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# Loch Monar

[NH 197 389]

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## Introduction

Smooth glaciated slabs by Loch Monar in Glen Strathfarrar show excellent examples of minor folding and fold interference patterns in thinly bedded psammities and semipelites of the Morar Group. J.G. Ramsay (1957a) carried out what is now recognized as a classic detailed structural synthesis of this area. This was one of the first geometrically rigorous studies of a complex folded area to be undertaken; similar work has since been done by many workers, but the original examples are featured in numerous structural geology textbooks. The dominant small-scale early folds form part of the kilometre-scale Monar Synform, which has been refolded by later upright structures (Figure 7.7), (Figure 7.8).

To the south and east of the site lies the thick Strathfarrar Lewisianoid Inlier, separated from the underlying Morar Group metasedimentary rocks by the Sgurr Beag Thrust, a major ductile shear-zone that dips steeply east in this area. South and east of the Lewisianoid inlier are Glenfinnan Group rocks. The Monar Synform folds all the units and appears to fold the Sgurr Beag Thrust. An early D1 deformation phase is present in the area, but generally only results in a bedding-parallel foliation, S1. Two subsequent major deformation phases, D2 and D3, are responsible for the spectacular interference pattern. The F2 Monar Synform is a large, gently W-plunging structure, which has been refolded by steeply plunging NE-trending F3 folds (Figure 7.8). Ramsay (1957a) originally referred to the two fold phases as 'F1' and 'F2' as he did not recognize the earlier S1 foliation and rare related minor structures. Tobisch *et al.* (1970) confused the terminology further by allocating the Monar Synform to a locally developed fold phase, the Orrin Phase, and the later folds to a Monar Phase (see (Table 7.2).)

Officers of the Geological Survey mapped the area in 1905 (Peach *et al.*, 1913), but it was not until J.G. Ramsay remapped the upper part of Glen Strathfarrar in detail with particular regard to the complex structural pattern that the full picture emerged. Ramsay collected large amounts of structural data and used it to illustrate the three-dimensional geometry of the fold pattern and the complex fold interference patterns. He synthesized the results in a series of seminal papers (Ramsay, 1957a, 1960, 1962), and the material has been used subsequently in textbooks on structural geology (Ramsay, 1967; Ramsay and Huber, 1987).

## Description

The GCR site lies at the southern end of Loch Monar, with the best exposures being a series of gently sloping glaciated slabs immediately below the road between the cut-off dam and the Loichel Tunnel Intake. Although once clean, the glacial slabs are now considerably vegetated, but some clean sections are still present, particularly at the north-west end of the section. The sections are typically not submerged, as the Loch Monar reservoir rarely attains its top water level. The mapping of J.G. Ramsay was done prior to the construction of the Monar Dam, and hence some localities now lie beneath the waters of the reservoir.

The exposures show excellent small-scale fold patterns in a sequence of thinly bedded, Moine psammities and subsidiary semipelites (Figure 7.9)a,b,c. Minor thin petite beds and amphibolite layers are also present. The psammities vary from quartzose to feldspathic and micaceous. The deformation occurred under amphibolite-facies conditions and a prominent S2 cleavage is developed, defined by biotite and muscovite. Garnet is developed in the pelitic units, and locally the rocks are gneissose, and quartz and quartz-feldspar pegmatite segregations are present.

In general, the beds dip very steeply to the south and SSE. Minor F2 folds are found on the limbs of the Monar Synform and show S-profiles on the steep southern limb of the synform and Z-profiles on the shallower-dipping northern limb. The F2 folds are refolded by later open to tight, small- to medium-scale, F3 folds whose axial planes strike north-east. A new

S3 axial-planar cleavage, again defined by biotite/muscovite growth, is pervasively developed and is the prominent planar fabric over much of the site area.

The fold interference patterns in the site area lie on the steep southern limb of the F2 Monar Synform and just south-east of an F3 antiformal hinge. In the F3 hinge area the related F2 and F3 minor fold structures show dominantly S-profile geometries when viewed down-plunge. However, a short distance south-east from the F3 antiform hinge zone, the minor F3 folds show dominantly Z-profile geometries. The S3 cleavage trends north-east and either dips very steeply south-east or is vertical. F2 fold axes plunge moderately to the WSW but locally where they have been re-orientated by D3 structures they plunge steeply south-west. F3 fold axes show a more-consistent direction of plunge, here typically 50°–65° to the south-west, but the amount varies dependent on the orientation of the bedding and earlier F2 folding effects. Ramsay (1967) has shown that there is more variation in the amount and direction of plunge of F3 axes on the steep southern limb of the Monar Synform than on the gentler dipping northern limb.

The combination of minor F2 S-profile folds and minor F3 Z-profile folds results in type-2 'mushroom' fold interference patterns. These occur when the fold axes and axial planes of the two fold phases are at high angle to each other, but the second fold-axis lies more-or-less within the first axial plane (Ramsay, 1967; Ramsay and Huber, 1987). Numerous examples of type-1 'dome and basin' interference patterns also occur, particularly in the south-east part of the section. These form when the axial planes and folds axes of the two fold phases lie at right angles to each other. Close to the hinge area of a minor F3 antiform, both type-2 'mushroom' and type-3 'crooked finger' fold interference patterns occur (Figure 7.9)a,b. The latter occur when the fold axes are sub-parallel, but the axial planes are at high angles to each other.

Quartz, quartz-feldspar and granitic pegmatite veins and pods generally post-date the F2 folds and are folded by F3. At the north-west end of the section near the F3 antiformal hinge, these syn- to post-D2 pegmatitic pods and veins are well seen (Figure 7.9)a,c. Later syn-F3, near-planar, thin pegmatite veins with diffuse boundaries, which lie sub-parallel to the S3 cleavage, are also developed here. More-extensive migmatization and pegmatite veining occur to the north-west of the site area.

## Interpretation

Fold interference structures are common in many parts of the Moine succession of the North-west Highlands. They are particularly well developed in lithologically varied, thinly layered rocks, typified by the Glenfinnan Group rocks (e.g. above Loch Eilt: see Fassfern to Lochailort Road Cuttings GCR site report, Chapter 8). They are also common in Morar Group rocks that lie adjacent to Lewisianoid inliers, such as in upper Glen Strathfarrar (this site), and in the Arnisdale–Loch Hourn area. The Loch Monar site exposes excellent F2 + F3 interference structures of three different types that are geometrically well constrained. Their interpretation by Ramsay (1957a, 1960, 1962) laid the groundwork for subsequent detailed structural studies both in the Moine outcrop and elsewhere in the world, and attempted to explain the mechanisms and constraints on the generation of such complex folding patterns. Ramsay (1957a) recognized the D2 and D3 phases (although referring to them as 'D1' and 'D2') as discrete deformation episodes, but envisaged them as part of the same orogenic movements. The early F2 folds originally had gentle W-plunging axes and formed part of a regional set of major antiformal and synformal structures with an overall northerly vergence. These imply that in this area there was at least a locally northward component of compression responsible for the D2 structures. Regional amphibolite-grade metamorphism, local migmatization, and the development of a penetrative cleavage all accompanied the generation of the folds.

Ramsay (1957a) noted that the geometry and orientation of the F3 folds are controlled by the orientation of the limbs of the F2 folds upon which they are superimposed. He did consider that during D3 there appears to have been some regeneration of F2 folding. The F2 folds appear to have tightened up and in the process the superimposed F3 structures were slightly deformed. The D3 deformation was probably responsible for inverting the steep southern limb of the Monar Synform.

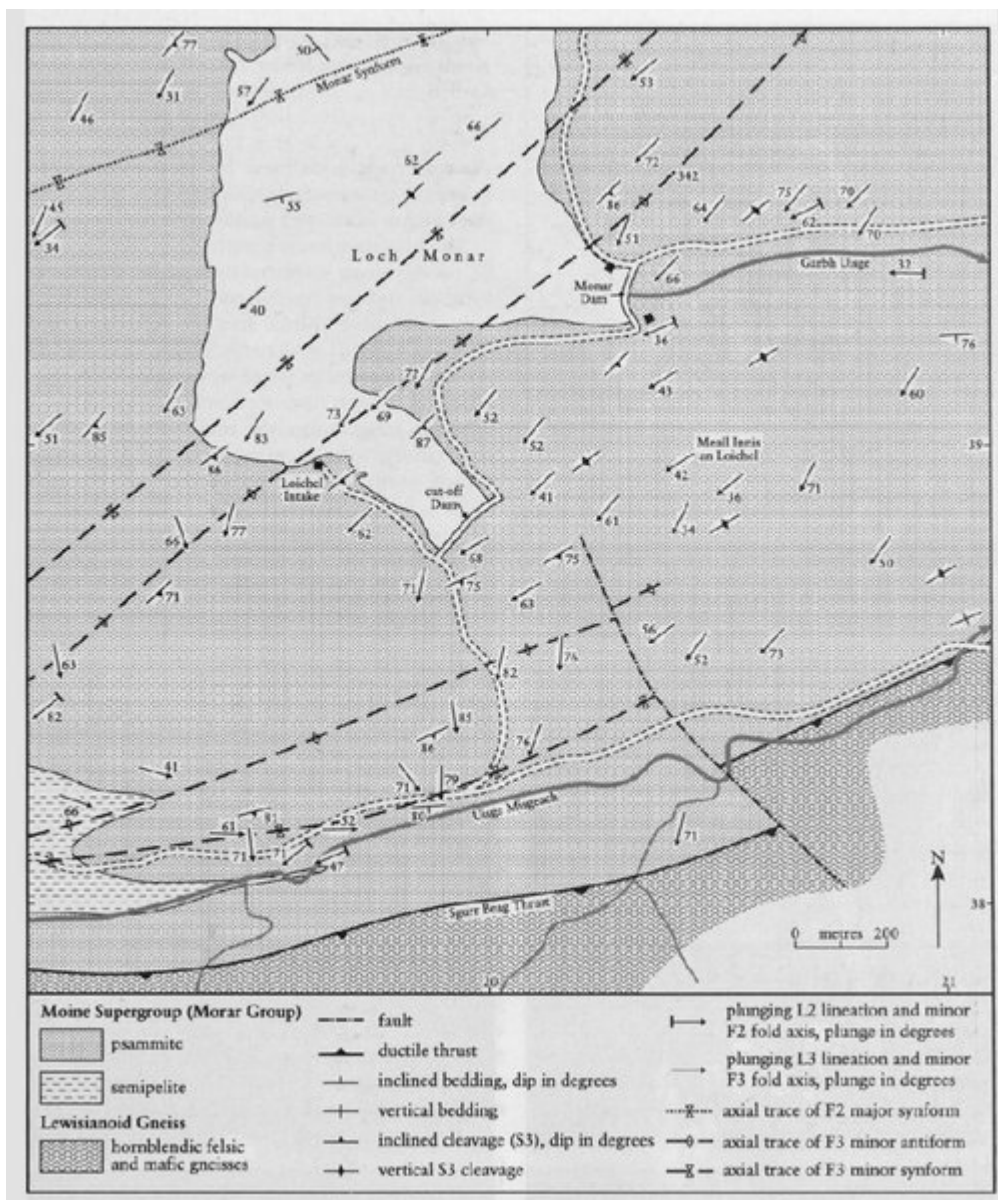
Tobisch *et al.* (1970) assessed the regional structural pattern from Glen Affric to Glen Cannich to Glen Strathfarrar. They allocated the Monar Synform and related minor structures to a locally developed Orrin Phase, which they interpreted as preceded by a Strathfarrar, Cannich and pre-Cannich phase. The Cannich phase gave rise to the main early folds and

related schistosity. Monar and Affric phases were also recognized as post-dating the Monar Synform. Powell (1974) rationalized these many fold phases, allocating them to two major penetrative deformation events, D2 and D3. Powell attributed D2 deformation (mainly Cannich Phase) to a Neoproterozoic event, and D3 (mainly Monar Phase) to a Grampian Event. Similar ductile fold and related structures do occur in much of the North-west Highlands, and commonly have been correlated. The F3 event is dated by U-Pb monazite ages of  $455 \pm 3$  Ma from the Glenfinnan area (Aftalion and van Breemen, 1980). If the two fold phases both relate to the Caledonian Orogeny then the D2 event probably occurred in the early Ordovician (c. 470–490 Ma) during the Grampian Event. However, fold chronologies are undoubtedly complex, and numerous geochronological studies suggest that pegmatite intrusion and D2-related metamorphism in the Moine rocks occurred during a Knoydartian orogenic event at around 750–800 Ma (e.g. van Breemen *et al.*, 1978; Rogers and Pankhurst, 1993; Tanner and Evans, 2003). In addition, the age of the D3 deformation has been questioned recently: it has been attributed to either the Grampian Event or the Scandian Event (Strachan *et al.*, 2002a).

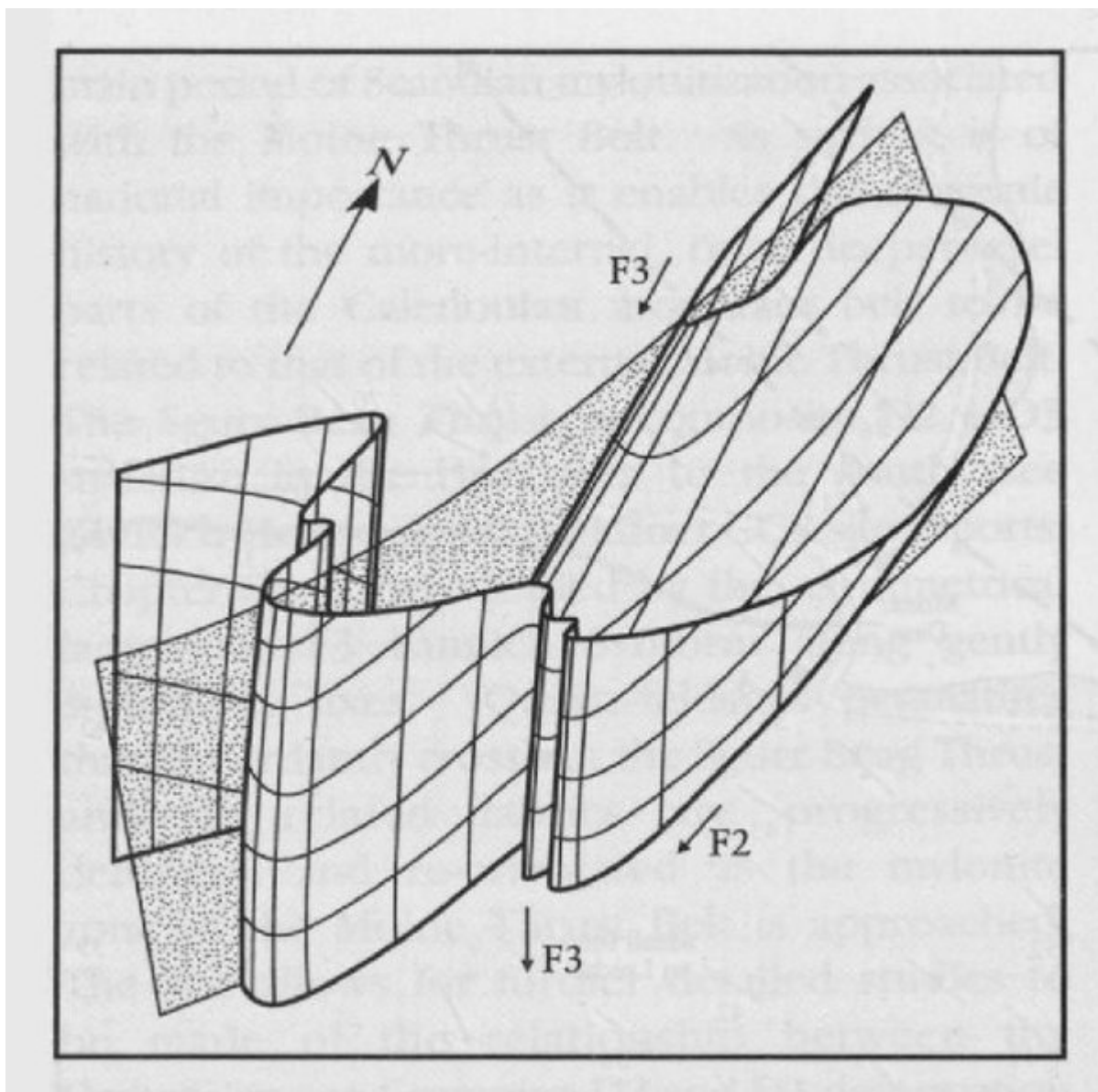
## Conclusions

The small-scale fold interference patterns involving thinly bedded Moine psammities and semipelites at the Loch Monar GCR site are among the best examples found in Britain. The three principal types of interference patterns, 'mushroom', 'crooked finger' and 'dome and basin', all can be seen at the site. Their geometry and mechanisms of formation have been rigorously studied (Ramsay, 1957a, 1960, 1962) and form a classic foundation on which subsequent work on structurally complex folded rocks has been based. Hence the site is of both national and international importance. The fold patterns result from the interaction of two distinct fold phases. The earlier phase resulted in a W-plunging major synform, the Monar Synform, and associated minor folds all with S- to SSE-dipping axial planes. The later phase is manifest as medium- to small-scale folds that plunge moderately steeply south-west with NE-trending near-vertical axial planes. Both fold phases were accompanied by amphibolite-facies metamorphism and developed penetrative axial-planar cleavages.

## [References](#)



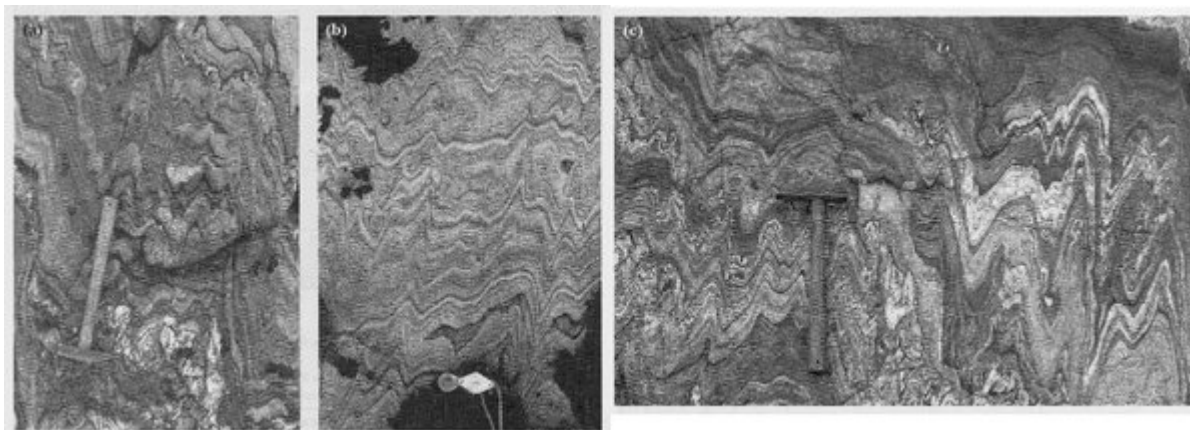
(Figure 7.7) Map of the Loch Monar GCR site and immediate surrounding area.



(Figure 7.8) Synoptic block diagram of the superposed folds at Loch Monar. After Ramsay and Huber (1987).

Lewis and Harris		North and South Uist, Barra	
Rock type	Structure and tectonic event	Rock type	Structure and tectonic event
Fault gouge, breccia, some cataclasite.	Steep faulting of Devonian, Carboniferous and Mesozoic age related to uplift and basin formation. Formation of Minch Fault.	Fault gouge, breccia, some cataclasite.	Steep faulting related to uplift and basin formation in the Devonian and Carboniferous. Dextral strike-slip on WNW-trending faults of Mesozoic age.
Phyllonite and mylonite. Folding of pre-existing mylonites. Crenulation cleavage. Lower greenschist-facies mineralogies.	Extension with top-to-the-E movements down-dip of mylonite belts. Probably of late Silurian or Early Devonian age. Related hydrous retrogression in OHFZ and footwall gneisses.	Phyllonite, mylonite, planar gouges.	Extension with top-to-the-E/ESE movements focused along mylonite belt margins. Probably of late Silurian or Early Devonian age.
Phyllonite and mylonite. Greenschist-facies mineralogies (biotite).	Thrust zones with movement towards the WNW. Attributed to sinistral strike-slip movements by some authors. Late Silurian (Scandian) age.	Phyllonite and mylonite. Greenschist-facies mineralogies (biotite).	Thrust zones with movement towards the WNW and possibly south-west. Attributed to sinistral strike-slip movements (top-to-the-NE) by some authors. Late Silurian (Scandian) age.
Pseudotachylite breccia and 'Mashed Gneiss'. Cataclasite and ultracataclasite zones. Gneisses with marked cataclastic and protomylonitic fabric.	Main thrust zones and lensoid zones of fault rock. Formed in relatively dry gneisses but now commonly retrogressed. Reflect major top-to-the-WNW thrust movements with multiple seismic movements. Mainly of late Silurian age (Scandian Event).	Pseudotachylite breccia and 'Mashed Gneiss'. Gneiss with marked cataclastic and protomylonitic fabric.	Well-defined western bounding thrust to OHFZ showing top-to-the-WNW movement. Some defined thrusts and areas of pseudotachylite development west of OHFZ. Local movement sense more variable. Probably of Late Silurian age (Scandian Event), but parts may be considerably older.
None identified.	Meso/Neoproterozoic Torridon Group sedimentary rocks preserved at depth in Minch Basin. Sequence thickest in hangingwall of OHFZ implying extensional movement along the fault zone at c. 1000 Ma.	None identified.	Meso/Neoproterozoic Torridon Group sedimentary rocks preserved at depth in Minch Basin. Sequence thickest in the hangingwall of OHFZ implying extensional movement along the fault zone at c. 1000 Ma.
Mylonitic gneisses.	Dextral oblique shear zone postulated in the Langavat Belt offsetting earlier elements of the OHFZ. Biotite cooling ages imply movement at c. 1100 Ma (Grenvillian).	No equivalent fault rocks identified.	
Mylonite, ultramylonite pseudotachylite and cataclasite. Lower amphibolite-grade mineralogies.	Mainly small-scale shallow E-dipping thrust zones with top-to-the-WNW sense of movement. Focused in part on Laxfordian granite sheets. Age of between 1550 Ma and 1100 Ma postulated.	No equivalent fault rocks identified.	

(Table 2.2) Rock types and kinematic history of the Outer Hebrides Fault Zone (OHFZ). Based on information from Fettes *et al.* (1992), MacInnes *et al.* (2000) and Imber *et al.* (2001).



(Figure 7.9) (a) Interference fold patterns ( $F_2 + F_3$ ) in thinly bedded Morar Group psammites, semipelites and pelites. Pegmatite veins are also present. Type-3 structures dominate here. The hammer is 37 cm long. Low-water exposure at Loch Monar, 300 m north-west of the cut-off dam. (Photo: J.R. Mendum, BGS No. P552321, reproduced with the permission of the Director, British Geological Survey, © NERC.) (b) Interference fold patterns ( $F_2 + F_3$ ) in thinly bedded Morar Group psammites and subsidiary semipelites. Type-1, Type-2 and Type-3 interference patterns are all represented here. The hand lens is 6 cm long. Low-water exposure at Loch Monar, 270 m north-west of the cut-off dam. (Photo: J.R.

*Mendum, BGS No. P552324, reproduced with the permission of the Director, British Geological Survey, © NERC.)(c)*  
*Interference fold patterns (F2 + F3) in thinly bedded Morar Group psammities and semipelites with early pegmatite veins. Type-2 and Type-3 interference patterns are represented here. The hammer is 37 cm long. Low-water exposure at Loch Monar, 220 m north-west of the cut-off dam. (Photo: J.R. Mendum, No. P552325, reproduced with the permission of the Director, British Geological Survey, © NERC.)*