STRUCTURAL EVOLUTION OF THE MOINE THRUST BELT IN NORTHERN ASSYNT (NW SCOTLAND): BALANCED CROSS SECTIONS AND FAULT ROCKS

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ABSTRACT

The Moine Thrust belt at Assynt is a classical example of a foreland propagating, thin-skinned thrust zone. In Northern Assynt, the obliquity of the structures to the direction of the tectonic transport has been previously interpreted (Coward 1982, 1984) as due to the differential movement of the Glencoul sheet. In this area of obliquely trending structures, several balanced cross sections have been attempted, based on a pre-existent detailed mapping. The imbricated pattern of the Cambro-Ordovician cover of the Glencoul sheet shows 40% shortening along the Beinn Uidhe section. In this case, the unconformable contact between the Lewisian basement and the Cambrian quartzite has worked as the basal decollement surface. Further to the south along the Cnoc an Droighinn section, a duplex structure (formed by the upper members of the Cambro-Ordovician sequence) underlying the Glencoul sheet is very well exposed. By means of a balanced cross section, it has been calculated that this structure has suffered 80% shortening. This figure would represent the shortening along a direction normal to the structures; using Cooper (1983) corrections, the correspondent shortening along the direction of the tectonic transport has been deduced to be 40%.

In Northern Assynt several steeply dipping faults (trending normal or slightly oblique to the tectonic transport) appear disrupting the Lewisian basement and the Cambro-Ordovician cover of the Glencoul sheet. Following previous interpretations they are considered as extensional structures formed during episodes of gravitational collapse of the wedge. In some cases these structures would bound the trailing edges of slices of rocks that have suffered an extensional displacement in the direction of the tectonic transport. In this paper, it is suggested that this displacement might have also produced folding and thrusting at the front of the slices. The extensional structures have been reactivated in a subsequent compressional episode which also produced back- folding and back-thrusting.

The study of the fault rocks associated with the aforementioned structures show a pattern coherent with a "piggy-back" sequence of thrusting. The thrusts developed earlier in the sequence (now occupying higher structural levels) carry fault rocks in which intracrystalline plasticity has been recognized to be the dominant deformation mechanism. Later thrusts (now outcropping at lower structural levels) show fault rocks produced by cataclastic deformation.

Key words: Moine Thrust Belt, thrust tectonics, extensional faults, balanced cross sections, fault rocks.

RESUMEN

El "Moine Thrust Belt" en Assynt es un ejemplo clásico de una tectónica de piel fina con propagación de las imbricaciones hacia el antepaís. En el Assynt septentrional, la oblicuidad de las estructuras con respecto a la dirección del transporte tectónico ha sido previamente interpretada (Coward, 1982, 1984) como debida al movimiento diferencial de la lámina del Glencoul. En este área de estructuras con dirección oblicua, se han ensayado varios cortes compensados. Las imbricaciones de la cobertera cambro-ordovícica de la lámina del Glencoul muestran un acortamiento del 40% a lo largo de la sección de Beinn Uidhe. En este caso el contacto discordante entre el basamento lewisiano y la cuarcita cámbrica ha funcionado como superficie de despeque. Más al sur, a lo largo de la sección del Cnoc an Droighinn un duplex formado por los miembros superiores de la secuencia cambro-ordovícica presenta una buena exposición. Mediante un corte compensado se ha calculado que esta estructura ha sufrido un acortamiento del 80%. Esta cifra representa el acortamiento particular a la dirección de los cabalgamientos; usando la corrección de Cooper (1983) se deduce que el acortamiento correspondiente en la dirección del transporte tectónico es del 40%.

En el Assynt septentrional diversas fallas subverticales (con dirección perpendicular u oblicua a la del transporte tectónico) atraviesan el basamento lewisiano y la cobertera cambro-ordovícica de la lámina del Glencoul. Siguiendo interpretaciones previas se considera que estas fallas son estructuras extensionales fomadas durante episodios de colapso gravitacional de la cuña orogénica. En algunos casos estas estructuras forman el límite posterior de masas rocosas que han sufrido un desplazamiento extensional en la dirección del transporte tectónico. En este artículo se sugiere que tal desplazamiento podría haber producido plegamiento e imbricaciones en el frente de la masa deslizada. Las estructuras extensionales han sido posteriormente reactivadas en un episodio compresivo que produjo replegamiento e imbricaciones con sentido retrovergente.

El estudio de las rocas de falla asociadas a las estructuras mencionadas muestra una pauta coherente con un modelo de imbricación del tipo *"piggy back"*. Los cabalgamientos desarrollados en los estadios iniciales (y que ahora ocupan niveles estructurales muy altos) producen rocas de falla en los que la plasticidad intracristalina es el mecanismo que domina la deformación. Los cabalgamientos generados en estadios finales (y que ahora afloran en niveles estructurales inferiores) muestran rocas de falla producidas por deformación cataclástica.

Palablas clave: Moine Thrust Belt, tectónica de cabalgamiento, fallas extensionales, cortes compensados, rocas de falla.

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1. INTRODUCTION: THE MOINE THRUST BELT

The Moine Thrust Zone is a belt of foreland thrusting and marks the NW boundary of the Caledonian Orogeny in Britain. The first comprehensive work on the thrust zone was given by Peach *et al.* (1907) in the classic NW Highlands memoir of the Geological Survey. Many other workers have studied detailed portions of the thrust belt (Ramsay, 1969; Soper and Brown, 1971; Soper and Wilkinson, 1975; Christie, 1960; Phemister 1960 and Johnson, 1960, 1961). Particular attention has been paid to problems of Moine stratigraphy, metamorphism and deformation (Johnson, 1975; Johnstone, 1975; Powell, 1974; Harris *et al.*, 1978). However it has not been since the very late seventies that a greater emphasis has been placed on the description and interpretation of the geometry and evolution of the thrust belt itself in terms of "thin skinned" tectonics, following the ideas previously developed in the Canadian Rocky Mountains and the Appalachians. Thus, the work of Elliot and Johnson (1980) —(including for the first time evaluations of the shortening across the belt using the technique of balanced cross sections)— and the overview of McClay and Coward (1981) may be considered as the starting points of a series of subsequent detailed and general studies focussing on the geometry of the belt (Coward, 1980; Coward, Kim and Park, 1980; Coward and Kim, 1981; Coward, 1982, 1983, 1984, 1985, 1988; Fischer and Coward, 1982; Coward and Potts, 1983; Coward, Neil and Talbot, in press; Butler, 1982, 1984, 1986; Butler and Coward, 1984; Soper and Barber, 1982).

The Moine Thrust Zone extends from Eribol in the north to Sleat in Skye, to the south, a distance of over 190 km (Fig. 1). The whole zone has suffered a tilting, some of which may have been isostatic, due to the weight of the overlying thrust slab, but some may be later due to Mesozoic crustal extension (Coward, 1983). This tilting, that produces a regional dip in the foreland between 10-15°, is surprisingly consistent along the length of the Moine Thrust Zone and is responsible for the excellent outcrop of the belt along the dip direction, which is also the transport direction. The width of exposure varies between O and 11 km depending on the level of erosion and on the structural geometry of the thrust belt.

The rocks of the Moine Thrust Zone were first described in detail by Peach *et al.* (1907). They form the northwest boundary to the Caledonian orogen in Britain. The foreland to the northwest consists of Proterozoic Lewisian gneiss, locally overlain by non-metamorphosed mid -to upper- Proterozoic Torridonian Sandstones and then by Cambro-Ordovician sediments (Fig. 2). These sediments consists of about 200 m of quarzites of which the lower part, The Basal Quarzite, is barren, while the upper part, The Pipe Rock, contains vertical worm burrows. In undeformed rock these pipes are normal to bedding and circular on the bedding planes and thus make ideal strain markers (c.f. Coward and Kim, 1981, Wilkinson *et al.*, 1975). The quarzites are overlain by dolomitic shales and sandstones, the Fucoid Beds, then by a 10 m. thick grit (the Serpulite Grit) and the highest Cambro-Ordorician sediments are a thick sequence of limestones and dolomites (the Durness Limestone).

Within the thrust belt there are several thrust sheets stacked on top of each other. The lowermost thrust sequence contains an imbricated stack of Cambro-Ordovician rocks and its basal thrust is termed the Sole Thrust. It is, therefore, the westernmost outcroping major thrust. The Sole Thrust climbs up stratigraphy

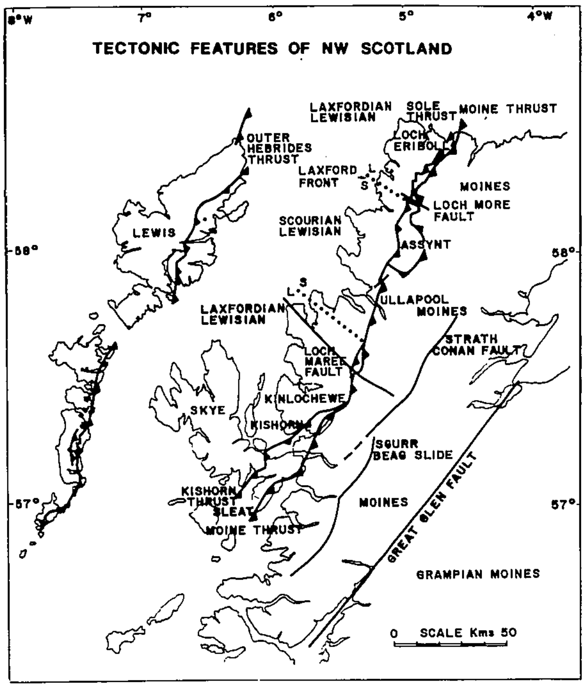

Fig. 1.-Location of major structural units of the NW Highlands, including The Moine Thrust Zone and the Outer Hebrides Thrust. Subdivisions in the Lewisian foreland are designated S: Scourian, L: Laxfordian (From McClay and Coward, 1981).

Fig. 1.-Localización de las principales unidades estructurales de los Highlands noroccidentales, incluyendo la zona imbricada del Moine y el cabalgamiento de las Hebrides exteriores. Las subdivisiones en el antepaís Lewisiano se designan S: Scourian; L: Laxfordian (Extraída de McClay y Coward, 1981).

from SE to NW. In the NW it lies in the Cambro-Ordovician sediments but to the east it must lie within the Lewisian gneisses as these materials are involved in the imbricate sequence. The eastermost thrust in the Belt is the Moine Thrust s.s. and carries mylonites and the Moine schists over the foreland. This is structurally the highest thrust and has been regarded by different authors either as the first thrust developed in the sequence of thrusting or the last one. As will be seen later, it is currently accepted that the Moine Thrust Belt represents a "piggy-back" model (Dahlstrom, 1969; Boyer and Elliot, 1981) "with complications" (Coward, 1982), so that the Moine Thrust s.s. is the oldest one, carried in a piggy-back fashion towards the east by the subsequent thrusts developed underneath.

The present paper deals with the structural evolution of the Moine Thrust Belt in the northern part of the Assynt District (NW of Scotland, fig. 2). One of the aims of the paper is the description of the various structures present in this particular area, and their integration in balanced cross sections. The problems that have arisen from the oblique attitude of the structures, for balancing purposes, will be also discussed. Special attention is paid to the fault rocks produced along the thrust planes and their relationship with the model of evolution proposed for the belt.

2. NORTHERN ASSYNT. GENERALITIES

From the geological point of view Northern Assynt can be very well distinguished from the rest of the Assynt District as a zone where the strike of the structures change dramatically from a predominantly NNE-SSW direction, south of river Traligill near Inchnadamph, to a NNW-SSE direction to the north of this river. The structures maintain this NNW-SSE strike for a certain distance, progressively changing until the former one is achieved again not far to the northwest of Glas Bheinn (Fig. 2).

After the general studies carried out early in the century by the Geological Survey workers (Peach *et al.*, 1907), and later by other geologists, (e.g. Bailey, 1935; Sabine, 1953), the general review of the Moine Thrust Belt in the Assynt District published by Elliot and Johnson in 1980 was the first in considering the modern concepts on thrust tectonics developed in the Canadian Rockies and the Appalachians. These authors used the map of the Geological Survey (Peach *et al.*, 1907) for their work to discussed on some of the more controversial aspects of the area and included a balanced cross section of Central Assynt.

However it has been Coward and co-workers who have produced the main investigation of the Assynt District and of Northern Assynt in particular. Their investigation was based on the detailed re-mapping of the area and on strain measurements (Kim and Coward, 1981; Coward, 1982, 1984, 1985; Coward *et al.*, in press).

One of the main conclusions derived from this recent work has been the reinterpretation of certain previously considered thrust structures, as extensional faults, and the discovery of new (extensional) faults. This fact led Coward (1982) to define the "surge" zones, which are described as being large- scale avalanche structures bounded by arcuate contractional faults in the front, and by irregular arcuate extensional faults to the rear. The whole surge zone would have appeared to have suffered an extensional displacement in the direction of the tectonic transport, moving considerably further than adjacent areas. Coward (1982) explained these structures as due to the gravity spreading of the thrust belt in response to the decrease of the basal strength of the wedge.

Another important result obtained in the aforementioned works has been an hypothesis for the observed obliquity of the structures in Northern Assynt. This hypothesis has mainly arisen from the analysis of the worm burrows ("pipes") contained in the Pipe Rock Unit. The "pipes" remain normal to bedding and circular on the bedding plane in the undeformed rock, and therefore provide ideal strain markers for estimating layer parallel strain ratios and layer parallel shear (Coward and Kim, 1981).

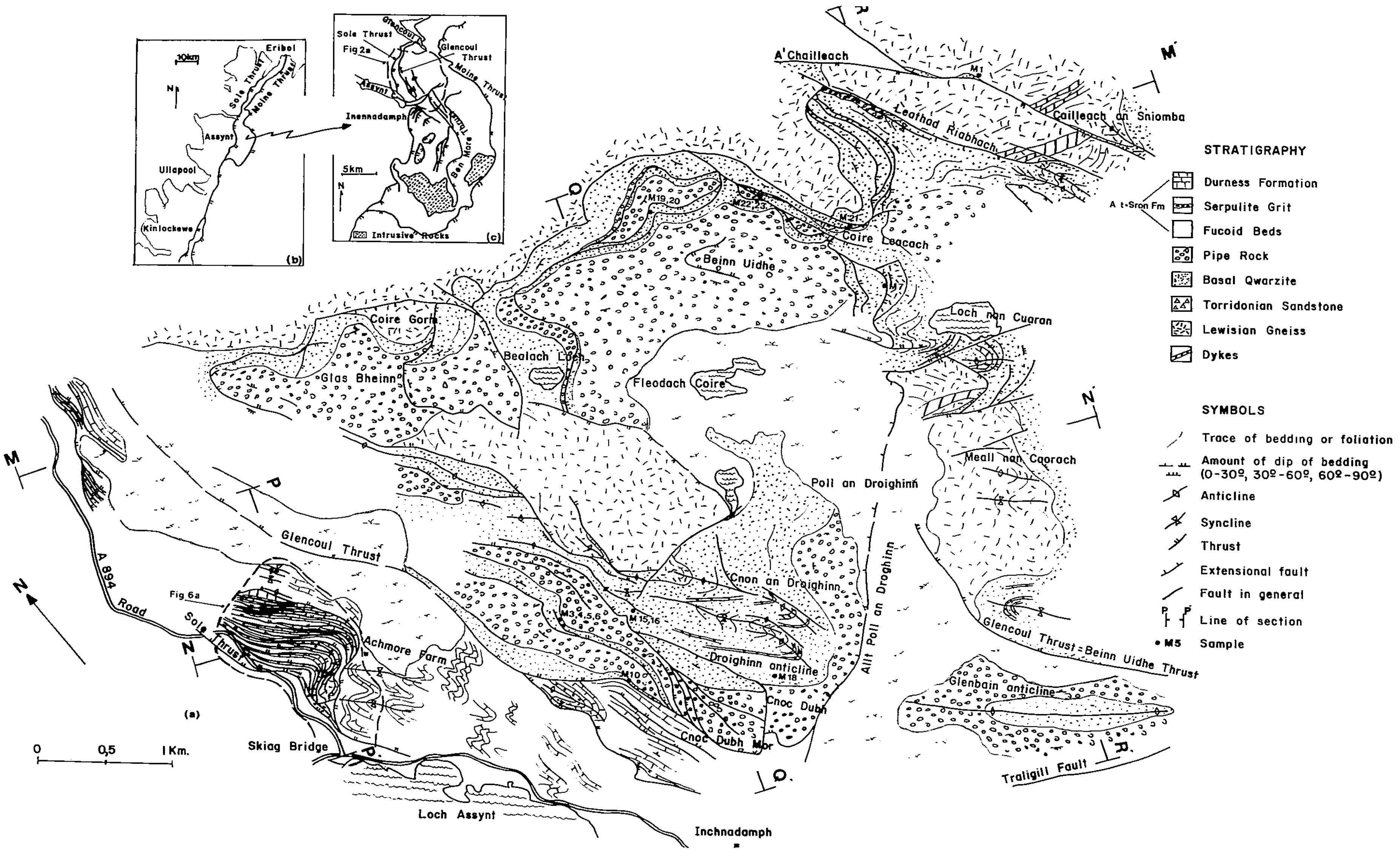

Fig. 2.-(a) Geological map of the area studied in the present paper, sketched and slightly modified from Coward (1981, 1982, 1984) and from unpublished data of the same author. M-M', N-N', P-P', Q-Q' and R-R' are the lines of the sections shown in Figs. 3, 5, 6 and 7 respectively. The names refer to localities or structures mentioned in the text. (b) Location map for NW Scotland. (c) Simplified map of Assynt. (b) and (c) are taken from Coward (1982).

Fig. 2.-(a) Mapa Geológico del área tratada en el presente artículo, simplificado y ligeramente modificado de Coward (1981, 1982, 1984) y de datos inéditos pertenecientes al mismo autor. M-M', N-N', P-P', Q-Q' y R-R' son las líneas de las secciones representadas en las figuras 3, 5, 6 y 7 respectivamente. Los nombres se refieren a localidades o estructuras mencionadas en el texto. (b) Mapa de localización del Noroeste de Escocia. (c) Mapa simplificado del distrito de Assynt. Las figuras (b) y (c) se han extraído de Coward, (1982).

The folds in Northern Assynt vary in trend from N-S to NW-SE. On the bedding surfaces, the "pipes" are elliptical with their long axes also trending NW-SE or N-S (Coward and Kim, op. cit). However the ellipses long axes are not always parallel to the fold axes but trend more N-S, thus, changing orientation slightly around the folds. This discordance between ellipse axes and fold axes has suggested to Coward and Kim (1981) a rotational component to the strain, in the bedding plane section. These authors described how to separate these strains into two components; (1) layer-parallel shortening and (2) shear strains on planes normal to the main thrust plane but with the same movement direction as the main bedding - parallel thrust shear. The same authors proposed then, a wide zone of differential sinistral movement as the ultimate cause for the development of the oblique trend of the structures in Northern Assynt.

In addition, Coward (1982, 1983, 1984, 1985) interprets a "piggy- back" thrust sequence as the general model of thrust development for the whole Assynt District and in particular for Northern Assynt within which the previously "anomalous" extensional and rotational features would be included. The thrust transport direction is supposed to be to the WNW, as determined from the trend of tear faults.

3. STRUCTURAL ELEMENTS OF NORTHERN ASSYNT

In Northern Assynt several main structural features can be distinguished (Fig. 2). Regionally speaking, apart from the Moine Thrust s.s. which outcrops farther to the east, three major thrusts have been considered which are, from west to east, the Sole, the Glencoul Thrust and the Ben More Thrust. Another structure, the Beinn Uidhe Thrust has been inferred by some of the workers to be a splay of the Ben More Thrust. The trace and lateral continuity of these thrusts has been a cause of controversy, especially in the area to the NE of Inchnadamph, where the Glencoul Thrust, the Beinn Uidhe Thrust and other adjacent structures have been interpreted in very different ways.

In between the Sole and The Glencoul Thrusts an imbricate stack of Cambro - Ordovician structures may be recognized (Fig. 2). This stack may be broadly separated into a lower duplex consisting of a large number of imbricate slices bearing Fucoid Beds, Serpulite Grit and Durness Limestone, and an upper duplex exclusively carrying slices of Durness Limestone.

Other distinctive structures of Northern Assynt are two large anticlines trending NW-SE and outcropping to the E. of Inchnadamph and lying next to each other. These are the Droighinn and the Glenbain anticlines (Fig. 2) and their relationship is intimately linked to the interpretation for the development of the Glencoul Thrust. Close to these anticlines there are two major outcrops of Lewisian basement (Fig. 2). One of them, the westernmost, is underneath the Basal Quartzite of the Droighinn anticline and therefore, forms the core of this structure. The other Lewisian inlier, outcropping in Meall nan Caorach is seen in the basement of the Cambro-Ordovician sequence of Beinn an Fhurain and overthrusts the Glenbain Anticline. Classically, these two outcrops have been considered by different workers as distinctive slices of basement separated by the Beinn Uidhe Thrust. However, it will be seen later that new reinterpretations identify these two slices as belonging to a larger unit which would have been splayed by an extensional fault, the easternmost part being incorporated to a surge zone (as defined and described by Coward, 1982).

Further to the north, the Glas Bheinn - Beinn Uidhe ridge is the southern limit of a vast outcrop of Lewisian basement. Along this ridge, interesting structures are exposed in section and this is possibly the best place in Northern Assynt to observe the relationship between extensional and compressional features.

Within this framework, two principal lines of section have been studied: the Glas Bheinn -Beinn Uidhe Section and the Cnoc an Droighinn section.

4. THE GLAS BHEINN - BEINN UIDHE SECTION

This Section, (M-M' in Fig. 2) has been drawn along the Glas Bheinn - Beinn Uidhe - Leathad Riabhack line, from the Sole Thrust, (which doesn't outcrop clearly but is supposed to be sited close to the A894 road) to the vicinity of Gorm Loch Mor. In this last locality the trace of the Ben More Thrust (which is easily recognised on the slopes to the south), is lost or at least is not as readily identified. It is assumed plane strain along the section (for simplification it will be called the Beinn Uidhe section) as it is parallel to the tectonic transport direction.

The partially balanced and restored cross section is presented in Fig. 3. Three main problems have arisen during the construction of the section. One is the evaluation of the displacement suffered by the Glencoul sheet. The other is the calculation of the shortening that took place in the Cambro -Ordovician cover, shortening that should have occurred before the emplacement of the Glencoul sheet and is most probably linked to the movement of previous thrusts (Ben More and/or Moine Thrusts). Another problem to be considered in this section is the presence of faults with very steep outcrop, which dramatically disrupt both the Cambro - Ordovician cover and the Lewisian Basement. Some of these faults are very obvious back-thrusts and are believed to have developed by taking advantage of previous extensional features. These three aspects will be now discussed in the same order that they have been presented.

The displacement of the Glencoul sheet cannot be deduced from the section because there is little or no outcrop of the overthrust units and it is necessary for the whole overthrust sequence to be observed before a

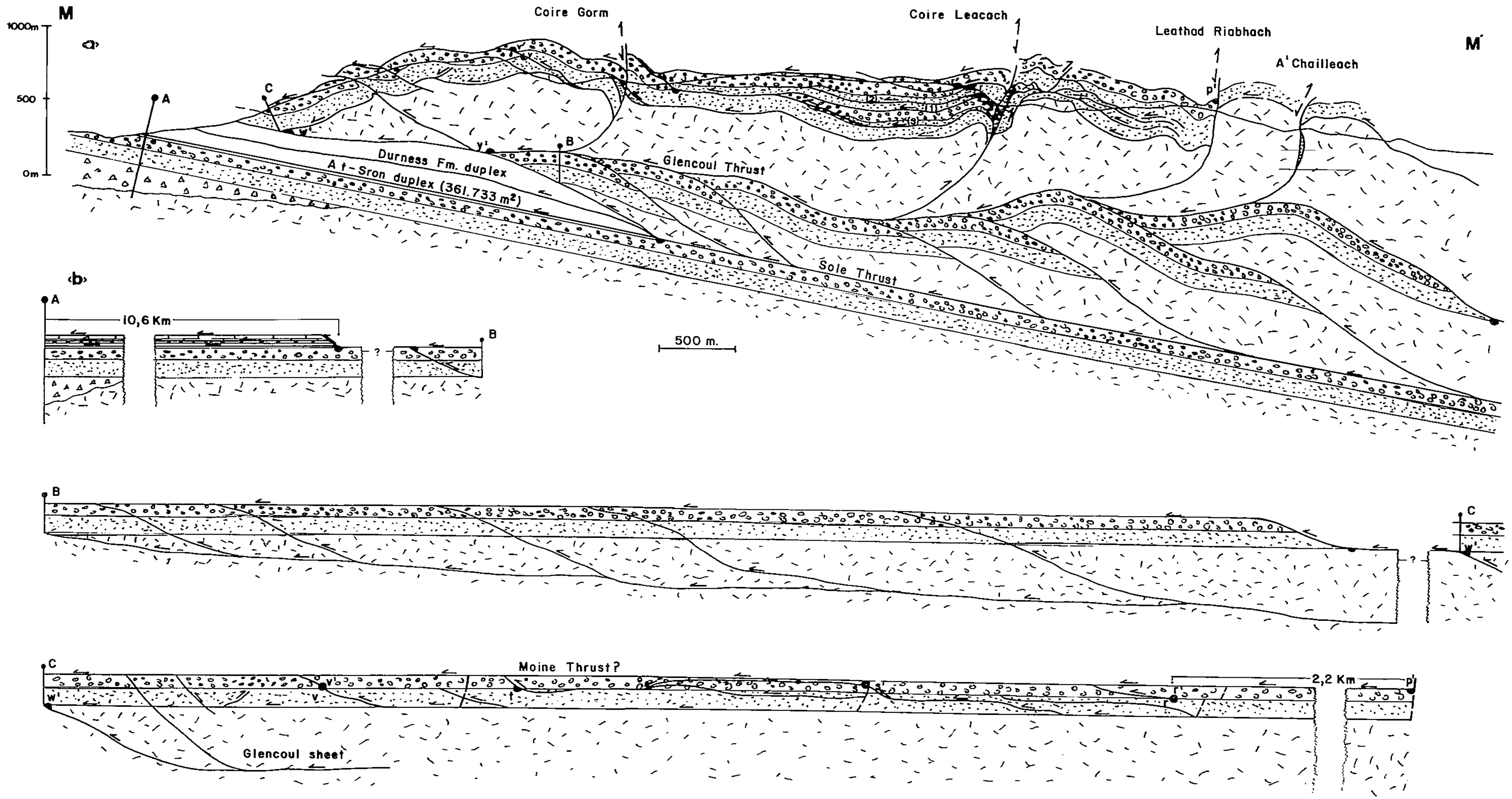

Fig. 3.-Beinn Uidhe Section (M-M' in Fig. 2a). (a) Partially balanced cross section. (b) Restored section. The estimated original length of the A t-Sron and Durness duplexes for the area shown in the deformed state (a) is 10.6 Km, which gives a shortening of 66 %. This calculation, made by the area balance method, is only orientative because the trailing edge(s) (point z) and structural thickness(es) of the duplex(es) are not known. The geometry of the imbricates (y'-x) underneath the Glencoul sheet is purely speculative and is so chosen just to accommodate the extensional features in the overlying sheet. The shortening suffered by the Cambro-Ordovician cover of the Glencoul sheet is 37 % between the C and r-r' reference points, and 41 % between r-r' and p'. See text for further discussion. (Symbols as in Fig. 2).

Fig. 3.-Sección del Beinn Uidhe (M-M' en la Fig. 2a). (a) Sección parcialmente compensada. (b) Sección restituída. La longitud original de los duplex formados por la formación A t-Sron y la caliza Durness estimada a partir del área medida en el estado deformado (a) es 10.6 Km, lo que implica un acortamiento del 66 %. Este cálculo, realizado por el método de la compensación de áreas, es simplemente orientativo puesto que el extremo(s) posterior(es) (punto z) y el engrosamiento(s) estructural(es) de los duplex son desconocidos. La geometría de las imbricaciones (y'-z) bajo la escama del Glencoul es puramente especulativa y ha sido así dibujada para acomodar las estructuras extensionales en la escama suprayacente. El acortamiento sufrido por la cobertera Cambro-Ordovicica de la escama del Glencoul es del 37 % entre los puntos C y r-r' y del 41 % entre r-r' y p. Ver texto para mayor discusión (Símbolos como en Fig. 2).

true determination of the overall displacement can be achieved. An attempt has been made, by the method of the area balance (Hossack, 1979), to evaluate the minimum displacement that could have taken place in the duplexes between the Sole and the Glencoul thrusts. The extent of these duplexes to the east, underneath the Glencoul Thrust, is not known and so, any suitable lengths are chosen.

For the length of the lower duplex, (in the deformed state) shown in Fig. 3a, the area measured on the section is 361.733 m^2. In this lower duplex an average thickness of 25 m of Fucoid Beds and 9 m of Serpulite Grit is supposed, for each slice. No Durness Limestone is considered to be involved in this lower duplex as its thickness is negligible. Therefore, the minimum original length of this lower duplex should be 10.6 km. As the assumed length of the lower duplex in the deformed state is 3.6 km, the resulting shortening would be 66%. This shortening would not represent the total amount of the displacement along the Glencoul Thrust but merely a proportion of it.

The upper duplex underneath the Glencoul Thrust exclusively consists of imbricates of Durness Limestone. It is assumed, for convenience, that this upper duplex suffered the same shortening, and at the same time as the lower one. From this assumption, considering its area in the deformed state (Fig. 3a), the average thickness of the Durness Limestone necessary to build up such a duplex is calculated. This thickness is found to be 34 meters which is in agreement with the field observations as only the lower (Ghurdaidh) member of the Durness Formation is present.

Without any outcrop only these kind of estimations can be done. However, as will be described later, in the easternmost part of the Cnoc an Droighinn section the excellent outcrop of the lower duplex allows more accurate calculations, which happen to match quite well in the one above.

The only estimations of the displacement suffered by the Glencoul Thrust come from the correlation of Lewisian structures between the Glencoul sheet and the foreland. Using this method, the correlation of a steeply dipping shear zone (the Laxfordian Front, Fig. 1) and other late Laxfordian structures, indicated to Coward *et al.* (1980) an estimate of 25-33 km for the displacement of the Glencoul Thrust. Using the same method but different Lewisian structures, Elliot and Johnson (1980) estimated a maximum of 21.5 km for the same displacement.

Another important feature that the detailed geological mapping revealed along the Beinn Uidhe section, is the imbrication suffered by the Cambro - Ordovician cover. These strong imbrications do not involve the basement which obviously suggests that the unconformity above the Lewisian gneisses is used as the detachment for the imbrication. Besides, it has been observed that any bedding surface may be a good detachment level.

The imbricates are easily observed on the Northern slopes of the Glas Bheinn but are seen mainly on the slopes of the Beinn Uidhe ridge itself (Fig. 2). The beds are usually seen to be dipping to the SSE between 5° and 30°. This allows for a good exposure of the structures. Although variable, the fold axes have an average plunge of 10° towards N190°. Thus, the general attitude of the bedding along the ridge is only disrupted where the steep faults, that will be described later, cut across both the basement and the cover. In that case the fold axes acquire a new imposed attitude, subparallel to the faults. For example, the folds in the vicinity of the Coire Leacach and the folds linked with the Leathad Riabhach fault plunge on average to 10° towards N165°.

The change of attitude of the folds along the whole section has to be considered when projecting the data on to the plane of section. In the Beinn Uidhe section therefore, the two different attitudes of the fold axes have been used correspondingly to project the data, being aware of the fact that the plunge of projection is an average and may need some eventual corrections.

The Basal Quartzite - Pipe Rock duplex has been restored and is shown in Fig. 3b. From the pin line C to the Coire Leacach fault, the line length method gives a minimum shortening of about 37%. This shortening refers only to the piling up of imbricates between the Glas Beinn and the Coire Leacach. The small imbricates of the western slopes of the Glas Beinn have their origin in the later extensional movements and are not included in this shortening. This extension and subsequent contraction, achieved by the movement of the major steep faults, is not believed to be very important along this section.

It is difficult to link the imbricate structure on the western side of Coire Leacach to that on the eastern side because it is not possible to identify the same stratigraphic level or structure on both sides. So, although the imbricate structure on the east side of the Coire Leacach has actually been projected onto the section, no line length restoration has been attempted. Instead, an area balance restoration has been attempted since there is an actual thickening of the sequence. This gives 41% shortening for this particular portion, which has to be added to the previous estimation.

The restoration of the imbricates west to the Coire Leacach show how the thrust which has achieved the main displacement marked (1) in Fig. 3a, cuts down section at a certain stage. The thrust marked (2) is considered as being formed more or less at the same time as (1). This represents a small detachment with minimal displacement. Underneath these two thrusts, a third thrust (3) developed with a maximum displacement of 200-300 metres. Previously formed thrusts can be recognized in upper levels, (e.g. at r-r'). Thus a piggy back model, with some complications seems to fit the evolution of this duplex.

The thrusts have progressed taking advantage of the bedding, generating very long flats as well as relatively long and shallow ramps. The hangingwalls usually develop gentle anticlines along their length, as a result of the accommodation of the beds above the thrust surface. That is to say that they may be regarded as fault-bend folds rather than fault-propagation folds (Jamison, 1986). On a smaller scale, many thrusts, back-thrusts and triangle zones, with displacements in the order of a few meters or centimeters, have been recognized.

These small scale thrusts, although individually do not produce much shortening, as a whole they may represent one of the main mechanisms of shortening and thickening. If considered within a larger scale process as is the evolution of a thrust belt, they represent individual features of a cataclastic flow deformation mechanism.

Cleavage is also seen as a small scale structure within the imbricates. It usually appears in patches in the form of a spaced fracture cleavage. Only locally, in areas where high strains are typical is a more pervasive and well defined cleavage found, trending subparallel to planes normal to the bedding and the tectonic transport direction.

The steep faults which cut across both the basement and cover have been already described by Coward (1981, 1982, 1984). Four of these structures are recognized along this section. These are, from west to east, the Coire Gorm fault, the Coire Leacach structure and the Leathad Riabhach and A'Chailleach faults (Figs. 2a and 3a). Coward (op.cit.) interpreted two of these structures, (the Coire Gorm and the Leathad Riabhach) as extensional faults which bounded different surge zones of varying size.

Coward (1982, Fig. 11) links the Coire Gorm fault to a small surge zone situated on the Glas Beinn and the Leathad Riabhach fault to another surge zone, which would occupy an important area of Northern Assynt and is much larger than the above mentioned structure (Coward, 1982, Fig. 9 and 10). Both faults bound their respective surge zones at their trailing edges and would carry associated roll over folds which are especially well exposed in the Leathad Riabhach structure.

According to the mapping evidence, the other two faults are described by the same author as back-thrusts. No further details about them are given, although it is pointed out that their timing (with respect to the extensional structures) is not clear.

This general interpretation is covered briefly in the present work. Certainly, both the extensional features and the back-thrusts are present in the section. The slabs of Lewisian gneiss overthrusting the Basal Quartzite al Coire Leacach are especially dramatic, as well as the extensional feature at Leathad Riabhach, with its well marked roll over folds. The same pattern, although not so well exposed occurs at Coire Gorm where there is observed a back-thrust of Lewisian gneiss over Basal Quartzite. The mapping also reveals an extensional contact between the two lithologies, including a roll over anticline.

Therefore it is proposed that the aforementioned structures are the consequence of the superimposition of a compressional event on a previous extensional one. This later compressional event would have mainly reactivated the pre-existent extensional structures, tightening the roll over associated folds, and would have produced back-thrusts as the new compressional structures.

The tightening of the structures is not exclusive of the Cambro - Ordovocian sequence. The portions of Lewisian basement outcropping in between the steep faults are not simply uplifted blocks but bulges or folds of large radius. Actually, the Cambro - Ordovician cover appears accommodated to those bulges. The Lewisian foliation is usually vertical or very steep and therefore cannot reflect this bulging. However, when the foliation is shallower a tendency for it to be folded around the hinges of these bulges can be observed, as happens to the south of the western side of the A'Chaileach fault (Fig. 2).

The existance of these folds and the bulging observed along the Beinn Uidhe Section suggests that throughout the development of thrusting and subsequent extension and tightening, at least at certain stages, the Lewisian basement has behaved, rheologically, in a ductile manner. The term ductile, as suggested by Rutter (1986) is used in the context of the ability to accommodate large, non localized strains. Quite often, the Lewisian gneiss shows small scale thrusts and a pervasive cracking in the same way as explained for the Cambian cover. Therefore it is suggested that the bulging or folding of the basement, which is a ductile behaviour (in the sense described previously) would be achieved by small scale cracking or microthrusting which is a brittle mode of deformation. The scale of the cracks and microthrusts, may be of the order of some meters or tenths of centimeters.

More specifically, the large radius folds of the Lewisian basement can be classified as back-folds in the sense that they face towards a direction opposite than that of the tectonic transport, usually showing the western limb to be steeper. The back-folding is revealed in surface by the attitude of the bedding in the Cambro - Ordovician sequence and is not only present on the Beinn Uidhe Section, but also further to the south on the eastern slopes of the Meall nan Caorach and the eastern edge of the Lewisian gneiss outcrop to the west of Fleodach Coire, where there is a clear tendency for the basement to overthrust the Basal Quartzite.

The aforementioned low angle extensional faults have been predicted by Davis, Suppe and Dahlen (1983) in their Acretionary Wedge Model. They are considered to bound zones of gravitational extensional flow where the frontal part of the thrust zone has moved further than its hinterland. Such extensional movements would result in the decrease of the surface slope to the thrust wedge thereby decreasing the taper angle of the wedge.

Coward (1985) applies the Davis, suppe and Dahlen (1983) model in the Assynt District where the geological mapping and the balanced sections outlines the fact that the Sole Thrust must have climbed from Lewisian gneisses to Cambrian sediments, assuming correctly that, the strength of the Lewisian rocks is much greater than that of the shaly mid-Cambrian rocks and the Durness Limestone. The climbing up of the whole wedge along its Sole, from the former to the later, would imply a decrease in the basal shear strength at the base of the wedge, and therefore the onset of the extensional faulting (Coward, 1985) (Fig. 4).

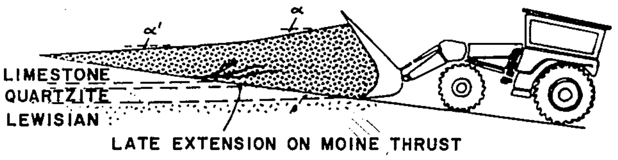

Fig. 4.-Cartoon to show the development of extensional structures by the collapse of a thrust wedge with a weak basal shear strength (modified after Davis, et al., 1983). (From Coward, 1985).

Fig. 4.-Esquema que muestra el desarrollo de estructuras extensionales por el colapso de un cuña orogénica que avanza con una débil resistencia a la cizalla basal modificada de Davis *et al.,* (1983). (Extraida de Coward, 1985).

More in detail, the localization of these normal faults must be ruled by the shape of the underlying structures. Thus they would develop above antiformal structures, the extensional sheet or surge zone taking advantage of the "slopes" of their "forelimbs" to slide down. The antiformal structures would be imposed by the shape of the proper sheet or achieved as a result of the accretion of imbricates beneath.

This last hypothesis has been systematically used in the cross section (Fig. 3a) to fill the gap between the Glencoul sheet and the Sole. The shape of the duplex drawn to fill this gap is conditioned by the localization of the bulges and major extensional features on the overlying Glencoul sheet. The imbrication of each slice within this duplex would cause the folding of the Glencoul sheet which, at a certain stage would fail in an extensional manner in order to achieve the equilibrium for the whole wedge. This sequence of events would be repeated several times as the whole complex progresses forward. The Glencoul Thrust would act passively or could attain some or the whole of the displacement of every single imbricate of the duplex and would be not only the roof thrust for that duplex but also the surface where all the extensional features would rejoin at depth.

In a similar way the subsequent compression may be explained as a sudden and relevant increase on the basal shear strength of the wedge. This might have caused the eventual pinning of the leading edge of the wedge and as a consequence, the tightening of most of the previous structures and the reactivation of the major extensional faults as back-thrusts.

5. THE CNOC AN DROIGHINN SECTION

This is the other section studied in detail in the paper. The line of section is shown as N-N' in Fig. 2 and the section itself in Fig. 5a. The section runs parallel to the assumed direction of tectonic transport from the A894 road near the Achmore Farm in the west, to the Meall nan Caorach slopes in the east. This precise line of section has been chosen because at the western end it crosses the maximum thickness of the imbricates underneath the Glencoul Thrust. Further to the east, the structures are not too oblique and are very nearly perpendicular to the line of section. Although the surface data have been taken on that line of section, the structures outcropping in the surrounding areas have also been considered and, when necessary, projected onto the plane of the section.

The main problem that has arisen in the construction of this cross section, is that of the obliquity of the structures to the regional tectonic transport direction and therefore with respect to the line of section as well. This problem is especially serious at the western end where the lower duplexes of the Upper Cambro - Ordovician sequence underneath the Glencoul Thrust are very well exposed trending to the NNW, oblique to the line of the section.

These duplexes have already been described by Coward (1984) who divided the imbricates underneath the Glencoul Thrust into three individual duplexes or systems, A, B and C, as shown in Fig. 5a and 6. The system A consists exclusively of imbricates of Durness Limestone and its roof thrust is the Glencoul Thrust. In the system B most of the imbricate slices carry Fucoid Beds, Serpulite Grit and Durness Limestone. The roof thrust of system B is considered to be the floor thrust for system A. The system C is the lowermost one and only carries a few imbricates, consisting mainly of Fucoid Beds and Serpulite Grit. The roof thrust of system C then, is the floor thruts for system B, and the floor thrust of system C is the Sole Thrust.

These duplexes have been interpreted by Coward (op. cit.) to form a piggy-back sequence. Thus, system B produces an obliquely trending culmination, folding the structures of system A (Fig. 2 and 6) and similarly the floor to system B is affected by folds produced in system C. The imbricates of system B themselves are supposed to have developed by the regularly spaced collapse of an obliquely trending footwall (i.e. oblique to the regional tectonic transport direction) to the overlying thrust system. As explained before, the oblique nature of the footwall collapse and hence the development of an oblique duplex zone is suggested by Coward (op. cit.) to have been due to the combination of a sinistral shear couple with the shear due to the thrust movement. The sinistral shear couple would have its ultimate cause in the differential movement of the Glencoul sheet.

The structure shown in Fig. 6a (taken from Coward, 1984) is supposed to be a down plunge view of systems B and C. The folded pattern of the imbricates would be a consequence of the stacking of imbricates in a footwall collapse fashion developing each time a fault-bent fold that is reflected on the overlying sheets. However, occasional fault-propagation folds have also

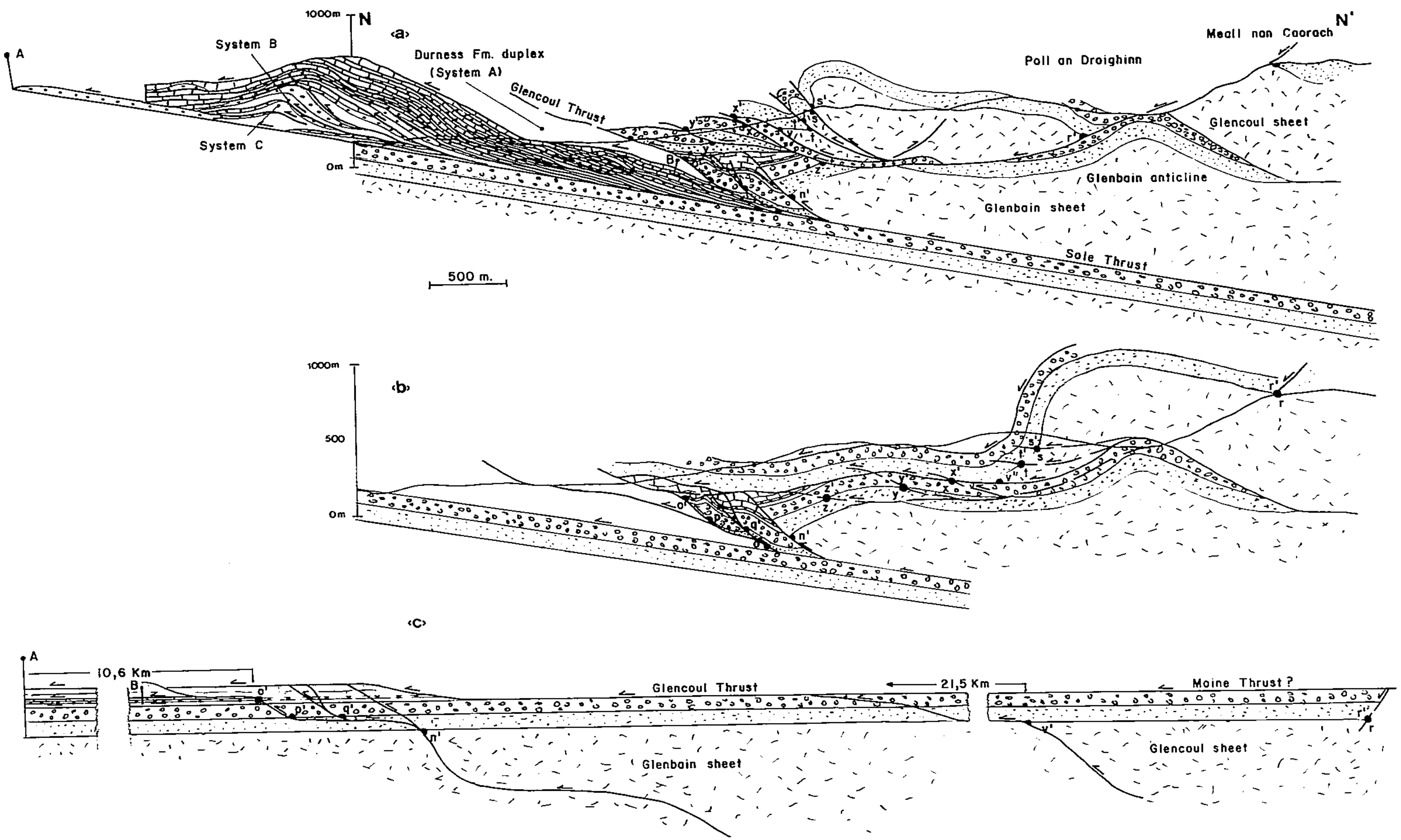

Fig. 5.-Cnoc an Droighinn Section (N-N' in Fig. 2). (a) Partially balanced cross section. B and C duplexes have been projected onto the plane of section from Fig. 6a but are not balanced. The eastern part of the section follow the idea of a later extensional displacement of the Glencoul sheet. The lower slices above the Glencoul thrust are considered to have been rooted out from an underlying antiformal structure (Glenbain sheet). (b) Speculative geometry just before the extensional movement. The extensional movement would have been induced by the antiformal shape of the underlying Glenbain sheet. The α supposed offset of the trailing edge of the surge zone (r'-r) would be 1.3 Km. (c) Restored section. The expected restored length of the B and C duplexes along this section (10.6 Km) is calculated from section P-P', using Cooper (1983) correction, ($\alpha' = 75°$) (see text for discussion). Therefore, the total displacement of the Glenbain sheet would be, at least, equivalent to the shortening suffered by the B and C duplexes. See text for further discussion. (Symbols as in Fig. 2).

Fig. 5.-Sección del Cnoc an Droighinn (N-N' en la Fig. 2). (a) Sección parcialmente compensada. Los duplex B y C han sido proyectados sobre el plano de la sección a partir de la figura 6a, pero no están compensados. La parte oriental de la sección sigue la idea de un desplazamiento extensional tardío de la lámina del Glencoul. Las esquirlas inferiores por encima del plano de cabalgamiento del Glencoul se consideran arrancadas de la estructura anticlinal infrayacente (lámina del Glenbain). (b) Geometría especulativa justo antes del movimiento extensional. El movimiento extensional estaría reducido por el desarrollo de un anticlinal en la lámina infrayacente del Glenbainn. El desplazamiento de la parte trasera de la masa deslizada (r'-r) es de 1.3 km. (c) Sección restituída. La longitud de los duplex B y C a lo largo de esta sección (estado previo a la deformación) es de 10.6 km, y se ha calculado a partir de la sección P-P' usando la corrección de Cooper (1983), siendo $\alpha' = 75°$. Por lo tanto, el desplazamiento total de la lámina del Glenbain será, al menos, equivalente al acortamiento sufrido por estos duplex. Ver texto para mayor discusión. (Símbolos como en la Fig. 2).

been recognized. In that case an obvious cleavage is associated with the folding, produced as a consequence of the strains developed at the tip of the fold.

The average plunge of the structure of Fig. 6a is 25° towards 13° as measured in the core of the culmination. However this plunge varies very quickly as it corresponds to a fold formed by the stacking of imbricates and not by buckling. The variations are both lateral, that is to the NE and SW, and longitudinal, to the NW and SE. In general, the plunge seems to become more moderate, in between 5 and 10 degrees, in all these directions.

For balancing purposes, the structure obtained in the section parallel to the regional tectonic transport direction (Fig. 5a) is not valid. The line length restoration of the structure, because of its obliquity with respect to the plane of the section, would give an unduly exagerated initial length of the shortened bed(s).

Cooper (1983) shows the way to calculate the strain in a section normal to the regional orogenic direction, from the measurements obtained in an oblique section and vice versa. The method assumes that the transport direction is perpendicular to the orogenic strike and that the normal section displays plane strain.

Cooper simulated the relations between e and e' (bulk shortenings in the normal and oblique sections respectively) for various values of α' (angle of obliquity in the deformed state) and constructed a graph that can be used to correct values of bulk shortening from oblique sections.

It is deduced that the reverse path can be followed as well. That is, knowing the bulk shortening in the normal section, the shortening in any oblique direction can be calculated. High values of a' need large corrections especially at low values of bulk strain. The gradients of the a' curves mean that lower values of bulk strain will be subjected to a larger percentage correction than higher values.

This method has been followed in the present work to calculate the shortening in the B and C duplexes. However some previous assumptions must be made. Although Coward (1984) believes that the later (lower) imbricates of system B and the whole system C do not show evidence of the sinistral couple and therefore should not be regarded as formed by the collapse of an obliquely trending footwall, it is believed and assumed here, that the whole B and C duplexes have actually been developed due to the spaced collapse of an obliquely trending footwall. Another assumption is that this collapse has occurred in one uniform direction which will be chosen as a "local" transport direction for the development of duplexes B and C.

Considering these assumptions, a section normal to the structures (Fig. 6b) will fullfil the requirements of containing the "local" transport direction and plane strain and therefore the structures can be balanced in that direction. The variable nature of the culmination as explained previously does not allow a fixed ideal direction normal to the structures. Furthermore, the hinge of the culmination is progressively displaced towards the NNE as the imbricates are accreted underneath. N040° has been chosen as the direction normal to the structures. However the section across the structure has been done following a N20° trend as in that direction the whole structure can be crossed, within a single section. The difference of 20° is small enough to guarantee not much distortion, and the method described previously can be used for correction.

The balanced section (following a N20° direction) of the duplexes B and C is depicted in Fig. 6b (P-P', in Fig. 2). The Sole Thrust remains horizontal as corresponds to a section subparallel to the strike of the beds in the foreland. The Serpulite Grit can be used as a good reference bed. The lengths of the lowermost slices are constrained because each slice shows its respective footwall and hangingwall cut offs. The lengths of the other sheets have been chosen arbitrarily, in part imposed by the structure formed underneath, and also trying to accomplish the folding shown by the overlying Durness Limestone duplex (System A). In the same figure (6 b, c) the length of the Serpulite Grit both in the deformed and in the undeformed states can be measured. The total length of the structure in the deformed state is 1.701 meters and the original "undeformed" length taken from the restoration is 7.749 meters. Therefore, the shortening measured in the 20° oblique section (N20°) is 78%. Now, applying Copper's method it can be calculated the total "deformed" and"undeformed" lengths of the structure in the normal section (N040°; α' = 20°). These are, respectively, 1.598 and 7.749 meters (see Hernaiz, 1988, for futher details). Notice that for large shortenings and small differences (α' = 20°) between the trend of the normal section and the trend of the oblique section in the deformed state, the undeformed lengths remain unvariable, and therefore the shortening hardly suffers any change (80%).

From this data the shortening in any other direction can be calculated. For example, in the direction of the tectonic transport (N295° = N115°; α' = 115 - 40 = 75° a 40 % of shortening should be expected. It isalgo deduced that the "deformed" and "undeformed"lengths of the structure in this new oblique section, are,respectively, 6.392 and 10.659 meters.

Because of the limitations given previously, thesecalculations have to be taken as aproximate. However, the data obtained before provide a certain constraint for thedrawing of the oblique section. In other words, the section of the B and C duplexes depicted in Fig. 5a has been drawn trying to fit the deformed lenth of the structure (6.392 m aprox.) obtained by means of Cooper's method.

The B and C duplexes as a whole, form a mixture of an antiformal stack and a hinterland dipping duplex (Fig. 6b). The C duplex itself can be regarded as a foreland dipping duplex. The hinterland dipping feature is depicted in the uppermost sheets; the antiformal stack is formed by the sheets in the middle of the structure, and as stated previously, the duplex C presents a foreland dipping pattern. Therefore it seems that the ratio

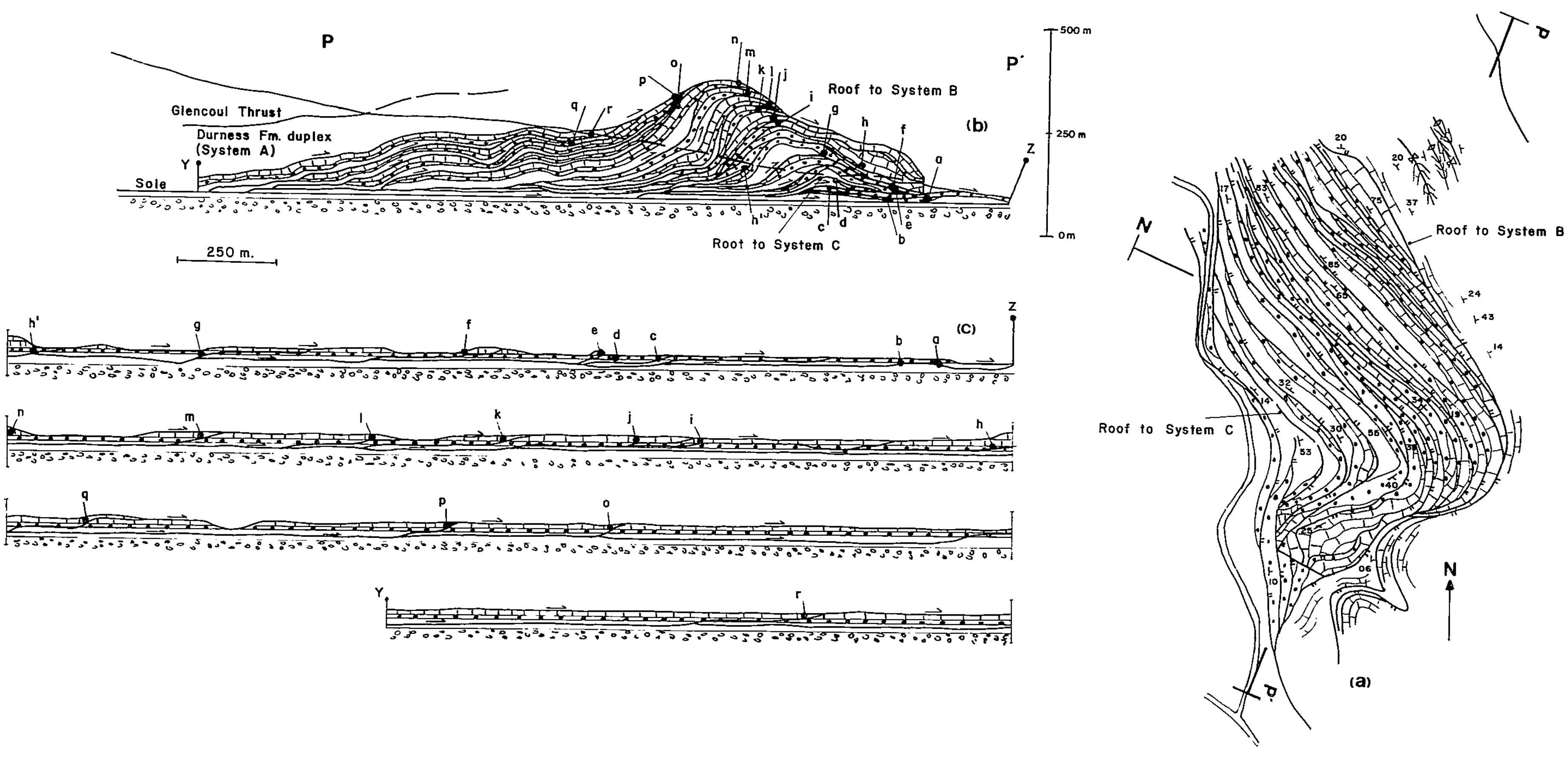

Fig. 6.-Section of the B and C duplexes underneath the Glencoul sheet (P-P' in Fig. 2). (a) Enlarged geological map of the B and C duplexes near Achmore Farm (From Coward, 1984). (b) Balanced cross section of the structure shown in Fig. 6a. It is assumed that the imbricates have developed from the pervasive collapse of an oblique trendig footwall (Coward, 1984) and that plane strain is conserved in a section perpendicular to the trend of the oblique footwalls. However, for convenience this cross section is slightly oblique (N20°; $\alpha' = 20$) to the 'normal' section (N40°; $\alpha = 0$). (c) Restored section. The length of the duplex in the deformed state (b) is 1.7 km; the restored length is 7.7 km. Therefore, the shortening (minimum) shown in the section is of 78 %. Using Cooper (1983) correction, shortenings of 80% and 40% respectively should be expected along a 'normal' section and a section trending parallel to the general transport direction. These estimations may give an idea of the extension of the duplexes underneath the Glencoul sheet, in any direction. See text for discussions. (Symbols as in Fig. 2).

Fig. 6.-Sección de los duplex B y C bajo la lámina del Glencoul (P-P' en la Fig. 2). (a) Mapa geológico ampliado de los duplex B y C cerca de Achmore Farm (Extraído de Coward, 1984). (b) Sección compensada de la estructura de la Fig. 6a. Se asume que las imbricaciones se han desarrollado por el progresivo colapso de un bloque de muro con dirección oblicua a la del transporte tectónico regional, y que hay deformación plana en una sección perpendicular a la dirección de los bloques de muro oblicuos. Sin embargo, por conveniencia la sección es ligeramente oblicua (N20°; $\alpha = 20$) a la perpendicular (N40°; $\alpha = 0$). (c) Sección restituída. La longitud del duplex en el estado deformado (b) es de 1.7 km; la longitud restituída es de 7.7 km. Por lo tanto el acortamiento (mínimo) es de 78%. Usando la corrección de Cooper (1983) se debe esperar acortamientos del 80% y 40% a lo largo de una sección perpendicular y de una sección paralela a la dirección de transporte tectónico regional, respectivamente. Estas estimaciones sirven para dar una idea de la extensión de los duplex bajo la lámina del Glencoul, en cualquier dirección. Ver texto para discusión. (Símbolos como en Fig. 2).

length of horses/displacement increases as the imbrication progresses. In general, the same can be said about the displacement itself although this is not absolutely certain as the upper sheets are longer than the lower ones. In any case, the B and C duplexes denote an easy slippage along the thrusts, certainly increasing as the process develops. This slippage may be related to the decrease in shear strength needed for the extensional structures to develop, as proposed by Coward (1985).

Another feature exposed on section P-P' (Fig. 6b) is the occasional anomalous paths followed by the thrusts, in the sense that sometimes they appear cutting down section for a certain length, quickly recovering the "correct" pattern of cutting up section. This feature is shown by some of the thrusts within the B and C duplexes, mainly when the slip along or through the Fucoid Beds. This pattern is especially followed by the roof thrust of system B, (Fig. 6b). This thrust, which formerly worked as a floor for system A, has left individual pods of Durness Limestone of a maximum thickness of 30 meters and an average of 10 metres, as it has overridden the underlying sequence. This means that it passed from cutting up to cutting down sequence quite easily although most of the time it followed a bedding parallel surface (flat), about 10 meters at above the base of the Durness Limestone.

The thrust pattern displays cutting up and down sections however most of the time it follows flats. This pattern has already been described for the imbricates of the Cambro - Ordovician cover along the Beinn Uidhe ridge. In both cases the bedding is very well displayed and becomes the main surface along which the thrusts develop and progress. Therefore, the anomalous described pattern should probably not be considered so in such well bedded lithologies.

In the central and eastern portions of the Cnoc an Droighinn section (Fig, 5a) the strike of the structures is very nearly normal to the transport direction and thus the problem of the obliquity of the structures is not so serious. This part of Northern Assynt has been interpreted in quite different ways by the various geologists that have worked in the area. The origin of the controversy has been the different interpretations given to the continuation to the south of the Glencoul Thrust and the relationship between the Glenbain and the Droighinn anticlines.

Coward (1982) suggested a new model based on the detailed re- mapping of the area, in which he incorporated the new interpreted extensional features. So, basically, he pointed out that just north of Inchnadamph, the Glencoul Thrust carries folded and imbricated Cambrian quartzites over Durness Limestone but this fault cuts down the stratigraphy and does not follow normal thrust rules. He recognised the Poll an Droighinn-Leathad Riabhach (Poll an Droighinn for simplicity) extensional fault that bounds the trailing edge of a major surge zone of about 8 x 8 km^2 which would have suffered a displacement of 1.75 km to the WNW. This fault would have offset the Glencoul Thrust whose original trace would remain at the bottom of the western slopes of Meall nan Caorach (Coward, 1982).

This model considers that the Cnoc an Droighinn and Glenbain anticlines (Fig. 2 and 5) are different structures. The former one is actually an anticlinorium constituted by a group of smaller folds and imbricates. They were interpreted by Coward (1982) as having developed during the emplacement of the Glencoul sheet. The extensional movement would not have produced any folding, but merely the displacement of a portion of the Glencoul sheet carrying all its overprinted structures.

This model has been partially followed to draw the eastern part of the Cnoc and Droighinn section (Fig. 5a). In the present work it is also assumed that the Cnoc an Droighinn and Glenbain antiforms are different structures. The Glenbain antiform is considered here to reflect, in surface, the folding of a whole thrust sheet. The folding could be due to the shape of the proper sheet or due to the existance of a duplex structure underneath, the so called Glenbain sheet. On the map, this antiform gives the impression to have been cut by the Poll an Droighinn extensional fault or, in any case, in a cross section that incorporates this fault, it seems coherent the model of an extensional fault cutting across the Glenbain structure.

In this case it is suggested here that some of the imbricates immediately above the Glencoul Thrust are slices rooted out from the top of the Glenbain structure. This is partly supported by the fact that the two or three slices of Pipe Rock and Basal Quartzite above the Glencoul thrust cannot carry basement. This appears to be due to the fact that there is no space for it (the basement) between the underlying imbricate structure (which has been projected onto the section from farther south) and the Glencoul Thrust itself (that in this place is cutting down section) (see cross section, Fig. 5a).

The slice of basement and Cambrian cover splayed from the Glencoul sheet would now appear on top of the above mentioned slices belonging to the Glenbain structure. In its extensional travel the slice of basement would generate thrusts at its front. These thrusts, which would splay from the main extensional fault, would produce folding, contrary to Coward (1982), both in the basement but mainly, in the Cambrian cover.

This new interpretation is based on the fact that the folds and thrusts at Cnoc an Droighinn and in general along the western slopes of the Glas Bheinn - Cnoc an Droighinn ridge (Fig. 2) do not show a clear piggyback pattern. The higher level fold axes do not appear folded by the folds developed beneath, but instead, their trends remain parallel. Moreover, some of their associated thrusts display a clear break-back relationship with respect to the underlying structures. The pattern shown by the group of folds and thrusts outcropping to the North of Cnoc an Droighinn (Fig. 2) is a good example of this relationship. The fold higher in the sequence laterally evolves into a thrust which brings Lewissian gneisses on top of Cambrian quartzites, cutting across the lower level folds. These folds and thrusts can be traced to the north and would form part of the folded and imbricated structure recognized on the estern slopes of Glas Behinn.

Therefore the bulk of the folding and thrusting exposed on the western slopes of the Glas Bleinn-Choc an Droighinn ridge is alternatively interpreted in this paper to have developed coevally and as a consequence of the extensional movement of a portion of the Glencoul sheet. Nevertheless some of this thrusting and folding might have developed during the previous emplacement of the Glencoul sheet, and would have been subsequently incorporated in the extensional movement. The Cnoc and Droighinn section (Fig. 5a) has been drawn following this hypothesis. Fig. 5b represents the same section just before the extensional movement.

In between the Beinn Uidhe and Cnoc and Droighinn sections there are several structures which are worth describing. For example, there is a well defined sinformal structure within the Cambrian quartzites running parallel to the Beinn Uidhe Ridge, whose axis is aligned along the Bealach and Fleodach Coire lochs (Fig. 2). North of Meall nan Caorach, in the vicinity of Loch nan Cuaran, there are several WNW trending folds and thrusts which are the continuity to the ESE of the aforementioned synform. In this location quite dramatic structures are supposed to reflect in surface the existence of a lateral ramp at depth. This interpretation has been followed to draw the sections Q-Q' and R-R' (Fig. 7), parallel to strike. In these sections it has been considered that both the duplex drawn underneath the Glencoul sheet along the Beinn Uidhe section, and the Glenbain sheet disappear laterally along lateral ramps parallel to the transport direction. These lateral hangingwall ramps would be sited quite close, one on top of another. The coincidence of these lateral maps would be the cause of the localisation of the strain on the Glencoul sheet above them. In Fig. 8 a schematic hangingwall sequence diagram is depicted, showing the supposed evolution of thrusting and the development of these lateral ramps.

6. FAULT ROCKS

As emphasised by Coward (1984), a change in the dominant deformation mechanism and thrust style, north and south of Assynt, can be readily observed. In the northern part of the thrust zone, the thrust structures were dominantly formed by ductile deformation, though in any cross-section through the thrust zone, the fault rocks developed on the later, lower thrusts are more cataclastic. However, in the southern part of the Moine Thrust zone, south of the Central Assynt region, cataclastic fault rocks are more important in some high-level, as well as low-level thrusts.

Following this general idea, the present chapter focusses on the study of the fault rocks associated with some of the structures mentioned in the previous chapters. This study is purely descriptive and its aim is to discern what kind of deformation mechanisms ruled the thrusting and faulting in Northern Assynt. For this purpose, deformed Cambrian quartzites have been examined using cathodoluminescence (CL) in the Scanning Electron Microscope (SEM) and with the conventional optical microscope. (Blenkinshop and Rutter, 1986; Knipe and Lloyd, in press).

6.1. Field observations

The original situation of the samples used for this microstructural study is shown in Fig. 2. They all belong to the Basal Quartzite unit. Samples M3, 4, 5, 6, M10, M15, 16 and M18 were collected in the vicinity of Cnoc an Droighinn. M18 is a fault rock produced as a consequence of the movement of an accommodation structure and the rest of the samples are fault rocks associated with the thrust planes. In the field, an increase in the intensity of the deformation can usually be observed either in the footwall or in the hanging wall, upon approaching the thrust plane. The fault rocks form a discrete level of crush material of variable thickness, although they usually do not exceed the 40-50 cm. Sometimes, however, the fault rocks and the deformation in the adjacent hangingwall and footwall may not be so evident. The general aspect of the fault rock is of an apparently random-fabric well cemented crush material. Sometimes, however, it is possible to recognise a coarse foliation formed by a gross orientation of finer grained (clay minerals and clast trails) material. The aforementioned samples will be representative of the deformation that took place along the Glencoul Thrust and some associated minor thrusts and faults.

Samples M21, M22, and M23 have been collected in the vicinity of Coire Leacach from the fault rocks related to the back-thrusts observed in this area. For this reason they will be used to account for the type of deformation that took place along these structures. The outcrops of the fault rocks related to the back-thrusts present the same aspect as described above. As will be seen later, the fault rocks collected both at Cnoc an Droighinn and at Coire Leacach may be regarded as cataclasites and therefore a brittle behaviour can be inferred for these structures.

Samples M1, M7 and M19, 20 have been collected from fault rocks associated with the Beinn Uidhe imbricates. In this case, there is not a discrete level of deformed material, but a progression in the intensity of the deformation as the thrust plane is approached. For this reason, and due to the slope debris which impede the direct observation of the proper thrust plane, it is difficult to ascertain the width of the deformed rock in the adjacent hangingwalls and footwalls. In the field, the deformation is revealed by the existence of a gross foliation and when the grain size is coarse enough, a flattening of the grains can also be observed in some hand specimens. This simple field evidence, supported by the microstructural observations, show a dominant plastic behaviour of the thrusts that produced the im-

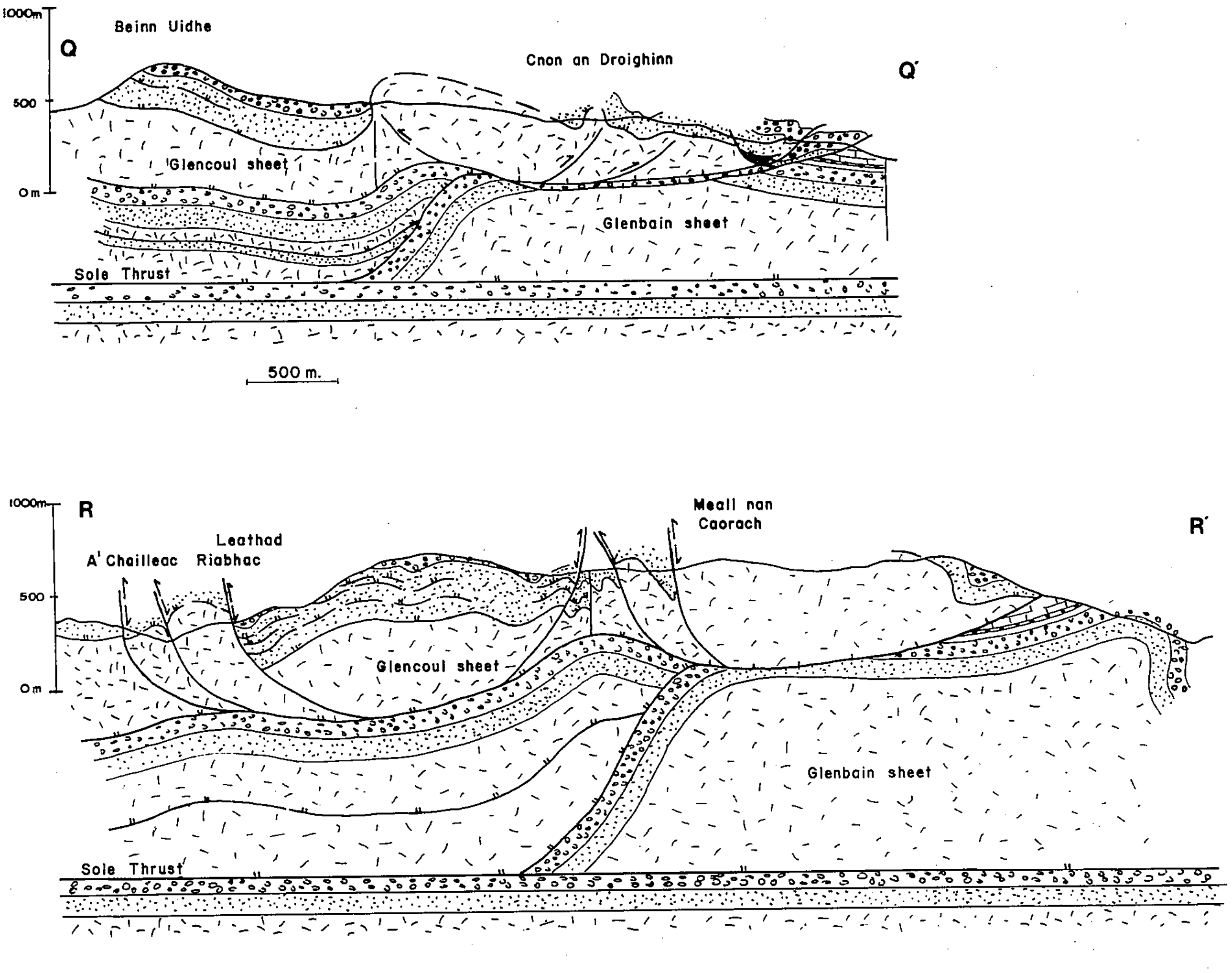

Fig. 7.- Sections parallel to strike (Q-Q' and R-R' in Fig. 2a). The lateral terminations of the lower structural units is the cause of the localization of the strain in the overlying Glencoul sheet. A later tightening of the structures is also observed along this section. See text for further discussion. (Symbols as in Fig. 2).

Fig. 7.-Secciones paralelas a la dirección del cinturón de cabalgamientos (Q- Q' y R-R' en la Fig. 2a). Las terminaciones laterales de las unidades estructurales inferiores son la causa de la localización de la deformación en la suprayacente lámina del Glencoul. También se observa a lo largo de estas secciones un tardío reapretamiento de las estructuras. Ver texto para mayor discusión. (Símbolos como en Fig. 2).

brication of the Cambro - Ordovician cover along the Beinn Uidhe ridge.

6.2. *Microstructural observations*

In the undeformed state the Basal Quartzite contains angular to subrounded detrital grains with an average diameter of 1 mm but which can also be much bigger (up to 10 mm), especially near the contact with the Lewisian gneiss. As already observed by Blenkinshop and Rutter (1986) and Knipe and Lloyd (in press), the Cambrian quartzite shows grains with quite variable provenance, many of them possessing complex intragranular microstructures which must be predepositional in origin. The grains are interlock on curved or irregular grain boundaries reflecting a certain amount of pressure solution due to postdeformational compactation. As it would be expected from the field observations two types of fault rocks have been recognized under the microscope, cataclasites and mylonites, as described below:

6.2.1. *Cataclasites*

The fault rocks collected from the thrusts in the vicinity of Cnoc an Droighinn and from the backthrusts at Coire Leacach show very similar microstructural pattern under the microscope. Therefore, unless the contrary is indicated, the following description will account for the whole of them. Most of these fault rocks can be classified as cataclasites (Sibson, 1977) and they present a proportion of matrix between the 25% and the 75% of the whole rock. Also some protocataclasites are recognized although the proportion of matrix is always very close to the limit of the 25%. The matrix

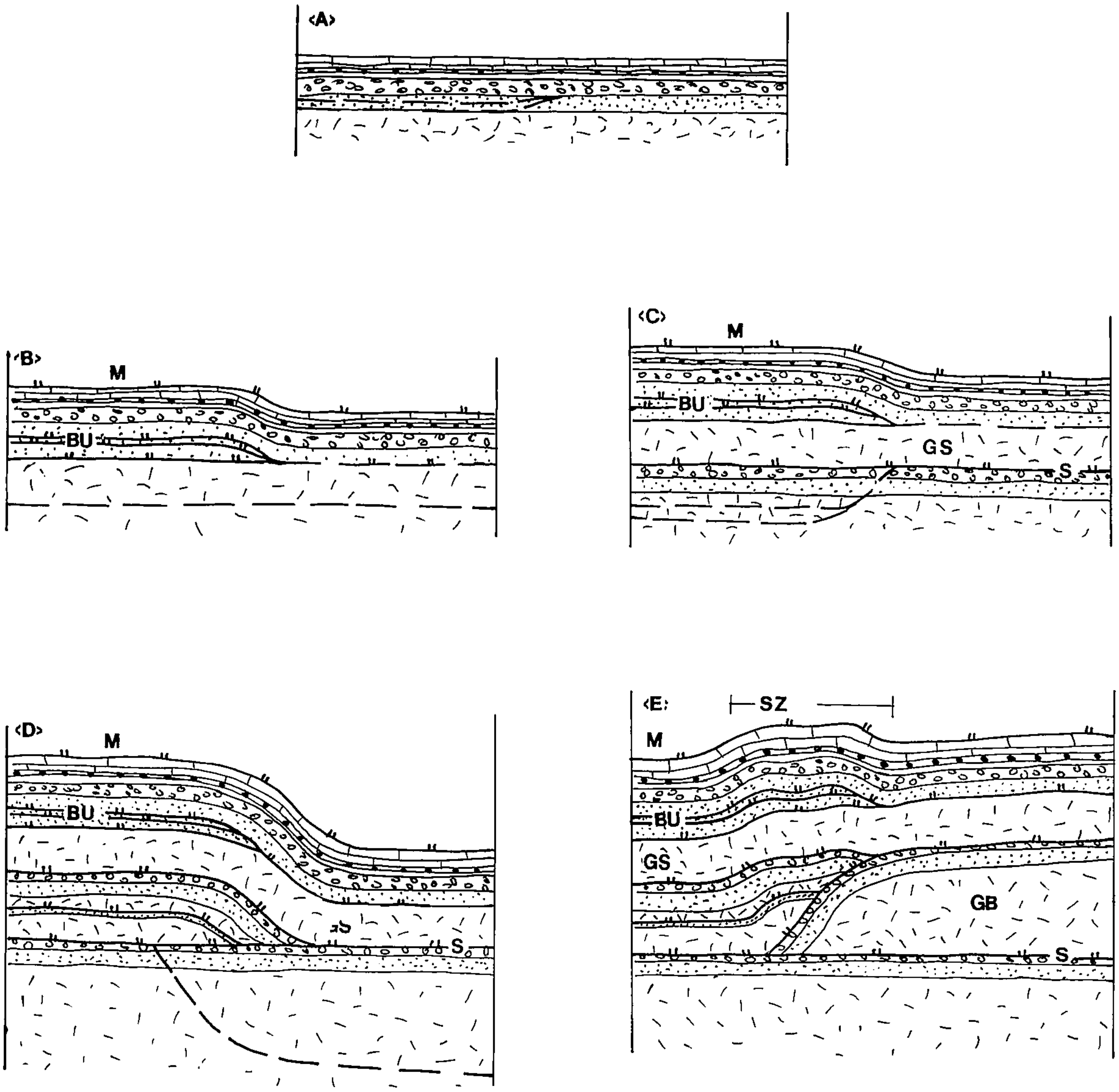

Fig. 8.-Idealized hanging wall sequence diagram showing the evolution of thrusting in Northern Assynt. (a) Initial situation. (b) Development of the Beinn Uidhe imbricates in the Cambro- Ordovician cover coevally with the displacement of the Moine Thrust. (c) Accretion of the Glencoul sheet. (d) Development of the duplex underneath the Glencoul sheet along the Beinn Uidhe section. (e) Accretion of the Glenbain sheet. The direction of the tectonic transport is WNW,out of paper. (S, means Sole Thrust; M, Moines; BU, Beinn Uidhe imbricates; GS, Glencoul sheet; GB, Glenbain sheet and SZ, strained zone).

Fig. 8.-Diagrama con la secuencia idealizada del bloque de techo mostrando la evolución de las imbricaciones en Northern Assynt. (a) Situación inicial. (b) Desarrollo de las imbricaciones del Beinn Uidhe en la cobertera Cambro-Ordovícica al mismo tiempo y como consecuencia del desplazamiento de la lámina del Moine. (c) Apilamiento de la lámina del Glencoul. (d) Desarrollo del duplex bajo la lámina del Glencoul en la transversal del Beinn Uidhe. (e) Apilameinto de la lámina del Glenbain. El sentido del transporte tectónico es ONO, hacia afuera del papel. (S, significa Sole Thrust; M, Moines; BU, escamas del Beinn Uidhe; GS, lámina del Glencoul; GB, lámina del Glenbain y SZ, zona de deformación).

is formed by small fragments of quartzite, non luminescent cement and, in lesser porportions, oxides and brown clay minerals. In the cataclasites (e.g. Fig. 10) the matrix surrounds isolated pods of intact or cracked rock whereas in the protocataclasites the matrix appears exclusively within the most evolved cracks and the original features of the rock are still recognizable (Fig. 9). These two situations are different steps of the progressive evolution of the fault rock. In similar fault rocks Blenkinsop and Rutter (op. cit) and Knipe and Lloyd (op. cit) have described several characteristic brittle microstructures, which also have been recognized here:

— *Intragranular microfractures.*

Intragranular microfractures (Fig. 10 and 11) (and in general, all other fractures) are very well depicted under cathodoluminesce because they are filled by nonluminescent cement. They are especially visible when

Fig. 9.-Different grades of evolution of shear fractures in a protocataclasite. In the centre of the picture several shear fractures break and displace the grains but only some incipient matrix has been developed along them. In the upper part of the picture a more evolved shear fracture has developed a band of matrix by the attrition of the adjacent grains. (Sample M18 under optical microscope, crossed polars. The width of the field of view is about 10^4 microns).

Fig. 9.-Diferentes grados de evolución de fracturas desarrolladas por cizalla en una protocataclasita. En el centro, varias fracturas rompen y desplazan los granos pero solo una matriz incipiente se ha desarrollado a lo largo de ellos. En la parte superior una fractura más evolucionada ha desarrollado una banda de matriz mediante la trituración de los granos adjacentes (Muestra M18, bajo microscopio óptico y nicoles cruzados. La anchura del campo de visión es 10^4 micras aprox.)

deformation is less intense (protocaclasites) although they may also be recognized in the isolated pods of rock included in the matrix of the cataclasites. They are a few tenths of microns wide and have purely extensional displacement, occurring entirely within single grains. They may cross through the whole grain or pinch out at a crack tip, and, as pointed out by Knippe and Lloyd (op. cit.), they may present a wide range of shapes, from single, straight patterns to a complex mesh which disintegrates quartz grains. The intragranular microfractures observed do not seem to follow any preferred orientation, although no detailed orientation study has been attempted to test this impression. Extensional intragranular cracks develop at the impingement points between grains following the stress trajectories which connect the most highly stressed contacts.

— *Intergranular or through-going microfractures.*

Intergranular (Blenkinsop and Rutter, op. cit.) or through-going (Knipe and Lloyd, op. cit.) microfractures (Fig. 10 and 11) develop at more advanced stages of deformation, by the linkage of intragranular microfractures. The linkage can be done by the interconnection of the intragranular microfractures by themselves, or by fracture propagation along/through grain boundaries. Generally speaking they show quite an irregular pattern. In some cases, they are formed by a network of subparallel, anastomosing features; in others, the through-going fractures show a complex pattern of meandering cracks. Therefore, rather than individual fractures, the concept of fracture path width (Knippe and Lloyd, op. cit.) can be used in the sense that the fractures, although apparently straight on the scale of the fracture length, actually have an irregular trace from on the grain-size scale. Intergranular fractures may be filled exclusively by non-luminescent cement and may show no shear displacement. However, as deformation progresses, it is more common to find them filled by a matrix of crushed material and then, it can be inferred that a relative (shear) movement between the two sides of the fracture has taken place. Thus, a shear fracture has developed (Fig. 9).-

— *Shear fractures zones.*

Knipe and Lloyd (op. cit.) state that the formation of through-going fractures lowers the shear yield/fracture strength of the rock, leading to initiate and localize shear deformation along them. Using the concept of fracture path width in the sense explained before, the width of the shear fractures zones will be several grain in diameter and along them, interfacial friction and grain comminution by intragranular fracturing will produce a progressive reduction of the intact rock to matrix. In addition to the comminuted debris of grains, the shear fracture matrix consists of cement which itself often shows evidence of subsequent fracturing (Fig. 11). This fact has also been observed by Blenkinshop and Rutter (op. cit.) who pointed out that cementation

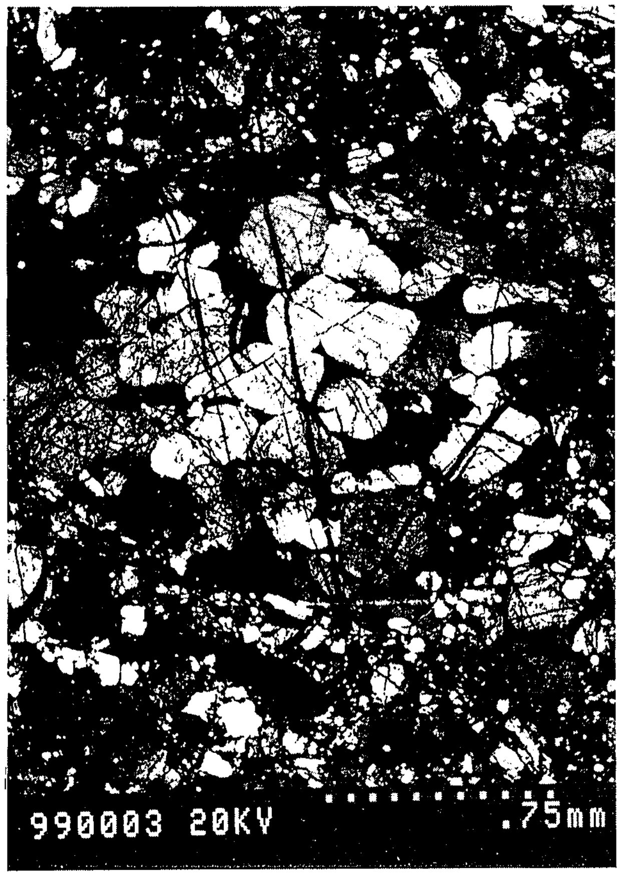

Fig. 10.-Through-going microfractures developed by the linkage of intragranular microfractures. Some of them show a shear component. Some intragranular microfractures are still present. The bulk of the rock (cataclasite) is matrix formed by small fragments of quartzite. The matrix surrounds pods of original rock which show an advanced state of attrition. Notice the non-luminescent quartz healing the cracks and within the matrix (Sample M5 under cathodoluminescence in the S.E.M.).

Fig. 10.-Microfracruras de mayor lontitud desarrolladas por la unión de microfracturas intragranulares. Algunas de ellas muestran una componente de cizalla. Todavía se conservan algunas fracturas intragranulares. La mayor parte de la roca (cataclasita) es matriz formada por pequeños fragmentos de cuarcita. La matriz rodea trozos de la roca original que muestran un avanzado estado de trituración. Se puede observar el cuarzo no luminescente sellando las grietas y dentro de la matriz (Muestra M5 bajo catodoluminescencia en el S.E.M.).

and cataclasis should proceed simultaneously. The matrix also contains oxides and brown and white phyllosillicate minerals which are thought to represent new growths. The proportion of phyllosilicates within the matrix is quite variable although never very important. They usually appear in patches or form non continuous and randomly disposed bands. Sometimes they form anastomosing subparallel bands, roughly following a preferred orientation. That is, they represent an incipient foliation.

To summarize, the general texture of the protocataclasites consists of a network of intergranular fractures, many of them evolved into shear fractures, separating fragments of intact quartzite which are damaged by intergranular extension microcracks. The general texture of the cataclasites consists of pods of intact or cracked rock included in a fine grained matrix formed by fragments of the original rock, quartz cement and, more rarely, oxides and phyllosilicates which eventually may depict an incipient foliation. This matrix may, in turn, show cyclic episodes of fracturing and cementation.

Apart from the described "brittle" features the fault rocks collected at Cnoc and Droghinn and at Coire Leacach show a wide range of low temperate plastic deformation microstructures. A high proportion of grains show undulose extinction. Banded extinction and deformation lamellae are also common and an incipient subgrain formation can be observed in many grains. Some of these microstructures might be inherited, but it certainly seems that the plastic deformation microstructures are too widespread and too well developed for the whole of them to be considered as inherited. Consequently, although cataclastic attrition of the rock was the dominant deformation mechanism, it is thought that there were favourable environmental conditions for some low temperate plasticity (dislocation glide) to occur.

With respect to the occurrence of diffusional mass transfer (DMT) processes, the existence of cyclic episodes of fracturing and cementation has already been

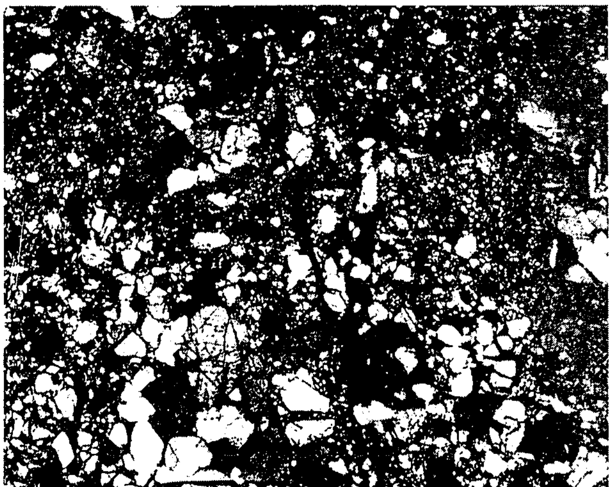

Fig. 11.-Different picture of the sample M5, in this case showing a healed through-going fracture across the matrix.

Fig. 11.-Otra imagen de la muestra M5.En este caso se observa una fractura sellada, de longitud mayor y desarrollada a través de la matriz.

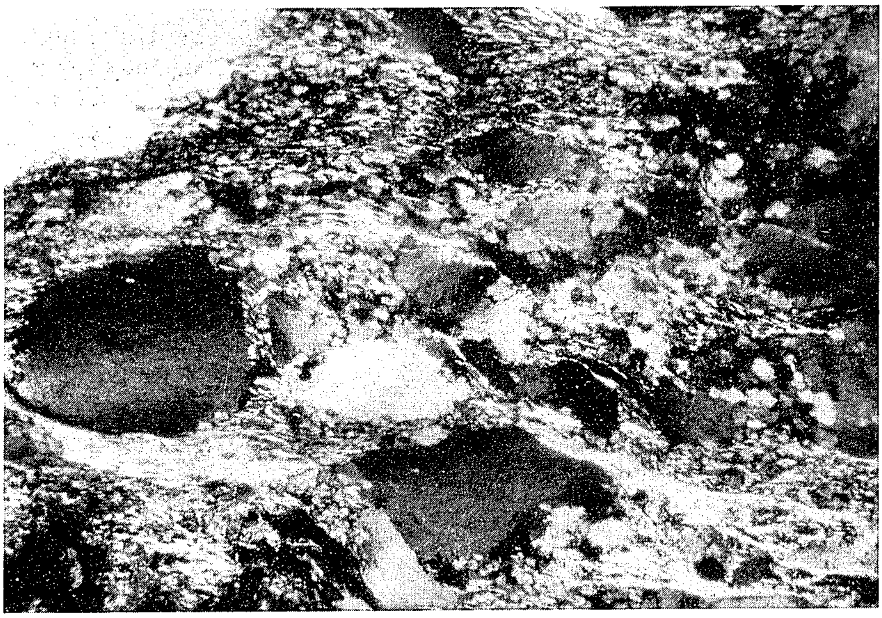

Fig. 12.-Dynamically recristallized grains, phyllosilicates and oxides forming the matrix of a protomylonite. Notice that the orientation of the bands of phylosilicates and new recrystallized material represent an incipient foliation (sample M1 under optical microscope, crossed polars. The width of the field of view is about 10^4 microns).

Fig. 12.-Granos formados por recristalización dinámica, filosilicatos y óxidos integrantes de la matriz de una protomilomita. Obsérvese que la orientación de las bandas de filosilicatos y el material recristalizado representan una foliación incipiente (Muestra M1 bajo microscopio óptico y nícoles cruzados. La anchura del campo de visión es 10^4 micras aprox.).

mentioned. The sinks form pressure dissolved non-luminescent quartz might be the healed fractures and matrix. However, there is no evidence of the sources. Apart from inherited ones, no other microstructures due to pressure - solution processes have been observed.

6.2.2. Mylonites

The fault rocks collected from the imbricated Cambro - Ordovician cover along the eastern part of the Beinn Uidhe section, show microstructures dominantly formed by plastic deformation. Samples M1 and M19, 20 consist of highly deformed coarse grains which have suffered dynamic recrystallization (Fig. 12). The original grains usually appear surrounded by a rim of new recrystallized grains, although the old contacts between grains still remain partially visible. More advanced stages of recrystallization are also present as narrow bands of fully recrystallized material. However, the proportion of the new recrystallized material does not exceed 25% of the whole rock and therefore these fault rocks can be classified as protomylonites. Dynamic recrystallization not only occurs along grain boundaries but also within the grains, taking advantage of pre-existing imperfections. The matrix also contains a variable proportion of phyllosilicates. These may appear in patches or form discontinuous bands which sometimes depict incipient mica-fish structures.

As it would be expected, undulose and banded extinction, as well as deformation lamellae, are common features within the grains. However, the internal distortion of the grains is especially revealed by a strong flattening (Fig. 13). This flattening is subparallel to the bedding (surface of decollement) and is inferred to be achieved by the movement of slip systems within grains and by the relative movement of the grains along grain boundaries. No evidence on high temperature diffusive mass transfer processes has been found, most probably inhibited by the coarse grain-size of the Basal Quartzite. The flattened grains, the occasionally flattened new recrystallized material, all together create a gross foliation, sometimes visible in hand specimes. The protomylonites also show a moderate crystallographic preferred orientation. Therefore, dislocation glide and dislocation climb are inferred to be the two principal deformation mechanisms that operated during the development of the Beinn Uidhe imbricates.

There is also evidence of cataclastic deformation in the protomylonites. Discrete fractures can be observed under the microscope. These fractures, about 100 microns wide, do not present sharp edges. On the contrary they appear partially obliterated by the coarse foliation marked by the flattened grains and the narrow bands of new recristallized material. The fractures are filled with a fine, non-luminescent material that under the optical microscope, appears as new recrystallized grains which seem to have the same slightly flattened pattern as the recrystallized grains of the matrix. Therefore, these cataclastic features seem to predate the plastic ones.

This kind of relationship is more evident in the sample M7 also taken from the Beinn Uidhe imbricates. This fault rock is a cataclasite with the same characteristics of those from Cnoc an Droighinn and Coi-

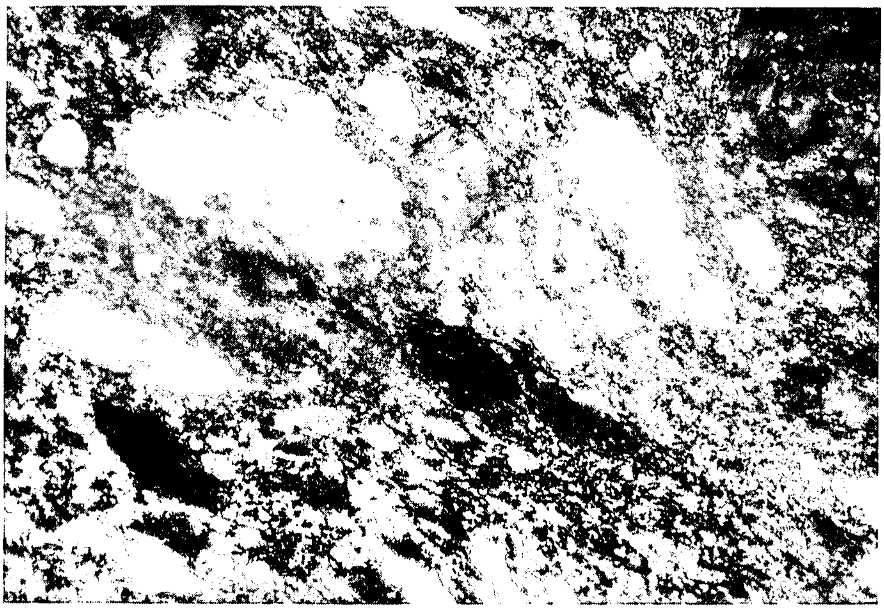

Fig. 13.-Superimposition of a plastic deformation on a cataclasite. The matrix of the cataclasite has been partially substitued by dynamically recrystallized material (Sample M7, under optical microscope, crossed polars. The width of the field of view is about 10^4 microns).

Fig. 13.-Superposición de una deformación plástica en una cataclasita. La matriz de la cataclasita ha sido parcialmente substituida por material dinámicamente recristalizado (Muestra M7, bajo microscopio óptico, nicoles cruzados. La anchura del campo de visión es 10^4 micras aprox.).

re Leacach described previously. However, in this case, a very obvious superimposed plastic deformation can be observed throughout the whole thin section. The superimposed plastic deformation is mainly revealed by the development of a dynamic recrystalization within the matrix of the cataclasite as well as along the cracks of the remaining original grains (Fig. 13). The general aspect of the rock is still of a cataclasite but an incipient (not inherited) foliation has already been developed by the alignement of the new recrystalized material. Certainly, a considerable proportion of the matrix has been substituted by the dynamically recrustallized grains and most of the cracks are infilled by this material. Original through-going fractures running across grains and matrix are observed to be partially obliterated by the foliation (Fig. 13).

Therefore, the fault rocks associated to the Beinn Uidhe imbricates, show a dominant plastic deformation features.

7. FAULT ROCKS AND THRUST SEQUENCES IN NORTHERN ASSYNT. DISCUSSION

In the last few years, geological mapping and deep seismic reflection profiling have proved that the external part of most orogenic belts are wedge shaped being thicker at the hinterland and progressively becoming thinner towards the foreland. The lower limit of the wedge, the Sole or Basal Thrust, has been commonly interpreted as a plane with a uniform dip of about 3° towards the hinterland, which would bottom out in an intracrustal subhorizontal detachment at about 10-15 km. below the present erosion level. This model was proposed for the Appalachians (Brewer *et al.*, 1981) and it has also been applied in the Southern Rocky Mountains (Price, 1981) and the Alps (Bott, 1971). However, in other cases some authors have identified the Basal Thrust rooting at a greater depth as a major decollement at about the level of the Moho discontinuity. In this case, the dip of the Basal Thrust at the shallower levels would be substantially greater (20-30°) than in the previous examples. This model has been proposed by Hsu (1979) in the Alps and by Smithson *et al.* (1978), and Brewer *et al.* (1981) in the Wind River uplift in the Rocky Mountain foreland of Wyoming.

Both models have been applied to NW Scotland. Barton (1978), Elliot and Johnson (1980), Coward (1980), and McClay and Coward (1981) state or imply that the Outer Isles, the Moine Thrust and the Internal Caledonide slide zones are all components of a regional scale duplex and root in a sub-horizontal floor thrust, some 10 Km. below the present erosion surface. On the other hand, Soper and Barber (1982) proposed a duplex of crustal dimensions, with the Moine Thrust initially dipping about 30° and rooting at the level of the Moho discontinuity.

Applying one model or the other, the duplexes would evolve in a piggy back or footwall collapse fashion, the easternmost and higher structural sheets coming from deeper levels of the crust than the westernmost and lower structural sheets. Consequently, the fault rocks associated with the different thrusts should reflect a range of deformation mechanisms (and therefore environmental conditions) according to this sequence (Sibson, 1977).

The observations made on the fault rocks collected in Northern Assynt, agree with the above generalized sequence schedule. The Beinn Uidhe imbricates, generated earlier and at deeper levels (probably as a consequence of the movement of the Moine Thrust) than the Cnoc and Droighinn thrusts and Coire Leacach back-thrusts, show that intracristalline plastic processes (ICP) are the dominant deformation mechanisms. For a rock mostly consisting of detrital grains of quartz as is the Basal Quartzite, this fact implies, very schematically, temperatures 300°C and pressures greater than 3.5 kbars. These conditions may be achieved at about 14-15 km of depth for a typical "orogenic" geothermal gradient of 20°C/km. The events of brittle deformation observed in the imbricates, are earlier than or coeval with the earlier stages of the plastic deformation, and may have been induced by episodic increase(s) in the strain rate and/or pore fluid pressure along the thrust plane.

The thrusts at Cnoc and Droighinn and the back-thrusts at Coire Leacach show fault rocks formed by cataclastic deformation, although some low temperature plasticity is also present. This kind of deformation implies temperatures probably under 300°C and correspondingly lower pressures lower than 3 - 3.5 kbars, conditions that can be achieved at depths of 12-13 km or shallower. The presence of clay minerals and oxides implies that pore fluid pressures should play an important role in the deformation processes. Therefore, in agreement with the field observations, these thrusts and back-thrusts have developed later than the Beinn Uidhe imbricates and after some degree of depressureization by erosion as the Glencoul sheet already occupied higher structural levels. The disruption of the Beinn Uidhe imbricates by the back- thrusts at Coire Leacach is a good example of the superimposition of a later, shallower, and brittle deformation on an earlier, deeper plastic one.

However, the faults rocks from Cnoc an Droghinn might not be representative of the deformation mechansims that ruled the emplacement of the Glencoul Thrust. If the thrusts at Cnoc an Droghinn and more specifically, the current position of the Glencoul Thrust were induced by an extensional movement the fault rocks would reflect the deformation mechanisms that governed this extensional movement, rather than the deformation mechanism related to the emplacement of the Glencoul Sheet. The fault rocks (M10), associated with the Glencoul Thrust at Cnoc an Drogihinn, show less deformation (protocataclasites) than should be expected for a thrust with such an important displacement. This fact may be in agreement with the extensional 'offset' of the Glencoul Thrust proposed by Coward (1982) and also considered in this work. As explained previously, the extensional episodes as a whole would be coeval with the emplacement of the Glencoul sheet, but each individual extensional movement would postdate the accretion of a new sheet or group of sheets.

8. CONCLUSIONS

Based on detailed mapping of the area published by Coward (1981, 1982, 1984) and on other unpublished data of the same author the general overview of the geological structure of Northern Assynt carried out in this work, has led to the following conclusions:

1. Two balanced sections in the direction of the tectonic transport have been attempted: the Beinn Uidhe section (Fig. 3) to the north and the Cnoc and Droghinn section (Fig. 5) to the south. The imbrication of the Cambro - Ordovician cover of the Glencoul sheet, has produce about 40% of shortening along the Beinn Uidhe Section. The Beinn Uidhe imbricates may be regarded as a duplex; the uncomformable contact between the Lewisian basement and the Basal Quartzite would be the floor thrust of the duplex, and the Moine Thrust (nowadays eroded) would have acted as roof thrust.

In the western half of the Cnoc Droighinn section, the trend of the structures is oblique to the direction of the tectonic transport. Although a very well exposed duplex (formed by the upper members of the Cambro - Ordovician sequence) has been projected on to the plane of the section, its restoration would give false values of shortening. Instead, a balanced cross section of this duplex has been attempted along a more favourable direction (approximately perpendicular to the trend of the structures). For this purpose, it has been assumed that the duplex has been formed by the pervasive collapse of an obliquely trending footwall (Coward, 1984) and that this collapse has occurred in a uniform direction, normal to the structures. The shortening produced in this duplex along the chosen section is 78%. Cooper (1983) corrections give 80% of shortening along a direction normal to the trend of the structures and 40% along a direction parallel to the tectonic transport. The last figure suggests that the length of B an C duplexes (underneath the Glencoul sheet in the direction of the tectonic transport) in the deformed state would be about 6 km. The corresponding restored length would be about 10 km.

2. Along the aforementioned sections (especially along the Beinn Uidhe one) steeply dipping faults, perpendicular or sligtly oblique to the direction of the tectonic transport are well exposed. Some of these faults show an important normal component and have associated roll over folds. Others are quite dramatic back-thrusts. As a whole, most of these structures are interpreted as extensional features developed as a result of drops in the basal shear strength of the wedge. They would have developed coevally with the emplacement of the Glencoul sheet, each extensional fault post- dating the accretion of a new sheet or group of sheets.

A later compressional event has also been recognized. It would have reactivated the pre-existent extensional faults and would have produced back-thrusts and back-folds as new compressional structures. The back-folding would not be exclusive to the Cambro - Ordovician cover but it is thought that the Lewisian basement also would have developed bulges or folds of long radius. The ductility of the Lewisian basement would have been achieved by a pervasive cataclastic flow. The ultimate case of the compressional event would have been a sudden rise in the basal shear strength of the orogenic wedge.

3. A general model of piggy-back thrusting is assumed for Northern Assynt. The model would be locally complicated by the previously mentioned, extensional episodes. In the Glencoul sheet there are areas of localized strain. The strain (that is revealed by folds, thrusts and strike-slip faults mostly trending subparallel to the tectonic transport direction) might have been produced by the coincidence of the lateral terminations of the underlying sheets or groups of sheets. Some of these structures might be originally extensional features, and would have been tightened by the subsequent compression.

4. The fault rocks, produced by the described structures, show a pattern coherent with the piggy-back model. The earlier thrusts, now occupying higher structural levels carry fault rocks (protomylonites) developed at deeper environmental conditions than the fault rocks (cataclasites) carried by the later, now structurally lower thrusts.

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