of the zone, S_2 emerges, now dipping steeply to moderately north, and within a few hundred metres further north, it dips gently northwest and S_6 is a weakly developed cross-cutting crenulation cleavage. In this 'Dunlewy Shear Zone' as discussed below, although S_2 steepens to vertical, bedding remains steep, because of the superimposition of the D_6 shear zone on the hinge

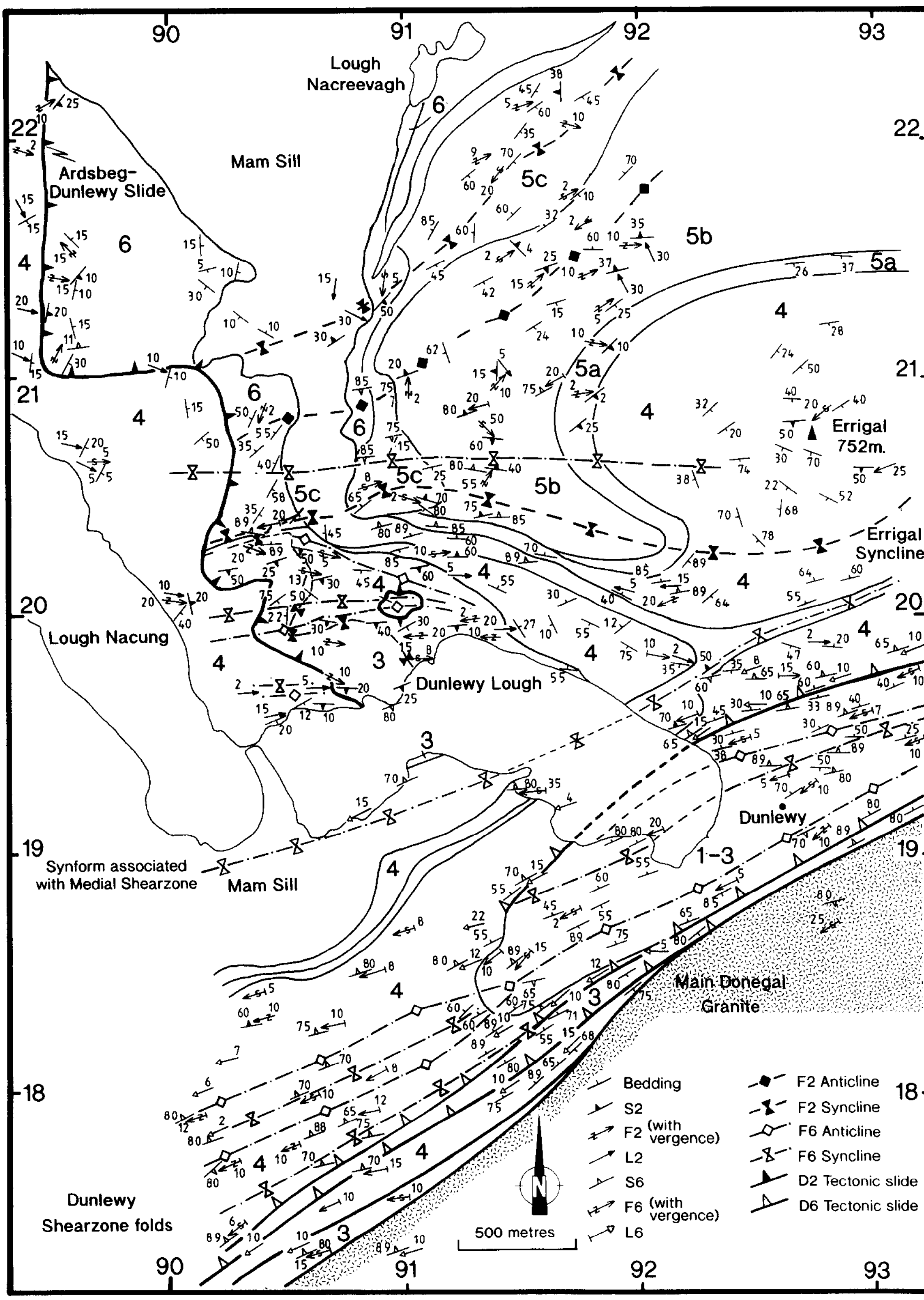

Fig. 3. Summary structural map of the Dunlewy area. Refer to Fig. 2 for details of Dalradian lithologies.

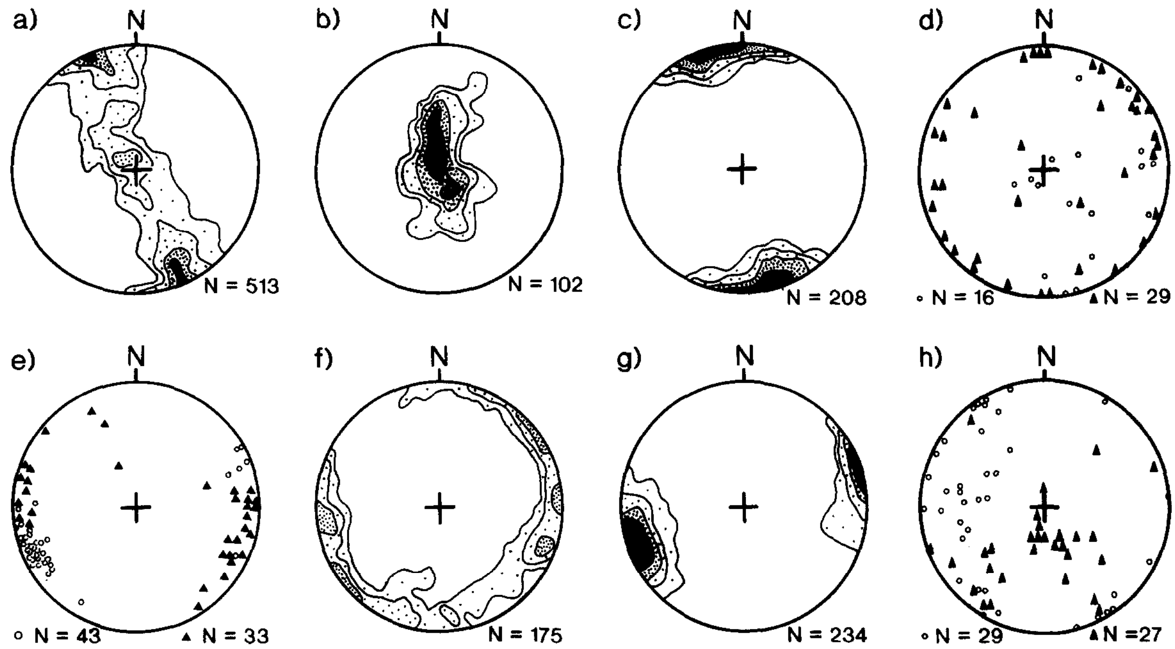

Fig. 4. Stereograms of structural data. (a) Poles to bedding; (b) poles to S_2; (c) poles to S_6; (d) poles to S_3 (open circles), D_3 intersection lineations and minor fold axes (triangles); (e) D_6 stretching lineation (open circles), D_2 stretching lineation (triangles); (f) D_2 intersection lineations and minor fold axes; (g) D_6 intersection lineations and minor fold axes; (h) poles to S_4 (open circles) D_4 intersection lineations and minor fold axes (triangles).

of the D_2 Errigal Syncline. Traced eastwards the Dunlewy Shear Zone runs in the middle to southern half of the quartzite outcrop and eventually joins with the Medial Shear Zone south of Errigal Mountain.

Main phase (D_2) *structures*

The largest scale D_2 structures can be divided into two tectonic units separated by the major Ardsbeg–Dunlewy Slide. The lower unit is very simple, consisting of a right-way-up sheet of Ards Quartzite with locally underlying Ards transition member. Above the slide, a feature itself marked by intense and blastomylonitic S_2, is the upper tectonic unit containing major folds, a large metadolerite, a great range of stratigraphy and a major facies change. The structure of the upper tectonic unit is now described.

In the summit area of Errigal mountain, and to the northwest and west, bedding in the Ards Quartzite is inverted and typically dips 20°–30° to the southeast on the upper overturned (short) limb of the major Errigal Syncline. Traced southwards down the mountainside, bedding dips around the hinge steepen to the south and eventually come to dip steeply to the north on its lower limb. Strike lines drawn on the axial plane joining the inflexion points on the south side of the mountain indicate that it dips gently northwest. This is confirmed by the general northwest dip of the S_2 cleavage. S_2 changes vergence but not facing across the major fold, thus indicating a D_2 age for the major structure. Although the axial plane dips northwest, the hinge itself, as exposed at the Ards Quartzite/Sessiagh Clonmass Formation boundary, plunges north-northeast. These relationships indicate therefore that the major fold here

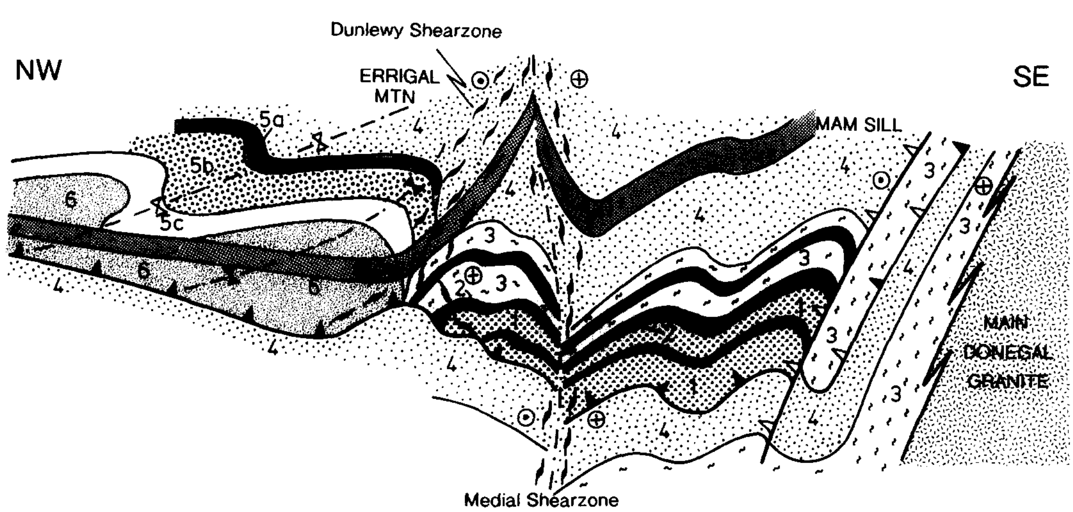

Fig. 5. Stylized and generalized section through the area. Lithology ornament as for Fig. 2. Horizontal frame is approximately 5 km.

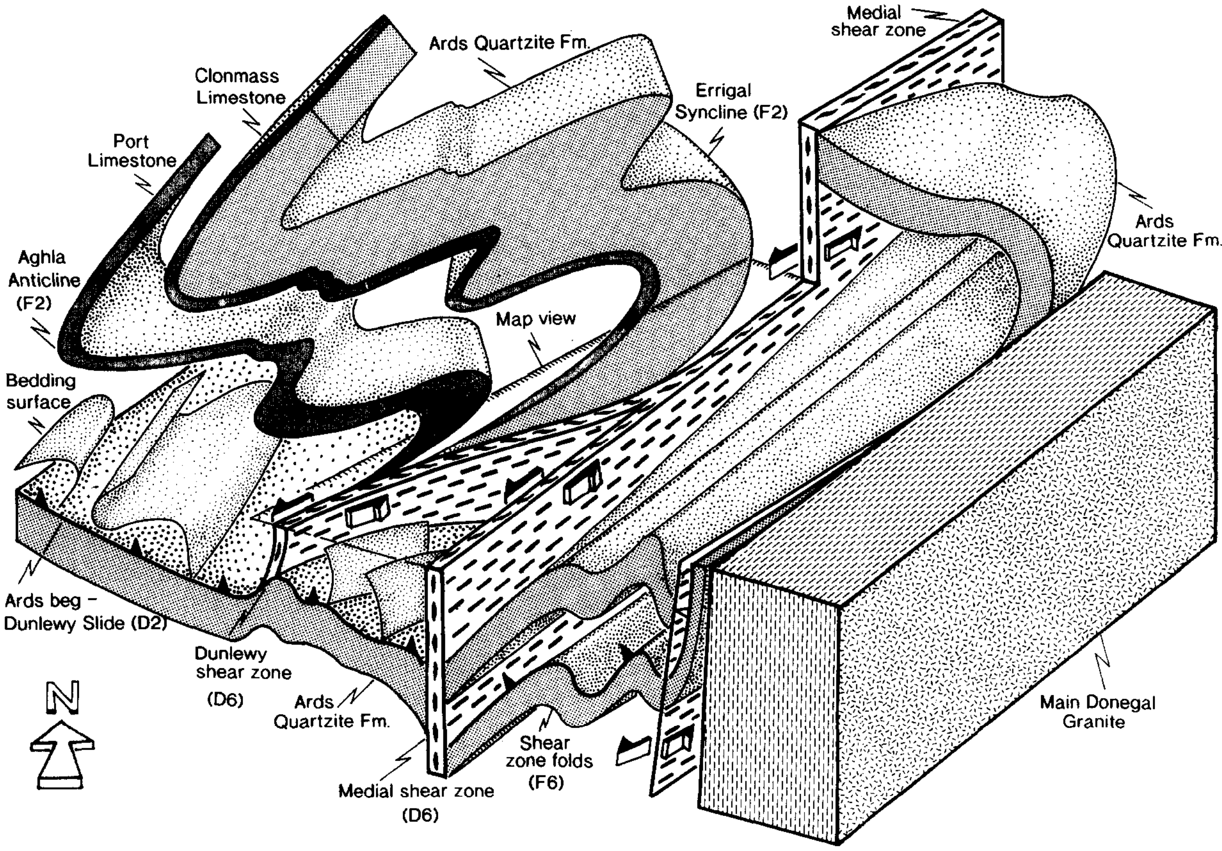

Fig. 6. Three-dimensional diagram of the structural relationships in the Dunlewy area.

faces gently down to the west-northwest. This, and the general NW-dip of the S_2 cleavage carries the upper inverted limb (in Sessiagh Clonmass Formation) several hundred metres down the northwest side of the mountain. These inverted rocks are brought to right way-up again within the Sessiagh–Clonmass Formation by a second-order F_2 NW-closing antiform with a NE–SW-trending axial trace. Further to the northwest they are returned to inversion by a complex SE closing F_2 fold hinge. In the townland of Meenacrevagh, this latter fold is refolded by the NNE–SSW-trending F_3 ESE-vergent monoformal hinge, mentioned previously. This structure locally makes S_2 dip southeast and face up to the northwest. The Ards Quartzite (lower tectonic unit) beneath the slide, S_2, containing a well developed gently SE-plunging L_2 stretching lineation, dips gently southeast. Bedding faces gently up to the northwest in this cleavage. Since facing in S_2 in the overlying tectonic unit is downwards towards the northwest, this results in the axial planes of the two F_2 second-order folds being truncated against the slide (see below).

Traced due west from Errigal, the gently NW-dipping axial plane of the Errigal Syncline is intersected by the WNW-striking D_6 Dunlewy Shear Zone. As a result the trend of the hinge swings parallel to the shear zone, the S_2 cleavage steepens its northwest dip, and facing in the S_2 cleavage on the immediate north side of the shear zone is steeply down to the northwest. Immediately to the north of Dunlewy Lough, Ards Pelite Formation overlies Ards Quartzite Formation across the Ardsbeg–Dunlewy Slide. Within the Ards Pelite Formation, bedding/S_2 cleavage relationships indicate a south closing gently upward north facing recumbent synclinal hinge. S_2 and the axial plane of this fold are gently warped by F_6 mesoscopic folds and one of these, a small periclinal antiform, exposes the lower tectonic unit and the Ardsbeg–Dunlewy Slide in a small structural inlier surrounded by Ards Pelite Formation (Fig. 2). Approaching the northern D_6 shear zone, S_2 steepens its southward dip so that facing in S_2 is steeply upwards to the northwest. This S_2 is deformed in the shear zone into an antiform. However bedding, in the now coaxial hinge of the Errigal Syncline, simply steepens. This is presumably because bedding originally lay in what was to become the extension field of the D_6 strain ellipsoid. Thus, bedding is steepened in this zone whilst S_2 is folded into an upright antiform, with its axis along the zone of highest D_6 strain (Figs. 2, 3 and 5). North of Dunlewy Lough, Ards Pelite Formation dips and youngs northwards through the Ards Transition Member into the Ards Quartzite Formation. The latter unit in turn youngs through transition rocks into the Sessiagh Clonmass Formation. This whole section is interpreted as an essentially unbroken stratigraphic sequence across the recumbent hinge (with bedding further steepened by D_6 sinistral shear) of the F_2 Errigal Syncline. Thus the F_2 synclinal hinge in Ards Pelite Formation south of Dunlewy village is correlated with the fold in quartzite on the mountain and the axial trace, affected by the topography and the narrow F_6 antiform of S_2, is shown (Fig. 3).

There is little significant reorientation of the strike of the axial plane of the Errigal Syncline into the D_6 shear zone. This is probably because it originally lay subparallel to the shear zone. As far as is known these steep beds in the hinge of the syncline strike straight downwards and are essentially truncated by the underlying gently inclined D_2 Ardsbeg–Dunlewy Slide. Similarly the steep S_6 fabrics of the Dunlewy Shear Zone do not penetrate far into the quartzites below the Ardsbeg–Dunlewy Slide since flat lying D_2 mylonites are well preserved there. However, these latter rocks do contain a D_2 stretching lineation reoriented from northwest–southeast to east–west by D_6 sinistral shear (see Sanderson *et al.* 1980, Hutton 1982a). Thus there is a D_6 strain component in the flat-lying mylonites (i.e. the E–W lineation is a composite lineation produced by the superposition of D_6 and D_2) and so the steep D_6 fabrics of the Dunlewy Shear Zone are modelled as rotating and detaching into the gently dipping D_2 slide zone (Fig. 5).

This description and discussion of the major D_2 and D_6 structures allows a structural synthesis to be made. Before proceeding to this, two locally and regionally important aspects of the geology and map pattern need to be briefly described.

Structural pattern and non-uniform stratigraphy

We must draw attention to the fact that not all of the stratigraphic cut out seen on the map can be attributed to tectonic attenuation and it is likely that the original stratigraphy was non-uniform and laterally variable. The evidence for this is seen on the north side of Dunlewy Lough and near Dunlewy village. Here there is a complete N-younging stratigraphic sequence from Ards Pelite through Ards Quartzite to Sessiagh Clonmass Formation and Lower Falcarragh Pelite. However, traced along strike for some 750 m to the west around Dunlewy village (Fig. 2) this situation changes dramatically with the whole of the Sessiagh Clonmass Formation, and then the Ards Quartzite thinning and disappearing until Ards Pelite is in juxtaposition with Lower Falcarragh Pelite. We consider this to be an original feature of the sedimentary basin rather than a result of tectonic cut out, for two principal reasons: first, although strains are obviously greater than normal in the D_6 Dunlewy Shear Zone the very highest strains are only restricted to the Ards Quartzite and particularly to its southern boundary where, however, Ards transition rocks are always present. This suggests that there is no actual dislocation. Secondly, strain analysis of deformed pebbles in the Ards Quartzite shows that although strains do increase within the quartzite towards the west (in the direction in which the unit tapers), these are not in any way high enough to account for the degree of tapering (a reduction of 400 m of thickness in 1 km of strike).

The demonstrable absence of mylonites associated with this ‘thinning’, coupled with the points noted above, leads us to conclude that the thinning and excision of these units is mainly syn-sedimentary and pre-tectonic. We will show elsewhere (Hutton & Alsop, work in preparation) that this is probably related to the major pre-tectonic strike swing in the Irish Caledonides.

Intrusive dolerite sheet as a structural marker

A prominent feature of the geology of the area is a major metadolerite sheet (the Mam Sill) (Fig. 2). From the map relationships and outcrop observations it seems that this large body intrudes between the regional main phase and shear zone structures, thus serving to separate these and clarify the nature and geometry of the later event. The evidence for the interdeformational age is as follows. When mapped southwards across the area, the sheet can be shown to truncate: (a) the axial traces of the second-order F_2 folds on the inverted limb of the major Errigal Syncline; (b) the axial plane of the large fold itself; and (c) to cut across the stratigraphy Falcarragh Pelite to Ards Quartzite. On entering the Dunlewy Shear Zone, the sheet clearly becomes vertical, is thinned, and is deflected eastwards by the sinistral shear strain. It is folded and may also be dislocated by the (D_6) Medial Shear Zone so that it appears on the southeast side of Dunlewy Lough as a gently NW-dipping sheet. Although the relationships indicate intrusion between the two major deformation events in the area, our observations further north show that the sheet is folded by mesoscopic F_3 folds, thus indicating a post D_2-pre D_3 age. A similar structural age has been recorded for a related, and possibly the same, intrusion on Horn Head to the north (Hutton 1979b) although the latter relationship has been criticized on geochemical grounds by Elsdon (1986).

STRUCTURAL SYNTHESIS: THE NATURE OF THE ARDSBEG–DUNLEWY SLIDE

The tracing of the Mam Sill across Dunlewy Lough allows the quartzite and immediately underlying units on the south of the lough to be correlated with the upper of the two tectonic units north of the lough (Figs. 2, 5 and 6). The broad D_6 synform, with the Medial Shear Zone along its axial plane, allows the lower tectonic unit (Ards Quartzite) to the north of the lough to be correlated with the southernmost of the Ards Quartzite imbricates to the south, in the ground immediately north of the Main Donegal Granite. The D_2 Ardsbeg–Dunlewy Slide therefore underlies the entire section and reappears in the south reactivated in the D_6 Main Donegal Granite Shear Zone. In the upper tectonic unit north of the lough only steep D_2 synclinal hinge and inverted D_2 limb rocks are seen. South of the lough only right-way-up D_2 normal limb rocks occur. The simplest way to explain this is by sinistral movement with a SW-plunging lineation along the Medial Shear Zone of an originally NNE-plunging D_2 Errigal Syncline. Thus the right-way-up rocks south of the lough are the lower normal limb of this fold with the hinge to the northeast and in the air (Fig. 6).

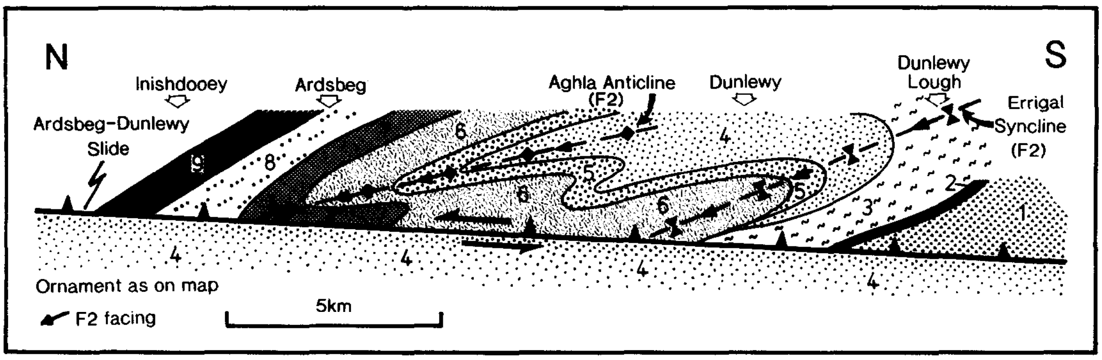

Fig. 7. Schematic diagram of structural and stratigraphic relationships across the Ardsbeg–Dunlewy Slide between the offshore islands and Dunlewy with the effects of the (D_6) shear zone structures removed. Lithology ornament as Figs. 2 and 5.

Undoing these D_6 strains reveals that the stratigraphy and D_2 folds of the upper tectonic unit are spectacularly cut across by the underlying D_2 Ardsbeg–Dunlewy Slide (Fig. 7). Thus immediately north of the Main Donegal Granite the Creeslough Formation lies on top of the Ards Quartzite of the lower tectonic unit. On the immediate north side of the Lough Ards Pelite overlies the Quartizite. Taking into account the lateral facies changes previously described, Lower Falcarragh Pelite next comes into contact. Further north around Gortahork and Ardsbeg [outside the mapped area (but see Rickard 1962)] Falcarragh Limestone overlies the slide, and offshore on Inishdooey the Loughros Formation, at the top of the succession, is in contact with the underlying Ards Quartzite (Rickard 1962). Thus, in a distance of 20 km, the whole of the Appin Group stratigraphy (~3 km of thickness) is truncated by this remarkable structure (see also Rickard 1962). In terms of structural truncation, the slide cuts from the lower normal to inverted limbs of the Errigal Syncline, it cuts across the subsidiary hinges of the inverted limb and further north observations indicate that it truncates the axial plane of the D_2 Aghla Anticline so that upper normal limb rocks are brought into contact with quartzite at Ardsbeg and on the islands to the north. Thus in terms of gross geometry and stratigraphic truncation, the cut-offs across the slide appear to be extensional in character, i.e. (generally) younger over older.

In outcrop the slide is a discrete plane separating quartzite in the footwall from the variable rocks of the hangingwall rocks. A small thickness (2–5 cm) of tectonic schist may be present. Mylonites of D_2 age are well developed in both footwall and hangingwall and are parallel to the contact. A strong stretching lineation usually trending NW–SE, is found. Strains from measured pebbles have $K \simeq 1$ shape factors (Fig. 8) and increase towards the contact (Hutton 1977a). Other deformational features such as minor F_2 fold axes and early quartz boudin necks become progressively parallel to the lineation direction approaching the slide. The age of the structure is demonstrated by the relative age of the mylonites and by the fact that between Dunlewy and the north coast, especially at [8905 2950] south of Ardsbeg, the structure is folded by $F3$ ESE-vergent monoforms. In

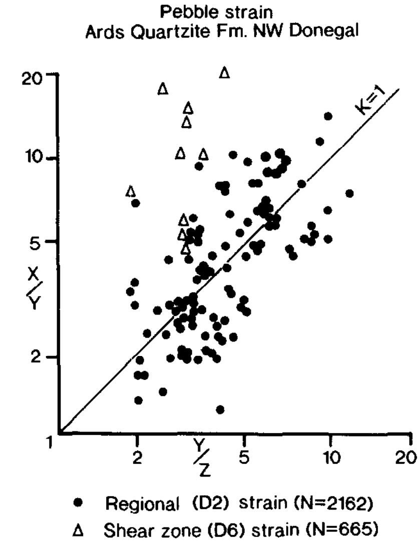

Fig. 8. Shapes of quartz pebbles in Quartzites (mainly Ards Quartzite) in NW Donegal on a log Flinn plot. The D_2 deformation is close to plane strain (K = 1).

terms of kinematic indicators, feldspar clasts in the Ards Quartzite at Ardsbeg and Dunlewy commonly have asymmetric tails. Both σ- and δ-types are seen and these show consistent shear sense of top towards the northwest. Extensional microshears are also well developed and are consistent with NW-overthrusting. Elsewhere in thin pelite bands within the quartzite beneath the slide, in the main thin tectonic schist along the slide and in the pelites in the hangingwall, extensional shears and extensional crenulation cleavages associated with the D_2 mineral lineation occur. These are in agreement with the clast data and indicate that, as with the other D_2 tectonic slides of Donegal (Hutton 1982b), the Ardsbeg–Dunlewy Slide is a thrust towards the northwest.

As shown in Fig. 7, the basic structural, as opposed to stratigraphic, arrangement is that of major D_2 folds in the hangingwall facing downwards in the direction of transport into a synchronous D_2 thrust. A simple way to account for this is by analogy with high crustal level deformation in thrust ramp–flat systems. The structurally necessary fault-bend folds that form in the hanging wall above a footwall ramp are folded *down* onto the upper flat. Adapting this model to a more ductile situation in the middle crust, an early formed but kinematically related recumbent fold pair will be carried up the ramp and folded so as to face downwards onto the upper flat (see Fig. 9d).

EXTENSIONAL GEOMETRIES IN A CONTRACTIONAL REGIME: MODELS

The growth fault model

A thrust with a hangingwall containing rocks some two-thirds of which are younger than the rocks of the footwall can be explained in one of two ways. It may be the result of thrusting affecting stratigraphy that contains original large lateral variations. The most developed variant of this is thrust reactivation of an original extensional growth fault (Soper & Anderton 1984). For this to work in the Ardsbeg–Dunlewy area, the Ards Quartzite (unit 4) would require the Falcarragh Pelites and Limestone and the Loughros Formation (units 6–9) to be across-strike time equivalents with the extensional fault running along the quartzite interface (Fig. 9a). The most compelling evidence that this could have happened is that facies changes do occur in the area (in the hangingwall in the east) but these do not in themselves demand the key (western) part of the interpretation. Arrayed against such an interpretation is that there are no smaller scale lithological and grain size lateral variations which might be expected in the hanging wall adjacent to the trace of the slide. So, as elegant in many ways as the thrust reactivated extensional growth fault model is, there is no compelling evidence to support it. This, in essence, was the main objection that Roberts & Treagus (1990) raised against the application of the Soper & Anderton (1984) model to the Scottish Dalradian examples.

The double thrusting model

An alternative explanation for younger over older stratigraphy across a thrust is that the thrusting took place in two stages: this is the 'breeching' mechanism of Butler (1984). An early thrust first transports older over younger rocks and then a second thrust transports the footwall rocks (which are young), on top of the hangingwall rocks of the first thrust (Fig. 9b). This model, as modified to fit the stratigraphic situation at Dunlewy, is shown schematically in Fig. 9(c & d). In support of this model is the fact that a second slide, which we interpret as a thrust, occurs beneath the Ardsbeg–Dunlewy Slide at Crockator (Fig. 10) (the Crockator slide) (see also Rickard 1963). The model also predicts that the footwall to this lower slide contains a normal upward younging sequence with Falcarragh Pelite at the top. This is also seen at Crockator, and the lower stratigraphy also occurs further west as a ghost stratigraphy in xenoliths in the adjacent Thorr Granite and in outcrop again on its western and southern sides in the Crohy Hills and at Lettermacaward, Mass and Portnoo. Set against the interpretation is the fact that the early thrust in the hangingwall of the later thrust (i.e. the roof thrust to the

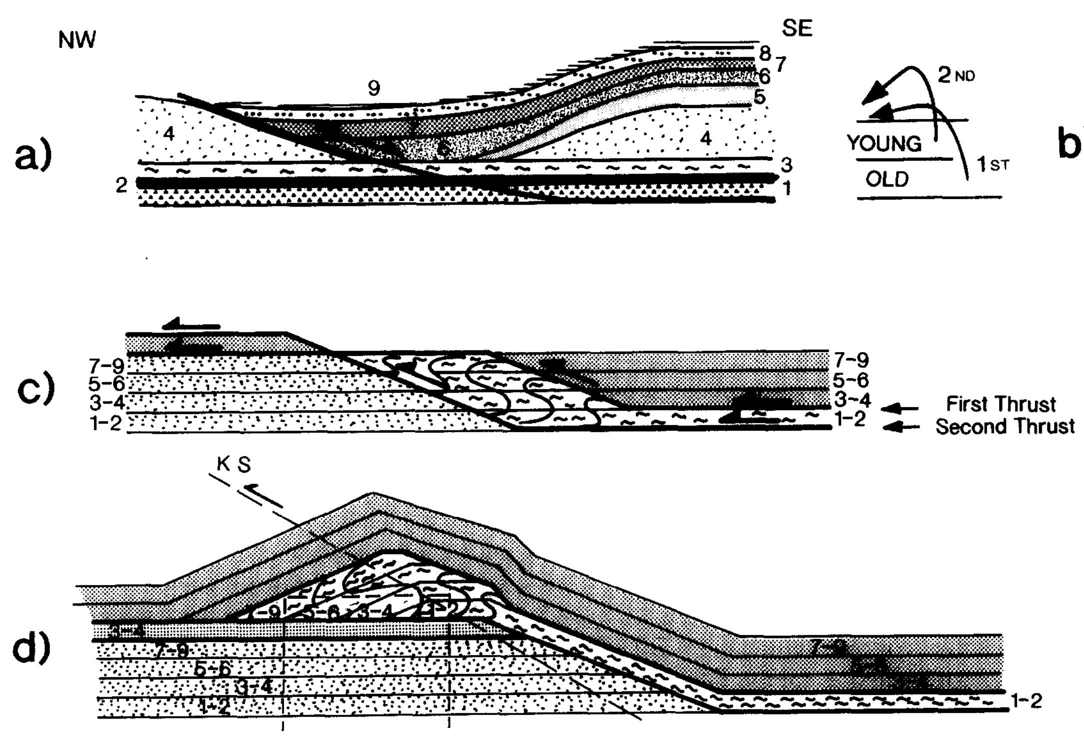

Fig. 9. Alternative structural and stratigraphic models: (a) thrust reactivation of an original syn-sedimentary extensional fault. Actual stratigraphic relationships observed at Dunlewy are shown in the hangingwall. Ornament as in local stratigraphy (see key of Fig. 2). (b) Simplified thrust breeching model. (c) & (d) Thrust breeching model schematically applied to the Dunlewy/NW Donegal situation. (c) Thrust layout prior to movement. (d) After movement. Ornament in (c) & (d) refers to nappes (as in Fig. 9). Stratigraphic units indicated by numbers (key as Figs. 1 and 2). KS = trace of later Knockateen Slide. Area inside dashed box = cross-section of observed geological relationships in Dunlewy—NW Donegal.

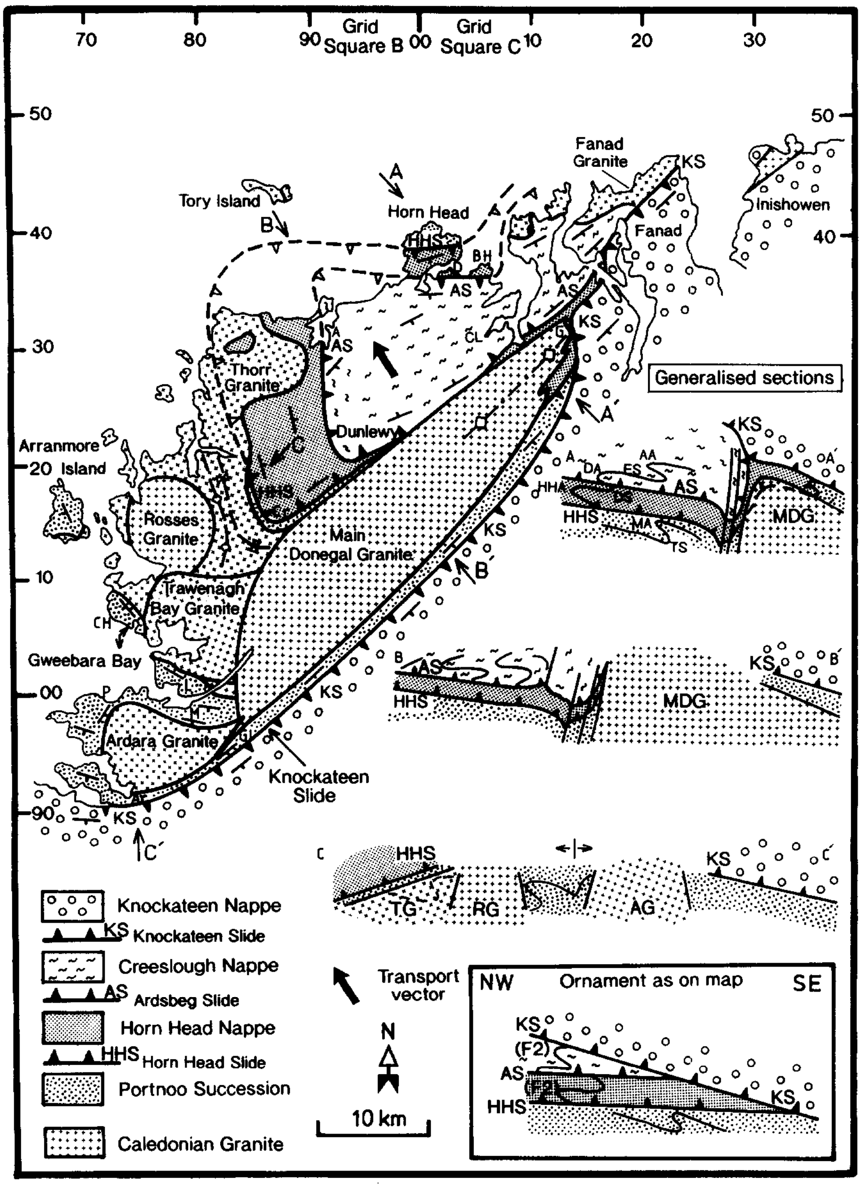

Fig. 10. Nappe interpretation of the NW Donegal Dalradian with (top) a schematic composite section NW–SE showing major $D2$ structures (KS = Knockateen Slide, AS = Ardsbeg Slide, HHS = Horn Head Slide, AA = Aghla Anticline, ES = Errigal Syncline, DA = Dunfanaghy Anticline, DS = Dunfanaghy Syncline, HHA = Horn Head Anticline, MA = Maghery Anticline, TS = Thorr Syncline). Actual sections A–A′, B–B′, C–C′ (MDG = Main Donegal Granite, TG = Thorr Granite, RG = Rosses Granite, AG = Ardara Granite). Locations on map (D = Dunfanaghy, BH = Breaghy Head, CL = Creeslough, A = Ardsbeg, G = Glen, Cr = Crockator, CH = Crohy Hills, L = Lettermacaward, P = Portnoo, M = Mass, Ar = Ardara, (GL = Glenties).

whole system) should outcrop somewhere to the northwest, but is not seen. This absence could be due to a combination of observed structural dip, topography and the closeness of the northern coastline. So there is no critical evidence against this model. It is thus concluded that the double thrusting model, combined with fault-bend folding to generate the downward facing, is more appropriate to the observed structural and stratigraphic relationships in the Ardsbeg–Dunlewy area than the model involving thrust reactivation of an extensional growth fault.

The two thrusts in the system need to occur respectively above and beneath the Errigal Syncline–Aghla Anticline fold package. It is proposed that the pre-thrust geometry was that of a lensoid D_2 fold package which acted as a resistant buttress to northwest propagating D_2 thrusts. The first (Crockator) thrust ramped up over the package and the second (Ardsbeg–Dunlewy) thrust cut beneath it and emerged at the northwest side to breech upwards across the early thrust, carrying the fold package up this ramp to fold it and cause it to face downward onto the flat to the northwest.

THE NW IRISH CALEDONIDES: A MAJOR THIN SKINNED FOLD AND THRUST BELT?

The recognition of two thrust-bounded Dalradian sheets in the Ardsbeg–Dunlewy–Crockator area can be extended throughout NW Donegal to allow a major nappe sequence to be established. This relies on a number of correlations (Fig. 10).

The upper-tectonic unit in the Dunlewy area (containing the stratigraphic sequence Creeslough Formation (1) up to the Loughros Formation (9), and the major Aghla Anticline–Errigal Syncline fold pair) extends through much of the area to the north and east. This unit is underlain to the north by the D_2 Dunfanaghy–Breaghy Head Slide. This was inferred to be a thrust by Hutton (1977a) and subsequently numerous NW-thrust-sense indicators were found in the highly imbricated hanging-wall on Breaghy Head (Jolley 1994). This slide is correlated with the Ardsbeg–Dunlewy Slide and the entire structure is named the Ardsbeg Slide, the location where it is best exposed. The rocks above this slide occur to the east in Rossguill and in NW Fanad where they are overridden by the major SE-dipping Knockateen Slide, also believed to be a thrust (White & Hutton 1985). The southern outcrop of the Ardsbeg Slide in the Dunlewy area is bent by the D_6 Main Donegal Granite Shear Zone to dip steeply northwest and strike northeast. Further to the northeast it is engulfed by that granite but reappears again contained within the D_6 Lackagh Slide (Hutton 1977b). Further northeast we consider it to be traceable into Fanad where it is truncated by the Knockateen Slide. Thus the rocks between the underlying Ardsbeg Slide and the overlying Knockateen Slide and containing stratigraphic units 1–9 and the D_2 Dunfanaghy Anticline–Errigal Syncline–Aghla Anticline structures form a nappe, here named the Creeslough Nappe.

To the north of the Ardsbeg Slide at Dunfanaghy the Ards Quartzite and Ards Peilite in the footwall are underlain by the Horn Head Slide, also a major D_2 thrust (Hutton 1982b). This suggests a correlation between this slide and the Crockator Slide: the whole structure now named the Horn Head Slide, and above this, the Horn Head Nappe, containing stratigraphic units 3 and 4. Only one major F_2 fold is known from this nappe: the Horn Head Anticline (Hutton 1982b). This slide is also deformed to dip northwest by the Main Donegal Granite Shear Zone and it is engulfed within this mass to the northeast. A major NE-trending D_6 NW-vergent antiform is likely to occur in the site of the granite at its northeast end. This slide may be correlated with a similar structure on the southeast side of the northeast end of the granite now dipping gently southeast and involving Ards Quartzite separated from Falcarragh Limestone and Pelite. This slide and the rocks of the Horn Head Nappe are also truncated by the overlying Knockateen Slide.

Beneath the Horn Head Slide at Crockator are outcrops of the Falcarragh Pelite, as previously noted. This is engulfed to the west by the Thorr Granite (Fig. 10), although a distinctive ghost stratigraphy involving Falcarragh Pelite and Sessiagh–Clonmass Formation in numerous xenoliths can be traced across the pluton (Pitcher & Berger 1972). Further west Dalradian outcrop reappears on Aranmore Island, in the Crohy Hills and in the Lettermacaward, Mass, Portnoo and Ardara/Glenties areas. This is a sequence, without major breaks from units 3 to 9 of the stratigraphic succession. The only major D_2 structure known from this area is the NE-facing Maghery Anticline in the Crohy Hills, a recumbent structure with axial plane close to sea level (Meneilly 1982). The repetition of stratigraphy within the Thorr Granite xenoliths (Pitcher & Berger 1972) together with our vergence observations suggests that this fold, together with an underlying complementary D_2 syncline (the Thorr Syncline) reappears within the Thorr Granite; the whole structure oblique to and truncated by the overlying slide at Crockator. South of the Crohy Hills, stratigraphy youngs steadily upwards on the upper normal limb of this Maghery Anticline to be truncated both in the south and to the northeast (along the southern side of the Main Donegal Granite) by the overlying Knockateen Slide. This sequence of rocks, for which no base is seen, is called the Portnoo Succession.

These correlations are the basis for the proposition that the Dalradian Geology of NW Donegal is dominated by a stack of thrust-nappes each containing distinctive, although not mutually exclusive, stratigraphy and in each case containing major D_2 recumbent NW-facing folds which are cut-off by the bounding D_2 thrust slides. This sequence was assembled by the D_2 deformation, associated through much of the area with a northwest–southeast transport direction, and the nappes were overridden, probably at a later stage in the same event, by the major Knockateen Slide, containing within its hanging wall entirely younger Dalradian rocks than those seen to the northwest.

Estimates of thrust displacements

The minimum displacement on the Ardsbeg Thrust is the exposed length of the thrust plane parallel to the NW–SE thrust direction (= 23 km) (Fig. 10, Table 2). This thrust sheet must have emerged from a ramp to the

Table 2. Calculations of thrust displacements: minimum figures on the left, maximum on the right. See text for explanation

	Width of nappe (km)	Distance to top of ramp (km)	Distance along ramp (8°) (km)	Model (km)	Total (km)
Ardsbeg Thrust	23	8	7	—	38
Horn Head Thrust	40	6	13	14	73
					Total 111
Knockateen Thrust	(20)			68	
Other thrust				68	
					Total 247

southeast of the underlying Horn Head Nappe, whose trailing edge is exposed a further 8 km to the south, thus making 31 km displacement. The stratigraphy of these Appin Group sediments is quite constant over long distances and so we can reconstruct a layer-cake template at depth. However we have chosen the minimum thicknesses quoted for each stratigraphic unit (Pitcher & Berger 1972) which further minimizes calculated displacements. The ramp angle is taken from the hangingwall cut-off angle along the Ardsbeg Slide (= 8°). Using this and a layer cake stratigraphy of known thickness allows stratigraphic cut-offs in the hangingwall to be restored to the footwall cut-offs on the ramp, and so a further 7 km may be added. This figure of 38 km on the Ardsbeg Slide is also minimized because we assume that the top of the emerging ramp lies at the trailing edge of the underlying nappe and not further south beneath the Knockateen Slide.

The minimum displacement of the Horn Head Nappe is likewise given by its length parallel to transport (= 40 km). This must have emerged south of the Portnoo Succession whose southernmost outcrops occur at the Knockateen Slide (Fig. 10) a further 6 km southeast (total 46 km). Applying now the double thrusting model we can add to this minimum displacement. The Horn Head Nappe must have crossed the width of the Creeslough Nappe (restored onto its ramp) before the Creeslough Nappe moved (Fig. 9c). This adds 14 km. Finally using the template with an 8° ramp angle, hangingwall and footwall cut-off restoration adds a further 13 km. This makes a total for the Horn Head Slide of 73 km. Thus total displacement between the Creeslough Nappe and the Portnoo Succession is approximately 100 km (minimum). Further shortening associated with the major folds in each nappe could be added. Reconstructions such as this usually assume plane strain with no material movement out of the section. In our case plane strain is documented by the shapes of stretched pebbles (Fig. 8) and the well developed D_2 stretching lineation seen throughout the area.

The basic structural geometry of the NW Donegal Dalradian deduced in this paper together with the likely scale of the tectonic translations involved indicates the presence of a major fold and thrust belt, previously unrecognized as such.

The approximate 100 km displacement is a minimum estimate. The Knockateen Slide, also considered to be a thrust (White & Hutton 1985) carries above it rocks that lie stratigraphically above those in the underlying nappes. So this is another example, albeit on a much larger scale, of younger rocks over older rocks across a thrust. The ramp angle of the Knockateen Slide over the lower nappes from the distance between the Horn Head and Ardsbeg Slide to Knockateen Slide branch points is approximately 7°. If the double thrusting model is applicable to the Knockateen Thrust (Fig. 10) this would give a minimum displacement on this structure of 68 km and a similar figure for an unseen but structurally necessary first thrust beneath the Portnoo succession. Adding these two figures to those from the northwest for the total displacement of Knockateen Slide hangingwall relative to unmoved foreland suggests a figure of approximately 250 km. This interpretation relies heavily on the correlation of the two slides seen on the north coast (the Horn Head Slide, and the Breaghy Head–Dunfanaghy Slide) with the two slides seen further west and southwest (the Crockator Slide and the Ardsbeg–Dunlewy Slide). If these are, in reality, four separate structures then the displacement estimates given here are not valid and are likely to be too large.

CONCLUSIONS

(1) Within the Appin Group mid-greenschist facies Dalradian rocks of the small but important Dunlewy area, an early (D_2) nappe complex, containing a major stratigraphic facies transition and a thick interdeformational dolerite sheet is refolded with slide reactivation by the sinistral shear zone associated with the Main Donegal Granite.

(2) Removing the affects of the late shear zone reveals that the major Ardsbeg–Dunlewy Slide contains rocks in the hangingwall most of which are younger than those in footwall. Major D_2 folds in the hangingwall face gently downwards to the northwest into the coeval slide. Shear sense indicators show that the slide is a thrust to the northwest.

(3) Although lateral facies variations are present in the area, thrust reactivation of an original sedimentary growth fault is not thought to be a suitable model to explain the stratigraphical and structural variations across the Ardsbeg–Dunlewy Slide. Instead, a thrust breeching mechanism involving younger rocks being transported on top of previously thrusted older rocks during foreland progradation of thrusts can more appropriately explain the stratigraphical relationships. Fault bend folding associated with this together with transporting a penecontemporaneous but early (and kinematically linked) major fold pair from a ramp onto an upper flat explains the observed facing relationships and structural geometry.

(4) The recognition of distinctive nappes in this area can be extended throughout the Dalradian of NW Donegal and three major regional nappes together with an underlying para-autochtonous succession can be identified. These are all bounded by D_2 ductile NW-overthrusts and they contain major NW-facing D_2 recumbent folds. Basic structural and stratigraphical considerations indicate that total displacements in the zone are between 100 and 250 km.

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