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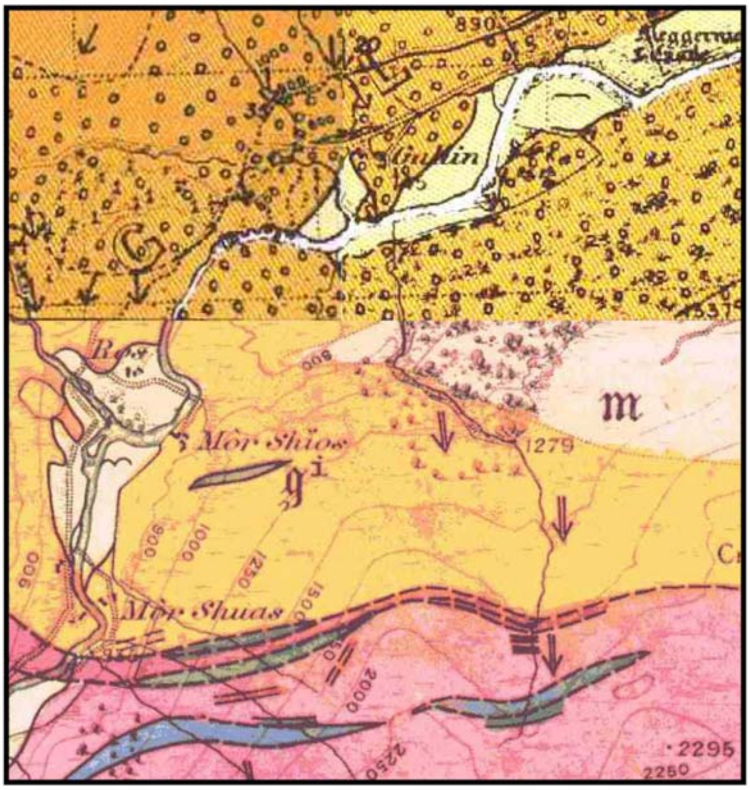
Lithostratigraphy and structure along the Boundary Slide Corridor: background, problems and strategy

Moine and Dalradian Basins Project

Integrated Geoscience Surveys (North)

Internal Report IR/03/053

Richard Smith and Maarten Krabbendam.



Geological map of Boundary Slide south of Meggernie Castle

BRITISH GEOLOGICAL SURVEY

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Foreword

"The most remarkable feature in the structure of the Glen Lyon area is the near approach that the Garnetiferous Micaschist makes to the undoubted flags of the 'Moine' type. [….].the breadth of ground separating these two quite distinct rock-units may be measured in yards. […..] This striking fact has never been satisfactorily explained not indeed does much attention appear to have been paid to it."

M. MacGregor, in: Hinxman, L W, Carruthers, R G, and Macgregor, M. 1923. The geology of Corrour and the Moor of Rannoch. *Memoir of the Geological Survey, Scotland*, Sheet 54.

Contents

FIGURES

1 Introduction

This report provides an assessment of future scientific studies and proposals for field mapping in and area defined here as the Boundary Slide Corridor (Figure 1), and regarded as a key strategic element within the Moine and Dalradian Basins Project area. The report is focussed on the northern part of the Killin-Crianlarich districts (Sheet 46) and the southern parts of the Loch Rannoch (Sheet 54W) and Blackwater (Sheet 54E) districts, although the corridor extends from the Loch Tay Fault in the east of the Schiehallion district (Sheet 55W), south-westwards to Glen Strae, near Dalmally. It therefore also includes parts of the Schiehallion, Dalmally (Sheet 45E) and Comrie (Sheet 47W) 1:50k geological sheets.

The first part of the report is concerned with the depositional history of the Dalradian Supergroup in Neoproterozoic time, and a summary of the main Caledonian structural and metamorphic features. Current understanding of the geology is briefly reviewed and provides the basis for the suggested strategy for future work. Earlier assessments of the Killin district (Sheet 46E, Wain 1999) and a summary of progress in that sheet (Hyslop 2001) are included in that review.

In addition the report has the following specific objectives (see Chapters 5-7):

- to summarise the stratigraphical and structural problems concerning the Boundary Slide with particular emphasis on the associated stratigraphical omission of significant parts of the Appin and Argyll Subgroups in the Central Highlands;
- to discuss possible, testable, hypotheses for the existence and development of the Boundary Slide and its associated stratigraphical omissions;
- to suggest key areas in the field where such problems may be addressed and hypotheses tested as part of the Moine Dalradian Basins Project.

The report then considers current understanding of the economic geology of the region in light of the revised strategy. Additional background information relating the economic geology is provided in Appendices 1-3.

1.1 PREVIOUS WORK

The Crianlairich-Glen Orchy-Rannoch area was previously mapped by the Geological Survey; the Balquhidder sheet (Sheet 46) was published in 1900 and the Corrour and Moor of Rannoch sheet (Sheet 54) in 1923. The Loch Rannoch and Blackwater sheets were both republished at 1:50k scale with minor revision in 1974; Sheet 45E (Dalmally) was published in 1992 and Sheet 55W (Schiehallion) in 2000 (BGS 2000).

There are no geological survey memoirs for the original Balquhidder and Crieff (Sheet 47) sheets but relevant memoirs have been published for the Corrour and Moor of Rannoch (Hinxman *et al.* 1923), Oban and Dalmally (Kynaston and Hill 1908) and Glencoe/Ben Nevis (Sheet 53E; Bailey and Maufe 1916, Bailey 1960) districts. More recently, memoirs for adjacent sheets Glen Roy (Sheet 63W; Key *et al.* 1997) and Schiehallion (Sheet 55W; Treagus 2000) have been published and contain information relevant to the project area.

In the Glen Lyon-Lochay area, the hydro-electric power scheme provided the opportunity to update the local geology (Johnstone and Smith 1965). Subsequently the BGS mineral reconnaissance programme completed comprehensive studies into the mineralisation of the area (Smith *et al.* 1977, Coleman and Cooper 2000).

A number of scientific papers and unpublished PhD theses cover more recent developments in the geology of the area. Many of these are listed in the Grampian Regional Guide (Stephenson and Gould 1995) and the Schiehallion memoir (Treagus 2000). More recent structural theses include those of Nell (1984) on the structure of Glen Lyon and Watkins (1982) on the Balquhidder area.

2 Current framework for lithostratigraphy and sedimentology in the Boundary Slide corridor

With regard to the Boundary Slide Corridor, the most up to date mapping published by the Geological Survey is that on the Schiehallion Sheet to the north-east of the corridor. This new map incorporates the standard Dalradian groups, subgroups and formations but these are not, of course, delimited on the 20th century one inch to one mile maps of Balquhidder and Crieff. The 1:50k scale lithostratigraphical maps of Loch Rannoch and Blackwater, both published in 1974, do include minor amendments to that early mapping taken from Bailey (1934). The present report is designed to focus on the lithostratigraphical relationships ranging from the uppermost part of the Grampian Group to the top of the Argyll Group. The principal formations concerned are outlined in Table 1. Towards the central part of the corridor outlined on Figure 1 there appears to be a major omission of Appin and lower Argyll Group strata which may relate to structural relationships across the Boundary Slide or perhaps to primary stratigraphical architecture, for example the result of facies changes over an ?inverted basin high of the Grampian Group; this issue is further addressed in sections 5and 6.

GROUP	SUBGROUP	FORMATION
Southern Highland		
Argyll	Tayvallich	Loch Tay Limestone
	Crinan	Ben Lui Schist
	Easdale	Ben Challum Quartzite Farragon Volcanic Ben Lawers Schist Ben Eagach Schist Carn Mairg Quartzite
	Islay	Schiehallion Quartzite and Boulder Bed
Appin	Blair Atholl	
	Ballachulish	
	Lochaber	
Grampian	Strathtummel Succession	

Table 1. Current Dalradian Lithostratigraphy in the Boundary Slide Corridor

Stratigraphical correlation in the area was addressed by Roberts and Treagus (1979) and based upon France (1971), Treagus (1964), Bailey and McCallien (1937) with some revision by P Nell and the authors. While a broad correlation of extensive and well-defined Dalradian sequences clearly exists between south-west Argyll and the Schiehallion areas (Harris *et al.* 1994 and Figure 2), the intervening ground, where “tectonic removal” is implicated in the apparent absence of key formations, is less well understood. The principal formations are reviewed below.

2.1 GRAMPIAN GROUP

Rocks in this region, generally regarded as the upper part of the Grampian Group, comprise a thick sequence of mainly quartzose psammites, mostly laminated or thinly bedded, with subordinate semipelites. They have formerly been termed the Eilde Flags, and can be correlated with the quartzose psammites of the Strathtummel Subgroup by comparison with similar rocks on the Ben Macdui (64E) Sheet, but are still not correlated with certainty within the Grampian Group. [Note that the term Atholl Subgroup used on the Schiehallion map is best abandoned to avoid confusion with the Blair Atholl Subgroup and since it contains only the Bruar Psammite Formation whose base is not defined.]

More work needs to be done on characterising the group in the corridor in terms of lithostratigraphy, sedimentology and structure although exposure and way-up evidence may be scarce. The Tummel and Kynachan Quartzite formations have been mapped on the east side of Schiehallion but the Grampian Group has not been subdivided (BGS, 2000) on the west side where these quartzites have not been recognised. The development of the quartzites within the Strathtummel Subgroup may be related to deltaic sand wedges deposited around the periphery of the Grampian Group depocentre or perhaps more locally on the margins of a 'central highland psammite' high. Equivalent quartzites are not apparent in the mapped Grampian Group farther to the west but are common in the Cromdale region of the East Grampians.

Whether or not the Grampian Group has affinities with the 'Younger' Moine as proposed by Thomas (1980) or the Dalradian (Harris *et al.*, 1994) is still, to some extent, debatable (see 2.2 below). To quote Harris *et al.* (1994), 'Strong grounds for keeping the Grampian Group separate from the Dalradian might lie in a demonstration that the rocks of the Grampian and Appin groups show dissimilarities greater than those between the other Dalradian groups'.

2.2 APPIN GROUP

Appin Group lithostratigraphy is, as a whole, poorly represented in the Boundary Slide corridor and typically comprises somewhat limited sequences of pelites, graphitic pelites, quartzites, limestones and calc-silcates. If these sequences are genuinely Appin Group and not a facies of, for example, the Easdale Subgroup, they could represent a condensed sequence of the Lochaber and/or Ballachulish subgroups (c.f. the Glen Banvie Formation on Sheets 55E and 64E). In addition to field assessment of the lithostratigraphical and sedimentological features of these formations, use must be made of the geochemical characteristics of any limestones and pelites in order to compare them with known Appin formations.

Rocks within the Boundary Slide corridor presently assigned to the Lochaber Subgroup appear to be more closely related lithostratigraphically and structurally to the Grampian Group (see further in Section 6). The subgroup is generally thinner than recorded in sequences to the south-west and north-east and the possibility that the Lochaber Subgroup, along with the Grampian Group, is also a condensed sequence over a 'central Highland' high should be investigated. East of the Tyndrum Fault (in Sheet 54E; BGS, 1974), a succession of garnet mica schists with lenses of limestone, succeeded by quartzite and modelled by Roberts and Treagus (1979) as infolded Lochaber Subgroup within Grampian Group must be compared with the typical Leven Schist Formation farther south-west.

A thin succession of Lochaber Subgroup metasedimentary rocks was interpreted (Roberts and Treagus, 1979) to lie between an upper and lower slide west of Schiehallion and east of the Bridge of Balgie Fault (Figure 1). The lower slide has been abandoned on the Schiehallion Sheet (BGS, 2000) and the Grampian Group passes directly into the base of the Lochaber Subgroup. Roberts and Treagus (1979) continued these two slides west of the Bridge of Balgie Fault, into the Beinn Dorain and Upper Glen Lyon areas, where they bounded Lochaber and Ballachulish/Blair Atholl subgroup rocks. Farther to the south-west however, in the Glen Orchy and Ben Lui areas, the Lochaber rocks pass down directly into the Grampian Group and only the upper (Boundary) slide is recognised.

The Blair Atholl subgroup is generally missing across this area. Typical representatives of the Blair Atholl subgroup such as the Blair Atholl Dark Limestone and the Cnoc an Fhithich Banded Semipelite have not been identified within the corridor. The Blair Atholl and Islay subgroups were thought to be tectonically excised on the Boundary Slide (Figure 2), models involving nondeposition, or subsequent erosion, may be equally valid if this region was one of positive relief during late Neoproterozoic times. West of Schiehallion, the Boundary Slide separates Easdale Subgroup from condensed (?highly attenuated) Ballachulish and Lochaber subgroups. The Blair Atholl Subgroup first occurs to the east around the northern tip of the 'Schiehallion triangle', where it appears to have largely replaced the Ballachulish Subgroup (see further under section 6). This relationship may be due to a switching of the depocentre to the east. Other facies changes should also be looked for within the Blair Atholl Subgroup.

2.3 ARGYLL GROUP

The Argyll Group comprises mainly psammites, pebbly quartzites, graphitic and calcareous pelites and semipelites with limestones generally coming in towards the top of the succession. The upper part of the group is relatively well represented in the Boundary Slide corridor (Figure 1) while the lower part, the Islay Subgroup, appears absent. Equivalents of the Schiehallion Quartzite and Boulder Bed formations (Islay Subgroup) have not been recognised within the corridor. Thick successions of the Schiehallion Quartzite and Schiehallion Boulder Bed formations present on the east side of the Errochty Synform are not represented on the west side. Such facies changes could be due to switching of deltas but also increasing basin instablility. This is demonstrated by the evidence of rifting and incoming of basic volcanic units towards the top of the group.

Most exposed formations belong to the Easdale Subgroup and are described below. The overlying Ben Lui Schist Formation is the sole representative of the Crinan Subgroup in this area and it is overlain in turn by the Loch Tay Limestone Formation of the Tayvallich Subgroup.

2.3.1 Easdale Subgroup

A near complete succession of the Easdale Subgroup is exposed within the Schiehallion 'triangle' (BGS, 2000). At the subgroup base, the Killiecrankie Schist Formation, comprising mainly semipelite, becomes interfingered upwards with the Carn Mairg Quartzite and Ben Eagach Schist graphitic pelites. At the western edge of Sheet 55W (Schiehallion), these formations are missing, perhaps excised or overlapped, and the succeeding Ben Lawers Schist Formation lies above the Boundary Slide. The Farragon Volcanic Formation (Table 1) is locally developed above the Ben Lawers Schist Formation. Lateral facies changes are common throughout the subgroup.

2.3.1.1 CARN MAIRG QUARTZITE FORMATION

This formation comprises mainly psammites containing several coarse-grained feldspathic and pebbly units, which it may be possible to map separately as on Sheet 55W (Schiehallion). Taken together, the geological maps of the Schiehallion and Pitlochry districts, to the east of the corridor, indicate that the thickness of the Carn Mairg Quartzite is increasing towards the west and includes a wedge of coarse feldspathic quartzite, deposited possibly as a result of deltaic channel switching. The formation as a whole may represent build up of deltaic or channel sandstone bodies within a rifted basin.

The formation also contains several thin bands of calc-silicate rock and graphitic pelitic and semipelitic bands. These lithologies are also found in the formations above and below the Carn Mairg Quartzite and so it will be important to consider not only the lithostratigraphical relationships but also the structural position of the units (i.e. interbedding/interlensing or interfolding).

2.3.1.2 Ben Eagach Schist Formation

The Ben Eagach Schist Formation is generally graphitic and pelitic although at its base it is dominantly semipelitic. It also contains thin lenses of quartzite and pebble conglomerate. The formation is absent locally where graphitic beds are missing and calcareous pelites and semipelites succeed the psammites of the Carn Mairg Formation. The Ben Eagach Schist Formation is associated with stratiform Ba and Pb mineralisation (see section 7). On Sheet 46E (Killin), a thin limestone bed is reported to lie locally at the junction of the Ben Eagach Schist and the Ben Lawers Schist formations and may provide a useful marker horizon. Thin metalimestones (tremolite-marbles) are reported within the formation in the Pitlochry district (BGS, 1981).

2.3.1.3 Ben Lawers Schist Formation

The Ben Lawers Schist Formation is characterised by calc-sericite schist and in the higher grade rocks to the north, biotite and hornblende-bearing schists. In the calcareous lithologies two types of carbonate have been reported (calcite and ?ferroan dolomite; Smith *et al.*, 1977) as well as local epidote. Garnets are sparse probably because the bulk composition is unfavourable to their growth. Quartzite beds are also present and calc quartzite beds, which tend to host pyrite, are commonly friable and white to pale buff coloured. A pyrite-bearing unit has also been mapped by Smith *et al.* (1984). A dull grey ?graphitic schist may be intercalated within the formation rather than being an infold of Ben Eagach Schist (Elles, 1926).The subdivisions and slides postulated by Elles (1926) have not been confirmed by later work (Smith *et al.*, 1984; Wain, 1999). However, the Sron Bheag Schist (Elles, 1926) appears to be distinguished as a transitional unit between the Ben Lawers and Ben Lui schist formations (Johnstone and Smith, 1965). This unit appears to be impersistent and associated with hornblende schists, which may be volcanic in origin. If this is correct, then the hornblende schists can be correlated with the Farragon Volcanic Formation (see below) to the north-east (Treagus, 2000). The Ben Challum Quartzite lies at or near the same horizon (Smith *et al.*, 1984; 1988) in the Tyndrum area. A study of the petrology of the 'Transition beds' on the Killin Sheet has shown that they have affinities with the Farragon Volcanic Formation and the Ben Challum Quartzite (Fortey and Smith, 2000). These rocks contain portions of tholeiitic, mafic to ultramafic material and quartz-rich sediment. Careful mapping will be needed to distinguish volcano-sedimentary hornblende schists belonging to the Farragon Volcanic Formation from concordant 'epidiorite' or amphibolite intrusions.

2.3.1.4 Farragon Volcanic Formation

This formation is impersistently present at the top of the Easdale Subgroup on Sheet 55W (Schiehallion) and would appear to extend westwards at least into Sheet 54W (Loch Rannoch). It is not documented, however, on Sheet 45E (Dalmally). The formation comprises a thin sequence of amphibolite schists with minor semipelite and quartzite interbeds; it is considered to be metavolaniclastic. Farther north-east on the Pitlochry Sheet, the Farragon Volcanic Formation is substantially thicker and includes epidotic schists and psammites.

2.3.1.5 Ben Challum Quartzite Formation

This unit has formation status (Smith *et al.*, 1984: 1988) in the Tyndrum area. The quartzite is associated with stratabound base metal mineralisation. Correlation is not certain; it may be a member of the Ben Lawers Schist Formation or more likely, be equivalent to the Farragon Volcanic Formation as this contains some quartzite lenses. Where the Ben Challum Quartzite Formation continues to the west of the Tyndrum Fault is not known and it has not been recognised to the north-east. The quartzite is intercalated with mica–schist and some concordant hornblende schists, up to 20 m thick, which are interpreted as originally being basaltic tuffs of sediments derived from a basaltic source (Fortey and Smith, 1986). They concluded that the Ben

Challum Quartzite was deposited in a distal shallow shelf environment and that the hornblende schists were the lateral equivalents of the Farragon Volcanic Formation.

2.3.2 Crinan Subgroup

The Ben Lui Schist Formation is the sole representative of the Crinan Subgroup within the Boundary Slide Corridor. Farther west, in the Loch Awe district, the sedimentary facies changes to one with more quartzitic psammites, which belong to the Crinan Grit Formation.

2.3.2.1 Ben Lui Schist Formation

The Ben Lui Schist Formation is a fairly uniform quartz-mica schist with garnets typically present. Subordinate quartzites and psammites occur and the formation is more quartzose towards the Sron Bheag Schist (Elles, 1926), i.e. the top of the Ben Lawers Schist Formation. Hornblende schist intercalations are described by Fortey and Smith (1986) and interpreted as being originally basaltic tuffs or sediment derived by erosion of basalt. Three metalimestone intercalations have been described from within the Ben Lui Schist of the Glen Lochay –Glen Lyon area (Johnstone and Smith, 1965). It is not clear if these are interbeds or infolds of Loch Tay Limestone (see Hyslop, 2001). To distinguish them from the Loch Tay Limestone, their sedimentology, structure and geochemistry should be studied. A similar metalimestone was mapped within the Ben Lui Schist on the Pitlochry Sheet (BGS, 1981).

Garnet mica schists between in the area of Meall Ghaordaigh are assigned to the Ben Lui Schist by Johnstone and Smith (1965), but to the Pitlochry Schist of the Southern Highland Group by Treagus (1991). This difference in interpretation results from different structural models of the area, which need to be resolved (see Hyslop, 2001). There are significant thickness variations in the Ben Lui Schist north of Glen Dochart (Johnstone and Smith, 1965), particularly close to the Boundary Slide in Glen Lyon, where tectonic attenuation or excision may have occurred. It is also possible that sedimentary facies changes occur across the formation if the Boundary Slide proves not to be a major structure (see section 8).

2.3.3 Tayvallich Subgroup

The Tayvallich Subgroup is represented in the Boundary Slide Corridor by the Loch Tay Limestone. Besides metalimestone units, the formation includes hornblende schists and calc-silicate horizons, which may have originally been volcaniclastic beds. Changes in thickness and sedimentary facies may be related to a depositional model.

2.3.3.1 Loch Tay Limestone Formation

The Loch Tay Limestone Formation includes metalimestone, mainly calcitic marble but with calc-silicate minerals in the less pure beds. The limestones are shown as impersistent on the original survey maps, possibly due to intercalations of pelitic schist, the result of structure or even lack of exposure. In places the limestone is associated with hornblende schists or epidiorites, which are generally concordant igneous bodies. They may be extrusive or intrusive in origin (see magmatic section). Wain (1999) discussed the problems of mapping the formation on the Killin Sheet. There do not appear to be major problems with mapping the Loch Tay Limestone on the Crianlarich sheet (Treagus, 1991; Johnstone and Smith, 1965). However, there are small lenses (or infolds?) of limestone which appear to lie stratigraphically below, within the Ben Lui and Ben Lawers schists.

In areas of low deformation to the south-west, the Loch Tay limestone contains ooids, but it has been considered to be a derived turbiditic limestone deposited in deep water (Anderton, 1985). Clastic input into the basin appears to have stopped and on the sediment-starved shelf, carbonate accumulated before being eroded and swept into submarine channels. The channelisation could account for the discontinuous nature of the limestone outcrops. Burt (in press) has recognised hummocky cross-bedding in quartzite beds near the top of the formation in Northern Ireland so locally the formation may have been deposited above the wave base. Elaine Burt's PhD thesis will shed more light on this subject.

Basic volcanism was active at this time and is reflected in the hornblende schists and intrusive epidiorites.

2.4 SOUTHERN HIGHLAND GROUP

This group has been the subject of most of the recent mapping in the Killin area (see Hyslop, 2001) and was previously assessed by Wain (1999). Elaine Burt is due to produce a PhD thesis on the sedimentology of the group in the near future. Recent reports have also been made on the Green Beds (Pickett, 1997; Hyslop and Pickett, 1998; Hyslop and Pickett, 1999a;b). Structurally it lies on the inverted limb of the Tay Fold Nappe. This group is therefore not considered to be a primary target for new work and is largely excluded from the Boundary Slide Corridor study.

3 Regional Metamorphism

3.1 MODELS OF DALRADIAN METAMORPHISM, INCLUDING P-T WORK AND P-T-T PATHS

After a century of research the overall metamorphic evolution of the Grampian Highlands and its relationship to tectonic processes is still not well understood, Wain (1999) reviewed previous work on the pattern of metamorphic zones and the relevance of index minerals. Maps of Barrovian zones, such as that of Atherton (1977), are not easy to interpret directly in terms of peak metamorphism, changes in P-T conditions and bulk composition or the structural evolution of the orogen.

To complete the overall tectonothermal evolution of the Dalradian orogen, detailed P-T-t paths should be related to its basinal and structural development. Wain (1999) reviewed the previous metamorphic studies within the area, particularly related to the Killin sheet. Points that need to be addressed in future work are listed below (the last two points relate more to the Southern Highland Group and are less relevant to the Boundary Slide Corridor).

- Does the Boundary Slide cut regional metamorphic isograds or is it overprinted by D2 metamorphism?
- What relationship exists between regional metamorphism, deformation and P-T-t paths?.
- Bulk composition and/or fluid content controls on metamorphic mineral assemblage.
- Geothermometry/barometry/isotope studies.
- Extent and timing of retrogression; links to post-Caledonian magmatism and/or faulting etc.?
- The attitude of isograds and regional scale inversion of the garnet isograd (Watkins, 1984, 1985), especially since metamorphic minerals overprint the main nappe-forming D1/D2 phases. Do they relate to later phases (D3/D4)?
- The 'albite porphyroblast zone' (Watkins, 1983); how does it relate to the other isograds?

4 Structural overview and setting for the Boundary Slide

The Boundary Slide corridor focuses on the part of the Tay Nappe and the Ben Lui fold complex above the Boundary Slide and the part of the Atholl Nappe immediately below (Figure 3). The principal ductile and brittle structural elements in the region are briefly reviewed in the following section before going on to concentrate on the possible nature of the Boundary Slide itself. The slide is seen as having an important role in the distribution of lithostratigraphical formations and on the subsequent deformation history of the Dalradian Supergroup.

4.1 ATHOLL NAPPE

The Atholl Nappe (Figure 3) is a large fold nappe, composed mainly of Grampian Group rocks with minor Lochaber Subgroup rocks, and lying structurally beneath the Boundary Slide. The fold nappe faces down to the south-east. Within the Atholl Nappe (Thomas, 1980), smaller scale D1 folds have been described in the Glen Orchy area (Roberts and Treagus, 1979). The downward facing Beinn Udlaidh Syncline lies below the Boundary Slide and above the Glen Orchy Anticline. These folds lie in the Glen Orchy dome which was probably produced by interference between north-east trending D3 and northerly trending D4 antiforms (Roberts and Treagus, 1979). Analogous structures are described from the Beinn Dorain area to the north-east. These structures require to be tested in the field. Note that the Beinn Udlaidh folds are currently the subject of research by Geoff Tanner (Glasgow Univ.); maps and reports will be deposited with BGS early in 2003.

Evidence for the Atholl Nappe and other south-east facing folds below the Boundary Slide in Glen Orchy (Thomas and Treagus, 1968) and upper Glen Lyon (Roberts and Treagus, 1979) should be examined. This study provides the opportunity to study the link between the fold complex of Glen Orchy and the Atholl Nappe as defined further east. Recently completed work (Leslie et al. 2002) in the Gaick region of Sheet 64W (Newtonmore), sheds further light on the fold structures beneath the Boundary Slide.

4.2 BEN LUI FOLD COMPLEX

The Ben Lui Fold Complex lies above the Boundary Slide and comprises the recumbent Dalmally Syncline, the Ra Chreag Anticline and the Ben Lui Syncline, all of D2 age (Roberts and Treagus, 1975). The complex is refolded by several upright structures (Johnstone and Smith, 1965) including the Ben Lawers Synform (Treagus, 1964). East of Schiechallion, a series of (now refolded) ?related recumbent folds has been documented by Treagus (1999) who suggested that the non-coaxial ('simple-shear') component of deformation increased upwards in this pile.

4.3 TAY NAPPE

Most of the Argyll and Southern Highland group rocks lie on the recumbent, inverted limb of the Tay Nappe (Stephenson and Gould, 1995). The fold nappe has been flattened and extended by subsequent D2 and possibly locally D3 episodes (Harris *et al.* 1976; Mendum and Fettes, 1985; Krabbendam *et al.* 1997). The flat lying inverted limb of the Tay Nappe is refolded by upright D3 (?) folds, such as the Ben Lawers Synform and the Loch Tay Antiform; on Sheet 46E this results in fairly complicated outcrop patterns of Upper Argyll and Southern Highland Group lithologies. The generally flat-lying, inverted limb of the Ardrishaig Anticline (regarded as the core of the Tay Nappe in SW Scotland) can be distinguished from the steeper dipping, right-way-up and attenuated succession on the lower limb of the Ben Lui antiformal 'syncline' (Roberts and Treagus, 1979) or the Ben Lui Fold Complex (Stephenson and Gould, 1995). The Ben Lawers Slide (Elles, 1926) between the Ben Lawers Schist and the underlying Ben Lui

Schist and Sron Bheag Schist is now discounted mainly on the evidence of lack of metamorphic breaks (Johnstone and Smith, 1965; Smith *et al.*, 1984).

4.4 GREAT GLEN FAULT SET

The set of major post-orogenic NE/NNE trending sinistral wrench faults between the Highland Boundary Fault and the Great Glen faults are important structures across the area of interest. In the east the main fault of this set is the Loch Tay fault; farther west are the Bridge of Balgie (or Killin) Fault, the Garabal Fault, the Tyndrum Fault and the Ericht-Laidon (Loch Awe-Glen Strae) Fault. The fault set can be compared to a pattern of Riedel shears developed between the Great Glen and Highland Boundary faults (Johnson and Frost, 1977). The main (net) movement on the faults is sinistral strike-slip with a component of downthrow generally to the south-east (Treagus, 1991). The Ericht-Laidon Fault lies along the length of Loch Laidon and has a sinistral strike-slip component as indicated by the offset of granite outcrops, of up to 7 km (cf. Loch Tay). Treagus *et al.* (1999) relate the development of the faults to a phase of sinistral transtension during the late Silurian, which also operated in other parts of the Caledonides, e.g. Greenland. Smith (1961) and Johnstone and Smith (1965) observed several zones of crushed and sheared rock in hydro-electric scheme tunnels crossing the Garabal and Bridge of Balgie faults and found evidence for fault movement both pre and post-dating the intrusion of late Silurian dykes.

Evidence for later dextral reactivation of the Tyndrum Fault (Treagus *et al.*, 1999) during the early Carboniferous was found during a study of base metal mineralisation. The Great Glen set of faults is cut by a several late Carboniferous dykes, which post-date the base metal mineralisation, but are only locally affected by minor dextral movements on the faults (Treagus *et al.*, 1999), indicating that major movement on these faults had ceased by the end of the Carboniferous.

5 The Boundary Slide

5.1 OVERVIEW

Treagus (1987) reviews and discusses the Boundary Slide Zone in terms of high ductile strain developed during D2; in essence a major ductile shear zone characterised by inhomogeneous strain where narrow brittle-ductile zones may accommodate discrete translations. Thomas (1980) describes 'banded zones' within the Grampian Group, in which sedimentary structures are generally lacking and there is a strong subparallel schistosity, which becomes more intense towards the Boundary Slide. The presence of a muscovite-rich schist with small quartz blebs (formerly the Beoil tectonic schist) was considered to mark the position of the slide (Thomas, 1980).

On the western side of the Errochty synform in Sheet 55W (see Figure 4), condensed Lochaber and Ballachulish subgroup successions are juxtaposed against the Easdale Subgroup. The Lochaber and Ballachulish subgroups are better developed on the eastern side of the Errochty Synform, where they pass up into the Blair Atholl and Islay subgroups. This suggested to Treagus (1987) that the Blair Atholl and Islay subgroups have been cut out on the western limb. However, the reduced importance of the slide zone on the eastern side (Treagus and King, 1978) and lateral sedimentary facies changes, such as those seen in the Schiehallion Quartzite, mean that the subgroups missing on the western side of the Errochty Synform may not have been deposited in the first place. Treagus (1987) admits that it is difficult to quantify either the direction or size of the movement on the slide. There are some stretched pebbles in the Meall Dubh Quartzite and a mica lineation in the adjacent pelites. As the components of the Appin/Argyll groups are truncated at progressively lower levels on the restored, pre-D4, north-west limb of a major D2 antiform, it is probable that movement on the slide was upwards to the north-west (Treagus, 1987).

At a more regional scale, the Boundary Slide is generally considered as a tectonic slide that coincides broadly with southern margin of Grampian Group. It can be traced from Glenfiddich in the East Grampians to the Etive Intrusive Complex in Lochaber, over a strike length in excess of 100 km and is sub-parallel to the main north-east – south-west Caledonian trend. It is displaced across steep north-north-east – south-south-west trending faults such as the Loch Tay Fault (Figures 1 and 4). The Etive and Rannoch Moor Granites obscure the trace of the slide in the south-west; north of these granites the Boundary Slide may link up with the Fort William Slide. The following general observations are worth mentioning at the outset:

- The Boundary Slide coincides broadly with the southern and structurally upper margin of Grampian Group. In detail, however, it commonly coincides with the southern and structurally upper margin of the outcrop of the Lochaber Subgroup.
- No Grampian Group rocks occur (for instance as inliers) south of the Boundary Slide.
- Inliers of Appin Group rocks do occur north of the Boundary Slide, but only very locally, and in such cases are mostly composed of the Lochaber Subgroup.
- The Boundary Slide tends to excise or attenuate stratigraphical sequence, rather than thicken or duplicate them.

5.2 CHANGING CHARACTER OF THE BOUNDARY SLIDE ACROSS THE GRAMPIAN HIGHLANDS

The lithostratigraphy and structure of the areas adjacent to the Boundary Slide is described below, starting from the north-east, where little complexity occurs, and moving progressively towards the south-east, where significant parts of the stratigraphy are omitted. (Figures 4 and 5).

5.2.1 Glenfiddich – Glenlivet Sector (Sheets 85E and 75W)

The geology adjacent to the top of the Grampian Groups is relatively simple in both the Glenfiddich (Sheet 85E) and Glenlivet (Sheet 75W) districts of the Eastern Grampians. The Dalradian sequence appears to be more or less complete with a relatively thick development of the Lochaber and Ballachulish Subgroups, and no obvious stratigraphical omissions. Most of the sequence is right-way up; all folds are upward facing to the north-west. A slide (the Boundary Slide?) is mapped at the top of the Lochaber Subgroup on Sheet 75W; this slide apparently duplicates Ballachulish Subgroup rocks and is associated with tight right-way-up, north-west facing folds. The simplest explanation here is that this slide occurs on the sheared out limb of a tight fold, and in this respect there is little that is remarkable in the area.

5.2.2 Braemar Sector (Sheet 65W)

This sector lies between the Cairngorm Pluton and the Loch Tay Fault (Figure 5a); data used here is taken from Sheet 65W Braemar and Upton (1986).

The area of the Boundary Slide in the Pitlochry and Braemar districts is transected by splays of the Loch Tay Fault. The Dalradian sequence appears to be largely complete and no obvious significant stratigraphical omissions occur in this region. The Boundary Slide is currently mapped at the *base* of the Lochaber Subgroup. The Lochaber Subgroup is rather thin whereas the Ballachulish Subgroup is quite thick and varied. The map shows a repetition of Lochaber, Ballachulish and Blair Atholl Subgroup rocks along the ‘Baddoch Burn Slide’, which lies to the south of the Boundary Slide.

Grampian Group rocks young right-way-up to south-east, towards the Boundary Slide. Appin Group rocks young right-way-up to south-east, away from the Boundary Slide and are deformed by north-west facing folds. Some downward south-east facing folds are also mapped; the area may lie at the changeover from generally upward north-west facing folds in the north-east and generally downward south-east facing folds in the south-west. Major slides seem once again (see 5.2.1) to coincide with the sheared out limbs of major D2 folds (Crane *et al.* 2003).

The Boundary Slide is shown to cut out Lochaber and Ballachulish Subgroup rocks just north-east of Braemar. This particular area, however, occurs in the alluvium flood plain of the River Dee and details might in reality be different to those shown on the published mapped.

5.2.2.1 Problems to focus on

The area south of the Boundary Slide has been mapped in great detail by Upton (1986) and no work is immediately required here, unless working hypotheses built further west require some critical area to be examined at a later stage.

5.2.3 Schiehallion Sector (Sheet 55W)

This is the sector between the Loch Tay Fault and the Errochty Synform closure (Figure 5b): data has been taken from the new (BGS 2000) Sheet 55W (Schiehallion), Treagus and King (1978), Treagus (1987) and Treagus (2000).

The structure south of the Boundary Slide is very complicated and treated in detail by Treagus (1987). Greatly simplified, the Boundary Slide dips to the south and is overlain by a series of downward south-facing D2 closures that refold south-facing D1 folds. Folding repeats and thickens the outcrop of Islay, Easdale and Blair Atholl Subgroup rocks; farther towards the Boundary Slide folds tighten and the outcrop of Lochaber and Ballachulish Subgroups is rather thin. On either side of the Boundary Slide folds face down to the south. Other relevant details are:

- D1 folds close underneath (north) of the Boundary Slide are shown on the cross-section of Sheet 65W to be upward facing, whereas D1 folds and D2 just above (south) the Boundary Slide are shown to be downward facing. However, the evidence for these interpretations (see cross-sections on Sheet 55W) may in reality be based on very few, rather highly strained exposures (??).
- An inlier of Lochaber Subgroup occurs in a downward facing syncline (inverted keel) north of, and structurally below, the Boundary Slide.

5.2.3.1 Problems to focus on

This area has been mapped in great detail and since much has already been published, no new work is immediately required here, unless working hypotheses built further west require some critical area to be examined at a later stage.

5.2.4 Errochty – Bridge of Balgie Sector (Sheets 54E and 55W)

This is the sector between the Errochty Synform closure and the Bridge of Balgie Fault (Figure 5c); data has been data taken from the new Sheet 55W (BGS 2000) and older Sheet 54E (BGS 1923). Data and interpretations from Nell (1984) have not been reviewed yet.

North of Bridge of Balgie, the Boundary Slide dips steeply towards the east-south-east. The northern half of the sector (Sheet 55W) has been remapped in detail; according to this mapping the Boundary Slide is underlain by an east-south-east – younging (right-way-up) Grampian Group succession overlain by a thin layer of Lochaber Group, a thin sliver of Ballachulish

Subgroup (?) and then the Boundary Slide. A microdiorite intrusion extends more or less along the trace of the slide in this region.

To the east-south-east of (and structurally above) the Boundary Slide there is an area of complicated D2 and D1 folding, affecting the Schiehallion Quartzite, Killiecrankie Schist, Carn Mairg Quartzite, Ben Eagach Schist and Ben Lawers Schist formations. Closest to the Boundary Slide is a D2 isoclinal syncline cored by Ben Lawers Schist and surrounded by Carn Mairg Quartzite. The Ben Eagach Subgroup is missing from this sequence; some Ben Eagach is shown near the fold closure in the north; most of the closure, however, appears to occur in Loch Errochty and is thus obscured. These relationships suggest that close to the Boundary Slide the Argyll Group sequence youngs to the east-south-east as already stated for the succession below the slide.

In terms of missing stratigraphy, the Ballachulish Subgroup is missing in the north and Lochaber Subgroup rocks are juxtaposed against Blair Atholl Subgroup rocks. Progressively south from Loch Errochty, first the Blair Atholl Subgroup, then the Islay Subgroup, and then the Killiecrankie Schist Formation and finally the Carn Mairg Quartzite Formation are 'cut out' until Ben Lawers Schist Formation is juxtaposed against the thin sliver of Lochaber Subgroup (Figure 5c). When the folds are unfolded (Figure 5c) this would, in stratigraphical terms, represent an onlapping relationship as deposition proceeded.

Sheet 54E represents Ben Lawers Schist Formation mapped directly against Grampian Group rocks; Lochaber Subgroup were probably was not differentiated from Grampian Group at this time. The microdiorite which follows the trace of the Boundary Slide on Sheet 54W appears to wander somewhat on Sheet 55E.

5.2.4.1 Problems to focus on

- Sheets 55W and 54E clearly do not fit and the large swathe of Ben Lawers Schist on Sheet 54E is most probably far more complicated than currently represented. There are clear problems in linking the complications of Sheet 55W with the simplicity of Sheet 54E. This area needs remapping where not covered by Nell (1984).
- The structure of the Boundary Slide in this area needs to be studied, (i.e. lineation directions, shear sense, micro-structure) and compared to that farther to the east and west.
- The microdiorite along the Boundary Slide may be very interesting to study. According to Sheet 55W it is 'Late Silurian'. Given that the Boundary Slide is supposedly syn-D2 and hence Ordovician this seems odd, unless it is entirely undeformed and simply followed a 'weak' zone. However, many other microdiorite dykes crosscut stratigraphy and D2 fold hinges without much apparent trouble (and appear to have been intruded sub-parallel to the axial plane of the late, 'D4' Bohespic Antiform), so a 'weakness' argument seems rather artificial. The field relationships with respect to the Boundary Slide and its state (deformed or not) are interesting problems.
- Is the sliver of Ballachulish Subgroup on the west-north-west of the Boundary Slide really Ballachulish Subgroup? Or is this rather uncertain and could it be re-assigned, bearing in mind the sliver is likely to be highly strained?
- Little is known about stratigraphy and structure (facing, lineation directions) of the Grampian Group; elucidation of these is essential to understanding the structure of this region.

5.2.5 Loch an Daimh – Glen Lyon Sector (Sheets 46E and 54E)

This is the sector between the Tyndrum Fault and the Bridge of Balgie Fault (Figure 5d); data has been taken from the existing Sheets 46 and 54E and Roberts and Treagus (1979). Very little modern work has been done in this area, although Thomas (1979, 1980) has worked in the Grampian Group. One of the tunnel traverses in Johnson and Smith (1965) occurs in this area, and some of those descriptions are clearly useful. The stratigraphical attribution of Roberts and Treagus (1979) was presumably made without much detailed work.

This area is characterised by two 'fish hook' structures (Meall a Bhoboir and Cross Crags) of ?Lochaber Subgroup rocks within the Grampian Group. These structures affect garnetiferous micaschist with subordinate marble and quartzite. Roberts and Treagus (1979) show them as two downward facing, antiformal synclines with Lochaber Subgroup rocks in the core; this stratigraphical attribution needs confirmation. The occurrence of quartzite on the southern margin of the largest, northern hook, suggest a rather asymmetric structure, possibly a fold sheared out along a slide.

At the southern margin of the Grampian Group there are (as in the Beinn Dorain Sector, see 5.2.6 below) two slides shown by Roberts and Treagus (1979); one separating the Grampian Group from Lochaber Subgroup, and one separating Lochaber Subgroup from Carn Mairg Quartzite Formation. In this area, Ballachulish, Blair Atholl and Islay Subgroups (assuming Carn Mairg quartzite is indeed not Islay quartzite) are absent. The sequence above the upper slide (Carn Mairg Quartzite Formation to Ben Lui Schist Formation) appears rather attenuated, with no (or very thin) Ben Eagach Schist Formation present between the Carn Mairg and the Ben Lawers formations. The Ben Lawers Schist Formation thins westward, as does the Carn Mairg Quartzite Formation. Small slivers of Ben Eagach Schist Formation are mapped. Close to the Bridge of Balgie Fault, the Carn Mairg Quartzite and the Ben Lawers Schist formations are also apparently omitted, so that Ben Lui Schist Formation is juxtaposed against against ?Lochaber Subgroup. Here, Grampian Group rocks are less than 1 km from Ben Lui Schist; this is the area of greatest stratigraphical omission identified anywhere along the Boundary Slide (Figures 4 and 5d), a "striking fact" indeed (MacGregor, in Hinxman et al, 1923, p.55).

5.2.5.1 Reconnaissance fieldwork (24/10/01) - Section in Allt Dubh Liath [NN 544 448] near Meggernie Castle

The results of reconnaissance fieldwork (24/10/01, JRM, AGL, RAS, DS and MK) are relevant here and are described form north to south (Figure 6).

- A large roadside quarry [NN 530 449] contains spectacular slump folding (including sheath folds) and cross-bedding in massive, thickly bedded Grampian Group psammites. Current bedding infers southerly sediment derivation, slump folds also rotation/failure towards north. The features suggest rapid deposition, possibly in a local depocentre. The preservation of these sedimentary structures suggests low strain.
- The lowest part of the stream section shows Grampian Group psammites with moderate south-south-east dip (30-40°) and a simple grain shape fabric with parallel orientation of muscovite and biotite on planar foliation surfaces. Upstream, there is a good, almost continuous, section, all in psammite. Locally, poorly preserved trough cross bedding were seen. Intrafolial isoclinal folds occur also, although it is possible that (some of). these originated as slump folds. Upstream from a prominent bend at [NN 545 443], the psammite becomes more feldspathic and then more quartzose. Here, sedimentary structures such as cross-bedding and trough cross-bedding are better preserved and all suggest a right way up succession. Around [NN 549 437] psammite gives way to a flaggy splintery grey semi pelite with ribboned quartz.
- Near [NN 5495 4373] laminated, possibly mylonitic white quartzite occurs, with mm scale feldspar porphyroclasts showing symmetric tails in a platy fabric. (Sample – ZY 204). No exposure occurs for c. 50 m upstream. Higher up a slab shows strong shear fabric (some top to west asymmetric quartz augen) in banded quartzose psammite and muscovite-biotite-garnet semipelite/micaceous psammite (+ pyrite).

- Scattered exposures for a few tens of metres upstream show highly pyritous quartz mica schist (?Ben Lawers) but thereafter all outcrop occurs in typical Ben Lui garnet mica schist. In total there is about 100m of section from the mylonitic quartzite to the first outcrop of unequivocal Ben Lui schist. Sheet 46 (Crianlarich) shows an occurrence of limestone higher up this section (not visted in 2001) – if this is a Loch Tay Limestone equivalent then the omission on slide may well account for significant part of Ben Lui Schist Formation as well as much of Argyll and Appin group below. Alternatively this is the intercalated limestone of the Ben Lui Schist, as discussed by Johnstone and Smith (1965).

The fieldwork showed that the existing 1-inch map boundaries are generally a good indication of distribution of gross lithological units, but the stratigraphical attribution will be critical to any model.

5.2.5.2 PROBLEMS TO FOCUS ON

- It is clear that there is a major stratigraphical omission in ground east of the Bridge of Balgie Fault. The nature of this omission, however, is unclear. Is it accompanied by very high strains? Which units thin out from west to east and in which order?
- The stratigraphy of the ‘fishhooks’ of Meall a’ Bhobouir and Cross Craigs has been assumed to be Lochaber Subgroup, but this needs verification. It may be possible to use limestone geochemistry as a discriminator. The structure of the ‘fishhooks’ is also unclear: are they symmetrical fold closures or sheared slivers?
- We need to know more about structure; facing, orientations in this area; currently Roberts and Treagus (1979) interpretation is rather unconstrained. Are all folds downward facing to south-east? What is the plunge of the folds? What is the relation between folds and the Boundary Slide?
- The structure and stratigraphy in north-west Sheet 46E (Killin) (Ben Lui – Ben Lawers formations etc.) will also be very interesting and important to unravel.

5.2.6 Beinn Dorain Sector (Sheets 46W and 54W)

This is the sector north-west of Tyndrum Fault and north-east of the A82 (Figure 5e) with data taken from the old Geological Survey Sheets (46 and 54W) and. France’s, PhD Thesis (1971). The latter provides an interesting data set (Figure 7) that is, however, sometimes difficult to interpret as it uses rather quaint stratigraphical terminology.

The Beinn Dorain Sector is a large, presumably fairly flat-lying, crescent shaped outcrop of Lochaber Subgroup (?) and Carn Mairg (?) Quartzite Formation that lies north-east of the A82 trunk road and the West Highland Railway and north-west of the Tyndrum Fault. The contacts follow roughly the contours of the crescent shaped topographical ridge, attesting to the gentle dips in this area. Overall, the rocks in the area appear to young towards the south-east, away from the slides. To the south-east of the Tyndrum Fault, the sequence from Carn Mairg Quartzite Formation to Ben Lui Schist Formation appears to be south-east dipping and right-way-up. France (1971) describes the following sequence from the railway to the top of Beinn Dorain; Moine psammite (=Grampian Group), a lower Slide, thin quartzite, marble and tremolite schist, followed by garnet mica schist, followed, on top of Bheinn Dorain, by thin limestone and Banded Quartzite. It appears that France equates this sequence with what we would now call Appin Group (Fig. 7; Table 2). Another, upper slide separates garnet mica schist from Carn Mairg Quartzite Formation (Roberts and Treagus 1979).

This correlation should be questioned, however. The quartzite on top of Beinn Dorain is at virtually the same structural level as the quartzite on top of the hills to the east across Ault Gleann (Beinn a Chasteill, Beinn nan Fuaran and Beinn a’ Chuirn, Fig. 6). This quartzite forms part of a large outcrop of Carn Mairg Quartzite that continues to Loch Lyon and appears to be stratigraphically continuous with Ben Eagach Schist and Ben Lawers Schist in the Meall Buidhe Syncline. It is quite unclear why these two quartzite occurrences are assigned to very different stratigraphical levels; a far simpler solution would be if they belong to the same formation. Furthermore, the sequence is not recognised on the Dalmally Sheet.

Loch Rannoch Succession on Beinn Dorain (France 1971)	**'Ballachulish Succession'** as correlated with Beinn Dorain (France 1971)	**Subgroups** (Harris *et al.* 1994)
Banded Quartzite (on top of Beinn Dorain)	??	??
Upper limestone (position uncertain)	Lismore Limestone	Blair Atholl
Pelite (grt-mica schist, very thick)	Cuil Bay Slate	
Upper Quartzite (very thin and discontinuous)	Appin Quartzite	Ballachulish
Pelite (grt-mica schist, very thick)	Ballachulish Slate	
Lower limestone (very thin)	Ballachulish Limestone	
Pelite (very thin)	Leven Schist	Lochaber
Lower Quartzite (very thin)	Glencoe Quartzite	
Semipelite	Loch Treig Schist	
Eilde Flags	Eilde Flags	Grampian Group

Table 2. Proposed correlation of the sequence on Beinn Dorain with the sequence in Ballachulish (France 1971).

Roberts and Treagus (1979) regard most of the sequence as part of the Lochaber Subgroup, but show the top of Beinn Dorain and Beinn an Dothaidh as outliers of Appin Group. Hence, they retain the lower and upper slide (Figure 4).

A ?refolded south-east facing syncline (Meall Buidhe Syncline, France, 1971) with Ben Eagach and Ben Lawers rocks in its core occurs in the Carn Mairg Quartzite. In the N part of Beinn Dorain, there is a wedge of calcareous phyllite, dark schist and marble above the Grampian Group (and just above the Lower Slide) shown on Sheet 54W (Blackwater). That does not sound like Lochaber Group; more likely perhaps Ballachulish or Blair Atholl Subgroup affinities?

5.2.6.1 PROBLEMS TO FOCUS ON

Careful assessment of France (1971) and new fieldwork on detailed sections in the Beinn Dorain sector and are essential to answer the following questions:

- Are there really two slides? What is the nature of these 'slides'?
- What is the stratigraphical status of the wedge of calcareous phyllite, limestone, graphitic schist on Sheet 54W?
- Are there truly Ballachulish Group outliers within the outcrop of Lochaber Group? What is the real stratigraphy?
- What is the general structure of the area in terms of facing, vergence, shear sense and lineation directions?

5.2.7 Dalmally – Glen Orchy Sector (Sheets 45E and 46W)

This is the sector between Tyndrum Fault and Glen Strae Fault, south-west of the A82 trunk road (Figure 3); data has been taken from the Sheet 45E (Dalmally), Thomas and Treagus (1968), Roberts and Treagus (1975) and the old Sheet 46.

In this sector the Boundary Slide appears at the top of the Leven Schist, which together with the Glencoe Quartzite makes up a fairly wide outcrop of the Lochaber Subgroup here. No slide is reported at the top of the Grampian Group (as in the two previous sectors); instead a transition from Grampian Group into Glencoe Quartzite and Leven Schist (Lochaber Subgroup) is documented; this is also seen in the Glen Orchy Inlier. The Boundary Slide juxtaposes Carn Mairg Quartzite Formation (Easdale Subgroup) against Lochaber Subgroup so that the entire Ballachulish and Blair Atholl and Islay Subgroups are omitted.

The sequences above and below Boundary Slide are right-way up; beds are gently south-west dipping and there appears to be no overall inversion (possibly because the position here is underneath the Ben Lawers Synform??). Most large folds on either side of the Boundary Slide are more or less recumbent and face to the south. To the north these are the folds of the Glen Orchy Inlier that fold Grampian Group and Lochaber Group; to the south of the Boundary Slide these are folds that involve the Argyll Group. Closer to the Boundary Slide, D1 folds may, however, change facing. The facing of D1 folds in the area is rather unclear (see Roberts and Treagus, 1975). Close to the Boundary Slide, minor folds under Boundary Slide have south-east vergence; minor D2 folds above the Boundary Slide have both north-west and south-east vergence (Roberts and Treagus, 1975).

It is a possibility that the Carn Mairg Quartzite (Easdale Subgroup) is in fact Islay Quartzite (Islay Subgroup); this would limit excision to Ballachulish and Blair Atholl Subgroups???

West of the Glenstrae Fault there is outcrop of ‘Islay’ Subgroup (semipelite with graphitic schist and quartzite) above and underneath the ‘Boundary Slide’. If Carn Mairg Quartzite is in fact Islay Quartzite than this could represent a remnant of Ballachulish and Blair Atholl Subgroups.

5.2.7.1 PROBLEMS TO FOCUS ON

The area represents a good area to check the stratigraphy of Beinn Dorain sector.

Geoff Tanner is currently working in this area and may focus on some of the problems below.

- Is the ‘Carn Mairg Quartzite’ really Carn Mairg Quartzite Formation and part of Easdale Subgroup, rather than Islay Quartzite Formation and part of the Islay Subgroup?
- What is the nature of the transition (supposedly stratigraphic) from Grampian Group into Lochaber Subgroup (Glencoe Quartzite and Leven Schist)? This seems to be a good area to study this transition.
- On the south side of the Glen Orchy Inlier, there is only a thin layer of Glencoe Quartzite Formation; in the main outcrop to the south there is suddenly a very thick outcrop (see Sheet 45E and cross-section in Thomas and Treagus 1968): any reason?
- Are the structures in Glen Orchy S facing? How do the Glen Orchy Structures map out on Sheet 46W?

5.2.8 Summary of observations

5.2.8.1 STRUCTURAL OBSERVATIONS

- The Boundary Slide is generally regarded as a high strain zone on the basis of field evidence such as ‘intense platy foliation’, but little microstructural work has been done on it. The Lower Slide in the Beinn Dorain area is described by France (1971) as commonly being transitional, with pelitic / semipelitic zones. The shear sense has been *assumed* to be top-to-north-west on the basis of vergence and facing of adjacent D2 folds; however, no shear sense indicators or stretching lineations have been described. Whereas there is no doubt that the Boundary Slide is a high strain zone, there is a problem in deciding whether or not there has been significant *non-coaxial* ('simple shear') strain and whether this deformation can have been responsible for excision of the stratigraphy. The lack of clear evidence of shear sense indicators and stretching lineations may be telling in this respect, but this needs to be checked.

- The Slide is folded by 'D3' and 'D4' folds and cut by north-north-east – south-south-west trending faults, such as the Loch Tay Fault.
- The Slide appears not to be folded by D2 (or D1) folds. The fabric appears to be continuous with the regional S2 fabric. This implies that the Slide is a D2 structure (and hence ± peak-metamorphic). The significance and kinematics of the Boundary Slide is likely to be related to the (fold) structures immediately above and below it. Whereas in some areas these are quite well constrained (e.g. Schiehallion area), in other areas these constraints are very poor as large areas are very poorly mapped and little new work has been done.
- The above constraints cannot rule out that the Slide originated earlier, while being reactivated during D2.
- To the north-east of Braemar major folds face up to north-west; south-west of Braemar major folds face down to south-east. Further to the south-west, e.g. in the Beinn Dorain – Dalmally sector the folds are effectively recumbent and south facing. Overall fold vergence appears to be consistently to the north-west.

5.2.8.2 Stratigraphical observations

- The Lochaber Subgroup is (almost) continuous beneath the Boundary Slide and stratigraphically over the Grampian Group.
- The Ballachulish, Blair Atholl and Islay Subgroup rocks are missing for > 70 km along strike.
- The stratigraphically largest omission occurs near Bridge of Balgie where Lochaber Subgroup appears to occur against Ben Lui Schist Formation, with a thin layer of Ben Lawers Schist Formation, also implying omission of almost the entire Easdale Subgroup.
- East of Schiehallion, the Ballachulish, Blair Atholl and Islay Subgroups appear to 'onlap' onto Lochaber Group (Figure 5c); such 'onlapping' geometry appears to be the norm rather than the exception in the critical Schiechallion – Glen Lyon area.
- In Lochaber, both onlap (in the Argyll Group) and offlap (in the Appin Group) occur (Rast and Litherland 1970). Below the Fort William Slide an offlap/erosional unconformity of Grampian Group against Lochaber Subgroup has been interpreted by Glover (1993).

6 The Boundary Slide and the fate of the Appin Group: hypotheses, problems and tests

There are several ways that can potentially explain the Boundary Slide and the omission of stratigraphy along it. The hypotheses can, for the sake of simplicity, be grouped as follows: those that are basically structural and assume a layer-cake stratigraphy, and those that are mainly stratigraphically and are fairly independent of post-depositional deformation. In reality, a combination of structural and stratigraphical complications may be required to reach the final answer. It is clear that the Boundary Slide did experience high strain, at issue here is whether this strain was responsible for stratigraphical omission, or whether the Boudnary Slide is simply a high strain zone that was focussed along a zone of rheological contrast, for instance formed along an unconformity. Some hypotheses have been advanced before, some not, or are here adopted in a modified form.

6.1 POST-DEPOSTIONAL CONTRACTION – LAYER-CAKE ASSUMPTION

Many hypotheses to date concerning the Dalradian structure and stratigraphy assume a more or less layer-cake stratigraphy and hence suggest that the stratigraphical omission of the Ballachulish, Blair Atholl and Islay Subgroups in the area concerned is tectonic. The note of 'tectonically removed' on the stratigraphical correlation diagram of Harris *et al.* (1994) is telling in this respect. Note also that the stratigraphical omissions highlighted in this report are rather under-represented in the correlation diagram of Harris *et al.* (1994). Whereas the stratigraphical omissions occur over a length of over 70km or about one quarter of the strike length of Dalradian outcrop, only one of the twelve columns representing mainland Scottish Dalradian stratigraphy has been devoted to the area (see Figure 2).

Tectonic slides have traditionally been thought to be responsible for excision and attenuation of stratigraphy of the Dalradian. Since most slides appear to be coeval with regional D2 and regional orogenic metamorphism, this would imply that the slides are contractional rather than extensional. A simple form of contractional slides might be sheared out limbs of recumbent folds or fold nappes, so that the slides are more or less functioning as thrusts. Soper and Anderton (1984) already pointed out that simple contractional slides (see Figure 8a) would juxtapose old rocks on top of young rocks and would duplicate or thicken a particular part of the stratigraphical sequence. On these two essential criteria, a simple contractional model for the Boundary Slide clearly fails (Figure 8a).

A more complicated tectonic scenario (Fig. 8b.) could involve earlier, large-scale inversion in a large-scale south facing fold nappe (e.g. the Tay Nappe). This phase is then followed by north-west directed thrusting. Such thrusting would put (inverted) younger rocks on top of (inverted) older rocks, resulting in a geometry as envisaged by Treagus (1987, partially based upon earlier work of Bailey). Such a scenario would indeed *locally* juxtapose old on young and would *locally* excise or attenuate stratigraphy. It is not relevant here that the kinematics of the Treagus model is based upon an upright, rather than recumbent D1 fold. On the whole, however, stratigraphical duplication is even greater. There are two aspects of the model that are problematical:

- The predicted duplication is only 'invisible' if the erosion level occurs at a very particular level. At a slightly higher or tilted erosion level one would expect significant outcrops of older Grampian Group rocks to occur as outliers to the south of the Boundary Slide, whereas at a slightly lower erosion level one would expect significant outcrops of younger Appin Group or even Argyll Group Rocks to occur as inliers to the north of the Boundary Slide. To rely on such a coincidence of exactly the right erosion level over a strike length of over 70 km is scientifically unsatisfactorily.
- Further to the above point is the prediction that the Boundary Slide as modelled would cut through the stratigraphy, both above and below the Slide. This is not compatible with the observation that Lochaber Subgroup rocks can be traced with remarkable continuity just underneath the Boundary Slide, whereas the stratigraphy above the Slide shows great variations.

6.2 SYN-DEPOSITIONAL EXTENSIONAL SLIDES

Soper and Anderton (1984) and Anderton (1988) suggested that many slides in the Dalradian were syn-depositional listric faults that were responsible for many of the lateral stratigraphical variations in the Dalradian Supergroup. The slides were envisaged to be re-activated during the Grampian Orogeny. This idea was first developed in the south-west Highlands and in Jura in particular (Anderton 1985) and later extended (Anderton 1988) further onto the mainland. The Fort William Slide, the Benderloch Slide and the Boundary Slide were all suggested to have originated as syn-depositional listric faults. Such faulting is expected to result in wedge shaped units (within a roll-over anticline) that thin gradually away from the fault, but sharply abut against it. Such a model clearly does not produce a layer-cake stratigraphy.

A syn-depositional listric origin of the Benderloch Slide and the Fort William Slide may well be appropriate (but see Glover, 1993 and below). For the Boundary Slide, however, the model (Figure 8c) is unsatisfactorily for the following reasons:

- In general, more “offlap” relationships are expected (i.e at the base of the overstepping Easdale Subgroup in Figure 8c) than “onlap”; this is not observed (c.f. Figure 5c).
- The “onlap” relations would be sharp, fault bound, and at high angles to the stratigraphy; again this is not observed (although large amounts of later deformation may alleviate this problem).
- The scale of the Boundary Slide, also in terms of stratigraphical omission, may be too large for a syn-depositonal listric fault; comparison with modern basins may elucidate this point.
- The slide would level out at a level that is much deeper than the units within the rollover anticline that terminate against the fault. In practice, this would imply that the ‘master-slide’ would root down deep into the Grampian Group, rather than follow the level of the Lochaber Group. The continuity of the Lochaber Group is not a predictable outcome of the model.

6.3 POST-DEPOSTIONAL EXTENSION – LAYER-CAKE ASSUMPTION

Since the Boundary Slide juxtaposes stratigraphically young rocks on old and is associated with large-scale stratigraphical omission (or excision), a post-depositional extensional origin makes a very attractive and logical explanation of the Slide (Figure 8d). No facies changes are required and a layer-cake stratigraphy is permissible but not necessarily required. If the extensional detachment should level out within, or at the top of, the Lochaber Subgroup (possibly because this would represent an easy glide surface?), the observation of continuous Lochaber Subgroup just below the Boundary Slide is satisfactorily explained. Further predictable and testable consequences of post-depositional extension are:

- The hangingwall sequence should have an “onlap” geometry against the underlying detachment
- The footwall sequence should have an “offlap” geometry against the overlying detachment.
- Stratigraphical omission should always be characterised by a high strain zone; further high strain zones may occur parallel to particular stratigraphical levels, e.g. in the figure at the contact of Ballachulish and Lochaber Subgroup and Easdale and Crinan.

In order to excise three to four entire subgroups (Ballachulish to Islay and most of the Easdale over a distance of ~ 70 km) with a total stratigraphical thickness in the order of 2 to 5 km, a very large amount of horizontal extension is required. Although post-depositional extension would fulfil many of the geometrical requirements, the main problem with this hypothesis is to fit such a large amount of horizontal extension in the geological history of the area. When and why would extension have happened? What other geological events are expected to be associated with such a significant extensional event and is there any evidence for such events? How would such a significant extensional event fit into the large-scale tectonic framework?

6.4 INTRA-BASINAL UNCONFORMITY

A further possibility could be that a significant break in deposition within the Dalradian Basin occurred; resulting in a large intra-basinal unconformity at the approximate level of the Boundary Slide (Figure 8e). This level could than be activated as a shear zone during the Grampian Orogeny. Glover (1993) suggested that the Fort William Slide is, in fact, an intra-basinal unconformity at the base of the Ballachulish Limestone. Spean Viaduct Quartzite (Lochaber Subgroup) down to Ft. William Formation (Grampian Group) are truncated by this unconformity.

If the level of the Boundary Slide should represent a large-scale unconformity then the following features might be expected:

- Some sort of basal conglomerate, or other facies typical of unconformities
- Far more "offlapping" relationships would occur than "onlaps".

6.5 INTRA-BASINAL HIGH

Another possible stratigraphical scenario that does not require large strains along the Boundary Slide is to invoke an intra-basinal high as depicted in Figure 8f. The resultant basin architecture would comprise more onlap relationships than offlaps, which appear consistent with the observations. In this way, the Lochaber Subgroup can form one continuous layer on top of the Grampian Group (if this scenario proves to be right, the Lochaber should probably be included into the Grampian Group). No large unconformity-related deposits need to develop, although some lateral facies changes are expected. The model as depicted, needs also to be checked for realism against modern basins.

6.6 GENERAL SUMMARY

There is great potential in the area defined here as the Boundary Slide Corridor to make a substantial contribution to understanding the nature of the Dalradian depositional record, especially so when ideas linked to sequence stratigraphical relationships can be applied to the architecture of the depocentre. Given the nature of events affecting the Laurentian margin at this time (latest Neoproterozoic), the model end-members outlined in Figure 8 can be integrated to varying degrees. It may be, for example, that the unconformity implied at the base of the Crinan Subgroup in the model in Figure 8d has regional significance across the entire Dalradian outcrop and would thus say much about Laurentian break-up history and syn-depositional extension at c. 600 Ma. It is worth noting in this context, that the conspicuous occurrences of serpentinite in the Scottish Highlands tend to occur at or around this stratigraphical level (see also in Appendix 1, Ben Lui Scist Formation ultramafic horizon and serpentinites).

7 Economic Geology

Significant stratabound metalliferous mineralisation occurs within the Dalradian Supergroup of the Grampian Highlands, essentially within the Argyll Group (Stephenson and Gould, 1995). It is perhaps not without significance that the best known, and currently exploited, stratabound mineralisation coincides with the sectors along the Boundary Slide structure where significant stratigraphical omission occurs (see discussion in sections 5 and6 above). Many of these deposits have strong volcanogenic exhalative signatures, better constraints on which will further enhance understanding of Dalradian deposition.

Post-Caledonian mineral veins of late Silurian to Carboniferous age, cut the Dalradian rocks and one of the most important mineralised Pb-Zn vein sets occurs at Tyndrum within the corridor. In addition veins and breccias contain gold mineralisation which is sourced from the volcano-sedimentary succession within the Dalradian Supergroup (Plant *et al.*, 1991). The wealth of data already held by BGS needs to be assessed and databased before recommendations for future strategy is made. Industrial and bulk minerals should also be considered.

These economically significant occurrences are described in greater detail in Appendices 1 and 2, the salient points are recorded below.

7.1 STRATABOUND METALLIFEROUS MINERALISATION

The Easdale (and to a lesser extent the Crinan and Tayvallich) subgroups are potential targets as sources of stratiform base metals (Pb, Zn, Cu, Ba) (Smith *et al.*, 1984). Baryte mineralisation is found within the Easdale Subgroup mainly, but not exclusively, on the Schiehallion and Pitlochry sheets around Aberfeldy. Bedded pyritiferous barytes ($BaSO_4$) is commonly enveloped by or associated with quartz-celsian (barium feldspar) rock and barian muscovite schist in a mineralised zone at the top of the Ben Eagach Schist Formation. Overall the Aberfeldy deposit probably represents the highest concentration of barium known world-wide (Stephenson and Gould, 1995). Scott *et al.* (1988) detailed other mineralised horizons in the area, both within the Ben Lawers Schist and those in the overlying Ben Challum Quarzite and Ben Lui Schist (Figure 15).

- The mineralised horizons in the Ben Eagach Schist, Ben Lawers Schist and Ben Challum Quartzite are not presently economic in the project area but clearly related to stratiform hydrothermal exhalites.
- Studies of the stratiform exhalites may reveal clues to the rifting within the Argyll Group basin which eventually led to volcanic activity. Understanding of the mineralising systems could be gained from such studies and predictions of economic finds made.
- No mineralisation is shown on the Loch Rannoch and Blackwater sheets but antigorite-serpentine bodies are mapped. They may have similar Cr enrichment to the Corrycharmaig body which lies close to the base of the Ben Lui Schist Formation. Close to the base of the Ben Lui Schist there is also a chromium enriched metasedimentary horizon (see Appendix 1).

7.2 STRUCTURAL INFLUENCE ON MINERALISATION

The main focus of mineralisation within the project area occurs around Tyndrum and Cononish where base metals and precious metals are associated with the Tyndrum Fault Zone (Treagus *et al.*, 1999). Treagus *et al.* (1999) recorded a late Silurian history of sinistral transtensional movement involving some dip slip displacement. Extensional phases are characterised by hydrothermal quartz veins and breccias associated with the early stages of precious metal mineralisation. Strike-slip movements have created cataclastic textures in which the later stages of precious metal mineralisation have utilised. During the Carboniferous, dextral strike-slip caused cataclastic and hydrothermal quartz veining which is associated with base metal mineralisation. Future study of the faults and fracture patterns may lead to predictions of deposits which are presently unknown. The new data of Tanner (Glasgow University) for the Cononish area will provide further understanding of the controls on mineralisation.

7.3 INDUSTRIAL MINERALS AND AGGREGATES

The industrial minerals and resources most likely to be encountered in the project area listed below are listed in Appendix 3. The relatively long distances to potential markets and the environmental sensitivity of the area, means that they are unlikely to be developed in the foreseeable future.

8 Quaternary

8.1 PREVIOUS WORK

The geomorphology of the Boundary Slide Corridor has been strongly influenced by Quaternary glaciations and the present glacial deposits relate to the Devensian, the latest part of the Quaternary history, which can be separated into the Main Late Devensian ice sheet and the Loch Lomond Readvance (Boulton *et al.*, 1991). The Main Late Devensian ice sheet covered most of the area and the ice-shed during this glaciation is thought to have been over, or just west of, Rannoch Moor (Sutherland, 1991). Striations and erratics as high as 1, 100 m OD in the Ben Nevis and Glencoe areas and Rannoch Granite erratics at over 1,000 m OD in the central Grampians have been taken as support for the idea that the last ice sheet overtopped all the mountains in the south-west Highlands (Sutherland, 1991). However, this proposition is not proven as the highest peaks are free of erratics (Stephenson and Gould, 1995) and may have remained as nunataks during the Devensian.

Relatively little Quaternary work appears to have been done on the Main Late Devensian of the western Grampians and most previous work has been done on the Loch Lomond Stadial. Wain (1999) gives a summary of the findings of Thompson (1972) on the Quaternary history of western Perthshire, i.e. mainly the Killin Sheet. The Loch Lomond Readvance was the phase of valley glaciation which occurred during the Loch Lomond Stadial, 10 000 – 11 000 ^{14}C years BP. Thompson mapped the eastern extent of the Loch Lomond Readvance by recording the distribution of 'fresh' hummocky moraine, but its full extent is still debated. The local flow of ice was inferred from the orientation of glacial striae and theoretical reconstructions were made of the valley glaciers in the area (Thompson, 1972). Thompson concluded that the Loch Lomond glaciation belonged to Pollen Zone III, and was separate from and later than the Main Late Devensian ice sheet of the Dimlington Stadial (26 000 – 13000 ^{14}C years BP). Thompson recognised the Loch Lomond Stadial moraines because they were characteristically composed of loose, unsorted, angular to subangular gravelly material with no evidence of later reworking by solifluction. However, Gray and Coxon (1991) remark that care must be taken to interpret the distribution of hummocky moraines in the context of landform assemblages over a large area.

End moraines may also be used to delimit the glaciers and in some places, recessional moraines occur up-valley of the end moraines (Gray and Coxon, 1991). Sand and gravel in recessional moraine ridges are recorded from Strath Fillan in the Tyndrum area (Stephenson and Gould, 1995). Other features to look for in delimiting ice fields are erratic boulders, weathering and bog stratigraphy contrasts (Gray and Coxon, 1991). They found protalus ramparts, rock glaciers and other periglacial features associated with the Loch Lomond Stadial. Maximum ages for the stadial have been calculated by dating shells or organic silts which have been over-ridden or transported by the glaciers. Minimum ages (c. 10, 200 BP) are provided by dating the earliest organic sediments at the base of kettle holes developed within the glacial limits. The Loch Lomond Stadial in the western part of the area, was studied by Thorp (1981; 1984; 1986; 1991). He mapped the limits of the Rannoch Moor, which was calculated to be over 400 m thick, although several nunataks were identified within the area. Thorp (1991) discusses hummocky moraine, areas of thicker drift and glaciofluvial deposits. He also notes the need for quantitative studies on till fabrics etc. and information to help reconcile the view that the Loch Lomond icefield was entirely wet-based with that of a palaeoclimate believed to be severe enough for permafrost.

8.2 FUTURE WORK

Quaternary deposits, including till and morainic deposits, were shown on some of the original geological survey fieldsheets. However, Quaternary deposits (other than blown sand, peat and alluvium), and the glacial features (other than roche moutonee and glacial striae) are not shown on the published one inch to one mile sheet for Balquhidder, but they are shown on the Loch Rannoch and Blackwater sheets.

- The original survey could form a basis for revising the Quaternary geology
- A new photogeological interpretation would be necessary
- Landsat images and digital terrain modelling may also be used.
- These interpretations could be tested in the field as surveys and traverses for the solid geology (and other geological work) were in progress.
- The more important sections and features could be studied in detail in the future by Quaternary specialists within BGS (Jon Merritt etc).
- Subsequently the glacial history and models involving the Main Late Devensian Glaciation and the Loch Lomond Readvance where ice caps were centred on Rannoch Moor could be developed for the area.
- A special Quaternary Memoir for the central/western Highlands could be a possibility.

9 Conclusions and Outline planning for Years 1 to 3.

Year 1 Strategic Mapping:

- 4 (possibly 5) geologists to spend c. 20 days each in northern 46W (Crianlarich), and 46E (Killin), southern 54E (Blackwater). Extend mapping eastwards from new PWG Tanner mapping on Beinn Udhlaidh across Beinn Dorain towards upper Glen Lyon. Stratigraphy/structure in "Slide zone" – two slides?
- Limestone samples for geochemistry discrimination.
- Physical properties study with a view to future detailed geophysics if required.

Year 2 Strategic Mapping:

- Same core team to extend into lower Glen Lyon/Bridge of Balgie with lithostrat./structural traversing south across remainder of Argyll Group outcrop as a minimum.
- UCAC post-doc on Ben Alder (Sheet 54W)?

Year 3 Strategic Mapping:

- Same Core team
- Rapid structural traversing across Southern Highland Group to complete 46W/46E.

- Rapid structural traversing across Sheet 54E (Blackwater) Grampian Group, complete 54E.

[Year 4 Strategic Mapping]

- Extend mapping into 45E (Dalmally), 54W Loch Rannoch, 47W Comrie.

Appendix 1 Stratabound Metalliferous Mineralisation

BEN EAGACH SCHIST ZONES

Within the Ben Eagach Schist Formation, the main economic mineral present is baryte. It is closely related to quartz-celsian rock, which is more extensively developed at Foss (Treagus, 2000) but it is not an economic mineral. Although the baryte is bedded, massive white or grey, sugary baryte at least 3 to 4 m thick is encountered locally. The baryte is also associated with small amounts of lead and zinc sulphides in sedimentary exhalative type horizons. Lenses of lead and zinc sulphides, containing up to 10% Pb + Zn have been discovered at Aberfeldy, but pyrite is the dominant sulphide mineral. Sphalerite and galena can attain economic grades within the quartz-celsian rock. Pyrrhotite, chalcopyrite, magnetite and tennantite are rare additional minerals. Fuchsite (Chromian mica) is also rare. Some dolomitic rocks are also present. Thin veins of baryte are considered to be the result of postmetamorphic remobilisation.

The deposit mined at Foss, near Aberfeldy, extends intermittently over 7 km north-eastwards to Duntandlich. It is up to 110 m thick and continues to a depth of at least 500 m. The maximum thickness of baryte in the mine is 15 m. The mineralised horizons are mainly situated on the southern limb of the D1 Creag na h- Iolaire Anticline, although extensive D2 and D3 folding have refolded the horizons causing problems for the mine, some of which is underground. Small north-east and north-north-easterly trending faults also affect the deposit causing up to 250 m of sinistral displacement on the Frenich Burn Fault.

The deposit at Duntandlich to the east (Treagus, 2000, Stephenson and Gould, 1995) has larger reserves but does not yet have planning permission to mine. This deposit lies at a level towards the base of the Ben Eagach Schist, which has already been quarried at Ben Eagach (Stephenson and Gould, 1995). The lower part of the Ben Eagach Schist Formation south of Dericambus in the Schiehallion district (Treagus, 2000; Coats and Pease, 1984) contains transitional quartzites with stratabound and podiform Zn-Pb sulphide mineralisation. Micaceous layers (0.1 m thick) are enriched in pyrrhotite and sphalerite with associated microscopic galena and chalcopyrite. This lower horizon appears to reflect an early exhalative (Sedex) episode.

The Foss deposit at the higher horizon is also considered to be of Sedex (sedimentary exhalative) type (Coats *et al.*, 1980 and see Treagus, 2000), forming from the exhalation of Ba-rich mineralising fluid onto the seafloor. These reduced fluids reacted with the sulphate in the relatively oxidised sea water. Scott *et al.*, (1991) studied sulphur isotopes to determine the origin and conditions of formation of the sulphates and sulphides within the Ben Eagagh Schist. The schist contains graphite, pyrite and pyrrhotite which at the regional metamorphic temperature of 500^0C would be in equilibrium with CH_4 rich fluid. This fluid would react with and reduce some of the sulphate in the reaction:

$$8H+ + 4BaSO_4 + CH_4 + 6C = 4Ba+ + 4H_2S + 7CO_2 + 2H_2O$$

Barium also reacted with the alumino-silcates in the sea floor muds to produce barian clays and cymrite (hydrated barium silicate; the sedimentary precursor to celsian). The exhaled silica was precipitated as chert within the mud and recrystallised during metamorphism. The various mineralised horizons reflect successive exhalative hydrothermal pulses, and their mineral content reflects the intensity of the exhalation and the distance from the centres. Sulphur isotope studies (Pattrick *et al.*, 1979, Willan and Coleman, 1983; Moles, 1986; Hall *et al.*, 1989; 1991; Scott *et al.*, 1991; Hall, 1993), indicate that the sulphate sulphur source was late Neoproterozoic sea water. Most of the associated sulphides are also isotopically heavy indicating sulphur of hydrothermal origin. Oxygen and strontium isotopes analyses support an origin by mixing hydrothermal fluids and sea water, while the source of the ore is in the older Dalradian lithiologies and the sub-Dalradian basement. The metalliferous fluids were probably exhaled into small rifted basins floored by carbonaceous muds in which bacteria may have assisted the fixation of the metals.

The Loch Lyon horizon of mineralisation has been described by Scott *et al.* (1998) and can be equated with the zone at Foss. It is a barium-enriched zone 1 – 3 m thick containing 4.5% Ba over a strike length of 4 km.

BEN LAWERS SCHIST ZONES

Towards the top of the Ben Lawers Schist in the Crianlarich area, a zone of pyritic enrichment (Pyritic Zone) can be traced intermittently along strike for over 180 km from Glen Shee to Knapdale (Smith, 1977; Smith *et al.*, 1977; Smith *et al.*, 1984). Base Metal values are low – Cu < 400ppm and Zn < 100 ppm, but at Meall Mor in Knapdale up to 1% Cu was recorded in pyritic quartzite (Smith *et al.*, 1978). In Allt a' Chaol Ghlinne (Fortey and Smith, 1986) the pyrite is disseminated in muscovitic schist, while 4.5 km to the north-east in Allt Challum, thin bands of dark biotite schist contain pyrite porphyroblasts up to 30 mm across and occur within calcareous mica schist. The pyrite zone has sharply defined upper and lower limits which do not coincide with any significant lithological changes in the Ben Lawers Schist. It extends eastwards into the Schiehallion area (Treagus, 2000) where it occurs close to the contact with the overlying Farragon Volcanic Formation. The zone may have formed from volcanic hydrothermal metal-bearing fluids rising as a buoyant plume from the sea floor and subsequently spreading laterally to deposit sulphides (Fortey and Smith, 1986; Scott *et al.*, 1991). Although a number of hydrothermal systems would be needed to produce such an extensive zone, the relatively constant distance of the zone below the Ben Challum Quartzite– Farragon Volcanic formations suggests that most operated at the same time.

Ben Challum Quartzite Formation horizons

According to Smith *et al.* (1981) and Fortey and Smith (1986), the Ben Challum Quartzite Formation in the Tyndrum area contains two distinct mineralised horizons. The lower one, the Auchtertyre horizon occurs in the upper half of the formation and extends over 9 km. In the Allt Auchtertyre to Alt a' Chaol Ghlinne section it averages 1250 ppm Zn and 340 ppm Cu over an apparent true width of 80 m. The main lithology is fine-grained (cherty) rusty-weathering quartzite with a little muscovite and pyritic bands and trails parallel to the lithological layering. The coarse crystallisation of the pyrite indicates that it recrystallised in situ as a result of metamorphism. Willan (1980) obtained values in hundreds of ppm for Cobalt, Nickel and Selenium from this horizon which is consistent with an exhalative origin and other stratabound Dalradian sulphides. The pelitic units within the Auchtertyre horizon are variously rich in muscovite, biotite, chlorite, hornblende, almandine and sodic plagioclase. Garnets in the Auchtertyre horizon have high Mn contents consistent with a distal expression of exhalative mineralisation (Fortey and Smith, 1986). The quartzites and schists also contain secondary (?hydrothermal) albite, the origin of which is uncertain.

The upper zone, the Ben Challum horizon, occurs intermittently 0-30 m below the top of the Ben Challum Quartzite and is about 15 m thick (Fortey and Smith, 1986). Weakly pyritic quartzite at its base is succeeded by highly pyritic mica-schist with interbedded hornblende schist and dolomitic biotite-schist. An overlying quartzite unit contains sphalerite and galena. The unit contains zones 1 m thick with 3% Zn which are considered to be siliceous exhalites. Fortey and Smith (1986) suggest that probable millimetre-scale graded bedding may have originated as part of a syndepositional breccia.

Ben Lui Schist Formation ultramafic horizon and serpentinites

Generally small bodies of serpentinite are known from near the base of the Ben Lui Schist. The largest of these is the Corrycharmaig body in Glen Lochay [NN 527 358], which is 500 m long. The body has been investigated for chromite and talc. The chromium concentrations are not considered of economic importance (Harrison, 1985) but serpentine may be a potential Mg-silicate resource and the talc is of industrial grade (see below). This altered ultramafic (mainly antigorite) body has been variously interpreted as an intrusion or of ophiolitic origin. It may have been emplaced as a diapir of serpentinised mantle in an area of thinned and rifted crust. It could also be an olistrolith as other smaller serpentinite bodies lie at about the same horizon in the Pitlochry and Braemar districts. In addition there is a Cr anomaly with detrital Cr-mica, chromite, Cr-magnetite, pyrrhotite and chalcopyrite (Smith and Fortey, 1986) in the metasediments at this level suggesting a clastic ultramafic input in part.

To the south-west of Loch Fyne in the Erins Quarztite which also lies within the Crinan Subgroup, contains a pyritic zone with chalcopyrite. The copper minerals were worked from this zone in the past adjacent to metabasaltic bodies suggesting that this mineralisation was partly volcanogenic in origin.

Appendix 2 Structural Influence on Mineralisation

TYNDRUM VEINS

Lead with silver as a valuable by product has been mined from veins at Tyndrum from 1741 intermittently until 1925. In all about 10 000 tons of lead ore were recovered as well as some zinc and copper. The veins occupy fractures running subparallel to the Tyndrum Fault, which trends around N040^0 (Pattrick, 1985). The majority of the ore came from the Hard vein which occupies a fracture in Grampian Group 'quartzite' 20 m to the east of the Tyndrum fault. The main ore minerals are galena and sphalerite with minor chalcopyrite. Massive quartz is the main gangue mineral together with some calcite and baryte. Silver- and cadmium-rich tetrahedrite occur within the massive galena. Veins containing uraninite post-date the main base metal mineralisation and may be a late oxidised stage of the main mineralisation (Pattrick, 1985). The Tyndrum Fault controlled the upward flow of hydrothermal fluids and its intersection with fractures in quartzites favoured the development of veins (Pattrick, 1985).

The gold- and silver-bearing quartz-sulphide veins on Cononish Hill have been trialed by Ennex International (Parker *et al.*, 1989; Clifford *et al.*, 1990). They proved 750,000 tonnes of ore grading 8.0 g/t Au and 43.0 g/t Ag within a single quartz-sulphide vein (Parker *et al.*, 1991). By comparison with Parnell *et al.* (2000) studying regional fluid flow and gold mineralisation in N. Ireland, the intersection of two structures is a significant factor in the location of these minerals. The structures could be the Tyndrum Fault set and the Cruachan lineament. The Tyndrum mineralisation lies on the intersection of the Tyndrum Fault and the north-South Loch Lomond lineament of Russell (1971). Parnell *et al.* (2000) found higher fluid flows in favourable zones of dilation and closer to the fluid source, probably developed during late Caledonian times. Later Lower Carboniferous ingress of sulphate rich fluids created the base metal deposits. The gold-bearing veins are considered to have formed at about 290-340^{0}C (Pattrick *et al.*, 1991), derived from a mixture of Devonian meteoric water and magmatic fluids. A later generation of galena bearing veins formed at about 140-200^{0}C and were probably related to dextral movements on the Tyndrum Fault and possibly related to the Permo-Carboniferous dykes. Sulphur isotope studies suggest that the sedimentary stratabound minerals provided the source for the later vein components. Subsequently, Treagus *et al.* (1999) provided evidence for a detailed history of movement on the Tyndrum fault and the mineralisation. Early quartz-pyrite-chalcopyrite veins formed in dilational fractures within a sinistral transtensional regime. These veins were later rotated and reactivated as Reidal shear zones in which gold-sulphide was deposited in cataclastic veins. This early mineralisation phase is dated at c. 410 Ma by K-Ar on K-feldspar, which places it about the time of Lower Devonian magmatism. The associated intrusions are believed by Treagus *et al.* 1991 to have been emplaced and deformed during the sinistral transtensional phase.

The subsequent phase of base metal mineralisation that occurs in cross cutting structures (both dilational and Reidal fractures) related to a later dextral transtension along the Tyndrum Fault. This later phase of mineralisation is related to an early Carboniferous thermal event, dated at 360-340 Ma by Ar-Ar on K-feldspar. Treagus *et al.* (1991) also relate a late Carboniferous resetting to the Permo-carboniferous dyke swarm, which although locally affected by minor dextral fault movements, generally postdates the major dextral faulting and base metal mineralisation..

Studies of the gold-bearing structures at Tyndrum indicate that they formed from CO_2-bearing fluids that contained 6 wt% NaCl at temperatures in the range 290-350^{0}C. Oxygen and hydrogen isotopic data suggest that the fluids were magmatic in origin but include a component of –

probably Lower Devonian meteoric water. The sulphur isotopic ratios indicate that there was a magmatic and country rock component to the sulphur. The magmatic component could be either granitic or appinitic. The base metal veins, which were formerly mined at Tyndrum, have a different character, and formed from highly saline and low temperature (140-200^{0}C) fluids.

The Bridge of Balgie Fault is locally associated with Pb-Zn vein mineralisation (Curtis *et al.*, 1993) and compares with the Tyndrum structures..

Gold-bearing structures have been investigated in the Calliachar and Urlar burns south-west of Aberfeldy, trending N150^0 within the Southern Highland Group (Treagus, 2000).

MAGMATIC/HYDROTHERMAL INFLUENCE ON MINERALISATION

The presently known occurrences of magmatic and related hydrothermal mineralisation within the project area are given below. They are most likely to be related to the post-Caledonian granitic and dioritic suites and future studies of the deposits may be linked in with those on the magmatism for the Moine and Dalradian Basins as a whole.

Quartz-pyrite-molybdenite and carbonate veins

At Blackmount, east of the Ericht-Laidon Fault and on the southern margin of the Moor of Rannoch Granite, there is a suite of quartz-pyrite-molybdenite veins that is closely associated with the late Caledonian granite intrusion. Molybdenite is also present on the west side of the Ericht-Laidon Fault, and it is possible that the two localities were adjacent prior to fault movement.

Quartz veins with disseminated minor sulphides including rare molybdenite occur within the Grampian Group in the north of the Schiehallion district (Treagus, 2000). They contain traces of galena, chalcopyrite, arsenopyrite and sphalerite. Carbonate (ferroan dolomite) veins are common in the Schiehallion area.

Lead, zinc and copper deposits

These elements occur in disseminated sulphides within felsite and diorite intrusions on the south side of Loch Tay at Ardtalnaig [NN 70 39] and Tomadashan [NN 69 38]. Pb and Ag mineralisation of this type occurs at Corrie Buie [NN 70 34] and Correbuichill (3 miles south of Tomnadashan). In addition minor lead veins are recorded from Lochearnhead and Meall Luaide, Glen Lyon [NN 58 44], and Pb and Cu mineralisation at Allt nan Sliabh, Killin [NN 59 31]. Similar mineralisation is associated with the Comrie dioritic intrusion to the east.

Appendix 3 Industrial Minerals and aggregates

MICA SCHIST

Dalradian mica-rich schists are a potential source of industrial (ground) mica and the Beoil Schist in the Schiehallion area has been of some interest (Harris and Turner, 1971). This schist has a high muscovite content, and was previously thought to be a tectonic schist (Harris and Turner, 1971) but has since been recognised as part of the Lochaber Group Dalradian. It may continue westwards around the Boundary Slide. The 7 ton composite sample tested by Moir and Henley (1967) was found to contain 35-55 wt% mica, with 25 to 30 wt% muscovite and 10- 20 wt% biotite. Mineral separation was effective when the rock was crushed and ground to 30 mesh. The quality was considered suitable for lubricants and insulation but the high iron content of the muscovite would prohibit its use where colour was important, e.g. in the paper industry (Harris and Turner, 1971). The Ben Lawers Schist Formation was also considered but was more heterogeneous in composition. The problem of quarrying a muscovite-rich zone in a complexly folded area was also a drawback, compared to the simpler outcrop pattern of the Beoil Schist.

TALC

The possibility of talc resources is limited to the altered serpentinite bodies and the impure originally dolomitic limestones of the Ballachulish Subgroup (compare with the Strath Fionan Pale Limestone at Dunalastair (Treagus, 2000). Part of the Corrycharmaig body is altered to talc and breunnerite (a magnesium-iron carbonate) (Grout and Smith, 1989b) and the rock generally contains 40-50% talc. Overall, the talc resources in the Grampian Highlands are small, scattered and restricted to relatively low grades (Grout and Smith, 1989b).

GARNET

Garnet is a metamorphic mineral found within many of the formations, such as the Ben Lui Schist. It represents a potential source of abrasives. The Beoil Schist is highly garnetiferous as well as being micaceous; the high proportion of mica would facilitate garnet separation (Treagus, 2000).

CARBONATES

The Loch Tay Limestone is a possible source of agricultural lime but presently Sheirglas Quarry near Blair Atholl is producing a purer limestone from the Blair Atholl Dark Limestone (Grout and Smith, 1989a).

BUILDING STONE AND AGGREGATE

The rocks are generally too remote from markets for stone and aggregate and most of the area is of scenic beauty so that it is unlikely that planning permission would be granted for quarrying.

SAND AND GRAVEL

These resources are limited in this area. Fluvio-glacial sand and gravel terraces are known from beside the Tulla River (Glacial Lake Tulla) (Hinxman *et al.*, 1923). In the Killin area most of the

Glacial deposits are described as moraine (Thompson, 1972) and so are not likely to provide good sources of sorted sand and gravel unless glacial outwash deposits can be located.

PEAT

Several areas of blanket and hill peat are delineated on the original survey maps. The remoteness from markets and the sensitivity of the environment makes their commercial development unlikely.

WATER

The larger lochs and reservoirs are important in hydro-electric schemes.

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11 Figures

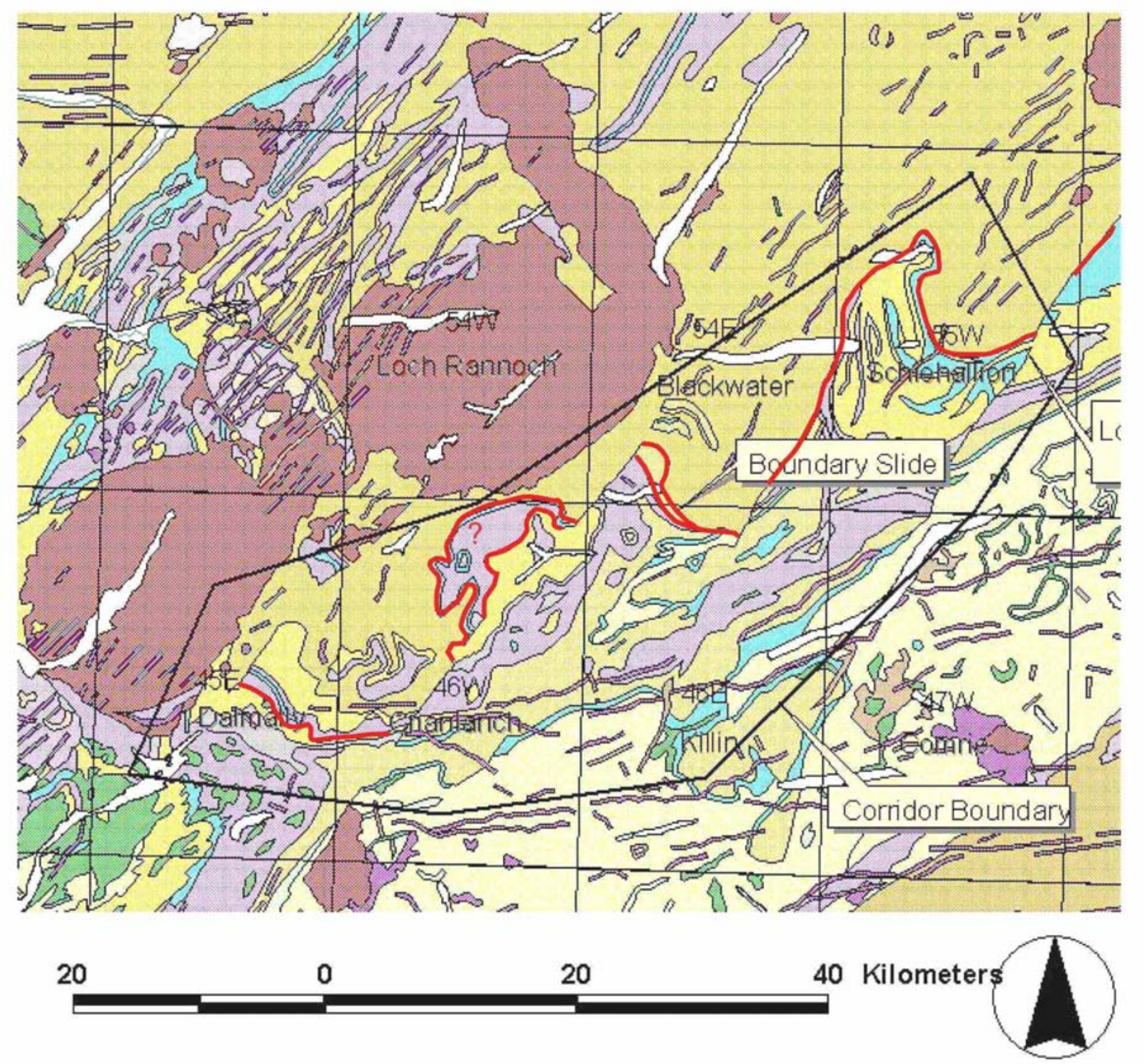


Figure 1. Overview geological map, based on the 1:625 k digital geological map, showing the position of the Boundary Slide Corridor. The Boundary Slide and associated slides are marked in red.

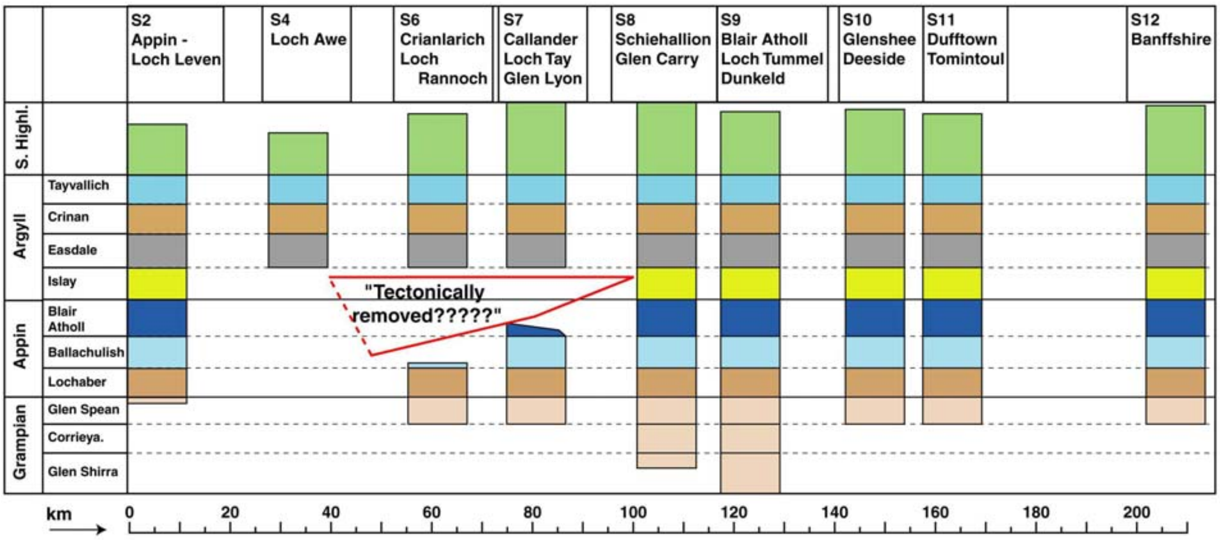


Figure 2 Dalradian lithostratigraphical columns, simplified after Harris *et al.* (1994), with spacing of columns corresponding to the approximate distance between the locations that they represent.

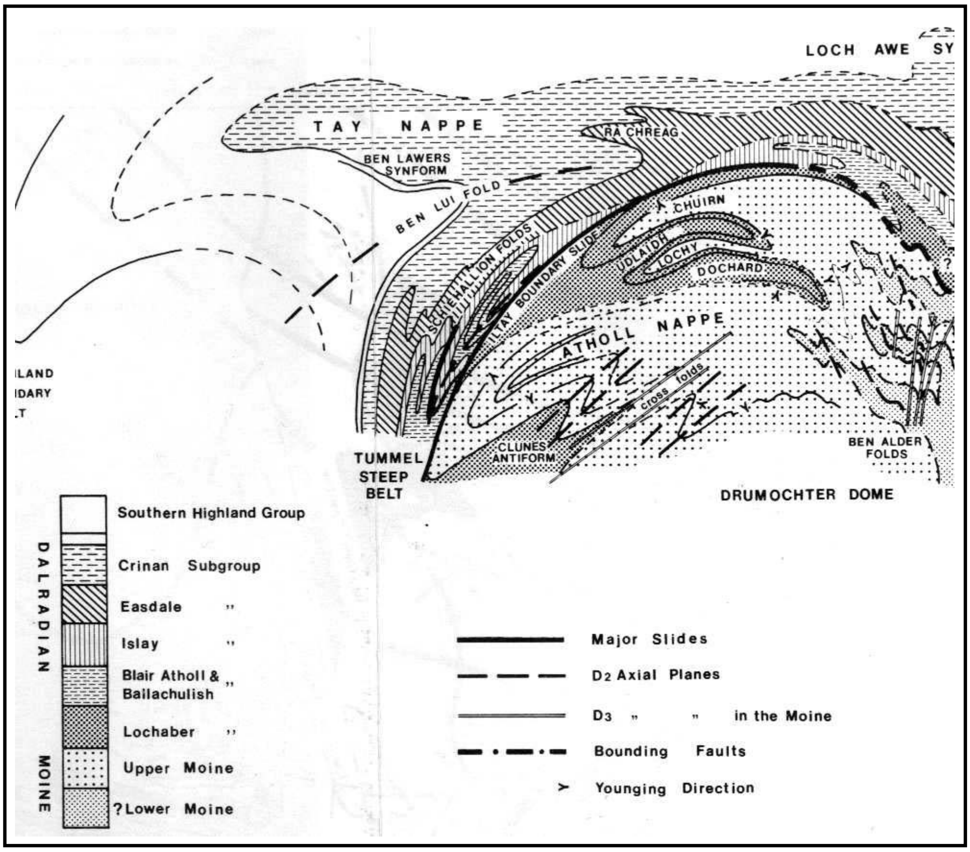


Figure 3 Schematic cross-section of Grampian Highlands, as envisaged by Thomas (1979). Note that the Boundary Slide is shown to occur structurally above most of the Lochaber Subgroup

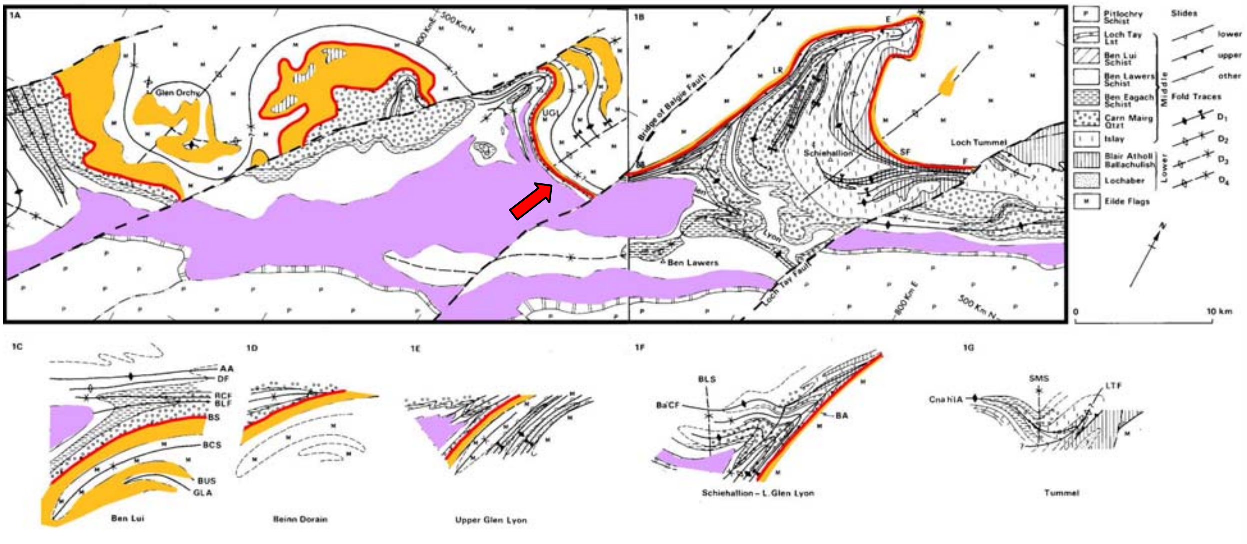


FIG. 1. Geological map and cross-sections of the Central Highlands from Ben Lui to Loch Tummel.

Figure 4. Geological map and cross-section of the Central Highlands, after Roberts and Treagus, 1979. Lochaber Subgroup and Crinan Subgroup are highlighted in pale brown and violet respectively, to highlight the small distance between the two subgroups south-west of Bridge of Balgie, in the Loch an Daimh Sector (see arrow).

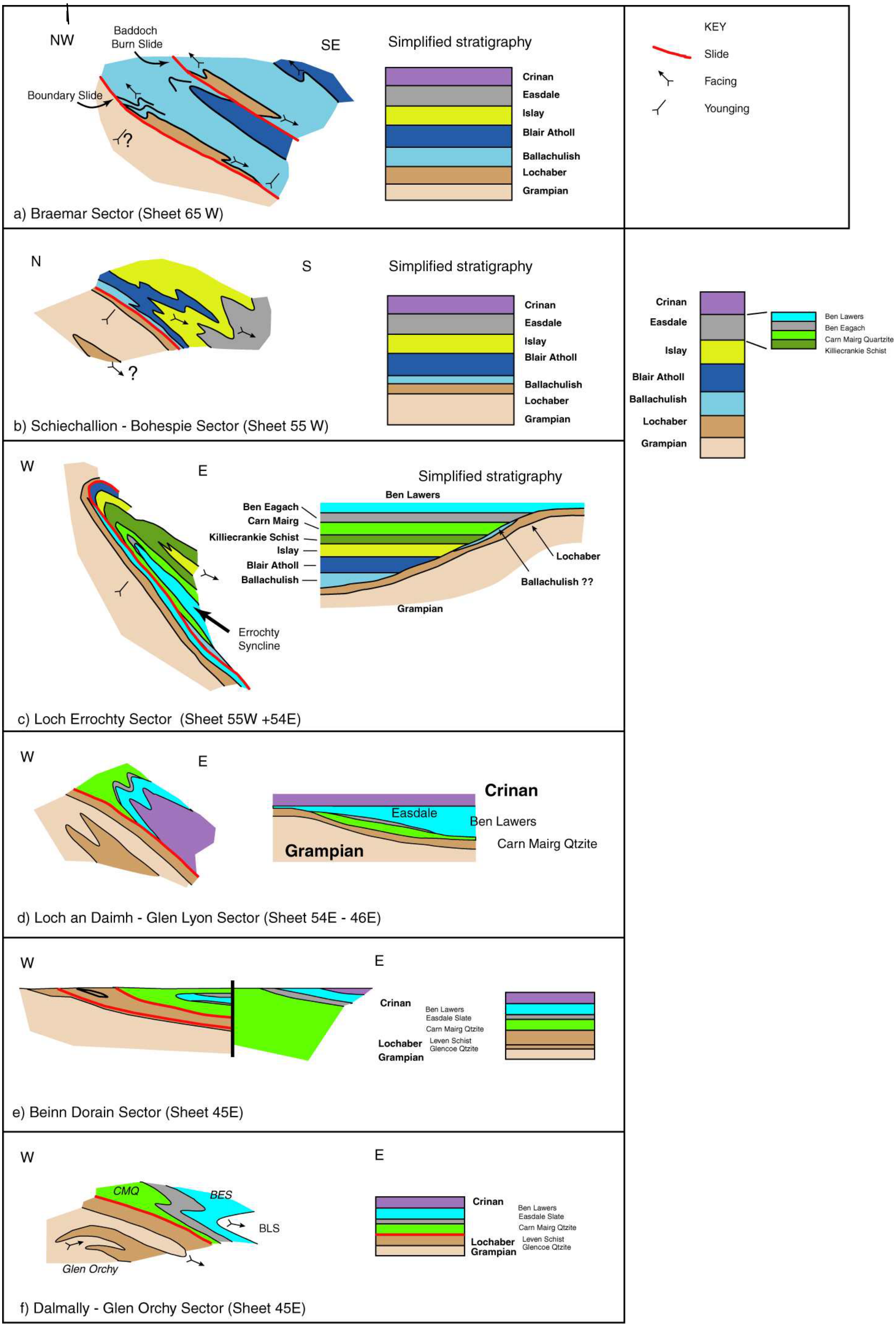


Figure 5: Schematic cross-section and lithostratigraphy of sectors along Boundary Slide

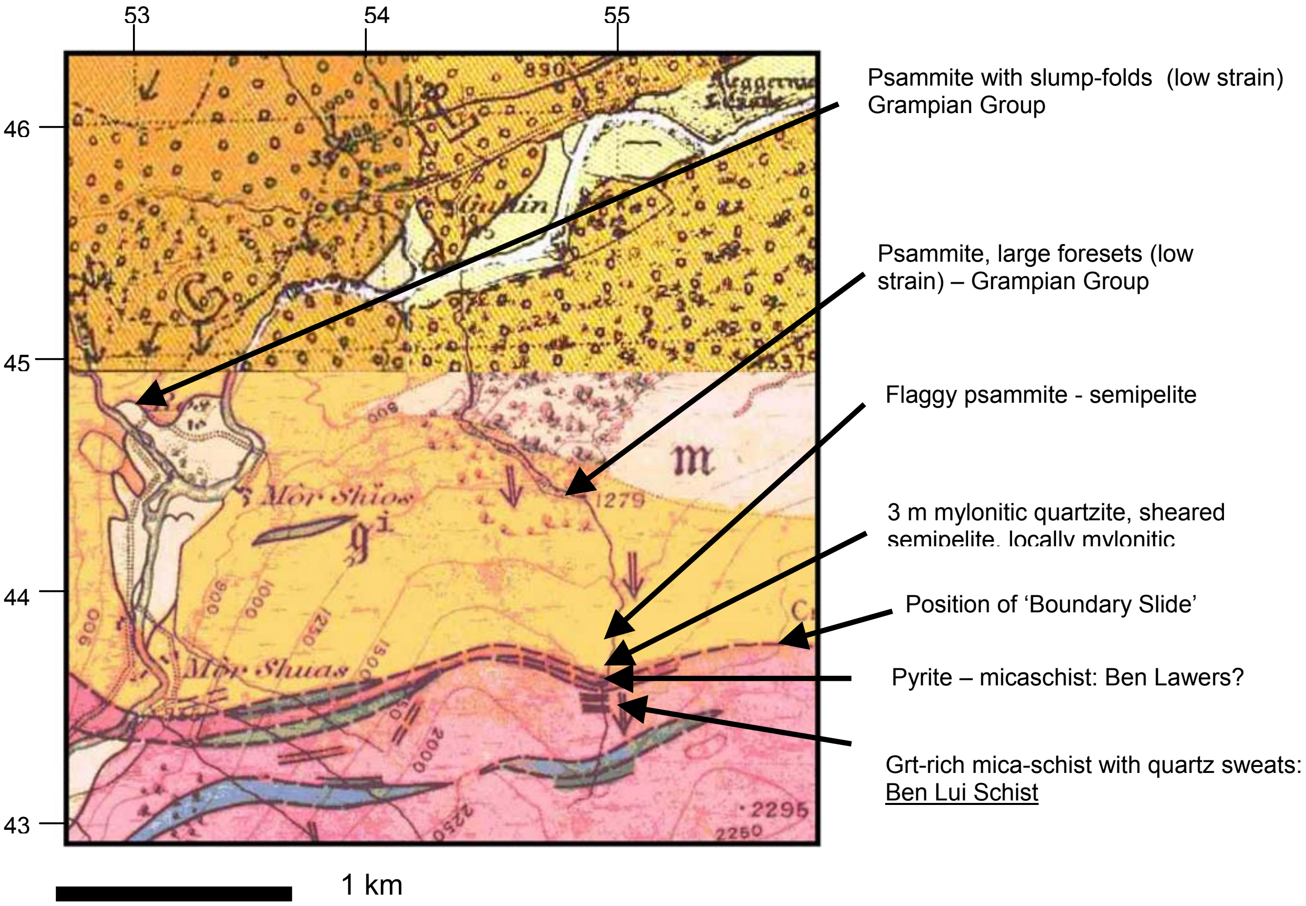


Figure 6: Geological map of Boundary Slide south of Meggernie Castle, Upper Glen Lyonbased upon the original Geological Survey Sheets 46E and 54E. Arrowed observations were made during a reconnaissance trip in 2001 by A G Leslie, J R Mendum, M Krabbendam, R A Smith and D Stephenson.

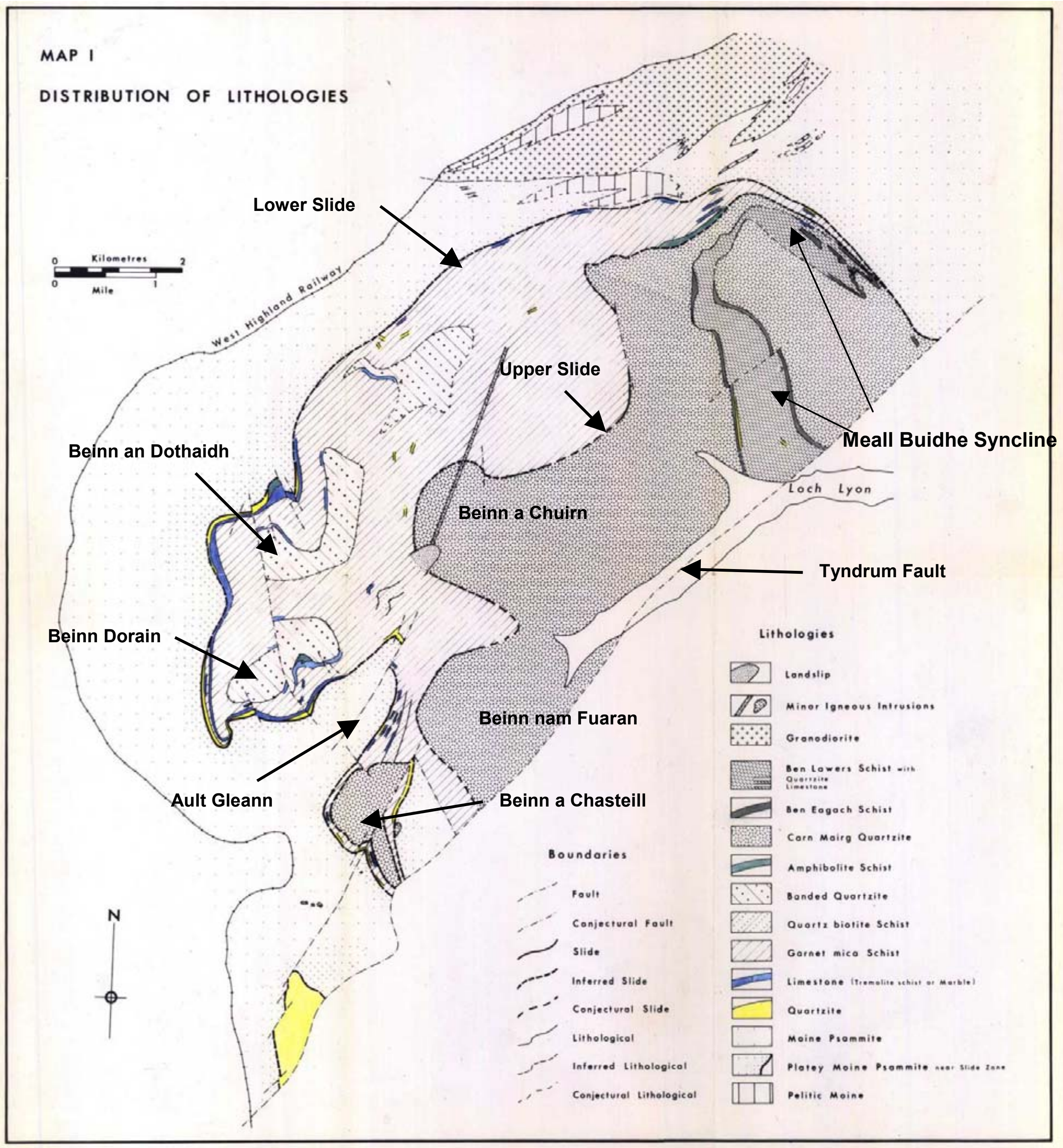
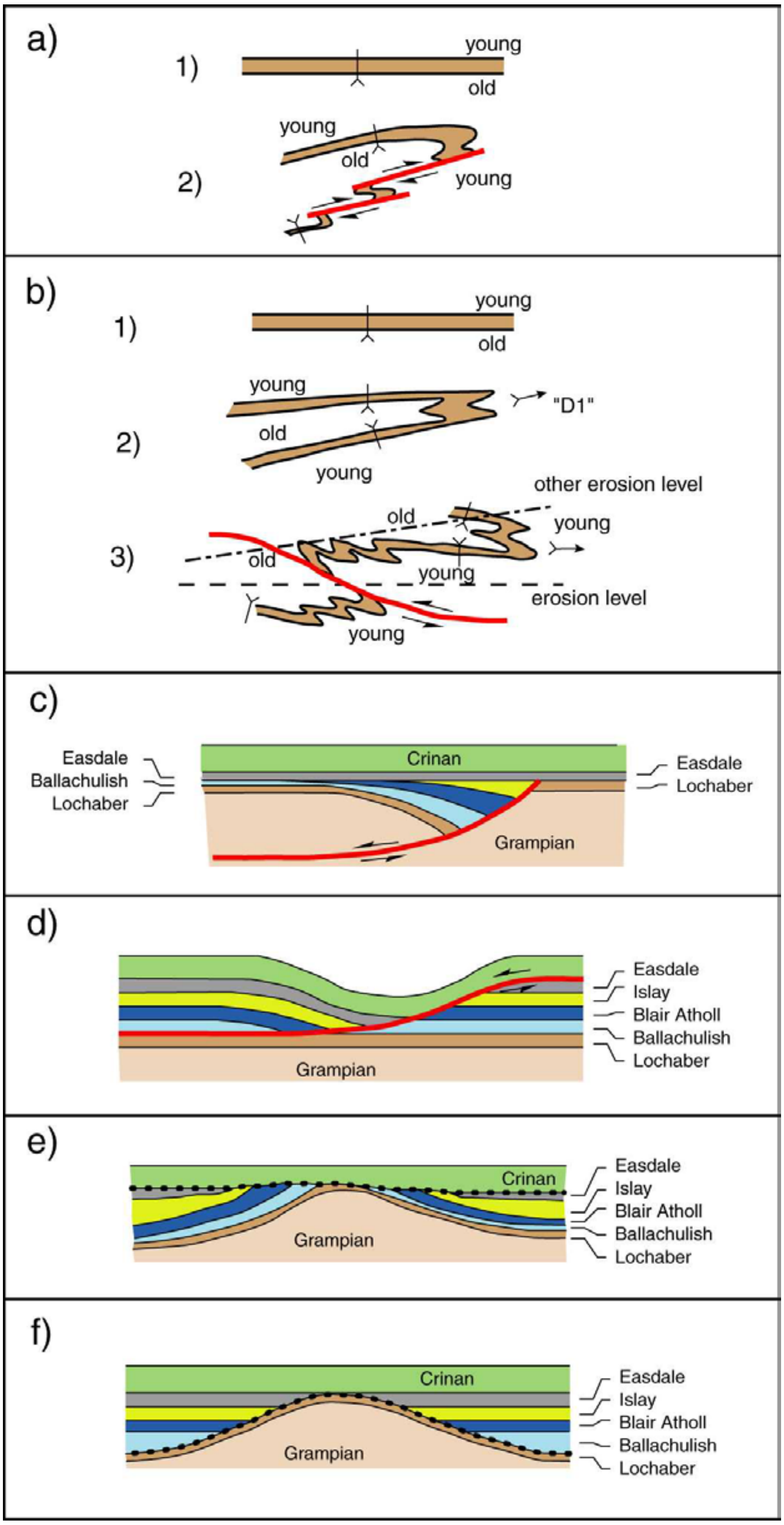


Figure 7: Geological map (France, 1971) from the Beinn Dorain area, annotated. The base of the Carn Mearg Quartzite is at virtually the same level as the base of the 'Banded Quartzite'.



a) Simple thrusting mechanism: Simple thrusting emplaces old over young and duplicates rather than omits stratigraphy (Soper and Anderton 1984)

b) Double thrusting mechanism.

Double thrusting can emplace locally young over old; however, it would duplicate the sequence even more. This duplication is only 'invisible' at a unique erosion level.

c) Syn-depositional extension

d) Post-depositional extension

e) Intra-basinal unconformity

f) Intra-basinal high

Figure 8: Hypotheses /explanations for stratigraphical omissions associated with the Boundary Slide: see Section 6 for explanation of the figures.