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The stratigraphy, correlation, provenance and palaeogeography of the Skiddaw Group (Ordovician) in the English Lake District.

A.H.Cooper[1], A.W.A. Rushton[1], S.G.Molyneux[1], R.A. Hughes[2], R.M. Moore[3] & B.C. Webb[4]

[1] British Geological Survey, Keyworth, Nottingham, NG12 5GG.
[2] British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA.
[3] Formerly Department of Earth Sciences, Leeds University, Leeds, LS2 9JT, now Britsh Gas, Reading.
[4] Formerly British Geological Survey, Newcastle upon Tyne, now 1 Grassfield Cottages, Nenthead, Alston, Cumbria, CA9 3LW.

Abstract: A new lithostratigraphy is presented for the Skiddaw Group (lower Ordovician) of the English Lake District. Two stratigraphical belts are described. Five formations are defined in the Northern Fells Belt, ranging in age from Tremadoc to early Llanvirn. They are all mudstone or sandstone dominated, of turbidite origin; in ascending order they are named the Bitter Beck, Watch Hill, Hope Beck, Loweswater and Kirk Stile formations. Two formations are defined in the Central Fells Belt, ranging in age from late Arenig to Llanvirn. These are the Buttermere Formation - a major olistostrome deposit - overlain by the Tarn Moor Formation, consisting of turbidite mudstones with volcaniclastic turbidite sandstone beds. A revised graptolite and new acritarch biostratigraphy for the Skiddaw Group is presented with eight graptolite biozones and thirteen acritarch assemblages and sub-assemblages. The provenance of the group is assessed from detailed petrographical and geochemical work. This suggests derivation, in the early Ordovician, largely from an old inactive continental arc terrane lying to the south-east, with the appearance of juvenile volcanic material in the Llanvirn. Comparisons and correlations of the Skiddaw Group are made with the Isle of Man and eastern Ireland.

1. Introduction

The Skiddaw Group comprises a thick succession of lower Ordovician clastic turbidites and slumped deposits which accumulated on the margin of Gondwana prior to the rifting off of the Eastern Avalonian microcontinent. It therefore provides evidence for the early Ordovician development of this part of the Gondwanan margin.

Since 1982, the British Geological Survey has re-surveyed the Skiddaw Group of the Cockermouth, Whitehaven and Keswick 1:50,000 scale geological maps (sheets 23, 28 & 29). The results of this re-survey, supplemented by further reconnaissance studies in the Black Combe (Ulverston, sheet 48), Ullswater (sheet 30) and Furness (sheet 48) areas, provide the basis for a revised lithostratigraphy for the Skiddaw Group, presented in this paper.

2. Previous classifications of the Skiddaw Group

Details of some earlier classifications were shown by Molyneux & Rushton (1988, p. 46). Sedimentary rocks exposed in the northern part of the Lake District were originally named Skiddaw Slates and Skiddaw Group by Sedgwick (1832). Ward, who undertook the first survey of the area in 1872, divided the Skiddaw Slates into five lithostratigraphical divisions (Ward 1876). Dixon (1925), Eastwood (1927) and Eastwood *et al.* (1931) later showed that some of Ward's divisions were laterally equivalent, and simplified the succession. Further simplification by Rose (1955) resulted in a two-fold classification and Jackson (1961) added an extra unit below Rose's divisions. Simpson (1967) proposed a different classification comprising eight formations, but gave different names to units now known to be structurally repeated, and took insufficient account of palaeontological evidence.

Different definitions of the Skiddaw Group have been proposed more recently by Jackson (1978), Wadge (1978) and Moseley (1984). Each agreed about the lower part of the group, but the upper part proved to be more problematical. The Latterbarrow Sandstone (Eastwood *et al.* 1931) was included at different stratigraphical positions in the group by all three authors. Allen & Cooper (1986) showed subsequently that the Latterbarrow Formation rests unconformably on the Skiddaw Group, and concluded that it is a basal deposit of the Borrowdale Volcanic Group. The Redmain Sandstone was considered by Eastwood (1927) to be equivalent to the Latterbarrow Sandstone, but was shown by Allen & Cooper (1986) to be a different unit. They designated it the Redmain Formation but reached no conclusion about its stratigraphical position in the Skiddaw Group.

The Tarn Moor Mudstones have been subject to further disagreement in the definition of the Skiddaw Group. Wadge (1978) placed them at the top of the Eycott Group; Jackson (1978) placed them at the top of the Skiddaw Group, but as lateral equivalents to the top of the Eycott Group. Moseley (1984) suggested that the Tarn Moor Mudstones were partly equivalent to and partly younger than the upper part of the Eycott Group, which he also equated with part of the Kirkstile Slate Formation. These different interpretations are resolved below.

3. Definition of the Skiddaw Group

3.a. Geographical distribution

The Skiddaw Group comprises a succession of greywackes and siltstones, up to 5 km thick and mainly of Tremadoc, Arenig and Llanvirn age, that is exposed principally in the Skiddaw Inlier and the adjoining Ullswater, Bampton, Black Combe and Furness inliers of the English Lake District (Figs 1 & 2). It also occurs in the Cross Fell (Cooper & Molyneux 1990 and references therein) and Teesdale inliers (Johnson 1961) to the east, and has been proved at depth in boreholes through the Carboniferous rocks of the Alston Block (Woolacot 1923; Burgess 1971). The only evidence for pre-Ordovician rocks is provided by an acritarch microflora from the vicinity of Eycott Hill, as discussed below under the Bitter Beck Formation.

- Figures 1 & 2 about here -

Two distinct stratigraphical belts are present within the Skiddaw Group, namely the Northern Fells Belt and the Central Fells Belt (Figs 1, 2 & 3). These belts are separated by a major wrench and thrust fault, the Causey Pike Fault, which can be traced through the Lake District to Cross Fell (Figs 1 & 2; Cooper & Molyneux 1990). This fault coincides with an important geophysical lineament, interpreted as a basement structure along which wrench movement has occurred and a concealed elongate granitic intrusion, responsible for the Crummock Water Aureole, was emplaced. These features suggest a possible shear zone origin (Cooper *et al.*, 1988; Hughes *et al.*, 1993).

In the southern Lake District, the Skiddaw Group inliers of Black Combe and Furness are geographically isolated south of the main exposures of the Central Fells Belt. They lie along and south of a major structural line, interpreted as an Acadian mountain front, in which the major fold structure is the Westmorland Monocline (Fig. 1; Kneller & Bell 1993). In the Black Combe area, this fold coincides with a major geophysical lineament, termed the Southern Borrowdales Lineament by Lee (1989). The geophysical lineament also coincides with the approximate position of the southern margin of the Borrowdale Volcanic Group volcanotectonic rift sytem, and the margin of the Lake District batholith (Cooper *et al*. 1993;

Kneller & Bell 1993). The area south of this line was termed the Southern Fells Belt by Cooper *et al*. (1993), but there are no differences in the Skiddaw Group rocks across the South Borrowdales Lineament. Consequently, in this paper we have chosen to use the term `Southern Lake District inliers' to encompass the Black Combe and Furness inliers.

- Figure 3 about here -

3.b. Formations in the Skiddaw Group

The Skiddaw Group of the Northern Fells Belt comprises the **Bitter Beck, Watch Hill, Hope Beck, Loweswater** and **Kirk Stile formations** (Figs 2, 3 & 4). Here it is unconformably overlain by the Eycott Volcanic Group (Millward & Molyneux 1992). At the northern end of the Cross Fell Inlier, also within the Northern Fells Belt, the Skiddaw Group includes the **Catterpallot Formation** (Cooper & Molyneux 1990) which is correlated with the Watch Hill and possibly Bitter Beck formations of the Skiddaw Inlier. The Redmain Formation, though geochemically distinctive (Allen & Cooper 1986), appears to represent a highly weathered part of the Loweswater Formation preserved immediately below the basal Carboniferous red beds and unconformity; it is not a mappable unit and its use is discontinued.

In the Central Fells Belt, the **Buttermere** and **Tarn Moor formations** of the Skiddaw Group (Figs 3, 12) are unconformably overlain by the Borrowdale Volcanic Group (Wadge 1978). What underlies the Buttermere Formation is unknown. The Central Fells Belt can be traced eastwards to Cross Fell (Figs 2, 3), where the component **Murton** and **Kirkland formations** were defined by Burgess & Wadge (1974) and revised by Cooper & Molyneux (1990). Strata equivalent to the Kirkland Formation are also present in the Teesdale Inlier (Fig. 1; Johnson 1961; Burgess & Holliday 1979).

The Skiddaw Group of the Southern Lake District inliers is undivided. Here, the overlying Borrowdale Volcanic Group (Fig. 3) abruptly attenuates southwards and is absent at Furness, where the Skiddaw Group is overlain by upper Ordovician (Cautleyan) mudstone and limestone (Rose & Dunham 1977). The Ingleton Group in the Beckermonds Scar Borehole, on the Askrigg Block, is equivalent to the Skiddaw Group in age (Wilson & Cornwell 1982).

4. Biostratigraphy of the Skiddaw Group

Graptolites and acritarchs are biostratigraphically the most useful fossils in the Skiddaw Group and their study is essential to understand the complex structure and stratigraphy. Neither the ubiquitous crustacean *Caryocaris* nor the rarer trilobites have proved of great stratigraphical value, though Fortey *et al.* (1989) showed that the trilobites have Gondwanan affinities. The statigraphical distribution of trilobites is shown in Figs 4 & 12.

4.a. Graptolites

Although the graptolites have been studied for over 100 years and the general faunal succession in the Skiddaw Group has served as a standard of reference for the lower Ordovician throughout England and Wales, a wholly satisfactory biostratigraphical subdivision of the group has not yet evolved. This is mainly because of the difficulty in making satisfactory collections of graptolites from the Skiddaw Group, the poor preservation of much of the material, and taxonomic difficulties with many of the earlier Ordovician graptolites. The graptolite zonation used here is based on that of Jackson (1961, 1978), with the addition of two divisions and the redefinition of others (Figs 4, 5, 12). Approximate correlation with the Australasian graptolitic succession is shown in Fig. 4.

- Figure 4 about here -

4.a.1. The murrayi *Biozone*

The *murrayi* Biozone is adopted from the Scandinavian succession (Lindholm 1991) where it occurs in the lower part of the Hunnebergian Stage. In the Skiddaw Group, it is recognized mainly by the presence of *Araneograptus murrayi* itself. In southern Scandinavia, Lindholm (1991) described an overlying *copiosus* Biozone but this has not been positively identified in the Skiddaw Group.

4.a.2. The phyllograptoides *Biozone*

In Scandinavia, the *copiosus* Biozone is succeeded by the *phyllograptoides* Biozone. The latter is adopted for the Skiddaw Group, although *Tetragraptus phyllograptoides* itself has not been found; it is recognized by the presence of *Didymograptus* (s.l.) *protobalticus* and *D. rigoletto* (Maletz *et al.* 1991), both of which occur in the upper part of the zone in Scandinavia. The upper boundary of the *phyllograptoides* Biozone is correlated with the top of the *approximatus* Biozone of the Australasian succession (Cooper & Lindholm 1990, p. 509). In Scandinavia, the succeeding zone of *D. balticus* is characterized by the appearance of the *Didymograptus constrictus* group of species. This is not known in the Skiddaw Group and no equivalent of the *balticus* Biozone has been recognized. The Hope Beck Formation is sparsely fossiliferous, so the upper boundary of the *phyllograptoides* Biozone and the lower boundary of the *varicosus* Biozone have not been located precisely.

4.a.3. The varicosus *Biozone*

The *deflexus* Biozone is the lowest zone of Jackson's (1978) succession but the true

Didymograptus (s.l.) *deflexus* (Elles & Wood 1901) is very rare in this zone, although it is present in the overlying zone. The term *deflexus* Biozone is therefore abandoned and the zone is here named after the common deflexed didymograptid which does occur at this level, a species referred to *D. varicosus* Wang. This is by far the commonest graptolite in the zone, but *D. (=Acrograptus?) filiformis* and a large form resembling *D. protobalticus* occur locally. The fauna occurs in the upper part of the Hope Beck Formation and the lower part of the Loweswater Formation.

4.a.4. The simulans *Biozone*

The faunal assemblage that succeeds the *varicosus* Biozone was formerly known as the *nitidus* Biozone, but this is a misnomer because *Didymograptus nitidus* is not present. The term is here abandoned. The assemblage, which is characterized by *Didymograptus* (s.l.) *simulans, D. (Acrograptus) nicholsoni,* the true *D. deflexus* and *Azygograptus* species, is here entitled the *simulans* Biozone. The occurrence of *I. victoriae* cf. *primulus* (see section 5.d.4) suggests a correlation with the Chewtonian Stage (Ch1-2 of Fig. 4). There appears to be some facies control over the distribution of this assemblage, because elements occur typically in sandstones at the top of the Loweswater Formation and in sandstone-rich strata in the lower part of the Kirk Stile Formation.

4.a.5. The gibberulus *Biozone*

The succeeding *Isograptus gibberulus* Biozone follows the revised usage of Fortey *et al.* (1990), though it is recognized that this is not very satisfactory, partly because of the general rarity of isograptids. *I. victoriae victoriae* and *I. caduceus gibberulus* indicate correlation with the Castlemainian Stage (Ca1-4). The commoner associates are extensiform didymograptids, but these are long-ranging and their taxonomy and nomenclature are in need of revision; so, although the *gibberulus* Biozone appears to be of considerable thickness, it has not yet been possible to subdivide it.

4.a.6. The hirundo *Biozone*

The use of the *hirundo* Biozone follows the restricted definition of Fortey *et al.* (1990). Significant elements include early diplograptids, *Aulograptus* and *Cryptograptus antennarius*. Maletz's (1992) suggested correlation with the Yapeenian (Ya) and lower Darriwilian (Da) is accepted here (Fig. 4).

4.a.7. The artus *Biozone*

The *artus* Biozone is a replacement name for the *bifidus* Biozone of earlier writers and is characterized by the appearance of *D. artus* and *D. spinulosus* (Fortey *et al.* 1990). The base of the *artus* Biozone has been located at two places in the Lake District (Fortey *et al.* 1990) and may also be present in Mosedale Beck [NY 356 242]. Skevington (1970, p. 404) suggested the possibility of distinguishing a subzone of *Nicholsonograptus fasciculatus* in the upper part of the *artus* Biozone, but this has yet to be tested in the field.

4.a.8. The murchisoni *Biozone*

The overlying *murchisoni* Biozone has not been recognized at outcrop, but was recognized in material obtained from the Tarn Moor tunnel (Skevington in Wadge *et al.* 1972).

4.b. Acritarchs

The study of acritarch floras in the Skiddaw Group was initiated relatively recently, but considerable progress has been made in elucidating the microfloral succession (Molyneux 1990), so that acritarchs complement graptolites as biostratigraphical indicators. Problems remain because the ranges of many taxa are not definitively known and some taxa have yet to be described. Nevertheless, five microfloral assemblages may be distinguished in the late Tremadoc and Arenig succession of the Northern Fells Belt, the lowest of these being divisible into five sub-assemblages (Fig. 5). Older Tremadoc assemblages have been found at various localities (Fig. 12) in the Central Fells Belt (e.g. Molyneux & Rushton 1985), though some if not all of these are recycled into a younger olistostrome deposit, named the Buttermere Formation, and so are not in succession. They include a lower Tremadoc assemblage from the Buttermere area and an upper Tremadoc assemblage from the River Calder. Moreover, it is possible to distinguish a Llanvirn assemblage from the older assemblages, for example in the Kirkland Formation of the Cross Fell Inlier (Cooper & Molyneux 1990). Thus a total of at least thirteen acritarch assemblages and sub-assemblages are distinguishable in the Skiddaw Group.

4.b.1. The Cymatiogalea messaoudii-Stelliferidium trifidum *assemblage*

The lowest acritarch assemblage recognized in the Northern Fells Belt is present in the Bitter Beck, Watch Hill and lower Hope Beck formations, and is referred to as the *Cymatiogalea messaoudii-Stelliferidium trifidum* assemblage. It is equivalent to the *trifidum* flora of Fortey *et al.* (1991); its composition was documented by Molyneux & Rushton (1988). This assemblage may be subdivided into five sub-assemblages, based on the successive appearance and progressive disappearance of species (Fig. 5). The lowest sub-assemblage **1** is represented in the Bitter Beck Formation. The base of sub-assemblage **2** coincides approximately with the base of the Watch Hill Formation and sub-assemblages **3** and **4** occur higher within the same formation. Sub-assemblage **5** appears at about the base of the Hope Beck Formation.

Acritarchs of the *messaoudii-trifidum* sub-assemblage 1 are associated with graptolites assigned to the *murrayi* Biozone, and those of sub-assemblage 3 occur with *Araneograptus murrayi* at Trusmadoor [NY 2777 3362]. Hence the lower part of the *messaoudii-trifidum* assemblage interval, up to and including sub-assemblage 3, encompasses the range of *A. murrayi*, and is therefore the same age as the *murrayi* and possibly the *copiosus* biozones. Acritarch species which indicate *messaoudii-trifidum* sub-assemblage 5 occur in close proximity to *Didymograptus rigoletto* in Burn Tod Gill [NY 2798 3341, NY 2797 3340, NY 2795 3341], suggesting that this sub-assemblage is of late *phyllograptoides* Biozone age. Thus, the Tremadoc-Arenig boundary (here regarded as basal *phyllograptoides* Biozone) lies between *messaoudii-trifidum* sub-assemblages 3 and 5 in the Skiddaw Group.

4.b.2. The Stelliferidium trifidum-Coryphidium bohemicum *assemblage*

The overlying assemblage, present in beds of the Hope Beck Formation in the valley of the R. Derwent [NY 1354 3269, NY 1352 3270], contains many taxa that range up from the underlying *messaoudii-trifidum* assemblage, but *C. messaoudii* is absent and *S. trifidum* is joined by *Coryphidium bohemicum* and *Striatotheca principalis parva* (Fig. 5). This assemblage is distinguished herein as the *Stelliferidium trifidum-Coryphidium bohemicum* assemblage.

4.b.3. The Coryphidium bohemicum *assemblage*

Beds of the Loweswater Formation in Jonah's Gill [NY 1902 3399 to NY 1904 3420], assigned to the *varicosus* Biozone, have yielded the next highest microflora, named herein the *Coryphidium bohemicum* assemblage. Diversity is much lower than in the underlying assemblages (Fig. 5). Acanthomorph acritarchs, notably *Polygonium* spp., are common, but *Stelliferidium trifidum* has not been recorded. Other taxa from the underlying assemblages that do not persist into this assemblage include *Acanthodiacrodium? dilatum* and *Vogtlandia coalita*. One of the most characteristic acritarchs is an undescribed acanthomorph with a spherical vesicle and short processes branching into long recurved filaments which lie at a tangent to the surface of the vesicle.

- Figure 5 about here -

4.b.4. Interzone

Acritarch assemblages from the lower part of the Loweswater Formation in the Lorton Fells, for example at Scawgill Quarry [NY 1775 2585] and on Burnbank Fell [NY 2278 2124], both in the *varicosus* Biozone, are generally sparse, of low diversity, and dominated by sphaeromorph or simple acanthomorph taxa, the latter including species of *Micrhystridium* and *Polygonium*. This microflora is difficult to characterize, and may be better regarded as an interzonal assemblage between the *bohemicum* assemblage of Jonah's Gill and the succeeding *Stelliferidium* sp. nov. assemblage (Fig. 5).

4.b.5. The Stelliferidium *sp. nov. assemblage*

This resembles the interzonal assemblage but also includes an undescribed species of *Stelliferidium* with short conical processes, and for this reason is referred to herein as the *Stelliferidium* sp. nov. assemblage. In addition, *Micrhystridium* cf. *aremoricanum* and *Acanthodiacrodium* cf. *simplex* may be present (Fig. 5). The *Stelliferidium* sp. nov. assemblage is known from Whinlatter Crag [NY 2021 2448], Tom Rudd Beck [NY 1712 2819], Embleton High Common [NY 1697 2794] and Barf [NY 2180 2645], in each case from beds of probable *simulans* Biozone age, and at Hodgson How Quarry [NY 2442 2361] where *gibberulus* Biozone graptolites have been recorded (Beckly & Maletz 1991).

4.b.6. The Frankea hamata-Striatotheca rarirrugulata *assemblage*

The youngest assemblage from the Northern Fells Belt occurs in the Kirk Stile Formation. Many of the taxa in the underlying assemblage range into this assemblage, but additional species are present so there is a net increase in diversity (Fig. 5). Species of *Frankea* and *Striatotheca* are particularly important and the assemblage is herein named the *Frankea hamata-Striatotheca rarirrugulata* assemblage. The *hamata-rarirrugulata* assemblage is present in the *hirundo* Biozone of the Black Combe Inlier (Rushton & Molyneux 1989), and occurs in close proximity to *gibberulus* Biozone graptolites in the Central Fells Belt, for example at Ramps Gill (see section 6.a.5). However, the presence of the *Stelliferidium* sp. nov. assemblage at Hodgson How Quarry suggests that the *hamata-rarirrugulata* assemblage does not range down to the base of the *gibberulus* Biozone.

4.c. The duration of graptolite and acritarch zones in the Skiddaw Group

A relative time scale for the early Ordovician, based on a consideration of accumulation rates for graptolitic shales (Cooper 1992), enables the duration of each zone in the Skiddaw Group to be suggested (Fig. 4). With the base of the Llanvirn at about 469 Ma and the base of the

Arenig at about 484 Ma (Cooper 1992, fig. 12), the base of the *gibberulus* Biozone, correlated with the base of the Castlemainian, is estimated at about 476 Ma, and the top of the *phyllograptoides* Biozone at about 479 Ma. The *copiosus* and *murrayi* biozones are estimated to be of equal duration between the base of the Arenig and the base of the *murrayi* Biozone at 490 Ma (Cooper 1992, fig. 12).

Based on these estimates, the duration of graptolite zones in the Skiddaw Group varies from about 1 Ma (*D. simulans* Biozone) to about 5 Ma (*T. phyllograptoides* Biozone), with the duration of the other zones falling between these figures. Estimates of the duration of the acritarch assemblages range from about 1 Ma for the *trifidum-bohemicum* assemblage to a maximum of 11 Ma for the *messaoudii-trifidum* assemblage. For the latter, however, the sub-assemblages vary in duration from about 1 Ma (sub-assemblage 5) to 4 Ma (sub-assemblage 4), with an average duration of 2.2 Ma.

5. The stratigraphy of the Northern Fells Belt

5.a. Bitter Beck Formation (new formation)

5.a.1. Type area

The type area is designated around Bitter Beck, east of Cockermouth [NY 1399 3113 to NY 1500 3133], where the upper part of the formation is exposed. North of here, the formation passes upwards transitionally into the Watch Hill Formation. No complete section through the Bitter Beck Formation occurs, the lowest strata being thrust over the Kirk Stile Formation along the Watch Hill Thrust which has a southerly displacement of around 5km (Hughes *et al.*, 1993, fig.3.).

5.a.2. Thickness

The formation is at least 500 m thick above the Watch Hill Thrust in the type area.

5.a.3. Lithologies

The Bitter Beck Formation is dominated by dark grey mudstone, silty mudstone and siltstone with minor amounts of sandstone. The beds, thinly laminated, probably represent distal turbidites and comprise graded siltstone beds with homogeneous mudstone laminae (Bouma D and E units). The sandstone component is pale grey, fine-grained, and forms generally thinly parallel to wavy laminated beds with irregular bases and tops. In places along Bitter Beck and at Cockermouth [NY 114 312], the beds exhibit abundant slump folding with dislocations sub-parallel to bedding. In exposures of the oldest part of the succession, proved between Elva Plain Farm [NY 175 316] and Higham Hall School [NY 180 316], the formation includes up to 20% of generally thin to medium bedded (3-30cm) fine-grained greywacke.

5.a.4. Biostratigraphy

The Bitter Beck Formation has yielded both acritarchs and graptolites (Molyneux & Rushton 1988). The *messaoudii-trifidum* acritarch sub-assemblage 1 and *Araneograptus murrayi* and *Didymograptus* cf. *D.* sp. 1 (of Lindholm, 1991, p.313) were recovered from exposures in Bitter Beck (around NY 1420 3122 and 1480 3137). These suggest that the formation lies within the *murrayi* Biozone (Fig. 4).

At Trusmadoor, the large *Dictyonema pulchellum* and *D.* sp. described by Rushton (1985) are now assigned to *Araneograptus murrayi*, following Lindholm (1991), and may represent the *murrayi* Biozone or the overlying *copiosus* Biozone; the associated acritarchs are of the *messaoudii-trifidum* sub-assemblage 3, suggesting a correlation with the Watch Hill Formation farther east.

5.a.5. The succession at Eycott Hill

Just below the unconformity at the base of the Eycott Volcanic Group on Eycott Hill [NY 382 305], exposures of siltstones and mudstones with possible soft sediment folds have yielded acritarch assemblages, including an assemblage that may be older than those found in the Bitter Beck Formation (Millward & Molyneux 1992). These acritarch assemblages indicate ages ranging from Middle or Late Cambrian to latest Tremadoc or earliest Arenig (see Millward & Molyneux, 1992, for locality details). The relationships between the exposures there are not clear, and much younger Skiddaw Group rocks are present about 1.5 km to the west (on the flank of Souther Fell [NY 36 29]). Two explanations for the presence of older strata in the area are possible. The succession may represent beds equivalent to and older than the Bitter Beck Formation seen elsewhere. Alternatively, the succession may be part of an olistostrome deposit, similar to the debris flows present in the Kirk Stile Formation at Beckgrains Bridge [NY 1904 3552] or the Buttermere Formation of the Central Fells Belt. Both the Beckgrains Bridge debris flow and the Buttermere Formation contain Tremadoc acritarchs, but in the former they occur in the same samples as acritarchs of the *hamata-rarirrugulata* assemblage and are clearly recycled. In the latter, they occur in strata that are juxtaposed against beds which yield the *hamata-rarirrugulata* assemblage and so are interpreted as occurring in slumped blocks. No assemblages of mixed ages have been recorded from the vicinity of Eycott Hill, and no juxtaposition of assemblages of disparate ages occurs there. The exposures are inconclusive and either interpretation remains a possibility.

5.b. Watch Hill Formation (here formalised)

This formation, defined here, is equivalent to the Watch Hill Grits of various authors and the `Grits Group' of Eastwood *et al*. (1968).

5.b.1. Type area

Watch Hill [NY 1495 3189], some 3 km ENE of Cockermouth, is designated as the type area. Numerous, mainly small exposures of the formation are present between Watch Hill [NY 14 31] and Setmurthy Plantation [NY 15 31], and in the tract north-north-eastwards from Setmurthy Common [NY 16 31] towards the valley of the River Derwent. Contrary to the interpretation of Banham *et al.* (1981), way-up evidence throughout the area indicates that the succession youngs northwards and is the correct way up.

5.b.2. Thickness

This is difficult to determine in the type area because of folding and possible faulting, but is generally between 550 m and 800 m (Fig. 3). The formation thins westwards to about 100 m at Cockermouth [NY 122 303] and eastwards to 40 m around Great Sca Fell [NY 291 339].

5.b.3. Boundaries

The boundary between the Watch Hill and Bitter Beck formations is gradational, marked by an increase in the proportion of sandstone and a decrease in the proportion of mudstone in the succession. The base of the Watch Hill Formation is defined at the level at which sandstone and siltstone predominate. In the type area, the lower boundary lies just below the quarry at the foot of Watch Hill [NY 1557 3146] and the upper boundary with the overlying Hope Beck Formation can only be inferred to within about 20 m near Hewthwaite Hall [NY 1516 3276]. Around Cockermouth, about 80 m of strata are exposed in the River Cocker, and the lower boundary of the formation can be seen near the old railway viaduct [NY 1222 3029]. The upper boundary is not exposed, but is inferred to lie just to the north of the Lorton Street road bridge [NY 1225 3040] between exposures of the Watch Hill and Hope Beck formations.

5.b.4. Lithologies

The rocks of the Watch Hill Formation are interbedded lithic wackes (with subordinate lithic arenites), siltstones and mudstones. The sandstone is typically brown-weathering, fine-grained to granular with abundant siltstone and mudstone intraclasts. Sandstone beds vary from very thinly to very thickly bedded (1cm to 1m+). Well-developed sedimentary structures are uncommon, but include normal grading and sole structures. Many of the thinner beds are irregular, producing lateral `pinch and swell' thickness variations (FIg. 6). The bases of the thicker units are generally sharp, but the tops are gradational and less well defined. Lateral thickness variations in the thicker beds are gradual and regular. Normal grading, parallel lamination, wavy lamination and rare ripple cross-lamination are present and occasionally occur together defining the Bouma turbidite sequence (Bouma 1962). The ripple drift cross-lamination is commonly disturbed by loading of the overlying sandstones. Basal flute casts in the type area suggest flow from an easterly direction (R.M.Moore, unpub. Ph.D. thesis, Univ Leeds, 1992).

- Figure 6 about here -

The siltstones and mudstones are generally thinly laminated to very thinly bedded (0.1-3cm) with parallel, wavy or cross-cutting laminae. Sandstone to siltstone/mudstone ratios vary vertically and laterally throughout the succession, but are typically around 60-70% sandstone and 30-40% siltstone and mudstone. Several km east of the type area, pebbly lithic wackes belonging to the Watch Hill Formation are present in exposures between Little Cockup [NY 2588 3323] and Great Sca Fell [NY 2900 3387]. The clasts in the lithic wackes are dominated by rounded and deformed siltstone and mudstone with abundant quartz and rock fragments. The sandstones are lithologically different from those of the type area (Fig. 13), and are also coarser grained with more clay matrix. Clasts of polycrystalline metamorphic quartz are more abundant than at Watch Hill, but monocrystalline quartz and feldspars are less abundant. Volcanic fragments are common and are dominated by rhyolite and feldspar-phyric clasts. The high lithic content of these wackes distinguishes them (Fig. 13) from other Watch Hill Formation samples, but this may be partly a function of grain-size. Petrographically, the lithic wackes dominantly contain monocrystalline quartz of plutonic origin and polycrystalline quartz of metamorphic type with subordinate chert and rhyolite. Alkali feldspars are dominant over plagioclase and the heavy minerals include tourmaline, zircon and opaque minerals.

The suggested presence of contemporaneous lavas in the Watch Hill Formation (Jackson 1961) has now been discounted and the Watch Hill felsite is now recognised as a sill (Hughes & Kokelaar 1993).

5.b.5. Biostratigraphy

Molyneux & Rushton (1988) have published detailed biostratigraphical evidence which dates the formation as latest Tremadoc or earliest Arenig (Fig. 4).

5.c. Hope Beck Formation (here formalised)

The Hope Beck Slates proposed by Jackson (1961) are here formalised as a formation.

5.c.1. Type area

The type area is that designated by Jackson (1961), in the vicinity of Hope Beck [NY 168 239]. The lower boundary of this succession is mentioned above, in the description of the Watch Hill Formation. The upper boundary with the overlying Loweswater Formation, described by Jackson (1961, 1978), occurs on the east flank of Dodd [NY 171 233] where there is a transition to the overlying sandstones of the Loweswater Formation. Jackson (1961) "used the presence of arenites 3 inches or more in thickness, as the criterion for separating the two formations. The boundary so defined is located on the east side of Dodd at about 1,100 feet O.D. [NY 171 233] and at 900 feet O.D. on the west side [NY 166 231]". Nowhere is a continuous sequence exposed and this part of the succession is poorly fossiliferous.

5.c.2. Other areas

North of Watch Hill, the formation is poorly exposed along the Derwent Valley. The upper 400 m of the formation is well exposed in the vicinity of Dodd [NY166 231] and Swinside Plantation.

5.c.3. Thickness

This is can not be determine in the type area, but in the region is probably between 600 m and 800 m.

5.c.4. Lithologies

The Hope Beck Formation mainly comprises dark grey siltstone and mudstone in laminated and very thin beds, with up to 5% of sandstone mainly in thin and medium beds; sporadic pebbly mudstone beds are also present. The siltstone and mudstone commonly exhibits grading passing up into homogeneous mudstone (Bouma D and E units). Bioturbation is common in these lithologies, but rarely destroys the lamination; it occurs mainly as sub-horizontal burrows, some of which are filled with faecal pellets. The sandstone is mainly quartz-rich lithic wacke with a little quartz wacke, generally medium to coarse-grained, but including numerous beds with granules and pebbles. The contained clasts include abundant monocrystalline plutonic quartz with common polycrystalline metamorphic quartz. Lithic grains include intraformational mudstone and siltstone, crenulated phyllite, quartz-mica schist and crushed chlorite clasts. The high quartz content and paucity of volcanic clasts in these sandstones contrasts markedly with those of the Watch Hill Formation (Fig. 13). The arenaceous beds exhibit sedimentary structures indicative of turbidite deposition in which A-B-C, B-C and C Bouma units are present, the mudstone and siltstones of the succession are also turbiditic representing the D units with probable hemipelagic E units. The pebbly mudstones are matrix-supported (50% matrix) and may represent debris flows. The contained clasts include contorted intraformational mudstone, siltstone and very fine-grained, heavy mineral-rich sandstone, the quartz content is similar to the sandstones, but rare volcanic lithic clasts including feldspar-phyric basalt and volcaniclastic grains also occur.

5.c.5. Biostratigraphy

Graptolites occur sparingly in this formation. Near the base, the presence of *Didymograptus protobalticus* and *D. rigoletto* (Maletz *et al.* 1991), associated with the *messaoudii-trifidum* sub-assemblage 5, indicates the upper part of the *phyllograptoides* Biozone (Fig. 4). Near the top, localities in Blaze Beck [NY 1771 2565 to 1809 2539] yielded faunas referable to the *varicosus* Biozone. Outcrops of the formation in the valley of the River Derwent have yielded acritarchs of the *messaoudii-trifidum* sub-assemblage 5 and the *trifidum-bohemicum* assemblage.

5.d. Loweswater Formation (here formalised)

The Loweswater Flags of previous authors are here formally renamed the Loweswater Formation. It occurs mainly in the western part of the Skiddaw inlier with a small faulted inlier in the east at Mungrisdale [NY 164 209] (Roberts 1992).

5.d.1. Type area

The lower boundary stratotype occurs on Dodd, [NY 171 233] and is described above with the Hope Beck Formation. An upper boundary was loosely defined between Thornthwaite and Whiteside (Jackson 1961). Here we define the upper boundary, also transitional, in a small quarry on the west flank of Whiteside End [NY 1660 2169]. Here the bedding thickness reduces rapidly over a few metres and the proportion of mudstone in the succession increases forming a mainly laminated facies (beds 0.5-1cm) of sandstone and mudstone with sporadic very thin and thin (1-7cm beds) of quartz-rich greywacke. The top of the formation is taken at the highest thin sandstone bed in the dominantly sandstone part of the succession.

5.d.2. Thickness

The thickness of approximately 900 m remains fairly constant in the north-western part of the Lake District, but decreases northwards to an estimated 450 m around Jonah's Gill [NY 190 343]. Thickness in the faulted inlier at Mungrisdale cannot be determined.

5.d.3. Lithologies

The sandstones of the Loweswater Formation are mainly quartz-rich feldspathic wackes, but include some quartz-rich lithic wackes (Fig. 13). The basal beds of the formation are thin, mainly fine-grained sandstones with cross- and convolute lamination, interbedded with siltstones and mudstone; these conform to the Bouma C-D-E sequence of sedimentary structures. The argillaceous beds form between 30% and 50% of the succession. About 50 m above the base of the formation, thicker wackes appear. These are fine to medium-grained, mainly parallel-laminated and ripple cross-laminated sandstones corresponding to Bouma B and C turbidite units (Fig. 7). Bed thickness increases gradually to a maximum of 1 m near the middle of the formation; concurrently the maximum grain-size increases to very coarse-grained, though most beds are still fine to medium-grained. Complete Bouma A-E sequences are present, the argillaceous D and E units comprising 10% to 20% of the succession. The upper part of the formation is a mirror image of the lower part, bed and grain size decreasing gradually while the percentage of siltstone and mudstone increases. High in the succession the arenaceous beds are mainly cross- and convolute-laminated Bouma C units.

- Figure 7 about here -

Most of the Loweswater Formation wackes contain on average 39% matrix (Fig. 13), and are quartz-rich (c. 40%), with feldspar more abundant than lithic fragments. Quartz is predominantly of strained monocrystalline type, with some large unstrained monocrystalline clasts. The plagioclase feldspars are dominantly andesine and form about 10% of the rock. The lithic grains constitute about 5% of the clasts and are mainly sandstone, siltstone and mudstone. They also include subordinate volcaniclastic and siliceous pyroclastic fragments, clasts of fine-grained volcanic and metamorphic rocks, and detrital mica.

About 10% of the beds in the formation contain more than 50% matrix; these are informally distinguished as `high-matrix wackes'. They are typified by poorly developed sedimentary structures, smooth bases, and normal grading, with ripple laminations sporadically preserved at their tops. These beds are commonly strongly cleaved because of their high matrix content. The detrital grains in the `high-matrix wackes' are generally unaltered, and of similar type and abundance to the other Loweswater Formation greywackes. Mature quartz wackes are present in Jonah's Gill [NY 181 343].

Beds within the Loweswater Formation are fairly continuous, but commonly show a slightly lenticular form when traced for distances of 100 m or so, as for example at Scawgill Quarry [NY 1770 2578]. Sporadic channel structures are also present and can be seen on Darling Fell, Loweswater [NY 1265 2218]. Here, channels filled with cross-stratified (0.5-1 m scale), medium- to coarse-grained sandstone cut into the underlying beds. A similar, but smaller, channel is present near Swinside Plantation [NY 1778 2482].

Most sandstone beds in the Loweswater Formation have planar bases, but scattered bottom structures also occur; these include channels, groove casts and flute casts. Structures were observed on 180 bedding surfaces in 11 areas across the Skiddaw Inlier, and stereographically restored measurements show currents mainly from the south-east or south-south-east (R.M.Moore, unpub. Ph.D. thesis, Univ Leeds, 1992). Flute casts measured on Embleton High Common [NY 1697 2794] indicate depositional currents from the south-west and a few examples of channels and grooves elsewhere have a similar trend. This information broadly agrees with Jackson (1961), who noted palaeocurrents

derived from the south at Scawgill and Mungrisdale [NY 362 307] and from the south-west at Gasgale Gill [NY 164 209]. These contrasting palaeocurrent directions are interpreted (R.M.Moore, unpub. Ph.D. thesis, Univ Leeds, 1992) as having been controlled by the basin floor topography comprising linear fault-bounded troughs orientated in a north-west direction and tilted to the north-east.

Small-scale slump folds, up to a few metres across, are present; in the north-west of the district, they are mainly overturned to the south-east (Webb & Cooper 1988). However, the origin of the major Loweswater Anticline, regarded by Webb & Cooper (1988) as an early gravity slide or slump, has been reconsidered and it is now thought more likely to be a later tectonic structure roughly co-axial with the small-scale slump folds and modified by sinistral strike-slip movement on the Causey Pike Fault (Hughes *et al.* 1993).

Bioturbation in the Loweswater Formation comprises mainly sub-horizontal, branched and unbranched, meandering, sub-cylindrical burrows, 0.3 cm to 1.5 cm in diameter, and includes looping burrows assigned to *Palaeochorda*. A few sub-vertical cylindrical burrows are also present, as are sporadic circular and meandering burrows.

5.d.4. Biostratigraphy

Body fossils are lacking from the Loweswater Formation, except in the lower and upper parts of the succession where siltstone and mudstone dominate. The basal beds of the succession, e.g. west of Blaze Bridge [NY 1790 2510], have yielded graptolites indicative of the *varicosus* Biozone (Fig. 4), including *Didymograptus varicosus*, *D.* cf. *protobalticus*, *D. filiformis*, *D. deflexus* s.s. (rare), and *Tetragraptus* species including rare *T. fruticosus*. The upper beds have yielded graptolites indicative of the *simulans* Biozone, including *D. simulans*, *D. infrequens*, *Pseudophyllograptus angustifolius* and *Azygograptus ellesi* (Beckly & Maletz 1991, p. 913); one specimen resembling *Isograptus victoriae primulus* has been found at Barf [NY 217 265]. Acritarchs are poorly represented in the lower part of the formation, except in Jonah's Gill where the *Coryphidium bohemicum* assemblage occurs. The *Stelliferidium* sp. nov. assemblage has been recorded from the upper part of the formation, for example on Embleton High Common, in Tom Rudd Beck, and at Barf (see section 4.b.5).

5.e. Kirk Stile Formation (here formalised)

The laminated mudstones and siltstones overlying the Loweswater Formation were originally referred to as Kirk Stile Slates and Mosser Slates. All were subsequently subsumed into the Kirk Stile Slates (see Jackson 1978, p. 87) and are here formally designated the Kirk Stile Formation.

5.e.1. Type area

The Kirk Stile Formation as defined here follows Jackson's (1978) usage, the base being defined at the top of the Loweswater Formation on Whiteside End (see above). The formation is not, however, conformably overlain by the Latterbarrow Formation as stated by Jackson (1978). The Kirk Stile Formation is named after the pub and church at Kirk Stile, Loweswater [NY 131 209]. The area surrounding Kirk Stile is poorly exposed and unfossiliferous. Consequently, we suggest the area, from the formation base on Whinlatter Pass [NY 203 245], through Sleet How [NY 206 228] to the youngest strata on Outerside [NY 214 216], to be a representative body stratotype for the formation. No upper boundary stratotype can be defined for the formation, which is unconformably overlain by the Eycott Volcanic Group (Millward & Molyneux 1992). The youngest part of the formation proved so far is earliest Llanvirn.

5.e.2. Thickness

The formation is between 1500 m and 2500 m thick, and some of this variation may be due to stacking of slumped masses.

5.e.3. Lithologies

The rocks are typically thinly laminated to very thinly bedded (0.1-2cm) dark grey siltstones and mudstones; grading is commonly present and the beds represent distal turbidite deposits (Bouma D and E units). About 600 m and 1300 m above the base of the formation there are local lenticular developments which include 20%-30% of lithic wacke; these sandstone-rich units are about 80 m and 120 m thick respectively. The lower sandstone unit can be traced from near Darling How Plantation [NY 1840 2701] eastwards through Lord's Seat [NY 2044 2657] to Bassenthwaite Lake [NY 2162 2805]. The upper unit is centred on Hogg Park [NY 207 287]. The sandstones are typically very thin- to thin-bedded (1-10 cm), with parallel lamination and ripple cross-lamination interpreted as Bouma B and B-C unit turbidite structures. The lithic wackes of the Kirk Stile Formation are highly altered, with much of the detrital mineralogy obscured by clay replacement. Strained quartz is the most abundant grain-type, feldspar is rare, and lithic grains are relatively common. The dominant lithic clasts are volcaniclastic siltstone and altered mafic volcanic clasts.

In the upper part of the formation, sporadic thick beds of sedimentary breccia occur in association with slumped beds described below. These are best seen on Outerside [NY 2132 2140] where they are hornfelsed by the Crummock Water aureole (Fig. 8). This deposit is the `Outerside fluxoturbidite' of Jackson (1978). Here the breccias include clasts up to about 0.2 m in diameter, mainly of siltstone and mudstone but with a few quartz-rich wackes. The clasts vary from sub-rounded to angular, set in a silty mudstone matrix.

- Figure 9 about here -

Another unit of massive breccia, more than 40 m thick, occurs at Beckgrains Bridge [NY 1904 3552]. It includes mudstone, siltstone and a few sandstone clasts, up to 0.5 m in diameter, forming 5-20% of the rock, set in a folded and sheared mudstone matrix. West of here, the breccia appears to be underlain by a slumped and deformed succession of wackes, siltstones and mudstones along Sunderland Gill [NY 1805 3498 to NY 1864 3514].

Graded bedding is the dominant sedimentary structure in the formation, with subordinate cross-lamination in sporadic coarse siltstone and very fine-grained sandstone beds. Much of the succession is disrupted by slump folding; this is well displayed near the base of the formation in Gasgale Gill [NY 1638 2097], and in the hornfelsed succession in the Crummock Water Aureole on Lad Hows (see figure 2a of Hughes *et al.*, 1993) [NY 1729 1925] and Causey Pike [NY 2183 2103]. Similar structures also occur on the west of Ullock Pike [NY 2395 2962 to 2398 2919]. The slumped beds commonly occur in 2-40 m thick units bounded by less disturbed and undisturbed beds, showing the slumping to be synsedimentary or early post-sedimentary.

5.e.4. Biostratigraphy

Graptolites indicate that the lower part of the Kirk Stile Formation is referable to the *simulans* Biozone. The *gibberulus* Biozone (Fig. 4) is recognized by the appearance of *Didymograptus extensus linearis, D. uniformis lepidus* and rare *Isograptus* spp. (Fortey *et al.* 1990) at a level about 700 m above the base of the formation, and ranges through much of its higher part. At some places, the lower parts of the formation contain monospecific assemblages of *Pseudophyllograptus angustifolius*. The upper part of the formation is characterized by the *hirundo* Biozone (Fig. 4) as restricted by Fortey *et al.* (1990). The youngest part of the formation so far proved lies on the north-east flank of Outerside [NY 211 215] and on Souther Fell near Hazelhurst [NY 362 289], where the graptolite faunas of the *hirundo* and *artus* biozones are adjacent and show that the succession lies across the Arenig-Llanvirn boundary (Fortey *et al*. 1990, table 2).

The *Stelliferidium* sp. nov. acritarch assemblage has been recorded at Hodgson How [NY 2442 2361] from beds that are of *gibberulus* Biozone age (Beckly & Maletz 1991) and are inferred to represent part of the Kirk Stile Formation. Elsewhere, for example in the Overwater Spillway [NY 2586 3552], the Southerndale-Watches area [NY 2406 3026] and in the River Cocker [NY 1208 2879], the Kirk Stile Formation has yielded acritarchs of the *hamata-rarirrugulata* assemblage.

Around Beckgrains Bridge (see above), the breccia has yielded acritarchs of the *hamata-rarirrugulata* assemblage (Fig. 4), but also contains recycled Tremadoc acritarchs such as *Acanthodiacrodium angustum*, *Cymatiogalea bellicosa, Saharidia fragilis* and species of

Acanthodiacrodium, *Cymatiogalea* and *Vulcanisphaera*. Moreover, the *hamata-rarirrugulata* assemblage from Beckgrains Bridge contains *Striatotheca frequens* and *Stellechinatum* cf. *celestum*, which suggest that its stratigraphical position may be close to the Arenig-Llanvirn boundary. If so, the age of this deposit may be close to that of the breccia on Outerside. However, both of these breccias might be younger than the Buttermere Formation olistostrome in the Central Fells Belt of the Lake District. This resembles the Beckgrains deposit in so far as it contains a mixture of Tremadoc and Arenig acritarchs (see section 6.a.5.), but has so far failed to yield latest Arenig or Llanvirn fossils, and is inferred to have been emplaced close to the *I. gibberulus - D. hirundo* biozonal boundary (see section 6.a.6).

6. The stratigraphy of the Central Fells Belt

6.a. Buttermere Formation (new formation)

The Buttermere Formation is an olistostrome deposit, at least 1500 m thick, comprising disrupted, sheared and folded mudstone, siltstone and sandstone turbidite olistoliths (Fig. 9) which have yielded macrofaunas and microfloras ranging in age from Tremadoc to late Arenig (Fig. 12). The bulk of the formation is undivided, but two members are present near the middle of the formation in the Buttermere area. These are the Goat Gills Member, a sedimentary breccia, and the overlying sandstone-dominated Robinson Member. The Robinson Member has also been mapped in the vicinity of Causey Pike (Cooper 1990, figs 24 & 26) and Swinside near Braithwaite. The Buttermere Formation and the Robinson Member were informally proposed by Webb & Cooper (1988) and Webb (1990) who described the large-scale slump folds in the succession. More details of the formation and the definition of the Goat Gills Member were presented by Webb (1992).

- Figure 9 about here -

6.a.1. Type area

The formation is best seen east of Buttermere village, around Sail Beck [NY 170 175 to NY 188 190], High Snockrigg [NY 187 169] and Robinson [NY 202 169]. The outcrop of the Buttermere Formation is bounded to the north-north-west by the Causey Pike Fault. To the south and south-east, the formation persists up to the overlying Borrowdale Volcanic Group unconformity. To the west, the extent of the formation is unclear, but exposures in the

River Calder may be referable to the Buttermere Formation or may represent the underlying succession (see below). The base and top of the formation are not seen, but the top is likely to be an irregular surface upon which the Tarn Moor Formation was deposited.

6.a.2. Lithologies

The bulk of the olistoliths in the Buttermere Formation are dark grey mudstone, commonly with pale grey siltstone and very fine- to medium-grained sandstone laminae. Other olistoliths are homogeneous dark grey mudstone and medium-grained greywacke sandstone. The olistoliths vary in size from granule up to a kilometre or more across; the bulk of them are 5-10 m across (Fig. 10). Some of the most instructive exposures of the formation are in Sail Beck ([NY 188 178] to [NY 188 180]), where water-polished slabs are exposed. Here, angular to sub-rounded, dark grey banded siltstone and mudstone olistoliths up to 8 m long are enclosed in a pale grey sandy and silty mudstone matrix. Some of the olistoliths are angular and were at least partly lithified before being incorporated in the deposit; others are ragged with injection structures into and from the matrix, suggesting they were in a plastic state when re-deposited. Very fine-grained quartz is present throughout the argillaceous matrix around the olistoliths, suggesting that it comprised a disaggregated mixture. From Hindscarth [NY 2156 1652] to the Newlands Valley [NY 234 199], some 400 m of siltstone and mudstone olistostrome deposits overlie and appear to be younger than the Robinson Member. The clasts and matrix are intensely deformed by minor folds and shears, many of which were generated during emplacement of the olistostrome (Webb & Cooper 1988).

- Figure 10 about here -

In addition to these outcrops in the Buttermere area, slump-folded mudstones, siltstones and sandstones yielding Tremadoc trilobites and acritarchs (Molyneux & Rushton 1985; Rushton 1988) have been found along the River Calder [NY 0687 1178]. These beds may represent part of the pre-Buttermere Formation succession, or a raft of old material within it. It is not known whether the Arenig strata, possibly of the *gibberulus* Biozone, that were recorded nearby at Beck Grains [NY 0776 1128] (Allen & Cooper, 1986) are also an olistolith.

6.a.3. Goat Gills Member

The Goat Gills Member is a locally developed breccia which lies approximately in the middle of the Buttermere Formation. It comprises both rounded and angular siltstone and fine-grained sandstone clasts, generally around 2.5 cm but up to 0.2 m across, set in a silty mudstone matrix (Webb 1990, 1992). The clasts are identical to lithologies present in the overlying Robinson Member (see below) and bedding is often clearly visible within them. There is little evidence of bedding or imbrication of the clasts within the breccia. Locally, within-clast bedding appears to be traceable through adjacent clasts suggesting at least partial in-situ disruption rather than complete debris flow. The Goat Gills Member crops out in the core of the major slump fold anticline at Goat Gills [NY 190 161], whence it extends some 600 m northwestwards across Goat Crags (Webb & Cooper 1988; Webb 1992). It is up to 100 m thick, but its base is not seen. Along the upper limb of the anticline, the breccia passes into highly disrupted and contorted siltstone and mudstone with sporadic sandstone boudins of sedimentary origin. Both the breccia and the overlying disturbed unit have yielded microfloras of Tremadoc age.

6.a.4. Robinson Member

The Robinson Member is a series of large sandstone-rich olistoliths, ranging in size up to 1 km across, near the middle of the Buttermere Formation. They are mainly quartz-rich lithic wackes and granule conglomerates interbedded with siltstone and mudstone; lithologically they are similar to the Loweswater Formation of the Northern Fells Belt.

The sandstone beds are typically 0.1 to 0.2 m thick, but coarse and granule-grained beds locally reach 2.5 m thick. The sandstones exhibit sedimentary structures typical of Bouma-type turbidites. Laminar, convolute and ripple drift bedding (Bouma B and C units) predominate but graded bedding (Bouma A unit) is common, particularly in the coarser beds. The bases of the sandstones are mainly planar, but flute marks are sporadically preserved (Fig. 11); because of the disturbed nature of the olistostrome deposits, the palaeocurrent orientations are mostly rotated and therefore useless. The interbeds are mainly mudstone and siltstone laminae from 0.1-0.3 mm thick and probably represent turbidite fines (Bouma D unit) rather than hemipelagite (Bouma E unit).

- Figure 11 about here -

Sandstones are typically quartz-rich lithic wackes with a matrix content of 28-57%. The clasts are dominantly of strained quartz with moderate amounts of feldspar and sedimentary lithic fragments. In the granule conglomerates, the quartz clasts are sub-rounded and rounded. Robinson Member sandstones are compositionally similar to sandstones in the Loweswater and Hope Beck formations and are probably of similar age.

The Robinson Member was highly disrupted during the emplacement of the Buttermere olistostrome, and its preservation is related to its position on major slump folds developed at that time. Major rafts of the member, 1 km or more in length, are preserved on the inverted limbs and in the hinge regions of major anticlines passing through Goat Crags, the Snockrigg area, Moss Force and through Robinson and Littledale (Webb & Cooper 1988; Webb 1990, 1992). Except where the Goat Gills Member is present, the Robinson Member is surrounded by an envelope of Buttermere Formation which is rich in sandstone boudins; this was annotated by Webb (1992, fig. 3.5) as `Mélange with sandstone (Robinson Member)'. We now consider that this sandstone-rich envelope is best included in the bulk of the Buttermere Formation as it does not constitute an easily mappable unit.

At Goat Crags [NY 1895 1624], the junction with the underlying Goat Gills Member is very locally conformable but the lowest beds of the Robinson Member are, in general, highly disturbed and, in Goat Gills [NY 1914 1630], truncated against the underlying unit. A maximum thickness of around 250 m of the Robinson Member is exposed in Littledale [NY 211 173], where the base of the unit is not seen.

Other large rafts of Robinson Member sandstone in the Buttermere Formation occur below Causey Pike [NY 2196 2074] (Cooper 1990). Here the greywackes are thin-, medium- and thick-bedded (3cm-1m) with parallel and ripple cross-lamination (Bouma B and C units); these structures also give good way-up evidence. East-north-east of Causey Pike [NY 228 211] the rocks are the correct way up and dip steeply southwards, but south of it [NY 219 207] the beds are inverted with complex disharmonic slump folds on a 20-150 m scale (Cooper 1990, fig. 26). Sandstones present at Swinside [NY 243 225] are probably also part of the Robinson Member.

6.a.5. Biostratigraphy

Fossils from the Buttermere Formation (which comprise trilobites as well as graptolites and acritarchs if the River Calder exposures are included) indicate a range of ages from early Tremadoc to late Arenig (Fig. 12). In addition to various graptolite faunas of the *gibberulus* and *simulans* biozones, graptolites from Buttermere Quarry, situated within a large siltstone and mudstone olistolith of the Buttermere Formation, are taken to indicate a level close to the *varicosus* - *simulans* biozonal boundary; those from Scope Beck, placed at about the same level on Fig. 12, indicate no more than a *varicosus* or *simulans* Biozone age. The

Stelliferidium sp. nov. and *hamata-rarirrugulata* acritarch assemblages may be readily identified in the Buttermere Formation, and those from Buttermere Quarry (Molyneux & Rushton 1988) and High House Crag are generally like the interzonal assemblage. Furthermore, Tremadoc assemblages are widespread (Fig. 12). They include lower Tremadoc acritarchs such as *Acanthodiacrodium ubui*, *Cymatiogalea bellicosa*, *Dasydiacrodium cilium*, *Micrhystridium diornamentum*, *Priscotheca tumida?* and *Stelliferidium cortinulum*, which indicate an early Tremadoc age (see Rasul 1979) for beds at Newlands Hause, in the upper part of Swinside Gill, on Goat Crag and on High Snockrigg. The acritarchs from Goat Crag are from the Goat Gills Member, some component of which is therefore early Tremadoc. Other species, notably *`Baltisphaeridium'* cf. *lasium*, *Polygonium delicatum*, *Stelliferidium fimbrium?* and *Vulcanisphaera frequens?* suggest a late Tremadoc age (Rasul 1979) for strata in Sail Beck, in the lower part of Swinside Gill, and on High Snockrigg, in addition to the upper Tremadoc assemblage from the River Calder (Molyneux & Rushton 1985).

There are three features of the Buttermere Formation that need further comment. In the first place, there is no evidence for uppermost Arenig rocks of the *hirundo* Biozone; the youngest rocks in the olistostrome lie within the *gibberulus* Biozone or within the range of the *hamata-rarirrugulata* assemblage. This has implications for the timing of emplacement of the olistostrome (see section 6.a.6).

Secondly, there is no evidence for the *messaoudii-trifidum* assemblage in the Buttermere Formation. The only evidence that beds of earliest Arenig age might be included in the olistostrome (Fig. 12) is derived from Robinson, where a doubtful specimen of the graptolite *Azygograptus validus* (see Beckly & Maletz 1991), associated with *Acrograptus filiformis*, may represent a level below the *varicosus* Biozone. Farther south, the succession passes upwards into poorly laminated silty mudstone on the NW flank of Hindscarth [NY 211 164]; this has yielded *Pseudophyllograptus*, possibly of mid-Arenig age. This evidence suggests that the Robinson Member is of early and middle Arenig age, and was subsequently disrupted and emplaced into the Buttermere Formation. On acritarch evidence, however, the Robinson Member on Goat Crag is correlated with the *Stelliferidium* sp. nov. assemblage. The absence of the *messaoudii-trifidum* assemblage from the Buttermere Formation is consistent with the origin of the olistostrome on the upper continental slope or outer continental shelf, where deposition of beds of latest Tremadoc and earliest Arenig age might have been restricted or absent during a time of eustatic regression (Fortey 1984).

The third feature of the Buttermere Formation is the juxtaposition of beds of widely varying ages. In Swinside Gill [NY 1901 1777 to NY 1900 1777] and `Second Gill' [NY 1881 1819 to NY 1880 1819], Tremadoc acritarch assemblages have been obtained from within a few metres of the late Arenig *hamata-rarirrugulata* assemblage (Fig. 12). There is no mixing of the assemblages to indicate recycling in the normally accepted sense, as occurs at Beckgrains Bridge in the Northern Fells Belt. The close proximity of rocks with such disparate ages, and the chaotic distribution of the biostratigraphical records, confirms that the bulk of the olistostrome deposit is composed of large clasts, blocks and rafts of siltstone, mudstone and subordinate sandstone set in a silty mudstone matrix. The clasts are of sufficient size that most of the samples collected for micropalaeontological analysis are from blocks of a single age. One sample from the foot of Swinside Gill [NY 1876 1779] contains a mixture of Tremadoc and Arenig acritarchs, suggesting that it was collected from the disaggregated matrix around the olistoliths. Even so, the Buttermere Formation is not an entirely chaotic deposit, but retains some relict stratigraphy. Thus sandstones of the Robinson Member, although highly disrupted, lie mainly at a single, mappable level.

- Figure 12 about here -

6.a.6. Age and emplacement direction of the olistostrome

As the Buttermere Formation contains blocks of material that range in age from Tremadoc to late Arenig (Fig. 12), and is overlain by the Tarn Moor Formation of latest Arenig and Llanvirn age, the age of olistostrome emplacement is inferred to be in the late Arenig, possibly at about the boundary between the *gibberulus* and *hirundo* biozones. From the shapes of the major slump folds, Webb & Cooper (1988) inferred that the olistostrome was emplaced by downslope movement towards the NNW. From the thickness of the formation and size of the enclosed olistoliths it is apparent that the bulk of the formation in the Buttermere area was emplaced in one massive slumping episode. However, the brecciated and sheared nature of the deposit means that it is impossible to distinguish any subsidiary slump masses which may be associated with the Buttermere olistostrome.

6.b. Tarn Moor Formation (here formalised)

The Tarn Moor Formation is proposed as a formal name for the succession of mudstones and siltstones, with subordinate volcanic turbidite and bentonite beds, that occur in the eastern part of the Central Fells Belt.

6.b.1. Type area

The Tarn Moor Formation is present in the south-eastern part of the Skiddaw Inlier and forms all of the Ullswater and Bampton inliers (Figs 1 & 2).

The name Tarn Moor Mudstone was originally proposed by Wadge *et al*. (1972) for mudstones of *D. murchisoni* Biozone age proved in the Tarn Moor Tunnel. It was included by Wadge (1978) in the Eycott Group, but Jackson (1978) included it in the Skiddaw Group along with the succession proved in the Tailbert-Lanshaw Tunnel described by Skevington (1970). Moseley (1984) changed its name to the Tarn Moor Mudstone Formation and placed it near the top of the Skiddaw Group as a partly lateral equivalent of the Eycott Group. Recent work by Millward & Molyneux (1992) indicates that correlation with the Eycott Group is unjustified, so the correlation of Jackson (1978) is more tenable. No formal description of the formation has been published. The Tarn Moor Formation equates with the Kirkland Formation of the Cross Fell Inlier (Burgess & Wadge 1974; Cooper & Molyneux 1990).

The base of the Tarn Moor Formation has not yet been proved, but its age and outcrop pattern indicate that it lies above the Buttermere Formation. If this is so, it is likely that its lower boundary is unconformable on the highly disrupted Buttermere Formation, though the time-break would be minimal. The top of the Tarn Moor Formation is likewise not seen as it is unconformably overlain by the Borrowdale Volcanic Group (Wadge 1972); the youngest part of the formation proved is in the Tarn Moor Tunnel (Wadge *et al*. 1969).

6.b.2. Thickness

The thickness of the formation is difficult to determine, but cross-sections suggest that it is probably around 1000-1500 m.

6.b.3. Lithology and biostratigraphy

A broadly applicable tripartite division of the formation is suggested by the outcrop pattern, and supported by biostratigraphical evidence. The lower part of the succession in the Skiddaw Inlier comprises laminated and thickly laminated mudstone with subordinate siltstone beds similar in nature to the Kirk Stile Formation of the Northern Fells Belt. The oldest proven part of the formation is south-east of Keswick at Causeway Foot [NY 2907 2197]) where acritarchs of the *hamata-rarirrugulata* assemblage occur and Birkett Beck [NY 3280 2469?] where high *I. gibberulus* or low *D. hirundo* Biozone graptolites and trilobites have been found. The lower Llanvirn *Didymograptus artus* Biozone occurs in Cawell Beck [NY 3416 2582], and also in Mosedale Beck [NY 3554 2416 to NY 3546 2307] where uppermost Arenig and lowermost Llanvirn are juxtaposed.

The middle part of the formation is typified by mudstone with up to 5% of tuffaceous beds. These range from bentonite beds a few centimetres thick to successions, up to 12 m thick, of tuffaceous turbidite sandstone beds. Tuffaceous sandstones are present in Matterdale Beck, where they occur in mudstones that have yielded graptolites indicative of the *artus* Biozone (Wadge 1972). Along Aik Beck [NY 4728 2248 to 4730 2227], the mudstones similarly contain thin tuffaceous sandstone beds and sporadic bentonite beds; graptolites from here, including *Acrograptus affinis* and *Didymograptus* cf. *murchisoni speciosus,* suggest a mid-Llanvirn age. Towards the south-east, the proportion of volcanic beds appears to increase to a maximum in the vicinity of Bampton [NY 530 166] and Shap [NY 548 144], where Dakyns *et al*. (1897) recorded abundant `ash' beds in the succession. These are typically 2-4 m thick but may be up to 12 m thick. Mudstones associated with sporadic tuff units in the Tailbert-Lanshaw Tunnel (Skevington 1970) have yielded graptolites of the *artus* Biozone.

The highest part of the formation proved so far is in the Tarn Moor Tunnel at the eastern end of the Ullswater Inlier, where Wadge *et al*. (1969, 1972) recorded mudstones of the *murchisoni* Biozone faulted against probable *artus* Biozone mudstones. Compared to the

rest of the formation, the highest mudstones of the Tarn Moor Formation are darker grey to black. Tuff bands have not been recorded.

7. The stratigraphy of the Southern Lake District inliers

The Skiddaw Group inliers of Black Combe and Furness are geographically isolated to the south of the main Central Fells Belt exposures (Fig. 1). Their relationships to the Central Fells Belt rocks are unclear, but they are biostratigraphically equivalent to the lower parts of the Tarn Moor Formation. They are stratigraphically undivided (Fig. 3) and have not been given any specific formation names. Around Black Combe the Skiddaw Group is overlain by the Borrowdale Volcanic Group (Fig. 3) which attenuates southwards and is missing in the Furness inliers where late Ordovician mudstones are present above the Skiddaw Group.

7.a. Black Combe

7.a.1. Thickness and lithology

The Black Combe Skiddaw Group succession of siltstones and mudstones, probably more than 1 km thick, was subdivided by Helm (1970) into three stratigraphical units on the basis of colour. The paler colours in these rocks are now recognized to be products of secondary metasomatism and metamorphism. The unaltered rocks correspond to the Whicham Blue Slates of Helm, whereas both the Fellside Mudstones and the Townend Olive Slates are altered, the latter being further affected by a pervasive cleavage fabric and numerous granitic sheets. This fabric is possibly related to the development of the Westmorland Monocline (Fig. 1) and represents part of the root structure of that fold (Kneller & Bell 1993).

The succession comprises mainly thinly laminated mudstones and siltstones. However, subordinate laminated to thinly-bedded (0.3-10cm) wackes form a succession 200-300 m thick on Knott Hill [SD 174 873]. They are present east of a north-south fault zone along the Whicham Valley and comprise mainly fine to medium-grained, hornfelsed wackes. Their stratigraphical relationships to the Whicham Blue Slates are unknown (Johnson 1992 and personal communication 1993).

7.a.2. Biostratigraphy. Graptolites and acritarchs from the Whicham Blue Slates (Rushton & Molyneux 1989) are of late Arenig *D. hirundo* Biozone age.

7.b. The Furness inliers

7.b.1. Thickness and lithology

The Skiddaw Group is poorly exposed in the Furness inliers (Fig. 1), where it is unconformably overlain by the High Haume Mudstone of Ashgill age (Rose & Dunham 1977). There is no good indication of the structure or thickness of the Skiddaw Group hereabouts. The Skiddaw Group rocks are dominantly medium dark grey mudstones in which it is often difficult to distinguish bedding, though this is sometimes indicated by silt laminae up to 2 mm thick.

7.b.2. Biostratigraphy

Graptolites indicate the *D. hirundo* Biozone (Rose & Dunham 1977). Acritarchs and chitinozoa reported to indicate a Llanvirn age have also been recorded (Rose & Dunham 1977), though this interpretation needs to be reassessed in the light of more recent work. The mudstones of the Furness inliers therefore appear to correlate with those of Black Combe (Fig. 3).

8. Provenance of the Skiddaw Group

From faunal provincialism, Fortey *et al.* (1989) argued that the Skiddaw Group was deposited in deep circumpolar water peripheral to the Gondwanan continent. We regard the group as deep-water slope and basin deposits formed on a continental margin.

8.a. Petrography

Within the Skiddaw Group, specific sources of material can be identified from the petrographical observations. Lithic fragments of granite, the dominance of untwinned and potassium feldspar over plagioclase, and the common occurrence of tourmaline, suggest the erosion of unroofed acid plutons in the source region. Evidence for pre-Llanvirn volcanism is lacking (Hughes & Kokelaar 1993). However, pyroclastic and volcaniclastic fragments present throughout the group suggest some erosion of arc-related deposits; from rare-earth geochemical studies (R.M.Moore, unpub. Ph.D. thesis, Univ Leeds, 1992), it is implied that these were probably derived from ancient non-coeval deposits. Fragments of cleaved granite, shale and quartz-mica schist suggest recycling of an orogenic source. The detritus enriched in quartz was presumably denuded from an ancient orogenic terrane and mature quartz-wackes were probably derived from shelf sands. A triangular Qm-F-Lt plot (Fig. 13) shows compositional variation between individual formations and their various lithological components. Data are spread across `quartzose recycled orogen', `continental block' and `mixed' provenance fields.

8.b. Geochemistry

Comparison with average multielement patterns for different tectonic settings (Floyd *et al.* 1991) shows components of both `continental arc/active margin' and `passive margin' provenance in the formations of the Skiddaw Group (Fig. 14). The Kirk Stile Formation has a larger mafic component, as indicated by high values of Cr and Ni, a large Nb anomaly and the presence of altered mafic clasts. All formations have a common wide range of clast types, but variations in their proportions leads to differences in composition between units.

- Figures 13 & 14 about here -

8.c. Source areas of the Skiddaw Group

We conclude that the Skiddaw Group was derived from an inactive continental arc terrane comprising siliceous volcanic deposits, unroofed acid plutons, cleaved and metamorphosed basement rocks and sedimentary strata, which were recycled into the Skiddaw Group depositional system. In the upper part of the group, during the Llanvirn, juvenile volcanic detritus increased in amount and diluted the older orogenic material. The palaeocurrent evidence suggests that the source area lay to the south-east of the depositional centre, though this could imply more about the topography of the depositional basin than overall transport directions.

9. The Skiddaw Group in its regional setting

Rocks of equivalent age and similar lithologies to the Skiddaw Group are exposed along strike to the south-west in the Isle of Man and south-eastern Ireland (Fig. 1). The stratigraphical belts and major structural lines may be traced laterally, though largely concealed beneath cover sequences. The Lower Palaeozoic structures may possibly be traced across the Irish Sea (and through Northern England) by following their expression both as reactivated faults and later basin margin synsedimentary faults such as those mapped by Jackson *et al.* (1987) (Fig. 1). The disposition of the East Irish Sea faults suggests that the Northern Fells Belt extends westwards to the Isle of Man and possibly into Ireland (Fig. 1). However, the correlation across the Causey Pike Fault in the Lake District, which separates areas of distinct stratigraphy, means that any comparisons of the Manx and Irish successions with the Skiddaw Group must take into account the possible transcurrent movements on this and related structures. The Causey Pike Fault had a long history in the Lake District. Initially, it influenced sedimentary slumping and olistostrome emplacement directions during the Arenig (Webb & Cooper, 1988). Subsequently, it became the focus of sinistral strike slip movement and synchronous granite empalcement followed by southerly directed thrust movements (Cooper *et al.*, 1988; Cooper, 1990; Cooper & Molyneux, 1990; Cooper *et al.*, 1992, 1993; Hughes *et al.*, 1993). While the Causey Pike Fault is undoubtedly a major structure through the Skiddaw Group the overall broad similarity between the sequences north and south of it would appear to preclude it being a terrane boundary. However, similar sedimentation could have occurred on both sides of the fault in widely separated areas on the Gondwanan continental margin. The only indication of possible movement amounts on the fault comes from the lack of continuety across it in the Lake District and Cross Fell, this possibly suggests a minimum sinistral movement of 70km. The late southerly directed thrust displacement at Causey Pike is about 0.5-1 km.

9.a. Comparison with the Ingleton Group

South and east of the Black Combe and Furness inliers, the Skiddaw Group is concealed beneath younger strata. To the east, greywackes of Arenig age (Ingleton Group) have been proved in the Beckermonds Scar Borehole [SD 8635 8016] (Fig. 1) on the Askrigg Block (Wilson & Cornwell 1982). The Ingleton Group rocks of the Chapel-le-dale Inlier have a south-easterly palaeocurrent derivation similar to the Loweswater Formation. However, their sedimentary characters and petrographical compositions are sufficiently different to conclude that they were unconnected (Leedal & Walker 1950; R.M.Moore, unpub. Ph.D. thesis, Univ Leeds, 1992). Furthermore, major basement faults separate the Askrigg Block from the Skiddaw Group of the Lake District and the past relationships of the two areas are unclear.

9.b. Comparison with the Isle of Man

The Manx Group of the Isle of Man is comparable in age, lithology and facies to the Skiddaw Group (Fig. 15). It comprises a thick pile predominantly of mudstone, siltstone and sandstone turbidites with sedimentary breccias (Gillott 1956; Simpson 1963), and has its closest similarities with the Skiddaw Group succession in the Northern Fells Belt.

Simpson (1963) erected a succession of twelve formations (Fig. 15). Though the Manx Group has so far proved to be only sparsely fossiliferous, the biostratigraphical evidence does not support the order of superposition in Simpson's (1963) scheme. This evidence suggests that formations towards the top of Simpson's succession are among the oldest exposed on the island, whereas the lowest formation in Simpson's scheme should be placed higher in the succession. A revised succession is suggested in Fig. 15. In this, formations with biostratigraphical evidence of age are distinguished from those without. The latter are placed in a succession that conserves Simpson's order of superposition as much as possible, but it has to be recognized that such a scheme is insecurely based in the absence of biostratigraphical control

- Figure 15 about here -

Dendroid graptolites indicate a probable Tremadoc age for the Cronk Sumark (= Cronkshamerk) Slates (Rushton 1993) a sequence of dark grey strongly cleaved laminated mudstones. If so, these rocks may have no direct correlatives in the Northern Fells Belt of the Lake District, being older than the Bitter Beck Formation (Fig. 15).

The Glen Dhoo Flags, overly the Cronk Sumark Slates in Simpson's (1963) scheme, and have yielded an acritarch microflora that Molyneux (1979) considered to be of probable latest Tremadoc age. The assemblage from the Glen Dhoo Flags certainly has much in common with the *messaoudii-trifidum* acritarch assemblage including an abundance of *Stelliferidium trifidum*, but lacks *Cymatiogalea messaoudii*. It does, however, contain *Coryphidium* cf. *bohemicum* and *Cymatiogalea* cf. *granulata*, suggesting correlation with the *trifidum-bohemicum* assemblage and an early Arenig rather than late Tremadoc age. A similar assemblage, hitherto regarded as latest Tremadoc (Molyneux, 1979) but now considered to be more probably early Arenig, occurs in the Lonan Flags, from which Arenig graptolites have also been recorded (Rushton 1993).

Acritarchs from the Niarbyl Flags were previously reported to indicate a possible Tremadoc age (Molyneux 1979), though it is now considered that they may also represent an impoverished *messaoudii-trifidum* assemblage of late Tremadoc or early Arenig age. A second microflora, from poorly exposed Niarbyl Flags interbedded with supposed volcanic rocks near Peel (Simpson 1963), was previously thought to be of late Arenig age (Molyneux 1979), but can now be reinterpreted as the uppermost sub-assemblage (5) of the *messaoudii-trifidum* assemblage. The microfloras suggest that the Niarbyl Flags are partly temporal equivalents to the topmost Watch Hill and basal Hope Beck formations in the Lake District. Lithologically the Glen Dhoo, Lonan and Niarbyl flags comprise 60-80% fine-grained quartz-rich greywacke sandstone beds and 20-40% siltstone and mudstone; the sedimentary structures they contain are mainly parallel and cross-lamination (Bouma B and C units). These sandstone units resemble the sandstones in the Hope Beck and Loweswater formations in the Lake District.

The `Peel volcanic rocks' were recorded as andesitic lava, tuff and agglomerate with sedimentary intercalations (Simpson 1963). Hughes & Kokelaar (1993) have re-interpreted two supposed Skiddaw Group lavas in the Lake District and Cross Fell inlier as sills. Thus the oldest primary volcanic material occuring in the Skiddaw Group is in the bentonite beds of the Tarn Moor Formation. No volcanic rocks of equivalent age to the Peel volcanics occur in the Skiddaw Group and the interpretation of the latter as a volcanic succession should be treated with caution.

Acritarchs from the Maughold Banded Group (Molyneux 1979) suggest the *Stelliferidium* sp. nov. assemblage, indicating a probable correlation with the upper part of the Loweswater Formation or the lower part of the Kirk Stile Formation. Those from the Lady Port Banded Group (Molyneux 1979) are typical of the *hamata-rarirrugulata* assemblage, and indicate a probable correlation with the Kirk Stile Formation. Lithologically the Maughold Banded

Group and the Lady Port Banded Group comprises laminae and thin beds (0.5-3cm) of grey and dark grey siltstone and mudstone; they closely resembles the Kirk Stile Formation in the Lake District with which they are correlated.

In Simpson's (1963) lithostratigraphical scheme, the Lady Port Banded Group is overlain by the Ballanayre Slump-Breccia. Since the Niarbyl Flags adjacent to the breccia are inferred to be of late Tremadoc or early Arenig age, their contact with the breccia must be faulted, as suggested by Roberts *et al.* (1990). From mica crystallinity studies, Roberts *et al.* (1990) also concluded that the Ballanayre Slump-Breccia was high in the Manx succession. The inferred age of this unit equates it with the breccia beds in the Kirk Stile Formation near Beckgrains Bridge, and with the Buttermere Formation olistostrome of the Central Fells Belt. The outcrop pattern also suggests that the Sulby Slump-Breccia may be young, tempting correlation with the Ballanayre Slump-Breccia. The Isle of Man slump breccias are debrites comprising mudstone-supported angular and rounded clasts, dominantly of mudstone, but also including greywacke sandstone clasts. Lithologically they are very similar to the debris-flow breccia beds in the Lake District.

For descriptive purposes Simpson (1963) used three lithological groups, the flaggy formations, the banded formations and the pelitic formations. The re-correlation presented by us shows that many of Simpson's flaggy formations are lateral equivalents. It is probable that, as more biostratigraphical control is established, some of the other lithologically similar formations (mainly shown in italics in figure 15) will also be established as equivalents.

9.c. Comparison with eastern Ireland

Several terranes have been postulated in eastern Ireland (reviewed in Murphy *et al.* 1991), among which are the Grangegeeth terrane in the north, the Bellewstown terrane, and the Leinster terrane in the south, the last of which may itself comprise numerous accreted terranes (Max *et al*. 1990).

Arenig strata are unproved in the Grangegeeth terrane, but the Llanvirn succession is a succession of volcanic tuffs with subordinate interbedded graptolitic mudstones of *D. artus* Biozone and possibly *D. murchisoni* Biozone age (references in Murphy *et al.* 1991). The graptolites are mainly scandent forms with `Atlantic province' affinities, like those of the Lake District. The occurrence of Llanvirn volcanic units interbedded with graptolitic mudstones invites comparison with the Tarn Moor Formation of Central Fells Belt, but the

Irish succession contains a much higher proportion of volcanic rocks. The unconformably overlying Grangegeeth Group of volcanic conglomerates, tuffs and shales has yielded abundant Caradoc shelly faunas. The volcanic rocks have tholeiitic affinities and geochemically compare most closely with the probable Llandeilo-Caradoc Eycott Volcanic Group (Millward & Molyneux 1992) which unconformably overlies the Northern Fells Belt of the Skiddaw Group in the Lake District. However, the shelly fauna from the Grangegeeth Group has Laurentian affinities, whereas the Eycott Volcanic Group is overlain by the Drygill Shales which have a Longvillian (mid-Caradoc) shelly fauna with Anglo-Welsh, and therefore Avalonian or Gondwanan, affinities (Dean 1963).

The Bellewstown terrane is separated from the Grangegeeth Terrane by the Slane Fault, which Todd *et al.* (1991) suggested to be a candidate for part of the Iapetus suture fault complex ("AIA" on Fig. 1). The Llanvirn rocks contain pendent didymograptids and (unlike the Skiddaw Group) a shelly fauna of Celtic affinity. This succession is unconformably capped by volcaniclastic turbidites, mudflows and mudrocks of latest Llanvirn to Caradoc age, with shelly faunas of Anglo-Welsh affinity that contrast with those of Grangegeeth. The volcanic successions have calc-alkaline affinities and Murphy (1987) compared them with the Borrowdale Volcanic Group of the Lake District (Central Fells Belt).

The Ordovician of the Leinster terrane (Murphy *et al.* 1991) shows fewer similarities with the Lake District succession than the other terranes. The succession along the northern edge of the Leinster terrane, at the Balbriggan and Herbertstown inliers, comprises unfossiliferous red and green mudrocks overlain by grey mudrocks and siltstones. These are themselves unconformably overlain by andesitic volcanic rocks, capped by mudrocks and siltstones that have yielded a middle Caradoc fauna (Romano 1980). No close comparison with the Ordovician of the Lake District is apparent. However, the passage from a dominantly marine mudstone/siltstone succession in the Ribband Group, of Cambrian to Llanvirn age, to the more volcanic-rich Duncannon Group of mainly Caradoc age (Parkes 1992), parallels the megasequence evolution of both the Lake District and Welsh areas (Woodcock 1990).

10. Palaeogeographical and plate tectonic setting

The sedimentological and provenance interpretations can be considered in the context of the palaeogeographical reconstructions of Scotese & McKerrow (1990, 1991) and McKerrow *et al.* (1991). Throughout the Skiddaw Group, the ancient orogenic terrane source area was probably the Gondwanan continent. The Skiddaw Group was deposited on the oceanward margin of this continent in a passive margin situation during the Tremadoc and Arenig. This contrasts with Wales where the Cambrian to Tremadoc passive margin became a volcanic arc in the late Tremadoc (Woodcock 1990) and a marginal basin from the Arenig to Caradoc. However, the Ordovician configuration of the Lake District, Irish and Welsh areas is equivocal (Kokelaar 1988) and major strike slip separations between them may account for the differences in the timing of the onset of subduction. The large amounts of quartz-rich detritus (such as in the Loweswater Formation) may have been derived from the large shelf area that fringed the continent throughout the Ordovician. During the Arenig, this shelf was the locus for extensive sandstone deposition such as the widespread Grès Armoricain and equivalents that fringed the Gondwanan continent (Robardet *et al.* 1990; Young 1990).

In the Lake District the margin became more unstable during the late Arenig, and the olistostrome of the Buttermere Formation was emplaced. The succeeding Tarn Moor Formation recorded the first volcanism coeval with the Skiddaw Group, with the influx of volcaniclastic turbidite deposits in the Llanvirn. The onset of volcanism may have been related to the rifting of the Eastern Avalonian microcontinent from Gondwana. It was followed by the northward drift of Eastern Avalonia with subduction along its margin; this probably caused the major uplift of the Skiddaw Group which was considerably eroded before the eruption of the largely subaerial Eycott and Borrowdale Volcanic groups (Hughes *et al.* 1993).

11. Conclusions

Two stratigraphical belts are present in the Skiddaw Group of the Lake District inlier. In the Northern Fells Belt, five formations range in age from Tremadoc to early Llanvirn. In the Central Fells Belt, the Buttermere Formation, an olistostrome deposit, is overlain by the Tarn Moor Formation. The Skiddaw Group is undivided in the Southern Lake District inliers of Black Combe and Furness. The Northern and Central belts are separated by the Causey Pike Fault.

The Skiddaw Group consists mainly of deep water clastic turbidites which accumulated on the oceanward margin of the Gondwanan continent. Provenance studies suggest derivation from a mature, inactive continental arc area comprising volcanic deposits, unroofed granitic plutons, and cleaved and metamorphosed sedimentary rocks. Instability of the continental margin in the late Arenig is indicated by the Buttermere Formation olistostrome. The lower Llanvirn part of the succession contains volcaniclastic turbidite beds, indicating contemporaneous volcanism, but the proximity of the source area is unknown. The Skiddaw Group volcanism and instability of the continental margin may have been related to the onset of subduction associated with the rifting of the Lake District part of Eastern Avalonia from Gondwana and the eruption of the overlying Borrowdale Volcanic Group.

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Figure captions

Figure 1. Distribution of the two stratigraphical belts of the Skiddaw Group in the Lake District and surrounding area. Inset map - Trans Irish Sea basement structures mapped in the Lower Palaeozoic sequences as syndepositional Upper Palaeozoic structures and as Mesozoic basin margins (from authors quoted in the text); their suggested continuation throughout the area and tentative delineation of terrane belts. For both maps the major basement structures in the Skiddaw Group and the overlying succession are shown with the following abbreviations: BF-Butterknowle Fault, CF-Craven Fault. CPF-Causey Pike Fault, DF-Dent Fault, EUF-Eubonia Fault, GF-Gilcrux Fault, LAF-Lagman Fault, LF-Lunedale Fault, LLF-Lowther Lodge Fault, MF-Maryport Fault, NF-Navan Fault, NFF-Ninety Fathom Fault, NSF-North Solway Fault, PF-Pennine Faults, SBF-Stublick Fault, SLF-Slane Fault, STF-Stockdale Fault. Deep boreholes mentioned in the text are also shown with the abbreviations AB-Allenheads Borehole, BS-Beckermonds Scar Borehole, RD-Roddymoor Borehole, RK-Rookhope Borehole. The alternative position of the Iapetus Suture is shown with the abbreviation AIA.

Figure 2. Generalised geological map of the Skiddaw Group in the northern Lake District. For location of map see figure 1. Locations of type localities and boundary statatypes mentioned in the text are shown as a spot with the following abbreviations: BB - Bitter Beck (Bitter Beck Formation); WH - Watch Hill (Watch Hill Formation); HB - Hope Beck (Hope Beck Formation); D - Dodd (Loweswater Formation, lower boundary statatype); L - Loweswater (Loweswater Formation); WE - Whiteside End (Kirkstile Formation, lower boundary statatype); K - Kirk Stile (Kirk Stile Formation); BU - Buttermere (Buttermere Formation, Goat Gills Member and Robinson Member); T - Tarn Moor Tunnel entrance (Tarn Moor Formation). Major faults in the area are shown with the following abbreviations: WHT - Watch Hill Thrust; LT - Loweswater Thrust; GT - Gasgale Thrust; CPF - Causey Pike Fault (thrust at Causey Pike).

Figure 3. Lithostratigraphical correlation diagram for the Skiddaw Group in the Lake District. Because the vertical scale of the diagram is thickness the time lines are correctly placed for the series boundaries only. * The Buttermere Formation olistostrome was emplaced over a short time interval in the late Arenig immediately prior to the deposition of the Tarn Moor Formation.

Figure 4. Correlation of acritarch and graptolite biostratigraphy with the lithostratigraphy of the Northern Fells Belt of the Lake District. Correlation with Baltic and Australasian biozones is after Cooper & Lindholm (1990) and the estimated time scale is after Cooper (1992). The approximate stratigraphical horizon of recorded trilobites is shown; * indicates taxa discussed by Fortey *et al.*, 1989. a, **Colpocoryphe* sp.; b, **Cyclopyge grandis* aff. *grandis*; c, *C. grandis brevirhachis*; d, *Degamella evansi*?; e, **Ectillaenus* sp.; f, **Gastropolus obtusicandatus*; g, *Hetercyclopyge* sp.; h, **Illaenopsis harrisoni*;

i, **Microparia* cf. *boia*; j, **Microparia* cf. *shelvensis*; k, **Novakella copei*; l, **Ormathops nicholsoni*; m, **Placoparia cambriensis*; n, **Plasiaspis ovata*; o, **Pricyclopyge binodosa binodosa*; p, **Psilacella doveri*; q, **Selenopeltis* sp.

Figure 5. Occurrence of selected acritarch taxa in acritarch assemblages of the Northern Fells Belt.

Figure 6. Watch Hill Formation, thick, medium and thin bedded greywackes and siltstones many in lenticular beds at Elva Hill near Cockermouth [NY 1724 3204].

Figure 7. Loweswater Formation at Swinside, Whinlatter Pass [NY 1781 2486]. Thick bedded parallel and cross-laminated (Bouma B and C units) greywacke turbidite bed with truncated cross-lamination showing the unit to be the correct way up.

Figure 8. Debris bed on the southern flank of Outerside [NY 2148 2149] showing sub-rounded clasts of bedded siltstone and a few sandstone clasts in a siltstone matrix; this rock is hornfelsed by the Crummock Water Aureole. The chisel of the hammer head is 7cm long.

Figure 9. Disharmonic slump folded greywackes and siltstones of the Buttermere Formation at Lambing Knott [NY 194 154] near Gatesgarth, Buttermere.

Figure 10. Sandstone olistolith, about 5m high, in the Buttermere Formation olistostrome at Moss Force, Newlands Hause near Buttermere [NY 1930 1740].

Figure 11. Robinson Member of the Buttermere Formation, massive greywacke bed with well developed flute casts on its base at Blea Crag, Scope Beck Newlands [NY 2135 1758]. BGS photograph D 3845.

Figure 12. Correlation of graptolite and acritarch biostratigraphy with lithostratigraphy in the Central Fells Belt. The columns headed `Macrofossil localities' and `Acritarch localities' give an indication of the range of ages of olistoliths in the Buttermere Formation, and their disposition. Question marks by the side of localities indicate uncertainty over the biostratigraphical unit represented.

Macrofossil localities: Addacomb Beck [NY 1993 1962]; Beck Grains [NY 0776 1128]; Buttermere Quarry [NY 1735 1721]; Calf Screes [NY 2138 1680]; Dry Gill [NY 1838 1829]; High Snockrigg [NY 1863 1682]; Ill Gill [NY 2015 1900]; Littledale Edge [NY 2132 1595]; Ramps Gill [NY 1918 1855]; River Calder [NY 0687 1174]; Robinson [NY 2010 1700]; Rowantree Beck [NY 1776 1816]; Rowling End [NY 2297 2031]; Scope Beck [NY 2187 1821]; Stonycroft Gill [NY 2284 2122]; Wilton [NY 0375 1110]; Ya Gill [NY 0738 1242]. Trilobites recorded are: Beck Grains [NY 0776 1178] - a, *Ellipsotaphrus sp.* b, *Heterocyclopyge* sp.; c, *Pricyclopyge binodosa* s.l.; River Calder [NY 0776 1128] - d, Tremadoc fauna (Rushton, 1988).

Acritarch localities: Buttermere [NY 1763 1704]; Buttermere Quarry [NY 1732 1726]; Goat Crag [NY 1944 1637] (*hamata-rarirrugulata* assemblage?), [NY 1894 1631] (lower Tremadoc assemblage, Goat Gills Member), [NY 1900 1646] (*Stelliferidium* sp. nov. assemblage, Robinson Member); High House Crag [NY 1733 1729]; High Hole Beck [NY 199 173]; High Snockrigg [NY 1842 1708] (*hamata-rarirrugulata* assemblage), [NY 1814 1710] (upper Tremadoc assemblage?), [NY 1857 1706] (lower Tremadoc and *Stelliferidium* sp. nov. assemblage); Knott Rigg [NY 1943 1822]; Low Bank [NY 1763 1750]; Newlands Hause [NY 1930 1762]; Ramps Gill [NY 1921 1857]; River Calder [NY 0687 1174]; Robinson Crag [NY 1998 1715]; Sail Beck [NY 1876 1791]; Scale Knott [NY 1538 1751]; Second Gill [NY 1881 1819] (upper Tremadoc assemblage), [NY 1880 1819] (*hamata-rarirrugulata* assemblage); Squat Beck [NY 1795 1775]; Swinside Gill [NY 1919 1782] (lower Tremadoc assemblage), [NY 1900 1777] (*hamata-rarirrugulata* assemblage), [NY 1875 1780] (upper Tremadoc assemblage); Whiteless Pike [NY 1796 1777].

Figure 13. Provenance discrimination diagram, Qm-F-Lt plot with the provenance fields of Dickinson *et al.* (1983), for greywackes of the Skiddaw Group; (modal analyses based on 100-300 points per slide). (a) Watch Hill Formation, (b) Hope Beck Formation, (c) Loweswater Formation, (d) Kirk Stile Formation.

Figure 14. (a) Multi-element variation diagrams for average sandstone compositions of different tectonic settings (Floyd *et al*. 1991), and (b) average greywacke compositions for formations of the Skiddaw Group.

Figure 15. Correlation of the Manx Group with the Skiddaw Group of the Northern Fells Belt. Manx Group formations in bold typeface have biostratigraphical evidence of age; this is also indicated by symbols indicating the graptolite and acritarch occurences in the Isle of Man and the equivalent occurrences in the Lake District (see text); the range of age possible for the Lonan Flags is indicated by the vertical arrows. Manx Group formations in italics have no biostratigraphical evidence of age; their suggested position conserves Simpson's (1963) order of succession as far as possible, but is insecurely based. The inferred position of the slump-breccias in the Manx succession approximates to the position of sedimentary breccias in the Skiddaw Group.

Figure 6. Watch Hill Formation, thick, medium and thin bedded (3-40cm) greywackes and siltstones many in lenticular beds at Elva Hill near Cockermouth [NY 1724 3204].

Figure 7. Loweswater Formation at Swinside, Whinlatter Pass [NY 1781 2486]. Thick bedded (60 cm) parallel and cross-laminated (Bouma B and C units) greywacke turbidite bed with truncated cross-lamination showing the unit to be the correct way up.

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