Keele UNIVERSITY

THE GEOLOGY AND GEOCHEMISTRY OF THE METASEDIMENTARY ROCKS OF THE LOCH LAGGAN - UPPER STRATHSPEY AREA, INVERNESS-SHIRE

VoL II

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VOLUME TWO

CHAPTER 6 : METAMORPHISM

6.1 Introduction

The metamorphic history of the Loch Laggan-Upper Strathspey area has been established through the study of the mineral assemblages and fabrics developed in various lithologies and their relationships with the deformational events.

As a consequence of the bulk chemistries of the various lithologies in this study area, aluminosilicate phases were not developed during the regional metamorphism, even where P.T. conditions may have been favourable. Therefore the classical Barrovian zones of metamorphic grade cannot be easily applied in this area.

The aluminosilicate phases, andalusite and sillimanite, together with cordierite are developed only in the thermal aureole of the Corrieyairack Granite Complex and their parageneses will be considered in detail in section 7.4 on contact metamorphism.

Mineral assemblages in both calc-silicates and semi-pelites indicate that low to middle amphibolite facies conditions prevailed at the climax of the regional metamorphism. Two main prograde regional metamorphic episodes, M1 prior to D1 and MP1, post tectonic to D1 separated by MS1 syntectonic to D1 were recognised. Both were approximately of the same grade, and were followed by the localised contact metamorphism in the aureole of the Corrieyairack Granite Complex and a widespread retrograde metamorphic event, MP3, which is post-tectonic to D3.

The petrology of the calc-silicate rocks collected in the present study area will now be discussed and related to the metamorphic events.

6.2 Calc-silicate Petrology and Metamorphism

6.2.1 Introduction

The calc-silicate rocks usually occur as pale and speckled thin bands and pods within their psammitic and semi-psammitic host rocks. The areal distribution of the collected calc-silicate parageneses is given in Fig. 6.1. Their mode of field occurrence has been described in Chapter 4.

Calc-silicate rocks are extensively developed in both the Moine rocks of both the NW and Central Highlands of Scotland and the Grampian Division rocks (Kennedy 1949; Winchester, 1970, 1974; Tanner, 1976, Powell et al, 1981). Kennedy (1949) first used them for metamorphic zonation in the Moines of the Western Highlands. He recognised four zones defined by the following mineral assemblages with increasing grade.

1. Zoisite-(calcite)-biotite
2. Zoisite-hornblende
3. Anorthite-hornblende
4. Anorthite-pyroxene.

He correlated zones 1 and 2 with Eskola's epidote-amphibolite facies, zone 3 with the amphibolite facies and zone 4 with the pyroxene-hornfels facies. He also correlated zones 3 and 4 with Barrow's kyanite and sillimanite zones, respectively, on the basis of occasional occurrences of these alumino silicates in adjoining pelitic units.

Tanner (1976) as a result of more extensive work in the Kinloch Hourn area of the Western Highlands, produced a modification of Kennedy's zonation which took into account the progressive increase in the anorthite content of plagioclase with metamorphic grade. He recognised the following assemblages:

1. Albite-zoisite-calcite-biotite-garnet (+ muscovite)
2. (a) Oligoclase-zoisite-calcite-biotite-garnet (-hornblende-muscovite)
   (b) Andesine-zoisite-biotite-garnet(-hornblende)
   (c) Andesine-zoisite-hornblende-garnet(-biotite)

3. (a) Bytownite/anorthite-hornblende-garnet

(b) Bytownite/anorthite-pyroxene-garnet(-hornblende)

He found precise correlation with the Barrovian zones difficult but correlated zones 2, 3a and 3b with the staurolite, kyanite and sillimanite zones respectively on the basis of rare occurrences of these minerals in the pelitic rocks within the various zones.

The control exerted by bulk rock chemistry, especially, the CaO/Al_2O_3 ratio, on the mineral assemblages developed in the calc-silicate rocks were recognised in several studies by Winchester (1972, 1974a, 1974b). Using the CaO/Al2O3 ratio as a compositional control, he precisely located metamorphic isograds in northern Ross-shire, Scotland (Winchester 1972, 1974a). In an extension of this work, he built up a zonal metamorphic map of the Scottish Caledonides (Winchester 1974b).

Winchester and Whittles (1979) used both bulk rock chemistry and the mineral assemblages of the calc-silicates in the Killin area, Inverness-shire, to determine the three-dimensional configuration of metamorphic isograds. Here, they recognised the following zones:

1. Pyroxene: pyroxene in all "white" calc-silicates with a CaO/Al_2O_3 ratio exceeding 0.7.
2. Bytownite : bytownite in all calc-silicates with a CaO/Al_2O_3 ratio exceeding 0.7.
3. Hornblende: hornblende in all calc-silicates with a CaO/Al_2O_3 ratio exceeding 0.4.
4. Hornblende + biotite: a transitional zone in which both hornblende and biotite may be present in calc-silicates with CaO/Al_2O_3 ratio exceeding 0.4.

Wells (1979) applied thermodynamic analysis to quantify the pressure-temperature conditions recorded by the calc-silicate mineral assemblages of part of the Central Highlands of Scotland. His results placed much of the region in the kyanite zone, although he did not have a good local control.

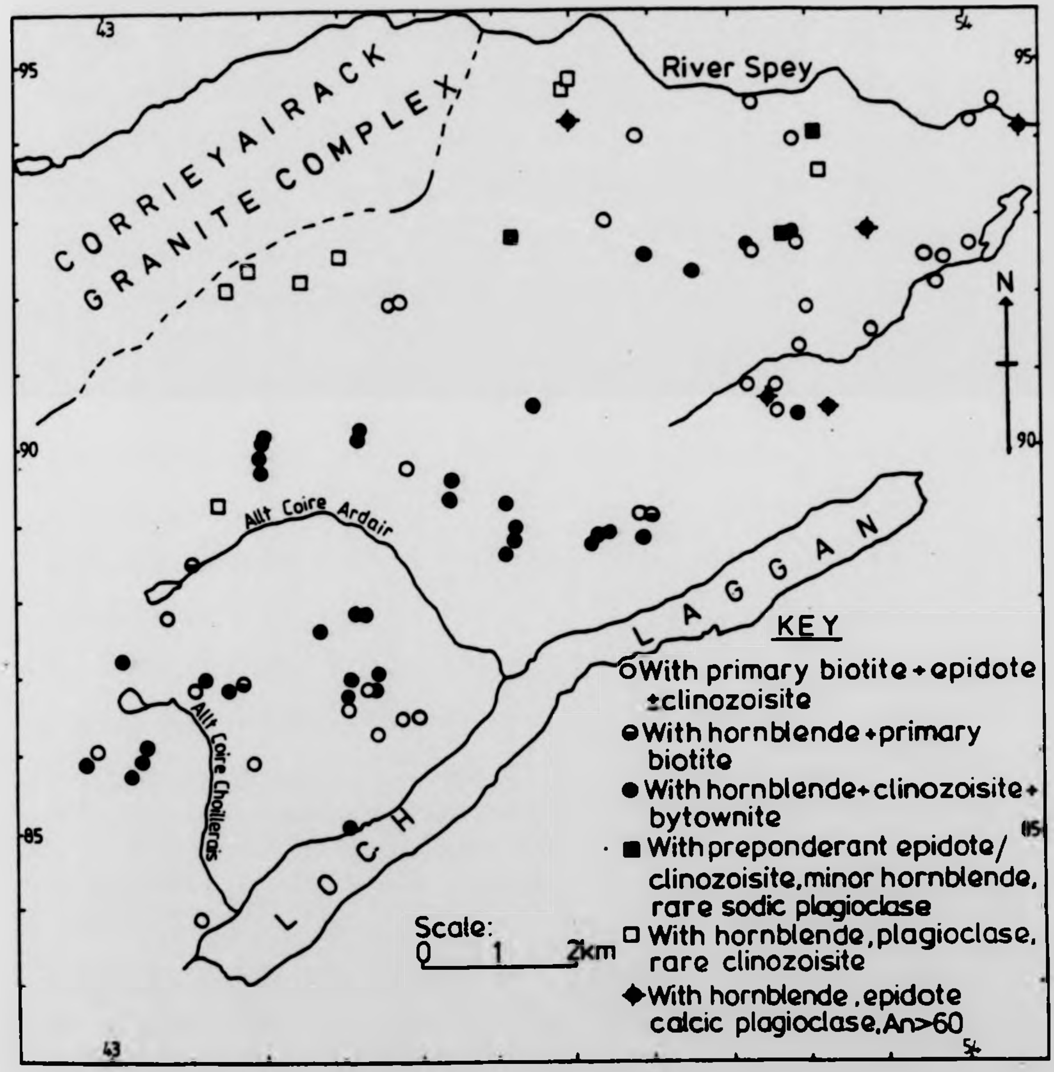

Fig.6.1:The geographical distribution of sampled calc-silicates

More recently Powell et al (1981) have used the marked variation of the anorthite content of the calc-silicate rocks in south western Highlands of Scotland to establish a major break defining the Sgurr Beag Slide.

Haselock (1982) has also used calc-silicate mineral assemblages in elucidating the metamorphic history of the Corrieyairack Pass area, north of the present study area. She recognised three episodes of regional metamorphism followed by a contact metamorphism associated with the intrusion of the Corrieyairack and Allt Crom Granite Complexes. Within this area she found an eastwards increase in peak metamorphic grade, on the basis of the occurrences of bytownite /anorthite in place of oligoclase/andesine in calc-silicates of comparable CaO/Al_2O_3 ratio.

Whittles (1981) and Haselock (1982) have also recognised a green variety of calc-silicate rocks, restricted to the Knockchoilum Semi-psammite and the Fechlin Psammite, which contain varying amounts of epidote, pyroxene, actinolitic amphibole, andesine, quartz and calcite but generally lacking garnet.

This variety, as well as the calcite-rich type described by Haselock (1982), are regarded as the products of local variations in the fugacity of fluid phases, particularly CO_2 and O_2 and the undetermined effects of the intrusive Foyers and Allt Crom Granites (see also Chapter 2 for a full discussion).

6.2.2 Petrography of the Calc-silicate rocks

Detailed petrographic study of 245 thin sections of the calc-silicate rocks has resulted in the recognition of the following mineral assemblages:

1. Epidote + biotite + oligoclase (andesine) $\pm$ garnet (+biotite$\pm$ muscovite$\pm$ zoisite$\pm$calcite$\pm$ sericite)
2. Epidote + hornblende + labradorite + garnet (+zoisite $\pm$calcite$\pm$ sericite)

3. Clinozoisite + biotite + andesine + garnet (+zoisite ± biotite ± muscovite +sericite).

4. Clinozoisite + hornblende ± biotite + bytownite + garnet (+ zoisite ±biotite ± sericite)

5. Hornblende + bytownite + garnet (+ zoisite ± epidote ± calcite + sericite).

Secondary retrograde mineral phases are placed in parentheses. Quartz is an abundant constituent of each assemblage and accessory phases include sphene, apatite, zircon and less commonly magnetite.

Assemblages 1 and 2 contain major epidote and this is reflected in their high oxidation ratios (Table 6.1, Appendix). Assemblages 3,4 and 5 comprise most of the observed calc-silicate parageneses and contain abundant primary clinozoisite.

Modal analyses of selected calc-silicate rocks reflecting the various assemblages were obtained by counting 500 to 1000 points per thin section, and are presented in Table 6.1.

Plagioclase compositions have been determined by the Michel-Levy method, by measuring maximum extinction angles on 010 planes.

Petrographic Descriptions

Assemblages 1 and 2

Epidote is the dominant epidote-group mineral.It commonly occurs as subhedral to anhedral grains 0.5 - 1.5 mm in diameter with the larger grains predominating in group 2 assemblages. They are commonly pleochroic from colourless to pale yellow-green and zoned with iron-rich cores and less iron-rich rims. Epidote also commonly rims allanite cores and is occasionally poikiloblastic, with small quartz, sphene, hornblende, garnet and biotite inclusions (Plate 6.1a).

Plate 6.1a : Epidote (E) intergrown with biotite and sphene, (S) in group 1 assemblage. NN 519912. Plane polarised light. Scale bar represents 0.1mm.

Plate 6.1b : Hornblende (H) intergrown with epidote, (E) and garnet, G, in group 2 assemblage. NN 528928. Plane polarised light. Scale bar represent 0.1mm.

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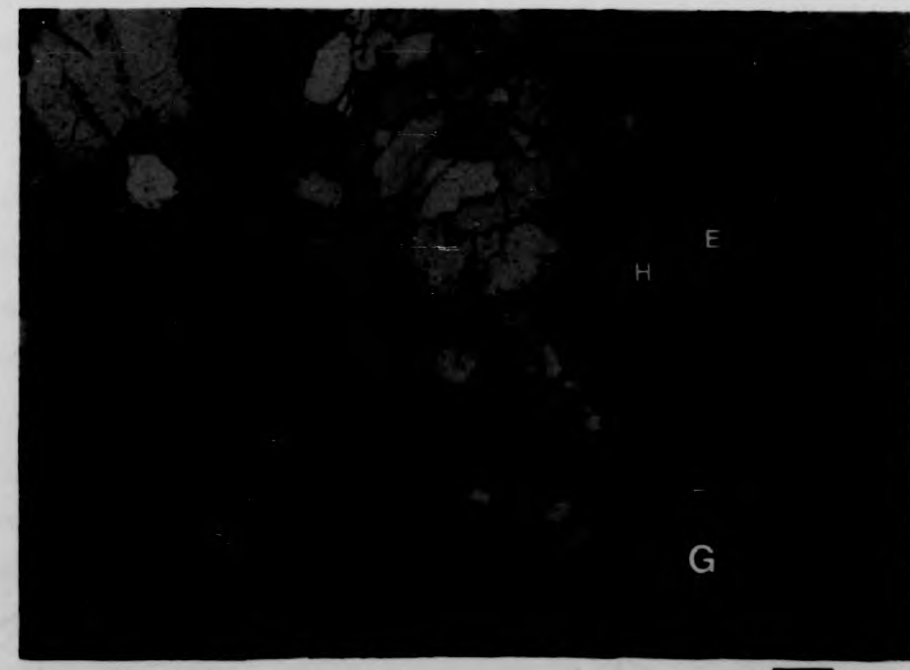

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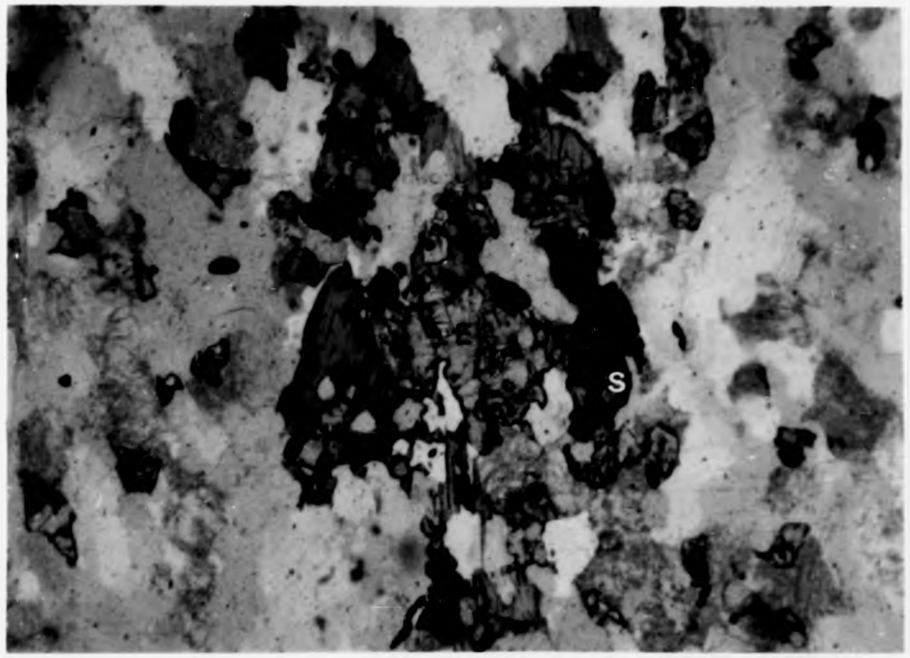

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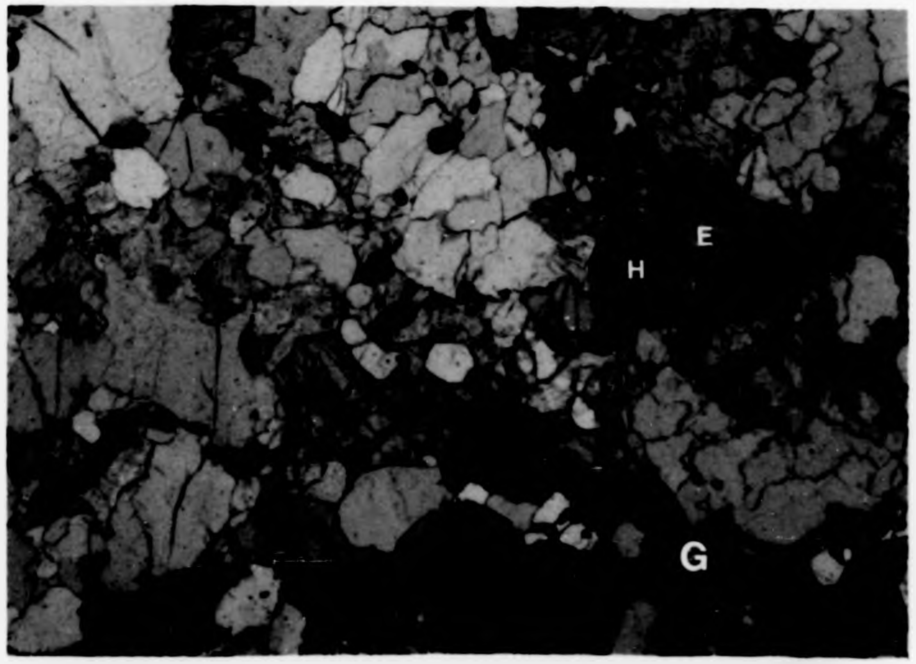

<u>Zoisite</u> occurs as small idioblastic to subidioblastic prisms 0.2 - 0.4 mm long often enclosed in plagioclase and occasionally intergrown with epidote.

<u>Biotite</u> occurs as subidioblastic laths about 0.5 - 1.0 mm long intergrown with epidote in group 1 assemblages (Plate 6.1a) Two generations of olive to reddish brown biotite may be present, the second generation biotite is commonly porphyroblastic and overgrows early minerals such as hornblende. Occasionally, the early biotite is overgrown by late disoriented muscovite porphyroblasts, while secondary chlorite may also be an alteration product.

<u>Hornblende</u> occurs in place of biotite as the major ferromagnesian phase in group 2 assemblages where it may be in a few instances partly replaced by second generation biotite. Hornblende occurs as green subidioblastic plates 1-2.5 mm long intergrown with epidote, quartz and plagioclase (Plate 6.1b). It also poikiloblastically encloses small quartz and clinozoisite grains. Early hornblende is occasionlly overgrown by late fibrous amphibole. Strained extinction as a result of late deformation, probably D4, is occasionally shown by the grains.

Late, colourless, acicular amphibole occasionally overgrows hornblende, epidote, and garnet. The exact identity of this amphibole is not clear. Analyses by Winchester (pers. comm) of similar late, pale amphiboles in some calc-silicate rocks showed that they have the same composition as hornblende.

<u>Garnet</u> occurs as subidioblastic to xenoblastic porphyroblasts 0.5-3mm in diameter with the coarser grains occurring in the group 2 assemblages. It is commonly full of inclusions of quartz, epidote, plagioclase, and hornblende. Textural relations in which tiny, xenoblastic, "corroded" garnet grains are surrounded by epidote, calcite and occasionally late fibrous amphibole suggest some late garnet replacement.

Plate 6.2a : Late colourless prismatic amphibole (A) intergrown with clinozoisite (CZ) and quartz (Q). NN 518927. Plane polarised light. Scale bar represents 0.1mm.

Plate 6.2b : Late zoisite (Z) intergrown with Clinozoisite (CZ), in calc-silicate. NN 520940. Crossed nicols. Scale bar represents 0.1mm

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Plagioclase occurs as subidioblastic to xenoblastic grains 0.2-1mm in diameter forming the groundmass of the rock. It often shows twinning on the albite law , and is commonly zoned with more anorthite rich cores. In group 1 assemblages it is oligoclase-andesine (An28-An50) and labradorite (An55-An70) in group 2 assemblages. It may be intensely sericitised and is occasionally overgrown by late muscovite and zoisite prisms which are disoriented.

Quartz occurs as xenoblastic grains 0.4-2mm long commonly showing undulose extinction and occasional, deformation bands as well as subgrain development.

Assemblages 3, 4 and 5

Clinozoisite occurs mainly in groups 3 and 4a and 5 as xenoblastic near-equidimensional grains 0.4-2mm in diameter. The coarser grains occur mainly in the group 4 assemblages. Clinozoisite is commonly intergrown with quartz and plagioclase (Plate 6.2a). It is occasionally rimmed by late zoisite and also by late biotite and acicular amphibole. Clinozoisite occasionally shows simple twinning and colour zoning.

Zoisite is a minor late phase sometimes intergrown with or rimming clinozoisite. It also occasionally occurs as small idioblastic prisms in retrogressed plagioclase (Plate 6.2b).

Biotite occurs as reddish-brown subidioblastic laths 0.5-1.6 mm long. Primary biotite occurs mainly in group 3 assemblages where it is commonly intergrown with clinozoisite. It may also occur as a late minor phase in all three assemblages in which it appears to replace hornblende (Plate 6.3a). Biotite itself is occasionally replaced along the cleavages by chlorite.

Hornblende forms between 1.5 to 20 modal percent in assemblage groups 4 and 5, increasing in modal abundance from group 4 to group 5. It often

Plate 6.3a :Late biotite (B) growing on and probably replacing hornblende (H) in calc-silicate. NN 500891. Plane polarised light. Scale bar represents 0.05mm

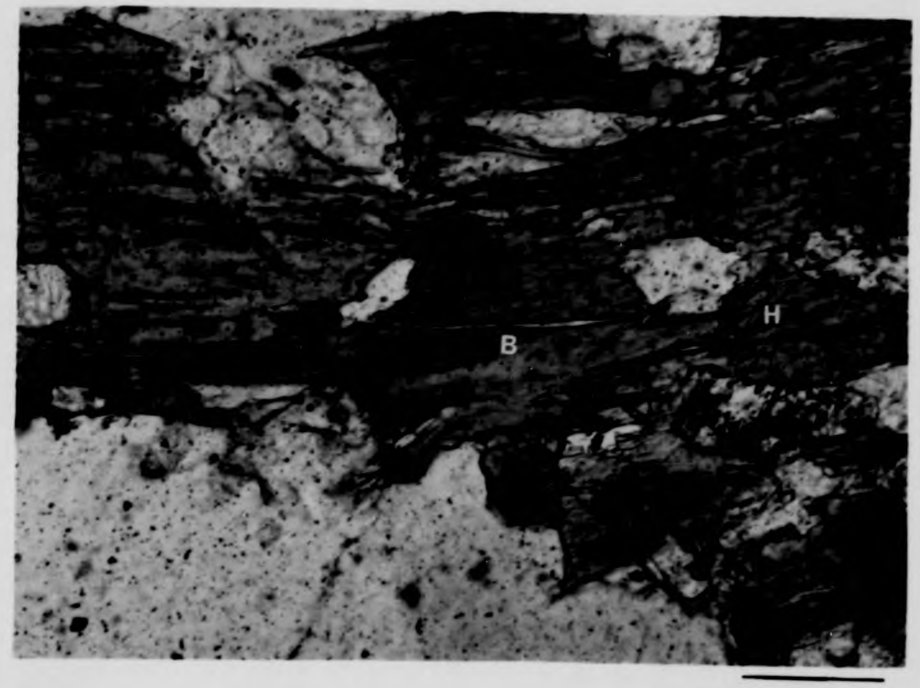

Plate 6.3b : Early garnet enveloped by hornblende grains defining S1. Calc-silicate NN 444893. Plane polarised light. Scale bar represents 0.1mm

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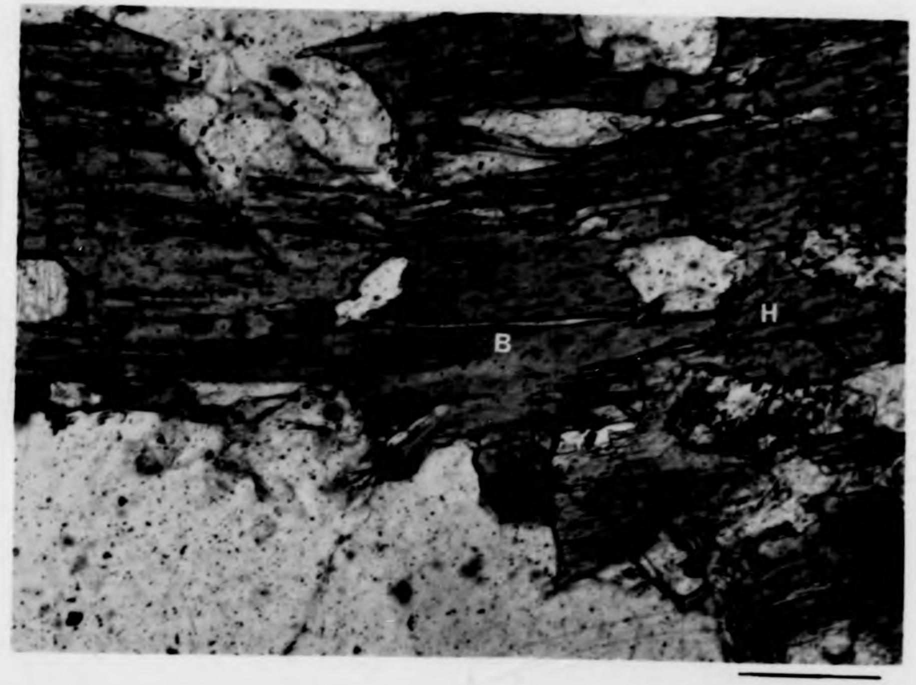

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Plane polarised light. Scale bar represents 0.1mm

	566	764	808	63	20	269	50	453	557	420	362	773	8350	3A	276
Quartz	33.4	48.9	39.1	39.7	39.0	23.4	38.8	37.6	31.2	56.2	23.3	37.9	30.8	23.5	38.9
Plagioclase	18.6	14.1	24.9	25.8	17.3	37.4	24.4	32.8	35.9	28.3	43.8	30.9	31.0	0.5	5.0
Biotite	5.9	8.2		4.8	-	2.4	11.2	0.1	2.0	-	1.1	0.6	-	-	-
Muscovite	1.0	1.5	2.5	1.0	-	-	0.1	3.6	-	-	-	-	-	-	-
Garnet	5.8	3.8	1.0	5.6	3.8	2.8	6.2	2.4	7.9	2.7	6.1	10.5	6.0	3.1	3.1
Hornblende	-	-		-	4.8	16.6	-	trace	3.6	7.5	18.1	17.6	19.00	2.0	1.3
Clinozoisite	4.2	-		0.5	-	2.0	2.6	18.00	17.2	3.4	3.6	0.2	-	68.0	43.9
Zoisite	1.9	1.4	0.5	5.6	1.2	-	-	trace	0.6	-		-	-	0.5	3.5
Epidote	26.9	20.8	30.4	14.0	26.5	15.00	-	-	0.5	-		-	-	-	-
Calcite	-	-		1.0	trace	0.2	0.4	trace	-	0.2	1.6	0.8	-	-	trace
Late Actinolite	-	-		-	6.2	-	-	-	trace	trace	-	0.8	-	0.2	3.1
Sphene	2.1	0.8	1.0	trace	0.8	0.2	0.8	0.8	1.0	1.2	2.0	trace	1.0	2.1	0.5
Ore	-	trace		trace	trace	-	-	-	-	trace	trace	trace	-	trace	-
Apatite	trace	"		"	trace	-	-	trace	trace	trace	trace	"	trace	trace	trace
Zircon	trace	"		"	trace	-		trace	trace	trace	trace	"	-	trace	trace
Chlorite	trace	"	0.5	"	-	-	0.4	1.2	trace	-	trace	0.5	-	-	o.5
Sericite						-	15.0	3.2					2.2		
Total	99.8	99.5	99.9	98.0	99.6	100	99.9	99.7	99.9	99.5	99.6	99.8	100	99.9	99.7

566, 764, 808, 63 : assemblage 1
20, 269 : assemblage 2
50, 453 : assemblage 3
557, 420, 362 : assemblage 4
773, 8350 : assemblage 5
3A, 276 : assemglages with preponderant clinozoisite.

TABLE 6.1 : Modal analyses of the calc-silicate rocks

occurs as green xenoblastic plates 0.5 - 2mm in length, poikiloblastically enclosing small quartz, clinozoisite and plagioclase grains. Two groups of hornblende grains may be recognised: 1. those syntectonic with garnet porphyroblasts (Plate 6.3b) and defining the S1 fabric, and 2. post-tectonic disoriented grains, probably formed post-D2.

Hornblende may be rimmed by late acicular amphibole, and is occasionally overgrown by late biotite (Plate 6.3a), and chlorite occasionally intergrown with calcite formed by the calcium released during hornblende breakdown.

Garnet occurs as subidioblastic to xenoblastic porphyroblasts 1-2.5 mm in diameter. Two generations of garnet were recognised: early syntectonic poikiloblasts full of inclusions of quartz, clinozoisite and wrapped in S1 by early hornblende laths (Plate 6.3b) and latter massive rims enclosing early hornblende (Plate 6.4a). Garnet is occasionally partially replaced by epidote, chlorite and calcite.

Plagioclase forms between 0.5 and 44 modal percent of the rock in assemblage groups 4 and 5 (see Table 6.1). It has a compositional range of andesine-labradorite (An35-58) in group 3 and labradorite-bytownite (An66-80) in group 4 and 5 assemblages. It forms xenoblastic grains 0.5-2mm in diameter constituting the groundmass of the calc-silicates.

It is commonly extensively replaced by sericite, late zoisite/clinozoisite (Plate 6.4b) and secondary muscovite.

Quartz occurs as xenoblastic grains 0.4 - 3mm in diameter which often show undulatory extinction and occasionally deformation bands. Quartz grains often show sub-grain development.

6.2.3 Mineral Reactions

The mineral assemblage present in each calc-silicate rock is determined

Plate 6.4a : Later garnet enclosing early hornblende (H).

Calc-silicate NN 444893

Plane polarised light. Scale bar represents 0.1mm.

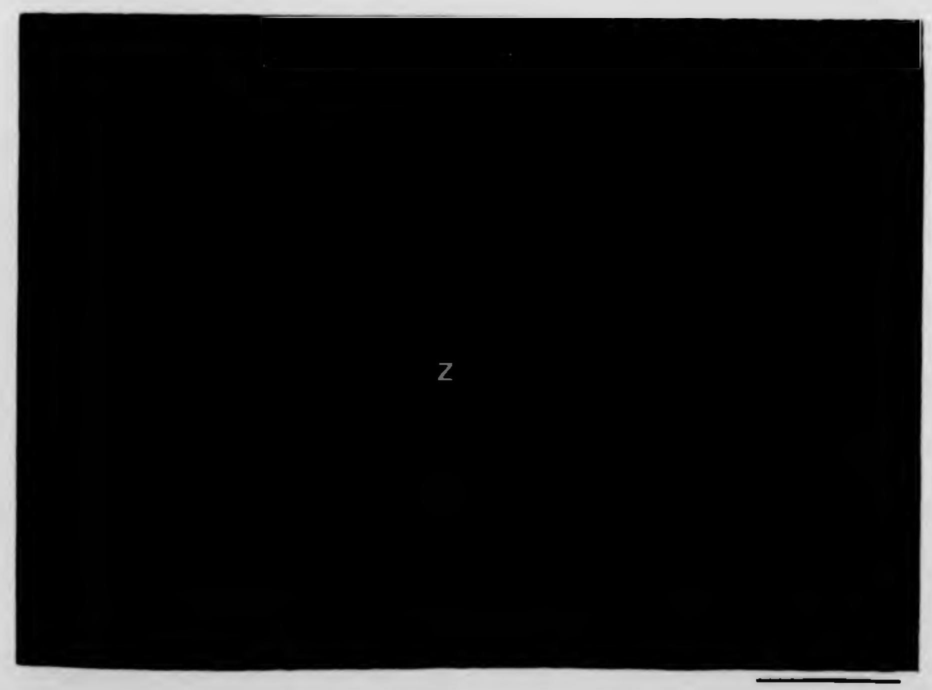


Plate 6.4b : Late pris m of zoisite (Z) growing across plagioclase

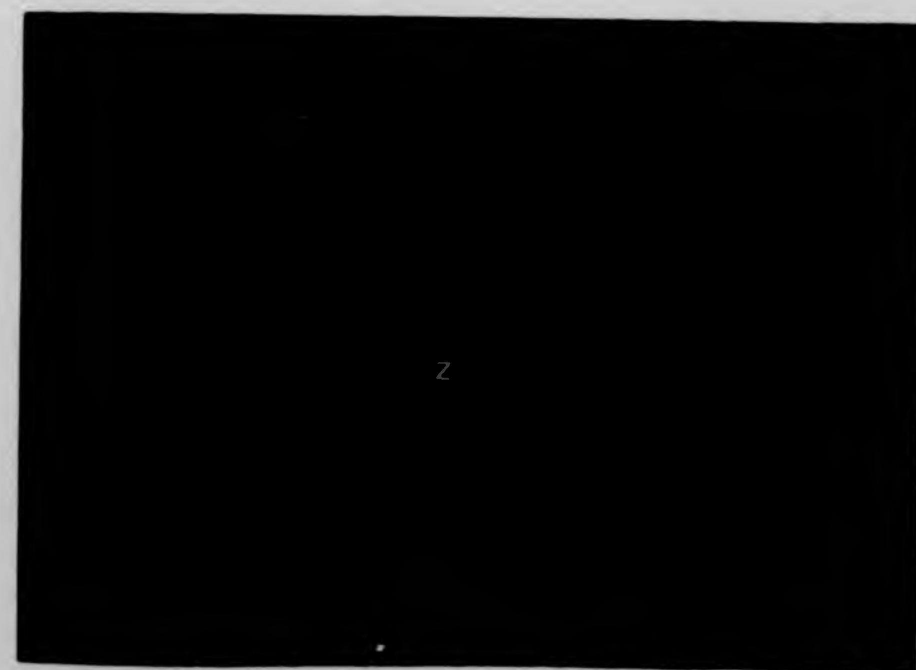
in a calc-silicate, NN 481886.

Plane polarised light. Scale bar represents 0.05mm.

Plate 6.4a : Later garnet enclosing early hornblende (H).

Calc-silicate NN 444893

Plane polarised light. Scale bar represents 0.1mm.



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(a)

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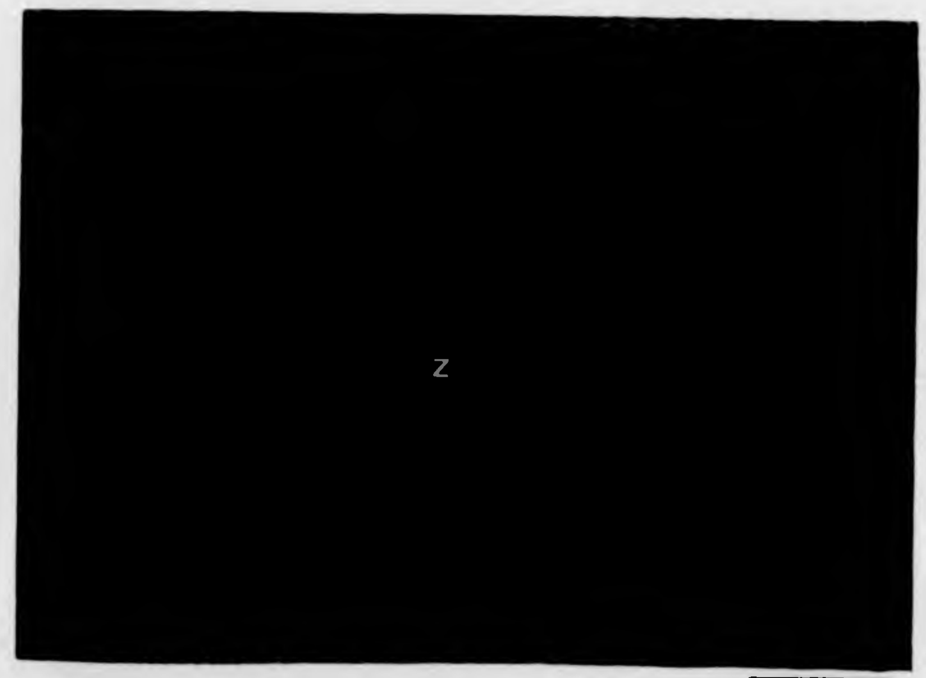
Plane polarised light. Scale bar represents 0.1mm.



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Plane polarised light. Scale bar represents 0.05mm.

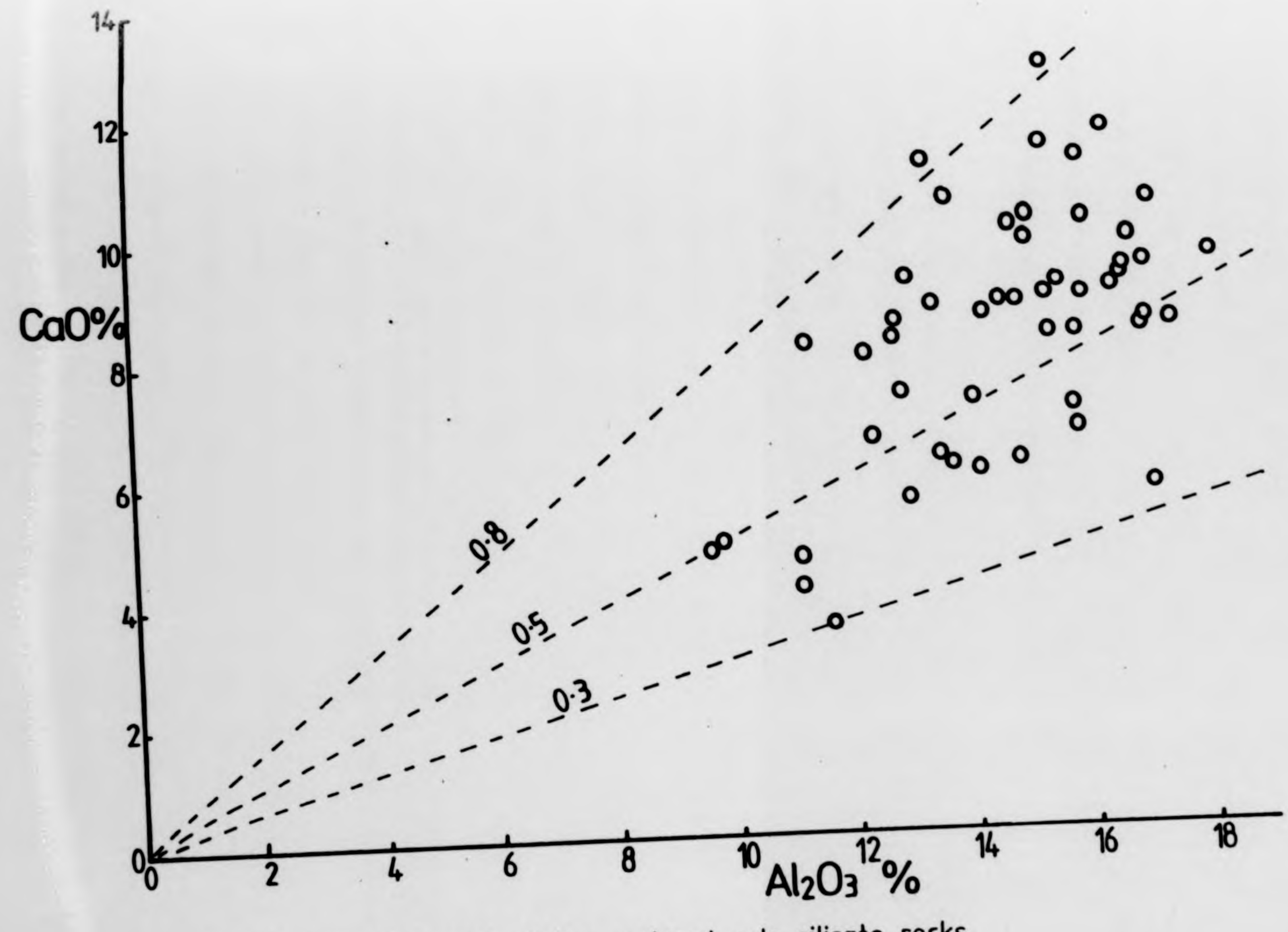

Fig. 6.2: $CaO-Al_2O_3$ plot of the analysed calc-silicate rocks

by the bulk chemical composition of the rock and the physical conditions including temperature and both lithostatic and fluid pressure, to which the rock has been subjected. The dominant control which the CaO/Al_2O_3 ratio of the calc-silicates have on their mineralogies have been recognised by Winchester (1972, 1974a, 1974b), Tanner (1976), Winchester and Whittles (1979) Tanner and Miller (1980), Powell et al. (1981) and Haselock (1982). They found that prograde reactions took place in rocks with higher CaO/Al_2O_3 ratios at relatively somewhat lower pressure and temperature conditions.

It is, therefore, necessary to constrain the CaO/Al_2O_3 ratio of the calc-silicate rocks within narrow limits when the mineral assemblages, developed within the various samples are considered. It is also very likely that other components probably influenced the mineral parageneses developed in the calc-silicate rocks. The following general trends were observed:

a. there is a general increase of CaO with increase in Al_2O_3 but this positive correlation is weak ($r = 0.46$, Fig 6.2)

b. Rocks with the lowest CaO/Al_2O_3 ratios i.e. 0.35-0.45, also possess the highest K_2O/Al_2O_3 ratios i.e. 0.1 - 0.15 (see Figs 6.2 and 6.3). These rocks typically contain primary biotite and some epidote. Garnet and andesine are always present but hornblende is not common.

c. Hornblende tends to be a major phase in calc-silicates with CaO/Al_2O_3 ratios exceeding 0.45. Also, the anorthite content of the associated plagioclase rises to labradorite-bytownite.

d. The relationship between the CaO/Al_2O_3 ratio of the rock and its anorthite content is however not a simple one. While the An content of the plagioclase generally increases with the CaO/Al_2O_3 ratio, it also depends on the partitioning of Ca^{++} between plagioclase and the coexisting Ca-bearing phases (including calcite). For a given CaO/Al_2O_3 ratio rocks with preponderant modal clinozoisite / epidote generally possess less An-rich plagioclase than those with preponderant hornblende (Compare Samples 3A and 773, table 6.1.)

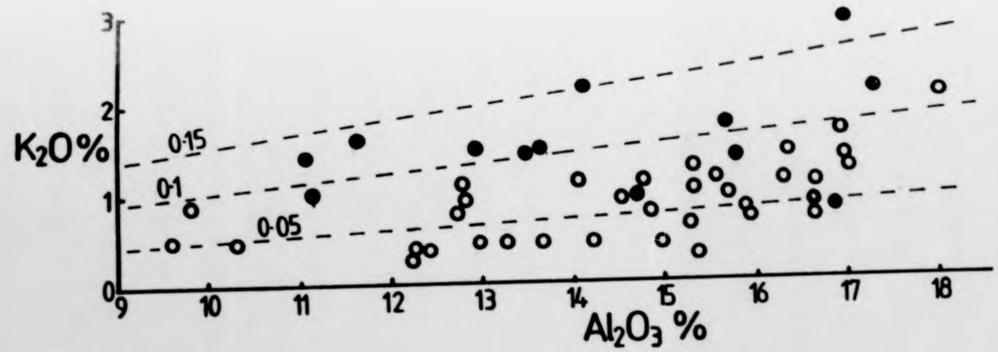

Fig. 6.3: $K_2O - Al_2O_3$ plot of the analysed calc-silicate rocks

Calc-silicates with plagioclase,

An < 70 : ●

An > 70 : o

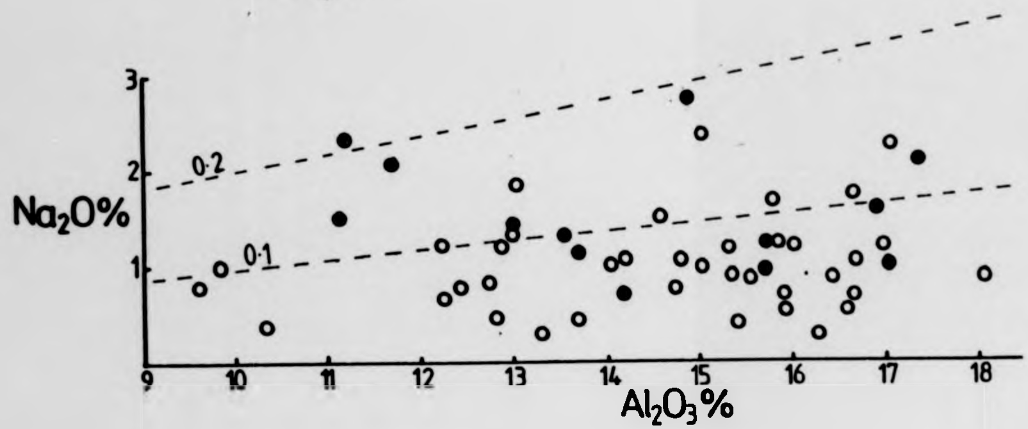

Fig. 6.4: $Na_2O - Al_2O_3$ plot of the analysed calc-silicate rocks

e. Plots of K_2O and Na_2O against Al_2O_3 (Figs 6.3 and 6.4) show that the highest alkali/Al_2O_3 ratios are found in rocks containing biotite, muscovite and less calcic plagioclase. These characteristics may represent original compositional features or record an influx of the alkalis under retrograde conditions (Tanner and Miller, 1980).

f. Also, plots of the atomic ratios K/Al and Na/Al against Ca/Al (Figs 6.5 and 6.6) show good negative correlations (r= 0.72 and -0.64 respectively) indicating antipathetic relationships between the alkalis and calcium. This may reflect original sedimentary compositional effects or metasomatism. Because some calc-silicate samples collected from different bands in the same location have been found to plot separately, the case for original compositional effect is strong. However, the case for some later metasomatism is also supported by the presence of secondary biotite and muscovite.

Petrographic evidence shows that the rocks of the Loch Laggan-Upper Strathspey area bear the effects of a widespread retrograde event in which earlier prograde minerals have been variously retrogressed to lower grade phases. This late retrogression in this region of the Highlands has been reported by Wells (1979), Clayburn (1981) and Haselock (1982). The main retrogressive phase transitions in this area include:

1. <u>The formation of late biotite and muscovite</u>

This is mainly controlled by the activity of K+ ions. Winchester (1972) proposed the following reaction for the retrograde replacement of hornblende by biotite in Fannich Forest, with the adjacent rocks acting as the source of microcline:

$$\underset{\text{Hornblende}}{2Ca_2(Mg,Fe)3\ Al_4Si_6O_{22}(OH)_2} + \underset{\text{microcline}}{2KAl\ Si_3O_8} = \underset{\text{biotite}}{K_2(Mg,Fe)_6Al_2Si_6O_{2o}(OH)_4}$$

$$+\underset{\text{quartz}}{4SiO_2} + \underset{\text{anorthite}}{4CaAl_2Si_2O8} \quad (1)$$

This reaction involves the production of a more anorthite-rich plagioclase, which is not compatible with the common association of biotite with less calcic

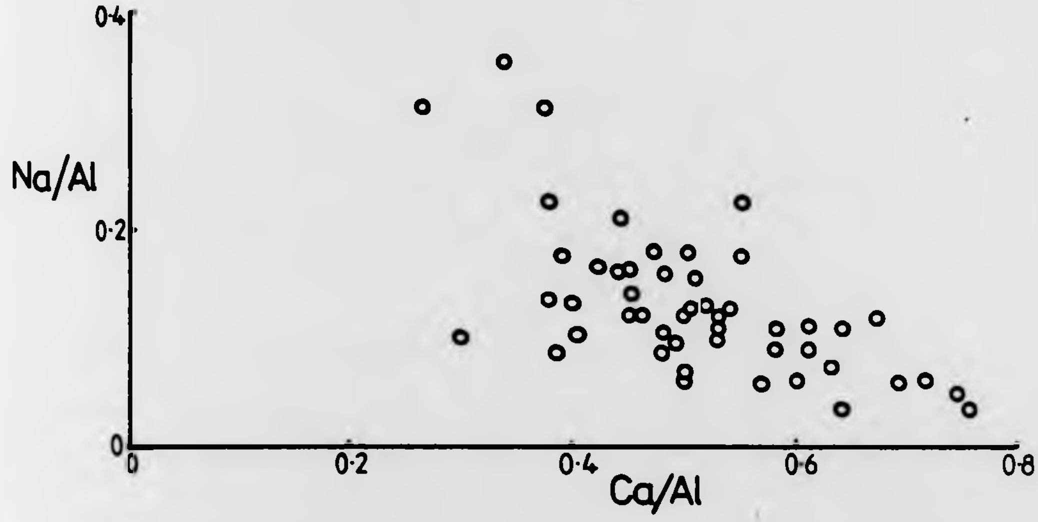

Fig. 6.5: Na/Al – Ca/Al plot of the analysed calc-silicate rocks

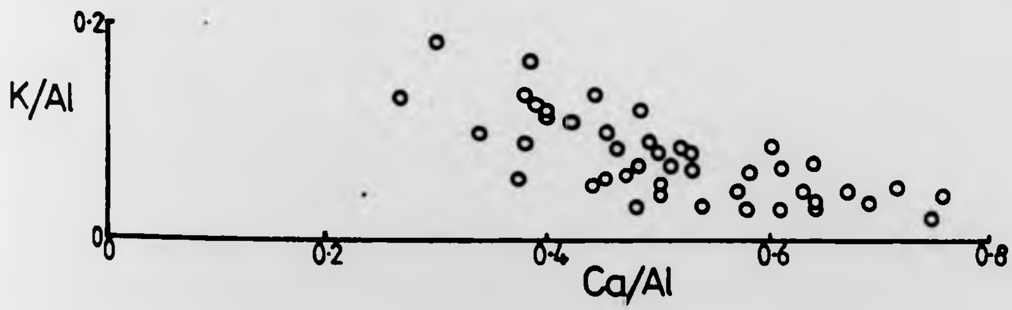

Fig. 6.6: K/Al – Ca/Al plot of the analysed calc-silicate rocks

plagioclase.

An alternative reaction put forward by Kennedy (1949) and quoted by Tanner (1976):

$$2Ca_2(Fe, Mg)_3Al_4\ Si_6\ O_{22}\ (OH)_2 + 2K^{++}\ 2OH^- = K_2(Fe,Mg)\ _6Al_2Si_6O_{20}(OH)_4 + 2Ca_2Al_3Si_3O_{12}(OH) \quad (2)$$

hornblende — biotite — clinozoisite

is more likely given the commonly observed formation of new zoisite/clinozoisite in association with biotite. K^+ would be derived from fluids emanating from the host rocks.

2. The formation of late zoisite/clinozoisite

The antipathetic relationship between preponderantly high modal clinozoisite and minor hornblende and plagioclase was observed in several calc-silicate samples (see Table 6.2). as well as textural evidence suggesting the breakdown of garnet.

The retrograde hydration of plagioclase with concomitant breakdown of garnet may be described as:

$$Ca_3Al_2Si_3O_{12} + 5CaAl_2Si_2O_8 + 2H_2O = 4\ Ca_2Al_3Si_3O_{12}(OH) + SiO_2 \quad (3)$$

grossular component of garnet — plagioclase — clinozoisite/zoisite

Alternatively this plagioclase replacement may be formulated as:

$$3CaAl_2Si_2O_8 + Ca^{++} + 2OH^- = 2\ Ca_2Al_3Si_3O_{12}(OH) \quad (4)$$

plagioclase — clinozoisite/zoisite

Ca^{++} comes from the breakdown of garnet as already observed. These reactions produce clinozoisite or zoisite at the expense of plagioclase and are compatible with petrographic observations. The rare plagioclase observed in these calc-silicates are typically less calcic than that in a hornblende-plagioclase -rich calc-silicate with the same CaO/Al_2O_3 ratio (see samples 3A and 773,

Table 6.1). These observations are in agreement with those of Winchester (1972) that plagioclase-free zoisite-quartz assemblages indicate retrograde replacement of plagioclase by zoisite.

The common association of hornblende, clinozoisite and plagioclase in calc-silicate rocks may be described as:

$$\text{Hornblende + calcic plagioclase} \rightleftharpoons \text{Epidote + less calcic plagioclase + garnet (andraditic)} \quad (5)$$

Petrochemical evidence from this study indicates that this equilibrium is strongly controlled by the oxidation ratio (molecular $2Fe_2O_3 \times 100/2Fe_2O_3+FeO$) of the rocks i.e. the oxygen fugacity of the system. High fO_2 displaces the equilibrium to the right producing epidote and more andraditic garnet at the expense of hornblende. This is evident from a comparison of the mineralogies of samples 557 and 566. These were collected from different calc-silicate bands in the same location (NN 444870) and possess the same CaO/Al_2O_3 ratio. Sample 557 (oxidation ratio= 37.77) contains 3.6% hornblende, 7.9% garnet, 17.2% clinozoisite and 35.9% plagioclase whereas sample 566 (oxidation ratio 52.08) contains no hornblende, 5.8% garnet, 31.1% epidote and 18.6% plagioclase. The chemical composition of the garnets have not been determined but it is probable that the garnet in sample 566 contains some andradite given the high oxidation ratio (i.e. Fe^{3+} content) of the rock.

This observation is consistent with the experimental findings of Gilbert (1966) who found the strong dependence of the ferropargasite stability field on oxygen fugacity. He found that at higher fO_2, controlled by nickel-bunsenite buffer, ferropargasite broke down to magnetite, plagioclse and andraditic garnet plus fluid. Also Ernst (1966) found that ferro tremolite is also unstable above fO_2 values buffered by bunsenite-nickel. These findings therefore indicate a strong fO_2 control on amphibole stability.

These results may therefore also be important in the interpretation of the epidotic calc-silicates (MacGregor, 1948; Winchester, 1975). Winchester (op cit.) suggested that these were probably derived from epidotic grits similar to those found in the Torridonian whereas the garnet-zoisite calc-silicates may have been derived from calcareous marls. He found that the only chemical difference between the two calc-silicate types was in the higher Sr content of the epidotic calc-silicates. No distinction was made between Fe^{3+} and Fe^{2+} in his analyses and hence no comparison of oxidation states.

The present study, in the Loch Laggan-Upper Strathspey area shows that these epidotic bands are the only type of calc-silicates which occur in the more highly oxidized rocks of the Garva Formation but they are also found in parts of the Chathalain, Glendoe and Carn Leac Formations. Samples of similar rocks collected about 2m from the Corrieyairack Granite complex, contain porphyroblastic hornblende, opaques and minor biotite, which show that at the low fO_2 values prevalent in the aureole of the pluton, hornblende is stabilised relative to biotite and epidote.

Several studies (Chinner, 1960; Eugster, 1959) have shown that the oxygen content of layered metamorphic rocks tend to stay relatively constant during metamorphism. The high fO_2 of stratigraphic units and lithological bands containing these epidotic calc-silicates may therefore largely reflect original sedimentary constitution. This may have led to the suppression of amphibole in favour of epidote which remained stable up to amphibolite facies conditions. These epidotic calc-silicates could therefore, be the product of interplay between fO_2, bulk rock chemistry and metamorphic grade.

It may be argued that the increased oxidation of the Garva rocks is the result of syntectonic oxidation (Wintsch, 1981) in the vicinity of the Gairbeinn Slide. However, given the widespread distribution of the epidotic bands, syntectonic oxidation may have been of little effect in their formation.

6.2.4 <u>The configuration of the bytownite isograd</u>

Winchester and Whittles (1979) relating the variation of mineral assemblages to the CaO/Al_2O_3 ratio of the calc-silicate rocks in the Killin area,

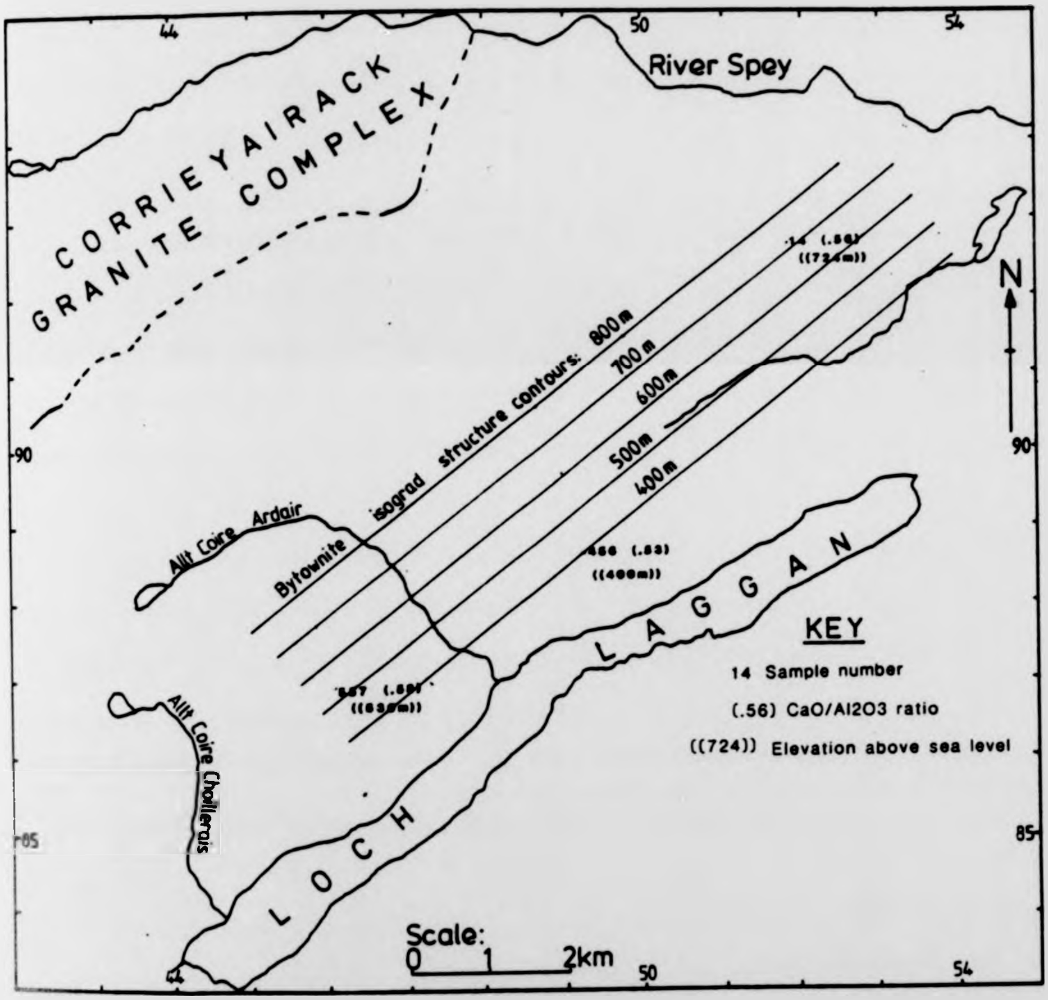

Fig.6.7a:_The bytownite isograd structure contours

used the critical ratio above which a mineral is developed to define its isograd. By a geometrical construction linking several locations with calc-silicates of the same critical ratio, they were able to define the attitude of the isograd.

Applying similar geometrical methods in the Loch-Laggan-Upper Srathspey area an outline of the attitude of the bytownite isograd surfaces were obtained. Three locations at which bytownite was present in rocks with a CaO/Al_2O_3 ratio in the range 0.53-0.58 were used in this construction. (See Figs 6.7 and 6.8).

In view of the very few applicable data points available only very general observations can be made concerning this isograd. It is not possible, because of this paucity of data to delineate the effects of the late faulting on the disposition of the isograd. More precise definition of the isograds must await more rigorous and detailed phase equilibria analyses.

The results obtained, so far, however, suggest that the bytownite isograd contours (Fig 6.7) strike NE-SW and dip shallowly to the SE. This strike is subparallel to the axial trace of the D2 major folds but the dip of the isograd surface (about 14^{o}) is much shallower than the dip of the foliation So/S1 (c.65^{o}). This may suggest that the isograd was not deformed by D2 and hence was established after this phase of deformation.

Relevant data is not available for the northern part of the Loch Laggan-Upper Strathspey area i.e. the Glenshirra Succession because of the scarcity of suitable calc-silicate rocks.

Two calc-silicate samples , 3A and 103A, collected from the base of the Coire nan Laogh Formation adjoining the Gairbeinn Slide possess CaO/Al_2O_3 ratios of 0.7 and 0.52 respectively. They are dominantly rich in clinozoisite and epidote ($>$ 68%) but contain albitic plagioclase ($<$ 5%). These observations suggest that marked retrogression has occurred in these rocks with reactions (3) and (4) having approached completion.

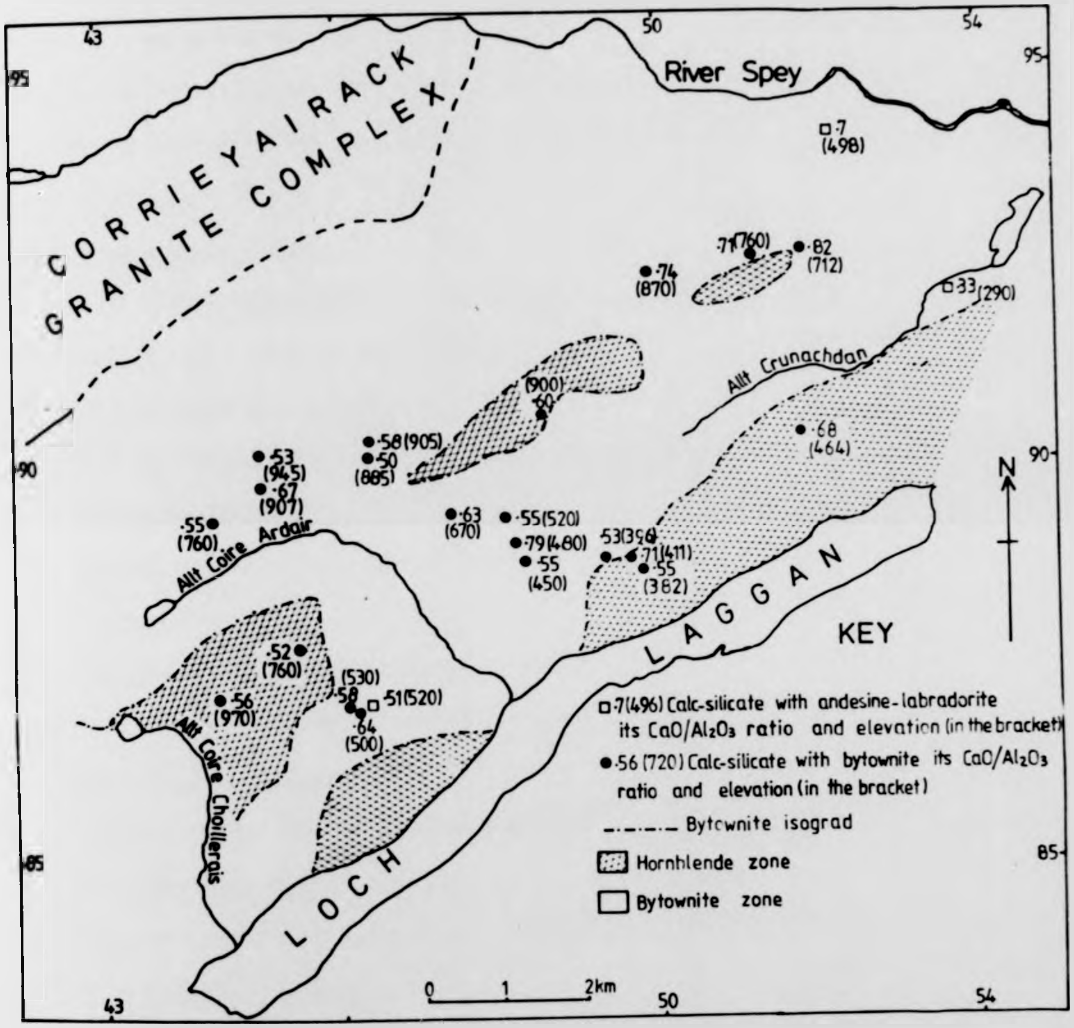

Fig.6.7b: The bytownite isograd

6.3 Metamorphism of the semi-pelites

The semi-pelitic rocks contain 16-21% by weight Al_2O_3 (Table 7.1, Chapter 7) and constitute the dominant component of the Coire nan Laogh and the Monadhliath Formations, and minor constituents of the other lithostratigraphic units where they occur as thin bands within the more dominant psammitic units.

6.3.1. Mineral parageneses

A detailed petrography of the semi-pelites has already been given in Chapter 3. The mineral assemblages in each formation is given below:

a. The Chathalain Formation

Quartz + oligoclase + biotite + muscovite ± garnet

b. The Garva Formation

Quartz + oligoclase + microcline + biotite ± muscovite ± epidote ± magnetite

c. The Coire nan Laogh Formation

Quartz + oligoclase + biotite + muscovite + garnet

d. The Glendoe Formation

Quartz + oligoclase + biotite + muscovite ± garnet ± epidote

e. The Monadhliath Formation

Quartz + oligoclase + biotite + muscovite ± garnet

f. The Carn Leac Formation

Quartz + oligoclase + biotite ± muscovite ± epidote ± garnet

Microstructural relations observed in the semi-pelites (plate 3.1) indicate a late retrogression shown by varying degrees of garnet breakdown subsequent to the peak of the regional metamorphism. In the reddish-brown biotite-bearing rocks, garnet broke down to biotite, quartz and some magnetite, while in the greenish-brown biotite-bearing rocks, the garnet broke down to plagioclase, biotite and possible epidote.

The petrographic differences between the Garva and the Coire nan Laogh Formations have already been noted (Chapter 3). In particular, the absence of garnet in the semi-pelites of the Garva Formation and its relative abundance in those of the Coire nan Laogh Formation may suggest that the Garva Formation is at a lower metamorphic grade than the Coire nan Laogh Formation. However, these differences may be the result of the chemical differences between the two formations, discussed in detail in Chapter 7. Rigorous phase equilibria analyses may elucidate this problem.

6.3.2 The absence of regional aluminosilicates: chemical control

The absence of some of the classical Barrovian regional metamorphic index minerals such as the aluminosilicates in the semi-pelitic rocks of the Loch Laggan-Upper Strathspey area has already been noted. The presence of hornblende and bytownite in the calc-silicate rocks at the climax of the regional metamorphism in this area suggests that P-T conditions were high enough for the formation of kyanite in rocks of suitable composition (Kennedy 1948; Winchester, 1970, 1974; Tanner, 1976; Wells, 1979).

This scarcity of the aluminosilicates in the Moine rocks has been recognised by several previous workers. Winchester (1974b) used a plot of CaO against Al_2O_3 to differentiate fields of aluminosilicate-bearing rocks from those in which they are absent. Several aluminosilicate-free semi-pelites in this study area fall within the aluminosilicate field defined by this plot (Fig 6.8). It would, therefore, appear that there are other factors which also influence the formation of these minerals.

Atherton and Brotherton (1972) observed that the occurrence of kyanite in the rocks of the Irish and Scottish Dalradian was controlled by the "available" M/FM ratio (i.e. mole MgO/MgO+ FeO), kyanite forming only when this ratio exceeded 0.54. Semi-pelites from the Loch Laggan-Upper Strathspey area have M/FM ratios less than 0.5 (Table 6.2) except the Garva Formation semi-pelites which contain significant amounts of oxide phases, ilmenite and magnetite (Table 3.1). The absence of kyanite in the rocks of this area therefore seems compatible with their low M/FM ratios, and in agreement with the findings of Atherton and Brotherton. However, other factors may also be responsible for this absence of kyanite.

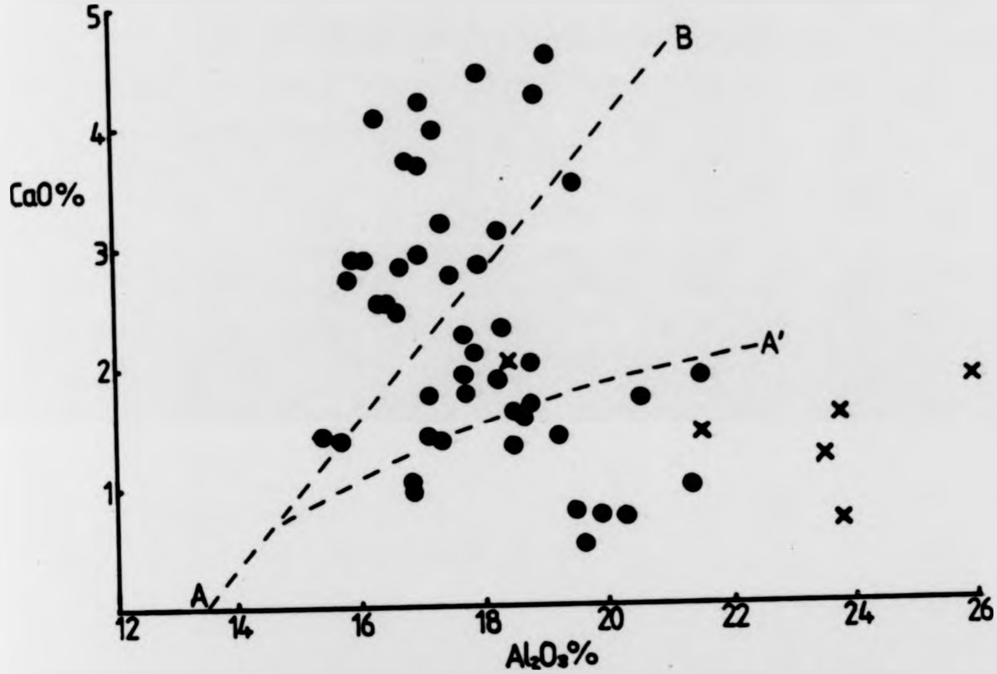

Fig.6.8: $CaO-Al_2O_3$ plot of the semi-pelites showing fields in which kyanite or sillimanite may be expected (after Winchester, 1974b)

× : Andalusite- and/or sillimanite-bearing semi-pelites from the thermal aureole of the Corrieyairack Granite Complex

●: Semi-pelites outside the aureole which lack the aluminosilicates

TABLE 6.2 MgO/FeO + MgO (molecular) ratios (M/FM)

for the semi-pelites

Formation	Range of M/FM	Mean M/FM
Chathàlain	0.44 - 0.5	0.48
Garva	0.44 - 0.66	0.55
Coire nan Laogh	0.40 - 0.47	0.43
Glendoe	0.38 - 0.49	0.47
Monadhliath	0.35 - 0.50	0.44

Haselock (1982) reported two occurrences of kyanite in the Creag Mhor Psammite of the Corrieyairack Pass area, in rocks with M/FM ratios, less than 0.45. Rocks with similar M/FM ratios were devoid of this mineral. She therefore concluded that there is no systematic relationship between M/FM and the presence of kyanite. The status of these two reported kyanite occurrences is however unclear given their proximity to the Corrieyairack Granite Complex. Although, she regarded them as having been formed during the regional metamorphism, they could, in fact, be contact metamorphic minerals.

In the Loch Laggan-Upper Strathspey area, there is no evidence to suggest that kyanite was ever formed even at the climactic stage of the regional metamorphism. This absence of aluminosilicates was therefore probably as a result of unfavourable chemical and physical conditions. Most of the Dalradian kyanite occurrences are in the so-called "per-aluminous" rocks (Chinner, 1967); much of the Dalradian sillimanite occurrences are largely confined to the high temperature zones near igneous bodies where regional and thermal metamorphism were broadly coeval(Atherton, 1977; Kneller and Leslie,1984), and difficult to differentiate. In the Grampian Division rocks of this study area , the bulk rock chemistry did not favour the formation of kyanite during the regional metamorphism, and late andalusite and sillimanite formed in the contact aureoles associated with the late igneous intrusions are clearly distinguishable.

These minerals developed in the contact aureole of the Corrieyairack Granite Complex will be discussed later in Section 6.7.

6.4 The relationship of metamorphism to deformation

Most of the calc-silicate rocks do not possess good mineral fabrics. However, in a few rocks (Plate 6.3b) hornblende laths defining S1 are observed to wrap around early garnet thus indicating an early or pre-D1 growth for the garnet and a D1 growth for the hornblende.

In the semi-pelitic rocks better-developed fabrics show that the early garnet is wrapped around by the S1 biotite fabric (plate 3.4), and also suggest an early or pre-D1 growth for this garnet.

Polyphase garnet growth is shown by some of the garnets (plates 3.4 and 3.5). At least two, and in some cases , three stages of garnet growth are often indicated: (a) first -stage characterised by the inclusion-rich cores; these inclusions are mainly tiny quartz, and minor plagiocalse and opaques.

(b) the second stage is marked by the inclusion-free rim which is wrapped by the S1 biotite fabric and so is probably early or pre-D1.

(c) some garnet grains contain a further inclusion-rich rim containing biotite grains which are aligned parallel to the S1 biotite fabric thus suggesting a post-D1 growth for this rim.

Later garnet growth probably, post-D1, is also illustrated in the calc-silicates by an inclusion-free rim on early hornblende (Plate 6.4a).

The similarity of mineral assemblages suggest that the early or pre-D1 metamorphism, M1, and the post-D1 metamorphism, MP1 are of broadly similar grade, although a syntectonic, MS1, metamorphism associated with the sliding may have been of a lower grade since only a biotite growth in the semi-pelitic rocks can be attributed to this event.

The occurence of some migmatitic segregations parallel to S1 in the semi-pelites suggest that local migmatisation took place during this episode of deformation, although most of the quartzo-feldspathic segregations have been deformed by D1 and hence may be slightly earlier. The petrography of these veins have been described in Chapter 3. Characteristics such as the similarity in the anorthite contents of leucosome and melanosome plagioclase suggest that they formed as a result of metamorphic segregation rather than anatexis.

Enhanced fluid transport and localisation in small shear zones associated with the D1 sliding probably promoted this metamorphic segregation which is most common in the vicinity of the Gairbeinn slide.

MP3 metamorphism, post-tectonic to D3 was a retrograde event which involved the partial or complete breakdown of garnet and its replacement by epidote/clinozoisite, calcite and chlorite in the calc-silicates, and randomly oriented biotite, quartz, and magnetite in the semi-pelites (Plate 3.1).

Table 6.3 : Summary of the Regional Metamorphic History with regard to crystallization of major/diagnostic phases

	Minerals	M1	MS1	MP1	M3
CALC-SILICATES	Hornblende	—	—	—	
	Bytownite	—	—	—	
	Andesine	—	—	—	—
	Clinozoisite/Epidote	—	—	—	—
	Zoisite				—
	Biotite	—	—	—	—
	Garnet	—		—	
	Muscovite				—
	Sericite				—
	Chlorite				—
	Acicular amphibole				—
SEMI-PELITES	Migmatitic Segregations	—	—		
	Garnet	—		—	
	Biotite	—	—	—	—
	Muscovite	—	—	—	—
	Chlorite				—

(MP1 conditions probably outlasted the D2 deformation) in the calc-silicates hornblende was partially replaced by hornblende and overgrown by pale, acicular amphibole, while calcic plagioclase was partially replaced by clinozoisite /zoisite and sericite.

This episode of metamorphism is also marked by the widespread growth of randomly oriented porphyroblastic muscovite in all the metasedimentary rocks, as well as in the early two-mica granite. The temporal relationship of this metamorphic event to the contact metamorphism is discussed later, in section 6.7.6.

A summary of the correlation of the metamorphic and deformational events is given in Table 6.3.

6.5 Physical conditions of the regional metamorphism

The mineral assemblages present in the rocks of the Loch Laggan-Upper Strathspey area indicate that middle amphibolite facies conditions (Turner 1981) prevailed at the climax of the regional metamorphism

Wells (1979), applying thermodynamic analysis of mineral equilibria in the calc-silicate rocks obtained a temperature of 560°C and a pressure of 7kb at Loch Laggan (NN462850). These figures are also compatible with middle amphibolite facies or kyanite grade conditions for the climactic M1/MP2 events.

6.6. Regional Correlations

Anderson (1956) reported the presence of garnet, hornblende, labradorite and clinozoisite in the calc-silicate rocks of this region. On the basis of this assemblage, and the presence of garnet, biotite, muscovite and oligoclase in the semi-pelitic rocks, he placed this region in the garnet or higher zones of metamorphism. He suggested that the sillimanite occurrences close to the Strathspey Complex implied a cogenetic relationship caused by the thermal effects of the complex.

Richardson and Powell (1976) applying thermodynamic analysis of mineral equilibria in carbonate and pelitic rocks obtained P-T estimates at the climax of regional metamorphism of 535°C and 5 kb corresponding to a depth of 18.5 km

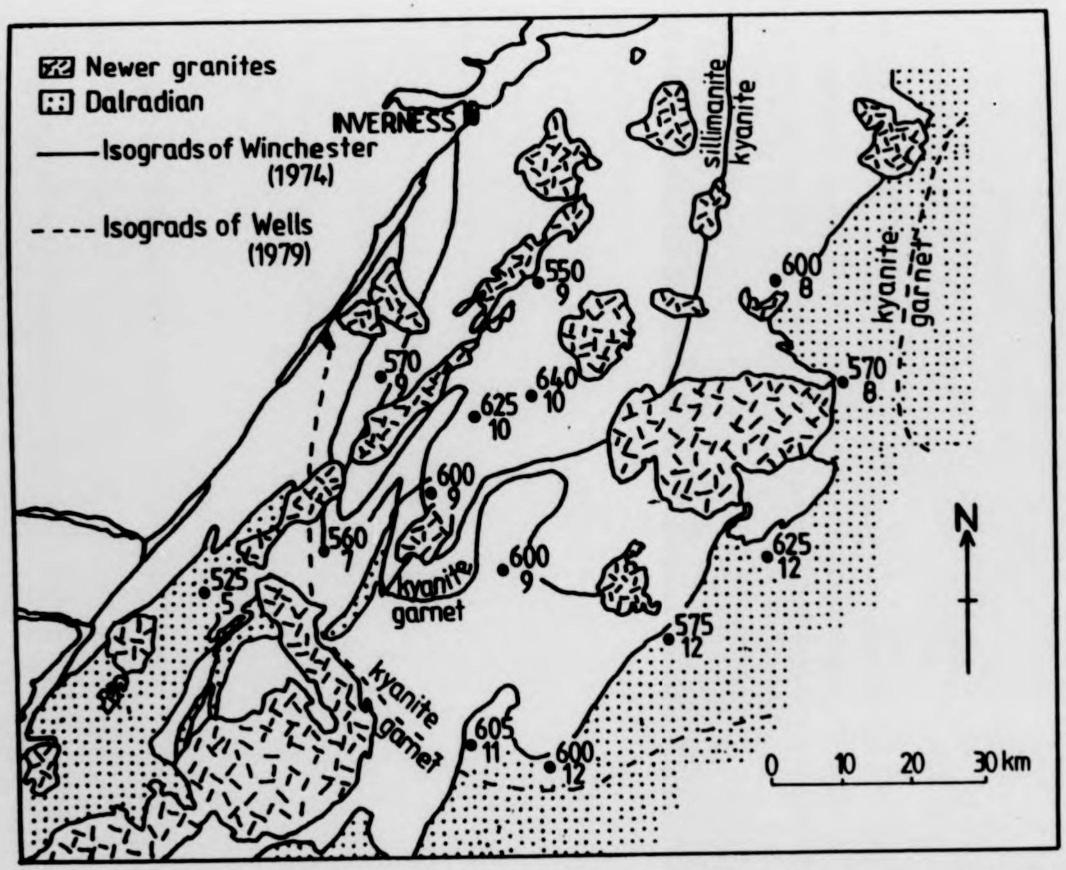

Fig.6.9: Map of the Central Highlands showing P-T estimates from Wells(1979), Wells and Richardson (1979), Richardson and Powell (1976). The isograds are from Winchester (1974a) and Wells (1979).

at the base of the Appin Group near Spean Bridge. Wells (1979) on the basis of P-T estimates from analysis of phase equilibria in calc-silicate rocks placed most of the Central Highlands in the kyanite zone (Fig 6.9).

Winchester and Whittles (1979), on the basis of the variation in the mineral assemblages of calc-silicate rocks, found an eastward increase in metamorphic grade in the Killin area.

Haselock (1982), placed the Corrieyairack Pass area in the middle to upper amphibolite facies on the basis of scarce pyroxene occurrence in calc-silicate rocks and the scarce kyanite in semi-pelites already referred to (section 6.3.3.) . She found a general increase in the anorthite contents of calc-silicate rocks with similar CaO/Al_2O_3 ratio towards the SE and hence a general increase in metamorphic grade in that direction.
The south-easterly dipping isograd surfaces obtained in the Loch Laggan-Upper Strathspey area complement the north-westerly dipping isograds of Winchester and Whittles (op. cit). in a metamorphic "antiform". Curiously, the axial trace of this "antiform" is near to the linear outcrop pattern of the Corrieyairack, Allt Crom and Findhorn granites. A close study of the map by Wells (1979, Fig 1) also reveals a similar pattern . This association of isograd configuration with the trend of the granitoid outcrops suggests a cogenetic relationship based on localised thermal fluxes possibly associated with uplift.

Clayburn (1981) has obtained a date of about 470 Ma for the peak of metamorphism in the semi-pelitic rocks of the Laggan Bridge Area, based on Rb-Sr dating of muscovite porphyroblasts. The exact stratigraphic status of these rocks is not clear. Also, the chronological context of these muscovite porphyroblasts in relation to the rocks of the present study area which contain at least two generations of muscovite is not known.

6.7 CONTACT METAMORPHISM

6.7.1 Introduction

The rocks surrounding the Corrieyairack Granite Complex in the present study area show effects of thermal metamorphism, which can be observed up to 500m from their contact with the pluton.

This contact metamorphism was superimposed on rocks which had already undergone amphibolite facies regional metamorphism (see previous sections). Outside the aureole, the country rocks contain biotite, plagioclase, quartz, muscovite and minor garnet in varying proportions.

The limited effect of the contact metamorphism has been ascribed to the intrusion of the pluton into rocks which were relatively hot at the time of intrusion (Watson 1965; Haselock 1982; Clayburn, 1981).

Haselock (1982) also observed the limited development of a thermal aureole around the Corrieyairack Granite Complex characterised by semi-pelites containing andalusite and sillimanite (fibrolite) in the Corrieyairack Pass area to the north of the intrusion.

6.7.2 Mineral assemblages in the contact aureole and metamorphic zonation

On the basis of the spatial distribution of the mineral assemblages developed in the contact aureole, two prograde metamorphic zones have been recognized (Fig 6.10). These zones are the result of metamorphic reactions, some of which can be inferred from the study of the fabrics of the co-existing mineral phases.

The modal compositions of the semi-pelitic rocks both within and outside the aureole were determined by counting 1000 points per thin section, and are given in Table 6.4. Plagioclase compositions have been determined by the Michel-Levy method using maximum extinction angles on 010 sections.

i. The outer aureole

Within this zone extending from between 500m and 200m from the contact semi-pelitic rocks contain andalusite + biotite + cordierite + plagioclase + quartz ± fibrolite ± K-feldspar

Andalusite occurs as subidioblastic porphyroblasts 1.5-3mm long with inclusions of biotite, quartz and magnetite. It is pleochroic from colourless to pink, $X < Y < Z$. This pleochroism indicates a significant Fe^{3+} content (Deer

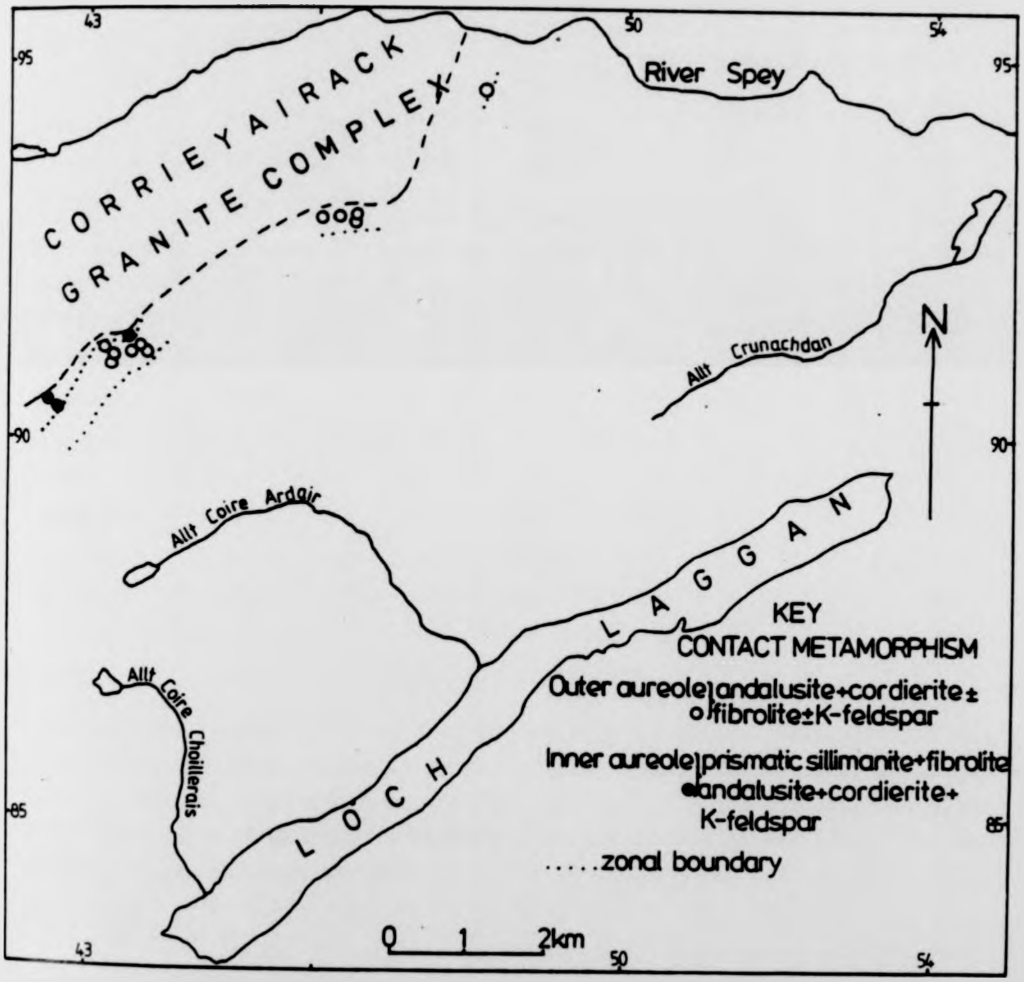

Fig.6.10: The zones of contact metamorphism

Table 6.4 : Modal analysis of spatially-varied Monadhliath semi-pelites

	233	430	442	229	231	634	628	8313
Quartz	22.4	24.1	25.5	15.4	29.4	14.2	21.2	15.3
Plagioclase	32.4	32.9	8.5	34.5	28.2	26.3	20.8	20.6
K-feldspar	-	-	-	trace	trace	trace	1.0	1.5
Biotite	35.6	27.8	25.8	32.6	33.5	41.5	30.6	31.6
Muscovite	7.5	14.6	39.8	4.9	2.8	3.0	0.4	0.5
Garnet	0.2	-	-	-	trace	-	-	-
Andalusite	-	-	-	1.4	1.8	11.1	7.2	14.2
Fibrolite	-	-	-	-	-	0.2	10.5	5.2
Sillimanite	-	-	-	-	-	-	0.5	1.1
Cordierite	-	-	-	-	-	-	6.5	8.8
Chlorite	0.9	trace	trace	4.8	1.9	0.5	0.1	0.2
Sericite	0.4	trace	trace	5.5	1.2	2.5	0.3	0.4
Spinel	-	-	-	-	-	trace	0.2	trace
Opaques	0.4	0.4	0.1	0.8	0.8	0.5	0.4	0.5
Zircon	trace	trace	trace	trace	trace	trace	trace	trace
Apatite	trace	trace	trace	trace	trace	trace	trace	trace
Total	99.5	99.8	99.7	99.9	99.6	99.8	99.7	99.9

233, 430, 442 : Outside the aureole

229, 231, 634 : outer aureole

628, 8313 : inner aureole

Plate 6.5a : Folded andalusite (D3) in semi-pelite in the outer aureole of the Corrieyairack Granite Complex. Monadhliath Formation NN 439913
Plane polarised light. Scale bar represents 0.2mm

Plate 6.5b : Garnet, relict-biotite and magnetite occurring as inclusions in corderite (C) in semi-pelite in the inner aureole.
Monadhliath Formation NN 427904.
Plane polarised light. Scale bar represents 0.1mm.

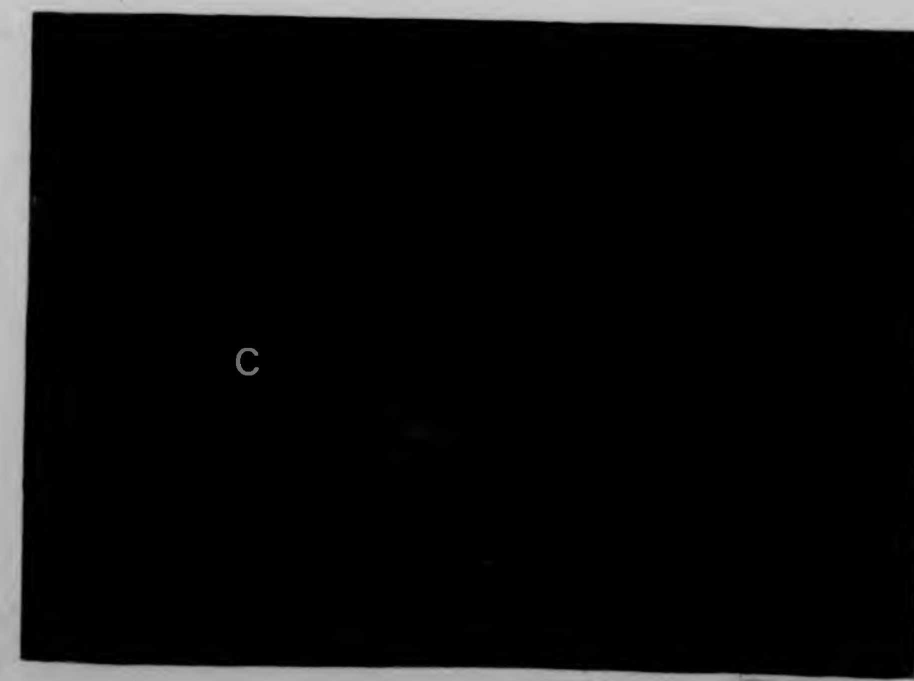

Plate 6.5a : Folded andalusite (D3) in semi-pelite in the outer aureole of the Corrieyairack Granite Complex. Monadhliath Formation NN 439913
Plane polarised light. Scale bar represents 0.2mm

Plate 6.5b : Garnet, relict-biotite and magnetite occurring as inclusions in corderite (C) in semi-pelite in the inner aureole.
Monadhliath Formation NN 427904.
Plane polarised light. Scale bar represents 0.1mm.

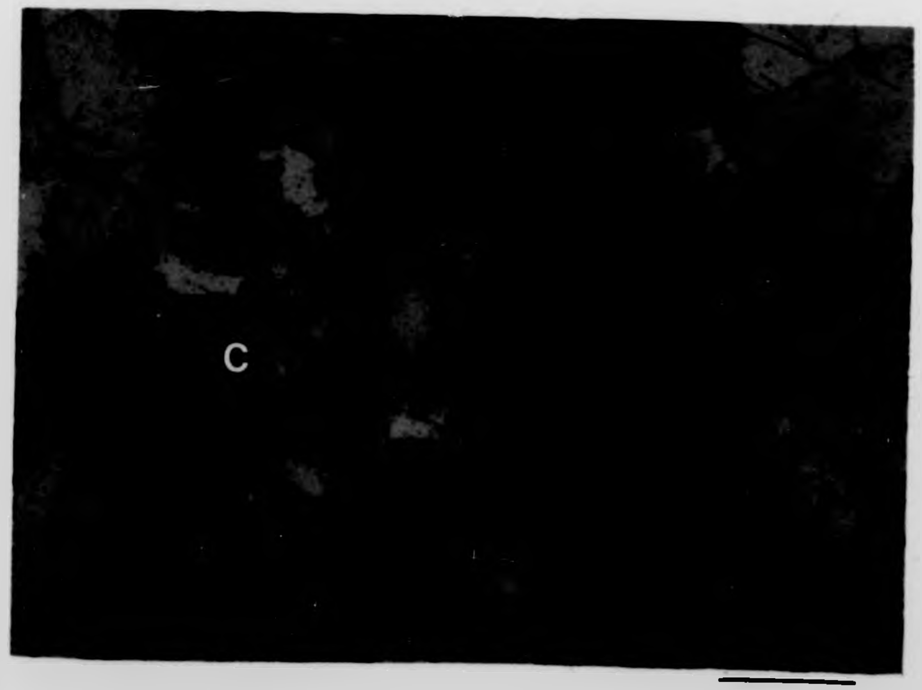

Plate 6.5a : Folded andalusite (D3) in semi-pelite in the outer aureole of the Corrieyairack Granite Complex. Monadhliath Formation NN 439913
Plane polarised light. Scale bar represents 0.2mm

Plate 6.5b : Garnet, relict-biotite and magnetite occurring as inclusions in corderite (C) in semi-pelite in the inner aureole.
Monadhliath Formation NN 427904.
Plane polarised light. Scale bar represents 0.1mm.

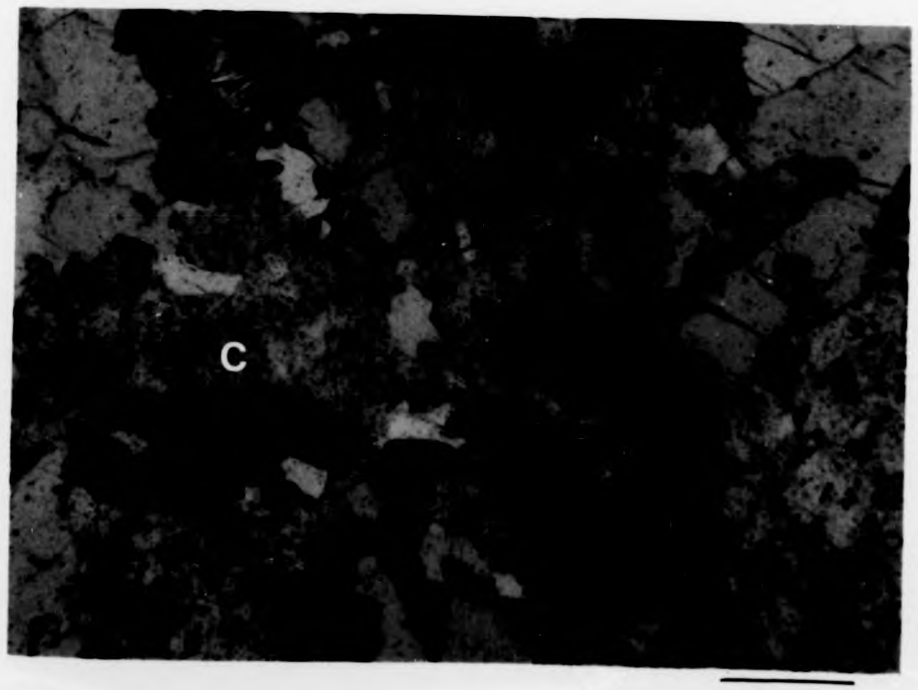

Plate 6.5a : Folded andalusite (D3) in semi-pelite in the outer aureole of the Corrieyairack Granite Complex. Monadhliath Formation NN 439913

Plane polarised light. Scale bar represents 0.2mm

Plate 6.5b : Garnet, relict-biotite and magnetite occurring as inclusions in corderite (C) in semi-pelite in the inner aureole.

Monadhliath Formation NN 427904.

Plane polarised light. Scale bar represents 0.1mm.

et al, 1982) . Andalusite is commonly partially replaced by sericite and late muscovite.

Andalusite grains are deformed and show strained extinction. In suitably oriented sections (Plate 6.5a) some andalusite grains are seen to be strongly crenulated parallel to the D3 crenulation of the rock noted elsewhere.

Fibrolitic sillimanite is a very minor constituent of some of the rocks (<0.25%). It is typically intergrown with tiny biotite grains and fine grains of opaques. It also occasionally grows across andalusite.

Cordierite occurs as xenoblastic plates 0.5-1.5mm in diamter containing inclusions of tiny biotite and magnetite grains, and occasionally rimming andalusite. It is commonly altered to yellowish "pinite".

Biotite occurs in two habits : (a) as tiny grains which are typically intergrown with fibrolite and occur as inclusions in andalusite and cordierite, and (b) porphyroblasts 0.5-1.5mm long. These reddish-to dark brown biotite grains define the regional S1 fabric which has been crenulated by D3 and overprinted by late disoriented biotite grains. Some of the biotite grains are darker than those in Semi-pelites outside the aureole.

Muscovite occurs in minor amounts (Table 6.3) both as small grains about 0.5mm long replacing andalusite and overgrowing biotite, and as late prophyroblasts cross-cutting the early mineral fabric.

Plagioclase occurs as oligoclase-andesine (An28-An46) grains 0.5-1 mm in diameter which are commonly intergrown with quartz in the leucrocatic bands of the semi-pelitic hornfelser. It commonly shows multiple twinning on the albite law, and may be weakly normally zoned .

Quartz occurs as xenoblastic grains 0.2-0.5 mm in diameter, commonly intergrown with plagioclase.

Accessory minerals include magnetite, which occurs in the groundmass of the rock and as inclusions in andalusite and is probably produced by the biotite and garnet breakdown reactions association with the formation of the aluminosilicates and zircon and apatite.

ii The inner aureole

This zone is 200-300 m wide and is defined by the presence of prismatic sillimanite, cordierite and K-feldspar as well as the other mineral phases already described from the outer zone.

Sillimanite occurs as subidioblastic prisms (Plate 6.6a) and porphyroblasts (plate 6.6b) 0.6-2mm long, occasionally containing inclusions of tiny biotite and magnetite grains. It also sometimes grows across andalusite and is often intergrown with K-feldspar and cordierite. This zone is also marked by an increase in the abundance of fibrolite up to 11 modal percent of the rock (Table 6.3).

Sillimanite grains are occasionally slightly bent (Plate 6.8a) and may show strained extinction as a result of late deformation.

Andalusite occurs as subidioblastic porphyroblasts 1-2.5 mm long containing inclusions of tiny biotite, ilmenite and spinel grains. It is often pleochroic from colourless to pink, probably as a result of some Fe^{3+} substitution for Al^{3+} (Deer et al, 1982). Andalusite grains are occasionally deformed and show strained extinction. Secondary muscovite occasionally may partially replace some andalusite.

Cordierite occurs as subidioblastic poikiloblasts up to 2 mm in diameter commonly full of inclusion of biotite, andalusite and ilmenite and overgrown by fibrolite (Plate 6.7a). It occasionally shows polysynthetic and sector twinning. It is also occasionally partially altered to "pinite", assuming a yellowish cast.

Biotite occurs as subidioblastic to xenoblastic reddish-to dark-brown grains in two habits: (a) tiny grains which occur mainly as inclusions in the aluminosilicates and cordierite, (b) porphyroblasts 0.6-1.8 mm long, some of which define the relict S1 fabric, which is overprinted by randomly oriented biotite grains.

The biotite grains are occasionally deformed and show strained extinction.

Muscovite occurs in minor amounts (Table 6.3) as late disoriented poikiloblasts 1-2mm long containing inclusions of tiny biotite grains and also occasionally

Plate 6.6a : Prismatic sillimanite, (S) and fibrolite (F) growing across andalusite (A) Small, relict grains of biotite occur in the groundmass and as inclusions in andalusite. Inner aureole, Monadhliath Formtion. NN 425904. Plane polarised light. Scale bar represents 0.1mm

Plate 6.6b : Prismatic sillimanite intergrown with corderite K-feldspar and magnetite. Inner aureole. Monadhliath Formation. NN 425904. Plane polarised light. Scale bar represents 0.1mm.

Plate 6.6a : Prismatic sillimanite,(S) and fibrolite (F) growing across andalusite (A) Small, relict grains of biotite occur in the groundmass and as inclusions in andalusite. Inner aureole, Monadhliath Formtion. NN 425904. Plane polarised light. Scale bar represents 0.1mm

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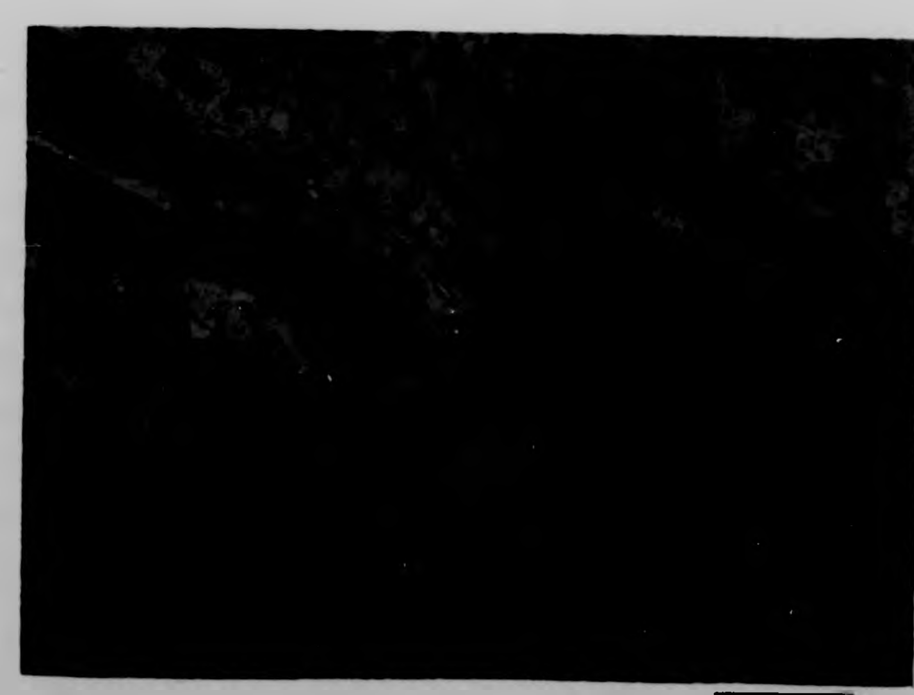

Plate 6.6a : Prismatic sillimanite,(S) and fibrolite (F) growing across andalusite (A) Small, relict grains of biotite occur in the groundmass and as inclusions in andalusite. Inner aureole, Monadhliath Formtion. NN 425904. Plane polarised light. Scale bar represents 0.1mm

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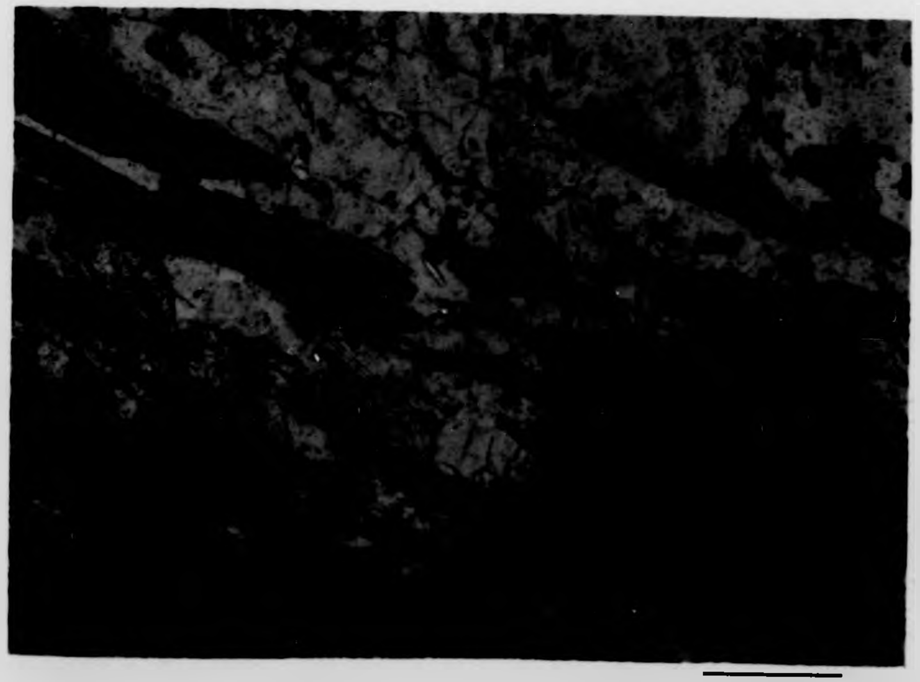

Plate 6.6a : Prismatic sillimanite,(S) and fibrolite (F) growing across andalusite (A) Small, relict grains of biotite occur in the groundmass and as inclusions in andalusite. Inner aureole, Monadhliath Formtion. NN 425904. Plane polarised light. Scale bar represents 0.1mm

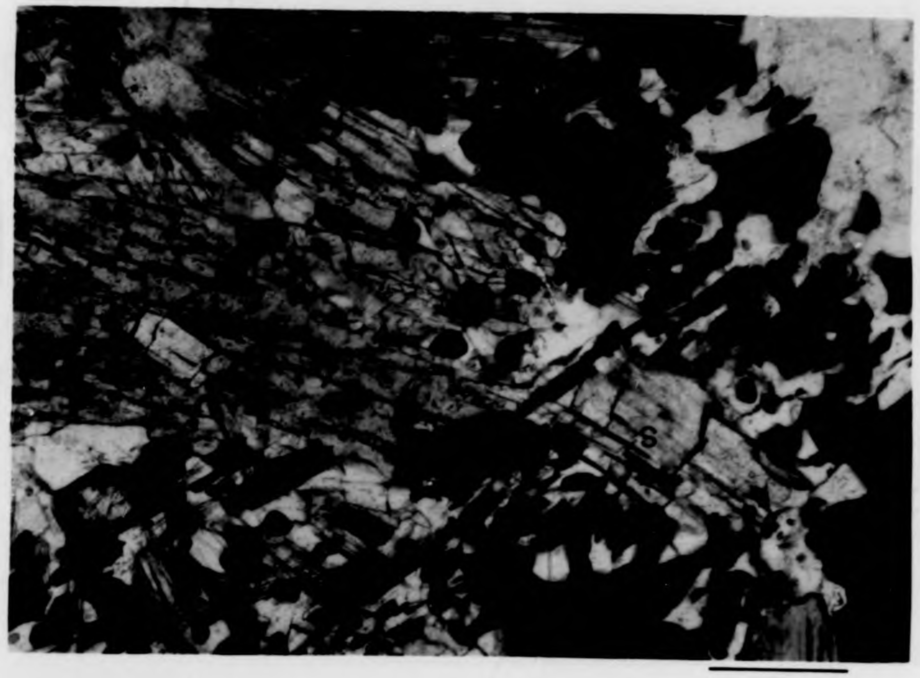

Plate 6.6b : Prismatic sillimanite intergrown with corderite K-feldspar and magnetite. Inner aureole. Monadhliath Formation. NN 425904. Plane polarised light. Scale bar represents 0.1mm.

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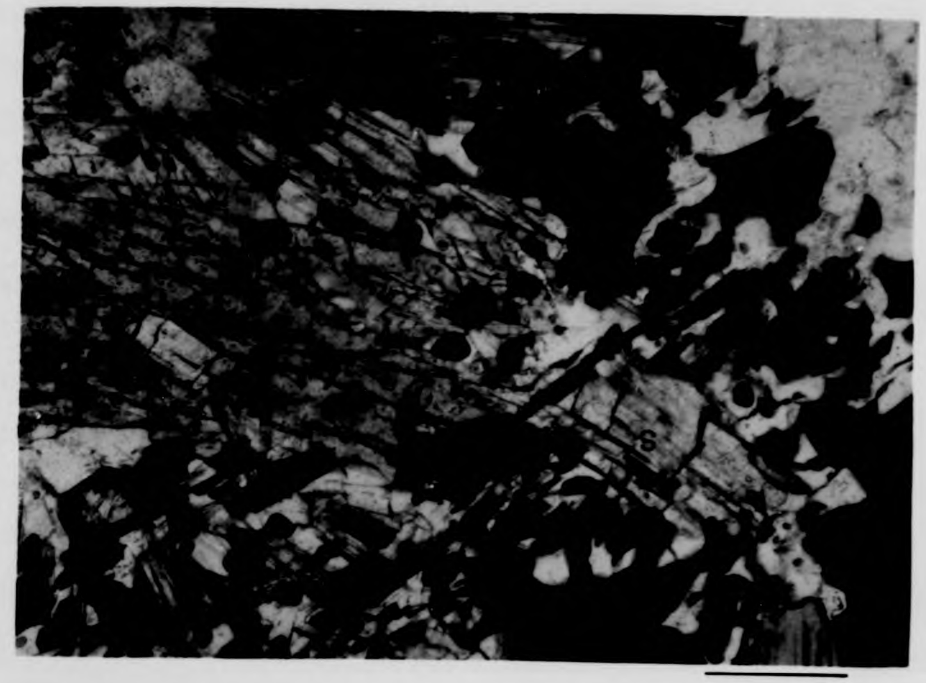


overgrowing bigger biotite grains. Sericite also occurs as minor late-stage retrograde replacement of andalusite.

Garnet (probably almandine) is a rare phase within this zone. It occurs as small xenoblastic grains 0.1 - 0.2 mm in diameter containing inclusions of magnetite (Plate 6.7b), and as inclusions in cordierite.

Plagioclase is oligoclase-andesine (An28-An38) and occurs as equant, subidioblastic grains about 0.5mm in diameter. It is commonly micro-antiperthitic, and occasionally has more calcic secondary overgrowths.

K-feldspar occurs as equant grains 0.3-0.5mm in diameter intergrown with cordierite, sillimanite and plagioclase. It occasionally contains inclusions of tiny biotite and fibrolite grains.

Quartz occurs as xenoblastic grains 0.2-0.5mm in diameter often intergrown with plagioclase in the leucocratic bands.

Accessory minerals include magnetite and spinel which occur as tiny inclusions in the aluminosilicate phases and cordierite. Isolated zircon and apatite grains are also present.

6.7.3 Mineral growth and reactions in the aureole

The sequence of mineral growth and associated reactions in the aureole rocks may be inferred from a study of rock fabrics. Textural evidence suggests that andalusite was the first aluminosilicate mineral to be formed. It probably grew at the expense of groundmass minerals including primary muscovite and garnet since both minerals are rare in the outer rocks although quite common in similar rocks belonging to the same formation outside the aureole. K-feldspar is also rare in these rocks. The andalusite-forming reaction may described as:

garnet + muscovite $\rightleftharpoons$ biotite (Annite) + andalusite + quartz (Mueller and Saxena, 1977). (1)

The partially resorbed appearance of andalusite and biotite found as inclusions in cordierite suggests that cordierite has grown at their expense.

Plate 6.7a : Cordierite (C) containing inclusions of fibrolite and tiny grains of biotite in a groundmass of biotite and K-feldspar.

Inner aureole. Monadhliath Formation. NN 425904.

Plane polarised light. Scale bar represents 0.1mm.

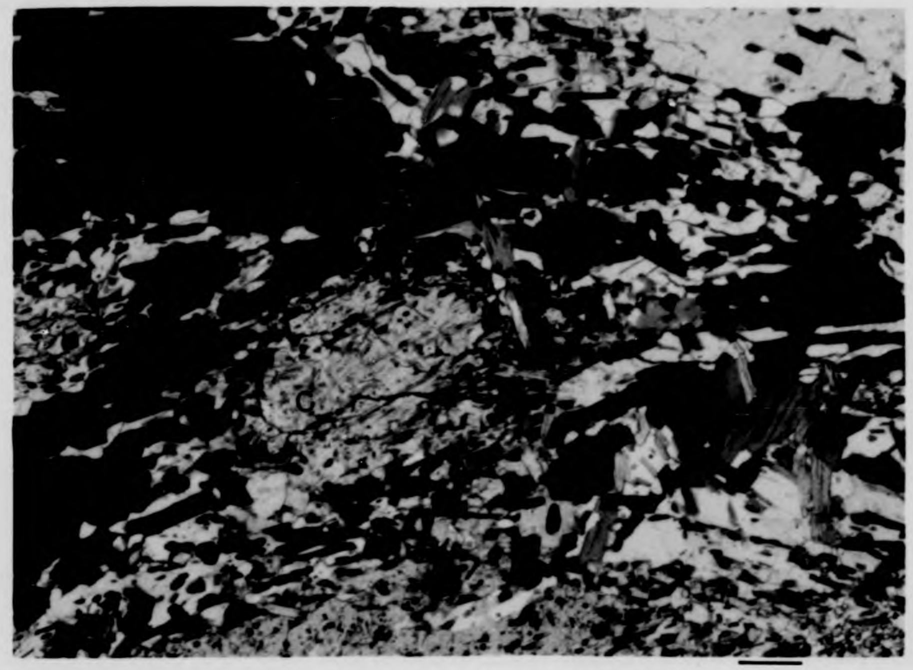


Plate 6.7b : Hornblende intergrown with opaques (magnetite?) in outer aureole calc-silicate. Glendoe Formation.

NN 452927.

Plane polarised light. Scale bar represents 0.1mm.

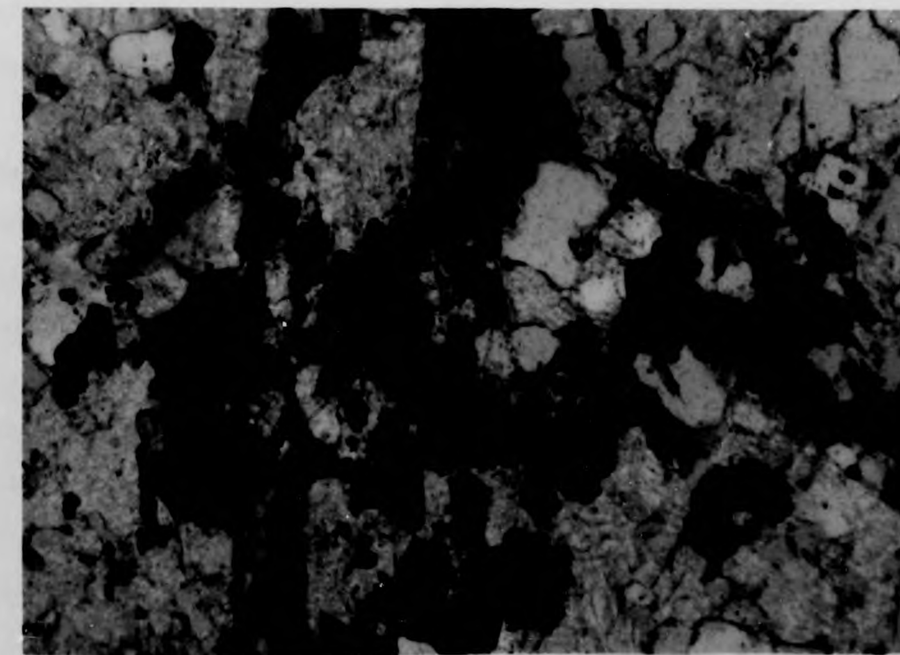


Plate 6.7a : Cordierite (C) containing inclusions of fibrolite and tiny grains of biotite in a groundmass of biotite and K-feldspar.
Inner aureole. Monadhliath Formation. NN 425904.
Plane polarised light. Scale bar represents 0.1mm.

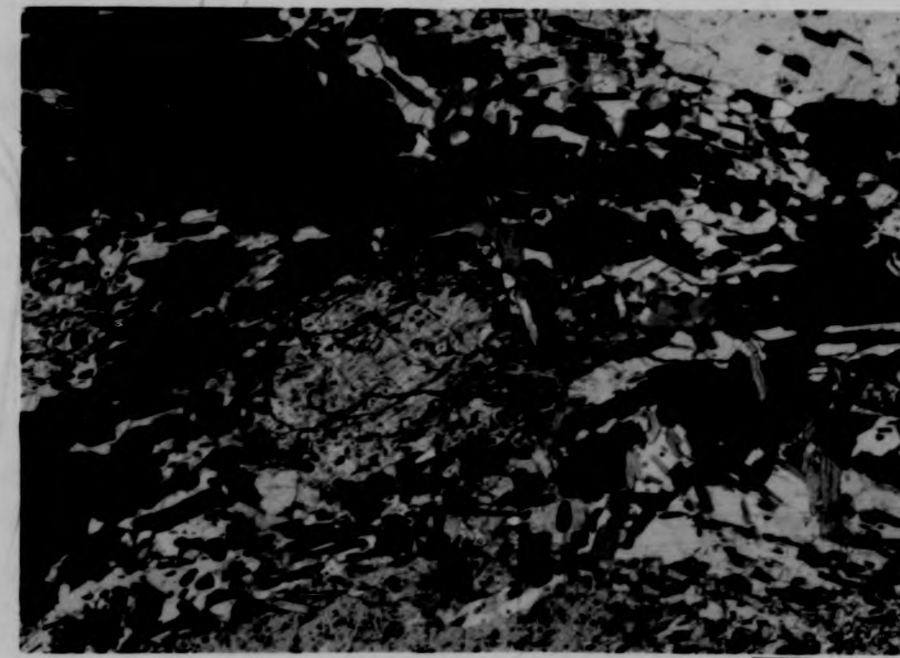


Plate 6.7b : Hornblende intergrown with opaques (magnetite?) in outer aureole calc-silicate. Glendoe Formation. NN 452927.
Plane polarised light. Scale bar represents 0.1mm.

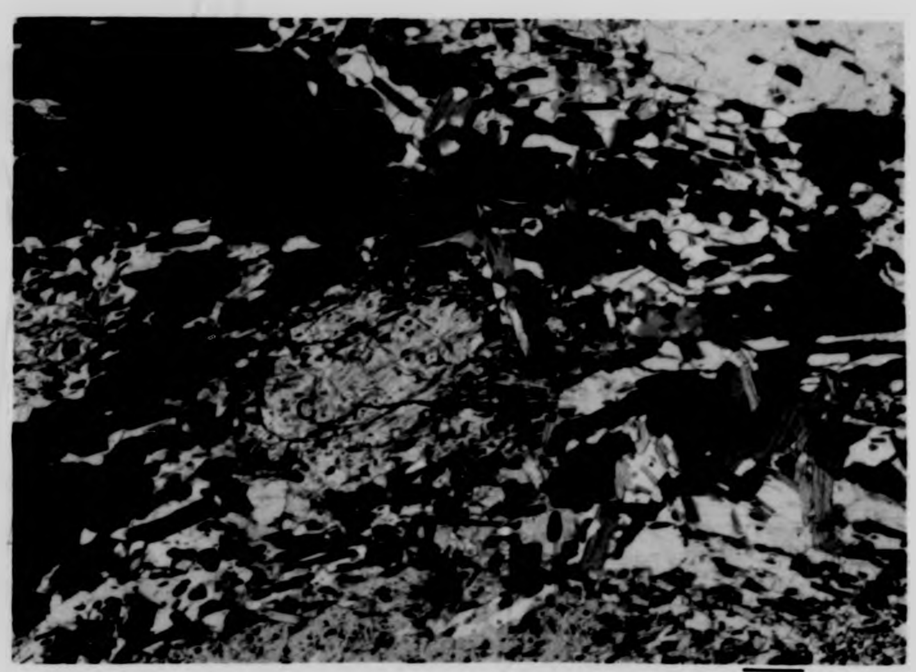
Plate 6.7a : Cordierite (C) containing inclusions of fibrolite and tiny grains of biotite in a groundmass of biotite and K-feldspar.

Inner aureole. Monadhliath Formation. NN 425904.

Plane polarised light. Scale bar represents 0.1mm.

Plate 6.7b : Hornblende intergrown with opaques (magnetite?) in outer aureole calc-silicate. Glendoe Formation. NN 452927.

Plane polarised light. Scale bar represents 0.1mm.



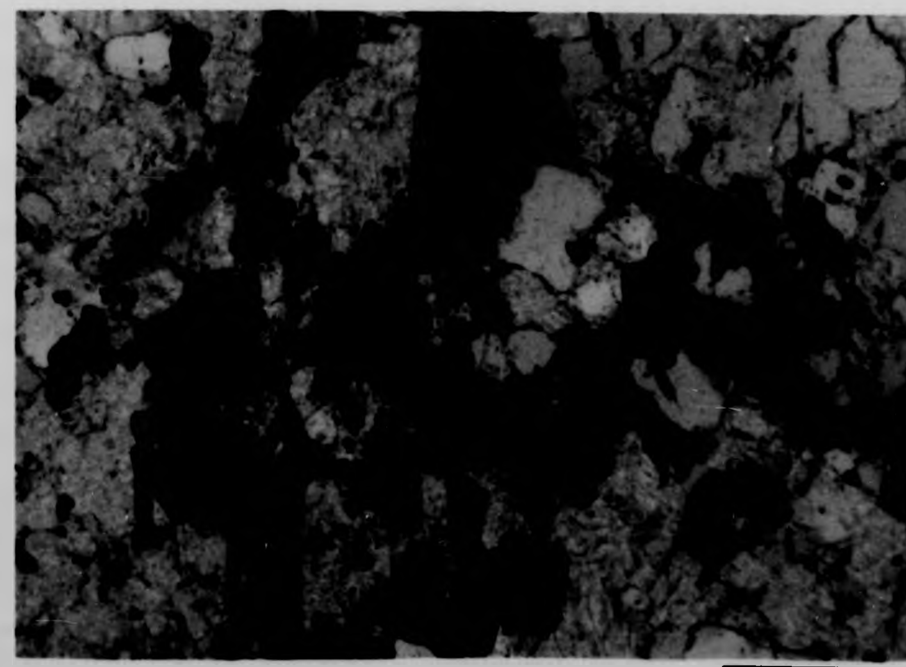


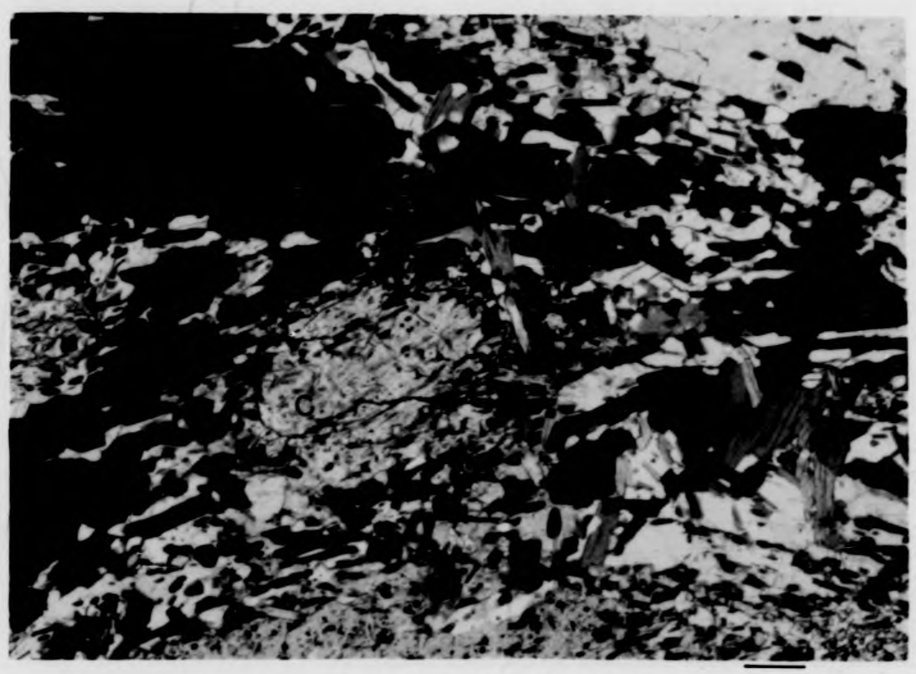
Plate 6.7a : Cordierite (C) containing inclusions of fibrolite and tiny grains of biotite in a groundmass of biotite and K-feldspar.

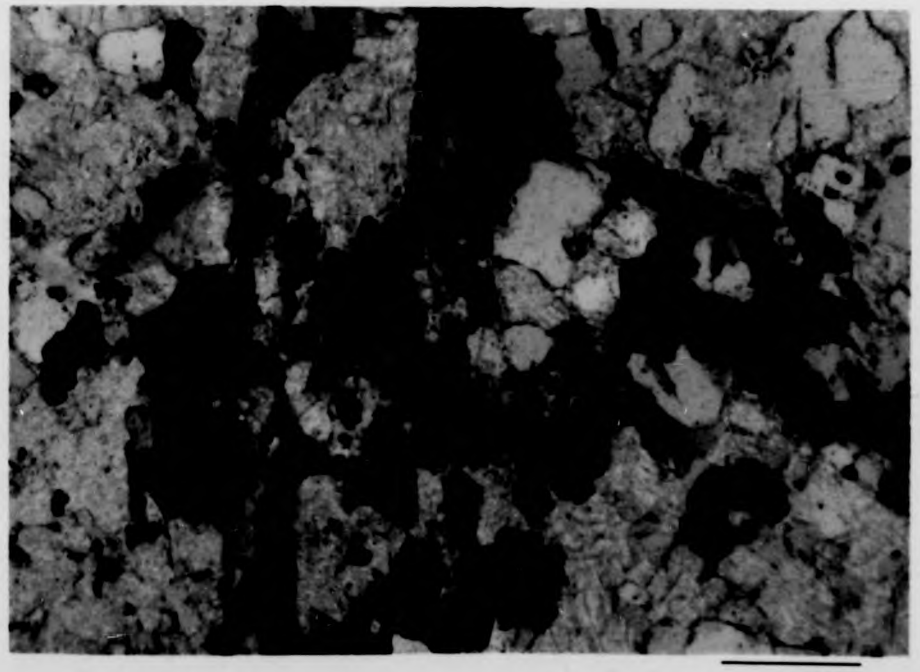
Inner aureole. Monadhliath Formation. NN 425904.

Plane polarised light. Scale bar represents 0.1mm.

Plate 6.7b : Hornblende intergrown with opaques (magnetite?) in outer aureole calc-silicate. Glendoe Formation. NN 452927.

Plane polarised light. Scale bar represents 0.1mm.





Thus with increasing temperature the cordierite and K-feldspar-producing reaction may be expressed as follows:

biotite + andalusite + quartz = cordierite + K-feldspar + H_2O (2)

In the inner aureole, the partially resorbed appearance of garnet enclosed in cordierite suggest its replacement by cordierite according to this reaction (Richardson, 1968; Holdaway and Lee, 1977):

garnet (almandine) + andalusite + quartz = Fe-cordierite (3)

The sillimanite-forming reactions are difficult to infer from the rock fabrics, but the absence of primary muscovite in the inner aureole rocks suggests that the following reaction may have occurred (Chatterjee and Johannes 1974):

muscovite + quartz = sillimanite + K-feldspar + H_2O (4)

Sillimanite co-exists with andalusite, cordierite and K-feldspar in the inner aureole. The coexistence of the aluminosilicate phases over a wide range of P.T. conditions has been reported from many places. This coexistence has been interpreted in terms of metastability (Hollister, 1969; Albee and Chodos, 1969; Naggar and Atherton, 1970) or of multivariance as a result of the substitution of Fe^{3+} for Al^{3+}.

Analytical studies (Okrusch and Evans,1970; Holdaway, 1971) show that andalusite and sillimanite may contain up to 3% and 1.1% by weight Fe_2O_3 respectively. No chemical analyses of the aluminosilicate phases from the Corrieyairack aureole is available but optical properties such as its pinkish pleochroism, suggest a significant Fe^{3+}content in the andalusite (Deer et al, 1982). The resulting multivariance may be responsible for the persistence of andalusite up to the higher temperatures of the inner aureole, in coexistence with sillimanite.

6.7.4 Bulk Rock Chemical Control on Mineral Growth

The sporadic and irregular development of the new aureole minerals, including the aluminosilicate phases, in the rocks close to the Corrieyairack pluton suggests that temperature was not the only control of mineral growth in the aureole.

A general observation is that the growth of the aluminosilicates is almost entirely restricted to the semi-pelitic rocks of the Monadhliath and Coire nan Laogh Formations within the aureole. Irregular hornfelsing of the Glendoe Formation semi-psammites and psammites cut by the pluton north of Beannain Beaga (NN 454915) has resulted only in the recrystallisation of the rocks. The thermal effects of the pluton are better shown by the thin calc-silicate bands (Plate 6.7b). The significant amount of opaques in the calc-silicate taken together with the absence of garnet suggest that much of the opaques has come from garnet breakdown as a result of thermally-induced recrystallisation.

Even within the Monadhliath and the Coire nan Laogh Formations, the growth of the new aureole minerals may be restricted to certain bands, while the remainder show only a recrystallisation of pre-existing minerals.

These observations indicate an important bulk-rock chemical control on the growth of the new aureole minerals, including the aluminosilicates. This control may be illustrated by some examples: Rock samples nos. 227 and 229 were collected from the outer aureole. Although sample 227 (a semi-psammite) was collected closer to the intrusion (at NN432913) than sample 229 (at NN4325912) it did not develop the new aureole minerals whereas sample 229 (a semi-pelite) contains andalusite and cordierite (Table 6.4).

Also rock sample numbers 627 and 628 were collected near the granodiorite contact (at NN 436914). Sample 627 is a psammite in contact with the granodiorite while sample 628 is a semi-pelite collected about 5m further away from 627. Sample 628 contains the new assemblage characteristic of the inner aureole whereas the psammitic sample 627 did not develop any of the new minerals (Table 6.4).

Chemical analyses of these rock samples are given in Table 6.5 and show the more pelitic characteristics (i.e. high Al_2O_3, K_2O, FeO and low SiO_2 contents) of the aluminosilicate-bearing rocks.

Naggar and Atherton (1970) have found that the growth of kyanite in the aureoles of the Donegal granites was restricted to aureole rocks with MgO/(MgO

Table 6.5: Bulk rock chemistry of aluminosilicate and non-alumino-silicate-bearing rocks from the thermal aureole.

	227	229	627	628
SiO_2	65.00	52.45	82.70	53.65
TiO_2	0.71	1.26	0.29	1.41
Al_2O_3	16.53	23.49	8.54	23.81
Fe_2O_3	1.05	1.71	0.31	1.37
FeO	4.12	5.70	1.01	4.83
MnO	0.14	0.11	0.03	0.09
MgO	2.28	2.88	1.09	1.82
CaO	3.50	1.23	1.42	0.68
Na_2O	3.04	2.73	3.23	3.28
K_2O	2.02	5.45	0.95	7.41
P_2O_5	0.25	0.11	0.08	0.22
Ba	341	1709	195	2120
Cr	45	68	23	103
Nb	15	20	17	20
Ni	34	35	14	27
Rb	106	184	30	185
Sr	306	410	264	118
Y	26	48	10	59
Zr	157	243	341	352

229 and 628 : aluminosilicate-bearing rocks

227 and 627 : non-aluminosilicate-bearing rocks

+ FeO) molecular ratios greater than 0.5. They found that the more iron-rich rocks formed staurolite instead of kyanite.

In the part of the aureole of the Corrieyairack Granite Complex outcropping in the present study area, no kyanite has been found. This observation apparently agrees with the calculated $MgO/(MgO + FeO)$ molecular ratios of less than 0.50 for the aureole rocks (Table 6.6). Haselock (1982) has, however, reported an occurrence of regional kyanite in aureole semi-pelites which also contain new fibrolite and andalusite produced by the contact metamorphism in the Corrieyairack Pass area, north of the present study area. The status of this kyanite is, however, not clear (section 6.3.2).

No staurolite has been found either in the Corrieyairack aureole of the present study area although the aureole rocks are evidently sufficiently iron-rich (Table 6.7) to induce staurolite growth under favourable circumstances. Other factors must therefore also be important. Naggar and Atherton (1970) have suggested that the absence of staurolite may be due to the overstepping of the staurolite-producing reaction in rapidly-heated thermal aureoles. However, given the unfavourable bulk chemical composition of these semi-pelites discussed earlier staurolite could not have been developed.

They also found that andalusite and sillimanite grew in rocks of both high and low $MgO/(MgO + FeO)$ ratios.

In an attempt to discover if any metasomatism has occurred during the contact metamorphism, the chemistry of the aureole semi-pelites with the new aureole minerals has compared to that of the other Monadhliath Formation semi-pelites outside the aureole (Table 6.7).

Statistical analyses involving the use of the Student's T Test shows that the two groups of samples differ at the 95% level of significance in SiO_2, TiO_2, Al_2O_3, FeO, MnO, Y, L.O.I., Rb and the oxidation ratio (mole $2 Fe_2O_3 \times 100/2 Fe_2O_3 + FeO$). The sample numbers considered are small so these observations must be assessed with caution.

The higher Al_2O_3, TiO_2, FeO, MnO and Y contents of the aureole rocks taken together with their lower SiO_2 and L.O.I., suggest their relative

Table 6.6: MgO/MgO + FeO (Molecular) (M/FM) ratios of aluminosilicate-bearing semi-pelites in the thermal aureole.

Sample	MgO	FeO	M/FM
225	3.06	7.11	0.43
229	2.88	5.70	0.47
231	2.68	5.85	0.45
501	2.23	5.17	0.43
628	1.82	4.83	0.40
642	2.54	5.96	0.43
644	2.69	5.57	0.46

enrichment as a result of the apparent loss of SiO2 and L.O.I. However, this apparent loss of SiO2 and L.O.I. should also cause a relative enrichment of the other major elements in the aureole rocks, but this is not the case.

It will be noted that these apparently enriched elements are commonly associated with clay minerals. In particular, TiO_2, MnO and Y are adsorbed by clay minerals (Wedepohl, 1969). This may suggest that much of the apparent difference in the chemistries of the two groups of semi-pelites is probably the result of sampling more pelitic bands in the thermal aureole.

The lower oxidation ratio of the aureole semi-pelites results from the reduction of Fe_2O_3 to FeO commonly associated with prograde metamorphism (Chinner, 1960, Turner, 1981). Also, their lower L.O.I. value is compatible with the dehydration reactions involved in the prograde metamorphism in the aureole.

In the Corrieyairack Pass area, Haselock (1982) noted higher than average concentrations of Na_2O, CaO and Sr for a sample collected 1m from the contact, and also an enrichment of K_2O, Ba and Rb in a sample collected 2m from the pluton. Given the fact that only single samples were considered, these differences may be due to her sampling peculiar bands rather than metasomatism associated with the intrusion of the granites.

6.7.5 Conditions of the Contact Metamorphism

The metamorphic reactions and the resultant mineral growths in the aureole are expressions of gradients in temperature, press, pH_2O and fO_2.

The absence of kyanite in the aureole rocks suggests pressures below the aluminosilicate phase diagram triple point i.e. below 5kb using the aluminosilicate stability data of Richardson et al (1969) or below 4 k bar using the data of Holdaway (1971) (Fig 6.11). Also an isobaric crystallisation path is assumed because of the relatively small area of the aureole.

The temperatures in the aureole are difficult to estimate because of the absence of compositional data on the coexisting phases.

Hoffer (1976) has experimentally determined the temperatures of the

Table 6.7a : Means of bulk-rock chemistries of aureole and non-aureole semi-pelites from the Monadhliath Formation

Table 6.7b: Mean bulk-rock chemistries of aureole and non-aureole semi-pelites normalised for Al_2O_3 constancy

	Aureole(n=6)	Outside(n=3)	Aureole(n=6)	Outside(n=3)
SiO_2	52.63 (2.20)	57.07 (2.47)	46.88 (5.33)	57.23 (4.52)
TiO_2	1.24 (.12)	0.98 (.04)	1.10 (.06)	.98 (.06)
Al_2O_3	23.19 (1.74)	20.49 (.77)	(20.49)	(20.49)
Fe_2O_3	1.56 (.14)	1.74 (.30)	1.40 (.22)	1.74 (.31)
FeO	5.84 (.68)	4.64 (.39)	5.21 (.88)	4.64 (.29)
MnO	0.13 (.02)	0.07 (.02)	0.12 (.02)	0.07 (.02)
MgO	2.61 (.39)	2.16 (.44)	2.33 (.43)	2.15 (.36)
CaO	1.41 (.38)	1.04 (.62)	1.26 (.35)	1.02 (.57)
Na_2O	2.73 (.89)	1.74 (.75)	2.39 (.71)	1.72 (.69)
K_2O	5.81 (.78)	6.14 (.67)	5.14 (.60)	6.18 (.38)
P_2O_5	0.28 (.09)	0.33 (.14)	0.25 (.09)	0.33 (.13)
L.O.I.	1.41 (0.48)	2.34 (.49)	1.41 (.48)	2.34 (.49)
Ba	1854 (225)	1656 (82)	1635 (118)	1657 (92)
Cr	82 (11)	75 (5)	73 (9)	75 (4)
Nb	19 (2)	16 (-)	16 (2)	16 (1)
Ni	47 (13)	33 (18)	42 (12)	32 (17)
Rb	196 (14)	206 (7)	174 (14)	206 (14)
Sr	276 (97)	186 (123)	244 (83)	182 (114)
Y	51 (6)	41 (4)	45 (3)	41 (5)
Zr	222 (68)	217 (93)	195 (55)	221 (101)
K_2O/Al_2O_3	0.25 (.03)	0.3 (.04)		
K/Rb	248 (40)	247 (22)		
Oxidation ratio	43 (1)	49 (3)		
CaO/Al_2O_3	0.06 (.02)	0.05 (.03)		
Na_2O/K_2O	0.47 (.18)	0.30 (.20)		
Rb/Sr	0.82 (.39)	1.60 (.93)		

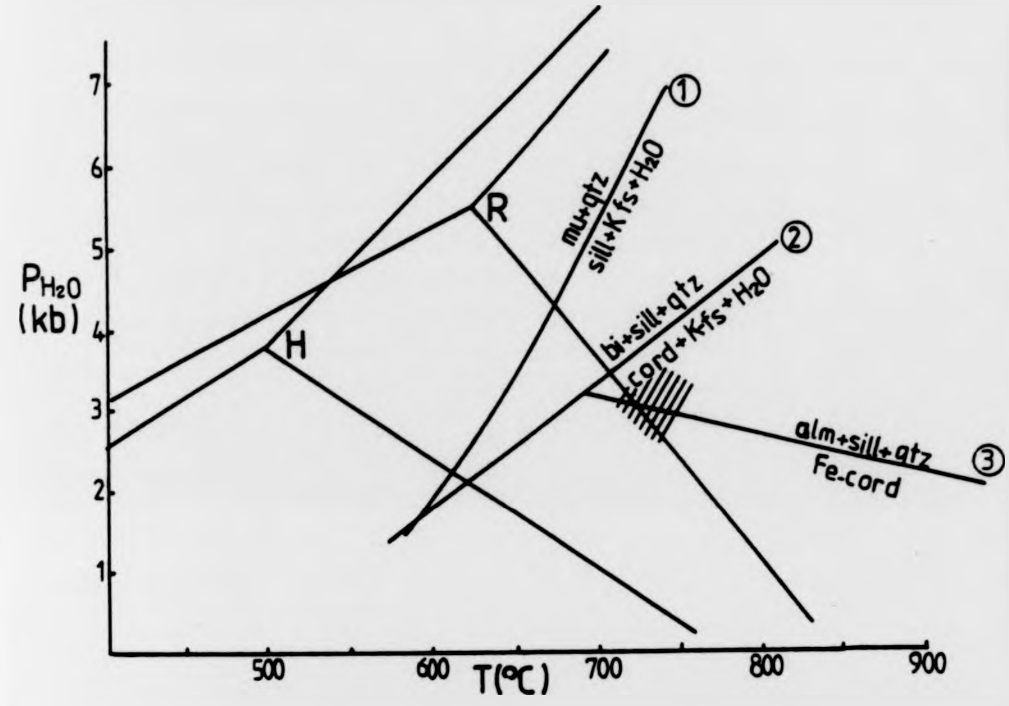


Fig.6.11: Selected experimentally calibrated reactions.
1. Chatterjee and Johannes (1974)
2. Hoffer (1976)
3. Richardson (1968), Holdaway and Lee (1977)

Aluminosilicate data: R-Richardson et al. (1969), H-Holdaway (1971)

Ornamented area: inferred field of inner aureole assemblage reaction:

biotite + sillimanite + quartz = cordierite + K-feldspar + water.

for intermediate X_{Fe} compositions at 650°C and 710°C for Ptotal = PH_2O of 2.5 and 3.5 k bars respectively.

The presence of this reaction assemblage in the rocks of the inner aureole suggests temperatures in the range determined above in this zone.

The above paragenesis of the inner aureole also indicates pyroxene-hornfels facies (Turner, 1981), while the mineral assemblage of the outer aureole indicates hornblende-hornfels facies conditions.

The assemblage : almandine + cordierite + K-feldspar + quartz has been observed in rocks of the inner aureole. Holdaway and Lee (1977) argue that this assemblage requires $PH_2O <$ Ptotal in order to form. This suggests that a H_2O was low in the aureole rocks. Since the prograde reactions are dehydration reactions, Hoffer's temperature data must therefore represent maximum figures.

6.7.6 The relative timing of the contact metamorphism

The relative timing of the contact metamorphism may be constrained by several lines of evidence. The aureole rocks lack primary muscovite but contain late porphyroblastic and smaller muscovite grains overgrowing and replacing the early minerals. This late muscovite is also found in the regionally metamorphosed country rocks as well as in the early two-mica granite (see Chapter 8) but has not been found in the later granodiorite. Textural evidence suggests that the growth of this muscovite occurred during the, MP3, metamorphic event after the third episode of deformation, D3.

These observations therefore, imply that the contact metamorphism pre-dated the MP3 event. They also suggest that MP3 may be consequent upon the intrusion of the granodiorites; large-scale hydrothermal convection (Norton and Knight, 1977; Ferry, 1978) set up by this intrusion may have caused increased activity of H_2O-rich fluids containing remobilised K^+ from the country rocks.

The deformation of some of the aureole andalusite (Plate 6.7a) parallel to the D3 crenulation suggest that their crystallisation is early and may have slightly pre-dated this deformation episode. On the other hand, sillimanite grains, although slightly bent and showing undulatory extinction, do not show this D3 deformation. This observation suggests that growth of the early andalusite may have been due to an early rise in temperature due to the intrusion of the early two-mica granite since it is also deformed by the D3 (see Chapter 5).

Anderson (1956) and Clayburn (1981) have observed that the Corrieyairack Complex consists of a series of intrusions, the late granodiorite intruding the early two-mica granite. Continued rise in aureole temperatures with intrusion of the granodiorite probably led to the growth of the less-deformed, post-D3 minerals.

CHAPTER 7: GEOCHEMISTRY OF THE METASEDIMENTS

7.1 Introduction:

The use of geochemistry in characterising and correlating metasedimentary rocks has been emphasised by numerous workers, including Shaw (1954, 1956), Taylor (1965), van de Kamp (1968), Senior and Leake (1978), Lambert et al (1981), Whittles (1981), Holland and Winchester (1981), Haselock (1982), Winchester et al (1983), Condie and Martell (1983), Bhatia (1983) and Hickman et al (1983).

Most workers on metasediments have found that metamorphism in the range from greenschist to amphibolite facies is largely isochemical except for the loss of volatiles: H_2O, CO_2 and S (Shaw, op.cit.; Taylor, op.cit.; Holland and Winchester, op.cit.). The mobility of most other elements is generally restricted to local redistribution during metamorphic recrystallisation.

In the northern Highlands of Scotland, Lambert et al. (1981), Winchester et al. (1983) and Holland and Winchester (1983) have found that each of the stratigraphic formations of the Moine and the Dalradian metasediments is geochemically unique. They attributed the unique chemical characteristics of each formation to original sedimentary differences arising from provenance, transport, depositional environment and diagenetic effects. Applying certain criteria they were able to correlate individual formations within the Moines of the northern Highlands, as well as differentiating the Moine pelites from those of the Appin Group of the Dalradian.

Haselock (1982) used several chemical criteria to show distinctions between the Grampian rocks of the Glenshirra Succession and those of the Corrieyairack Succession (see Chapter 2), in the Corrieyairack Pass area.

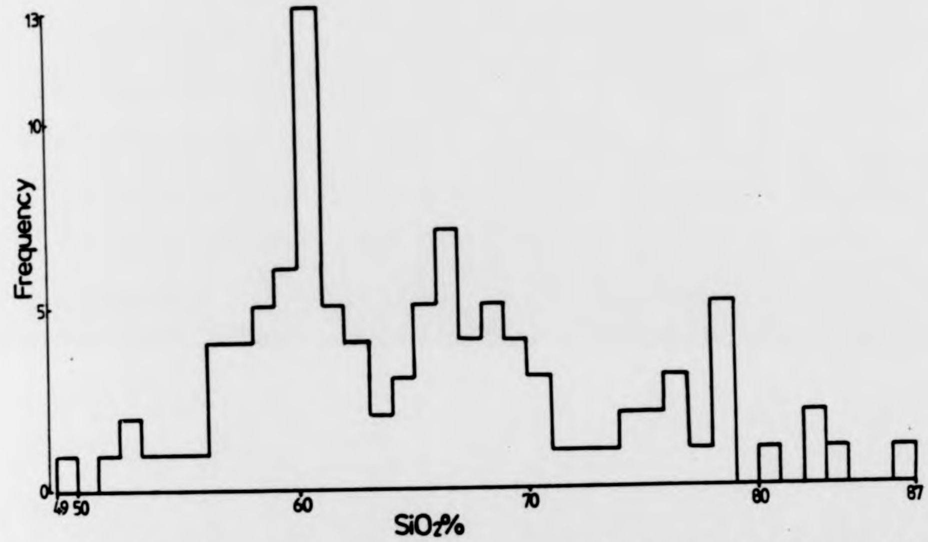


Fig.7.1: The distribution of the analysed samples in terms of their SiO_2 contents

An attempt is made here to make a geochemical characterisation of the metasedimentary rocks of the Loch Laggan and Upper Strathspey area with regard to their provenance, maturity, depositional environment, diagenesis and other sedimentary processes.

102 samples of the metasedimentary rocks from the various lithostratigraphic units of the study area, except the Carn Leac Formation, have been analysed for eleven major and eight trace elements. (Analytical methods and the list of results are given in Appendices I and II). A frequency histogram (Fig.7.1) shows the distribution of the analysed samples on the basis of their SiO_2 contents. As defined in Chapter 3 semi-pelites generally contain less than 64% SiO_2, semi-psammites generally contain 63-74% SiO_2, and psammites contain over 75% SiO_2.

In order to offset the effect of silica dilution in the more psammitic lithologies, comparisons of the chemistries of the various stratigraphic units are restricted to rocks of the same lithological type.

7.2 Possible effects of metamorphism and deformation on the chemical composition of the metasediments.

The metasedimentary rocks of the Loch Laggan-Upper Strathspey area have been subjected to amphibolite facies metamorphism and localised intense deformation. It is therefore necessary to assess the effects of these tectonothermal processes on bulk rock chemistry before the chemical variations between the various lithostratigraphic units can be related to differences in the original sedimentary rocks.

As already noted, most students of the geochemistry of metasediments consider regional metamorphism up to the amphibolite facies to be broadly isochemical except where there is sufficient evidence for metasomatic introduction or loss of chemical components. This evidence may consist of restricted development of exotic mineral phases reflecting the nature of the added elements or the suppression of certain phases by the loss of some chemical components.

Metasomatic effects in the rocks of this area are most likely to be observed along shear zones or in the contact zone of the Corrieyairack pluton. The possibility of metasomatism associated with contact metamorphism in the aureole of the pluton has already been discussed in Chapter 6, and hence samples from the contact aureole have been excluded from calculations of the mean compositions of the lithologies compared.

The intense deformation observed in the Coire nan Laogh Formation may be expected to be reflected in changes in bulk rock chemistries of the basal section near the contact with the Garva Formation (Gairbeinn Slide) relative to the upper part of the Formation. However, a comparison of the mean values of the semi-pelites from the two sections (Table 7.4) shows no marked differences in bulk rock chemistry. There is however a very slight enhancement of Ba, K/Rb, CaO, K_2O/Na_2O, Ni and a depletion of Y, Sr and oxidation ratio in the semi-pelites up to 50m from the contact. This could either be attributed to metasomatic changes or to original sedimentary differences. On the whole these differences are insignificant and a student's t-test of the chemical data shows that both groups of samples come from similar populations (at a 95% level of confidence). This similarity suggests that the tectonothermal effects only caused very localised redistribution of chemical components. Kerrich et al. (1977) have observed that in shear deformation at high temperature under amphibolite facies conditions of metamorphism strain is accommodated by ductile, crystal-plastic processes which are essentially isochemical and isovolumetric. Haselock (1982) also found no significant differences between the basal migmatitic section and the upper non-migmatitic part of the Coire nan Laogh semi-pelite in the Corrieyairack Pass area.

Hence isochemical metamorphism (except for the loss of volatiles) is likely to characterise most of the study area and is therefore assumed in the following considerations of chemical variations among the various lithostratigraphic units.

7.3 Chemical variation between the lithostratigraphic units

7.3.1 Semi-pelites

A comparison of the mean concentrations of the various elements (Table 7.1) shows that the Garva Formation is clearly distinct from the rest. Statistical analysis shows that it has higher values of TiO_2, oxidation ration (mol $\frac{2Fe_2O_3 \times 100}{2Fe_2O_3 + FeO}$), Sr/CaO, Ba/Rb, K/Rb, CaO/Y, P_2O_5/Y, Sr/Y and lower Y/Al_2O_3, K/Ba, Rb/Sr and total iron + MgO than the other formations.

Chathalain Formation semi-pelites, in common with Garva Formation semi-pelites, have a higher K_2O/Al_2O_3 and Sr/CaO than those of the Corrieyairack Succession but share comparable low Ba/Rb, K/Rb, CaO/Y, P_2O_5/Y, Sr/Y with the Corrieyairack semi-pelites.

The semi-pelites within the Corrieyairack Succession have lower Sr/CaO, K/Rb and K_2O/Al_2O_3 (Table 7.1) than those of the Garva Formation.

7.3.2 Semi-psammites

A survey of the mean concentrations of the various elements (Table 7.2) shows that the Garva and Chathalain semi-psammites share common features which distinguish them from those in the Corrieyairack Succession. They contain the highest values of SiO_2, oxidation ratio, K_2O/Al_2O_3, Sr/CaO, Zr and lower values of Al_2O_3, P_2O_5. They share with the semi-psammites of the Glendoe Formation higher values of K_2O/Al_2O_3, Sr/CaO and Ba contents (Table 7.2) than the semi-psammites of the other Corrieyairack Succession formations.

Table 7.1: Means of semi-pelites from the Loch Laggan-Upper Strathspey area

	A	B	C	D	E
SiO_2	59.45(3.48)	60.53(2.11)	59.84(1.45)	60.10(2.36)	58.99(3.14)
TiO_2	1.02(0.13)	1.40(0.6)	0.97(0.04)	1.04(0.41)	0.96(0.09)
Al_2O_3	18.66(2.22)	17.20(0.93)	18.58(0.65)	17.64(1.56)	18.98(2.01)
Fe_2O_3	1.93(0.44)	3.83(1.99)	1.67(0.35)	1.47(0.38)	1.43(0.47)
FeO	5.27(0.86)	2.67(1.06)	5.10(0.94)	4.76(1.20)	5.08(0.66)
MnO	0.10(0.02)	0.10(0.02)	0.12(0.06)	0.14(0.08)	0.10(0.03)
MgO	2.74(0.64)	1.82(0.61)	2.20(0.29)	2.35(0.37)	2.22(0.45)
CaO	1.08(0.29)	2.75(0.97)	2.14(0.98)	3.52(1.5)	1.58(0.87)
Na_2O	2.00(0.77)	3.70(0.59)	2.56(0.98)	3.20(0.59)	2.36(1.05)
K_2O	5.27(0.88)	4.26(1.24)	3.52(0.95)	3.24(1.09)	4.84(1.51)
P_2O_5	0.17(0.08)	0.17(0.03)	0.39(0.10)	0.40(0.21)	0.31(0.12)
LOI	1.84(0.44)	0.93(0.48)	1.78(0.58)	1.23(0.42)	1.75(0.75)
Ba	894(219)	1533(408)	753(224)	814(308)	1256(508)
Cr	71(11)	58(19)	64(5)	60(14)	71(8)
Nb	17(3)	12(2)	17(2)	17(4)	16(1)
Ni	48(12)	23(8)	37(12)	31(7)	32(15)
Rb	199(35)	80(34)	156(27)	147(28)	180(28)
Sr	199(110)	628(200)	277(105)	369(68)	259(121)
Y	38(6)	12(5)	39(8)	40(21)	40(6)
Zr	215(29)	254(88)	189(23)	371(351)	228(76)
O.R.	24.65	56.36	22.83	21.36	20.20
K/Rb	220	442	187	183	223
Sr/CaO	184	228	129	105	164
Ba/Rb	4.49	19.16	4.83	5.54	6.98
K_2O/Al_2O_3	0.28	0.25	0.19	0.18	0.26
Fe_2O_3total+MgO	10.53	8.62	9.54	9.11	9.30
K/Ba	49	23	39	22	32
CaO/Y	284	2115	549	880	395
P_2O_5/Y	45	131	74	100	78
Rb/Sr	1.0	0.13	0.56	0.40	0.69
Sr/Y	5.24	48.31	7.10	9.23	6.48
M1	3.4	2.35	3.33	2.9	3.14
K_2O/Na_2O	2.64	1.15	1.38	0.48	2.05
$K_2O/(CaO+Na_2O)$	1.70	0.66	0.75	0.48	1.23

A Chathalain Formation (5 analyses)
B Garva Formation (11 analyses)
C Coire nan Laogh Formation (14 analyses)
D Glendoe Formation (8 analyses)
E Monadhliath Formation (7 analyses)

Table 7.2: Means of semi-psammites from the Loch Laggan-Upper Strathspey area

	A	B	C	D	E	F
SiO_2	69.09(2.48)	69.79(2.98)	67.68(2.82)	66.72(0.93)	66.71(0.80)	68.06(2.17)
TiO_2	0.67(0.13)	0.69(0.25)	0.75(0.10)	0.68(0.03)	0.70(0.05)	0.67(0.06)
Al_2O_3	13.81(1.10)	14.02(1.37)	15.34(1.37)	15.83(1.15)	15.08(0.51)	14.62(1.34)
Fe_2O_3	1.85(0.88)	1.44(0.80)	1.24(0.22)	0.87(0.18)	1.38(0.20)	1.12(0.18)
FeO	3.16(1.37)	2.05(0.91)	3.51(0.38)	3.98(0.51)	3.74(0.41)	3.52(0.56)
MnO	0.11(0)	0.07(0.03)	0.07(0.01)	0.15(0.05)	0.08(0.02)	0.10(0.04)
MgO	1.72(0.17)	1.25(0.44)	1.63(0.28)	1.73(0.53)	1.98(0.14)	1.80(0.32)
CaO	1.47(0.29)	1.70(1.02)	1.60(0.58)	3.18(0.87)	1.67(0.57)	2.39(0.80)
Na_2O	3.10(0.22)	3.20)0.70)	2.88(0.64)	3.78(0.56)	3.00(0.40)	3.84(0.74)
K_2O	3.36(0.80)	4.26(1.20)	2.90(0.95)	1.75(0.26)	3.55(0.73)	2.18(0.65)
P_2O_5	0.13(0.03)	0.12(0.05)	0.20(0.07)	0.24(0.05)	0.17(0.02)	0.18(0.05)
LOI	0.77(0.20)	0.78(0.32)	1.53(0.46)	0.71(0.11)	1.10(0.26)	0.70(0.18)
Ba	685(96)	1137(285)	609(194)	420(112)	876(193)	510(253)
Cr	43(2)	36(15)	44(6)	46(3)	47(4)	45(4)
Nb	16(4)	13(2)	18(1)	16(1)	15(2)	15(1)
Ni	27(16)	18(7)	19(12)	27(4)	29(3)	29(5)
Rb	134(22)	102(17)	132(32)	87(9)	125(20)	102(17)
Sr	253(34)	381(51)	242(40)	389(36)	287(24)	360(72)
Y	22(2)	17(7)	24(8)	28(3)	25(4)	22(5)
Zr	247(134)	300(126)	226(19)	228(14)	198(34)	209(67)
O.R.	34.34	38.68	24.08	16.56	24.62	22.22
K/Rb	208	347	182	167	236	177
Ba/Rb	5	11	5	5	7	5
K_2O/Na_2O	1.08	1.33	1.01	0.46	1.18	0.57
$K_2O/(Na_2O+CaO)$	0.74	0.87	0.65	0.25	0.76	0.35
Sr/CaO	172	224	151	122	172	151
CaO/Y	668	1000	667	1136	668	1086
Rb/Sr	0.53	0.27	0.55	0.22	0.44	0.28
Sr/Y	11.5	22.41	10.1	13.89	11.48	16.36
Fe_2O_3total+MgO	7.05	4.95	6.73	6.98	7.47	6.79

A Chathalain Formation (3 analyses)
B Garva Formation (10 analyses)
C Coire nan Laogh Formation (5 analyses)
D Transitional Semi-psammite (3 analyses)
E Glendoe Formation (8 analyses)
F Monadhliath Formation (4 analyses)

O.R. Oxidation ratio

7.3.3 The psammites

Only a small number of psammite analyses are available from the Corrieyairack Succession, hence the following observations must be assessed with some caution.

The Garva psammites possess higher K/Rb, Ba/Rb, Sr/CaO, oxidation ratio and lower Fe_2O_3 total + MgO than those of the other formations.

On a plot of log Na_2O/K_2O against log SiO_2/Al_2O_3 (Fig.7.7) (Pettijohn et al, 1973) 39% of the samples of the semi-psammites and psammites of the Glenshirra Succession plot in the field of lithic arenites, 13% plot as arkose and 48% plot as greywackes. On the other hand 89% of the Corrieyairack samples plot as greywackes and only 11% plot in the field of lithic arenites.

On the (Fe_2O_3 total + MgO)-Na_2O-K_2O plot of Blatt et al. (1980) (Fig.7.13) 56% of the Glenshirra Succession semi-psammites and psammites classify as arkoses, 26% plot as lithic sandstones and 26% plot as greywackes. According to this scheme of classification, 54% of the Corrieyairack Succession rocks plot as greywackes and 46% plot as lithic sandstones.

Despite the differences in the proportions of the samples plotting in the various fields, both classification schemes produce broadly similar results. These indicate that the Glenshirra rocks were somewhat more arkosic lithic arenites whereas the Corrieyairack sandstones were mainly greywackes.

In both classification schemes, there is an overlap between the Glenshirra and the Corrieyairack Successions with the Glendoe Formation rocks occupying an intermediate position between the two.

Table 7.3: Means of psammites from the Loch Laggan-Upper Strathspey area

	A	B	C	D	E	F
SiO_2	77.51(2.04)	81.69(4.01)	77.61	78.81	76.78(3.04)	78.75(3.68)
TiO_2	0.50(0.41)	0.53(0.37)	0.41	0.47	0.53(0.19)	0.38(0.17)
Al_2O_3	10.62(1.01)	8.95(1.78)	11.30	10.36	10.71(1.63)	10.18(1.60)
Fe_2O_3	0.98(0.72)	0.70(0.20)	0.58	0.86	0.78(0.40)	0.57(0.39)
FeO	1.67(0.92)	1.07(0.42)	1.32	2.16	2.42(0.36)	1.76(0.71)
MnO	0.05(0.03)	0.03(0.02)	0.04	0.04	0.07(0.04)	0.08(0.05)
MgO	0.81(0.20)	0.71(0.13)	0.96	0.95	1.27(0.04)	1.15(0.23)
CaO	1.02(0.49)	0.65(0.28)	1.51	0.55	2.13(1.17)	2.04(0.66)
Na_2O	2.60(0.36)	1.92(0.46)	3.41	2.02	2.25(1.20)	3.08(0.37)
K_2O	2.96(1.13)	2.73(1.17)	1.49	2.98	2.17(0.53)	1.14(0.21)
P_2O_5	0.05(0.03)	0.05(0.03)	1.10	0.08	0.10(0.01)	0.11(0.03)
L.O.I.	0.57(0.29)	0.69(0.14)			0.82(0.18)	0.47(0.13)
Ba	723(209)	694(285)	408	735	502(33)	293(215)
Cr	31(18)	25(11)	23	32	30(5)	30(11)
Nb	14(2)	16(6)	17	15	18(5)	17(2)
Ni	14(4)	12(4)	10	14	16(3)	18(6)
Rb	98(10)	72(29)	51	101	91(6)	45(13)
Sr	197(24)	189(66)	275	144	265(12)	329(108)
Y	12(6)	9(5)	12	18	17(2)	17(6)
Zr	274(311)	269(188)	249	234	215(114)	250(98)
O.R.	34.60	36.37	28.44	26.79	22.54	22.47
K/Rb	273	315	242	245	198	210
Ba/Rb	8	10	8	7	6	7
$K_2O/(Na_2O+CaO)$	0.82	1.06	0.30	1.16	0.50	0.22
Sr/CaO	193	291	182	262	124	161
Rb/Sr	0.46	0.38	0.19	0.70	0.34	0.14
Fe_2O_3total+MgO	3.63	2.59	2.99	4.186	4.71	3.66
TiO_2/P_2O_5	10	10.6	4.1	5.9	5.3	3.5
Zr/P_2O_5	.55	.54	.25	.29	.215	.23

A Chathalain Formation (5 analyses)
B Garva Formation (5 analyses)
C Coire nan Laogh Formation (1 analysis)
D Transitional Formation (1 analysis)
E Glendoe Formation (1 analysis)
F Monadhliath Formation (3 analyses)
O.R. Oxidation ratio

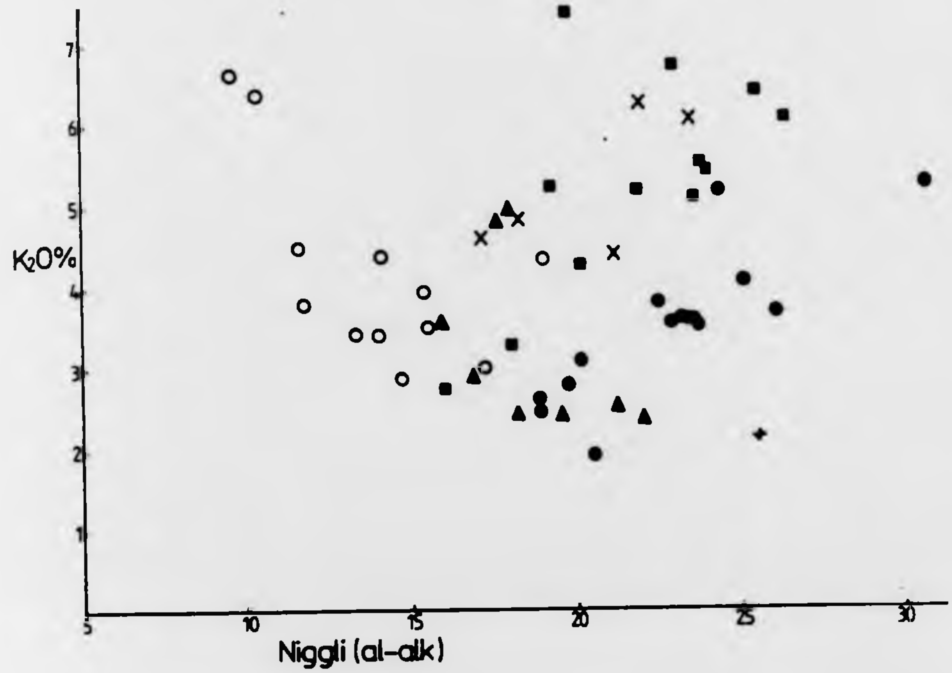


Fig.7.2: K_2O - Niggli(al-alk) plot for semi-pelites

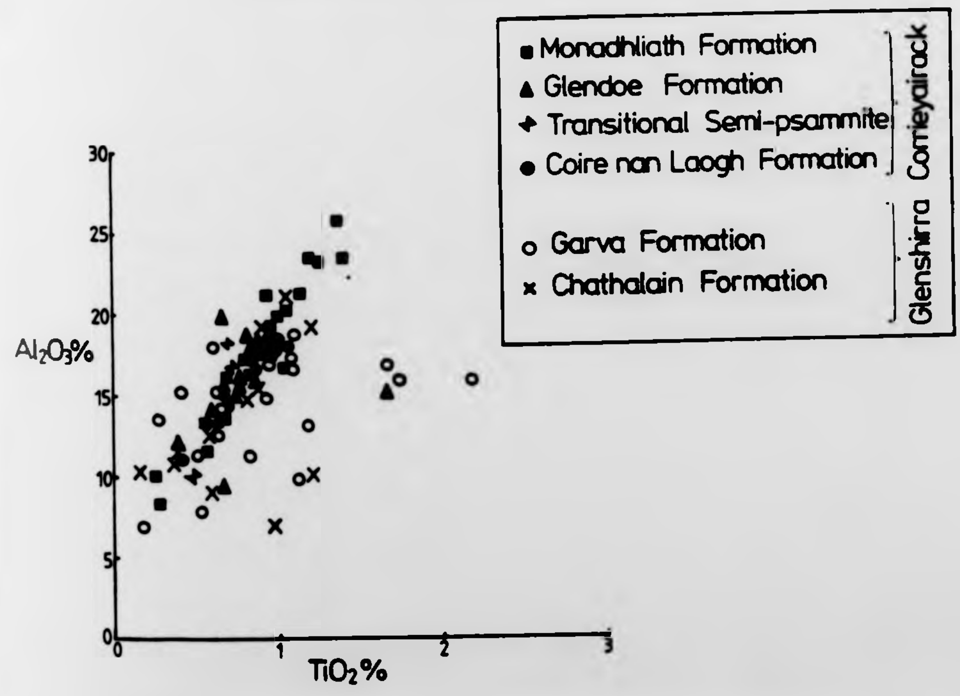


Fig.7.3: Al_2O_3-TiO_2 plot for all rock types

7.4 Interpretation of the variations between the two successions

7.4.1 Semi-pelites

The high K_2O/Al_2O_3 value of the Glenshirra semi-pelites, taken together with their high Sr/CaO indicates the presence of detrital K-feldspar. This interpretation is supported, especially with reference to the semi-pelites of the Garva Formation by their higher mean K/Rb, Ba/Rb, K/Ba, and Rb/Sr values (Taylor, 1965). Petrographic evidence in support of this interpretation is also provided by the common occurrence of clasts of microdine in these semi-pelites (Chapter 3). This view is also supported by a K_2O-Niggli(al-alk) variation diagram (Fig.7.2), which discriminates K_2O contained in clay minerals or sheet silicates from that contained within detrital alkali feldspars (Senior and Leake, 1978). This plot shows that the semi-pelites of the Glenshirra Succession, especially those in the Garva Formation, contain high K_2O concentrations locked up in detrital K-feldspar.

The relatively high proportion of alkali-feldspar to clay minerals inferred in the Garva Formation suggests that they were deposited as immature first-cycle sediments with little or no time for the alkali feldspars to be decomposed. Probably the high CaO/Y and Sr/Y ratios in the Garva semi-pelites also indicate high proportions of detrital Sr-accepting and Y-rejecting CaO phases such as plagioclase (Lambert and Holland, 1974), this again being a sign of the relative immaturity of the sediment.

Englund and Jorgensen (1973) have observed that weathering is characterised by a gradual decrease of Na_2O, K_2O and CaO, and an increase in the Al_2O_3 content of pelitic rocks. They proposed that the degree of weathering can be described by the following expression:

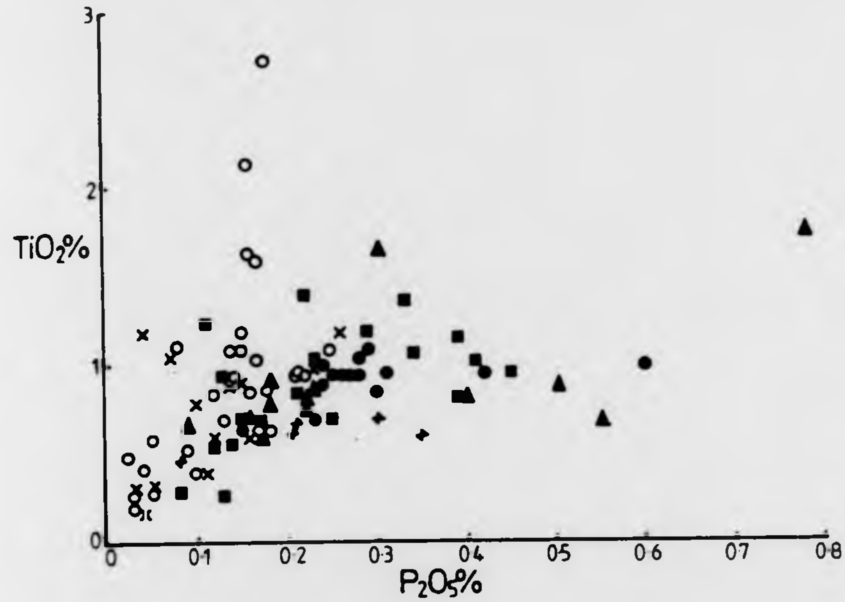


Fig.7.5: TiO_2 - P_2O_5 plot for all rock types

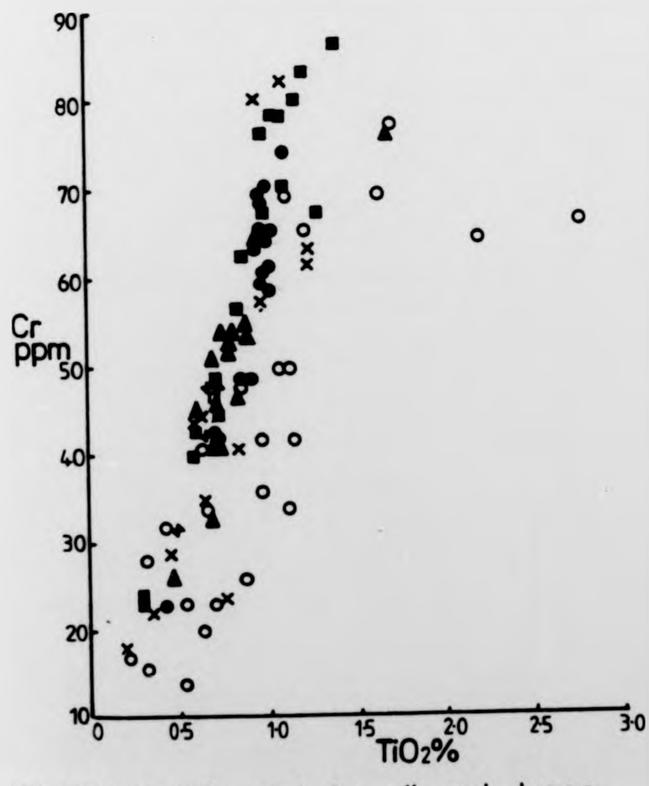


Fig.7.4: Cr-TiO_2 plot for all rock types

Table 7.4: Means of semi-pelites from the Coire nan Laogh Formation

	A	B
SiO_2	59.79(1.11)	59.89(1.83)
TiO_2	0.99(.04)	0.96(.04)
Al_2O_3	18.55(.39)	18.62(.87)
Fe_2O_3	1.61(.18)	1.74(.48)
FeO	5.38(.81)	5.03(.95)
MnO	0.10(.03)	0.13(.07)
MgO	2.22(.29)	2.17(.31)
CaO	2.26(1.10)	2.02(.90)
Na_2O	2.40(.85)	2.72(1.13)
K_2O	3.54(1.03)	3.49(.93)
P_2O_5	0.30(.14)	0.28(.06)
Ba	811(250)	696(196)
Cr	67(5)	63(4)
Nb	16(2)	17(2)
Ni	41(4)	32(16)
Rb	154(29)	157(27)
Sr	267(85)	288(129)
Y	37(10)	41(5)
Zr	190(18)	187(29)
K_2O/Al_2O_3	0.19	0.19
Ba/Rb	5.27	4.43
K/Rb	190.82	184.54
K_2O/Na_2O	1.48	1.28
CaO/Sr	84.64	70.14
SiO_2/Al_2O_3	3.22	3.22
TiO_2/Al_2O_3	0.053	0.052
$K_2O/(Na_2O+CaO)$	0.76	0.74
Total Fe/Al_2O_3	0.41	0.39
O.R.	21.08	23.91

A Mean of semi-pelites from the basal section of the Coire nan Laogh Formation (7 analyses)

B Mean of semi-pelites from the upper section of the Coire nan Laogh Formation (7 analyses)

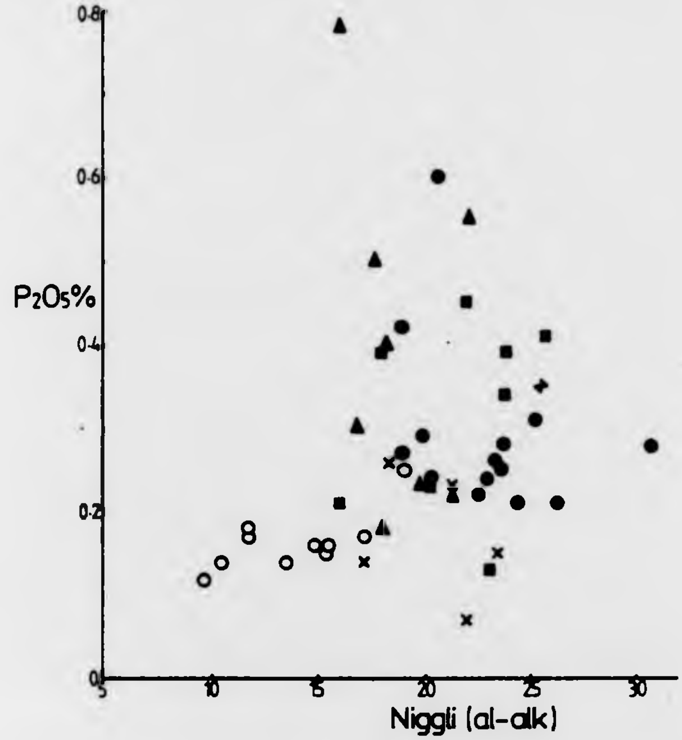


Fig.7.6: P_2O_5 - Niggli (al-alk) plot for the semi-pelites

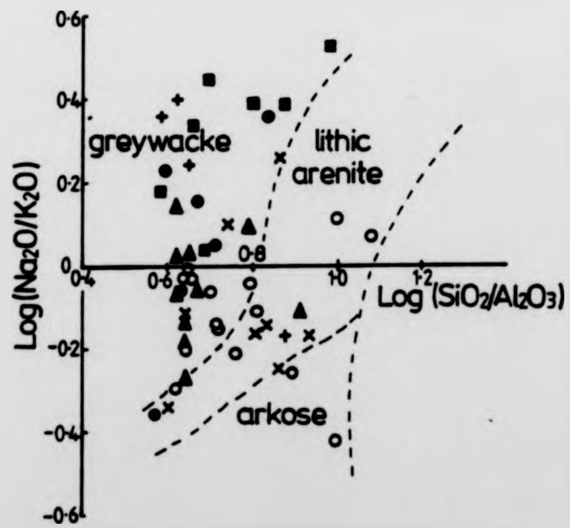


Fig.7.7: The classification of the psammites and semi-psammites (after Pettijohn et al, 1972)

$$M1 \quad \frac{FeO + MgO + Al_2O_3}{K_2O + Na_2O + CaO}$$

Low values of M1 typify unweathered sediments. Application of this index to the semi-pelitic rocks studied here, shows that those in the Garva Formation have the lowest M1 value, and therefore are the least "mature".

This immaturity is a reflection of the high detrital feldspar content of the semi-pelites of the Garva Formation in contrast to the higher original clay mineral content of those of the Corrieyairack Succession and the Chathalain Formation. It may therefore reflect the relatively higher rate of erosion relative to weathering for the source rocks of the Garva Formation, or perhaps the presence of fewer mafic minerals in the Garva Formation and hence in its source rocks.

The generally higher TiO_2/Al_2O_3 ratios of the semi-pelites in the Garva Formation may either be a result of the greater absorption of TiO_2 by clay minerals or of the presence of detrital Ti-bearing phases in the original sediment. The scatter shown by the semi-pelites of the Glenshirra Succession in contrast to those of the Corrieyairack Succession on the TiO_2-Al_2O_3 and the Cr-TiO_2 plots (Figs. 7.3 and 7.4, respectively) suggests that they contained detrital Ti-bearing phases. The exact identity of these detrital phases is not known; they could have been sphene and ilmenite which are still commonly observed in the metasediments, or other Ti-bearing phases such as rutile.

7.4.2 <u>Semi-psammites</u>

The high mean K_2O/Al_2O_3, Sr/CaO, K/Rb and K_2O (CaO+Na_2O) of the semi-psammites of the Glenshirra Succession, especially those of the Garva Formation, taken together with its higher mean Ba/Rb and lower K/Ba again indicate the presence of detrital K-feldspar in the psammites, and also reflects their preponderantly lithic and arkosic nature (Fig.7.12).

The high mean K_2O/Al_2O_3, Sr/CaO, Ba/Rb ratios of the semi-psammites of the Glendoe Formation also suggests the presence of some detrital K-feldspar in these rocks. Petrographic evidence in support of this interpretation is given by the common observation of microcline porphyroclasts in the Garva Formation semi-psammites and also their less common occurrence in those of the Glendoe Formation.

The higher mean concentrations of Zr in the semi-psammites of the Glenshirra Succession also indicates a slightly higher proportion of detrital zircon in these rocks.

The higher mean oxidation ratios (Chinner, 1960) of the Glenshirra Succession rocks suggests that they were deposited in relatively more oxidising environments compared with those of the Corrieyairack Succession. This interpretation is supported by both the lithic and arkosic nature of the rocks and sedimentological analyses (Chapter 4) which suggests that they were probably formed as subaerial alluvial or shallow water deposits, in contrast to the Corrieyairack semi-psammites which were deposited in marine environments.

7.4.3 Psammites

The higher mean K_2O/Al_2O_3, K/Rb, Ba/Rb, $K_2O/(Na_2O+C_2O)$ Sr/CaO and Ba/Rb ratios of the psammites of the Glenshirra Succession also indicate a higher detrital K-feldspar to illite and plagioclase content, which is shared by the Transitional Semi-psammite. The presence of detrital K-feldspar represented by inferred porphyroclasts of microcline reflects the relative immaturity of these rocks for reasons already stated.

Again the higher oxidation ratios of the Garva and Chathalain psammites is suggestive of their deposition in relatively oxidising environments (Chinner, 1965) as was also inferred for their semi-psammites. This higher oxidation state was probably inherited from the original sediments as discussed by Chinner (op.cit.) and cannot be attributed to later tectono-metamorphic events.

The chemical differences between the Glenshirra and the Corrieyairack Successions is also illustrated by the plot of TiO_2 vs P_2O_5 for all rock types (Fig.7.5). This shows that whereas the Glenshirra Succession rocks contained more TiO_2, much of which has been inferred to be in detrital phases, the Corrieyairack Succession rocks contain relatively more P_2O_5. Much of this P_2O_5 probably originates from detrital apatite grains, as shown by the scatter and lack of correlation shown by the plot of P_2O_5 vs Niggli (al-alk) in the semi-pelitic rocks (Fig.7.6).

This chemical difference between the rocks of the two successions may be the result of a difference in provenance or in depositional environments. A detailed discussion of the provenance of their original sediments is given later; sedimentological analyses (see Chapter 4) has broadly suggested alluvial or shallow-water sedimentary environment for the Glenshirra Succession sediments and a marine environment for those of the Corrieyairack Succession.

The absence of calc-silicate pods in the Garva Formation and their relative abundance in the formations of the Corrieyairack Succession may be partly attributed to its lower CaO content compared with those of the Corrieyairack Succession and partly to the marked immaturity of the Garva rocks in which most of the CaO is contained in the semi-pelites.

The rapid burial and very low permeability of the semi-pelites may have prevented the dissolution of Ca-bearing phases and the mobilisation of the Ca^{++} ions and their subsequent diffusion to centres of calc-silicate concretion formation.

7.5 Variation within successions

7.5.1 The Glenshirra Succession

a) Semi-pelites

The student's t-test shows that the semi-pelites of the Chathalain Formation have significantly higher FeO, MgO, Nb, Ni, Rb and Y but lower CaO, Na_2O, Ba, Sr and oxidation ratio than those of the Garva Formation at the 95% level of confidence (Table 7.1).

These differences suggest that the sediments that formed the semi-pelites of the Chathalain Formation contained more mafic minerals e.g. chlorite than those that formed the semi-pelites of the Garva Formation which contained more detrital plagioclase and allanite.

The higher K/Rb and Ba/Rb ratios of the semi-pelites of the Garva Formation also suggest that they contained a higher proportion of detrital K-feldspar to clay minerals than those of the Chathalain Formation. This, together with the higher M1 value of the Chathalain Formation semi-pelites (Table 7.9), imply that they are more "mature" than those of the Garva Formation as a result of the greater decomposition of the original feldspar in their source rocks.

The excellent discrimination of the semi-pelites of the Chathalain Formation from those of the Garva Formation obtained from Y-Sr and Y-Zr plots (Figs.7.8 and 7.9, respectively) is a reflection of the higher proportion of Y-rich, Ca-poor minerals such as the micas (Lambert and Holland, 1974) to detrital feldspar

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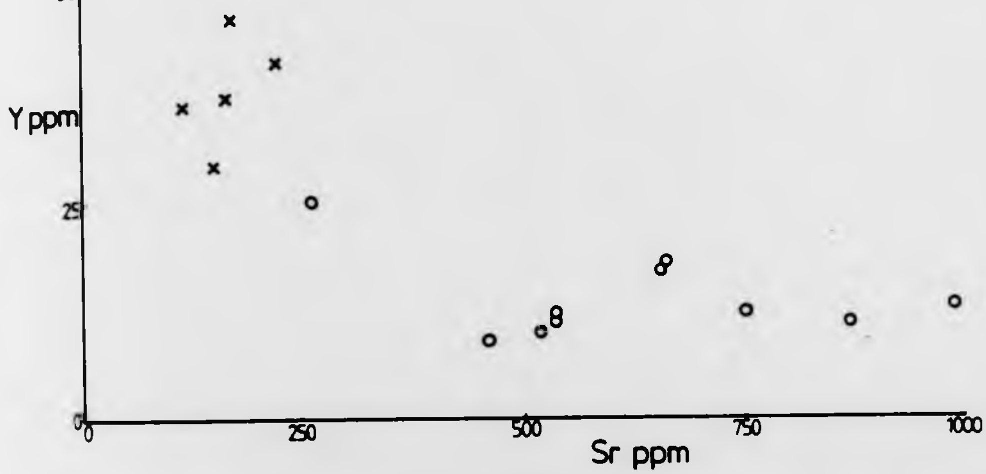


Fig.7.8: Y-Sr plot for the semi-pelites of the Glenshirra Succession

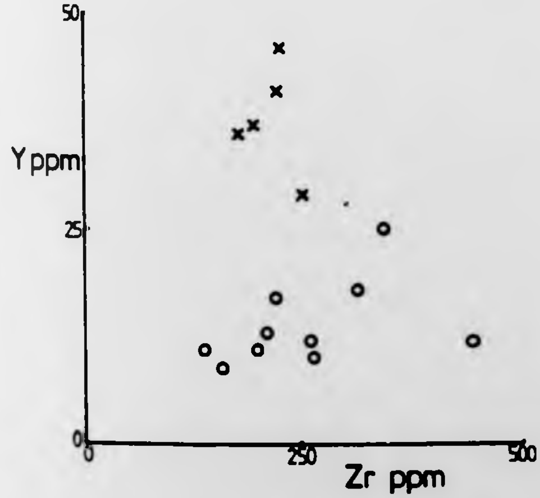


Fig.7.9: Y-Zr plot for the semi-pelites of the Glenshirra Succession

and zircon in the former.

The higher oxidation ratio of the Garva semi-pelites suggest that they were deposited in a more oxidising (aerated) environment than those of the Chathalain Formation (Chinner, 1960). This is consistent with the sedimentological inferences (Chapter 4) that the Garva sediments were deposited in alluvial environments.

b) Semi-psammites

The student's t-test shows that the semi-psammites of the Chathalain Formation have significantly higher MnO and Rb but lower Ba and Sr contents than those of the Garva Formation at the 95% level of confidence (Table 7.2).

These differences together with the higher K/Rb, Ba/Rb, Sr/CaO, Sr/Y, Zr/Y ratios but lower Fe_2O_3 total + MgO content of the semi-psammites of the Garva Formation (Table 7.2) indicate that they contained a higher proportion of detrital K-feldspar and zircon to chlorite and clay minerals compared to those of the Chathalain Formation.

These differences are consistent with the observations made with regard to the associated semi-pelites and may suggest that the source rocks of the Chathalain Formation sediments had a higher proportion of basic material than those that supplied the sediments of the Garva Formation.

c) Psammites

A student's t-test shows a significant difference only in the Na_2O content of the two formations at the 95% level of confidence.

The higher Na_2O content of the Chathalain psammites, taken together with their lower $K_2O(CaO+Na_2O)$ ratio, suggests that they had a higher proportion of detrital plagioclase to K-feldspar in their original sediments compared with the Garva psammites. This may suggest that there was a slightly higher proportion of plagioclase in the source rocks of the psammites of the Chathalain Formation.

7.5.2 The Corrieyairack Succession

a) Semi-pelites

Among the Corrieyairack Succession semi-pelites, those of the Monadhliath Formation are distinct from the rest, in containing the highest mean K/Rb, Ba/Rb, K_2O/Al_2O_3 and lower K/Ba ratios (Table 7.1). These characteristics indicate that it had the highest proportion of detrital K-feldspar to illite in the original sediments, and was hence probably less mature than the other Corrieyairack Succession semi-pelites.

The Monadhliath semi-pelite also have lower mean CaO and Sr than the other Corrieyairack Succession semi-pelites (Table 7.1), which taken together with their higher mean ($K_2O/CaO+Na_2O$) ratio (Table 7.1) indicates that it had a lower detrital plagioclase to K-feldspar ratio in the original sediments.

The semi-pelites of the Glendoe Formation have the lowest mean $K_2O/(CaO+Na_2O)$, K_2O/Al_2O_3, Sr/CaO, K/Rb, and the highest mean CaO, Na_2O and Sr, which indicate that they had by contrast the highest plagioclase to K-feldspar ratio of all the Corrieyairack Succession semi-pelites. It also reflects the more calcareous nature of much of the semi-pelites in the Glendoe Formation, which often contain some epidote or clinozoisite. The Glendoe semi-pelites also contain more zircon than the rest, suggesting a higher input of refractory heavy minerals.

The chemical differences between the two major semi-pelitic formations - the Coire nan Laogh and the Monadhliath Formations are graphically illustrated in several two-component plots: (Figs.7.2, 7.10, 7.11). These show higher K_2O/Al_2O_3,

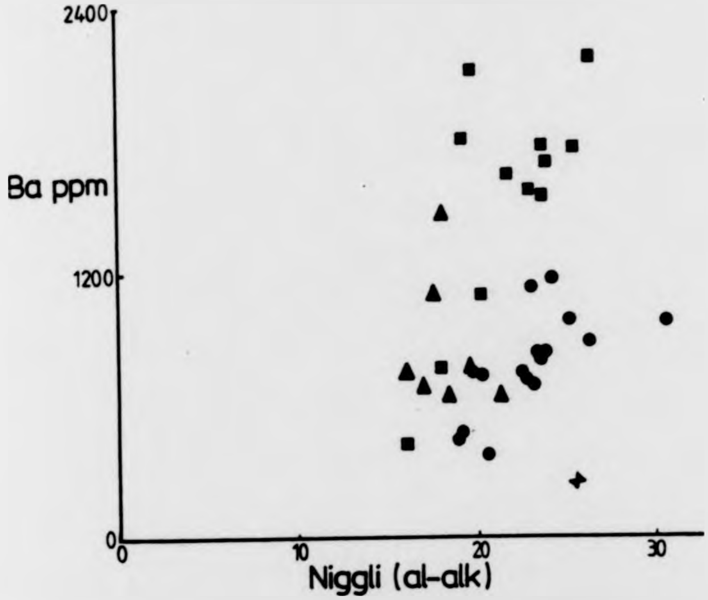


Fig.7.11: Ba-Niggli(al-alk) plot for the semi-pelites of the Corrieyairack Succession

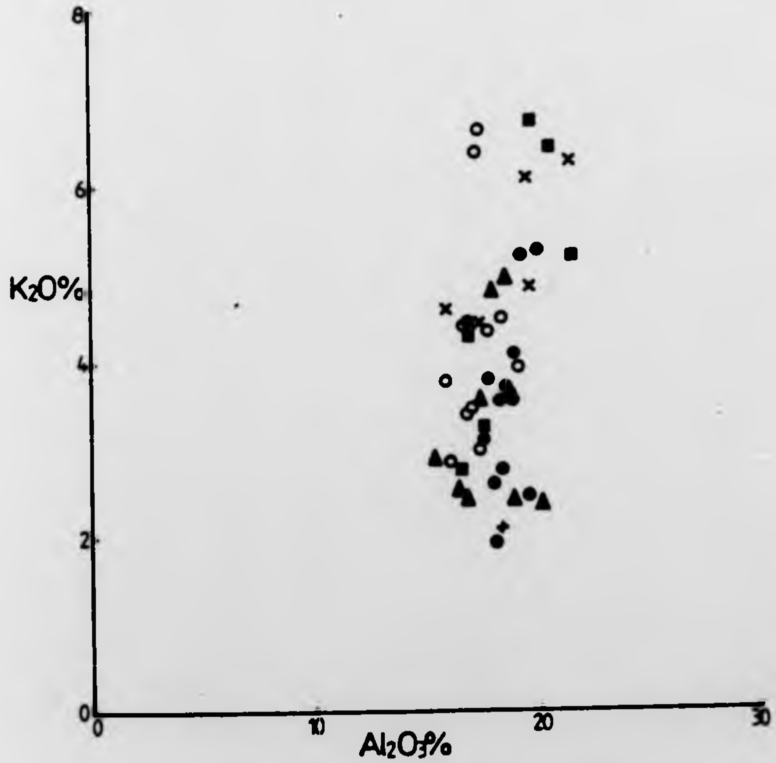


Fig.7.10: K_2O-Al_2O_3 plot for the semi-pelites

Table 7.5: Results of the discriminant function analysis

COIRE NAN LAOGH AND MONADHLIATH SEMI-PELITES

Standardised canonical discrminant function coefficients

Function 1 (major elements)		Function 1 (trace elements)	
Al	-1.39689	Ba	2.39961
Fe_3	-1.31869	Ni	-0.86748
Ca	-1.89935	Rb	-0.72483
Na	2.01471	Sr	1.75352
K	2.84052	Y	-0.64198
P	1.65924	Zr	0.93434

Canonical discriminant functions evaluated at group means
(croup centroids)

Majors: Group	Function 1	Group	Function 1 (trace elements)
1	-1.43844	1	-1.21672
2	3.28785	2	2.43345

Classification results, majors
100% success

Classification result, trace elements
95.24% success

K_2O/Niggli (al-alk), Ba/Rb, Ba/Niggli (al-alk) in the Monadhliath semi-pelites compared with those of the Coire nan Laogh Formation, reflecting the higher detrital K-feldspar to illite ratio in the sediments of the Monadhliath semi-pelites. This characteristic, together with the lower M1 value of the Monadhliath semi-pelites suggests that they were less "mature" than those of the Coire nan Laogh Formation. These inferences are supported by student's t-test results which show a significant difference in the K_2O and Ba contents of the two groups of semi-pelites at the 95% level of confidence.

Discriminant analysis (Table 7.5 and Appendix 3) show that the most important contributors to the discriminant function between the two units are K, Na, Ba and Sr whereas the negative contributors are Ca, Al and Fe^{3+}. These imply a higher proportion of detrital alkali feldspar to plagioclase and chlorite in the Monadhliath semi-pelites.

Their similar Fe_2O_3 total+MgO, Ni and Cr contents suggest that they had a similar proposition of basic detritus in their sediments and hence a similar proportion of mafic minerals in their source rocks.

b) Semi-psammites

The semi-psammites of the Glendoe Formation have the highest values of K_2O and Ba than other semi-psammites in the Corrieyairack Succession (Table 7.2). The student's t-test also shows that they have a significantly higher content of Sr than those of the Coire nan Laogh Formation but a lower Sr content than those of the Transitional and Monadhliath Formations at the 95% level of confidence.

The higher K/Rb, Ba/Rb, $K_2O(CaO+Na_2O)$ and Sr/CaO ratios of the Glendoe semi-psammites indicate that they contained a higher

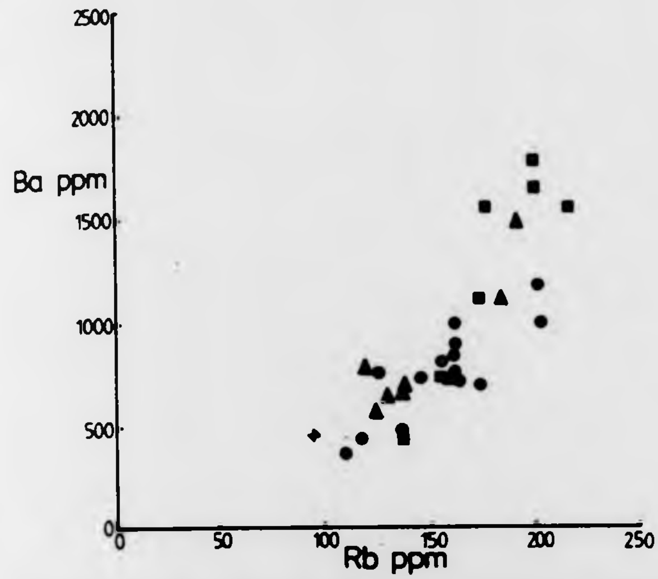


Fig.7.12: Ba-Rb plot for the semi-pelites of the Corrieyairack Succession

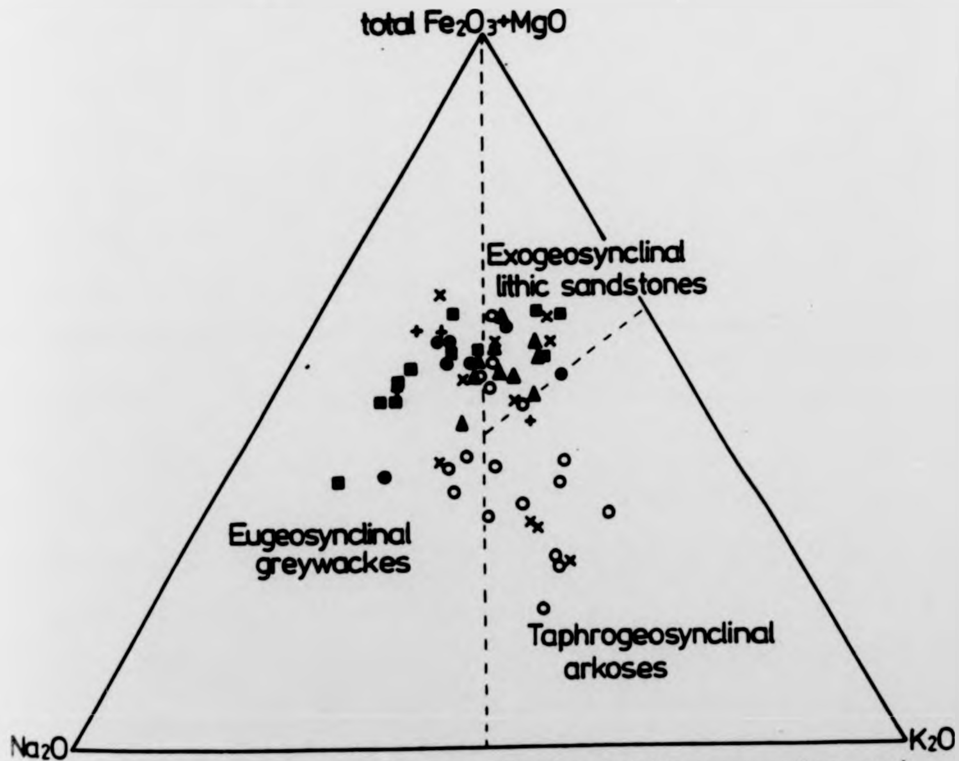


Fig.7.13: Geochemical and tectonic classification of the psammites and semi-psammites (after Blatt et al.,1980)

proportion of detrital K-feldspar to plagioclase than the other semi-psammites of the succession. This inference is supported by the more common occurrence of microcline grains in the Glendoe semi-psammites than in the other Corrieyairack Succession semi-psammites. This higher K-feldspar content of the Glendoe semi-psammites may suggest either that they had a higher granitoid input in their source rocks or that their source rocks had undergone a less intense chemical weathering than the other units permitting detrital microcline to survive.

The higher Sr content of the Transitional semi-psammites is accounted for by their higher CaO contents (Taylor, 1965) and probably indicates the existence of relatively higher plagioclase content in the original sediment. Their lowest K_2O $(CaO+Na_2O)$, K/Rb, Sr/CaO ratios (Table 7.2) indicate that they had the lowest proposition of detrital K-feldspar to plagioclase in their original sediments.

The contents of many other trace elements such as Cr, Ni, Y and Zr vary within narrow limits only, suggesting that the proportion of the detritus supplied from basic sources remained fairly constant throughout the period of deposition of the Corrieyairack Succession.

c) Psammites

Only a few samples of this lithological type from the Corrieyairack Succession were analysed (Table 7.3) a reflection of its relative scarcity in this succession.

The Glendoe psammites tend to have higher K_2O and Rb contents than those of the Monadhliath Formation. This taken together with the higher $K_2O(CaO+Na_2O)$ ratio of the Glendoe psammites suggests that they contained more detrital K-feldspar to plagioclase ratio and also possibly more detrital mica since most of them plot in the lithic sandstone field of Fig.7.13.

Only one psammite analysis each is available for the Coire nan Laogh and the Transitional Formations and hence it is not worthwhile comparing these with the other formations.

7.6a <u>Provenance of the original sediments</u>

The provenance of sedimentary rocks is usually inferred from the framework constituents of the rocks if they could be identified (Dickinson, 1970; Dickinson and Suczek, 1979; Dickinson and Valloni, 1980; Valloni and Maynard, 1981; Potter, 1978; Pettijohn 1975; Schmab, 1975). In this respect, the psammites and semi-psammites of the various lithostratigraphic units probably offer the best evidence for provenance characterisation of the metasediments. Unfortunately, given the repeated deformation and metamorphism up to the amphibolite facies suffered by these rocks most sedimentary textures have been obliterated and original detrital constituents can be identified with some confidence only in the Garva Formation psammites and semi-psammites. Detrital modal analyses cannot, therefore, be applied and reliance must be placed largely on the chemistry of the psammites and semi-psammites.

Difficulties arise, however, when attempts are made to relate detrital rock composition with bulk chemical analyses of sedimentary or metasedimentary rocks. This is because of possible diagenetic introduction of some components present in the cements or loss of others by intrastratal dissolution. Element concentrations in the source rocks may also have undergone some change during weathering and subsequent transport. However, in immature clastic rocks such as those in the Loch Laggan-Upper Strathspey area, these problems may be minimal, making it possible for provenance to be inferred from bulk rock chemistry.

On a CaO-Na_2O-K_2O ternary diagram on which the average compositions

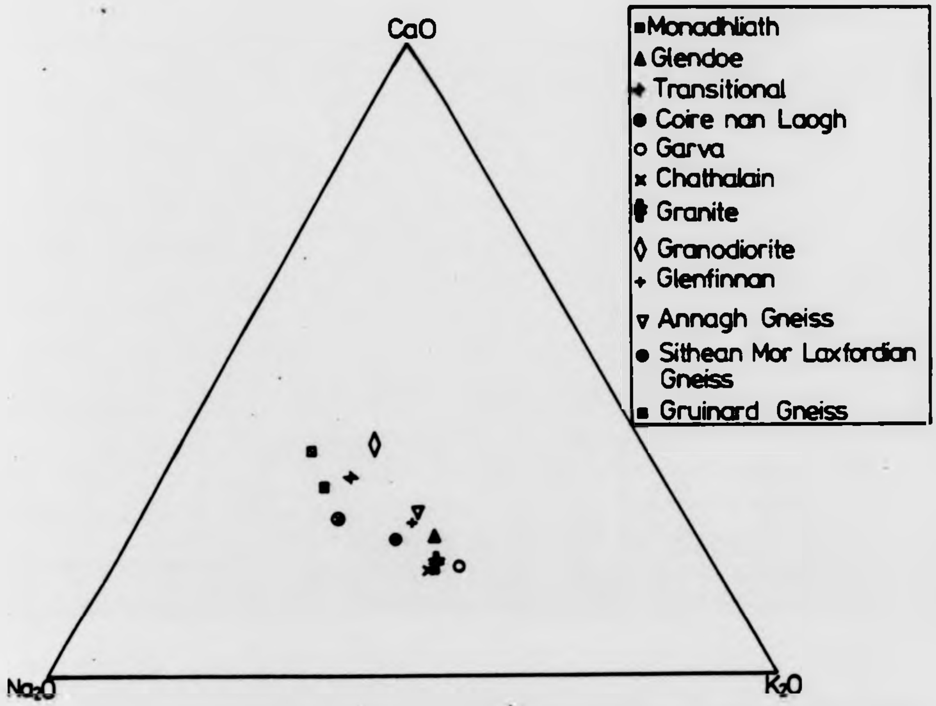


Fig.7.14: $CaO-Na_2O-K_2O$ plot for the means of semi-psammites and psammites of the various formations, and some possible source rocks

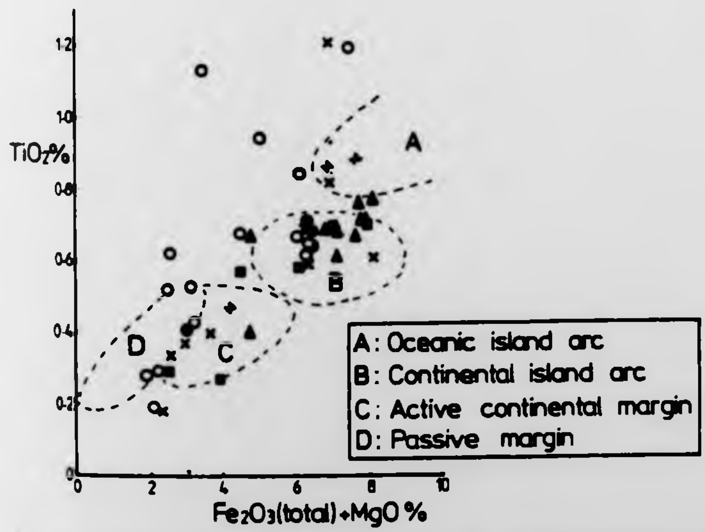


Fig.7.15: $TiO_2-Fe_2O_3$(total)+MgO plot for the semi-psammites and psammites

of granite and granodiorite (Le Maitre, 1976), Gruinard Gneiss and the Laxfordian Gneiss of Sithean Mor (Holland and Lambert, 1973), Annagh Gneiss (Winchester and Max, 1984) and the psammites of the Glenfinnan Division (Winchester et al, 1983) are plotted (Fig.7.14), the means of the psammites and semi-psammites in the Chathalain, Garva and Glendoe Formations lie close to those of granite.

The mean of the Coire non Laogh semi-psammites and psammites lies close to those of the Annagh Gneiss and the Glenfinnan Division psammites, while the means of the Monadhliath and Transitional rocks are intermediate between those of the Grunard Gneiss and the Laxfordian of Sithean Mor, and of granodiorite and the Laxfordian of Sithean Mor, respectively.

The Garva semi-psammites and psammites contain inferred detrital porphyroclasts of microcline, and since they are the most immature of the rocks in the Loch Laggan-Upper Strathspey area they should most closely resemble their source rocks. The sediments of the Garva Formation were, therefore, probably derived from rocks corresponding to the average granite or the Annagh Gneiss. The higher Fe_2O_3 total, MgO, Cr and Ni contents of the Garva rocks compared with those of the average granite suggest that their source rocks were probably a mixture of both granitic rocks and those similar to the Annagh Gneiss.

The relatively more mature sediments of the Chathalain and Glendoe Formations may have been derived also from rocks similar to the Annagh Gneiss, the Glenfinnan Division or a mixture of these and some granitic rocks. The differences between these formations and the Garva Formation may be attributed to a variation in the degree of weathering suffered by their various sediments, as well as changes in provenance such as the relative proportions of the granitic rocks to the gneisses.

The source of the more mature sediments of the Coire nan Laogh, Transitional and Monadhliath Formations is more difficult to infer on the basis of available evidence.

Compared with the Sithean Mor Laxfordian Gneiss, the Coire nan Laogh semi-psammites are enriched in K_2O but depleted in Na_2O and CaO. These differences are consistent with loss of Na_2O and CaO as a result of the weathering of similar gneissic rocks, hence similar gneisses are possible source rocks for the Coire nan Laogh rocks.

Compared with the average Gruinard Gneiss, the Monadhliath semi-psammites and psammites are enriched in K_2O, have similar Na_2O contents but are depleted in CaO. This is also consistent with the loss of CaO during weathering. However the very low concentrations of K_2O and Rb in the Gruinard Gneiss may preclude this and similar Lewisian gneisses from being possible source rocks (see also Plant et al, 1984), except those that have been remobilised and intruded by evolved granites.

7.6b <u>The tectonic affiliation of the metasediments</u>

The geochemical classification scheme of Blatt et al (1980), already referred to, relates the compositions of sedimentary rocks to their tectonic setting in terms of the old geosynclinal terminology (Fig.7.13). Based on this plot, most of the Glenshirra semi-psammites and psammites classify as taphrogeosynclinal (i.e. sandstones deposited in deep fault basins on the craton), grading into exogeosynclinal (i.e. sandstones on the edge of cratons). On the other hand, most of the Corrieyairack rocks plot as eugeosynclinal with some overlap into the exogeosynclinal field.

Recently many studies have explored the relationship between sands or sandstone composition and plate tectonic setting (Crook, 1974; Schwab, 1975; Potter, 1978; Dickinson and Suczek, 1979; Dickinson and Valloni, 1980; Valloni and Maynard, 1981; Maynard et al, 1982; Bhatia, 1983). These workers have found systematic variations in both framework constituents and bulk rock chemistry or sediment chemistry as a function of the plate-tectonic environment.

Maynard et al (1982) found that K_2O/Na_2O ratios greater than 1.0

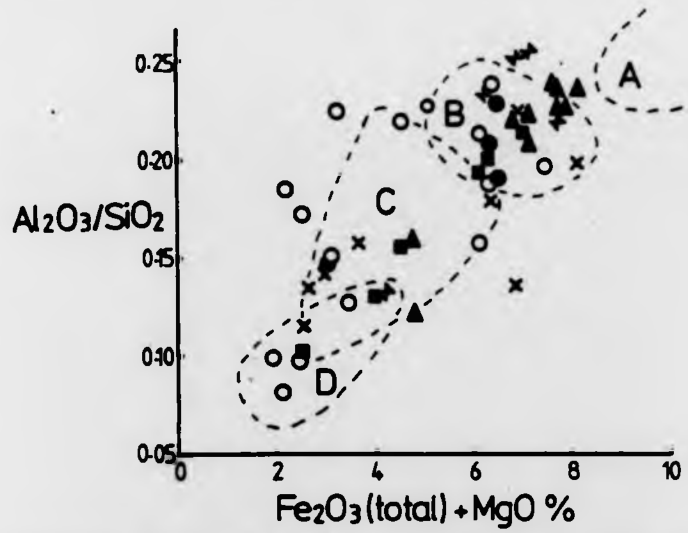


Fig.7.16: Al_2O_3/SiO_2–Fe_2O (total)+MgO plot for semi-psammites and psammites

(Fields are as defined in Fig.7.15)

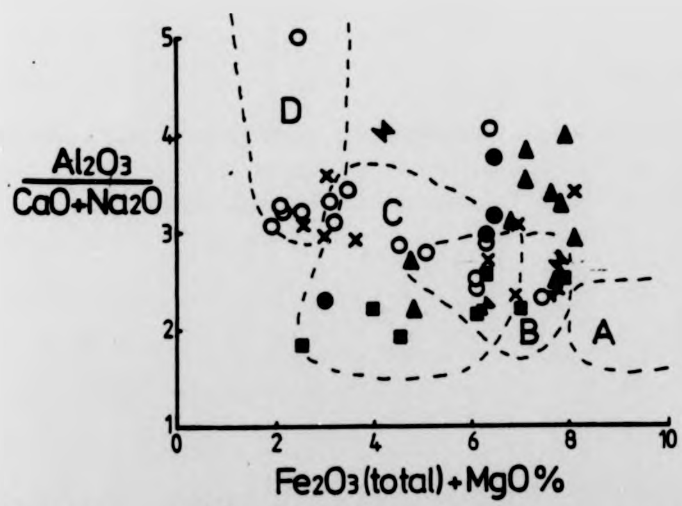


Fig.7.17: $\frac{Al_2O_3}{CaO+Na_2O}$ –Fe_2O_3(total)+MgO plot for semi-psammites and psammites
(Fields are as defined in Fig.7.15)

characterised sands from passive (trailing-edge) continental margins while sands from active settings have lower ratios. An examination of the K_2O/Na_2O ratios of the psammitic rocks of the various formations of the Loch Laggan-Upper Strathspey area (Tables 7.2 and 7.3) indicates that the psammites and semi-psammites of the Glenshirra Succession along with those of the Glendoe Formation tend to have values greater than 1.0, whereas those of the Coire non Laogh, Monadhliath and Transitional Formations tend to have K_2O/Na_2O ratios less than 1.0. The narrowness of this criterion renders these results less definitive, because the K_2O/Na_2O ratio may depend more strongly on source rock composition and/or diagenetic metasomatism rather than on tectonic environment.

Bhatia (1983) in his study of the sandstone suites of Eastern Australia obtained optimum discrimination of the sandstone from the various tectonic settings with plots of Fe_2O_3 (total)+MgO against TiO_2, Al_2O_3/SiO_2 and $Al_2O_3/(CaO+Na_2O)$ (Figs.7.15, 7.16 and 7.17).

Applying these discriminant diagrams to the psammites and semi-psammites of the Loch Laggan-Upper Strathspey area, the following results were obtained:

Approximately 44% of the samples from the Chathalain Formation fall into the field of "active continental margin" sandstones, while 21% of the samples plot in the field of "continental island arc" sandstones.

Approximately 31% of the samples from the Garva Formation plot in the field of "passive margin" sandstones, 21% plot in the "active continental margin" field, while 23% plot in the field of "continental island arc" sandstones.

Approximately 42% of the samples of the Coire non Laogh Formation plot as "continental island arc" sandstones, and 22% fall in the field of "active continental margin" sandstones.

63% of samples from the Transitional semi-psammite plot as "continental island arc" sandstones.

Approximately 52% of the samples from the Glendoe Formation plot as "continental island arc" sandstones, while 18% plot in the "active continental margin" field.

Also, approximately 52% of the samples from the Monadhliath Formation plot in the field of "continental island arc" sandstones, while 43% plot as "active continental margin" sandstones.

On the whole, therefore, most of the rocks of the Corrieyairack Succession classify as "continental island arc" sandstones, while most of the rocks of the Chathalain Formation classify as "active continental margin" rocks, although a few samples show the characteristics of the other three tectonic fields. (See Figs.7.15, 7.16 and 7.17).

A wide scatter was obtained for the rocks of the Garva Formation, the samples overlapping the "passive margin", "active continental margin", and the "continental island arc" fields. This scatter may be the result of the high, inferred detrital Fe-Ti phases in the formation. Such scatter may also result from the heterogeneity of the source rocks for the sediments.

In some of the diagrams some samples plot outside the fields defined by Bhatia (op.cit) and since some of his samples of the Australian rocks also plot outside the defined fields, it is possible that these fields are too restricted.

The classifications obtained above for the rocks of the various formation are in good agreement with those obtained in the schemes of Blatt et al (1980) and Maynard et al (1982), and indicate the consistency of the various parameters used in the classification schemes.

It is likely that these parameters pertain much more to the provenance of the sediments than to their actual depositional environments.

The precise position of the source rocks for the sediments forming the rocks of the Loch Laggan-Upper Strathspey area in the context of the plate tectonic development of the Central Highlands is currently unclear.

The calc-alkaline composition of their inferred basement source rocks is, however, similar to that of the rocks of active continental margins (Tarney, 1976). The "continental island arc" nature of most of the samples from the Corrieyairack Succession suggest that their sediments contained a higher proportion of basic detritus probably derived from volcanic or basic rock sources.

Several lines of evidence discussed earlier suggest that these relatively immature, first-cycle clastic sediments were derived from uplifted upper and middle continental, granite-gneissose and associated volcanic rocks, and deposited in environments ranging from alluvial to more basinal submarine fan settings (see Chapter 4).

7.7 Comparison with metasediments in the Corrieyairack Pass and Killin areas

a) The Glenshirra Succession

i) Semi-pelites

The Creag Mhor Formation semi-pelites of Haselock (1982) contain significantly higher MnO, Nb and Rb than the Chathalain Formation semi-pelites. However, because of the small size of the samples considered and the very low concentrations of MnO and Nb in these rocks, care must be taken in assessing these differences (Table 7.6).

The higher K/Rb, Ba/Rb and lower Rb/Sr ratios of the Chathalain Formation semi-pelites compared with those of the Creag Mhor Formation suggest that the former had a higher proportion of detrital K-feldspar to illite, and hence were probably less "mature".

Table 7.6: Means of semi-pelites from the Glenshirra Succession of the Loch Laggan-Upper Strathspey and the Corrieyairack Pass areas

	A	B	C	D
SiO_2	59.45(3.48)	53.95(3.50)	60.53(2.11)	56.00(4.24)
TiO_2	1.02(0.13)	1.09(0.24)	1.40(0.6)	1.05(0.01)
Al_2O_3	18.66(2.22)	18.82(1.58)	17.20(0.93)	19.42(1.29)
Fe_2O_3	1.93(0.44)	2.73(0.87)	3.83(1.99)	4.79(0.76)
FeO	5.27(0.86)	6.52(2.13)	2.67(1.06)	3.47(2.63)
MnO	0.10(0.02)	0.19(0.04)	0.10(0.02)	0.15(0.08)
MgO	2.74(0.64)	3.51(0.80)	1.82(0.61)	2.81(1.73)
CaO	1.08(0.29)	1.28(0.21)	2.75(0.97)	1.59(0.57)
Na_2O	2.00(0.77)	1.94(0.21)	3.70(0.59)	2.03(1.94)
K_2O	5.27(0.88)	7.14(1.72)	4.26(1.24)	5.77(0.82)
P_2O_5	0.17(0.08)	0.23(0.04)	0.17(0.03)	0.33(0.06)
Ba	894(219)	1099(143)	1533(408)	1269(15)
Cr	71(11)	82(12)	58(19)	83(37)
Nb	17(3)	23(2)	12(2)	15(3)
Ni	48(12)	49(1)	23(8)	88(41)
Rb	199(35)	304(8)	80(34)	153(18)
Sr	199(110)	176(16)	628(200)	283(173)
Y	38(6)	49(7)	13(5)	33(10)
Zr	215(29)	253(119)	254(88)	280(166)
Sr/CaO	184	138	228	178
K/Rb	220	195	442	313
K/Ba	49	54	23	38
Ba/Rb	4.49	3.62	19.16	8.29
CaO/Y	284	261	2115	482
P_2O_5	45	47	131	100
Rb/Sr	1.0	1.73	0.13	0.54

A Chathalain Formation (5 analyses)
B Creag Mhor Formation (3 analyses)
C Garva Formation (11 analyses)
D Allt Luaidhe Formation (2 analyses)

The higher total iron, MgO, and Cr content of the Creag Mhor semi-pelites suggest that they probably contained more detrital chlorite derived from the decomposition of mafic minerals than those of the Chathalain Formation.

The student's t-test shows that the Allt Luaidhe Formation semi-pelites contain significantly higher Al_2O_3, P_2O_5, Ni, Rb and Y, but lower SiO_2, Na_2O and Sr than those of the Garva Formation, at the 95% level of confidence. However, given the very small number of samples from the Allt Luaidhe Formation, these observations must be assessed with caution.

The higher K/Rb, Ba/Rb and lower Rb/Sr ratios and Al_2O_3 content of the Garva semi-pelites suggests that they had a higher proportion of detrital K-feldspar to illite, and hence were probably less mature. The higher total iron, MgO and Ni content of the Allt Luaidhe semi-pelites suggests that they had a higher proportion of detrital chlorite to K-feldspar. Also the higher P_2O_5 and Y content of the Allt Luaidhe semi-pelites suggests that they had a higher content of detrital apatite than those of the Garva Formation.

The greater maturity of the Glenshirra Succession in the Corrieyairack Pass area inferred from these geochemical criteria is therefore consistent with the sedimentological observation that paleocurrent and hence sediment transfer direction was towards the NNW (Chapter 4), implying a more extended transport for the sediments of the Corrieyairack Pass area.

ii) <u>Semi-psammites and Psammites</u>

The Creag Mhor psammites are chemically similar to the Chathalain psammites. The student's t-test shows that they differ significantly only in their Nb contents, at the 95% level of significance. The slightly higher Nb and P_2O_5 contents of the Creag

Table 7.7: Means of psammites and semi-psammites from the Glenshirra Succession of the Corrieyairack Pass area

	A	B	C
SiO_2	76.76(3.57)	66.92(8.08)	65.08(4.85)
TiO_2	0.33(0.11)	0.79(0.09)	1.09(0.80)
Al_2O_3	11.00(1.65)	15.46(3.26)	15.93(2.15)
Fe_2O_3	0.84(0.78)	1.69(0.60)	2.27(1.74)
FeO	1.14(0.56)	1.74(0.03)	2.03(1.05)
MnO	0.05(0.01)	0.08(0.01)	0.08(0.02)
MgO	1.01(0.99)	1.29(1.24)	1.28(0.57)
CaO	1.06(0.22)	1.39(0.86)	2.85(0.35)
Na_2O	2.80(0.60)	3.69(1.43)	3.61(0.53)
K_2O	3.82(0.72)	4.41(1.67)	3.80(0.48)
P_2O_5	0.07(0.08)	0.81(0.13)	0.12(0.07)
Ba	886(126)	1268(611)	1802(874)
Cr	18(5)	29(25)	34(10)
Nb	28(8)	26(11)	14(12)
Ni	14(3)	19(11)	18(5)
Rb	102(28)	98(37)	58(27)
Sr	234(34)	343(233)	709(333)
Y	13(6)	19(9)	9(4)
Zr	191(119)	319(84)	259(154)
K_2O/Al_2O_3	0.35	0.29	0.24
K/Rb	311	374	544
K/Ba	36	29	18
Ba/Rb	9	13	31
$K_2O/(CaO+Na_2O)$	0.99	0.87	0.59
Sr/CaO	221	247	249

A Creag Mhor Formation (Corrieyairack Pass area, 7 analyses)

B Allt Luaidhe Formation (Corrieyairack Pass area, 4 analyses)

C Gairbeinn Pebbly Semi-psammite (Corrieyairack Pass area, 5 analyses)

Mhor psammites suggest that they had a higher content of detrital apatite and oxide phases. Also the slightly higher K/Rb, $K_2O/(CaO+Na_2O)$ and Ba/Rb ratios of the Creag Mhor psammites suggest that they contained a slightly higher proportion of detrital K-feldspar to plagioclase and hence were a little more "mature" than the Chathalain psammites. Again, this observation is consistent with the conclusions reached for the associated semi-pelites.

The Allt Luaidhe Formation semi-psammites are also chemically similar to those of the Garva Formation, differing significantly only in their Nb contents presumably for the same reasons suggested above.

The slightly higher K/Rb, Ba/Rb and Sr/CaO ratios of the Allt Luaidhe semi-psammites suggest that they had a somewhat higher content of detrital K-feldspar, while the semi-psammites in both formations contain similar amounts of total iron, MgO, Cr, Ni and MnO suggesting a similar content of basic detritus derived from their source rocks.

Analyses of the Gairbeinn Pebbly Semi-psammite (Haselock, 1982) are, strictly, not comparable with those of the Garva Formation because they were only obtained from the matrix of the rock. These matrix analyses contain higher CaO, Ba and lower Rb than the Garva semi-psammites. The higher K/Rb, Ba/Rb and Sr/CaO ratios of the Gairbeinn Pebbly semi-psammite matrix suggest that if contained a higher proportion of detrital K-feldspar in their sediments. Also, the higher TiO_2 and total iron content of the Gairbeinn pebble matrix suggest that it may have contained a higher proportion of detrital ilmenite than the Garva semi-psammites.

b) The Corrieyairack Succession

i) Semi-pelites

The Coire nan Laogh semi-pelites of the Corrieyairack Pass area (Haselock, 1982) contain significantly higher Fe_2O_3, Ba, and Nb but lower FeO, Cr and Ni than the stratigraphically equivalent formation in the Loch Laggan-Upper Strathspey area, as indicated by a student's t-test at the 95% level of confidence (Table 7.8).

These features suggest that the Corrieyairack Pass area Coire non Laogh semi-pelites were more oxidised than those of the present study area. The higher K/Rb, Ba/Rb and Sr/CaO ratios of the Corrieyairack Pass semi-pelites suggest that they contained a higher proportion of detrital K-feldspar to illite than those of the Loch Laggan-Upper Strathspey area. The higher Nb content of the Corrieyairack Pass area semi-pelites is additional evidence of a higher content of detrital heavy minerals in these rocks.

By contrast, the higher FeO, Cr and Ni content of the semi-pelites of the Loch Laggan-Upper Strathspey area suggest that they had a higher proportion of basic detritus in their source rocks.

The semi-pelites of the Glendoe Formation in the Loch Laggan-Upper Strathspey area contain significantly higher CaO, Na_2O and Sr but lower Ba than those of the Knockchoilum Formation in the Corrieyairack Pass area. These differences, taken together with the higher K/Rb, Ba/Rb and Sr/CaO ratios of the Knockchoilum semi-pelites indicate that they contained a higher proportion of detrital K-feldspar to plagioclase than those of the Glendoe Formation. This suggests that the Knockchoilum semi-pelites were slightly more "mature" than those of the Glendoe Formation. Their comparable contents of total iron, MgO, Cr and Ni (Tables 7.1 and 7.8) suggest that they had similar proportions of basic detritus in their source rocks.

Table 7.8: Means of semi-pelites from the Corrieyairack Succession in the Loch Laggan-Upper Strathspey, Corrieyairack Pass, and the Killin areas

	A	B	C	D	E	F	G	H	I
SiO_2	59.84(1.45)	59.59(4.09)	60.10(2.36)	59.25(4.51)	56.79(4.43)	59.74(4.10)	58.99(1.14)	60.63(3.26)	58.07(4.61)
TiO_2	0.97(0.04)	0.91(0.41)	1.04(0.41)	0.88(0.13)	0.95(0.13)	0.88(0.15)	0.96(0.09)	0.87(0.12)	0.94(0.14)
Al_2O_3	18.58(0.65)	18.46(1.73)	17.64(1.56)	17.99(1.57)	18.77(2.05)	16.83(2.18)	18.99(2.01)	17.41(1.88)	18.94(2.44)
Fe_2O_3	1.67(0.35)	2.84(1.76)	1.47(0.38)	1.30(0.19)	*8.29(1.36)	*7.71(1.34)	1.43(0.47)	1.54(0.75)	*7.56(1.61)
FeO	5.10(0.94)	3.84(1.89)	4.76(1.20)	4.82(1.13)	-	-	5.08(0.66)	5.01(0.91)	-
MnO	0.12(0.06)	0.13(0.10)	0.14(0.08)	0.12(0.03)	0.13(0.02)	0.16(0.07)	0.10(0.03)	0.15(0.05)	0.19(0.04)
MgO	2.20(0.29)	2.20(0.55)	2.35(0.37)	2.70(0.42)	2.68(0.48)	2.50(0.48)	2.22(0.45)	2.41(0.50)	2.49(0.52)
CaO	2.14(0.98)	1.89(0.51)	3.52(1.50)	1.91(0.76)	1.54(0.30)	2.35(2.10)	1.58(0.87)	2.56(0.86)	2.32(1.13)
Na_2O	2.56(0.38)	2.68(0.91)	3.20(0.59)	2.46(0.52)	2.46(0.66)	3.16(0.98)	2.36(1.05)	3.49(1.05)	2.74(1.50)
K_2O	3.52(0.45)	3.83(0.65)	3.24(1.09)	4.71(1.67)	4.88(0.97)	3.32(1.18)	4.84(1.51)	2.91(1.15)	3.86(2.19)
P_2O_5	0.29(0.10)	0.29(0.08)	0.40(0.21)	0.33(0.18)	0.23(0.07)	0.27(0.09)	0.31(0.12)	0.27(0.12)	0.27(0.06)
ppm									
Ba	753(224)	1019(262)	814(308)	1245(241)	-	-	1256(508)	768(305)	-
Cr	64(5)	57(11)	60(14)	59(9)	114(13)	111(23)	71(8)	67(12)	116(21)
Nb	17(2)	29(5)	17(4)	22(8)	17(3)	17(2)	16(1)	25(4)	15(5)
Ni	37(12)	23(9)	31(7)	39(7)	43(5)	38(5)	32(15)	38(7)	36(8)
Rb	156(27)	157(18)	147(28)	167(3)	187(26)	138(41)	180(28)	132(37)	163(71)
Sr	277(105)	262(78)	369(68)	275(65)	242(69)	312(80)	259(121)	357(103)	295(276)
Y	39(8)	34(5)	40(21)	36(12)	36(8)	41(8)	40(6)	37(11)	34(5)
Zr	189(23)	197(40)	371(351)	219(54)	168(32)	225(94)	228(76)	241(86)	214(109)
Sr/CaO	129	139		144	157.14	132		139	127
K/Rb	187	202		234	215.45	201		183	197
K/Ba	39	31		31				31	
Ba/Rb	4.83	6.49		7.46				5.82	
CaO/Y	549	556		531	428	560		692	682
P_2O_5/Y	74	85		92	64	64		73	79
Rb/Sr	0.56	0.60		0.61	0.78	0.44		0.37	0.55
Sr/Y	7.10	7.91		7.64	6.72	7.40		9.65	8.68
K_2O/(CaO+Na_2O)	0.75	0.84		1.08	1.22	0.60		0.48	0.76

*Total iron as Fe_2O_3

A Coire nan Laogh Formation (Loch Laggan-Upper Strathspey area, 14 analyses)
B Coire nan Laogh Formation (Corrieyairack Pass area, 10 analyses)
C Glendoe Formation (Loch Laggan-Upper Strathspey area, 9 analyses)
D Knockchoilum Formation (Corrieyairack Pass area, 6 analyses)
E Knockchoilum Formation (Killin area, 9 analyses)
F Glendoe Formation (Killin area, 10 analyses)
G Monadhliath Formation (Loch Laggan-Upper Strathspey area, 7 analyses)
H Monadhliath Formation (Corrieyairack Pass area, 23 analyses)
I Monadhliath Formation (Killin area, 5 analyses)

The Monadhliath semi-pelites of the Corrieyairack Pass area (Haselock, op.cit.) contain significantly higher amounts of MnO, CaO, Na_2O, Nb but lower K_2O, Ba and Rb than the Monadhliath Formation semi-pelites of the Loch Laggan-Upper Strathspey area (Table 7.8).

These differences suggest that the Monadhliath semi-pelites of the Corrieyairack Pass area contained a higher proportion of detrital plagioclase to K-feldspar than those of the Loch Laggan-Upper Strathspey area.

As a result of the small number of samples considered and the very low concentrations of MnO and Nb in these rocks, the differences in the content of these two elements must be assessed with caution. These differences may not, in reality, be significant.

The similarity in the total iron, MgO, Cr and Ni contents of the two groups of semi-pelites suggest that they both contained similar proportions of basic detritus in their sediments, and hence had a similar provenance.

Statistically, there is no significant difference between the chemistries of Glendoe Formation semi-pelites in the Killin area (Whittles, 1981) and those of the Loch Laggan-Upper Strathspey area, except for the higher Cr and Ni contents of the Killin area semi-pelites. This may suggest that the Killin area rocks contained a higher proportion of basic detritus in their sediments.

Compared with the Knockchoilum Formation semi-pelites of the Killin area (Whittles, 1981), the Glendoe Formation semi-pelites of the present study area contain significantly higher CaO, Na_2O, P_2O_5 and Sr but lower K_2O, total iron, Cr, Ni and Rb.

These differences imply a higher proportion of detrital plagioclase to illite and chlorite in the Glendoe semi-pelites of the Loch Laggan-Upper Strathspey area, and hence their greater immaturity. This observation is consistent with paleocurrent trends and hence sediment transfer towards the NNW (Chapter 4) and implies a more extended transport for the Killin area sediments.

The Monadhliath semi-pelites of the Killin area (Whittles, 1981) are chemically similar to the Monadhliath semi-pelites of the present study area. The student's t-test shows a significant difference only in their contents of MnO and Cr, at the 95% level of confidence. The small numbers of the samples considered suggest that these differences may not, in reality, be truly significant, and should be assessed with caution. However, they may suggest that the Killin area sediments contained a slightly higher proportion of basic detritus.

ii) Semi-psammites

The Coire nan Laogh semi-psammites of the Corrieyairack Pass area (Haselock, 1982) (Table 7.9) contain significantly higher MnO, CaO, Sr and Nb but lower K_2O than stratigraphically equivalent semi-psammites of the Loch Laggan-Upper Strathspey area. These differences taken together with its lower K_2O $(CaO+Na_2O)$ ratio imply that the semi-psammites of the Corrieyairack Pass area contained a higher proportion of detrital plagioclase to K-feldspar.

Their higher Nb and P_2O_5 contents may suggest that they also contained higher proportion of detrital heavy minerals including apatite and oxide phases. They, however, contain similar concentrations of total iron, MgO, Cr and Ni indicating a similar proportion of basic detritus in their sediments and hence source rocks.

The Knockchoilum semi-psammites of the Corrieyairack Pass area (Haselock, op.cit.) (Table 7.9) contain significantly higher Sr and Nb but lower K_2O and Ba than the Glendoe semi-psammites of

Table 7.9: Means of semi-psammites from the Corrieyairack Pass and Killin areas

	A	B	C	D	E
SiO_2	65.31(2.67)	66.84(4.06)	70.01(1.78)	69.40(2.76)	68.90(0.74)
TiO_2	0.64(0.06)	0.67(0.15)	0.55(0.11)	0.68(0.09)	0.64(0.06)
Al_2O_3	17.08(1.93)	14.17(1.79)	13.47(0.89)	13.87(1.38)	13.33(0.98)
Fe_2O_3	0.97(0.13)	1.03(0.50)	0.78(0.18)	*4.81(0.75)	*4.34(0.58)
FeO	3.74(0.45)	3.72(1.06)	2.91(0.25)	-	-
MnO	0.25(0.02)	0.11(0.04)	0.12(0.06)	0.09(0.02)	0.12(0.03)
MgO	1.58(0.36)	2.16(0.64)	1.40(0.19)	1.60(0.27)	1.42(0.19)
CaO	4.05(1.13)	2.51(1.70)	2.65(0.85)	1.57(0.24)	2.92(1.17)
Na_2O	3.48(1.39)	3.37(0.50)	3.87(0.43)	3.08(0.53)	3.11(0.52)
K_2O	1.43(0.45)	2.63(0.84)	1.75(1.04)	2.93(0.45)	2.15(0.57)
P_2O_5	0.35(0.14)	0.21(0.09)	0.14(0.06)	0.15(0.04)	0.15(0.03)
Ba	350(280)	677(216)	516(325)	-	-
Cr	38(7)	42(7)	34(3)	85(13)	81(6)
Nb	29(9)	24(5)	24(7)	16(3)	17(2)
Ni	36(12)	28(6)	25(5)	30(3)	28(2)
Rb	76(42)	106(30)	71(24)	101(21)	89(13)
Sr	410(98)	327(51)	439(107)	263(42)	367(71)
Y	25(2)	29(6)	22(5)	29(5)	32(5)
Zr	219(31)	250(107)	270(129)	225(68)	265(67)
K/Rb	156	206	205	241	201
K/Ba	34	32	28	-	-
Ba/Rb	5	6	7	-	-
$K_2O(CaO+Na_2O)$	0.19	0.45	0.27	0.63	0.36
Fe_2O_3total+MgO	6.70	7.32	5.40	6.41	5.76

*Total iron as Fe_2O_3

A Coirenan Laogh Formation (Corrieyairack Pass area, 3 analyses)

B Knockchoilum Formation (Corrieyairack Pass area, 21 analyses)

C Monadhliath Formation (Corrieyairack Pass area, 6 analyses)

D Knockchoilum Formation (Killin area, 4 analyses)

E Glendoe Formation (Killin area, 9 analyses) the Loch Laggan-Upper Strathspey area. These differences taken together with the higher mean CaO and Zr values of the Knockcholium semi-psammites suggest that they contained a higher proportion of detrital plagioclase and heavy minerals to K-feldspar than the Glendoe semi-psammites.

This is exactly the opposite of the differences observed between their associated semi-pelites and may imply that the Glendoe Formation sediments which were largely graded turbidites (see Chapter 4) were less well sorted than those of the Knockcholium Formation.

Again the Monadhliath Formation semi-psammites of the Corrieyairack Pass area contain significantly more Nb but less Fe_2O_3, FeO, MgO and Cr than the stratigraphically equivalent semi-psammites of the Logh Laggan-Upper Strathspey area.

These differences imply a higher proportion of basic detritus in the sediments of the Loch Laggan-Upper Strathspey area semi-psammites, but proportionately less detrital heavy minerals, when their lower mean Zr content is also considered.

Compared with the Glendoe semi-psammites of the Killin area (Whittles, 1981) (Table 7.9), the stratigraphically equivalent rocks of the present study area contain significantly higher Al_2O_3, TiO_2, MgO, K_2O, Rb but lower SiO_2, MnO, CaO, total iron, Cr, Sr, Y and Zr. These differences suggest that the Glendoe semi-psammites of the Loch Laggan-Upper Strathspey contained a higher proportion of clay minerals to plagioclase (and possibly carbonate) and detrital heavy minerals than those of the Killin area.

Also, the Glendoe semi-psammites of the present study area contain significantly higher Al_2O_3, MgO but lower SiO_2 and Cr than the Knockcholium semi-psammites of the Killin area. Again this implies a higher proportion of clay mineral to quartz in the Loch Laggan-Upper Strathspey rocks.

The higher Cr content of the Killin rocks is difficult to explain since the Glendoe semi-psammites contain higher total iron and MgO than the Killin rocks. Given the small number of samples considered, it is possible that this difference in their Cr contents is not really significant.

Psammite analyses are not available from the formations of the Corrieyairack Succession in the Corrieyairack Pass and Killin areas.

7.8 Comparison with other metasediments from the Scottish Highlands

Lambert et al. (1981) have found that the most useful geochemical parameters for distinguishing the more mature semi-pelites of the lower part of the Dalradian Appin Group from those of the Moines of the northern Highlands were the following element ratios: CaO/Y, P_2O_5/Y, K/Rb, Rb/Sr; CaO/Y<310, P_2O_5/Y<55, K/Rb<240 and Rb/Sr>0.65 characterising the Appin Group semi-pelites.

Except for the Chathalain semi-pelites, semi-pelites of the other lithostratigraphic units in Loch Laggan-Upper Strathspey area have much higher mean CaO/Y, P_2O_5/Y and K/Rb ratios than the Appin Group semi-pelites (Table 7.1). Except for the Monadhliath and Chathalain semi-pelites, the semi-pelites of the other formations of the present study area also have lower mean Rb/Sr ratios than the Appin Group rocks. These semi-pelites therefore possess "Moine"-like chemical characteristics with regard to these chemical parameters, whereas the Chathalain semi-pelites are thus similar to those of the "mature" Appin Group in certain respects.

Such similarities cannot, however, be equated with stratigraphical equivalence. Such correlations must be based on detailed sedimentological, structural and chronological equivalence.

Analyses published by Lambert et al. (1981) and Winchester et al. (1983) (Table 7.10) show that the Basal Morar semi-pelite contains higher P_2O_5, Rb, Y and Zr but less TiO_2 than the Garva semi-pelites. These differences taken together with the higher K/Rb, Ba/Rb, Sr/CaO, CaO/Y and lower Rb/Sr ratios of the Garva semi-pelites suggest that they contained a higher proportion of detrital K-feldspur and TiO_2-bearing phases to clay minerals, apatite and zircon than those of the Basal Morar Pelite. They may also be related to some differences in the mineralogy of the source rocks for the two units.

The Garva and Chathalain psammites are chemically similar to the

Table 7.10: Means of semi-pelites from parts of the Scottish Highlands

	A	B	C
SiO_2	60.1	63.13(1.05)	62.22(4.66)
TiO_2	0.86	0.80(0.07)	1.14(0.28)
Al_2O_3	17.3	17.33(0.21)	16.13(1.33)
Fe_2O_3	*6.2	0.73(0.36)	1.70(0.38)
FeO		4.98(0.26)	5.07(1.11)
MnO	0.09	0.13(0.02)	0.10(0.03)
MgO	2.2	2.01(0.11)	3.45(1.31)
CaO	2.7	2.03(0.65)	1.69(0.70)
Na_2O	3.8	3.38(0.45)	2.32(0.55)
K_2O	4.3	3.10(0.90)	5.95(1.42)
P_2O_5	0.25	0.24(0.03)	0.21(0.06)
Ba	1210	898(270)	1075(325)
Cr	-	63(8)	68(72)
Nb	11	20(5)	23(6)
Ni	27	32(4)	23(8)
Rb	114	125(32)	217(58)
Sr	506	347(74)	264(49)
Y	27	37(3)	49(17)
Zr	320	199(52)	466(393)

*Total iron as Fe_2O_3

	A	B	C
K/Rb	313	206	228
Ba/Rb	11	7	5
Rb/Sr	0.23	0.36	0.82
Sr/CaO	187	171	156
CaO/Y	1000	549	345
P_2O_5/Y	93	65	43

A Basal Morar Pelite (25 analyses)

B Glenshero Lodge area (5 analyses)

C Tummel Psammite (16 analyses)

Lower Morar Psammites (Table 7.11). The higher total iron, MgO and Cr contents of the Morar Psammites suggest that their sediments contained a higher proportion of basic detritus.

Analyses of supposedly Central Highland Division semi-pelites near the Glenshero Lodge (NN550932) (J.A. Winchester, personal comm.) (Table 7.10) show that they are chemically similar to the Glendoe semi-pelites except for their significantly higher SiO_2 and lower Fe_2O_3 contents. The slightly higher total iron and MgO contents of the Glendoe semi-pelites taken together with their lower K/Rb, Ba/Rb ratios suggest that they contained a slightly higher proportion of chlorite to detrital K-feldspar, and hence were a little more "mature".

Also, analyses of the Tummel semi-pelites (J.A. Winchester, personal comm.) (Table 7.10) show that they are closest chemically to the Chathalain semi-pelites, except for the significantly higher Al_2O_3 and Ni contents of the Chathalain rocks. These differences may be the result of sampling more pelitic bands in the Chathalain Formation since both groups of semi-pelites contain similar total iron and MgO concentrations.

Analyses of the Eilde Flags (Hickman, 1972) quoted by Haselock (1982) (Table 7.11) show that the semi-psammites contain significantly less total iron, P_2O_5, Ba, Sr but higher Y than those of the Garva Formation. These differences taken together with the higher SiO_2 content of the Eilde semi-psammites suggest that they were more mature. They also indicate that the Garva semi-psammites contained a higher proportion of heavy minerals and basic detritus in their sediments, and hence were probably from a different provenance.

A plot of Sr/Y against Al_2O_3/Na_2O ratios of Lewisian Gneisses and various northern and central Highland semi-pelites (Fig.7.18) (Winchester, pers. comm.) shows a negative correlation of Sr/Y with Al_2O_3/Na_2O.

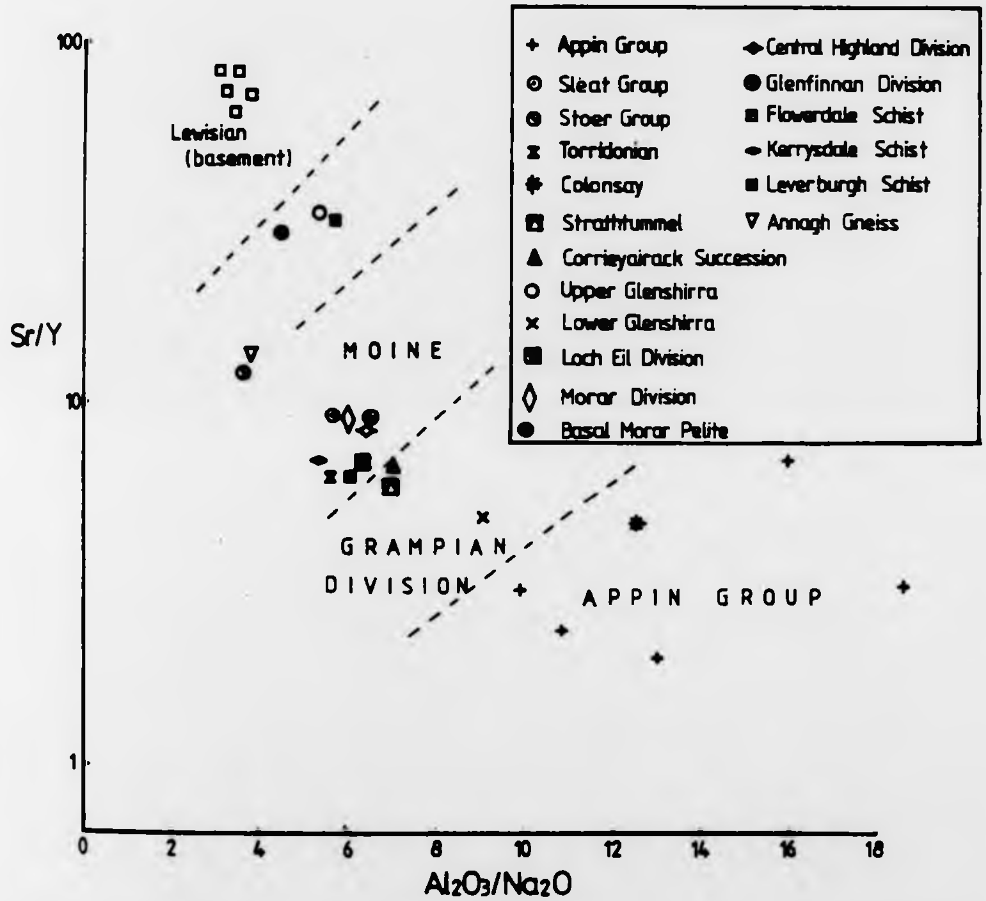


Fig.7.18: $Sr/Y-Al_2O_3/Na_2O$ plot for the Lewisian basement gneisses and various semi-pelitic rocks

Table 7.11: Means of psammites and semi-psammites from parts of the Scottish Highlands

	A	B	C	D
SiO_2	75.04	75.16	77.35	72.03(2.54)
TiO_2	0.55	o.76	0.61	.70(.26)
Al_2O_3	11.91	11.48	11.06	12.77(3.14)
*Fe_2O_3	3.05	3.05	3.12	3.14(.87)
MnO	0.06	0.05	0.07	.05(.02)
MgO	0.81	0.73	0.88	1.81(3.08)
CaO	1.26	1.44	1.56	2.20(1.50)
Na_2O	2.65	2.46	2.43	3.11(1.28)
K_2O	3.91	4.00	2.39	3.26(.97)
P_2O_5	0.15	0.12	0.10	.06(.05)
Ba	879	938	628	776(318)
Cr	106	111	30	-
Nb	8	12	13	15(4)
Ni	6	8	15	-
Rb	117	116	66	84(27)
Sr	348	311	290	179(70)
Y	17	21	21	26(8)
Zr	257	391	273	698(358)
K/Rb	280	290	300	322
Ba/Rb	7.5	8	9.5	9
$K_2O(CaO+Na_2O)$	1.0	1.02	0.6	0.61
Sr/CaO	276	216	186	81
Rb/Sr	0.34	0.37	0.23	0.47
Fe_2O_3total+MgO	3.81	3.78	4.00	4.95

A Lower Morar Psammite No.2 (29 analyses)
B Lower Morar Psammite No.4 (18 analyses)
C Glenfinnan Division (16 analyses)
D Eilde Flags semi-psammites (24 analyses)

* Fe_2O_3 = total iron as Fe_2O_3

High Sr/Y and low Al_2O_3/Na_2O ratios characterises the Lewisian, and with decreasing Sr/Y and increasing Al_2O_3/Na_2O ratios the semi-pelitic rocks in the various units plot in the order shown in Fig.7.18. The Basal Morar Pelite and those of the Garva and Gairbeinn Pebbly unit plot closest to the Lewisian gneisses, whereas those of the Lower Dalradian Appin Group are farthest from the Lewisian.

This diagram which is essentially a plot of plagioclase against clay minerals suggests an increasing proportion of clay minerals to plagioclase from the Basal Morar Pelite and the Upper Glenshirra Succession semi-pelites to those of the Lower Dalradian. It implies an increase in sediment "maturity" from the former group of rocks to the pelites of the Appin Group. In this respect, it seems that the Basal Morar Pelite retains most of the characteristics of its inferred Lewisian-like source rocks (Plant et al, 1984). In this respect the semi-pelites of the upper part of the Glenshirra Succession are similar to those of the Basal Morar unit in resembling first-cycle sediments.

The semi-pelites of the remaining Moine, Grampian and Torridonian units appear to have been derived from more chemically weathered rocks, while those of the Appin Group appear to have been more recycled and may have been second generation sediments (see also Plant et al, op.cit.).

CHAPTER 8

IGNEOUS ACTIVITY

8.1 Introduction

A wide range of igneous rocks intrude the metasediments of the Loch Laggan-Upper Strathspey area. They include dykes, sills and stocks of microdiorites (sensu Smith, 1979), andesites, granitic pegmatites, granites, porphyritic felsites as well as the batholithic Corrieyairack Granite Complex.

Some of these igneous rocks were described by Anderson (1956) and a more detailed petrologic and isotopic study of the granites and pegmatite complexes has been recently undertaken by Clayburn (1981). The detailed petrology of these igneous rocks is beyond the scope of this research, but a brief description of their petrography and their relationship to the late deformation phase, D3, are discussed below. The thermal effects of the Corrieyairack Granite Complex on the country rocks has been discussed in Chapter 6.

8.2 The Corrieyairack Granite Complex

The Corrieyairack Granite Complex is a composite elongate body 20km long and 1.6 to 4.8 km wide (Fig 8.1) trending NE-SW (Anderson, 1956; Clayburn, 1981; Haselock, 1982) comprising early pink granites of the Corrieyairack vein complex, which were later cut and partially removed by the later hornblende granodiorite (Clayburn, op. cit.). Only the latter granitic variety was observed in this study area.

The contacts of the complex with the country rocks are often marked by extensive veining and it also contains xenoliths of the metasediments.

a. Early pink granite

Clayburn (op. cit.) describes this as a medium-grained, leucocratic granite varying in colour from white to red, the colour variations arising from

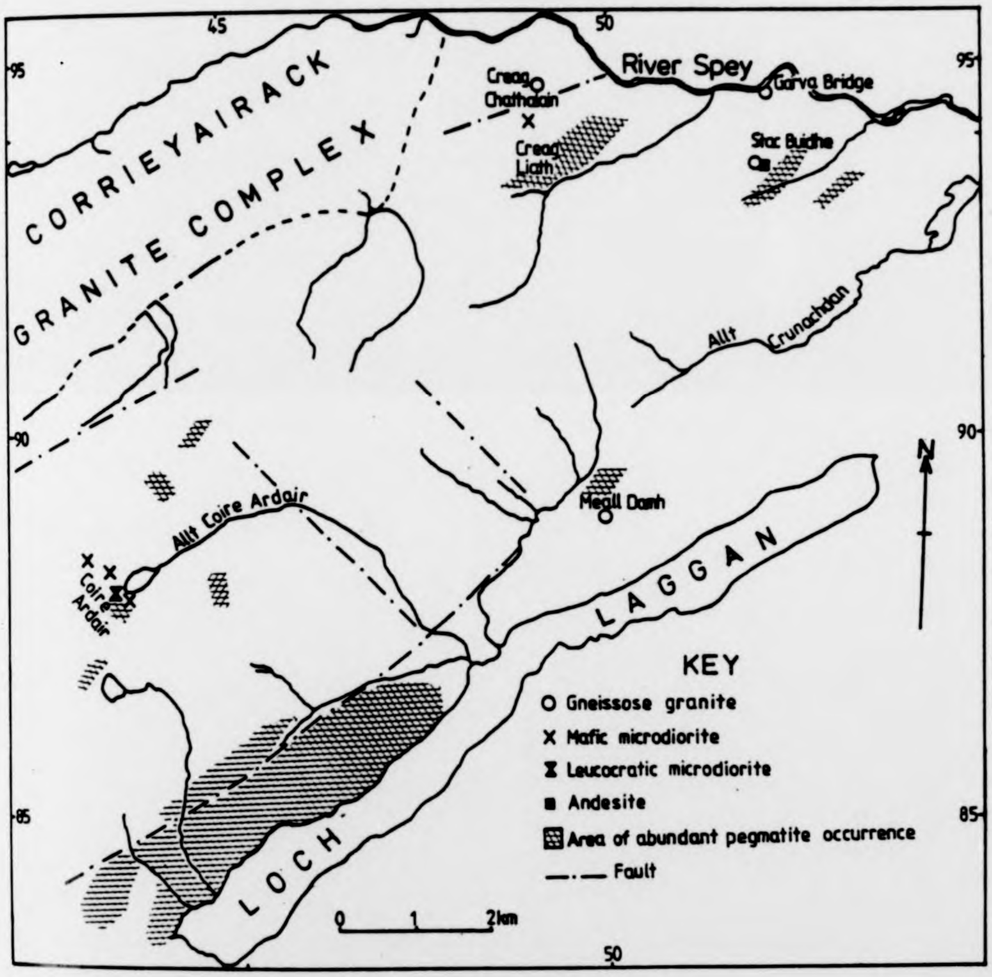


Fig.8.1: The distribution of the igneous bodies

the changing proportions of pink feldspar. Essentially the rock contains microcline, orthoclase, plagioclase and quartz with minor amounts of biotite and muscovite as well as accessory zircon, apatite, sphene and opaques. Clayburn also observed garnet in the more evolved aplites and pegmatites associated with the granite.

b. The Hornblende granodiorite

The hornblende granodiorite is medium-grained and consists of plagioclase (c. 60%), orthoclase (c.15%), quartz (c.17%) biotite (c.6%), and hornblende (c.2%) as well as accessory sphene, zircon, apatite and opaques. (Plate 8.1).

Plagioclase has the composition of oligoclase (An 22-28) and occurs as euhedral to subhedral grains which occasionally show oscillatory zoning and sericitised cores. Plagioclase albite twin lamellae may be bent as a result of late deformation (D4).

Orthoclase may be perthitic and occasionally shares myrmekitic intergrowths with plagioclase.

Quartz occurs as anhedral grains which show weak undulatory (strained) extinction.

Biotite occurs as brown, subhedral grains and as anhedral inclusions in hornblende. It may be partially altered to greenish chlorite.

Hornblende occurs as greenish, euhedral to subhedral prisms which occasionally show multiple twinning.

8.3 The Loch Laggan Pegmatite Complex

The Loch Laggan Pegmatite Complex (Anderson, 1956) consists of a concentration of vertical dykes in a belt trending NE-SW north-west of Loch Laggan from its western end to Garva Bridge (NN 522947) (Fig 8.1). According to Anderson (op. cit.) and Clayburn (op. cit.) the pegmatites extend both to the SW and NE beyond the present study area. The main focal centres of pegmatite dyke intrusions in this study area occur extensively immediately north of Loch Laggan, on the southern slopes of Creag Liath (NN 494936) and the

Plate 8.1 : Corrieyairack Granodiorite containing hornblende with inclusions of magnetite, and also biotite, plagioclase and quartz. Plane polarised light Scale bar represents 0.1mm

Plate 8.2 : Large microcline phenocryst containing smaller grains of quartz, plagioclase. Pink Pegmatite. NN 508940. Crossed nicols. Scale bar represents 0.2mm.

Plate 8.1 : Corrieyairack Granodiorite containing hornblende with inclusions of magnetite, and also biotite, plagioclase and quartz. Plane polarised light Scale bar represents 0.1mm

Plate 8.2 : Large microcline phenocryst containing smaller grains of quartz, plagioclase. Pink Pegmatite. NN 508940. Crossed nicols. Scale bar represents 0.2mm.

Plate 8.1 : Corrieyairack Granodiorite containing hornblende with inclusions of magnetite, and also biotite, plagioclase and quartz. Plane polarised light Scale bar represents 0.1mm

Plate 8.2 : Large microcline phenocryst containing smaller grains of quartz, plagioclase. Pink Pegmatite. NN 508940. Crossed nicols. Scale bar represents 0.2mm.

south-easterly slopes of Stac Buidhe (NN 522928) where they may locally occupy up to 70% of the exposed rock area. They vary from greyish to pink granite pegmatites. In some places, e.g. at NN 484885, early members of this pegmatite dyke complex have been folded during D3 (Plate 5.12, Chapter 5).

8.3a Pink Pegmatites

The pink pegmatites are more abundant than the grey variety. They consist predominantly of microcline (c.70%), plagioclase (c.4.5%) and quartz (c.25%) with very minor muscovite.

Microcline occurs as very coarse grains up to 20cm in diameter which is occasionally perthitic and contains inclusions of small plagioclase grains (Plate 8.2).

Plagioclase composition is albite (An6-8) with twin lamellae which are occasionally bent by late deformation (D4). It may be partially sericitised.

Quartz occurs as anhedral grains, up to 1cm in diameter, intergrown with microcline, and show undulatory extinction.

Muscovite occurs as rare inclusions in microcline. Opaques probably magnetite occur as accessories.

8.3b Grey pegmatitic granites

The grey pegmatitic granites are generally porphyritic and contain megacrysts of perthitic microline up to 20 cm in diameter which together with smaller microcline grains comprise up to 65% of the rock. Plagioclase (4%) occurs as anhedral albite-oligoclase (An10-15) inclusions in microcline. Plagioclase albite twin lamellae are occasionally bent by late deformation (D4). Quartz (c.25%) occurs as anhedral grains up to 1cm in diameter which are intergrown with microcline and show undulatory (strained) extinction. Muscovite (c.4%) occurs as subhedral inclusions in microcline. Biotite occurs as rare laths, 0.5-1.5mm long, contained in microcline.

Clayburn (1981) has also reported garnet from some of the "white" pegmatites of the Loch Laggan Complex, but none was seen in the few samples collected in this study.

These pegmatitic granites may represent the effects of injection of volatile-rich pegmatite fluids into granitic veins. By Loch Laggan cross-cutting relationships imply that several, up to four broadly contemporaneous suites of pegmatites and aplitic veins are present.

The concentration of these pegmatites near Loch Laggan may suggest that an unexposed batholith exists at depth.

8.4 Porphyritic Felsites

These are pink, fine-grained rocks which have been observed to cut and hence post-date the pegmatites and the granites of both the Loch Laggan and Corrieyairack complexes respectively.

The felsites contain phenocrysts of orthoclase, quartz and plagioclase up to 2mm in diameter in a ground mass consisting of fine-grained orthoclase and quartz (Plate 8.3). The plagioclase feldspars are extensively sericitised.

Discussion

The late alteration observed in the granites, pegmatites and felsites suggest late-stage volatile activity. Since these rocks largely represent the last stages of the evolution of a granitid magma, high volatile concentrations are to be expected. Clayburn (op. cit.) has suggested that some of the muscovite grains in the pegmatites may be the product of this later alteration. Similar, deuteric alteration has been reported in the granodiorite of the Corrieyairack Pass area (Haselock, 1982).

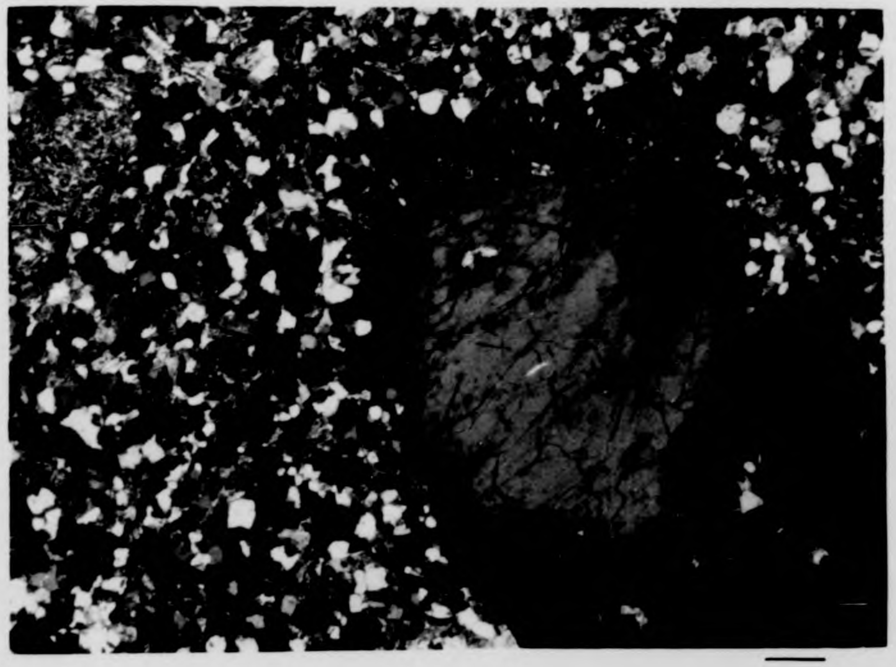
Isotopic analyses of Sr, Pb and Nd (Clayburn, op. cit.) indicate that these granitic rocks were the products of crustal melting in response to adiabatic decompression of the Grampian metamorphic pile arising from uplift and erosion.

8.5 Weakly gneissose granites

Dykes of foliated granites have been found intruding the

Plate 8.3 : Phenocrysts of orthoclase in a groundmass of fine-grained K-feldspar and quartz. Porphyritic felsite of the Loch Laggan Complex. NN 459850.
Crossed nicols. Scale bar represents 0.1mm.

Plate 8.4 : Aligned biotite and early muscovite grains defining the lineation in early gneissose granite. Late porphyroblastic muscovite (M) is at upper left-hand corner. NN 522947.
Plane polarised light. Scale bar represents 0.1mm



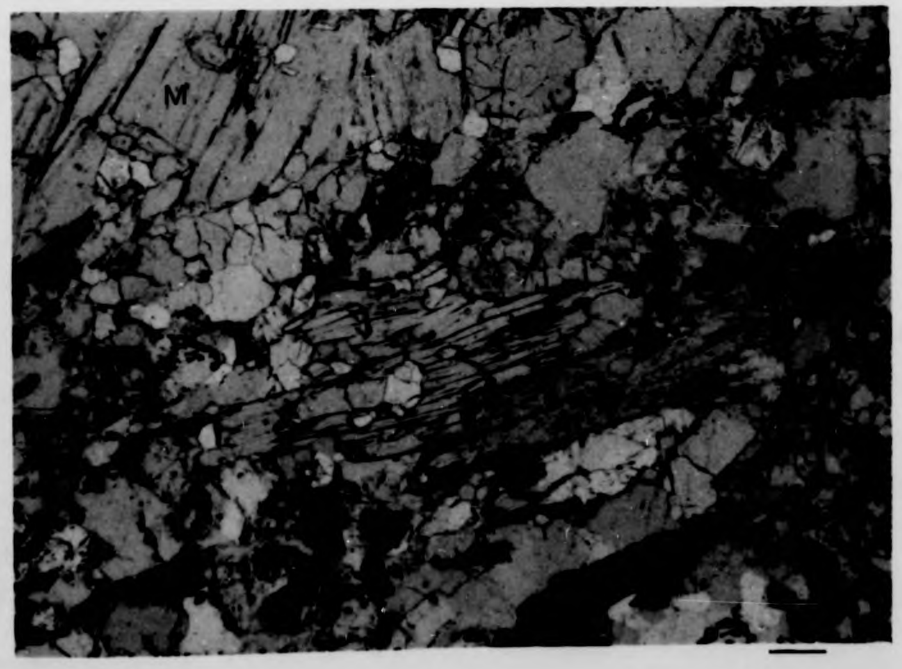


Plate 8.3 : Phenocrysts of orthoclase in a groundmass of fine-grained K-feldspar and quartz. Porphyritic felsite of the Loch Laggan Complex. NN 459850.
Crossed nicols. Scale bar represents 0.1mm.

Plate 8.4 : Aligned biotite and early muscovite grains defining the lineation in early gneissose granite. Late porphyroblastic muscovite (M) is at upper left-hand corner. NN 522947.
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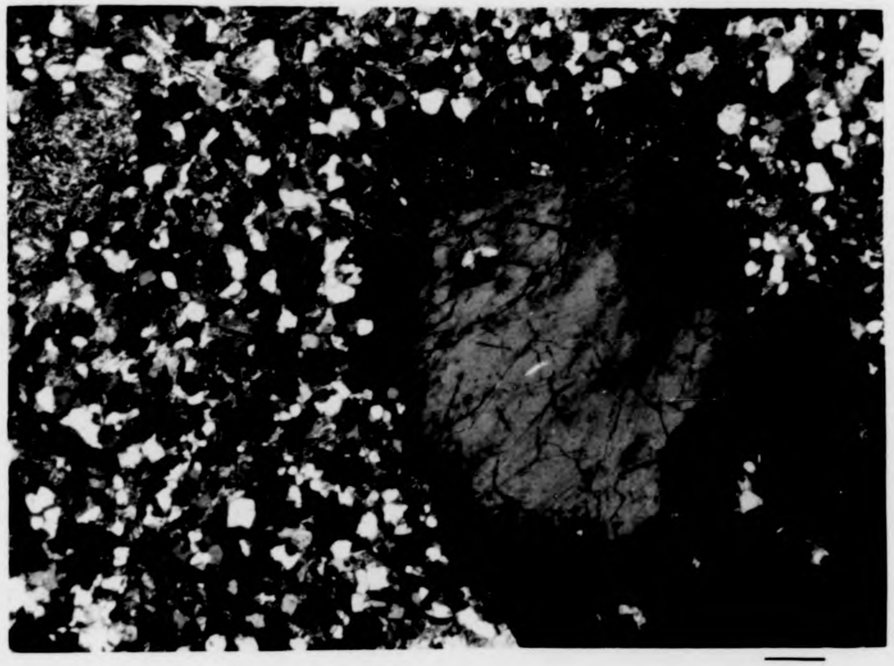
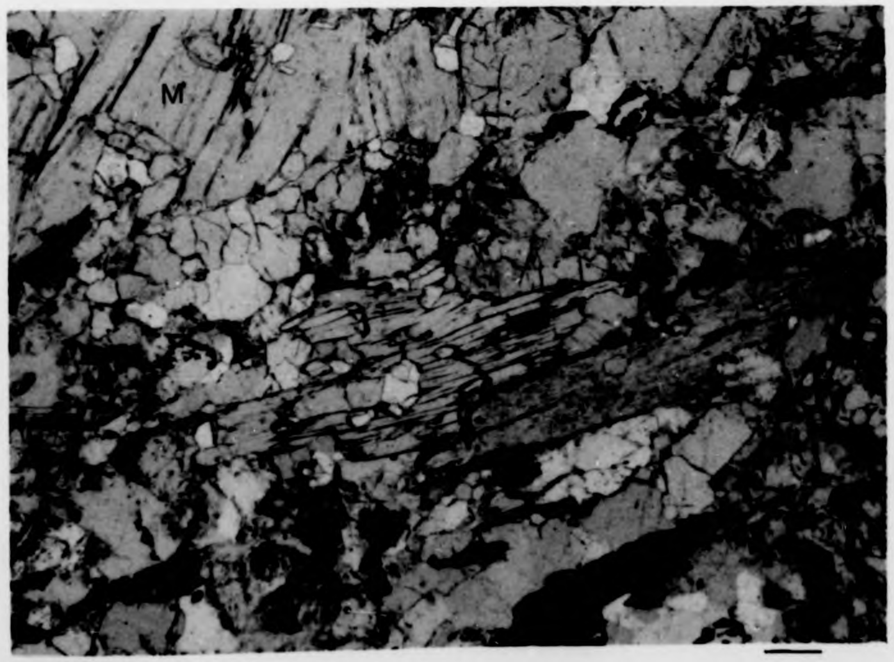




metasediments at several localities (Fig 8.1). These granites are relatively rare compared to the earlier described granitic bodies. Both pink and grey varieties of these gneissose granites have been observed on Creag Chathalain (NN 491947) but no direct relationship could be seen between them in the field, although Clayburn (op. cit.) suggested that they pass gradationally into one another. The colour variation arises from the varying proportions of microcline to plagioclase in the rocks. Also the plagioclase-rich rocks lack muscovite. Textural evidence suggests that these rocks have been metamorphosed; their gneissosity is defined by the preferred orientation of biotite, early muscovite grains and elongate quartz grains.

It has also been observed that these granites are intruded by the andesite at NN 520937 indicating that these granites are earlier than the andesite.

Biotite is usually the more abundant mica, constituting about 6% of the rock. It occurs as anhedral grains, 0.5-1mm long, which define the lineation (Plate 8.4) and is occasionally partially replaced by chlorite.

Muscovite is a minor constituent in the microcline-rich variety. Two generations of muscovite were recognised: an earlier aligned group of grains 0.5-1mm long and a later porphyroblastic suite consisting of grains 1.2-1.5mm long cross-cutting and enclosing earlier-formed minerals (Plate 8.4).

Microcline may comprise up to 31% of the pink gneissose granite. It occurs both as small grains about 0.5mm in diameter and larger ones 1.5-2mm in diameter which are occasionally perthitic.

Plagioclase is oligoclase (An14-20) and occurs as subhedral grains 0.5-1mm in diameter, occasionally sharing myrmekitic boundaries with microcline grains. It may constitute up to 50% of the grey varieties of gneissose granites.

Quartz comprises up to 18% of the rock occurring as anhedral grains 0.5-1mm in diameter and showing undulatory extinction. Accessory minerals include opaques (probably magnetite) epidote, apatite and zircon.

Discussion

The presence of biotite fabrics in some of the granites of this area has been attributed to inheritance from absorbed xenoliths (Clayburn 1981).

However, the observed parallelism of the granite mica fabrics to the regional D3 lineations suggests that this pervasive fabric in the granites is the result of their intrusion during this episode of deformation (Chapter 5). This lineation in the granites is cross-cut by the late porphyro blastic muscovite inferred (Chapter 6) to be the product of the M3 metamorphic event, which probably produced the recrystallised, metamorphic fabric observed in these rocks.

8.6 The microdiorite suite

The microdiorites (sensu Smith, 1979) occur as thin 0.1-0.5 m thick subconcordant dykes and sills in the metasediments (Fig 8.1). The thinner sheets are usually fine-grained while the thicker ones possess fine-grained chilled margins and sharp contacts with the host rocks. Rare cross-cutting relationships (eg at NN 433881) indicate that the microdiorites post-date the pegmatites.

The microdiorites are unfoliated, equigranular rocks varying in composition from dark, hornblende-rich rocks to a leucocratic, plagioclase-rich variety.

a. Mafic microdiorite consists predominantly of hornblende (up to 70%) with varying amounts of colourless amphibole, plagioclase and epidote. Colourless amphibole and epidote are more abundant in the more highly altered rocks.

Hornblende occurs as green to brownish subhedral grains 0.5-2mm long commonly overgrown by late, colourless amphibole thought to be actinolite (Plate 8.5). In the more highly altered rocks, this secondary amphibole becomes very abundant (Plate 8.6). Some of the hornblende grains may be bent by late deformation inferred to be D4.

Secondary, colourless amphibole occurs as pale green or colourless, acicular grains 0.8-1.5mm long which commonly overgrows or replaces hornblende. It may comprise up to 40% of the highly altered microdiorites.

Plate 8.5 : Hornblende overgrown by pale, actinolitic? amphibole. in mafic microdiorite. NN 432881, Plane polarised light. Scale bar represents 0.1mm

Plate 8.6: More intensely altered mafic microdiorite. Hornblende has been more extensively replaced by pale actinolitic? amphibole, and plagioclase by epidote and albite. NN 431884. Plane polarised light. Scale bar represents 0.1mm

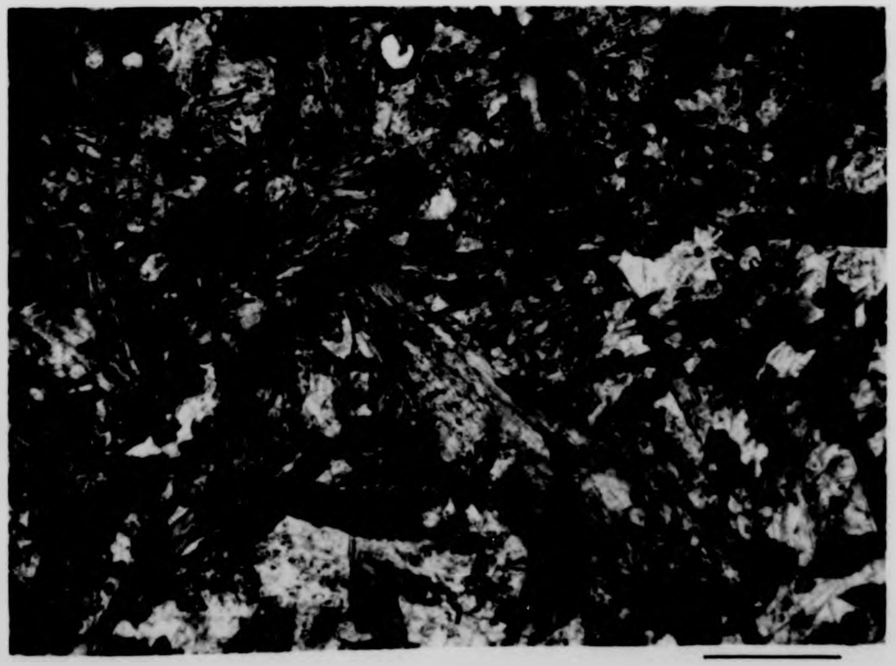


Plate 8.5 : Hornblende overgrown by pale, actinolitic? amphibole. in mafic microdiorite. NN 432881, Plane polarised light. Scale bar represents 0.1mm

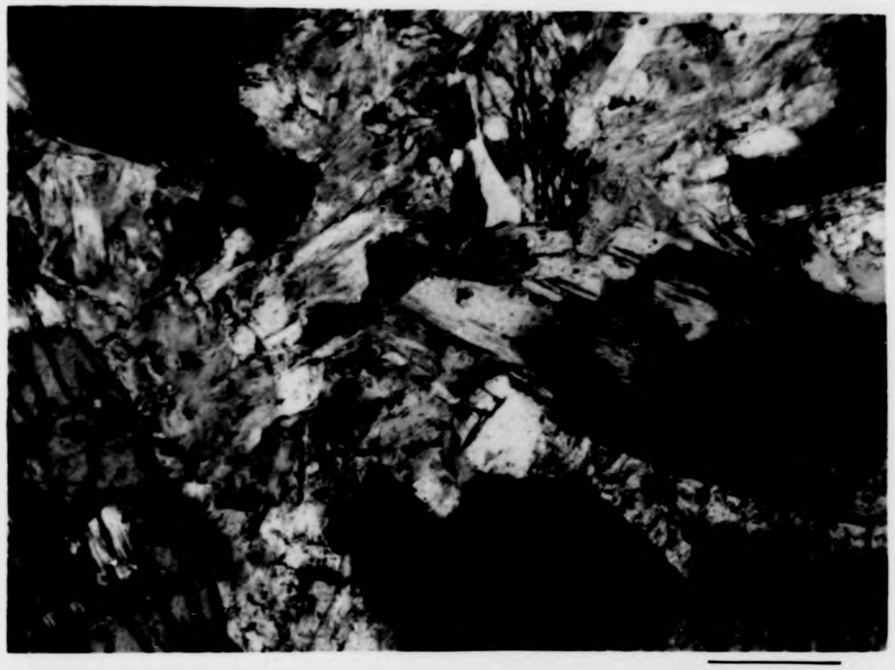
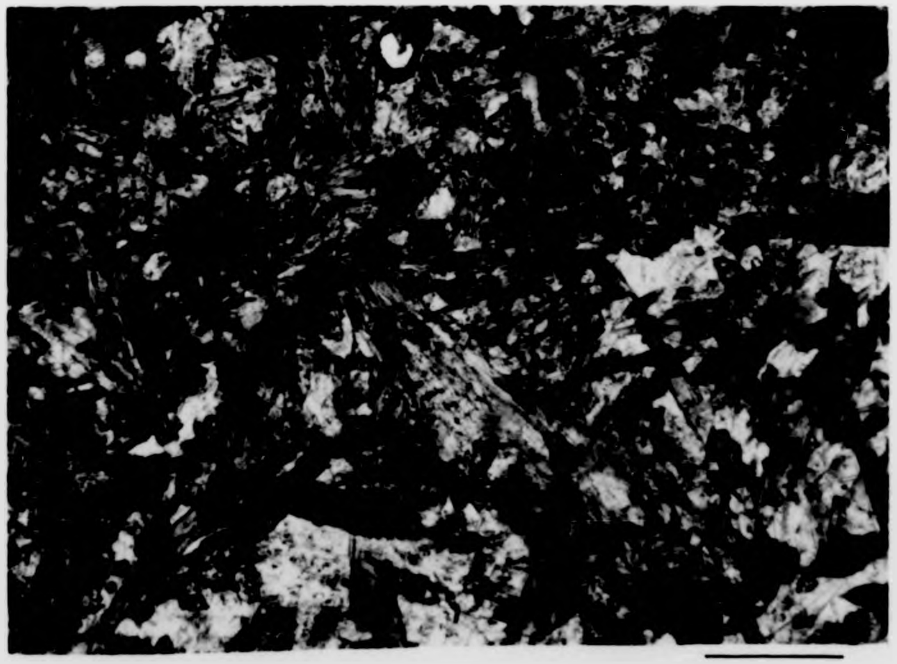


Plate 8.6: More intensely altered mafic microdiorite. Hornblende has been more extensively replaced by pale actinolitic? amphibole, and plagioclase by epidote and albite. NN 431884. Plane polarised light. Scale bar represents 0.1mm



Epidote occurs mainly in the more highly altered rocks as xenoblastic grains, 0.5-1.5mm in diameter (Plate 8.6) It is commonly intergrown with albite and the late, colourless amphibole.

Biotite may constitute up to 20% of the rock in some of the very highly altered rocks where it occurs as greenish brown subidioblastic grains overgrowing hornblende, and intergrown with pale, acicular amphibole. Some biotite is partially chloritised.

In the least altered rocks, the plagioclase composition is oligoclase (An 20-25) which occurs as anhedral grains 0.8-1.6mm in diameter, comprising up to 25% of some samples , and is commonly sericitised. Albitic plagioclase occurs in the more highly altered rocks (Plate 8.6). Plagioclase may show oscillatory zoning.

Quartz is a very minor constituent of these rocks, comprising less than 1% of the groundmass in highly altered samples.

Accessory minerals include epidote and apatite.

b. Leucocratic microdiorite

A dyke of an unfoliated rock consisting almost entirely of plagioclase was found intruding the semi-psammites exposed in the crags of Coire Ardair (NN434877) (Fig 8.1). Although, this leucocratic dyke occurs in close proximity to some of the mafic microdiorite dykes described above, no direct physical relationship could be found between these two varieties of the microdiorite suite.

Plagioclase (andesine An34-38) comprises up to 90% of the rock and occurs as euhedral to subhedral grains 0.5-2mm in diameter which commonly show oscillatory zoning. The cores of the plagioclase grains are commonly sericitised.

Quartz is a rare constitutent of these rocks and occurs as fine interstitial grains in the groundmass.

Epidote is occasionally present as a late alteration product of plagioclase.

Chlorite is also occasionally present, and intergrown with epidote and opaques. It is occasionally observed overgrowing relict, brown biotite.

Accessory minerals include opaques (magnetite and a little pyrite).

Discussion

Analyses by Haselock (1982) and Whittles (1981) of similar rocks of the microdiorite suite collected from the Corrieyairack Pass area suggest that they are chemically similar to calc-alkaline lamprophyres as well as to the "meta-appinites" of northern Ross-shire (Winchester, 1976) and the appinites from Appin (Wright and Bowes, 1979) and Donegal (Hall, 1967; French, 1976). Hall (op. cit.), Wright and Bowes (op. cit.) suggest that these rocks were products of a crustal accumulation of hydrous basaltic magma enriched in some trace elements and potassium.

Textural observations described earlier therefore suggest that the mineral assemblages are the result of varying degrees of the alteration of the primary igneous mineralogies following initial crystallisation. Similar observations have also been reported by the afore-mentioned works.

The leucocratic microdiorites (andesinites?) may represent a special fraction of the differentiating basaltic magma (Wright and Bowes, op. cit.)

Field evidence indicates that the emplacement of the microdiorites post-dated that of the pegmatites.

8.7 Andesite

A body of grey andesitic rock has been found at NN520937, south of Stac Buidhe (Fig 8.1). It forms part of a larger body about 500m^2 in area, whose northern margins consists of an earlier dyke of gneissose granite which it has cross-cut. This granite has also been found as xenoliths in the andesite.

Clinopyroxene comprises about 15% of the rock and occurs as pale, brown subhedral grains, up to 1.5mm in diameter. It is commonly replaced and pseudomorphed by chlorite and opaques (Plate 8.7).

Garnet occurs as rare anhedral to enhedral grains up to 1.5mm in diameter

Plate 8.7: Clinopyroxene phenocryst in a groundmass of small plagioclase laths and opaques. The clinopyroxene is partially replaced by chlorite.
Andesite. NN 521936.
Plane polarised light. Scale bar represents 0.1mm.

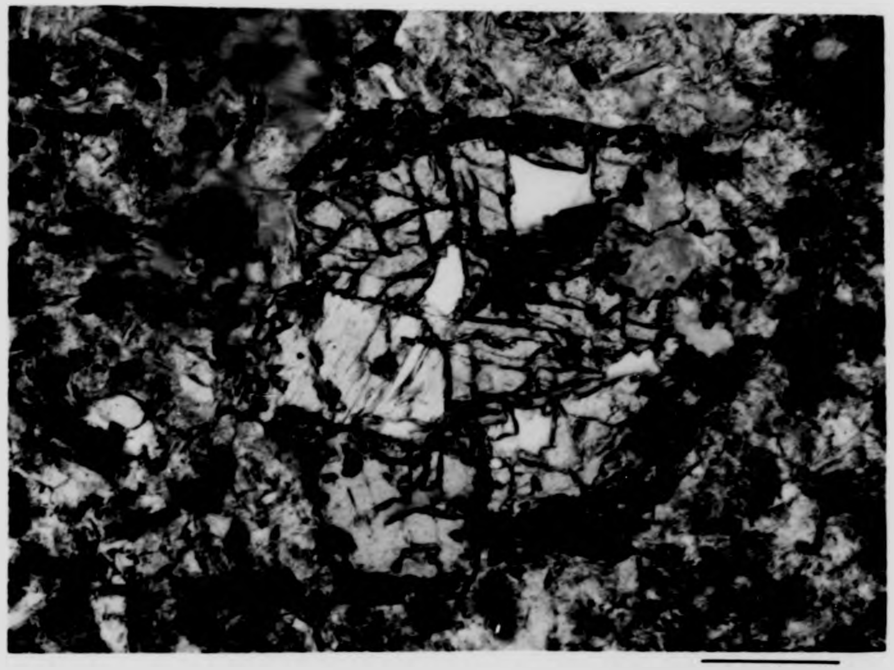


Plate 8.8 : Phenocrysts of plagioclase in a groundmass of small grains of plagioclase, magnetite and little calcite. Andesite. NN 521936.
Plane polarised light. Scale bar represents 0.1mm.

Plate 8.7: Clinopyroxene phenocryst in a groundmass of small plagioclase laths and opaques. The clinopyroxene is partially replaced by chlorite.

Andesite. NN 521936.

Plane polarised light. Scale bar represents 0.1mm.

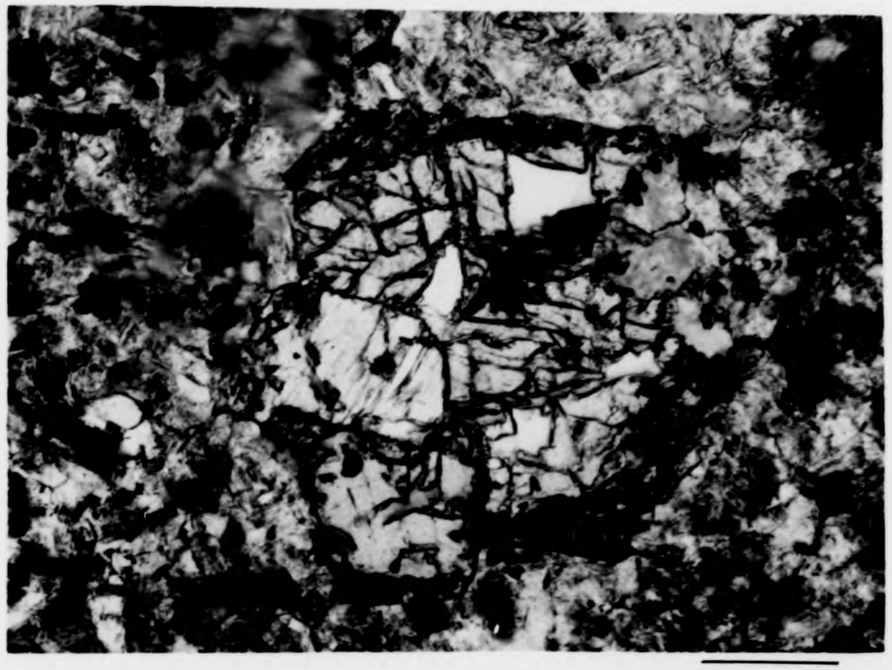
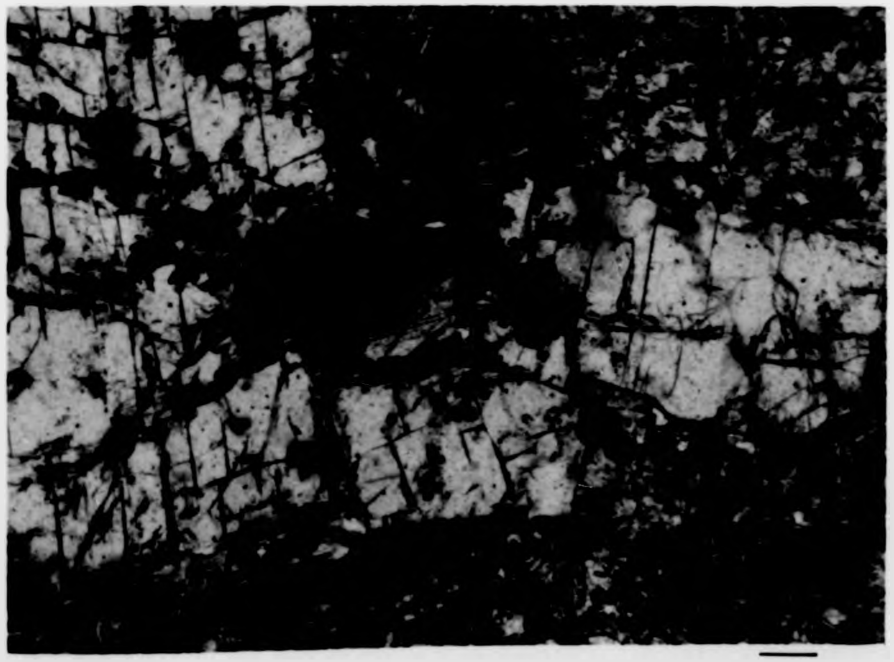


Plate 8.8 : Phenocrysts of plagioclase in a groundmass of small grains of plagioclase, magnetite and little calcite. Andesite. NN 521936.

Plane polarised light. Scale bar represents 0.1mm.



which is occasionally fractured and overgrown by secondary chlorite and opaques.

Plagioclase (andesine An34-45) comprises about 70% of the rock and indicates that the rock is an andesite. It occurs as phenocrysts up to 3.5mm long and occasionally show complex oscillatory zoning. The groundmass of the rock also consists of tiny plagioclase laths intergrown with opaques. Plagioclase phenocrysts occasionally show corroded outlines and are commonly sericitised and replaced by calcite (Plate 8.8). Their albite thin lamellae are occasionally bent by late deformation, probably D4.

Quartz is rare and occurs as fine grains typically intergrown with the secondary calcite.

Accessory minerals include opaques, apatite and calcite.

Discussion

Following chemical and mineralogical studies of the Devonian lavas of the Lorne Plateau, Scotland, Groome and Hall (1974) have suggested that these lavas are genetically related to the "appinitic" intrusions. They argued that the appinites dykes acted as feeders for the lavas. As no direct relationship could be seen in the field between the andesites and the microdiorites of the present study area, it is not possible to say how they are related.

Whittles (1981) has reported the occurrence of "younger basalts" consisting of augite and andesine plagioclase in the Killin area.

The origin of garnet in the andesite of the present study area is problematical. If it had crystallised with the rest of the phenocrysts in the rock, a high pressure environment (below 9kb) at great depths corresponding to the lower crust or upper mantle is indicated (Green and Ringwood, 1968).

On the other hand, these garnets could be xenocrysts derived from the metasedimentary country rocks which locally contain garnet. Information available, so far, does not allow an unequivocal conclusion to be made. However, such garnets have been reported from calc-alkaline magmas (Green and

Ringwood, op. cit; Oliver, 1956) similar to that inferred to have produced the andesite of this study area.

8.8 Timing of the intrusion of the igneous rocks

The widespread occurrence of deformed minerals in the igneous rocks indicates that they were emplaced prior to the late, dominantly brittle episode of deformation, D4 (Chapter 5).

Field relationships and studies of rock fabrics indicate that the earliest igneous intrusions were the weakly gneissose granites which have been inferred to be syn-to late-tectonic to D3. Clayburn (op. cit.) has obtained an Rb/Sr age of 439 $\pm$ 7Ma for the emplacement of these rocks. This was probably accompanied or followed by the intrusion of the pegmatites which have also yielded similar ages (Clayburn, op. cit) and have been deformed by D3 (Chapter 5).

Their date of intrusion is comparable with c.443 Ma obtained by van Breemen and Piasecki (1983) for the intrusion of the Glen Kyllachy Granite.

These early intrusives were followed by the rocks of the microdiorite suite and the andesite, and then the Corrieyairack hornblende granodiorite which has been dated at 405Ma (Clayburn, op. cit.) and finally by the porphyritic felsites which are all post-tectonic to D3. The age of the granodiorite is slightly younger than c.413Ma obtained by van Breemen and Piasecki (op. cit.) for the post-tectonic Findhorn Granite, but is comparable with c.404Ma obtained by Brown et al (1968) for the Allt Crom Granite.

This correspondence in the ages obtained for these late, granitic rocks accords with the proposition by Anderson (1956) that the Corrieyairack and the Allt Crom intrusions are parts of a large batholith extending at depth from the Corrieyairack Pass to the Findhorn Valley beyond Tomatin.

The main NE-SW trend of the igneous bodies is close to the inferred direction of the maximum principal stress, σ_1, that gave rise to D3 folding (see Chapter 5). This suggests that fractures generated by this stress system may have provided weak zones then exploited by the intruding igneous rocks.

Table 8.1 : Timing of the igneous activity and the relationship to regional deformation

Age (Ma)	Deformation	Igneous Activity
	(D4) Late, brittle movements	
		Porphyritic felsite
405		Hornblende granodiorite
		Andesite
		The microdiorite suite
		Granite pegmatites
440	D3	Weakly gneissose, biotite granites
Age uncertain {	D2	
	D1	

CHAPTER 9 : CONCLUSIONS AND DISCUSSION

9.1 Summary of conclusions

a. The metasedimentary rocks of the Loch Laggan -Upper Strathspey area consist of a varied assemblage of psammites, semi-psammite- and semi-pelites with sporadically-developed thin calc-silicate bands and pods.

The entire lithostratigraphic sequence has been subdivided mainly on a lithological basis into seven formations comprising two successions, the Glenshirra and Corrieyairack successions, which are separated by a tectonic break, the Gairbeinn Slide. The lithostratigraphic sequence exposed in this area is at least 6.8 km thick.

b. Petrographically, the Garva Formation is distinct from the other formations; its higher content of heavy minerals: magnetite, ilmenite, sphene and epidote as well as microcline indicates that its sediments were slightly arkosic and more proximal compared with the other formations which were largely greywackes.

c. Geochemical analysis also distinguishes the semi-pelites of the Garva Formation which are less "mature" than those of the other formations implying that their source rocks had undergone less chemical weathering and faster erosion and that the detritus were deposited more quickly.

The semi-psammites and psammites of the Garva and Chathalain Formations emerge mainly as lithic arenites with some arkose whereas those of the Corrieyairack Succession classify dominantly as greywackes, although lithic arenites also occur within the Glendoe Formation.

Provenance analysis suggests that the sediments which formed the rocks of the present study area were derived from calc-alkaline basement sources similar to the Annagh Gneiss or reworked Lewisian-type gneisses perhaps intruded by evolved granites. Studies also suggest that these source rocks may have been located in tectonic environments ranging from "passive margins" through "active continental margins" to "continental island arcs". However, because there maybe some differences between the scale and style of tectonic processes in the Pre-cambrian and those in the Phanerozoic, such deductions can be only tentative.

d. Sedimentological studies suggest that the sediments which formed these rocks were deposited in varied environments. The Garva Formation was probably deposited in an alluvial environment, the Chathalain Formation was probably deposited in a shallow water environment. The depositional environments of the Corrieyairack Succession probably ranged from deltaic for the Coire nan Laogh Formation to deeper-water submarine turbidite fans for the Glendoe and Monadhliath Formations. The Carn Leac Formation shows more tractional sedimentary structures and probably records a shallowing of the depositional basin with increased current activities.

Paleocurrent indicators suggest that the sediments were transported from the south to the north. For the inferred submarine fans of the Glendoe and Monadhliath Formations this implies a northerly paleoslope and sediment sources to the south. For the Chathalain and Garva Formations these currents may have been redistributing sediments derived from basement sources situated to the NW or W.

Although lithological, sedimentological and chemical differences distinguish the various formations recognised in this study area individually, the absence of any chronostratigraphic criteria together with the problems caused by diachronism and lateral facies changes pose serious problems to stratigraphic correlation.

The calc-silicate bands and pods were the result of localised precipitation of carbonates from oversaturated pore fluids during the diagenesis of the sediments. They were restricted to permeable bands only.

e. The metasediments have been subjected to polyphase deformation and metamorphism. The first episode of deformation produced a penetrative foliation S1 which is generally subparallel to the bedding S0. This foliation is axial planar to minor isoclinal folds of bedding and early quartz and

and quartzo-feldspathic veins. Continued D1 movements led to displacement on the Gairbeinn Slide. NW-facing, medium scale reumbent D1 isoclinal folds are developed locally near the slide and on Meall Ghoirleag (NN517907).

The second phase of deformation produced minor, tight to close, subvertical folds and a crenulation of S1 and refolding of D1 structures. The major D2 structure is the Laggan Antiform which trends ENE-WSW except locally near Na Cnapanan where its axial trace has been rotated to NNE trend by the later D3 folding.

The third episode of deformation resulted in the re-orientation of D1 and D2 structures. D3 produced open minor folds associated with a crenulation of S1. Major D3 folds which generally trend NW-SE include the Coire Ardair Synform, Carn Liath Antiform and the Allt a Chrannaig Synform.

The fourth episode of deformation involved brittle movements on ENE-WSW trending faults and fractures, and on a less common conjugate set trending NW-SE. One fault displaces the axial trace of the Laggan Antiform by about 4Km.

f. Middle amphibolite facies metamorphism of the rocks lasted from early D1 to D2 times. Lower grade upper greenschist conditions followed D3, while localised contact metamorphism was associated with the intrusion of the Corrieyairack Granite Complex.

The climax of the regional metamorphism was pre-D2, and involved the growth of garnet, biotite and muscovite in the semi-pelites, and hornblende, garnet, bytownite and clinozoisite in the calc-silicates of suitable composition. Late, retrograde metamorphism involved the breakdown of bytownite to clinozoisite (zoisite), partial replacement of hornblende by biotite, growth of fibrous, colourless, amphibole, partial replacement of garnet by calcite, and chlorite in the calc-silicates, and the replacement of garnet by biotite, quartz and magnetite in the semi-pelites.

Contact metamorphism in the aureole of the Corrieyairack Granite complex led to the growth of andalusite and cordierite in the outer aureole, and fibrolite, prismatic sillimanite and K-feldspar as well as the outer aureole minerals in the inner aureole.

g. The metasediments were intruded by late Caledonian granitic rocks. The earliest intrusions were of the weakly foliated two-mica granites and granite pegmatites dated at 440Ma; these were probably syn- to late D3. Then followed the intrusion of the microdiorites and andesites and finally the hornblende granites (dated at 405Ma) and the felsites which were probably emplaced a little later.

9.2 Discussion and Regional Implications

a. Stratigraphy

The various formations recognised in this study area have been broadly correlated with those mapped by Haselock (1982), Whittles (1981) and Haselock et al (1982) in the Corrieyairack Pass and Killin areas.

The rocks mapped in the Loch Laggan-Upper Strathspey area are also lithologically similar to those of the "younger" Moines of the N.W. Highlands (Strachan , 1982, Piasecki and van Breemen, 1979, 1983; Piasecki et al. 1981) but are different from the rocks of the lower Dalradian Appin Group (Hickman 1975; Harris et al. 1978). In view of this the rocks studied in this area have been placed in the Grampian Divison. However, Harris et al (1975, 1978) consider these rocks to be part of the Dalradian Supergroup and refer to them as the Grampian Group.

b. Chemostratigraphical correlations

The use of geochemistry as an aid to stratigraphical correlation in the Scottish Highlands has been discussed by Lambert et al. (1981, 1982), Winchester et al. (1981), Hickman and Wright (1983) and Holland and Winchester (1983).

The present work finds that there are broad similarities in the bulk rock chemistries of the lithostratigraphical units in the Loch Laggan-Upper Strathspey area and those correlated with them in them in the Corrieyairack

Pass area (Haselock 1982) and in the Killin area (Whittles 1981). The slight chemical variations observed between the semi-pelites in the present study area and those in the Corrieyairack Pass and Killin areas which suggest that the latter are slightly more mature are consistent with the sedimentological observations that paleocurrents and hence sediment transport was approximately from the south to the north.

However, the marked chemical contrast recognised by Haselock (1982, 1984) between the Glenshirra and the Corrieyairack Successions has not been found to be so distinct in the Loch Laggan-Upper Strathspey area. While there are chemical and petrographic differences between the Garva Formation and the formations of the Corrieyairack Succession, differences are also found between it and the Chathalain Formation, which in some chemical respects is more similar to the Appin Group.

The geochemistry of the rocks of the Loch Laggan-Upper Strathspey area are broadly similar to those of the Moines of the N.W. Highlands (Lambert et al, op. cit., Winchester et al, op. cit.) but are different from the rocks of the lower Dalradian Appin Group. The differences between the Moine and the Grampian Division on the one hand and those of the lower Dalradian on the other, result from the greater "maturity" of the Dalradian rocks. This may be the result of a difference in their provenance, i.e. the Dalradian may have been second generation sediments or may have been derived from similar but more intensely weathered and sorted protoliths. The geochemical similarity of the Grampian Division rocks to those of the Moine does not however prove that the latter are Moine ; it may merely indicate that both groups of rocks had a similar provenance.

c. Sedimentology

Harris et al. (1978) and Anderton (1982) have contended that the Grampian "Group" rocks form part of the Lower Dalradian which were deposited on a stable subsiding shelf. This conclusion has been based on Hickman's (1975) suggestion that the Eilde Flags of the Lochaber were probably deposited on coastal plain or tidal environments.

Detailed sedimentological analyses of the rocks of the Loch Laggan - Upper Strathspey area, discussed earlier suggest that they were deposited in environments quite different from those proposed for the Lower Dalradian rocks, although their sediment transport directions were generally the same, namely, from the south to the north (see Hickman, 1975).

d. Structure

The three principal phases of deformation which have been recognised in this study area can be correlated with the major deformational events identified in the Forest of Atholl and north Schiehallion areas (Thomas , 1979, 1980), the Lochaber district to the S.W. (Roberts and Treagus 1977; Treagus, 1974; Hickman, 1978) and the Corrieyairack Pass and Killin areas (Whittles, 1981; Haselock,1982; Haselock et al, 1982). The specific correlations which can be made with these areas have been discussed in Chapter 5.

Although comparable deformational events have been recognised in these areas, the geometries and importance of specific events may vary from place to place as a result of several factors including rock competence and stratigraphical level.

Thomas (1980) proposed that the two early phases of deformation D1 and D2, were associated with the Grampian Orogeny, with the underthrusting of the "younger" Moine by "older" Moine and the Lewisian basement. He attributed the later deformations D3 and D4 to the late Grampian or Caledonian Orogeny as a result of continental collision associated with the closing of the Iapetus Ocean in the late Ordovician (Lambert and McKerrow, 1976). The effects of both events have been recognised in the Grampian Division and the Dalradian Supergroup rocks of the Grampian Highlands.

The effects of a late Proterozoic tectonothermal event, the Morarian Orogeny, has been recognised in the "older" Moine basement and the lower levels of the Grampian Division (Piasecki, 1980; Piasecki and van Breemen, 1979, 1983; Piasecki et al, 1981). They attributed the first phase of deformation recognised in the lower part of the Grampian Division and the movement on the Grampian Slide separating the Central Highland and Grampian Divisions to this event which has been dated at 750Ma.

This late Proterozoic event has not yet been recognised in the higher stratigraphical levels of the Grampian Division studied here and in the Dalradian. Also no unconformity marking the epeirogenic stage of this event has yet been recognised in the approximately 7 Km thick section of the Grampian Division rocks of the Loch Laggan-Upper Strathspey area or in the Corrieyairack Pass area (Haselock, 1982). The absence of an unconformity between the upper and lower levels of the division may be attributed to this event having affected only the basement and the deeper levels of the Grampian Division while sedimentation was still going on (Piasecki and van Breemen, op. cit.).

For the amphibolite facies metamorphism associated with the emplacement of the dated syntectonic pegmatites, pressure equivalent to, at least, 15Km of rock cover is required. Unfortunately the total thickness of the Grampian Division is not yet known. It may or may not be sufficiently thick.

Hickman (1975) and Haselock (1982) have reported that the upper part of the Grampian Division passes by a normal sedimentary transition into the rocks of the Appin Group. This implies additional sedimentary cover and hence pressure for this 750Ma event and may suggest that the Appin Group was deposited prior to this event. The age of deposition of the Appin Group is not definitely known. Also the Vendian Tillite which marks the base of the Argyll Group of the Dalradian Supergroup is unsuitable as a marker for the unconformity (Piasecki and van Breemen, op. cit; Winchester , pers. comm.)

Alternatively, sufficient pressure could have been provided by imbricate thrusting and tectonic thickening accompanying the 750Ma event. Although several slides have been recognised within the rocks of the Grampian Division and the Appin Group (Thomas, op. cit; Haselock, et al, 1982) their timing and geometrical implications are not clear, largely as a result of poor chronological and stratigraphical constraints. Also the problem of the unconformity remains unresolved. Perhaps any unconformity if it exists has been obscured by later tectonometamorphic convergence and would be extremely difficult to identify.

These problems underscore the need for more detailed studies of the various rocks of the Grampian Division designed to elucidate their chronological and stratigraphical relationships.

The rocks of both successions in the Loch Laggan-Upper Strathspey area have undergone the same number of phases of deformation and metamorphism which may be tentatively correlated with the Grampian and Caledonian orogenies.

APPENDIX A

ANALYTICAL TECHNIQUES

Whole rock analyses

157 samples of metasedimentary rocks including 54 of the calc-silicate rocks were analysed for ten major and eight trace elements by X-ray Fluorescence.

Approximately 1Kg of each sample was collected except for the calc-silicates, smaller samples of which were commonly obtained because of the thinness of the bands and pods. The complete list of the analyses and sample locations are given in Appendix B.

The samples were split into small pieces using a Denbigh fly-press rock splitter after the removal of all weathered material. The split samples were then passed through a Sturtevant 2" x 5" jaw crusher, which reduced the rocks to chips between 0.3 and 0.6 cm in size. The samples were then homogenised by successive coning and quartering until two quarters approximately 120gm in weight were selected.

The quarters were then crushed in a tungsten carbide Tema mill for approximately 15 secs (for FeO determination) and 30 secs (for X.R.F. analyses). After further homogenisation approximately 20gm of the fraction for X.R.F. was milled for 30 mins in a Glen Creston M280 tungsten carbide ball mill.

Analyses for major elements were performed on glass discs produced by mixing 0.5 gm of the rock powder, which had been ignited to 1000^{o}C , with 2.5gm of Spectroflux 101A (Lithium Metaborate). The mixture was then fused over a Meker burner until a clear melt was obtained. This melt was cast in a brass mould with a copper binding ring,the excess melt being pressed out with an aluminium plunger.

Analyses for the trace elements and Na were carried out on pressed powder pellets. These were prepared by mixing 8-10 drops of Mowiol (N90/98) binder with 6 gm of the powdered sample in an agate mortar with a pestle. This was then pressed in a hydraulic press between two tungsten carbide formers at a pressure of 25 tons per square inch for 4 minutes and then dried in an oven overnight.

Analyses for both major and trace elements were performed on a Phillips PW 1212 fully automatic sequential X-ray spectrometer in the Department of Geology, University of Keele. The operating conditions are given in Tables A1 and A2.

Each "glass" bead was run three times for the major elements and the mean of the three analyses noted. For the trace elements and Na two cycles were run for each side of the pressed pellet. Because of the shallow penetration of the X-rays, these represent duplicate analyses. Both peak and background counts were recorded and the net counts were used with or without corrections for interference effects. A Keele Geochemistry Laboratory standard was run simultaneously with the studied samples as a drift monitor.

A selection of international standards (Flanagan, 1974) and Keele Geochemistry Laboratory standards were run and were used for the construction of calibrations after the application of the Norrish and Hutton (1969) correction matrix. The apparent fluorescence values obtained for the samples were also corrected using the same matrix in reverse. A silica brick and a fire brick were used as additional standards to improve the accuracy of the calibrations at high SiO_2 and Al_2O_3 values.

The machine detection limits and precision estimates are given in Table A3.

FeO values were determined by titration against potassium dichromate. 0.5gm of rock powder was dissolved in a 1:1 mixture of $H_2S_2O_4$ and HF over a steam bath for 15 mins. Any excess acid was neutralised with 500 ml of saturated boric acid and the resulting solution was titrated against potassium dichromate, with sodium diphenlylamine sulphonate as the indicator.

TABLE A.1.: X.R.F. Operating Conditions : Major Elements

Tube	Cr									W
Element	Na	Mg	Al	Si	P	K	Ca	Ti	Fe	Mn
Atomic No.	11	12	13	14	15	19	20	22	26	25
Peak	Ka	Ka	Ka	Ka	Ka	Ka	Ka	Ka	Ka	Ka
Peak 2	55.23	43.61	144.93	109.12	140.99	50.61	113.19	86.20	85.78	95.33
Background	+1.77	+2.89	-6.43	-4.12	+4.01	+2.89	+2.31	+2.30	+1.72	+1.87
Volts (Kv)	40	40	60	40	60	40	40	40	60	60
Current (mA)	32	32	24	16	24	8	8	8	8	32
Collimator	coarse	coarse	coarse	coarse	coarse	coarse	fine	fine	fine	fine
Counter	flow	flow	flow	flow	flow	flow	flow	flow	flow	flow
Crystal	T AP	KAP	PE	PE	GE	PE	LiF_{200}	LiF_{200}	LiF_{200}	LiF_{200}
Metbod	ABS	ABS	AR	AR	ABS	AR	AR	AR	AR	ABS
Time (sec)	40	100	FC	FC	40	FC	FC	FC	FC	40
Counts	FT	FT	10^4	10^4	FT	10^4	10^4	10^4	10^4	FT
No. of cycles	4	3	3	3	3	3	3	3	3	3
Disc/P.P.	PP	FD	FD	FD	FD	FD	FD	FD	FD	FD/PP
Machine	1212	1212	1212	1212	1212	1212	1212	1212	1212	1220

2 μ window used throughout.

TABLE A.2 : X.R.F. Operating Conditions : Trace Elements

Tube	W				Mo			
Element	Cr	Ni	Nb	Ba	Rb	Sr	Y	Zr
Atomic No.	24	28	41	56	37	38	39	40
Peak	Ka	Ka	Ka	$L\beta_2$	Ka	Ka	Ka	Ka
Peak 2	69.34	71.24	30.39	115.29	37.95	35.82	33.85	32.06
Background	+5.66	+2.26	-0.44	-1.29	+0.75 -1.10	+1.03 -1.02	+0.94 -0.85	+0.95 -0.46
Volts (Kv)	60	60	60	60	60	60	60	60
Current (mA)	28	28	30	30	28	28	28	28
Collimator	fine	fine	fine	coarse	fine	fine	fine	fine
Counter	flow	flow	scint	flow	scint	scint	scint	scint
Crystal	LiF_{200}	LiF_{200}	LiF_{200}	LiF_{200}	LiF_{200}	LiF_{200}	LiF_{200}	LiF_{200}
Method	ABS	ABS	ABS	ABS	ABS	ABS	ABS	ABS
Time (sec)	40	40	40	40	40	40	40	40
Counts	FT	FT	FT	FT	FT	FT	FT	FT
No. of cycles	2/4	2/4	4	4	4	4	4	4
Disc/P.P.	PP	PP	PP	PP	PP	PP	PP	PP
Machine	1212	1220	1212	1220	1212	1212	1212	1212

Table A3. Calculated machine precision and detection limits

Element	Precision (wt %)	Detection limit (wt %)
SiO_2	0.95	0.088
TiO_2	0.02	0.003
Al_2O_3	0.23	0.035
Fe_2O_3	0.12	0.017
FeO	0.02*	-
MnO	0.005	0.002
MgO	0.35	0.32
CaO	0.079	0.009
Na_2O	0.07	0.034
K_2O	0.02	0.003
P_2O_5	0.009	0.006
L.O.I.	0.02*	-
	(ppm)	(ppm)
Ba	56	37
Cr	2	1
Nb	3	3
Ni	4	4
Rb	7	4
Sr	6	3
Y	5	3
Zr	13	9

* From duplicate determinations.

$$\text{Precision} = \frac{\text{Standard deviation background(s)} + \text{Standard deviation peak}}{\text{Slope factor}}$$

$$\text{Detection limit} = \frac{2 \times \text{Standard deviation background}}{\text{Slope factor}}$$

Appendix B. Tables of Analyses

Table B.1. Analyses of Metasediments

Sample No.	492	71b	213	621	8221	487	490	617	74	204	214
SiO_2	56.94	55.62	61.50	64.24	58.95	68.57	71.78	66.91	78.98	75.05	80.14
TiO_2	0.93	1.07	0.98	0.89	1.21	0.61	0.59	0.82	0.18	1.21	0.34
Al_2O_3	19.48	21.34	17.18	15.70	19.58	13.58	12.85	15.01	10.65	10.24	9.21
Fe_2O_3	2.48	1.27	1.94	2.11	1.85	1.31	2.87	1.38	0.564	2.24	0.80
FeO	6.27	5.72	4.78	4.07	5.50	4.42	1.70	3.37	0.98	3.21	1.02
MnO	0.11	0.11	0.11	0.11	0.07	0.11	0.11	0.11	0.03	0.11	0.03
MgO	2.78	2.53	2.27	2.30	3.83	1.87	1.54	1.76	0.64	1.04	0.58
CaO	0.77	0.97	1.40	1.37	0.88	1.16	1.51	1.74	0.58	1.85	0.74
Na_2O	0.84	2.10	1.93	2.15	3.00	2.86	3.29	3.15	2.37	2.52	2.36
K_2O	6.12	6.30	4.43	4.63	4.85	3.27	2.61	4.21	4.20	1.40	3.33
P_2O_5	0.15	0.07	0.23	0.14	0.26	0.16	0.12	0.10	0.04	0.04	0.03
L.O.I.	2.34	1.87	1.90	1.26	n.d.	0.99	0.73	0.59	0.47	0.61	0.41
Total	99.91	99.60	99.18	99.42	99.98	99.41	99.88	99.53	99.79	99.89	99.00
Ba	1076	1067	836	544	948	682	591	782	980	564	848
Cr	81	83	69	58	64	45	44	41	18	62	22
Nb	13	17	16	17	20	13	14	20	12	17	13
Ni	57	58	44	33		33	27	22	12	10	13
Rb	223	240	178	201	153	148	109	145	104	86	87
Sr	114	172	164	153	391	215	264	280	163	221	200
Y	36	46	37	29	41	21	22	24	08	22	07
Zr	178	226	195	253	222	136	209	396	50	820	156

(n.d. = not determined)

Sample No.	493	619	6	30	102	247	248	249	252	310	311
SiO_2	76.42	76.96	61.74	60.21	57.80	62.99	59.65	58.26	61.73	64.65	60.33
TiO_2	0.40	0.37	1.05	1.01	1.61	0.86	1.11	2.75	0.96	1.09	2.17
Al_2O_3	11.97	11.01	17.27	16.69	18.30	17.35	19.08	15.85	17.15	16.81	16.00
Fe_2O_3	0.85	0.444	3.58	2.15	4.89	1.02	3.55	7.64	3.15	3.85	5.93
FeO	1.76	1.40	2.28	4.25	2.44	2.93	1.77	2.19	2.00	1.29	2.64
MnO	0.04	0.04	0.10	0.12	0.12	0.08	0.07	0.12	0.07	0.06	0.10
MgO	0.82	0.95	1.40	2.83	2.31	1.44	1.76	2.41	1.06	0.88	1.54
CaO	0.90	1.04	3.89	2.42	2.31	1.34	4.54	2.70	1.75	2.86	2.87
Na_2O	3.19	2.68	3.76	3.21	4.55	3.67	4.28	3.55	3.49	4.60	3.70
K_2O	2.23	3.66	3.00	4.39	4.50	6.64	3.94	3.81	6.41	3.43	2.87
P_2O_5	0.11	0.05	0.17	0.18	0.17	0.12	0.15	0.18	0.14	0.14	0.16
LOI	1.05	0.30	0.47	2.12	1.09	0.79	0.79	0.60	1.00	0.51	0.77
Total	99.94	99.05	98.94	99.58	100.37	99.56	100.89	100.32	99.12	99.33	99.38
Ba	464	758	1720	1501	1367	2119	1943	1689	1990	1247	967
Cr	29	24	50	86	70	26	50	67	42	34	65
Nb	14	15	10	12	09	12	10	15	10	13	11
Ni	20	14	26	31	25	10	19	19	19	14	24
Rb	77	97	48	90	81	109	54	68	93	47	59
Sr	215	184	867	660	748	534	989	534	458	687	517
Y	15	10	11	18	12	11	13	12	09	10	10
Zr	126	216	137	315	261	199	210	446	161	232	266

Sample No.	P1	720	31	101	103	115	130	245	312	505A	690
SiO_2	58.33	60.16	67.15	73.89	72.89	69.76	68.22	69.32	68.08	65.10	74.15
TiO_2	1.67	1.09	0.94	0.29	0.84	0.62	0.67	0.68	1.19	0.65	0.62
Al_2O_3	16.98	17.68	15.17	13.70	11.43	13.13	14.53	15.20	13.38	15.41	12.70
Fe_2O_3	5.56	1.79	1.54	0.53	1.56	1.20	1.44	2.21	1.70	3.07	0.52
FeO	2.65	4.90	1.99	0.74	2.77	2.84	2.78	1.15	3.54	1.85	1.18
MnO	0.12	0.11	0.09	0.03	0.07	0.06	0.11	0.06	0.10	0.07	0.04
MgO	2.18	2.18	1.30	0.82	1.49	1.92	1.56	1.02	1.80	1.22	0.64
CaO	3.63	1.89	1.68	0.56	2.07	1.72	3.21	0.72	3.51	0.64	1.22
Na_2O	3.34	2.60	3.79	3.75	2.50	2.86	2.88	4.62	2.28	3.17	2.76
K_2O	3.50	4.35	4.09	5.30	2.74	3.95	3.10	4.66	2.60	6.22	4.56
P_2O_5	0.16	0.25	0.14	0.05	0.16	0.14	0.18	0.13	0.15	0.17	0.05
L.O.I.	0.64	1.41	1.00	0.56	0.69	0.70	0.84	0.82	0.74	1.56	0.42
Total	99.04	98.93	99.11	100.28	99.51	99.23	99.83	100.69	99.98	99.31	99.00
Ba	1457	866	1431	1053	727	1018	986	1582	807	1240	1054
Cr	78	70	36	13	48	41	45	23	66	34	20
Nb	11	16	12	09	15	12	12	13	14	15	15
Ni	27	41	16	07	24	25	28	9	21	19	10
Rb	67	164	83	91	109	140	115	98	90	104	82
Sr	654	262	432	293	376	377	392	403	424	331	330
Y	17	25	11	11	29	18	23	10	17	25	11
Zr	218	344	384	169	499	251	271	196	520	224	295

Sample No.	630b	627	630a	646	227	450	452	645
SiO_2	62.24	82.70	78.13	75.42	65.00	70.03	69.11	68.09
TiO_2	1.04	0.29	0.27	0.57	0.71	0.58	0.69	0.70
Al_2O_3	16.86	8.54	10.26	11.74	16.53	13.58	13.81	14.56
Fe_2O_3	1.47	0.31	0.39	1.02	1.05	1.30	0.90	1.21
FeO	5.84	1.01	2.42	1.86	4.12	2.81	3.37	3.77
MnO	0.08	0.03	0.13	0.08	0.14	0.05	0.07	0.13
MgO	2.23	1.09	0.95	1.40	2.28	1.67	1.66	1.58
CaO	1.02	1.42	1.95	2.74	3.50	1.65	2.00	2.40
Na_2O	2.09	3.23	2.66	3.35	3.04	4.67	3.44	4.21
K_2O	4.28	0.95	1.09	1.37	2.02	1.66	3.13	1.92
P_2O_5	0.23	0.08	0.13	0.12	0.25	0.14	0.15	0.17
L.O.I.	1.74	0.35	0.45	0.61	0.80	0.90	0.55	0.53
Total	99.78	100.10	99.10	100.49	99.89	99.34	99.24	99.67
Ba	1096	195	145	540	341	404	886	408
Cr	79	23	23	43	45	40	47	49
Nb	15	17	16	19	15	14	16	13
Ni	24	14	15	25	34	31	25	24
Rb	173	30	54	51	106	79	119	105
Sr	309	264	269	454	306	462	313	358
Y	42	10	22	20	26	15	19	26
Zr	298	341	147	263	157	148	242	287

Sample No.	718	P2	P3	76	313	703	11	3b	104	131	132
SiO_2	69.36	78.43	83.54	76.84	82.90	86.73	56.16	59.26	57.64	60.97	60.59
TiO_2	0.43	1.13	0.28	0.53	0.52	0.19	0.94	0.95	1.08	0.96	0.99
Al_2O_3	15.54	9.92	8.23	11.53	8.04	7.01	19.48	19.21	18.27	18.34	18.74
Fe_2O_3	0.64	0.70	0.44	0.86	0.93	0.59	1.20	1.64	1.51	1.87	1.45
FeO	1.62	1.76	0.82	1.19	0.78	0.81	6.10	5.33	6.84	4.38	5.09
MnO	0.04	0.05	0.02	0.05	0.03	0.02	0.28	0.09	0.15	0.08	0.08
MgO	0.76	0.78	0.57	0.89	0.65	0.64	2.37	2.41	2.56	2.02	1.99
CaO	1.65	0.85	0.77	0.90	0.23	0.50	3.48	1.40	3.10	1.96	2.02
Na_2O	3.38	2.05	1.91	2.60	1.38	1.65	4.19	1.39	3.13	2.45	2.71
K_2O	5.35	3.74	1.49	3.38	3.61	1.41	2.47	5.22	2.77	3.57	3.55
P_2O_5	0.04	0.08	0.03	0.09	0.02	0.03	0.42	0.21	0.29	0.25	0.24
L.O.I.	0.49	0.47	0.79	0.75	0.63	0.81	0.98	1.96	1.24	1.93	1.63
Total	99.46	100.14	98.98	99.73	99.79	100.47	98.73	99.65	99.36	99.27	99.64
Ba	1467	972	437	832	889	342	436	1172	746	805	712
Cr	32	42	28	14	23	17	70	69	75	60	66
Nb	11	24	12	19	13	10	16	14	17	15	18
Ni	16	10	16	6	12	14	52	44	44	36	41
Rb	104	103	43	63	102	47	118	201	127	156	163
Sr	454	213	202	282	124	126	531	162	392	273	275
Y	13	09	05	17	07	07	47	22	56	34	39
Zr	191	468	138	463	220	58	154	188	204	186	213

Sample No.	133b	135	253	315	317	318	506	704	711	321	319
SiO_2	61.18	61.11	60.55	59.78	60.57	60.85	60.42	59.90	58.79	70.93	64.59
TiO_2	0.95	0.96	0.92	0.99	0.95	1.04	0.96	0.97	0.96	0.64	0.85
Al_2O_3	17.74	18.03	17.69	18.03	18.78	19.96	18.49	18.78	18.63	13.51	16.88
Fe_2O_3	1.91	1.20	1.80	1.41	1.93	2.56	1.83	1.53	1.56	1.15	1.48
FeO	3.90	4.91	4.90	4.74	5.15	3.90	5.32	5.97	6.32	3.37	3.66
MnO	0.07	0.09	0.11	0.15	0.12	0.09	0.08	0.08	0.15	0.07	0.07
MgO	1.91	1.99	2.56	1.90	2.34	1.70	2.07	2.60	2.33	1.57	1.33
CaO	1.74	2.80	2.24	4.38	1.61	0.75	1.32	1.67	1.54	1.39	0.96
Na_2O	2.45	3.88	3.00	3.70	2.44	0.77	1.84	1.57	2.30	2.88	1.94
K_2O	3.82	2.62	3.10	1.92	3.56	5.27	3.68	4.10	3.60	2.57	4.45
P_2O_5	0.22	0.27	0.24	0.60	0.28	0.28	0.21	0.31	0.26	0.15	0.30
L.O.I.	1.70	1.14	1.52	0.79	1.88	2.65	2.71	2.00	2.16	1.41	2.24
Total	98.03	99.55	99.16	98.92	100.18	100.25	99.51	100.14	99.30	100.01	99.14
Ba	753	455	728	371	828	985	889	983	684	417	818
Cr	60	60	64	62	66	59	65	71	61	35	49
Nb	18	17	14	18	18	20	17	14	16	18	18
Ni	42	38	45	35	19	9	43	47	22	10	16
Rb	162	137	146	110	161	202	162	162	174	122	187
Sr	225	369	293	359	216	137	195	211	246	236	191
Y	34	38	43	38	36	44	40	33	44	15	32
Zr	217	209	190	201	160	220	180	160	160	250	231

Sample No.	320	316	710	44	40a	38	40b	41	35	56	63b
SiO_2	67.64	70.05	65.20	77.61	62.41	66.79	67.61	65.76	78.81	58.89	63.37
TiO_2	0.68	0.71	0.87	0.41	0.72	0.67	0.66	0.71	0.47	0.67	0.79
Al_2O_3	15.38	14.51	16.40	11.30	18.36	15.62	14.80	17.07	10.36	20.11	16.30
Fe_2O_3	1.42	0.94	1.20	0.58	0.82	1.07	0.74	0.79	0.86	1.78	1.04
FeO	2.99	3.50	4.02	1.32	3.98	3.64	4.56	3.73	2.16	2.58	4.05
MnO	0.08	0.06	0.07	0.04	0.34	0.10	0.16	0.20	0.04	0.32	0.11
MgO	1.69	1.49	2.07	0.96	1.50	1.13	1.90	2.15	0.95	1.97	1.94
CaO	1.39	1.74	2.50	1.51	5.03	2.56	2.81	4.17	0.55	6.47	4.05
Na_2O	2.70	3.20	3.68	3.41	2.80	4.43	3.43	3.48	2.02	3.72	3.08
K_2O	3.11	2.19	2.16	1.49	2.13	1.75	2.00	1.51	2.98	2.34	2.52
P_2O_5	0.23	0.13	0.18	0.10	0.35	0.21	0.21	0.30	0.08	0.55	0.22
L.O.I.	1.70	1.20	1.09	0.61	0.96	0.82	0.60	0.70	0.831	1.17	1.04
Total	99.34	100.11	99.88	99.50	99.84	99.19	99.98	100.97	100.35	100.84	99.01
Ba	556	810	443	408	454	492	478	291	735	535	644
Cr	43	42	49	23	44	48	43	48	32	41	54
Nb	18	17	17	17	16	16	15	16	15	17	14
Ni	7	30	34	10	30	25	25	32	14	27	29
Rb	129	105	118	51	94	92	92	76	102	125	127
Sr	250	229	302	275	411	424	352	391	144	424	397
Y	17	25	31	12	42	31	35	28	18	31	33
Zr	219	197	231	249	167	238	234	212	234	128	205

Sample No.	20b	49	50b	59b	85	158	62	17b	24	26	45
SiO_2	59.57	60.96	63.55	59.45	57.32	57.69	67.14	65.70	66.54	66.85	66.19
TiO_2	0.82	1.66	0.87	0.87	1.74	0.92	0.69	0.76	0.71	0.68	0.77
Al_2O_3	18.91	15.20	16.84	17.92	17.36	18.51	14.78	15.47	15.00	14.85	15.64
Fe_2O_3	1.44	1.83	0.86	1.90	1.34	1.60	1.31	0.97	1.57	1.54	1.35
FeO	4.36	5.94	4.36	4.87	6.29	5.60	3.24	4.15	3.82	3.23	4.28
MnO	0.08	0.14	0.10	0.10	0.12	0.11	0.07	0.11	0.07	0.07	0.09
MgO	2.63	2.43	2.08	2.61	2.19	2.97	1.89	2.12	2.10	1.97	2.00
CaO	4.23	2.86	3.67	2.11	3.14	1.60	1.55	2.97	1.48	1.06	1.83
Na_2O	4.21	2.67	3.31	2.59	3.47	2.57	3.21	3.33	2.30	2.83	3.50
K_2O	2.43	2.87	2.42	4.81	3.56	4.95	2.98	2.43	4.23	4.50	3.33
P_2O_5	0.40	0.30	0.23	0.50	0.78	0.18	0.17	0.22	0.15	0.15	0.18
L.O.I.	0.75	1.16	0.69	1.42	1.84	1.75	1.58	0.70	1.04	1.13	0.88
Total	100.30	98.67	99.45	99.68	99.15	99.06	98.97	99.39	99.44	99.21	100.52
Ba	616	669	755	1095	740	1454	837	515	1052	1091	710
Cr	47	77	55	54	83	65	46	52	46	43	53
Nb	16	22	14	14	24	13	13	15	15	17	16
Ni	27	22	33	30	30	46	30	33	26	26	27
Rb	129	138	120	184	160	191	88	125	142	127	123
Sr	465	392	372	249	350	302	288	307	272	243	303
Y	27	59	24	31	84	32	31	27	16	23	25
Zr	197	988	245	203	880	125	217	220	214	213	226

Sample No.	46a	81	401	1Ab	54	231	233	234	236	442	454
SiO_2	68.37	66.52	66.34	74.63	78.93	56.56	54.53	60.77	62.15	56.26	60.42
TiO_2	0.61	0.71	0.67	0.40	0.67	1.07	0.95	0.83	0.85	1.03	0.96
Al_2O_3	14.21	14.95	15.73	11.87	9.56	20.58	21.52	17.48	16.47	20.29	19.66
Fe_2O_3	1.36	1.34	1.56	0.50	1.07	1.65	1.56	0.98	0.70	2.16	1.49
FeO	3.37	3.92	3.90	2.68	2.17	5.85	4.92	4.52	5.41	4.92	4.09
MnO	0.07	0.09	0.07	0.04	0.10	0.14	0.10	0.13	0.10	0.08	0.04
MgO	1.97	2.10	1.68	1.25	1.30	2.68	2.74	2.49	1.64	2.08	1.66
CaO	1.44	1.50	1.50	1.31	2.96	1.71	1.90	2.73	2.50	0.73	0.48
Na_2O	2.60	3.09	3.17	3.09	1.40	1.88	2.75	3.41	3.91	0.95	1.51
K_2O	3.00	4.19	3.70	2.54	1.79	5.12	5.22	3.27	2.76	6.45	6.76
P_2O_5	0.17	0.16	0.15	0.10	0.09	0.34	0.45	0.39	0.21	0.41	0.13
L.O.I.	1.27	1.06	1.14	0.69	0.95	1.88	1.92	0.95	0.71	2.97	2.10
Total	98.82	100.06	100.04	99.40	101.22	100.11	99.12	98.44	98.02	98.85	99.74
Ba	834	991	975	525	478	1542	1639	770	418	1764	1564
Cr	45	41	51	26	33	71	77	57	63	79	68
Nb	13	13	16	14	21	17	16	15	15	16	16
Ni	33	29	31	18	14	46	58	26	32	15	25
Rb	110	137	151	86	95	177	201	156	138	201	216
Sr	272	293	319	256	273	220	359	390	337	86	113
Y	25	27	22	15	18	47	38	30	37	38	46
Zr	158	206	131	134	295	191	132	195	259	174	346

Table B2 : Analyses of aluminosilicate-bearing semi-pelites

Sample No.	225	229	628	642	644	501
SiO_2	52.51	52.45	53.65	51.24	49.38	60.12
TiO_2	1.15	1.26	1.41	1.20	1.37	0.95
Al_2O_3	21.53	23.49	23.81	23.77	25.97	18.36
Fe_2O_3	1.74	1.71	1.37	1.52	1.40	1.19
FeO	7.11	5.70	4.83	5.96	5.57	5.17
MnO	0.16	0.11	0.00	0.15	0.13	0.09
MgO	3.06	2.88	1.82	2.54	2.69	2.23
CaO	1.43	1.23	0.68	1.55	1.86	1.94
Na_2O	1.63	2.73	3.28	4.30	2.54	2.51
K_2O	5.54	5.45	7.41	5.26	6.09	3.62
P_2O_5	0.39	0.11	0.22	0.29	0.33	0.31
LOI.	2.01	2.13	1.03	0.95	1.43	2.39
Total	99.04	99.87	100.13	99.40	99.37	98.89
ppm						
Ba	1775	1709	2120	1799	2179	1133
Cr	81	68	103	84	87	70
Nb	16	20	20	22	17	15
Ni	61	35	27	62	51	47
Rb	207	184	185	215	206	142
Sr	268	410	118	376	263	250
Y	43	48	59	52	58	39
Zr	131	243	352	194	218	195

Table B.3. Analyses of Calc-silicate rocks

Sample No.	3A	103A	830	832	147	269	353	362	276	363	365
SiO_2	72.98	60.95	69.35	61.26	71.79	65/18	68.62	60.07	63.68	69.26	74.37
TiO_2	0.41	0.77	0.53	0.86	0.60	0.78	0.65	0.75	0.62	0.89	0.72
Al_2O_3	12.39	18.09	12.99	15.28	12.96	15.76	14.22	16.97	15.41	12.82	10.28
Fe_2O_3	1.78	2.16	0.45	1.60	1.49	1.62	1.21	1.50	2.65	1.34	1.56
FeO	0.80	2.09	1.76	3.78	1.81	2.55	2.49	3.99	1.52	2.65	2.35
MnO	0.22	0.31	0.37	0.50	0.21	0.20	0.35	0.54	0.39	0.36	0.30
MgO	1.17	1.37	1.27	2.03	1.29	1.43	1.04	2.11	1.23	1.03	0.86
CaO	8.69	9.48	9.16	11.30	5.53	8.22	8.52	9.29	12.66	8.45	8.09
Na_2O	0.80	0.96	0.85	1.10	1.38	1.71	1.10	1.24	0.45	0.49	0.39
K_2O	0.36	2.06	0.43	0.62	1.51	0.88	0.44	1.30	0.28	1.05	0.49
P_2O_5	0.18	0.43	0.16	0.35	0.15	0.27	0.17	0.31	0.23	0.38	0.15
L.O.I.	1.03	1.62	1.53	1.69	1.23	1.42	0.78	1.36	1.28	1.21	0.71
Total	100.90	100.50	99.04	100.79	100.15	100.12	99.74	99.86	100.58	100.21	100.53
CaO/Al_2O_3	0.79	0.52	0.71	0.74	0.43	0.52	0.60	0.55	0.82	0.66	0.79

Sample No.	14a	16a	120a	63a	27a	47a	50a	424	462	526	331
SiO_2	68.60	66.16	66.65	61.07	76.42	75.38	62.63	62.54	65.05	75.87	67.05
TiO_2	0.56	0.88	0.68	0.78	0.54	0.59	0.89	0.83	0.61	0.44	0.94
Al_2O_3	12.84	15.72	13.71	17.33	11.15	11.10	17.06	15.32	16.40	11.71	13.48
Fe_2O_3	1.32	1.58	2.29	2.16	1.27	1.76	1.02	2.85	1.17	0.96	1.85
FeO	3.52	2.01	1.98	1.82	1.39	1.82	3.62	2.67	2.16	1.61	2.5
MnO	1.08	0.30	0.45	0.31	0.07	0.20	0.43	0.21	0.46	0.17	0.27
MgO	1.41	1.26	1.98	1.21	0.78	0.86	1.32	1.60	0.90	0.69	1.55
CaO	7.25	6.99	10.40	8.37	4.17	4.65	5.64	8.83	8.94	3.49	6.18
Na_2O	1.21	0.98	0.46	2.16	2.36	1.51	1.06	1.21	0.94	2.13	1.36
K_2O	0.84	1.71	0.44	2.14	1.02	1.38	2.89	1.23	1.41	1.54	1.39
P_2O_5	0.31	0.40	0.20	0.57	0.10	0.17	0.75	0.27	0.32	0.13	0.23
L.O.I.	0.65	1.85	0.91	1.99	0.79	0.97	1.61	1.44	1.34	0.76	1.29
Total	99.99	100.07	100.38	100.11	100.21	100.57	99.30	99.29	99.93	99.67	98.36
CaO/Al_2O_3	0.56	0.44	0.76	0.48	0.37	0.42	0.33	0.58	0.55	0.30	0.46

Sample No.	561	803	808	557	563	566	573	601	603	655	661
SiO_2	59.56	70.09	66.30	61.26	71.95	65.54	62.14	63.30	61.48	67.09	65.94
TiO_2	0.73	0.66	0.56	0.75	0.55	0.82	0.73	0.59	1.02	0.60	0.72
Al_2O_3	17.05	12.73	14.15	16.70	12.25	14.80	15.90	17.14	16.97	14.85	15.80
Fe_2O_3	4.21	1.87	3.80	2.01	2.17	2.33	1.97	1.09	1.13	2.31	2.53
FeO	1.68	1.55	1.70	2.98	1.54	1.93	3.17	2.97	3.78	2.19	2.39
MnO	0.50	0.27	0.21	0.31	0.19	0.29	0.48	0.19	0.26	0.16	0.20
MgO	1.58	1.62	1.58	2.19	0.91	1.59	1.97	2.09	1.89	1.91	1.97
CaO	10.28	8.17	6.01	9.74	7.88	8.70	11.07	5.29	5.80	6.14	6.59
Na_2O	2.32	0.86	0.75	1.09	0.68	1.09	0.74	1.38	1.15	2.81	1.31
K_2O	1.21	0.76	2.14	1.02	0.31	1.08	0.67	2.68	2.66	0.77	1.34
P_2O_5	0.29	0.33	0.30	0.39	0.19	0.29	0.47	0.25	0.50	0.24	0.26
L.O.I.	1.42	1.02	2.34	1.49	0.62	1.35	1.07	2.25	2.31	0.61	1.33
Total	101.02	100.10	100.01	100.26	99.41	100.02	100.73	99.54	99.38	99.93	100.64
CaO/Al_2O_3	0.60	0.64	0.42	0.58	0.64	0.59	0.70	0.31	0.34	0.41	0.42

Sample No.	684	748	764	765	769	367	398	414	422	456	457
SiO_2	70.15	66.47	65.98	65.12	64.42	63.70	61.88	65.13	79.71	68.21	66.31
TiO_2	0.69	0.63	0.56	0.65	0.70	0.57	0.64	0.67	0.50	0.60	0.93
Al_2O_3	13.24	14.55	15.51	14.72	14.99	16.63	16.94	15.96	9.58	15.34	13.28
Fe_2O_3	1.93	2.62	2.75	1.32	3.33	1.73	2.26	1.29	0.80	1.22	2.5
FeO	2.03	1.54	1.25	2.71	0.98	2.21	2.63	3.07	1.67	1.45	2.15
MnO	0.11	0.31	0.20	0.33	0.25	0.27	0.25	0.39	0.11	0.40	0.48
MgO	1.52	1.20	1.69	1.23	1.75	1.94	1.85	1.37	0.77	1.24	1.03
CaO	3.88	8.76	9.00	9.95	9.75	9.19	8.40	10.04	4.75	8.19	11.05
Na_2O	2.50	1.55	0.94	0.80	2.42	1.80	1.22	0.58	0.81	0.98	0.29
K_2O	1.61	0.95	1.16	0.91	0.46	0.70	1.62	0.65	0.50	1.01	0.52
P_2O_5	0.18	0.22	0.20	0.33	0.31	0.32	0.24	0.26	0.09	0.21	0.29
L.O.I.	0.97	1.88	1.36	1.47	1.05	0.98	1.81	0.85	0.61	1.18	1.03
Total	99.03	100.85	100.73	99.84	100.52	100.28	100.03	100.59	100.09	100.19	100.09
CaO/Al_2O_3	0.29	0.60	0.58	0.68	0.65	0.55	0.50	0.63	0.50	0.53	0.83

Sample No.	458	556	433	435	447	381	392	420	453	773
SiO_2	60.23	69.16	64.06	64.68	77.13	64.19	66.41	74.93	70.61	65.46
TiO_2	1.03	0.80	0.64	0.96	0.46	0.73	0.66	0.46	0.45	0.67
Al_2O_3	16.34	14.05	16.62	15.02	9.79	15.91	16.90	12.33	13.71	16.61
Fe_2O_3	3.89	1.22	0.85	1.62	0.59	1.54	1.51	0.60	1.26	0.83
FeO	2.23	2.78	4.07	3.34	1.98	2.89	1.64	1.48	2.10	3.46
MnO	0.38	0.24	0.42	0.30	0.19	0.26	0.25	0.16	0.28	0.32
MgO	2.38	1.81	1.47	1.40	1.22	1.19	1.73	0.61	1.25	2.12
CaO	11.54	7.17	9.12	10.09	4.88	8.84	8.23	6.53	6.05	9.13
Na_2O	0.37	1.05	0.68	1.03	0.99	1.23	1.64	1.21	1.11	0.60
K_2O	1.07	1.09	0.81	0.44	0.90	0.76	0.79	0.36	1.44	0.65
P_2O_5	0.38	0.24	0.18	0.24	0.08	0.27	0.20	0.08	0.19	0.20
L.O.I.	1.15	0.96	0.71	0.83	0.91	1.07	0.99	0.78	1.18	0.88
Total	101.25	100.875	100.07	100.31	99.35	99.21	101.13	99.69	99.84	101.31
CaO/Al_2O_3	0.71	0.51	0.55	0.67	0.50	0.56	0.49	0.53	0.44	0.55

APPENDIX C: SAMPLE LOCATIONS

Table C 1 : Metasediments

Sample No.	Grid Reference	Rock Type	Formation
492	NN 488949	semi-pelite	Chathalain
716	NN 489948	semi-pelite	Chathalain
213	NN 492940	semi-pelite	Chathalain
621	NN 496942	semi-pelite	Chathalain
8221	NN 477945	semi-pelite	Chathalain
487	NN 490946	semi-psammite	Chathalain
490	NN 489948	semi-psammite	Chathalain
617	NN 496942	semi-psammite	Chathalain
74	NN 490945	psammite	Chathalain
204	NN 491942	psammite	Chathalain
214	NN 492940	psammite	Chathalain
493	NN 48895)	psammite	Chathalain
619	NN 497942	psammite	Chathalain
6	NN 520941	semi-pelite	Garva
30	NN 513944	semi-pelite	Garva
102	NN 482026	semi-pelite	Garva
247	NN 488928	semi-pelite	Garva
248	NN 488927	semi-pelite	Garva
249	NN 485928	semi-pelite	Garva
252	NN 488926	semi-pelite	Garva
310	NN 493929	semi-pelite	Garva
311	NN 493929	semi-pelite	Garva
1	NN 519940	semi-pelite	Garva
720	NN 522947	semi-pelite	Garva
31	NN 508940	semi-psammite	Garva
101	NN 481927	semi-psammite	Garva
103	NN 482926	semi-psammite	Garva
115	NN 518939	semi-psammite	Garva
130	NN 521941	semi-psammite	Garva
245	NN 491930	semi-psammite	Garva
312	NN 494929	semi-psammite	Garva
505a	NN 467926	semi-psammite	Garva
690	NN 522947	semi-psammite	Garva
718	NN 517946	semi-psammite	Garva
2	NN 518939	psammite	Garva
3	NN 519939	psammite	Garva
76	NN 512946	psammite	Garva
313	NN 494928	psammite	Garva
703	NN 499928	psammite	Garva
11	NN 520935	semi-pelite	Coire nan Laogh
36	NN 519938	semi-pelite	Coire nan Laogh
104	NN 482925	semi-pelite	Coire nan Laogh
131	NN 521940	semi-pelite	Coire nan Laogh
132	NN 520939	semi-pelite	Coire nan Laogh
133b	NN 520939	semi-pelite	Coire nan Laogh
135	NN 519939	semi-pelite	Coire nan Laogh
253	NN 486926	semi-pelite	Coire nan Laogh
315	NN 495928	semi-pelite	Coire nan Laogh
317	NN 495927	semi-pelite	Coire nan Laogh
318	NN 496927	semi-pelite	Coire nan Laogh
506	NN 467926	semi-pelite	Coire nan Laogh

Sample No.	Grid Reference	Rock Type	Formation
704	NN 499928	semi-pelite	Coire nan Laogh
711	NN 499927	semi-pelite	Coire nan Laogh
321	NN 498926	semi-psammite	Coire nan Laogh
319	NN 497927	semi-psammite	Coire nan Laogh
320	NN 498926	semi-psammite	Coire nan Laogh
316	NN 495927	semi-psammite	Coire nan Laogh
710	NN 499927	semi-psammite	Coire nan Laogh
44	NN 524939	psammite	Coire nan Laogh
40a	NN 526934	semi-pelite	Transitional
38	NN 529935	semi-psammite	Transitional
40b	NN 526934	semi-psammite	Transitional
41	NN 525934	semi-psammite	Transitional
35	NN 531938	psammite	Transitional
56	NN 523919	semi-pelite	Glendoe
63b	NN 529914	semi-pelite	Glendoe
20b	NN 528928	semi-pelite	Glendoe
49	NN 536922	semi-pelite	Glendoe
50b	NN 535922	semi-pelite	Glendoe
59b	NN 538918	semi-pelite	Glendoe
85	NN 516908	semi-pelite	Glendoe
158	NN 508888	semi-pelite	Glendoe
62	NN 529915	semi-psammite	Glendoe
17b	NN 541927	semi-psammite	Glendoe
24	NN 523919	semi-psammite	Glendoe
26	NN 517912	semi-psammite	Glendoe
45	NN 539924	semi-psammite	Glendoe
46a	NN 538923	semi-psammite	Glendoe
81	NN 535907	semi-psammite	Glendoe
401	NN 451858	semi-psammite	Glendoe
14b	NN 518927	psammite	Glendoe
52	NN 534920	psammite	Glendoe
231	NN 433911	semi-pelite	Monadhliath
233	NN 432911	semi-pelite	Monadhliath
234	NN 434912	semi-pelite	Monadhliath
236	NN 434913	semi-pelite	Monadhliath
442	NN 443898	semi-pelite	Monadhliath
454	NN 437878	semi-pelite	Monadhliath
630b	NN 436913	semi-pelite	Monadhliath
227	NN 432913	semi-psammite	Monadhliath
450	NN 438876	semi-psammite	Monadhliath
452	NN 438877	semi-psammite	Monadhliath
645	NN 437916	semi-psammite	Monadhliath
627	NN 435914	psammite	Monadhliath
630a	NN 436913	psammite	Monadhliath
646	NN 437917	psammite	Monadhliath

Table C2: Aluminosilicate-bearing semi-pelites from the contact aureole.

Sample No	Grid Reference	Formation
225	NN 431913	Monadhliath
229	NN 433912	Monadhliath
638	NN 435914	Monadhliath
642	NN 439913	Monadhliath
644	NN 438916	Monadhliath
501	NN 466928	Coire nan Laogh

Table C3. Calc-silicates

Sample No	Grid Reference	Formation
3A	NN 519938	Coire nan Laogh
103A	NN 482926	Coire nan Laogh
830	NN 512926	Transitional
832	NN 499924	Transitional
147	NN 500891	Glendoe
269	NN 457876	Glendoe
353	NN 485906	Glendoe
362	NN 481886	Glendoe
276	NN 518927	Glendoe
363	NN 482887	Glendoe
365	NN 482889	Glendoe
14A	NN 518927	Glendoe
16A	NN 513926	Glendoe
20A	NN 528928	Glendoe
63A	NN 529914	Glendoe
27A	NN 519912	Glendoe
47A	NN 537922	Glendoe
50A	NN 535922	Glendoe
424	NN 463902	Glendoe
462	NN 498887	Glendoe
526	NN 534924	Glendoe
331	NN 447869	Glendoe
561	NN 461868	Glendoe
803	NN 462878	Glendoe
808	NN 470865	Glendoe
557	NN 461870	Glendoe
563	NN 462870	Glendoe
566	NN 463869	Glendoe
573	NN 464869	Glendoe
601	NN 468919	Glendoe
603	NN 467919	Glendoe
655	NN 449923	Glendoe
661	NN 446921	Glendoe
684	NN 456919	Glendoe
748	NN 520918	Glendoe
764	NN 517905	Glendoe
765	NN 519904	Glendoe
769	NN 523905	Glendoe
367	NN 481892	Glendoe
398	NN 446868	Glendoe
414	NN 475894	Glendoe
422	NN 462901	Glendoe
456	NN 492887	Glendoe
457	NN 493888	Glendoe
458	NN 494888	Glendoe
556	NN 462871	Glendoe
433	NN 450896	Monadhliath
435	NN 450898	Monadhliath
447	NN 441884	Monadhliath

381	NN 443870	Monadhliath
392	NN 433872	Monadhliath
420	NN 450901	Monadhliath
453	NN 438877	Monadhliath
773	NN 444893	Monadhliath

APPENDIX D

Discriminant Function Analysis

Discriminant Function analysis of the chemistry of some of the metasediments of the Loch Laggan-Upper Strathspey area has been performed in order to test the differences between the semi-pelitic rocks of Coire nan Laogh and Monadhliath Formations, as well as to elucidate other distinguishing characteristics which may not have been picked out during the comparisons and analyses described earlier.

In particular, the problem of closure, or the constant sum of geochemical data may cause the suppression of important differences between the groups when the data are plotted on triangular diagrams or bivariate plots.

The principle of discriminant function analysis

The aim of discriminant function analysis is to find a mathematical combination of the discriminating variables in such a way as to produce as wide a separation of the groups as possible. The discriminant functions are derived in the form of the following equation:

$$Di = di_1Z_1 + di_2Z_2 + \ldots dipZp$$

where Di is the score on the discriminant function, d is the weighting coefficient, and z is the standardised value of the P discriminating variable used in the analysis.

The maximum number of functions which can be derived is either one less than the number of groups or equal to the number of discriminating variables if there are more groups than variables. The standardised discriminant function coefficients are important since they measure the relative contribution of the associated variables to the function. The sign associated with the variable indicates whether it is making a positive or a negative contribution.

Since there are many more discriminating variables (elements) than necessary to achieve a satisfactory discrimination, a step-wise procedure was used to select the most useful variables according to a certain criterion. This step-wise procedure first selects the single best-discriminating variable.

A second discriminating variable is then selected so as to best improve the value of the discriminant criterion in combination with the first variable. The third and subsequent variables are selected according to their ability to contribute to further discrimination. At each step, variables already selected may be removed if they are found to reduce discrimination when combined with more recently selected variables. Eventually all variables will have been selected, or it will be found that the remaining variables are no longer able to contribute to further discrimination. At this point, the procedure is stopped and further analysis is carried out using only the selected variables.

The Wilk's Lamda method was used as the step-wise criterion which gives the overall multivariate F ratio for the test of differences between group centroids. The variable which maximises the F ratio also minimises Wilk's Lamda, a measure of the group discrimination. This test takes into consideration the differences between the centroids and the cohesion within the groups.

As a test of the efficacy of the discriminant function, the original set of data were classified using a separate linear combination of the discriminating variables for each group. A probability of group membership is then produced which is used to assign each sample to the group with the highest probability.

More detailed discussion of discriminant function analysis is given in Davis (1973, Le Maitre (1984) and Nie et al (1975).

Discriminant analysis of the metasediments of the present study area was performed using the program from the Statistical Package for the Social Sciences (SPSS, Nie et al, 1975) available from the University of Manchester Regional Computer Centre (UMRCC).

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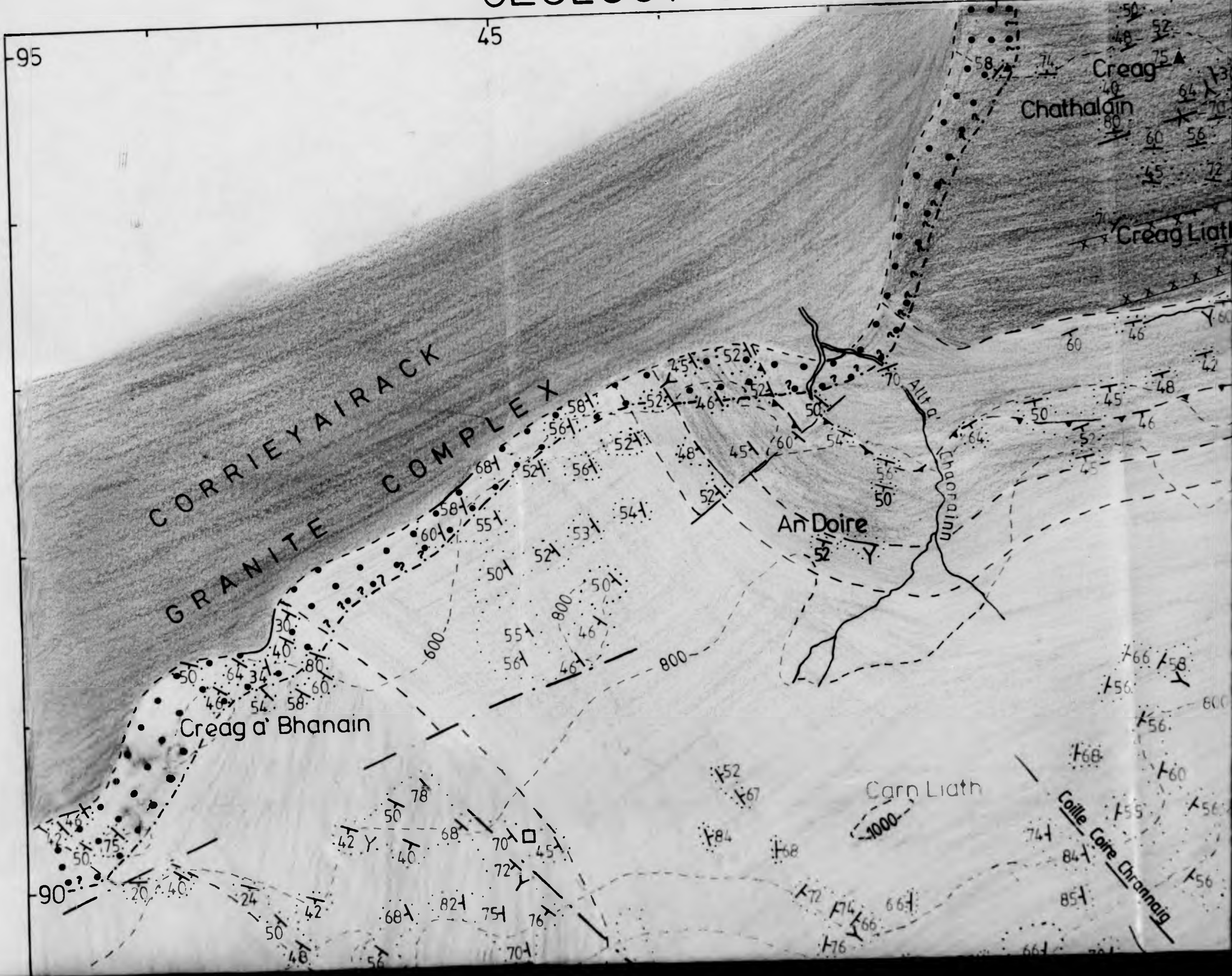
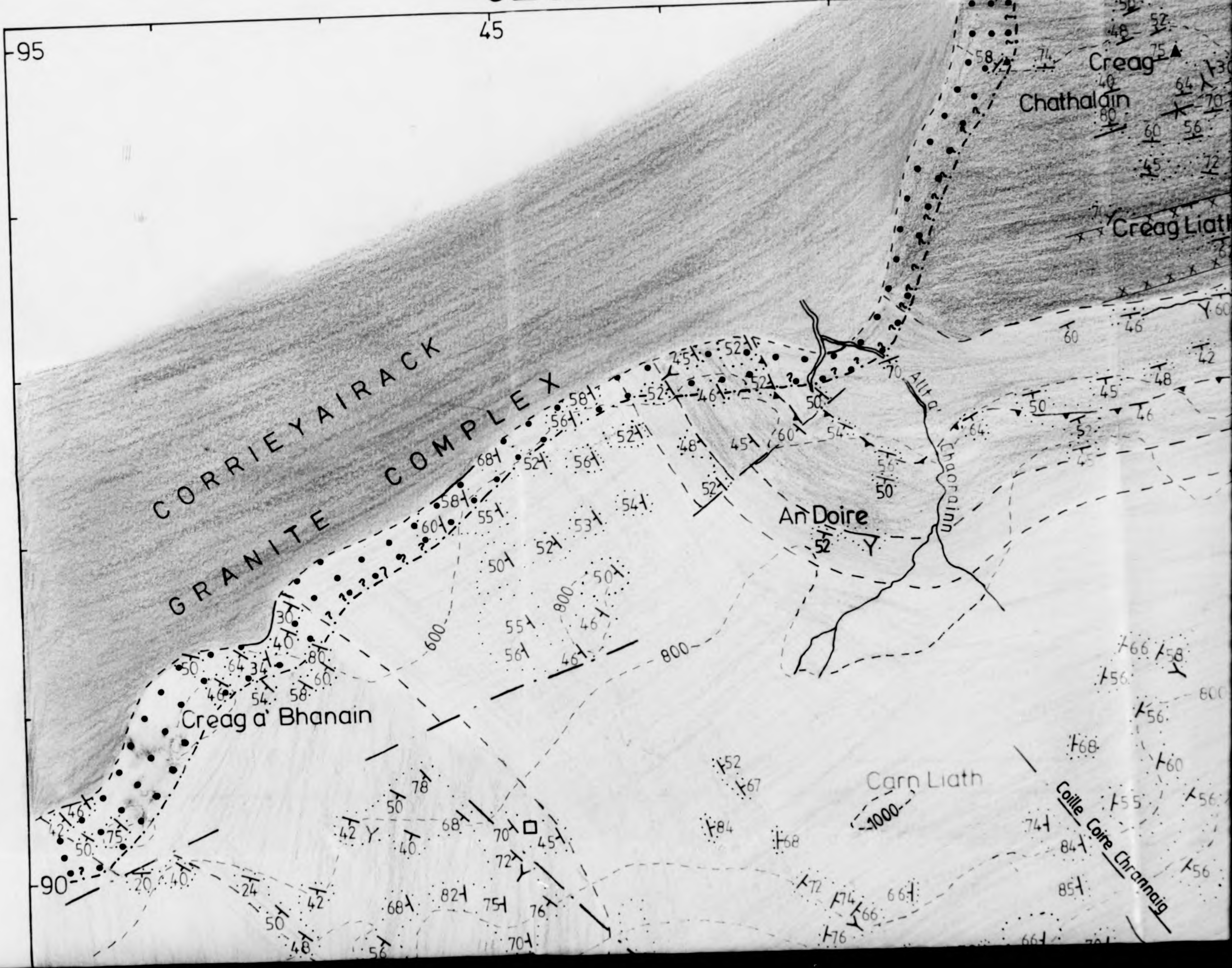
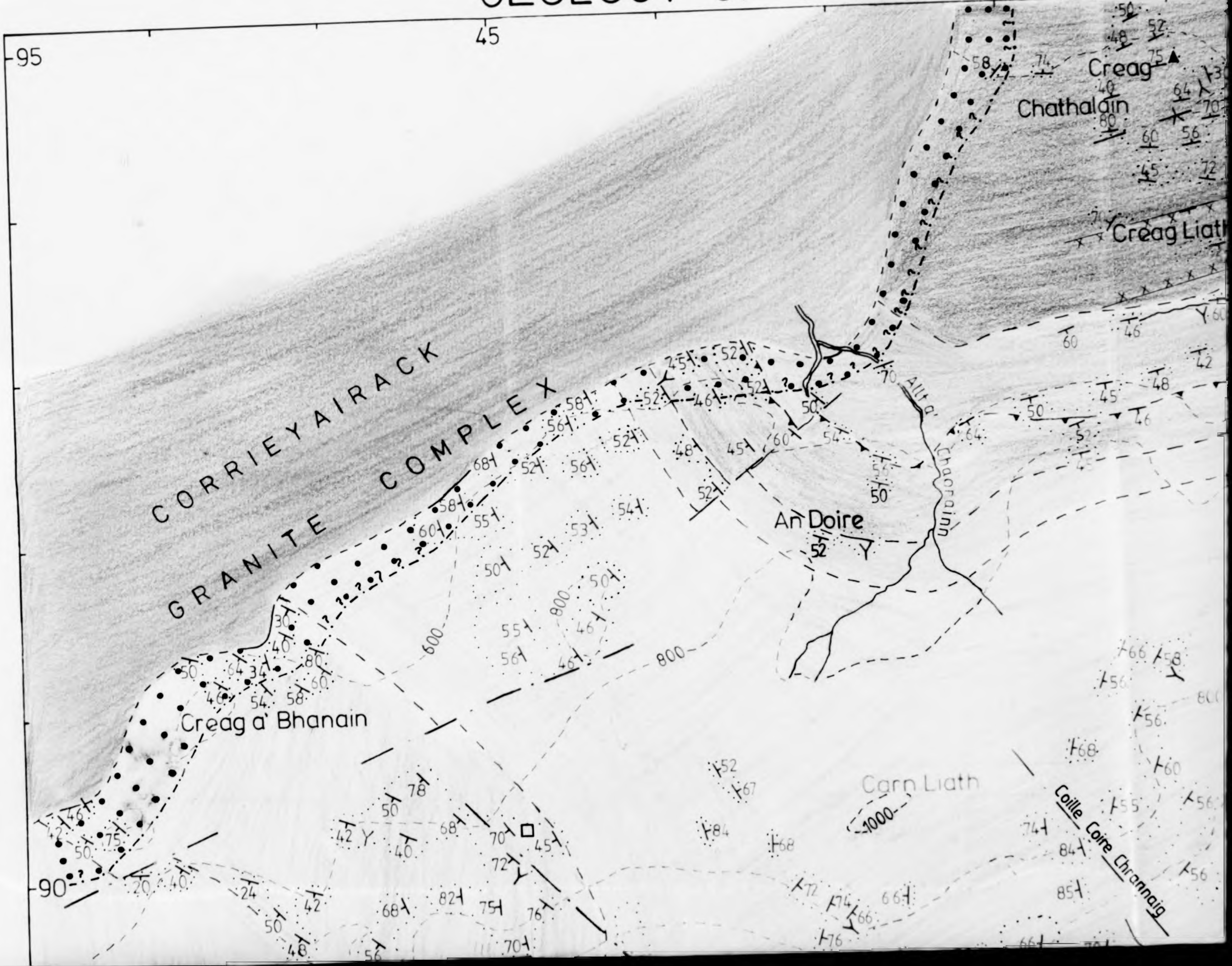
GEOLOGY OF THE LOCH LAGGAN



GEOLOGY OF THE LOCH LAGGAN



GEOLOGY OF THE LOCH LAGGAN

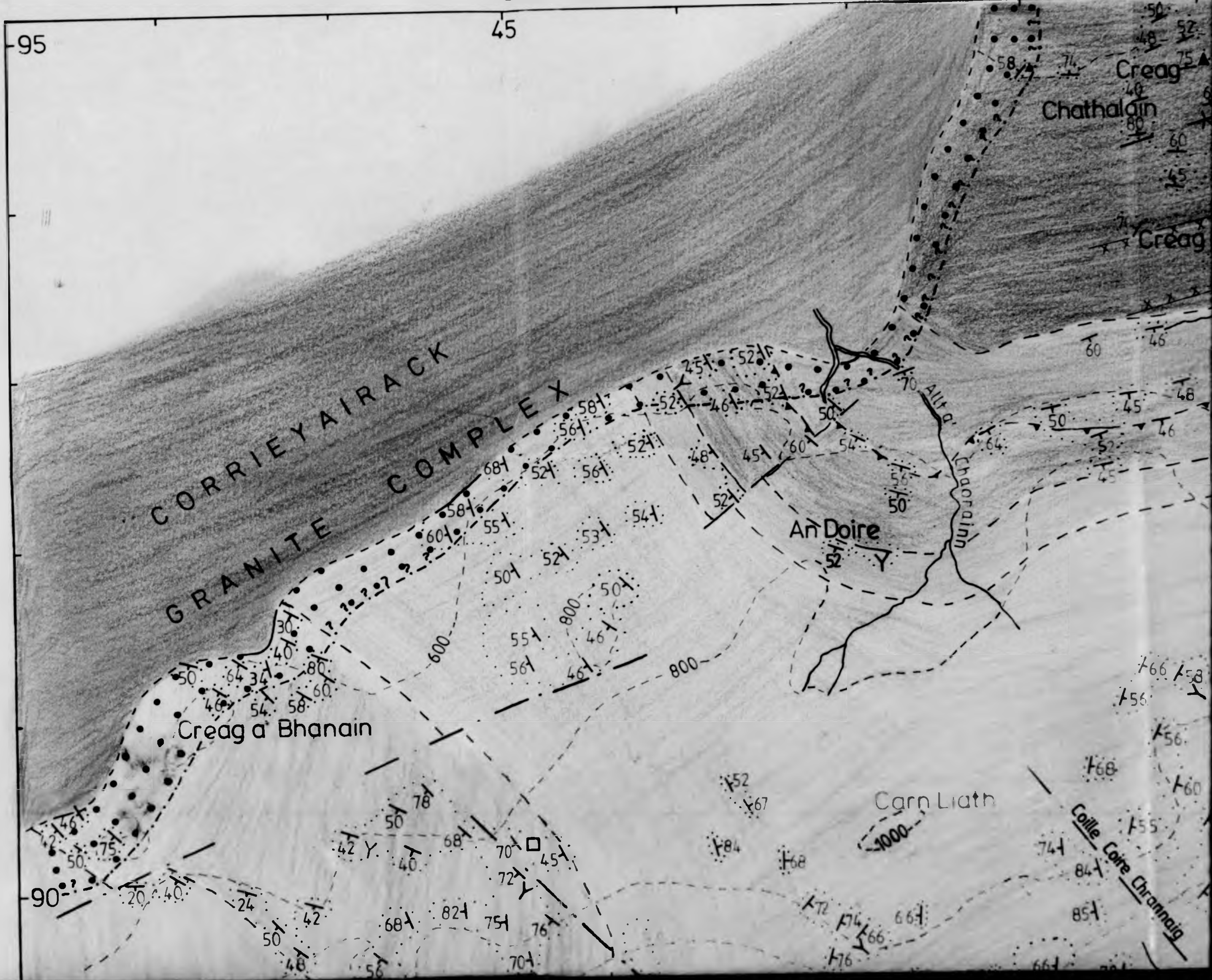


A2

EOLOGY OF THE LOCH LAGGAN-UPPER STRATHSPEY AREA

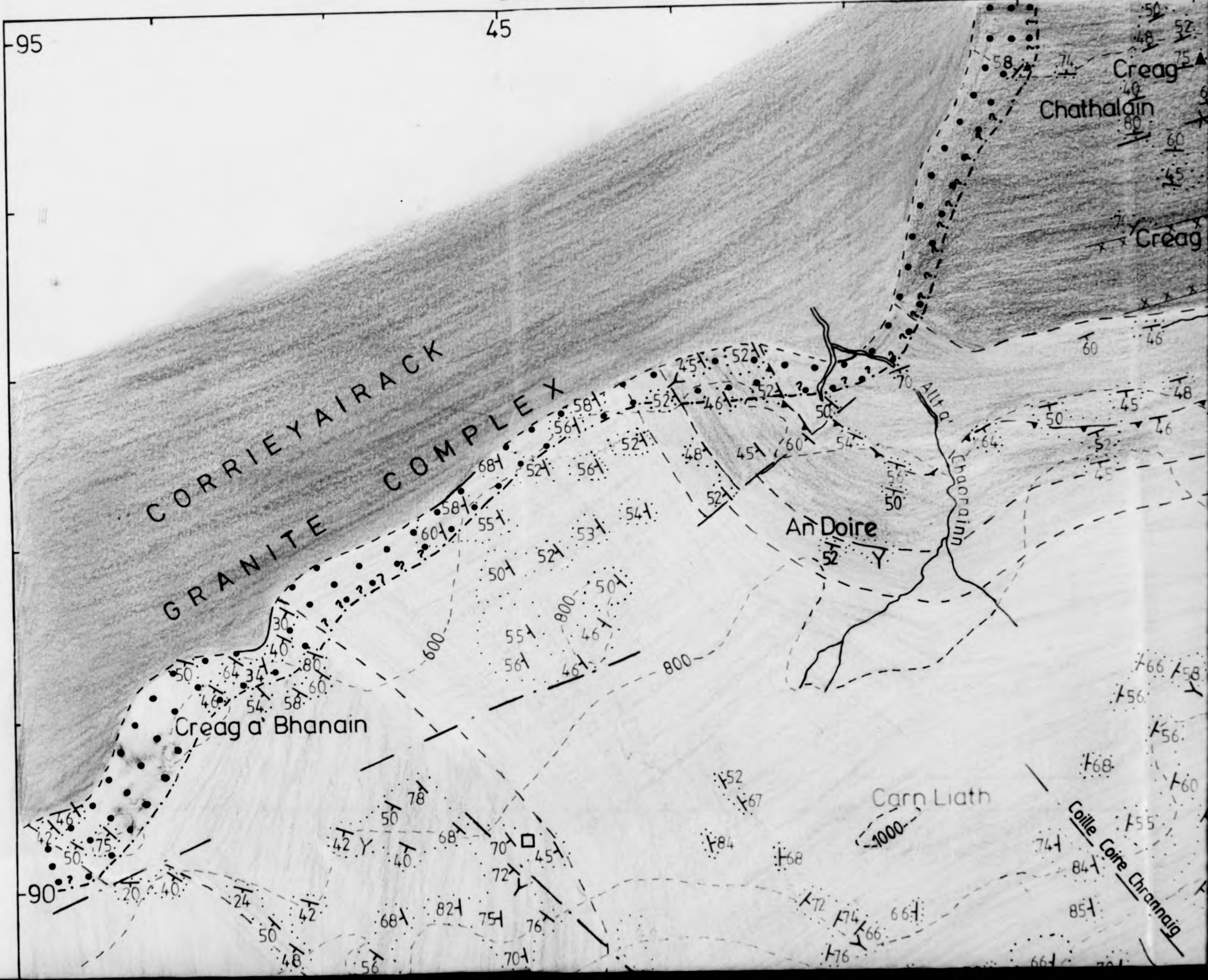
A1

GEOLOGY OF THE LOCH LAGG



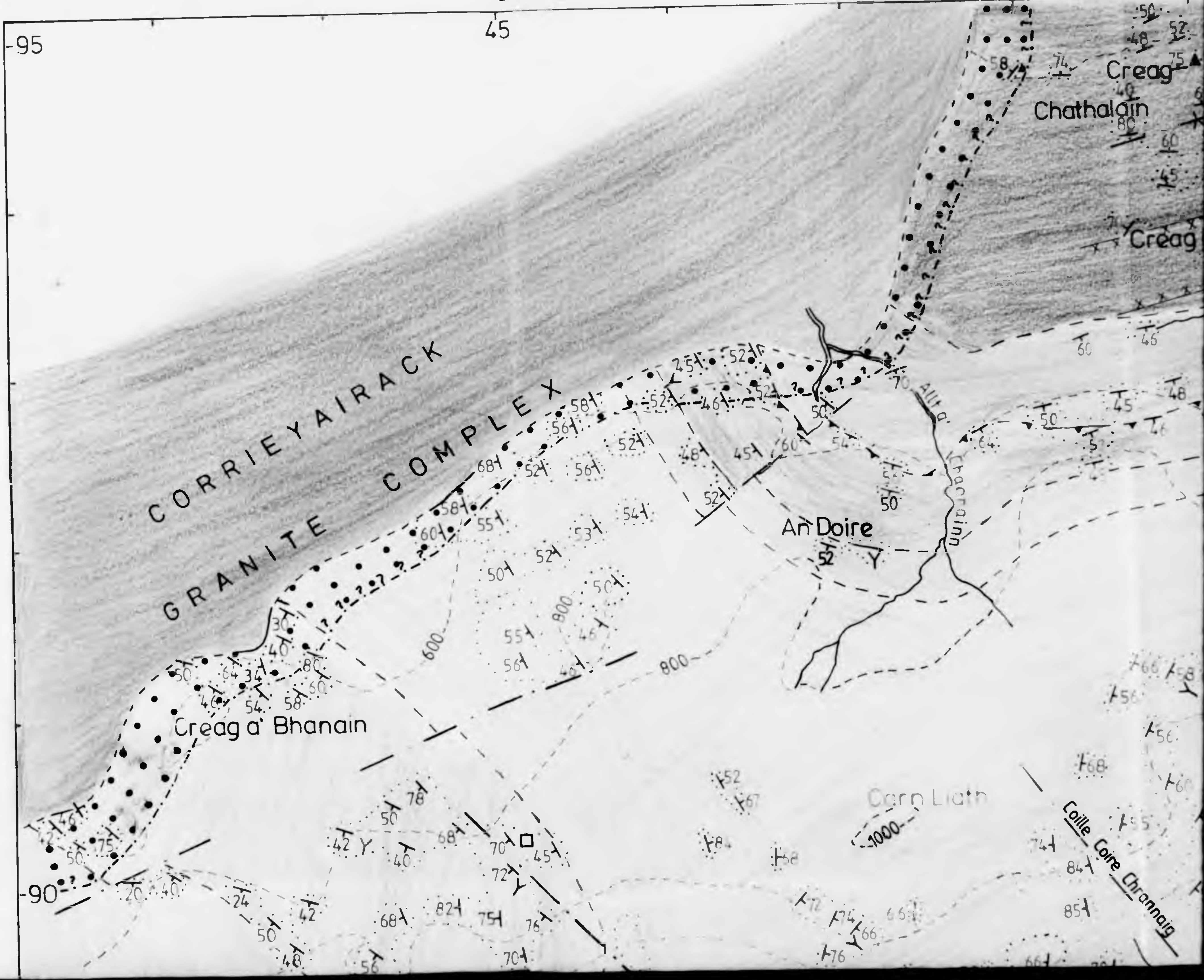
A1

GEOLOGY OF THE LOCH LAGGA



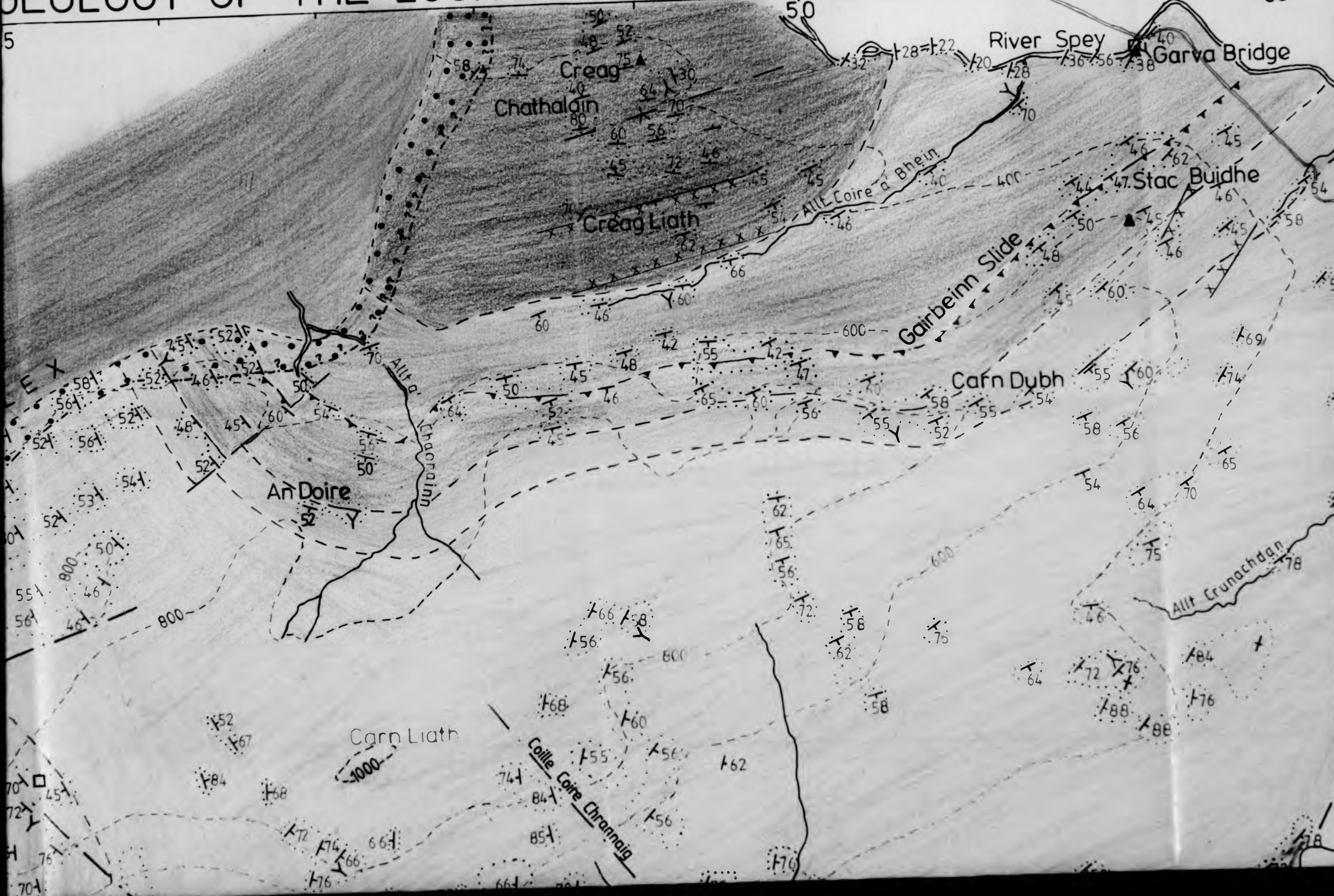
A1

GEOLOGY OF THE LOCH LAGGA



A2

GEOLOGY OF THE LOCH LAGGAN–UPPER STRATHSPEY AREA

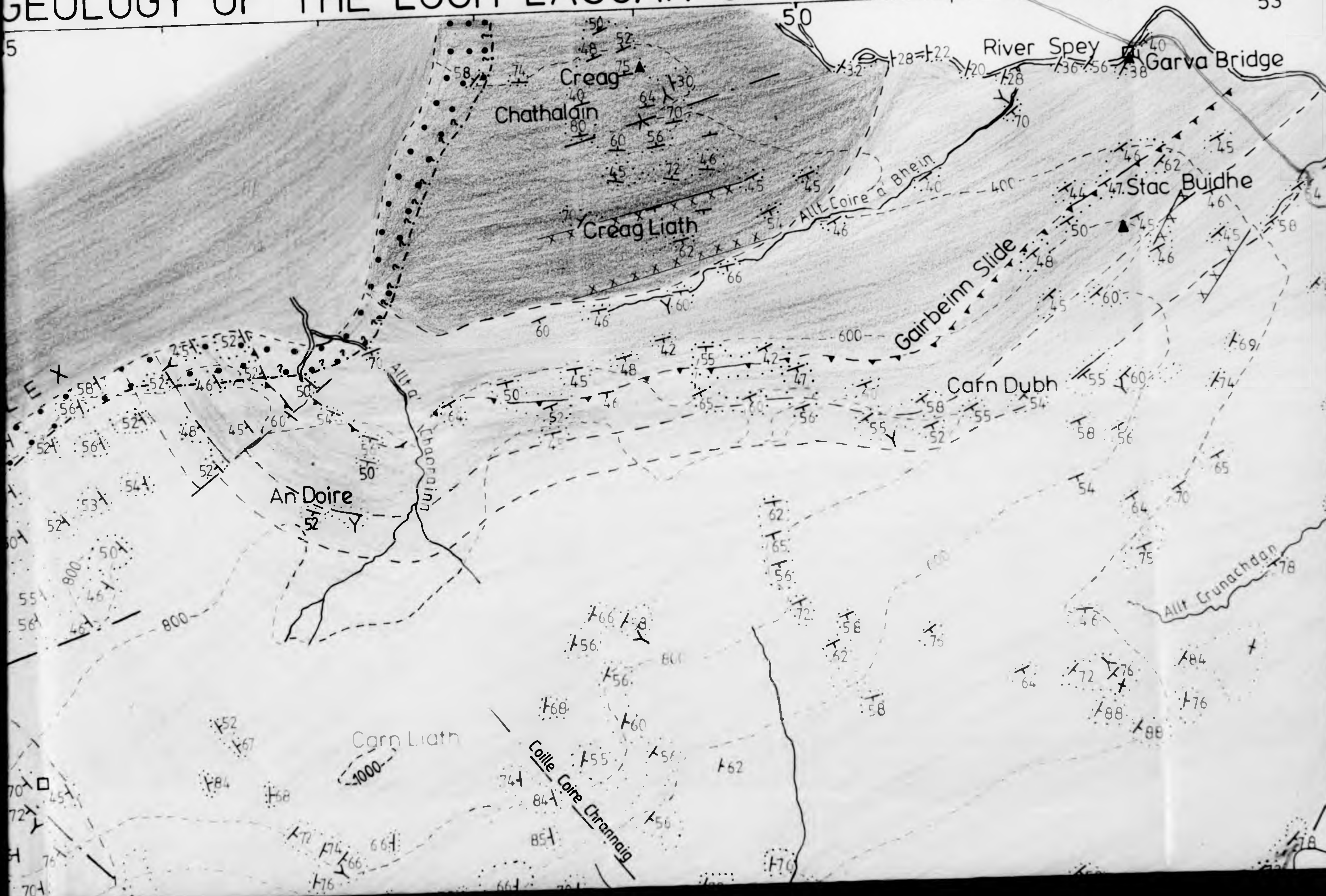


A2

GEOLOGY OF THE LOCH LAGGAN-UPPER STRATHSPEY AREA

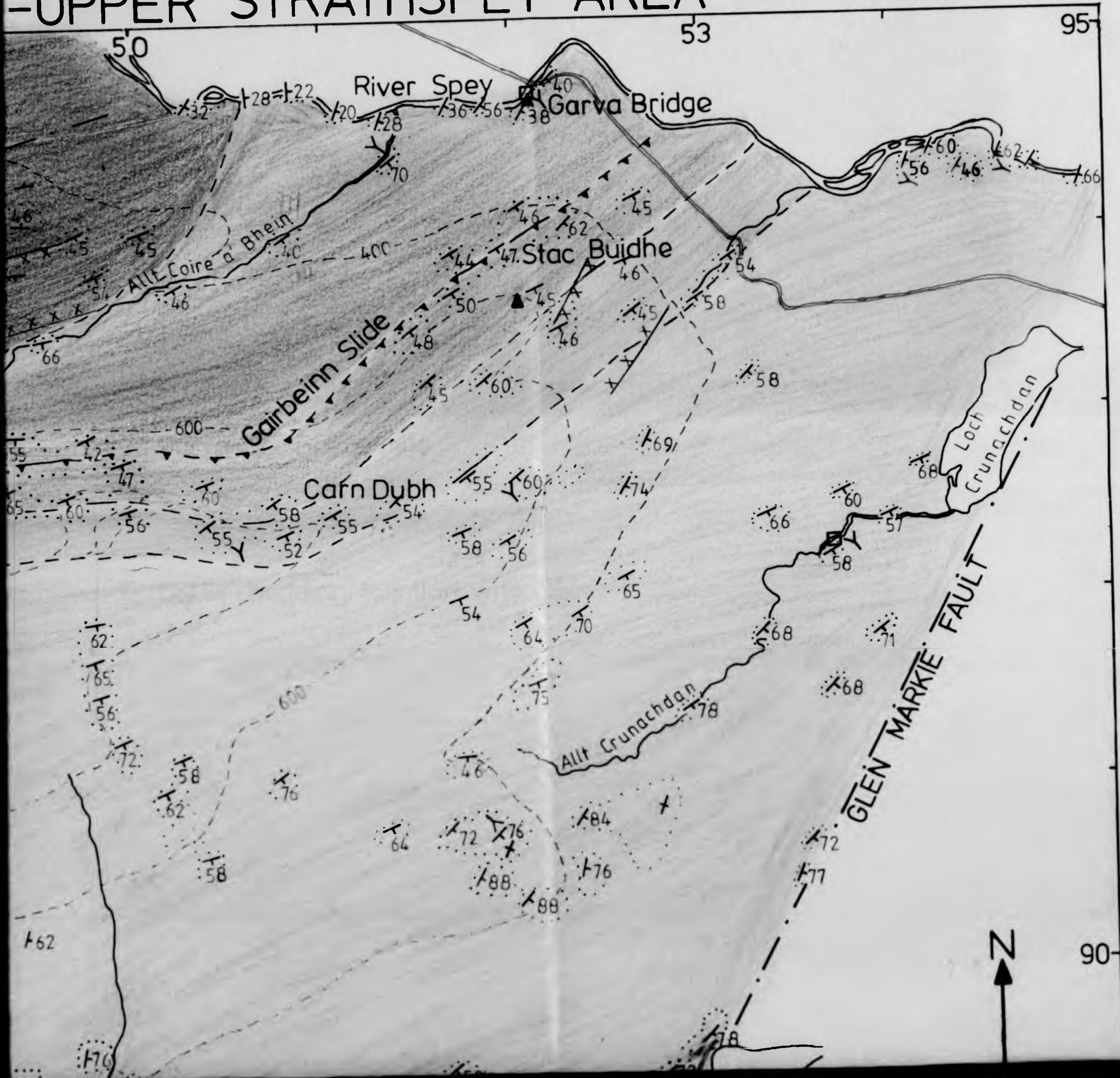
A2

GEOLOGY OF THE LOCH LAGGAN-UPPER STRATHSPEY AREA



A3

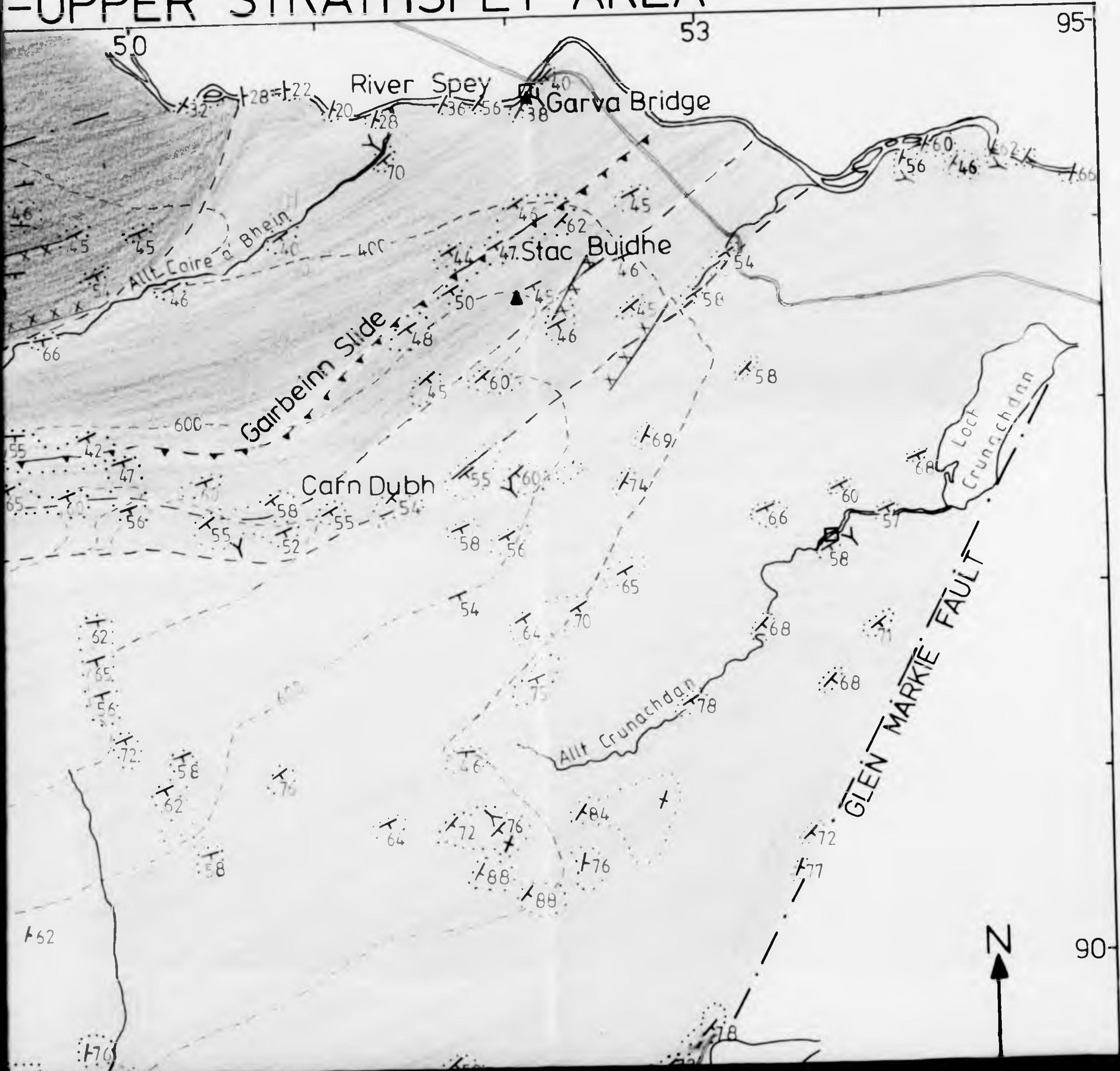
-UPPER STRATHSPEY AREA



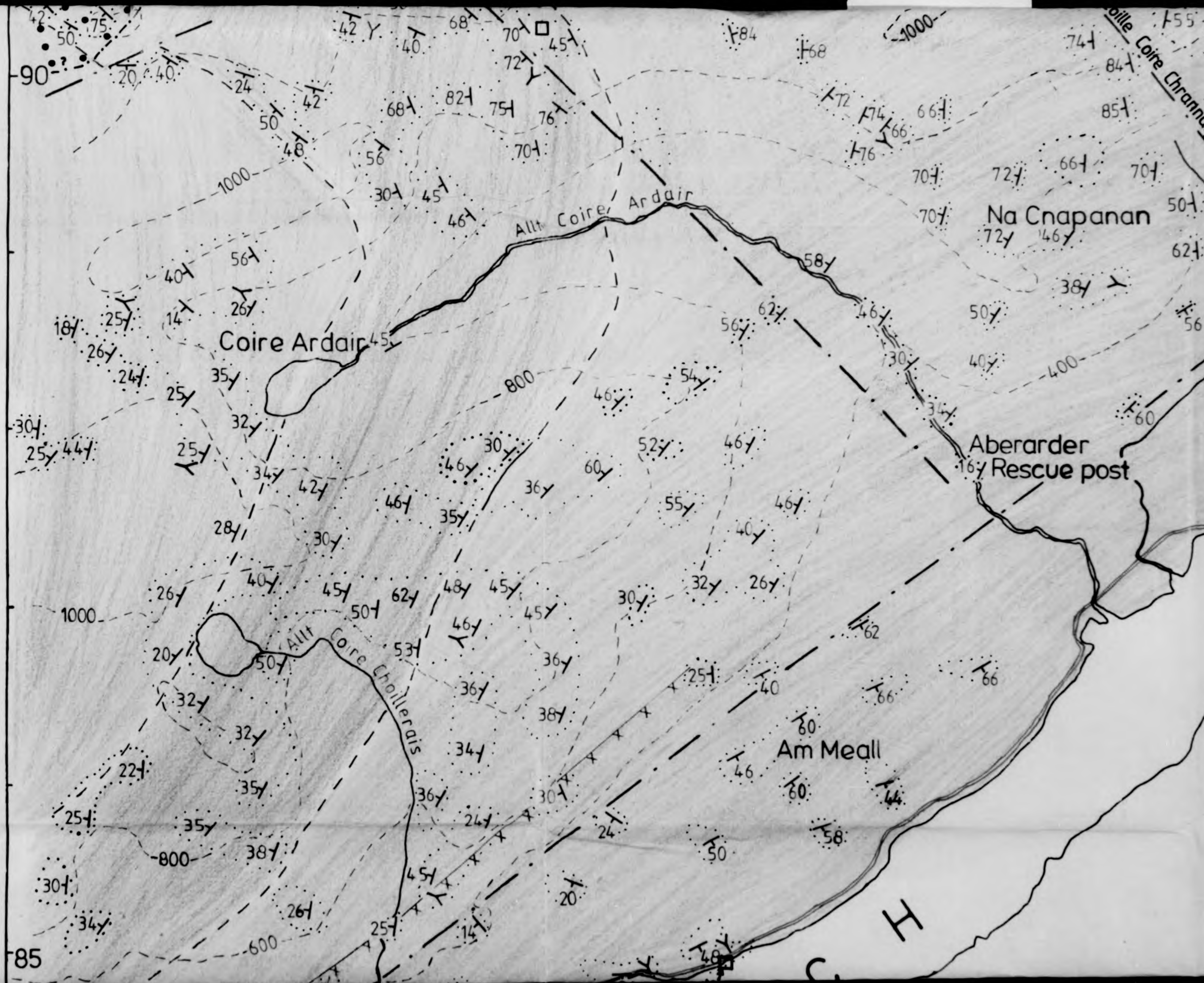
A3

-UPPER STRATHSPEY AREA

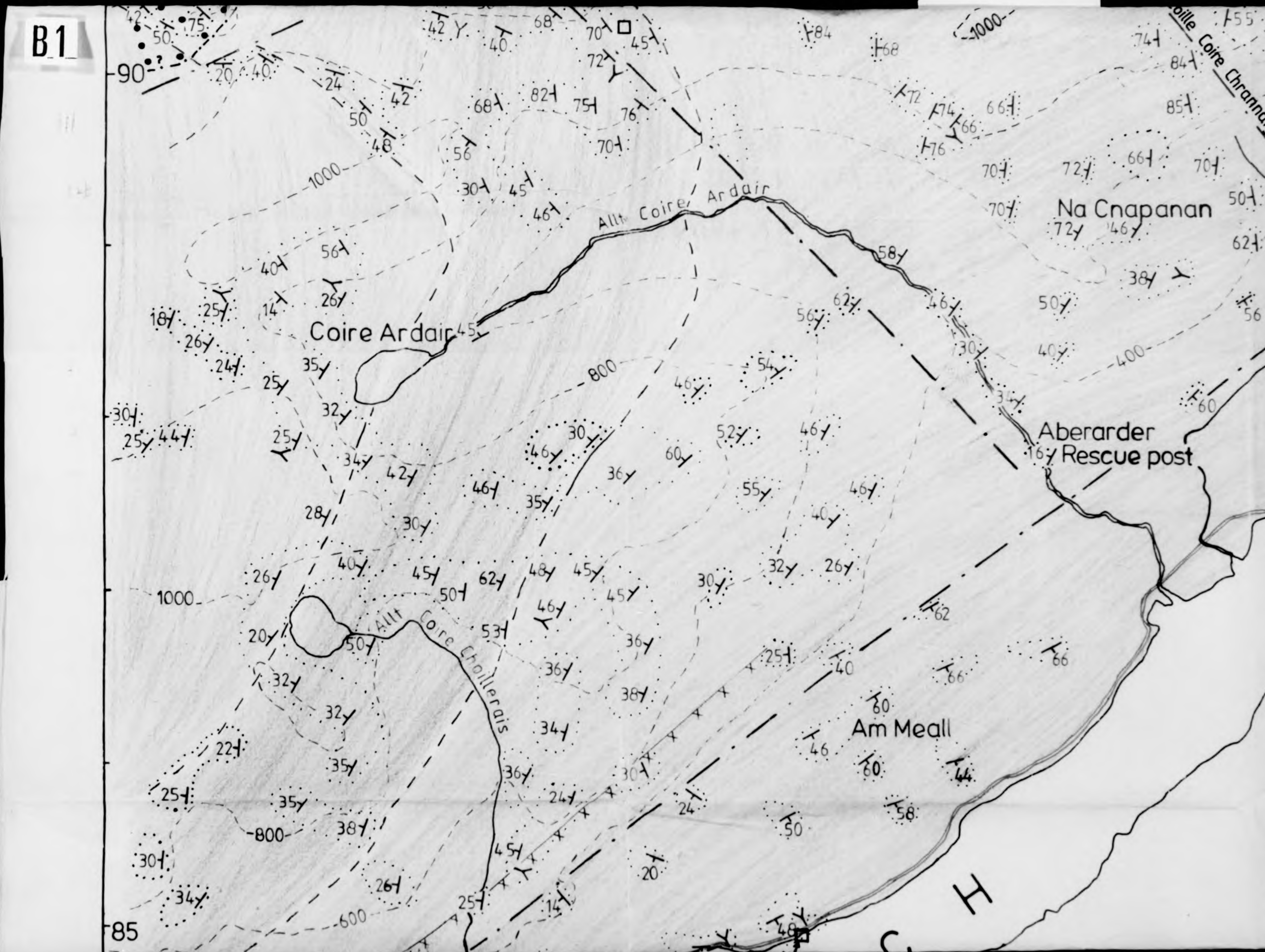
-UPPER STRATHSPEY AREA

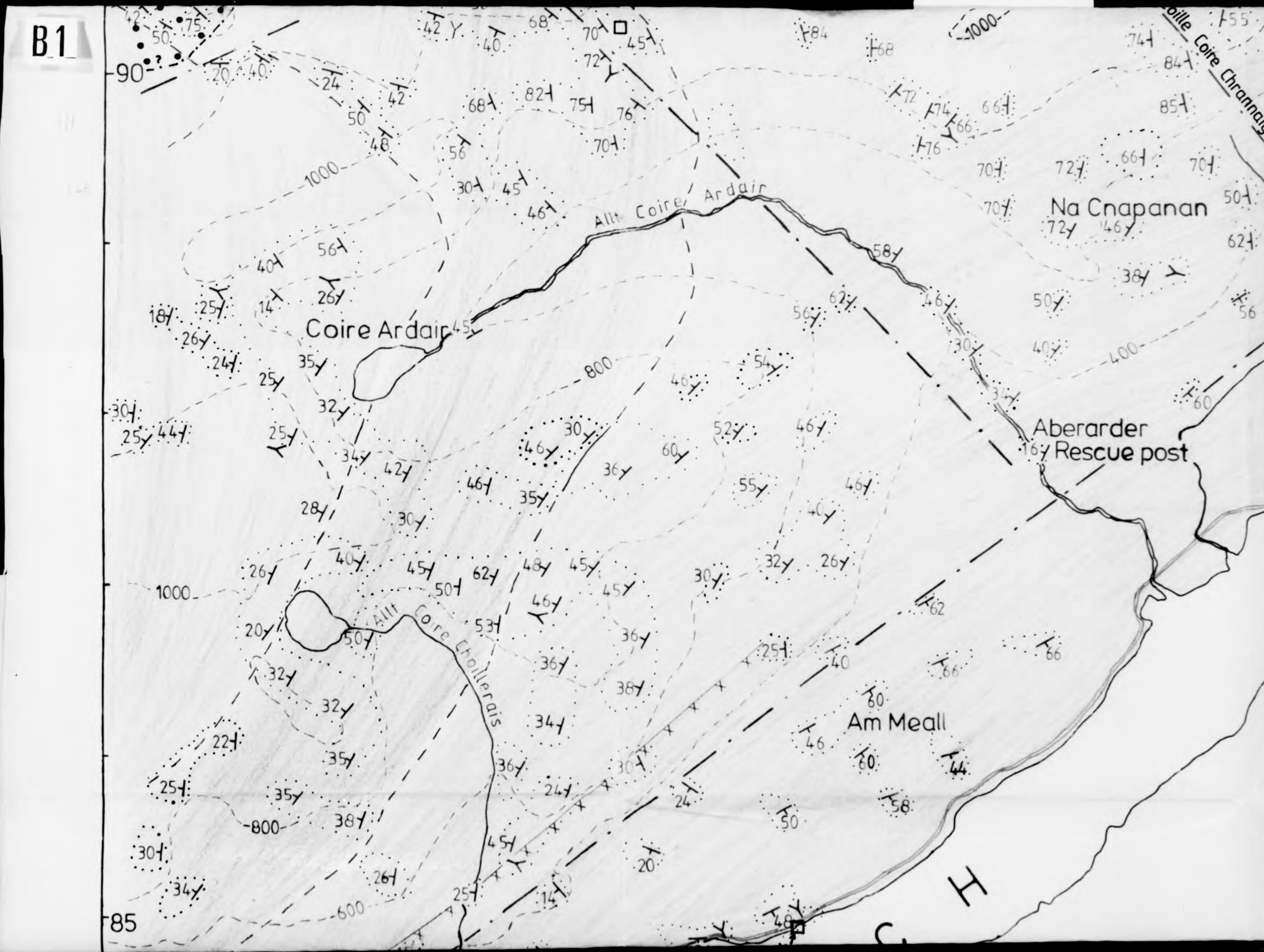


B1

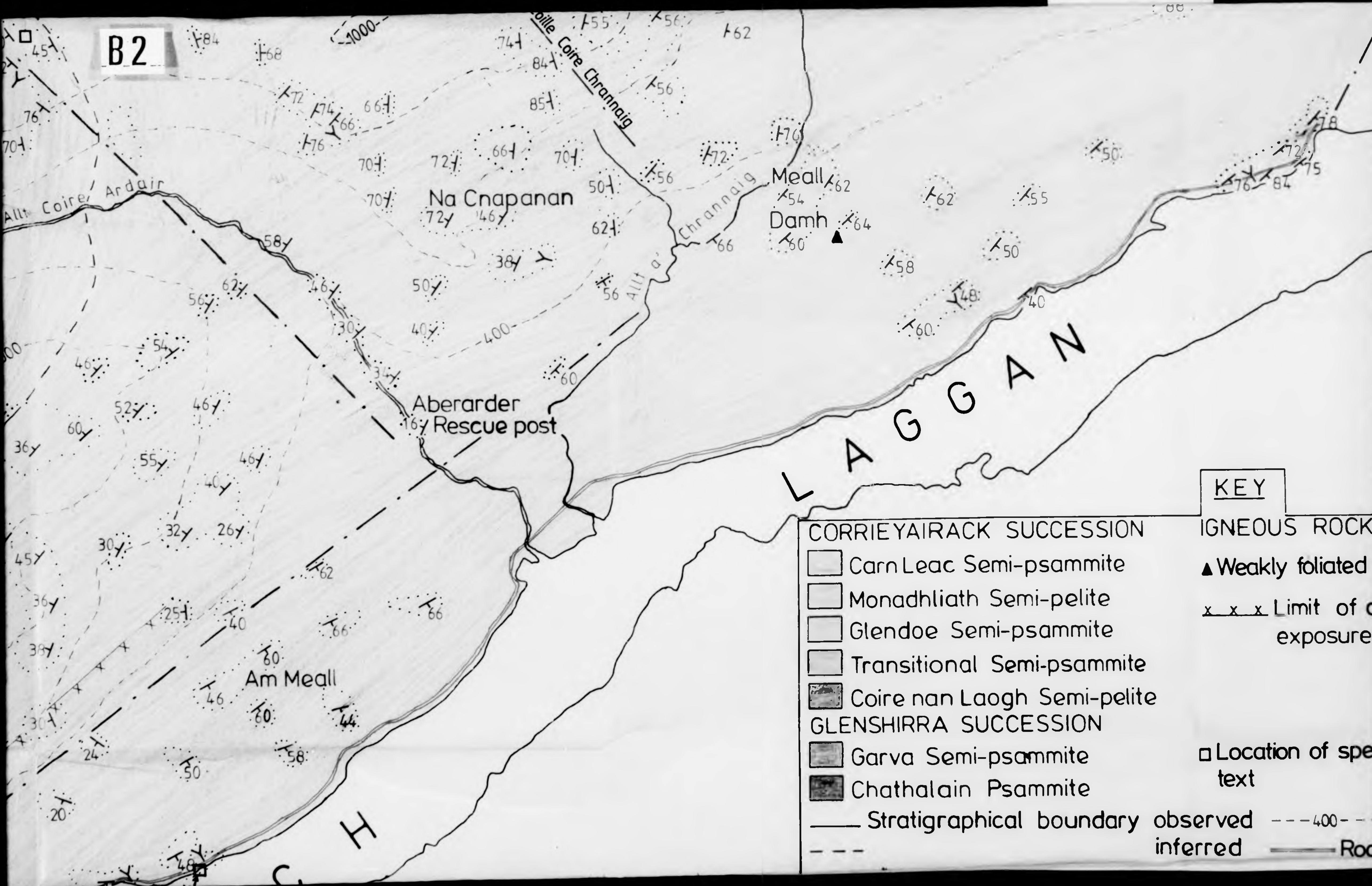


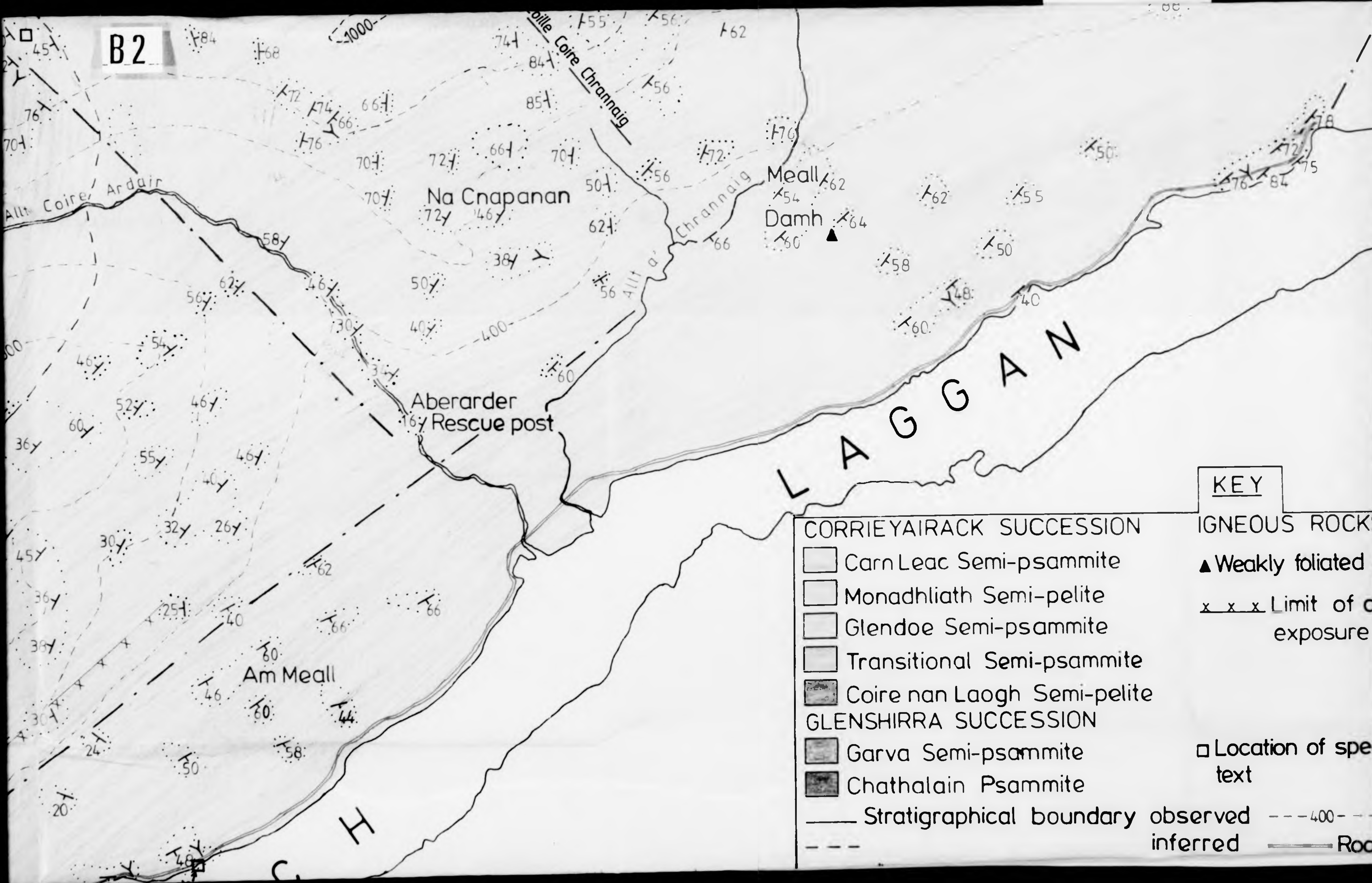
90
85
1000
800
600
400
Coire Ardair
Allt Coire Ardair
Na Cnapanan
Aberarder
Rescue post
Allt Coire Chollerais
Am Meall
oille Coire Chrannaig


B1
90
85
Coire Ardair
Allt Coire Ardair
Allt Coire Chollerais
Na Cnapanan
Aberarder
Rescue post
Am Meall
Coille Coire Chrannaig
1000
800
600
400
H

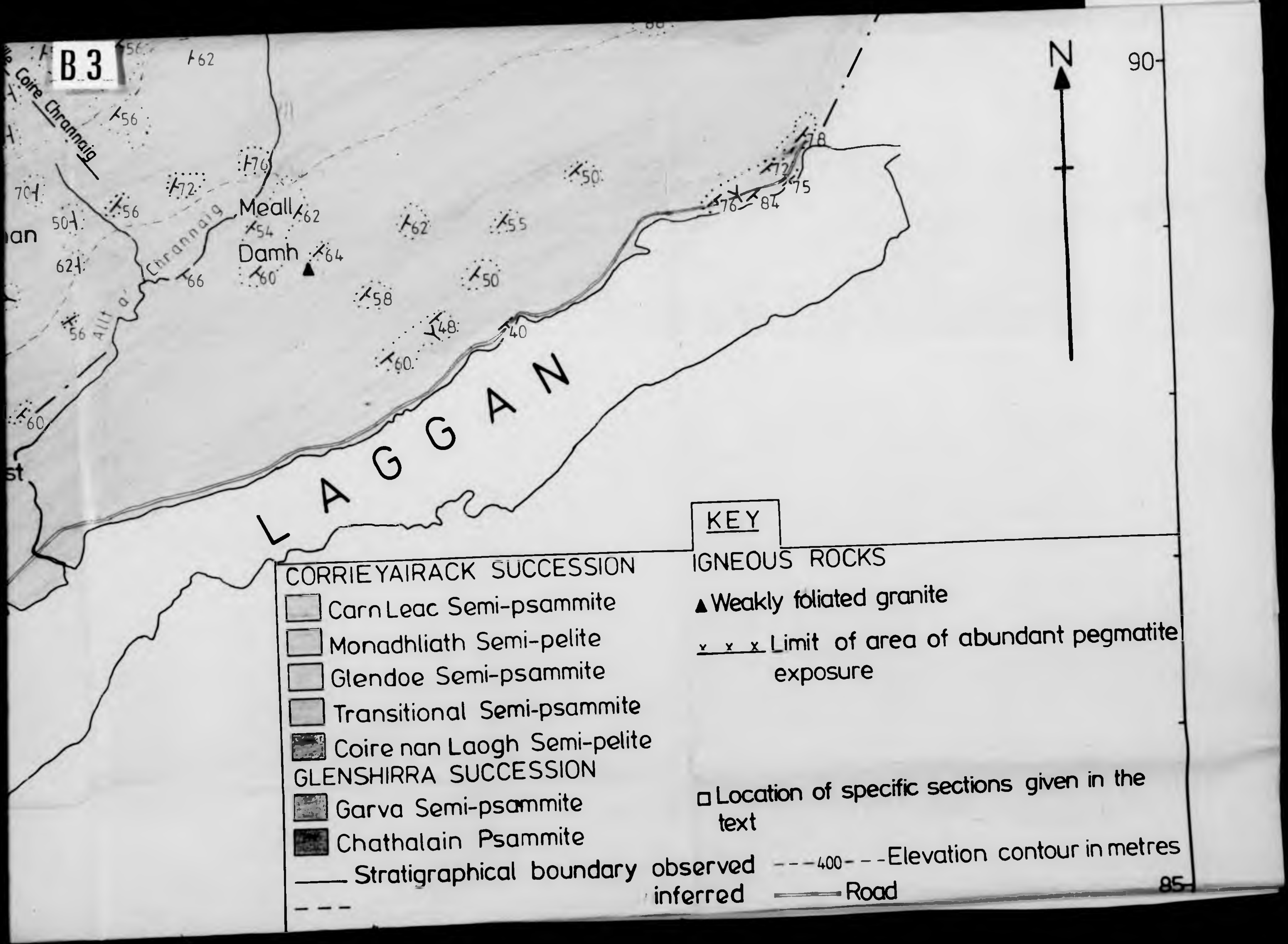

B1
90
85
Coire Ardair
Allt Coire Ardair
Allt Coire Chollerais
Na Cnapanan
Aberarder
Rescue post
Am Meall
Coille Coire Chrannaig
1000
800
600
400
H

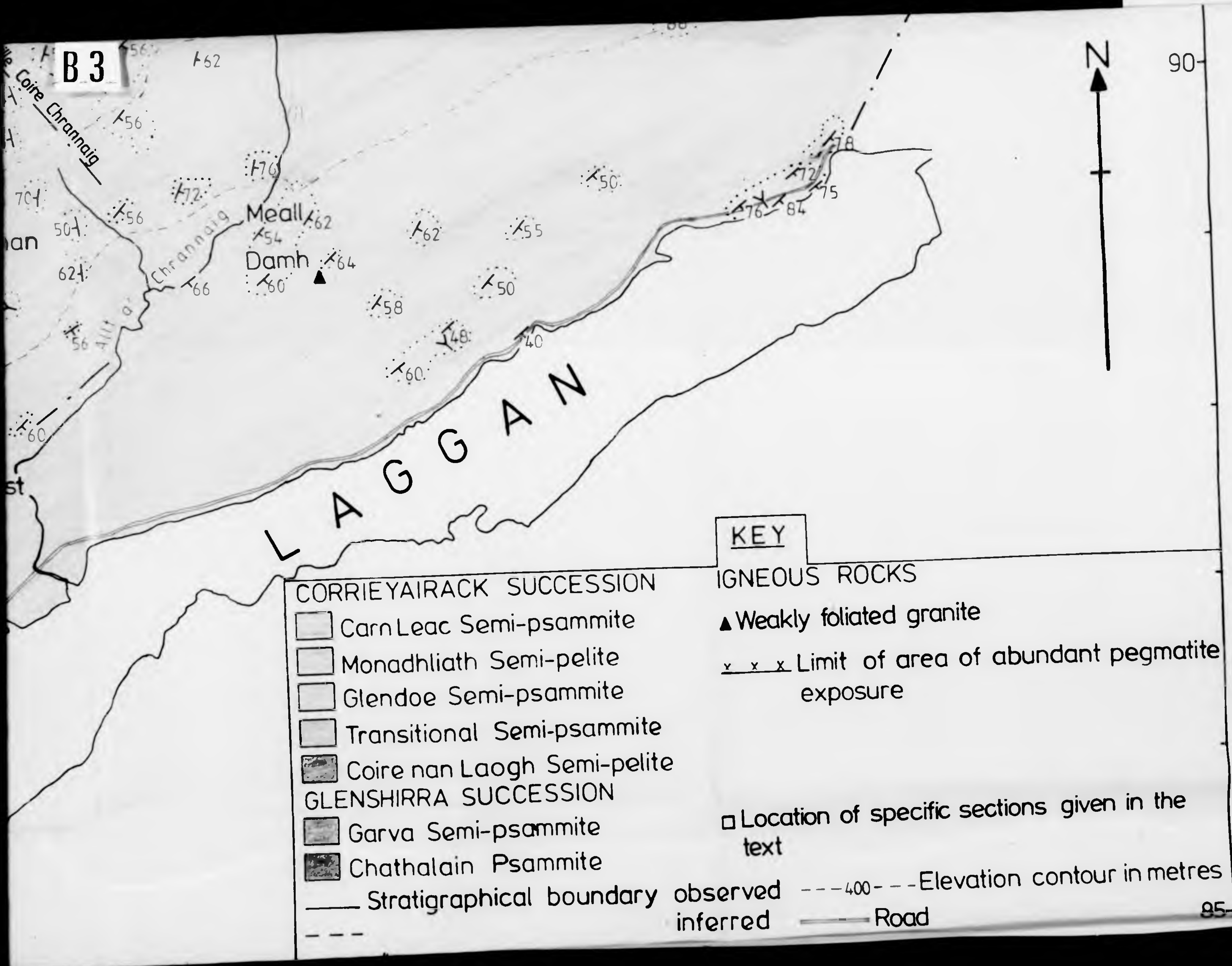

B2
Allt Coire Ardair
Coille Coire Chrannaig
Na Cnapanan
Meall Damh
Allt a' Chrannaig
Aberarder Rescue post
Am Meall
LAGGAN
KEY
CORRIEYAIRACK SUCCESSION
Carn Leac Semi-psammite
Monadhliath Semi-pelite
Glendoe Semi-psammite
Transitional Semi-psammite
Coire nan Laogh Semi-pelite
GLENSHIRRA SUCCESSION
Garva Semi-psammite
Chathalain Psammite
Stratigraphical boundary observed
inferred
IGNEOUS ROCKS
Weakly foliated
Limit of
exposure
Location of spe
text

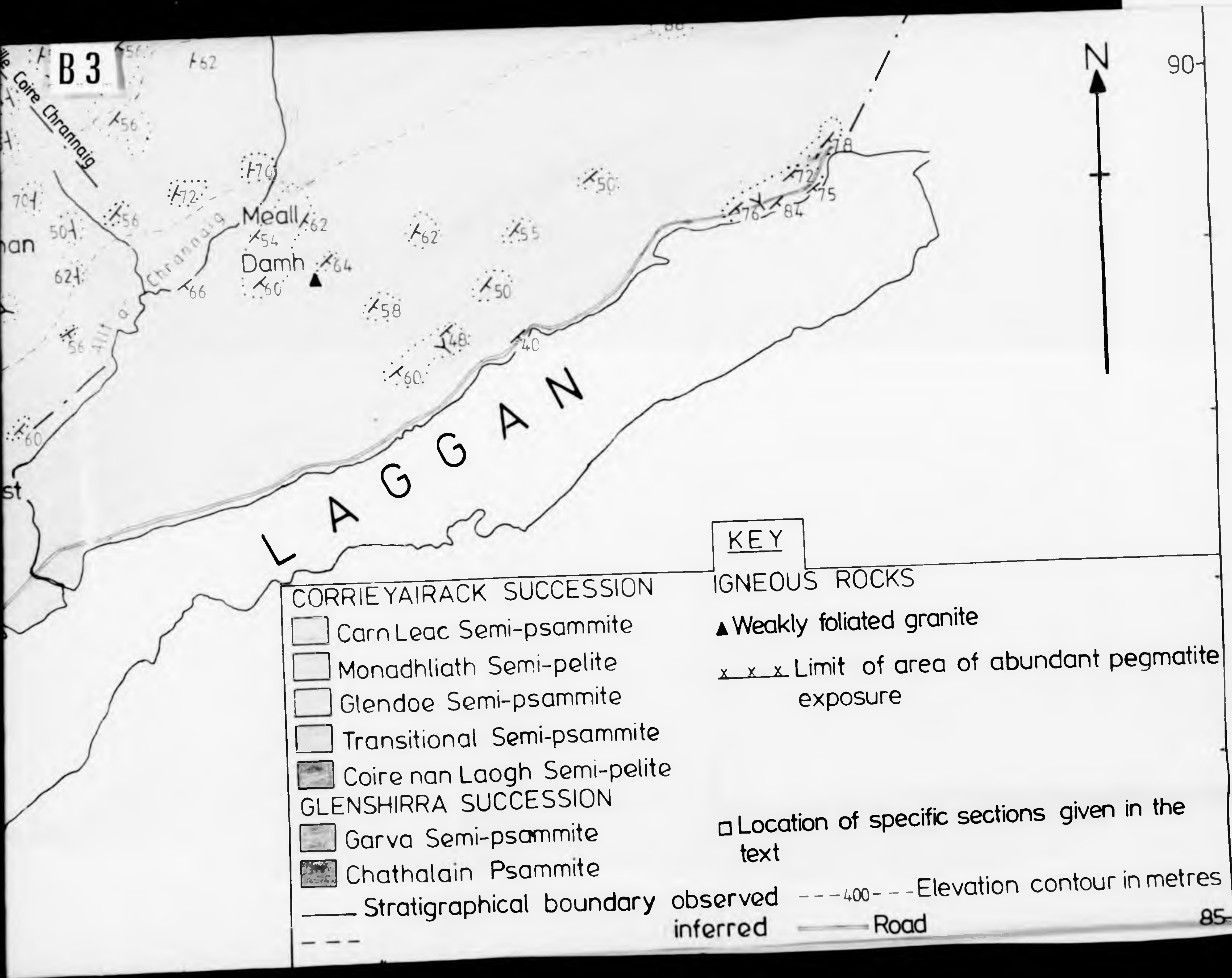

B2
Na Cnapanan
Meall Damh
Aberarder Rescue post
Am Meall
Allt Coire Ardair
Allt a' Chrannaig
oille Coire Chrannaig
LAGGAN
H
KEY
CORRIEYAIRACK SUCCESSION
Carn Leac Semi-psammite
Monadhliath Semi-pelite
Glendoe Semi-psammite
Transitional Semi-psammite
Coire nan Laogh Semi-pelite
GLENSHIRRA SUCCESSION
Garva Semi-psammite
Chathalain Psammite
Stratigraphical boundary observed
inferred
IGNEOUS ROCKS
Weakly foliated
Limit of a
exposure
Location of spec
text
Roa



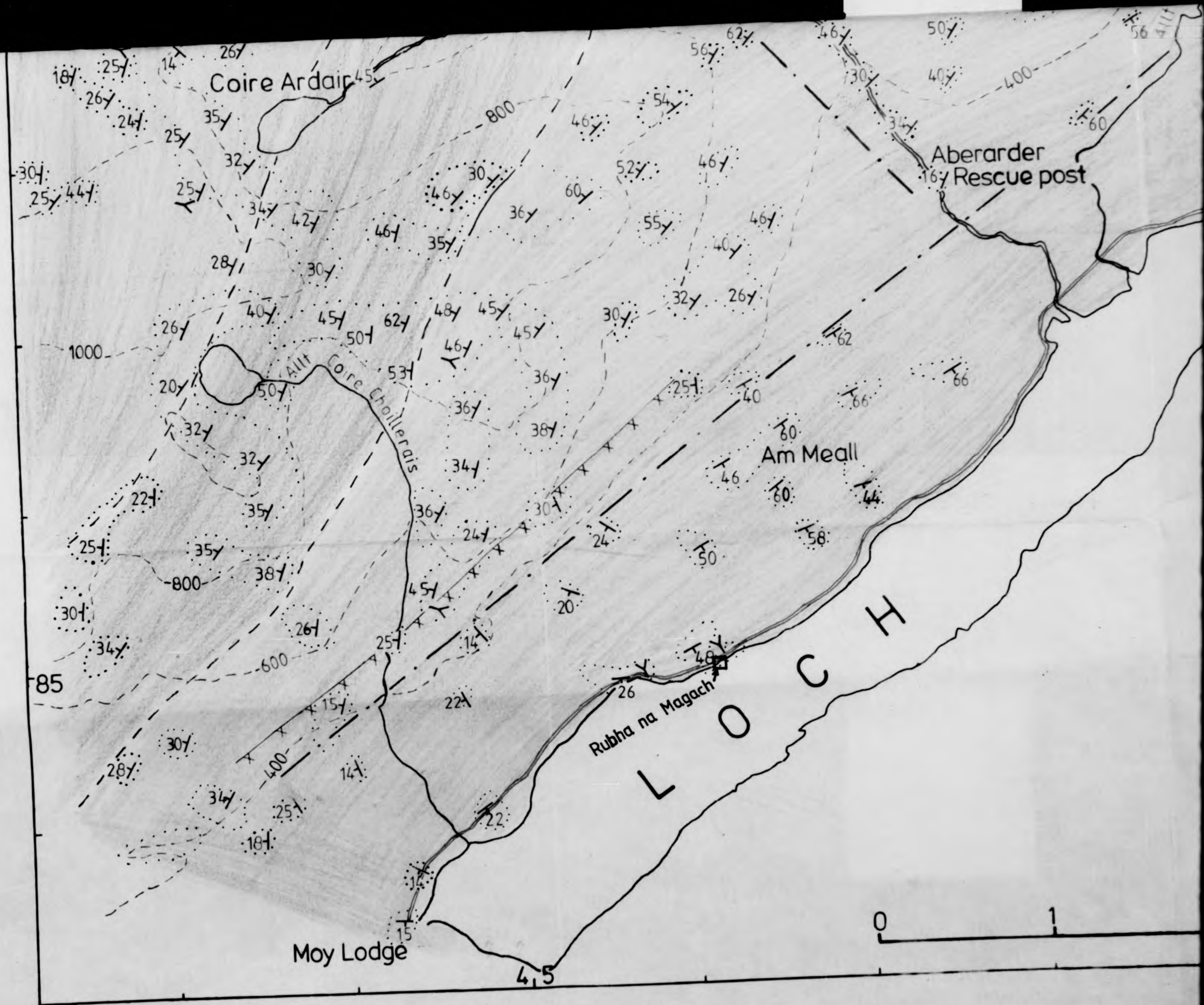
B2
Na Cnapanan
Meall
Damh
Aberarder
Rescue post
Am Meall
Allt Coire Ardair
Allt a' Chrannaig
Coille Coire Chrannaig
LAGGAN
C H
KEY
CORRIEYAIRACK SUCCESSION
Carn Leac Semi-psammite
Monadhliath Semi-pelite
Glendoe Semi-psammite
Transitional Semi-psammite
Coire nan Laogh Semi-pelite
GLENSHIRRA SUCCESSION
Garva Semi-psammite
Chathalain Psammite
Stratigraphical boundary observed
inferred
IGNEOUS ROCKS
Weakly foliated
Limit of a
exposure
Location of spec
text
400
Roa


B3
Coire Chrannaig
Meall Damh
Allt a' Chrannaig
LAGGAN
N
90
85
KEY
CORRIEYAIRACK SUCCESSION
Carn Leac Semi-psammite
Monadhliath Semi-pelite
Glendoe Semi-psammite
Transitional Semi-psammite
Coire nan Laogh Semi-pelite
GLENSHIRRA SUCCESSION
Garva Semi-psammite
Chathalain Psammite
Stratigraphical boundary observed
inferred
IGNEOUS ROCKS
Weakly foliated granite
Limit of area of abundant pegmatite exposure
Location of specific sections given in the text
400 Elevation contour in metres
Road

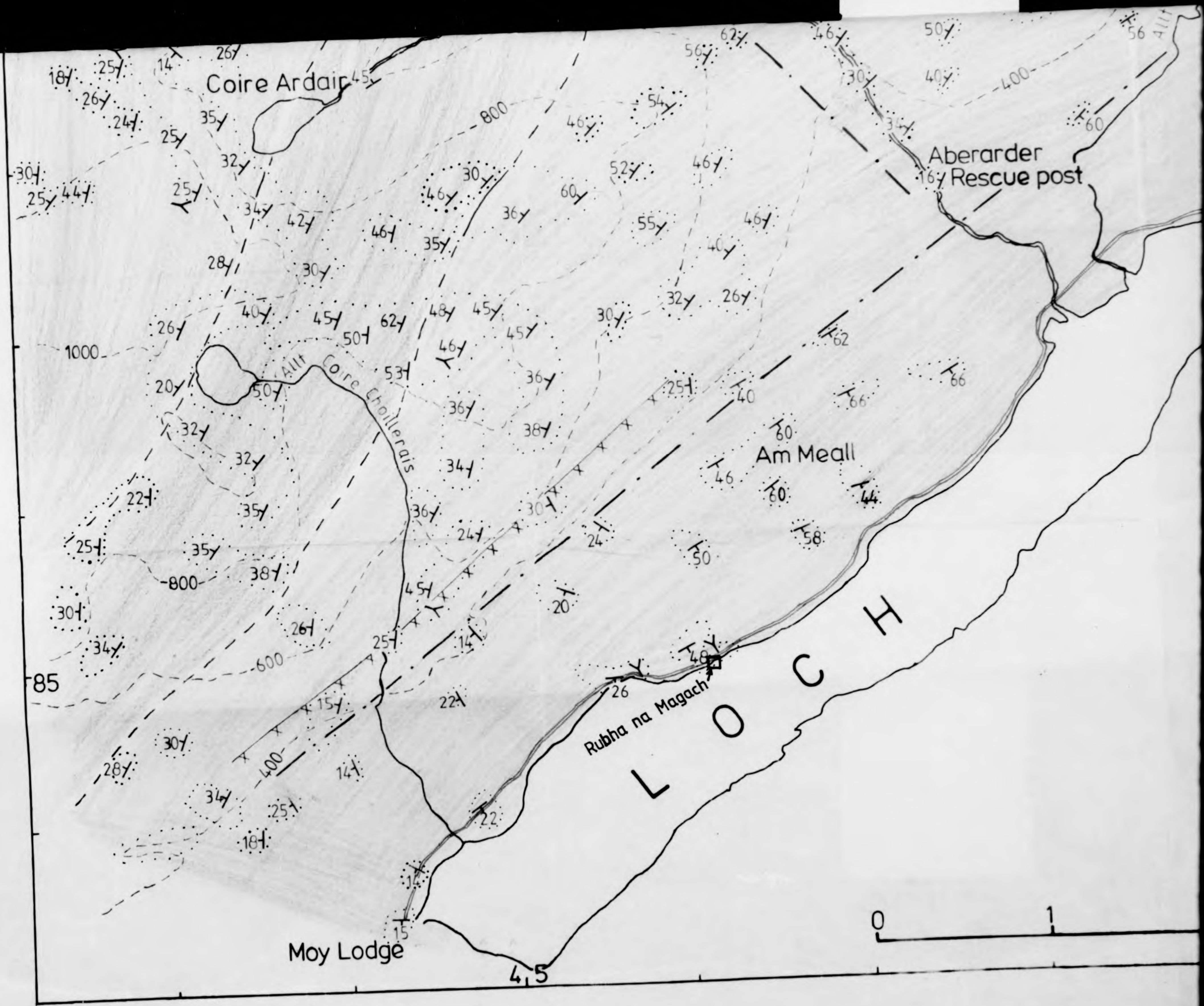

B3
Coire Chrannaig
Allt a' Chrannaig
Meall Damh
LAGGAN
N
90
85
KEY
CORRIEYAIRACK SUCCESSION
Carn Leac Semi-psammite
Monadhliath Semi-pelite
Glendoe Semi-psammite
Transitional Semi-psammite
Coire nan Laogh Semi-pelite
GLENSHIRRA SUCCESSION
Garva Semi-psammite
Chathalain Psammite
Stratigraphical boundary observed
inferred
IGNEOUS ROCKS
Weakly foliated granite
Limit of area of abundant pegmatite exposure
Location of specific sections given in the text
400 Elevation contour in metres
Road


B3
Coire Chrannaig
Allt a' Chrannaig
Meall Damh
LAGGAN
N
90
85
KEY
CORRIEYAIRACK SUCCESSION
Carn Leac Semi-psammite
Monadhliath Semi-pelite
Glendoe Semi-psammite
Transitional Semi-psammite
Coire nan Laogh Semi-pelite
GLENSHIRRA SUCCESSION
Garva Semi-psammite
Chathalain Psammite
Stratigraphical boundary observed
inferred
IGNEOUS ROCKS
Weakly foliated granite
Limit of area of abundant pegmatite exposure
Location of specific sections given in the text
Elevation contour in metres
Road

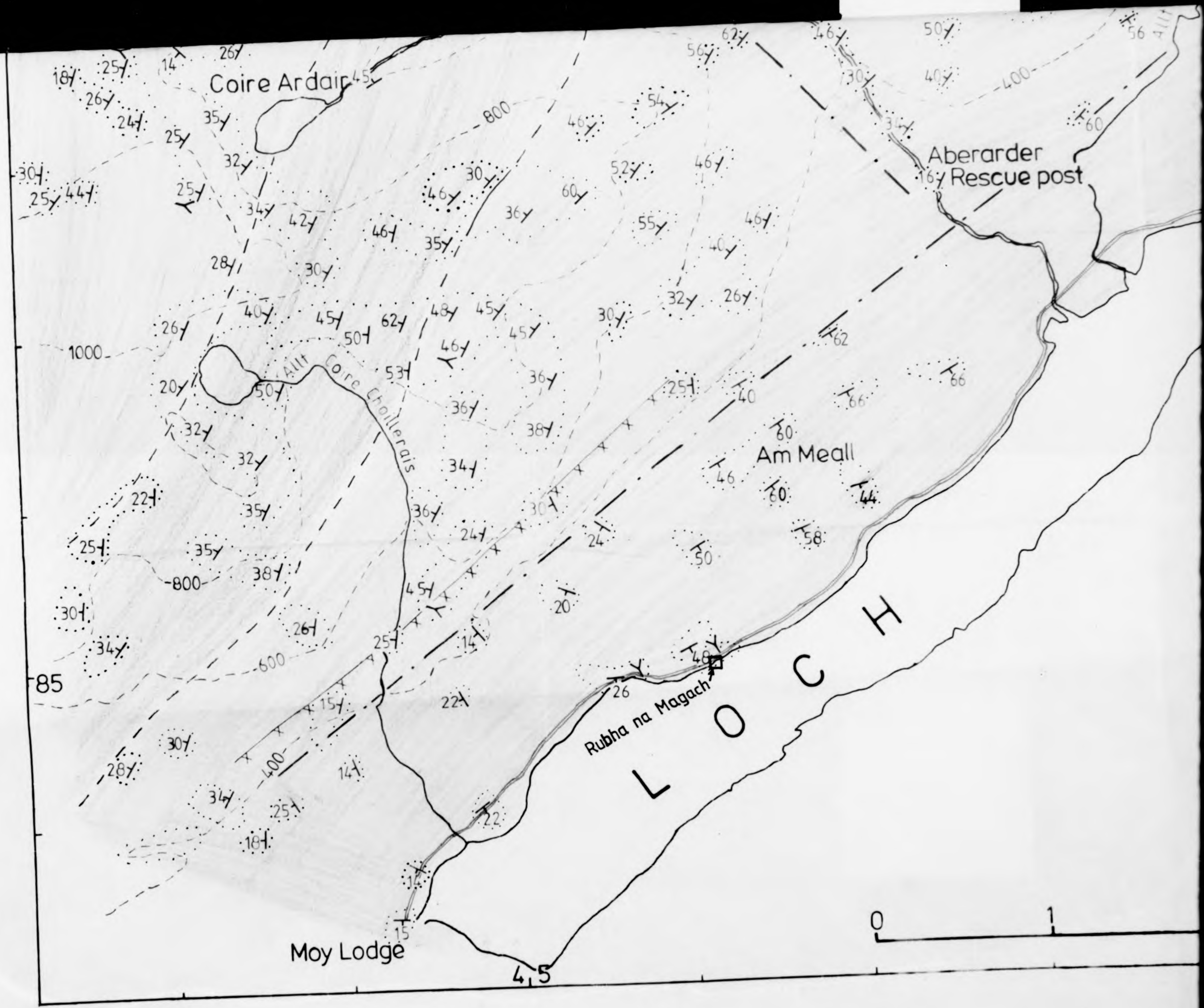
C 1

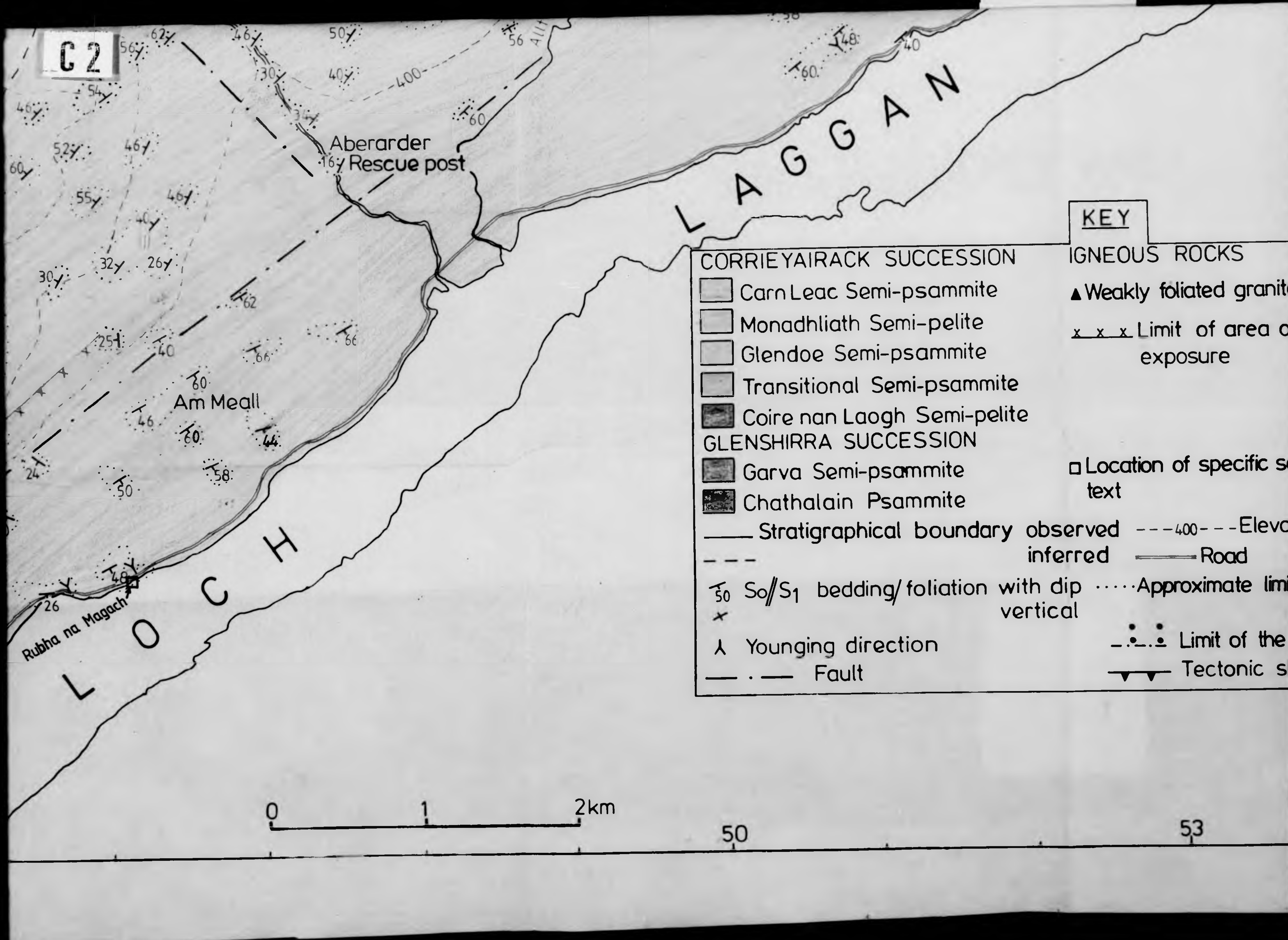

Coire Ardair
Aberarder
Rescue post
Allt Coire Choillerais
Am Meall
Rubha na Magach
LOCH
Moy Lodge
1000
800
600
400
85
4 5
0
1

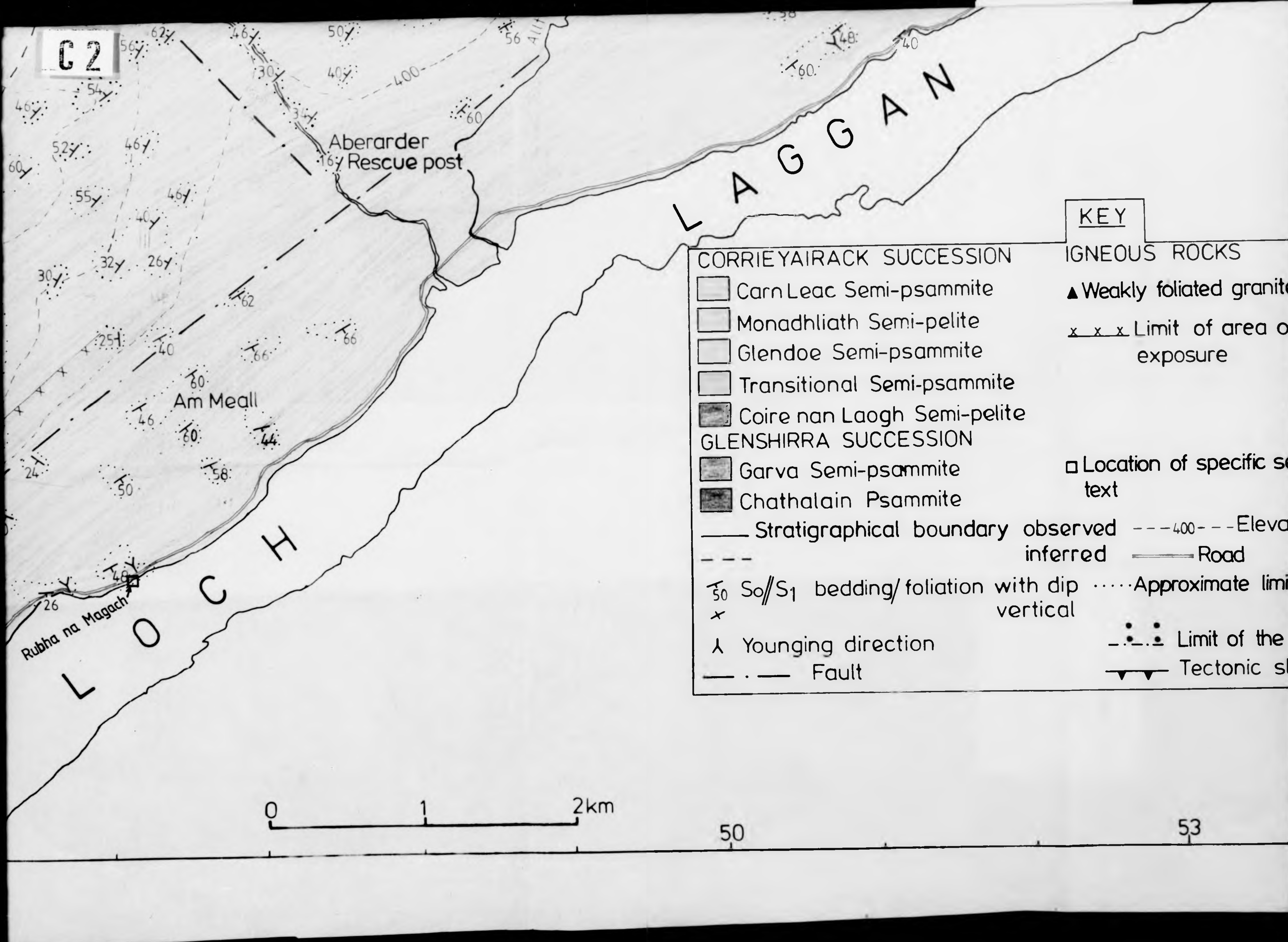
C 1

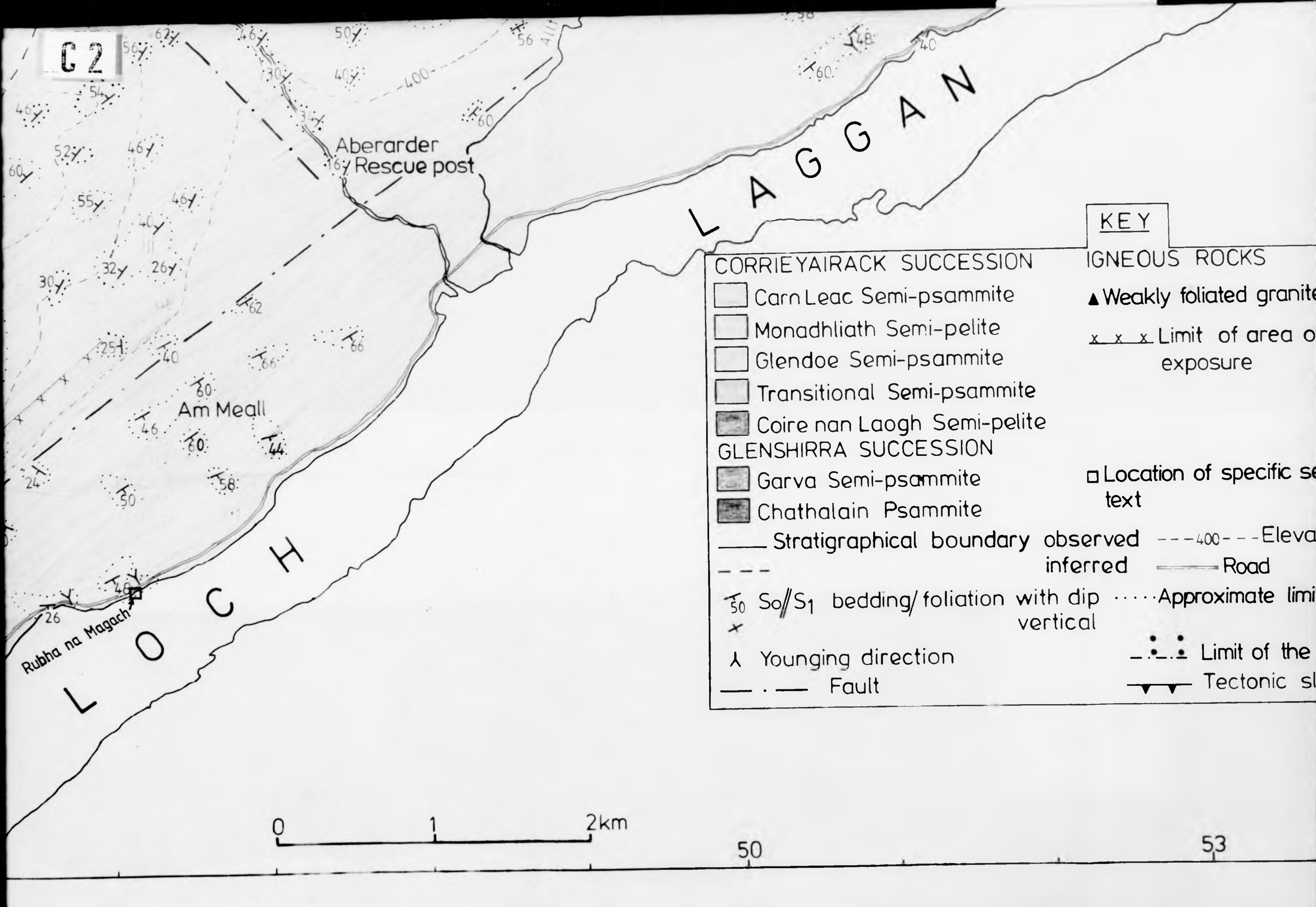

Coire Ardair
Aberarder
Rescue post
Allt Coire Choillerais
Am Meall
Rubha na Magach
LOCH
Moy Lodge
85
4 5
0
1

C 1

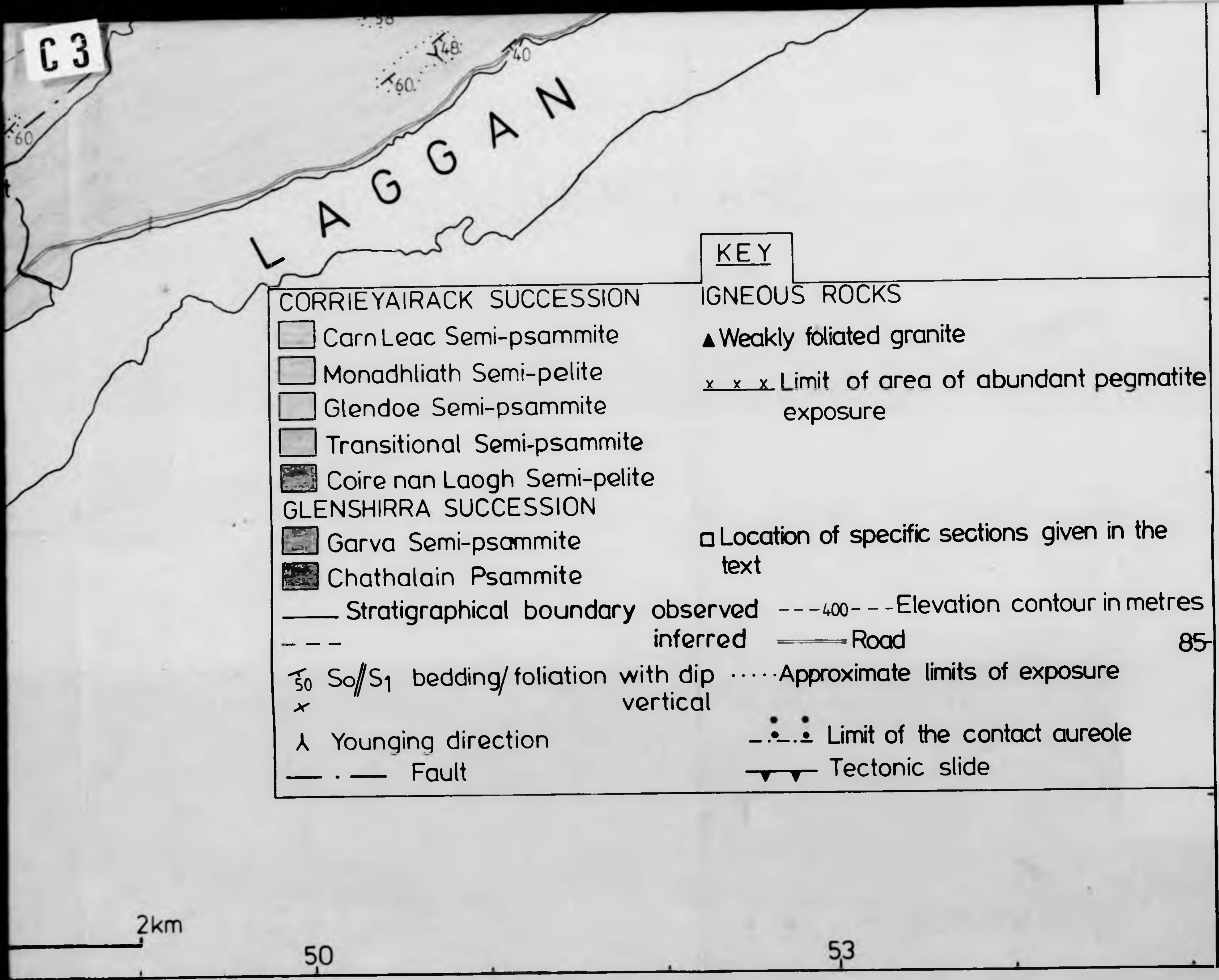

Coire Ardair
Aberarder
Rescue post
Allt Coire Choillerais
Am Meall
Rubha na Magach
L O C H
Moy Lodge
1000
800
600
400
85
45
0
1

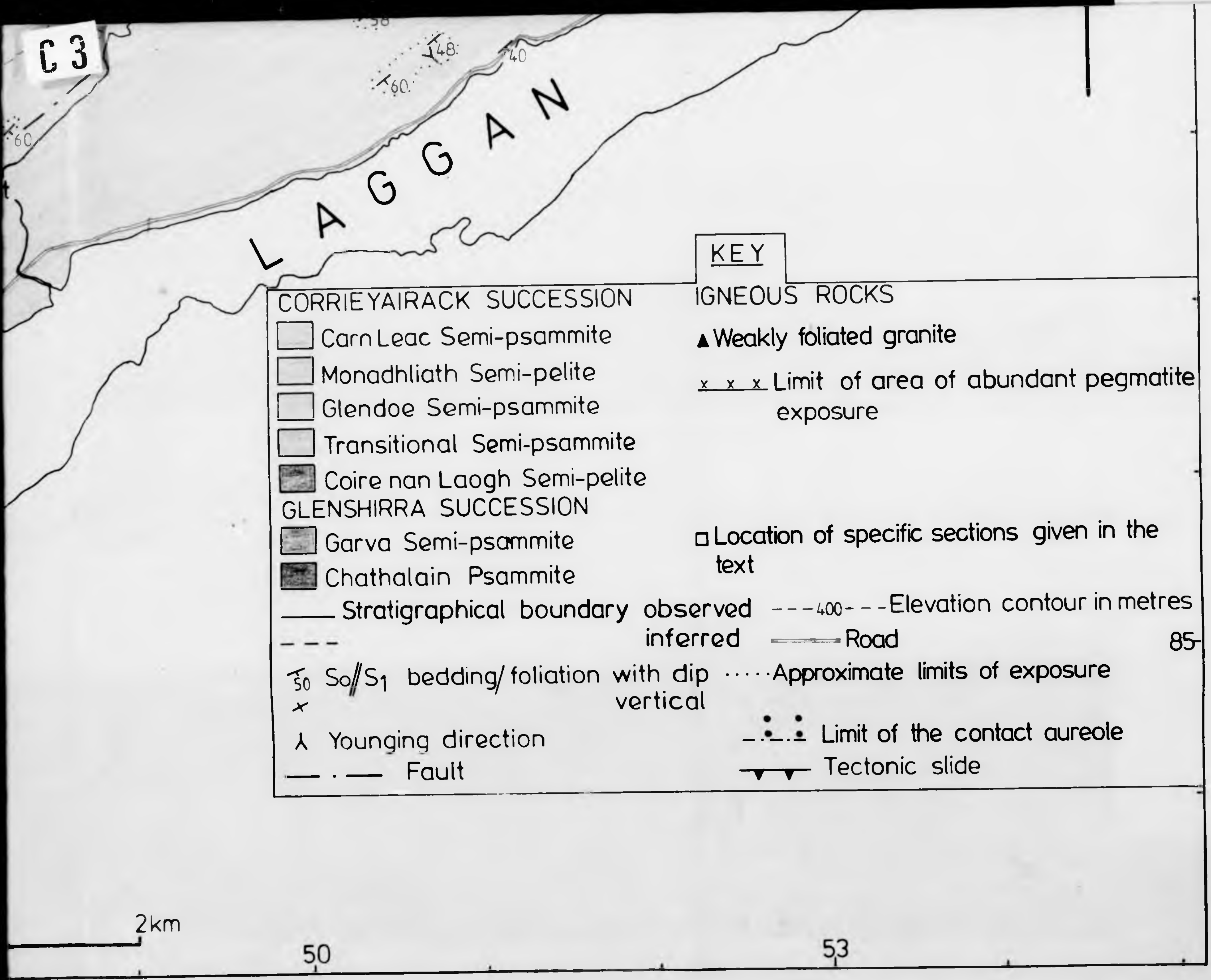

C2
Aberarder
Rescue post
Am Meall
Rubha na Magach
LOCH LAGGAN
KEY
CORRIEYAIRACK SUCCESSION
Carn Leac Semi-psammite
Monadhliath Semi-pelite
Glendoe Semi-psammite
Transitional Semi-psammite
Coire nan Laogh Semi-pelite
GLENSHIRRA SUCCESSION
Garva Semi-psammite
Chathalain Psammite
Stratigraphical boundary observed
inferred
So//S1 bedding/foliation with dip
vertical
Younging direction
Fault
IGNEOUS ROCKS
Weakly foliated granite
Limit of area of exposure
Location of specific se
text
400 Eleva
Road
Approximate limi
Limit of the
Tectonic sl
0
1
2km
50
53

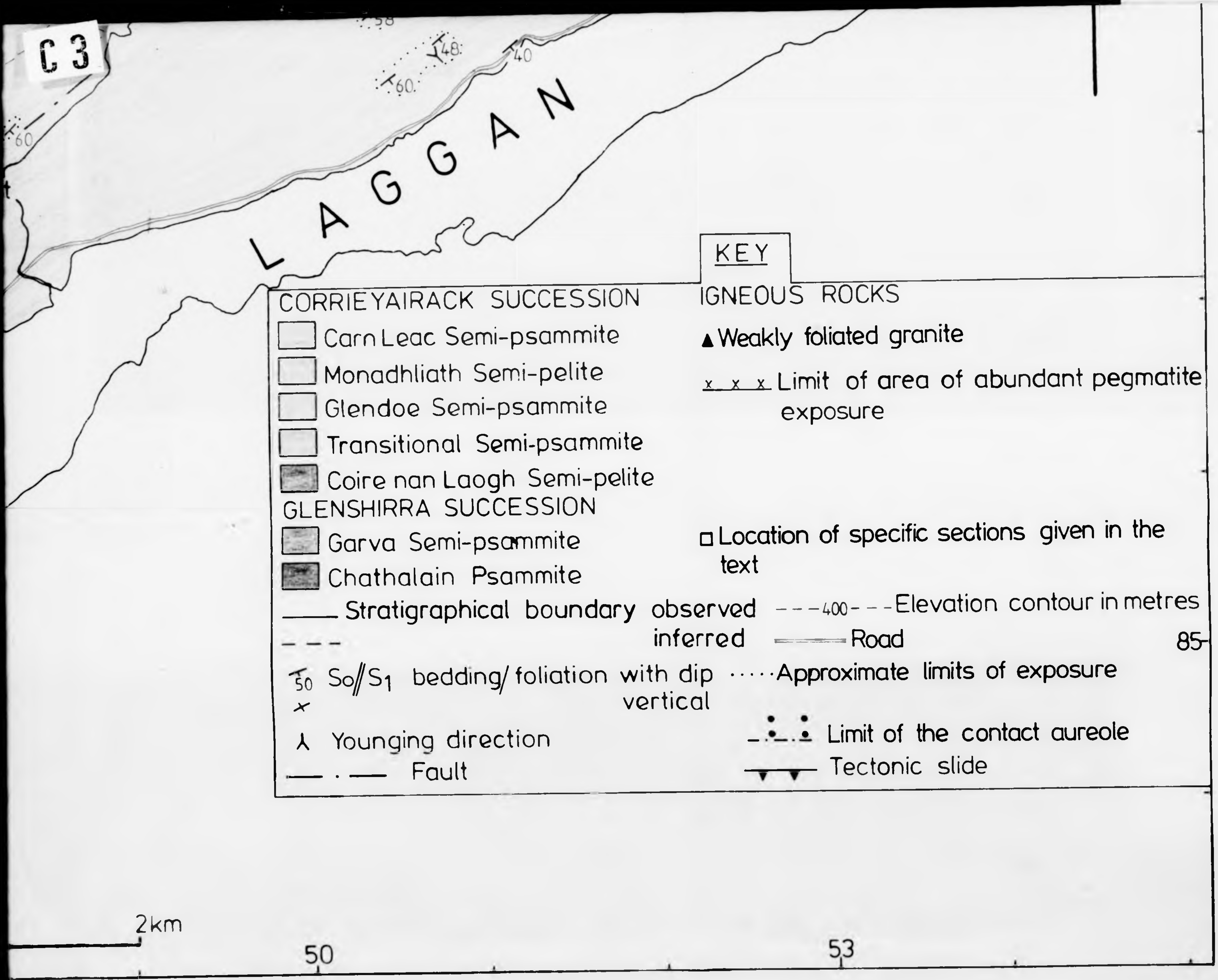

C 2
Aberarder
Rescue post
Am Meall
Rubha na Magach
LOCH LAGGAN
-400-
0 1 2km
50
53
KEY
CORRIEYAIRACK SUCCESSION
Carn Leac Semi-psammite
Monadhliath Semi-pelite
Glendoe Semi-psammite
Transitional Semi-psammite
Coire nan Laogh Semi-pelite
GLENSHIRRA SUCCESSION
Garva Semi-psammite
Chathalain Psammite
Stratigraphical boundary observed
inferred
So//S1 bedding/ foliation with dip
vertical
Younging direction
Fault
IGNEOUS ROCKS
Weakly foliated granite
Limit of area of exposure
Location of specific se
text
Eleva
Road
Approximate limi
Limit of the
Tectonic sl



C 2
Aberarder
Rescue post
Am Meall
Rubha na Magach
LOCH LAGGAN
400
0
1
2km
50
53
KEY
CORRIEYAIRACK SUCCESSION
Carn Leac Semi-psammite
Monadhliath Semi-pelite
Glendoe Semi-psammite
Transitional Semi-psammite
Coire nan Laogh Semi-pelite
GLENSHIRRA SUCCESSION
Garva Semi-psammite
Chathalain Psammite
Stratigraphical boundary observed
inferred
So//S1 bedding/foliation with dip
vertical
Younging direction
Fault
IGNEOUS ROCKS
Weakly foliated granite
Limit of area of
exposure
Location of specific se
text
Elevat
Road
Approximate limi
Limit of the
Tectonic sl


C 3
LAGGAN
KEY
CORRIEYAIRACK SUCCESSION
Carn Leac Semi-psammite
Monadhliath Semi-pelite
Glendoe Semi-psammite
Transitional Semi-psammite
Coire nan Laogh Semi-pelite
GLENSHIRRA SUCCESSION
Garva Semi-psammite
Chathalain Psammite
Stratigraphical boundary observed
inferred
So//S1 bedding/foliation with dip
vertical
Younging direction
Fault
IGNEOUS ROCKS
Weakly foliated granite
Limit of area of abundant pegmatite exposure
Location of specific sections given in the text
400 Elevation contour in metres
Road
Approximate limits of exposure
Limit of the contact aureole
Tectonic slide
2km
50
53
85

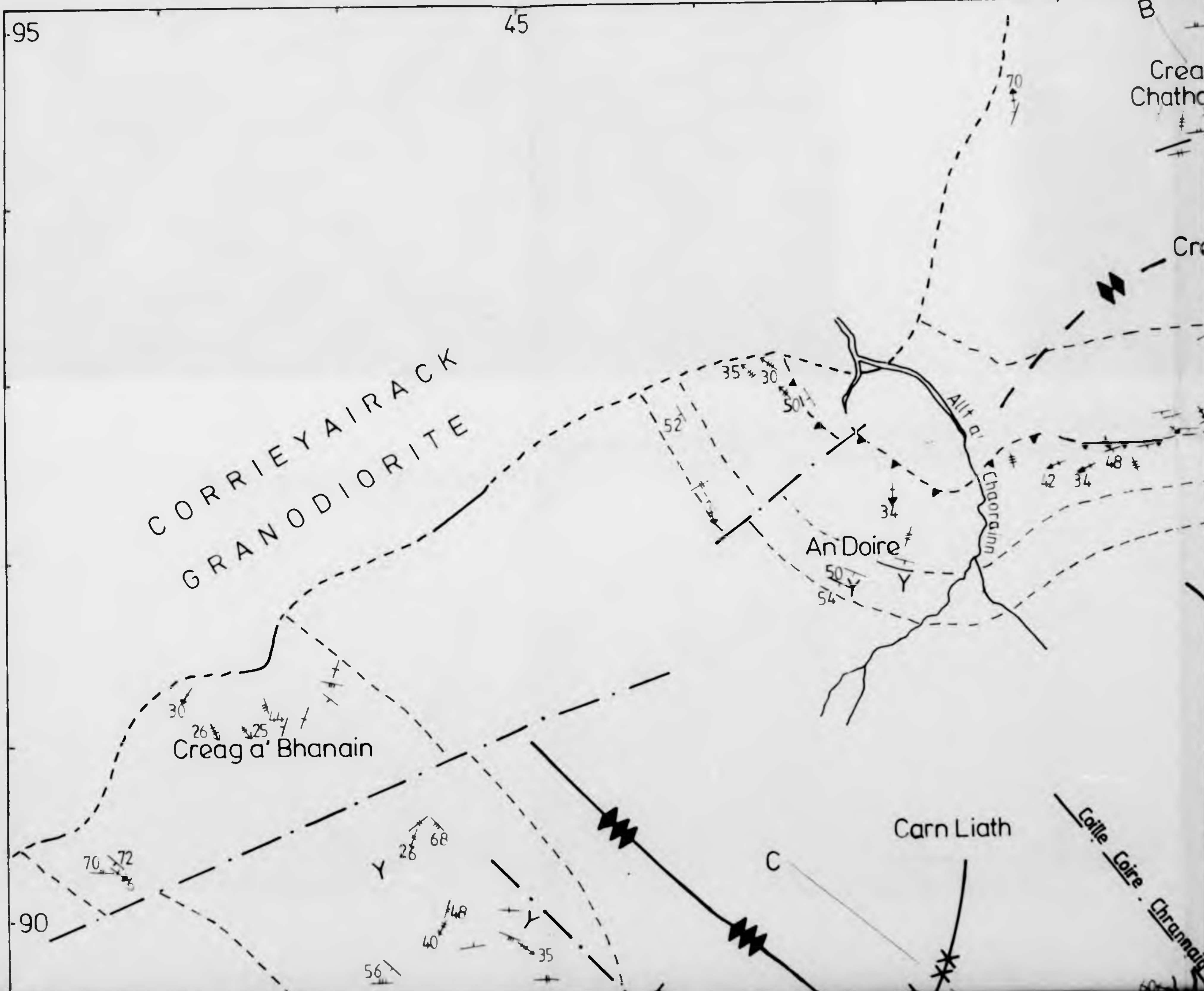

C 3
LAGGAN
48
40
60
60
KEY
CORRIEYAIRACK SUCCESSION
Carn Leac Semi-psammite
Monadhliath Semi-pelite
Glendoe Semi-psammite
Transitional Semi-psammite
Coire nan Laogh Semi-pelite
GLENSHIRRA SUCCESSION
Garva Semi-psammite
Chathalain Psammite
Stratigraphical boundary observed
inferred
50 So//S1 bedding/foliation with dip
vertical
Younging direction
Fault
IGNEOUS ROCKS
Weakly foliated granite
x x x Limit of area of abundant pegmatite exposure
Location of specific sections given in the text
400 Elevation contour in metres
Road
Approximate limits of exposure
Limit of the contact aureole
Tectonic slide
85
2km
50
53


C 3
LAGGAN
KEY
CORRIEYAIRACK SUCCESSION
Carn Leac Semi-psammite
Monadhliath Semi-pelite
Glendoe Semi-psammite
Transitional Semi-psammite
Coire nan Laogh Semi-pelite
GLENSHIRRA SUCCESSION
Garva Semi-psammite
Chathalain Psammite
Stratigraphical boundary observed
inferred
So//S1 bedding/foliation with dip
vertical
Younging direction
Fault
IGNEOUS ROCKS
Weakly foliated granite
Limit of area of abundant pegmatite exposure
Location of specific sections given in the text
400 Elevation contour in metres
Road
Approximate limits of exposure
Limit of the contact aureole
Tectonic slide
2km
50
53
85

2

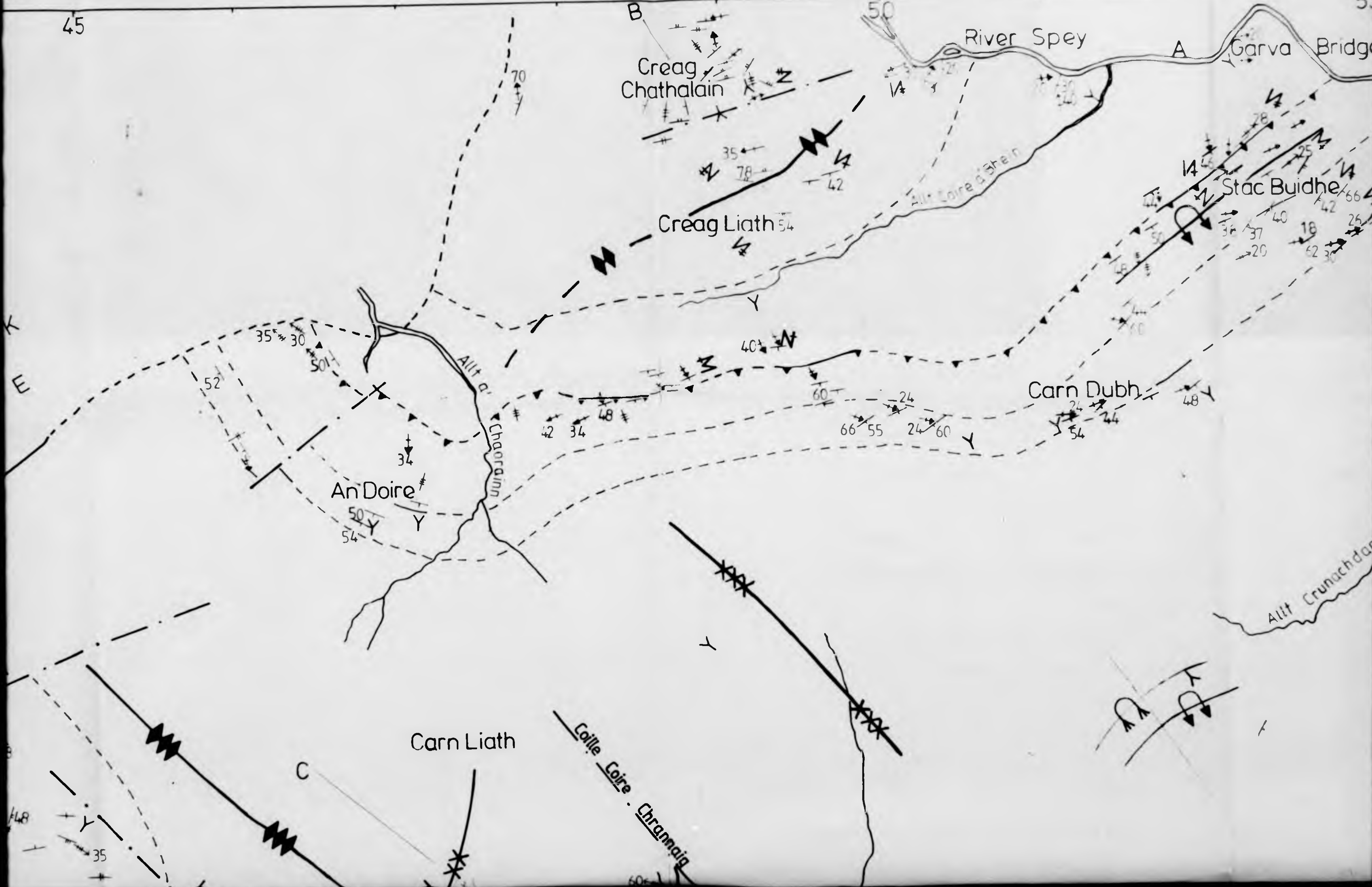
A1

STRUCTURAL GEOLOGY OF THE LOCH LAG



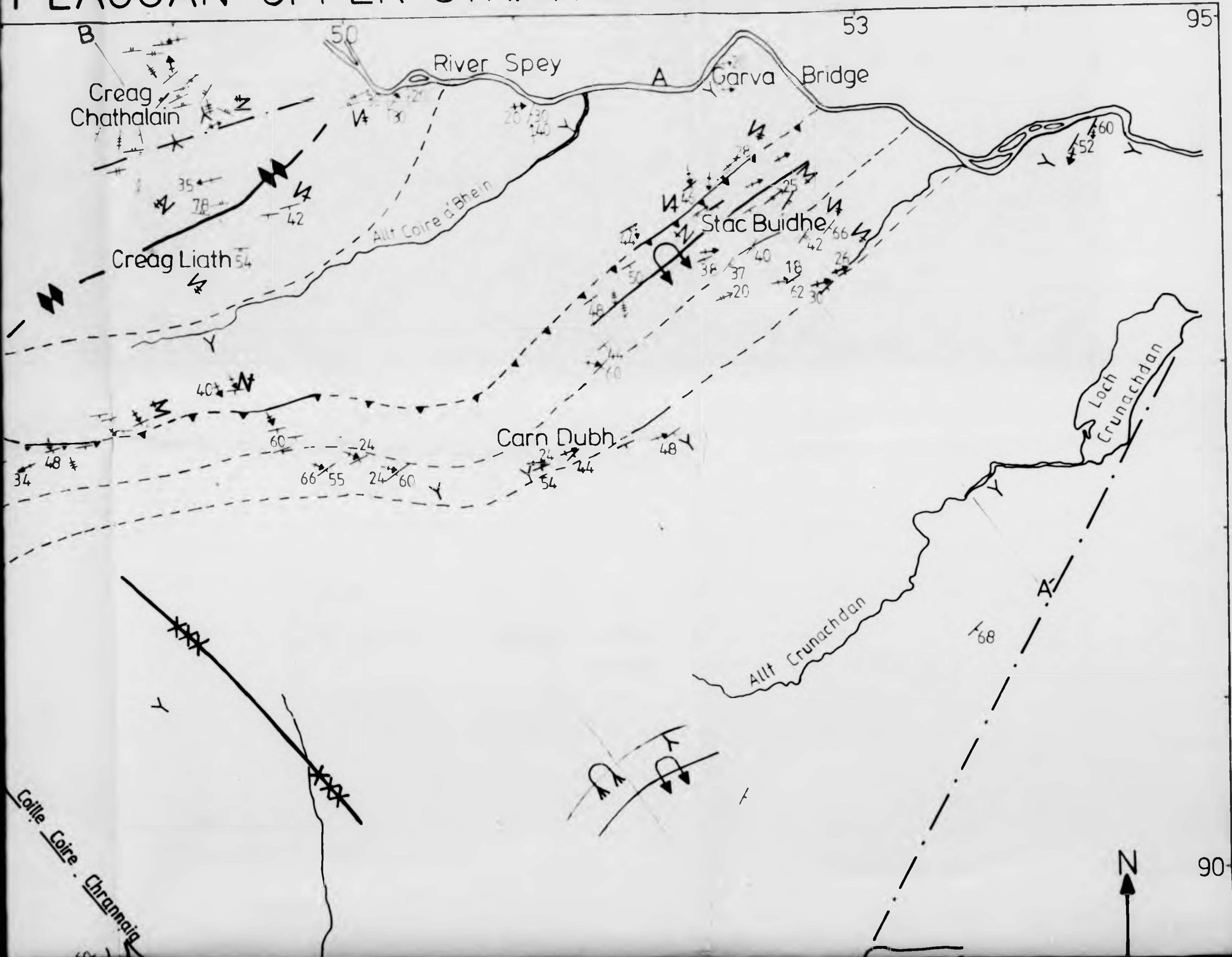
A2

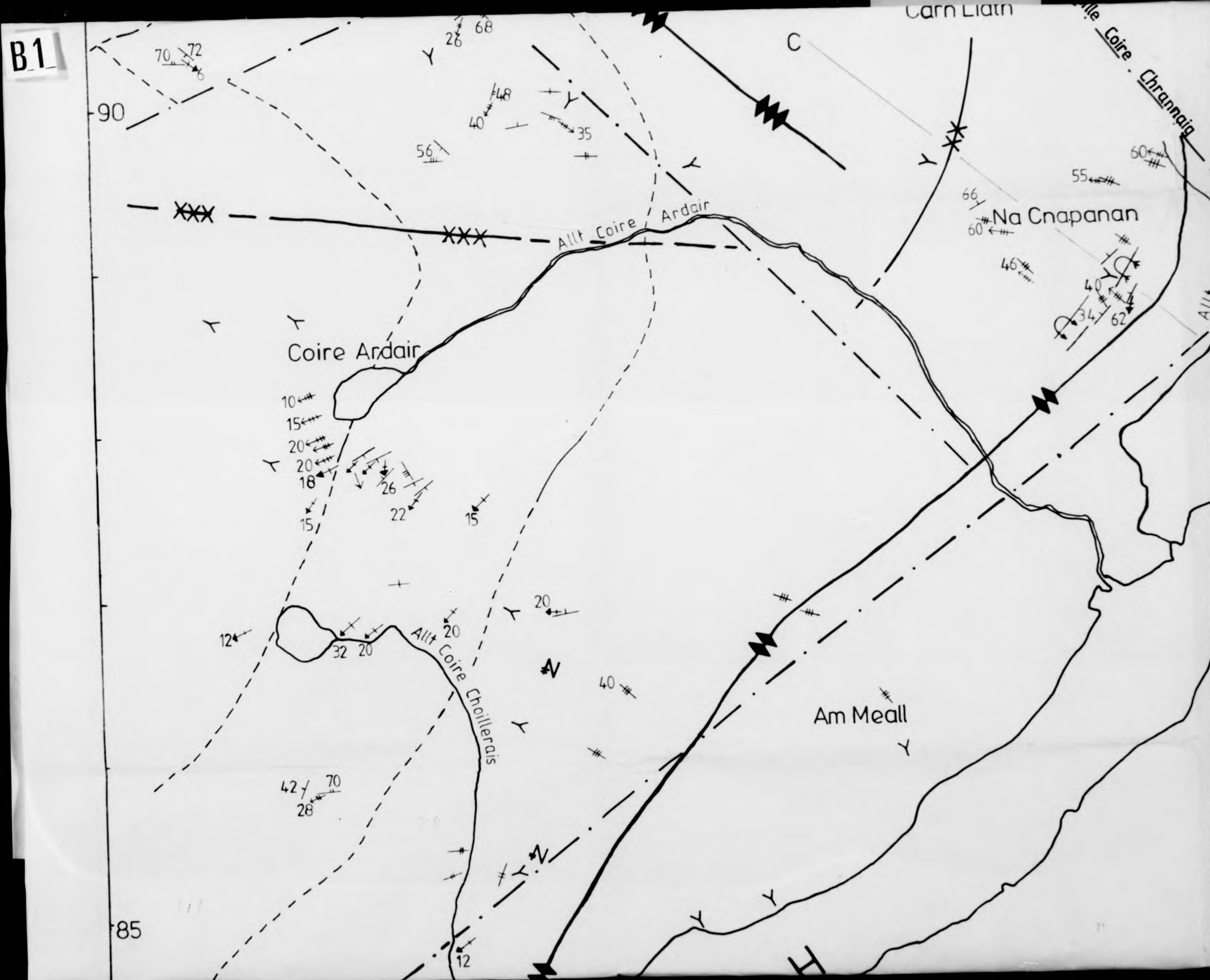
AL GEOLOGY OF THE LOCH LAGGAN-UPPER STRATHSPEY AREA



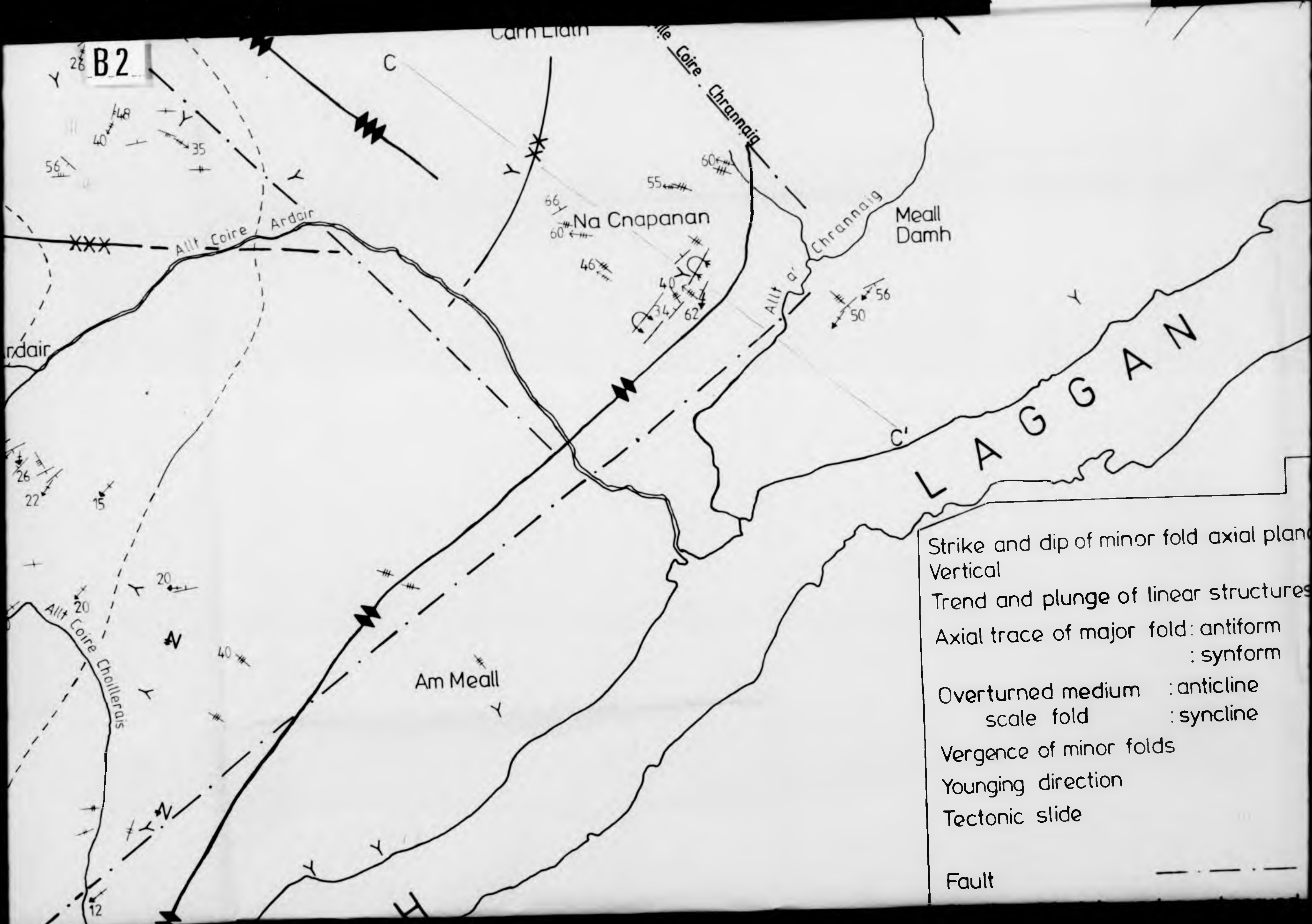
A3

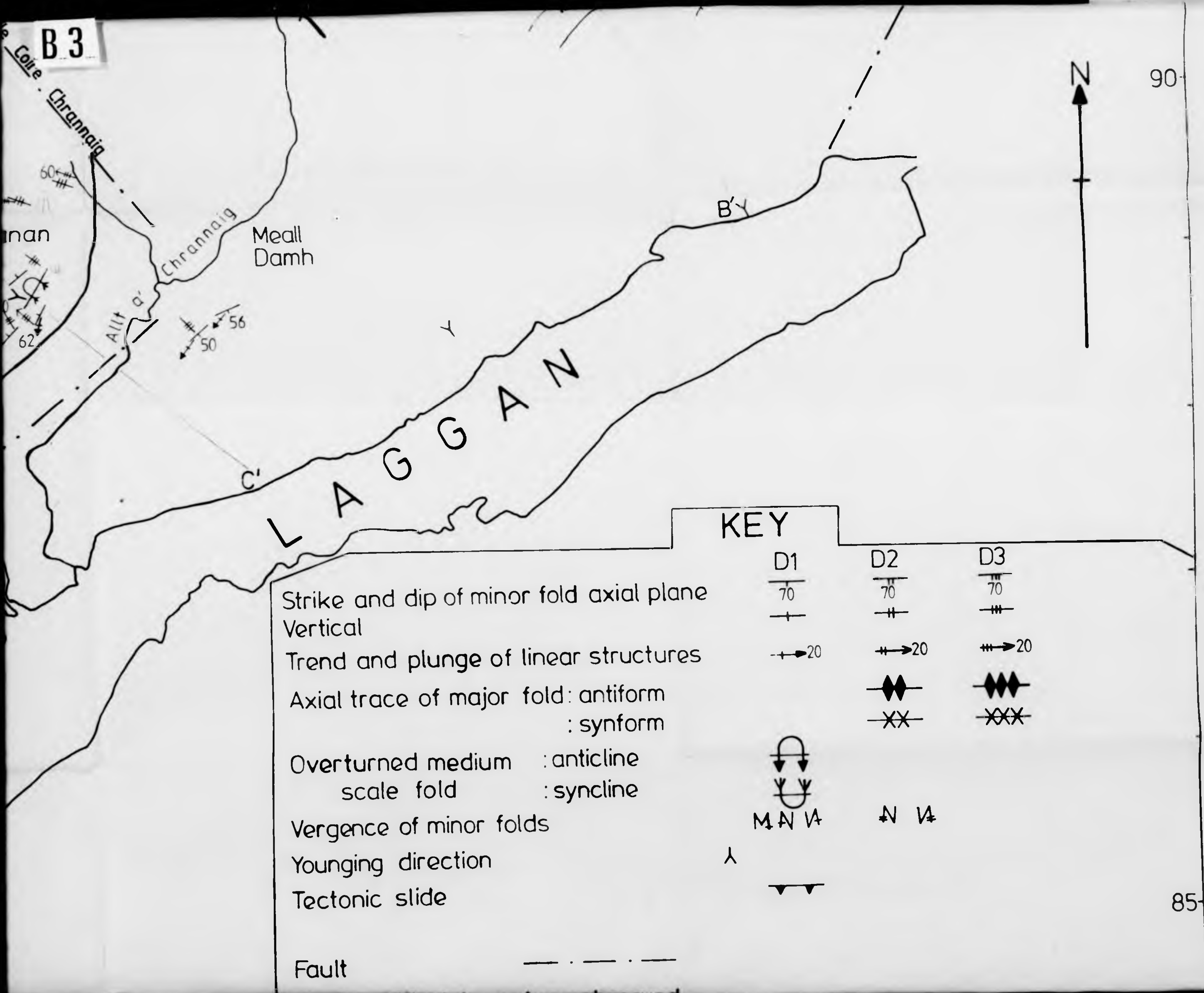
LAGGAN-UPPER STRATHSPEY AREA





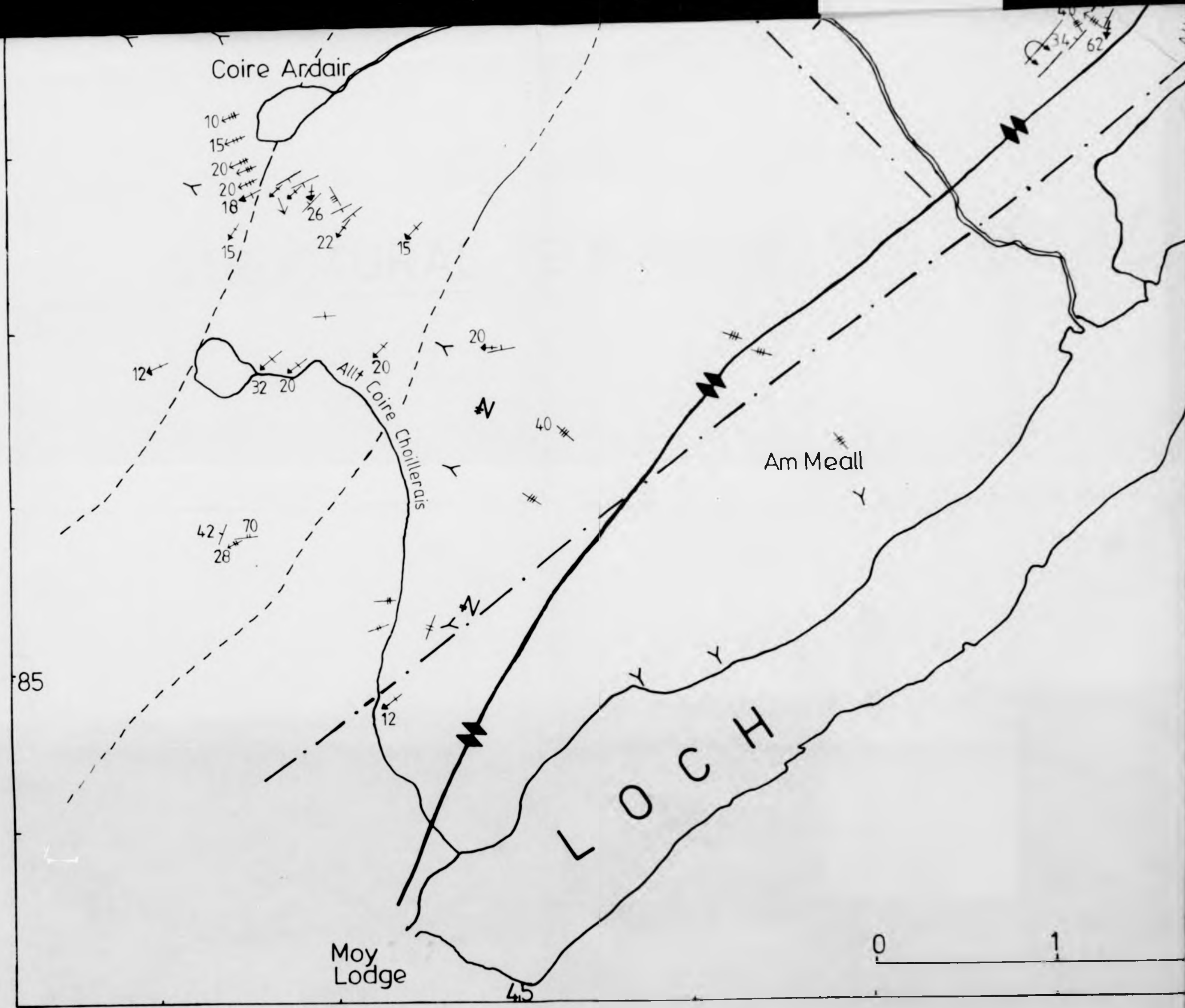
B1
90
85
Carn Liath
C
Coire Chrannaig
Na Cnapanan
Allt Coire Ardair
Coire Ardair
Allt Coire Choillerais
Am Meall


B2
Carn Liath
C
C'
Coire Chrannaig
Na Cnapanan
Meall Damh
Allt Coire Ardair
Allt a' Chrannaig
rdair
LAGGAN
Am Meall
Allt Coire Choillerais
Strike and dip of minor fold axial plane
Vertical
Trend and plunge of linear structures
Axial trace of major fold: antiform
: synform
Overturned medium scale fold : anticline
: syncline
Vergence of minor folds
Younging direction
Tectonic slide
Fault

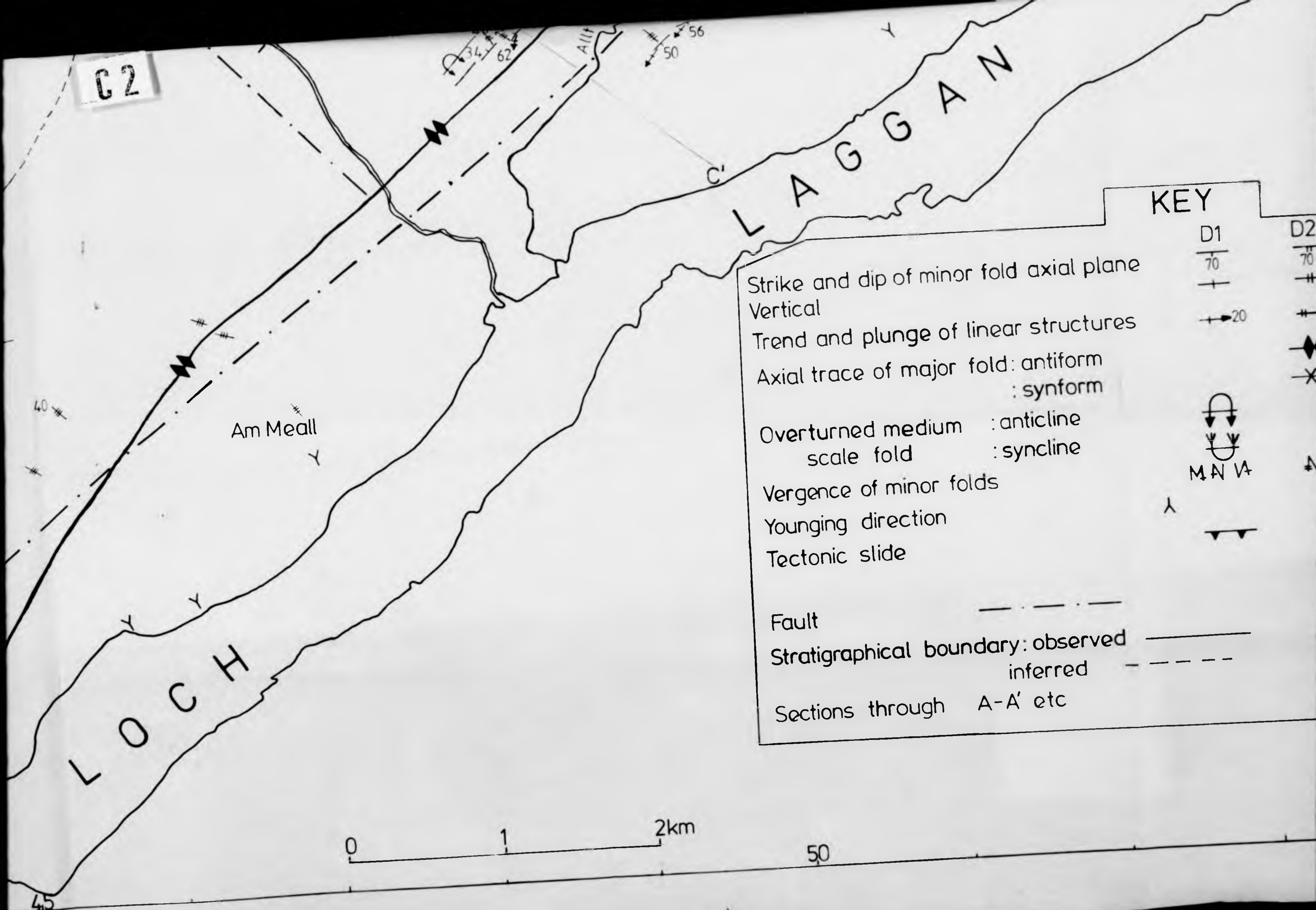


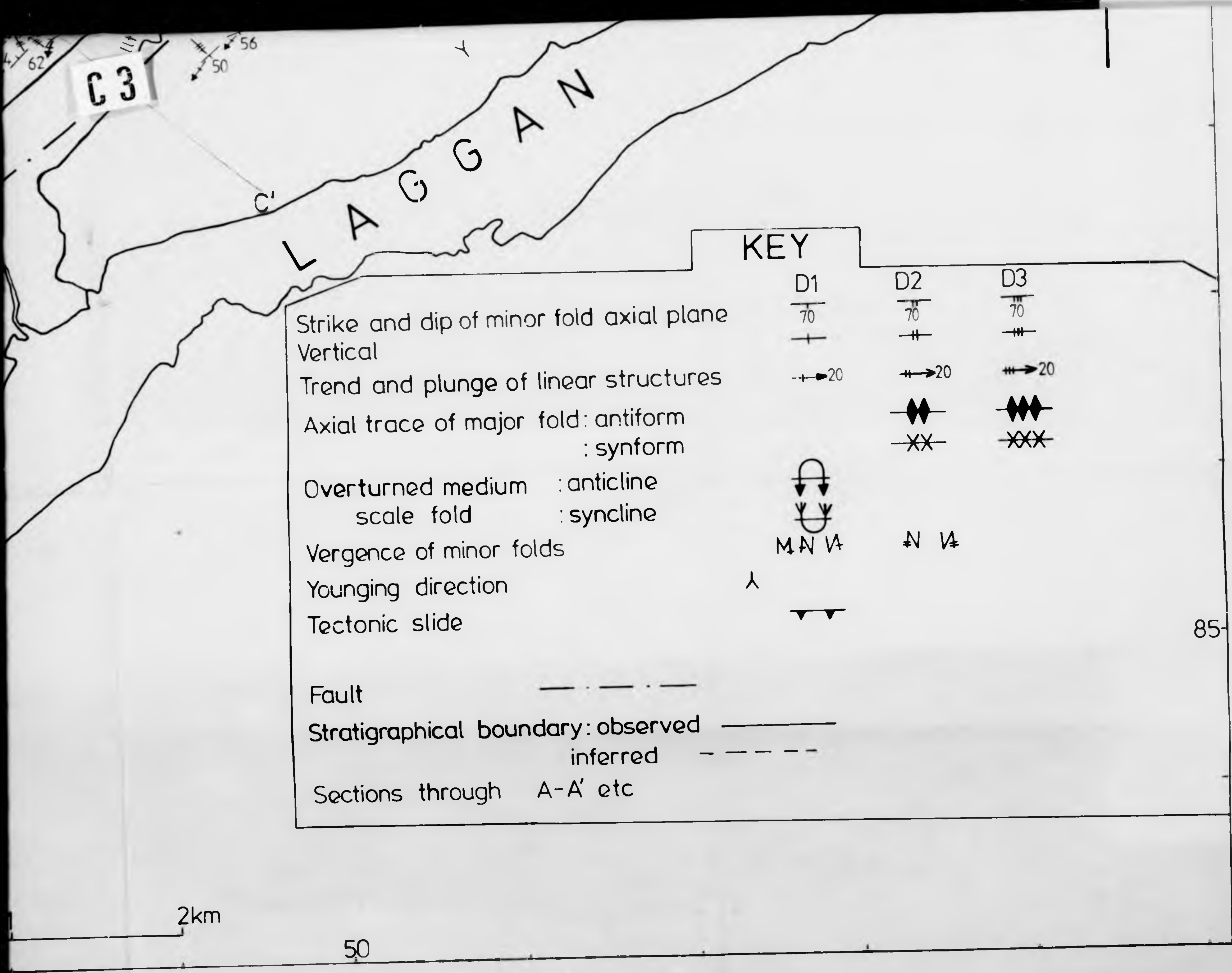
B 3
Coire Chrannaig
Chrannaig
Allt a'
Meall Damh
60
56
50
62
B'
C'
LAGGAN
N
90
85
KEY
D1
D2
D3
70
Strike and dip of minor fold axial plane
Vertical
Trend and plunge of linear structures
20
Axial trace of major fold : antiform
: synform
Overturned medium scale fold : anticline
: syncline
Vergence of minor folds
Younging direction
Tectonic slide
Fault

C 1



Coire Ardair
Allt Coire Choillerais
Am Meall
LOCH
Moy Lodge
85
45
0
1

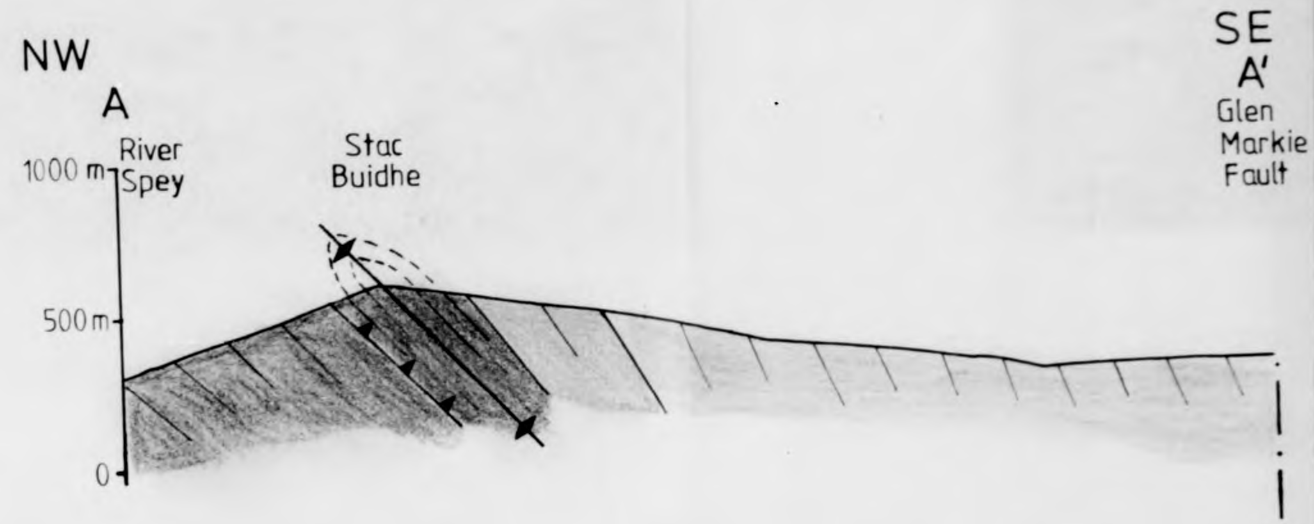

C2
LOCH LAGGAN
Am Meall
C'
KEY
D1
D2
Strike and dip of minor fold axial plane
Vertical
Trend and plunge of linear structures
Axial trace of major fold: antiform
: synform
Overturned medium scale fold : anticline
: syncline
Vergence of minor folds
Younging direction
Tectonic slide
Fault
Stratigraphical boundary: observed
inferred
Sections through A-A' etc
0
1
2km
50
45

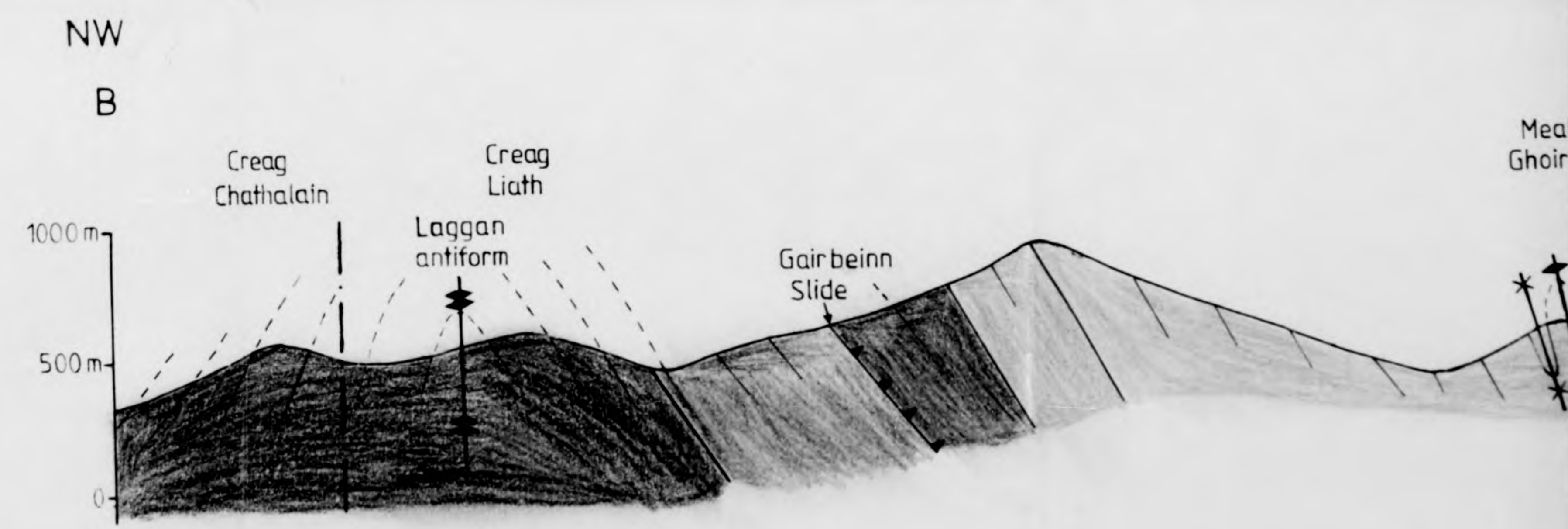


C 3
LAGGAN
C'
56
50
62
KEY
D1
D2
D3
Strike and dip of minor fold axial plane
70
Vertical
Trend and plunge of linear structures
20
Axial trace of major fold: antiform
: synform
Overturned medium scale fold
: anticline
: syncline
Vergence of minor folds
Younging direction
Tectonic slide
Fault
Stratigraphical boundary: observed
inferred
Sections through A-A' etc
85
2km
50

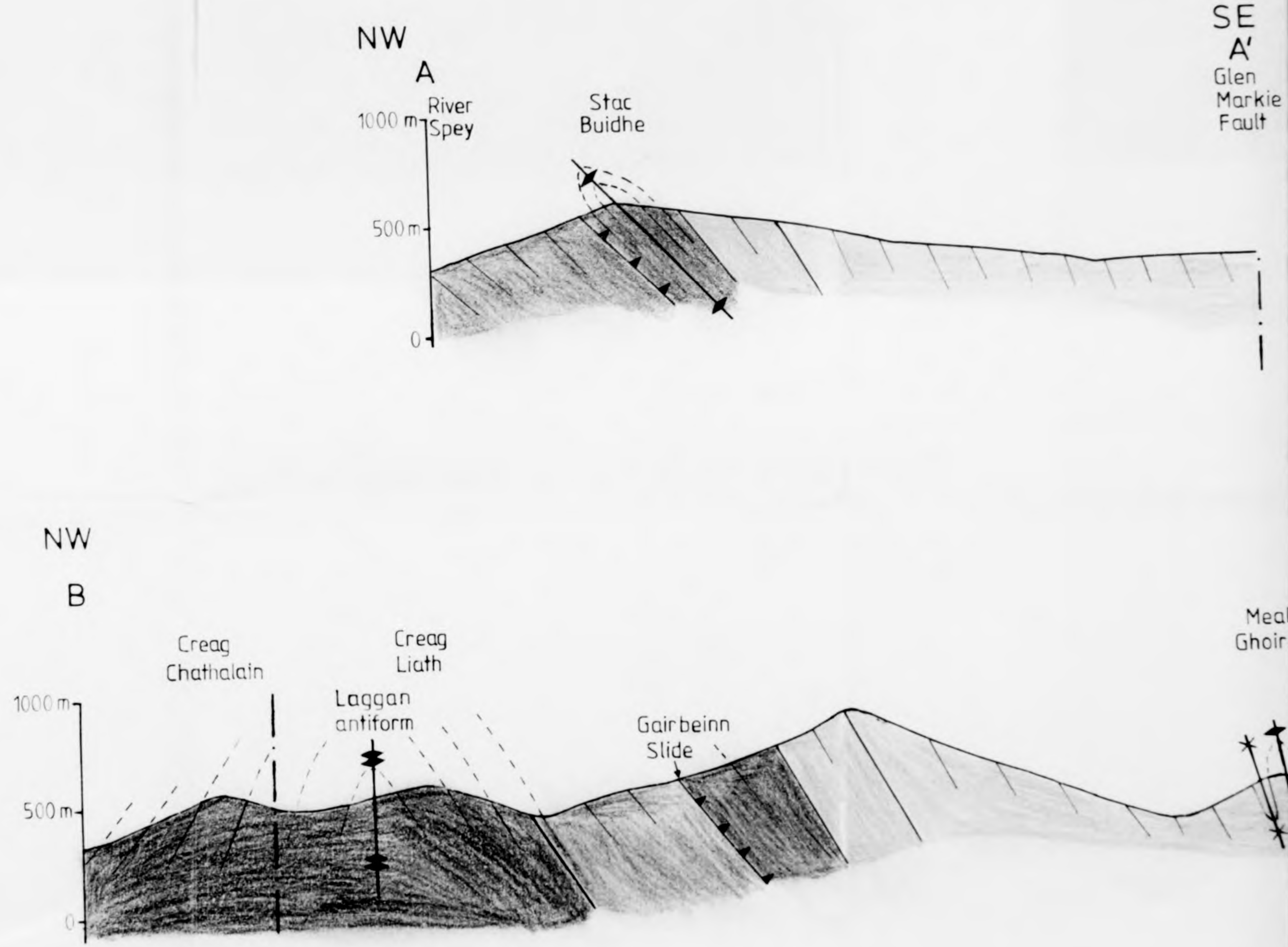
3

A1


NW
A
SE
A'
River Spey
Stac Buidhe
Glen Markie Fault
1000 m
500 m
0

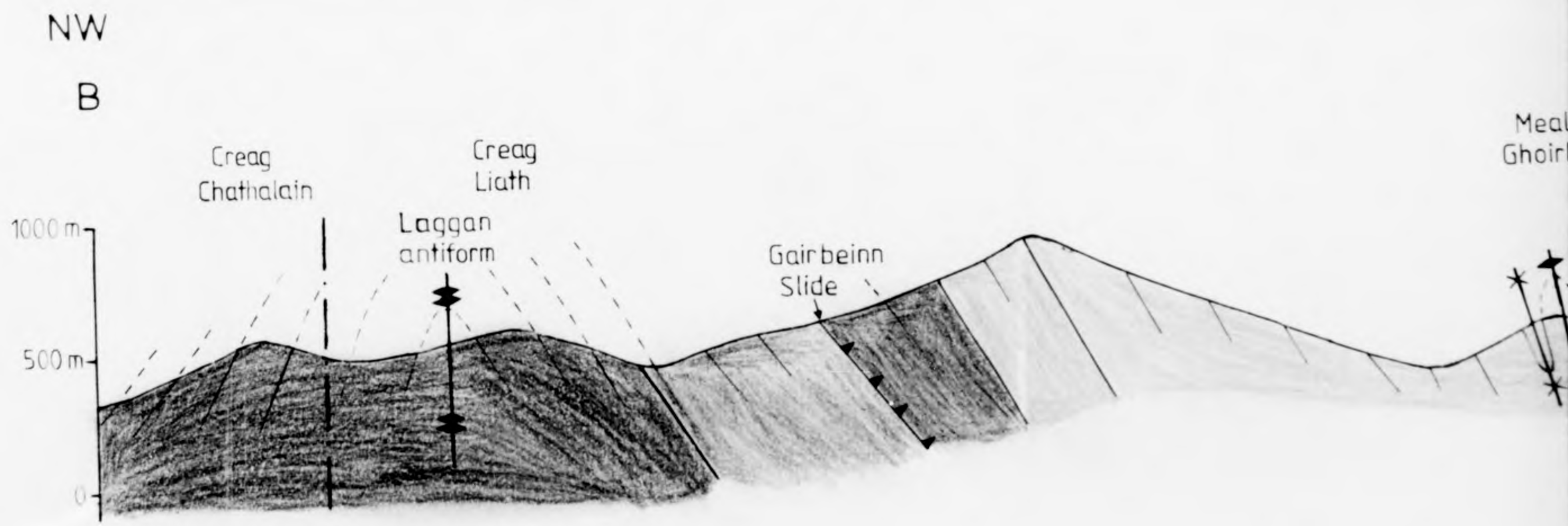

NW
B
Creag Chathalain
Creag Liath
Laggan antiform
Gairbeinn Slide
1000 m
500 m
0

A1

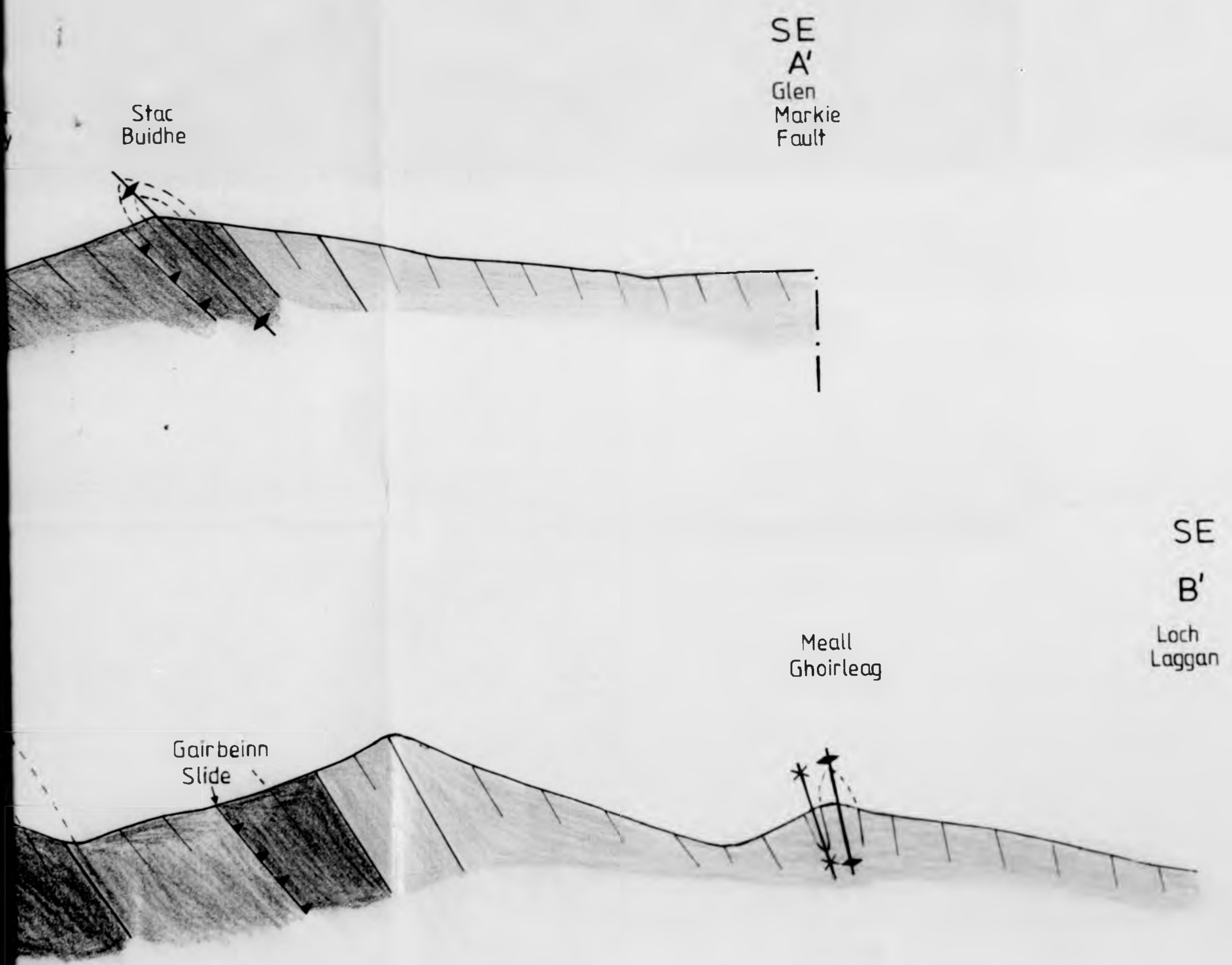

NW
A
River
Spey
Stac
Buidhe
SE
A'
Glen
Markie
Fault
1000 m
500 m
0
NW
B
Creag
Chathalain
Creag
Liath
Laggan
antiform
Gairbeinn
Slide
1000 m
500 m
0

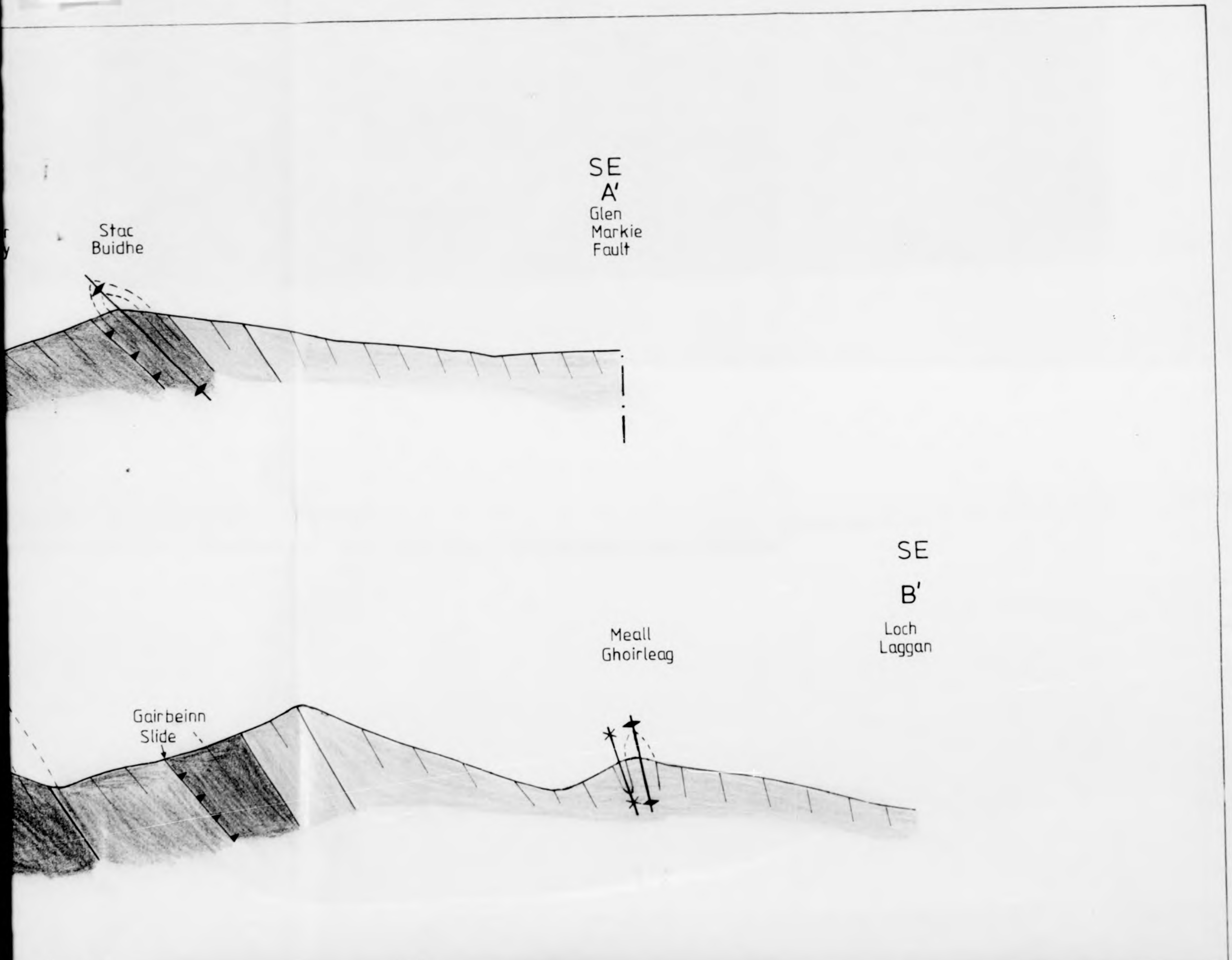
A1


NW
A
River Spey
Stac Buidhe
1000 m
500 m
0
SE
A'
Glen Markie Fault

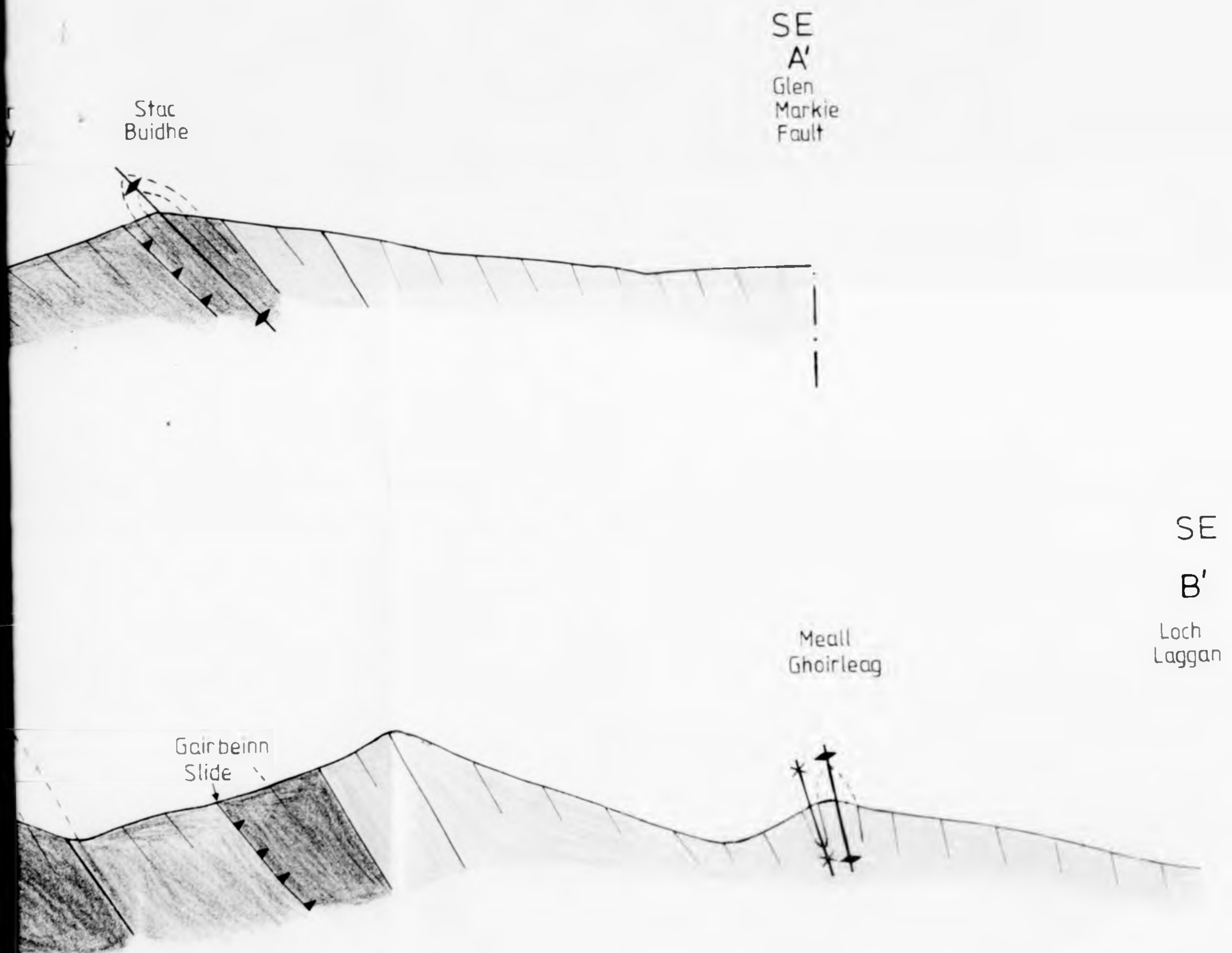

NW
B
Creag Chathalain
Creag Liath
Laggan antiform
Gairbeinn Slide
1000 m
500 m
0
Meal
Ghoir

A2

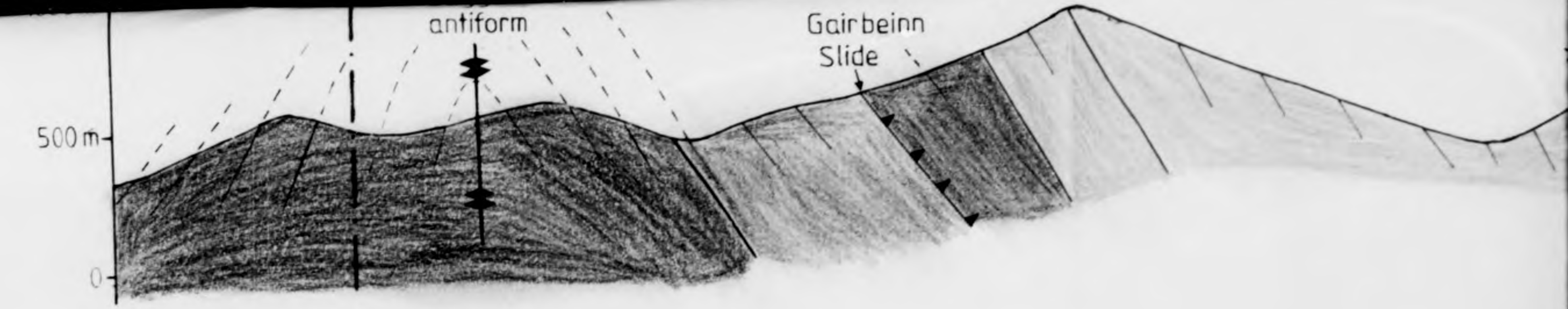

SE
A'
Glen
Markie
Fault
Stac
Buidhe
SE
B'
Loch
Laggan
Meall
Ghoirleag
Gairbeinn
Slide


SE
A′
Glen Markie Fault
Stac Buidhe
SE
B′
Loch Laggan
Meall Ghoirleag
Gairbeinn Slide

A2

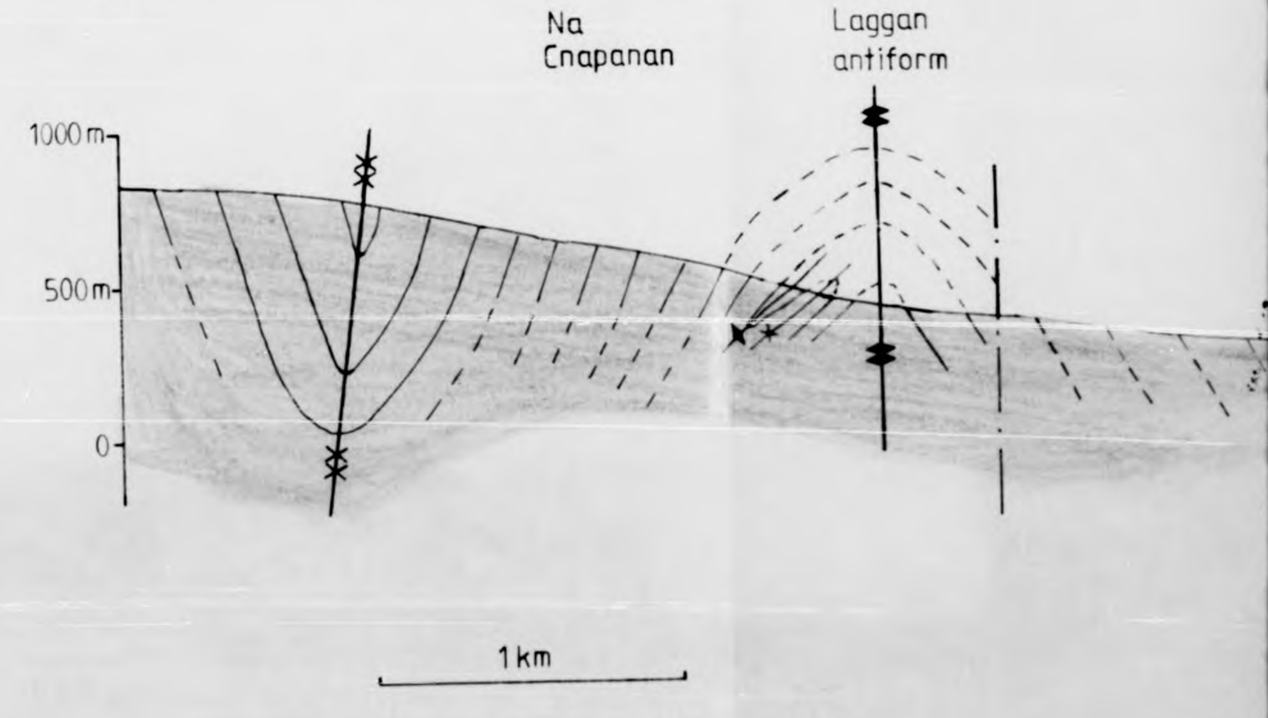

SE
A'
Glen
Markie
Fault
Stac
Buidhe
SE
B'
Loch
Laggan
Meall
Ghoirleag
Gairbeinn
Slide

B1

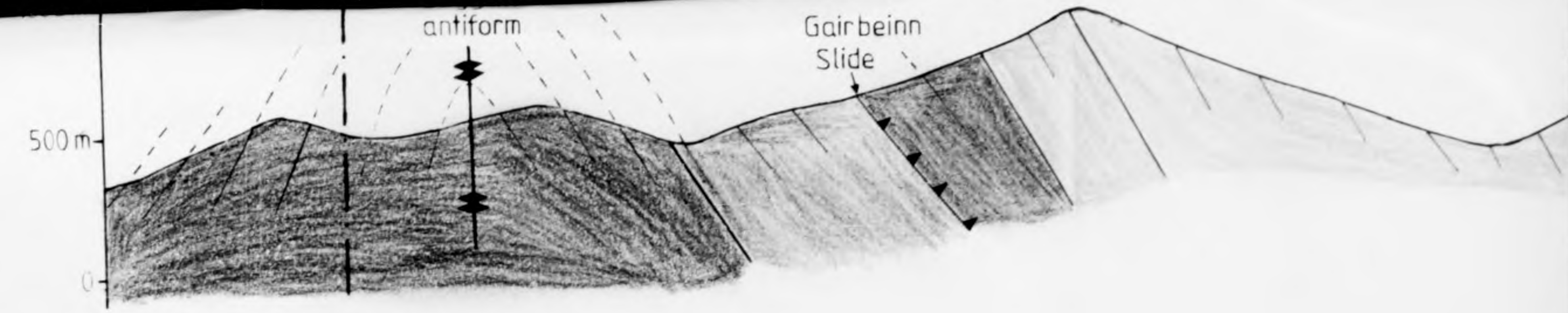

antiform
Gairbeinn
Slide
500 m
0

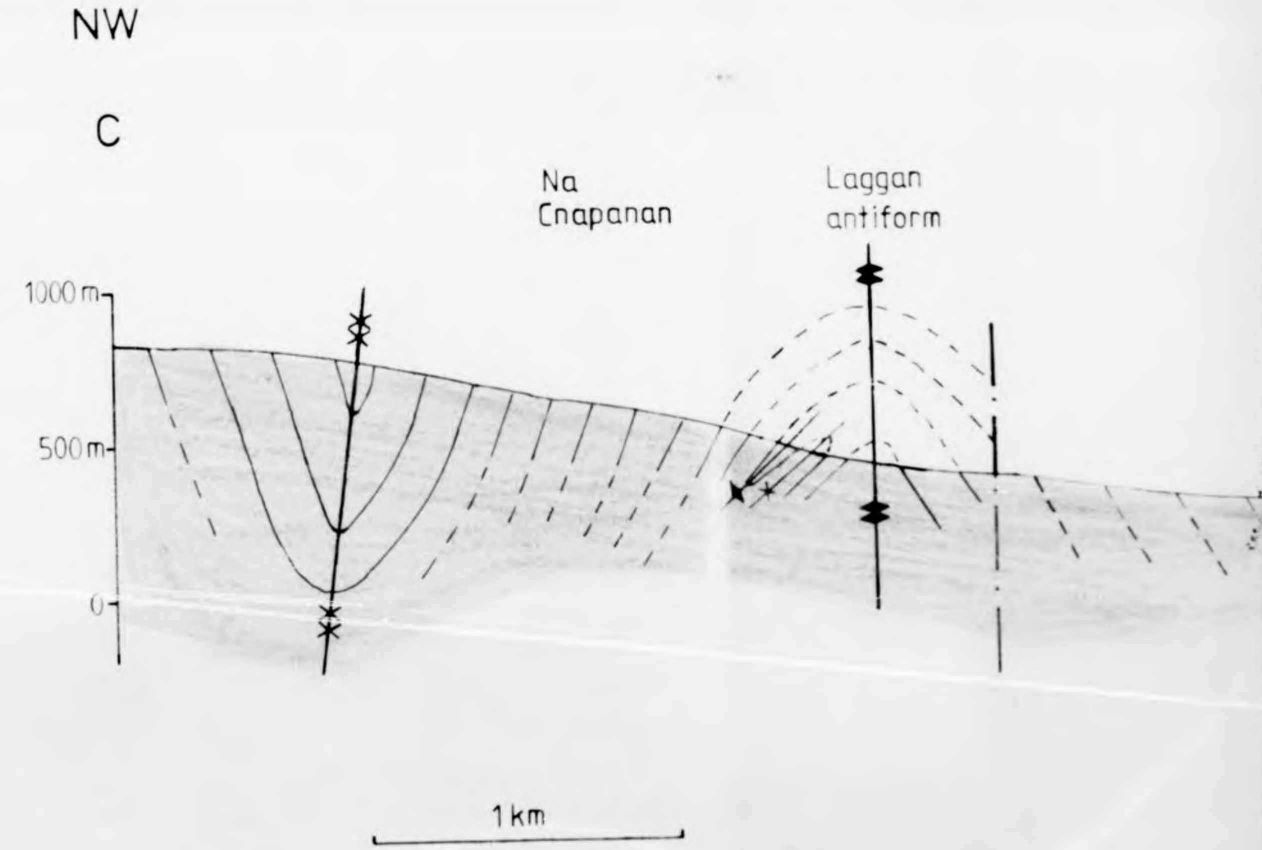
NW

C


Na
Cnapanan
Laggan
antiform
1000 m
500 m
0
1 km

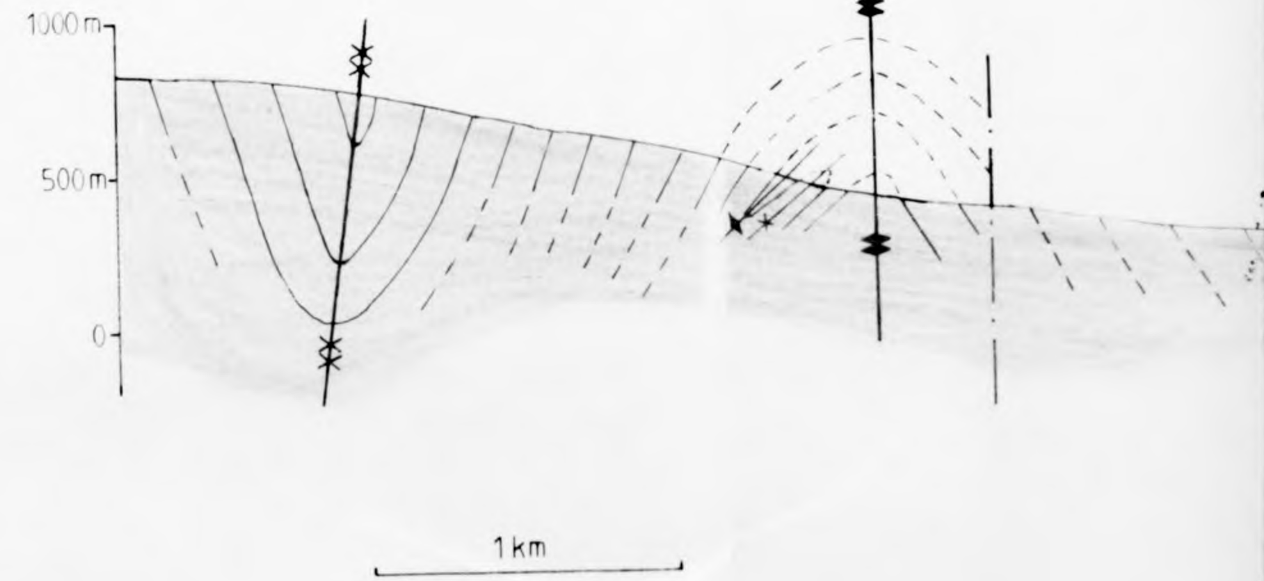
B1

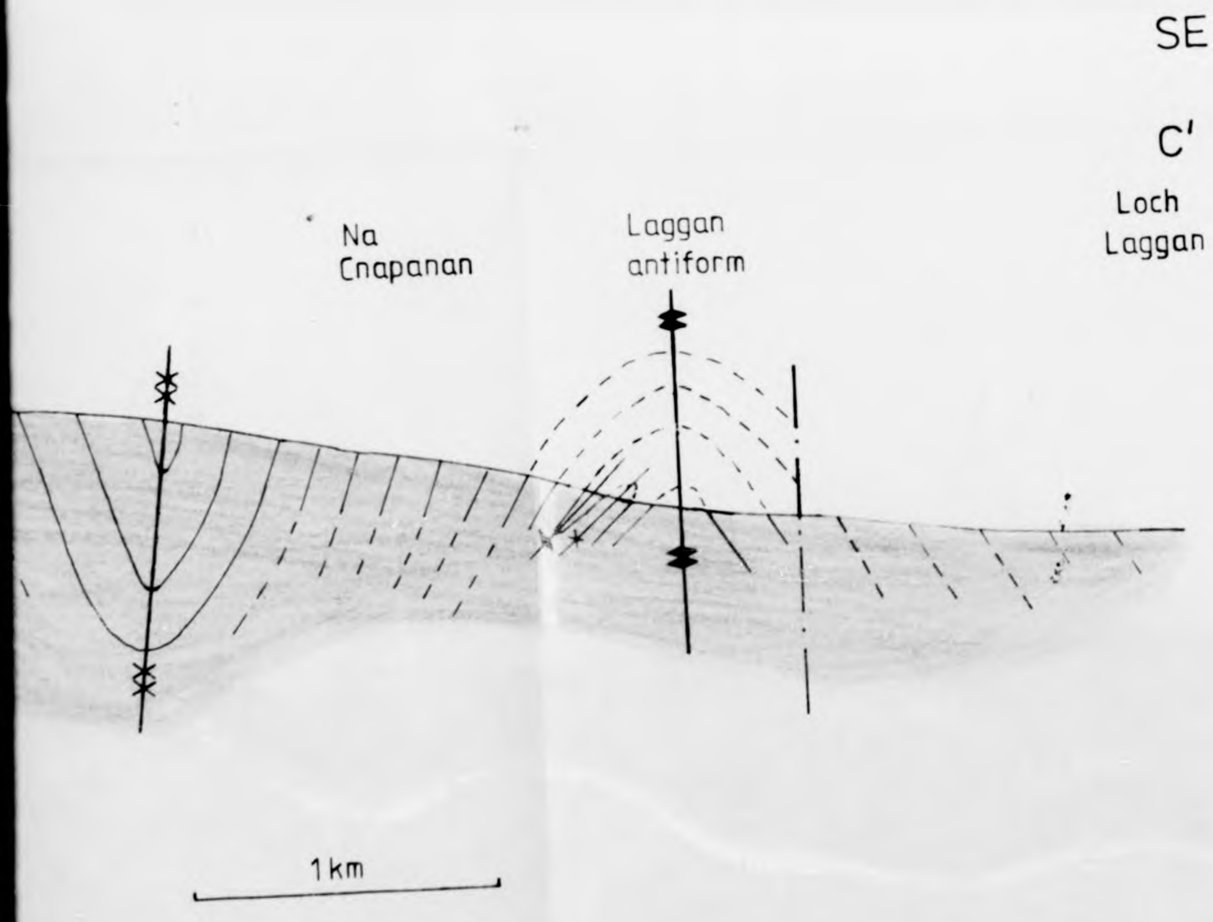

antiform
Gairbeinn
Slide
500 m
0


NW
C
Na
Cnapanan
Laggan
antiform
1000 m
500 m
0
1 km

B1


antiform
Gairbeinn
Slide
500 m
0


NW
C
Na
Cnapanan
Laggan
antiform
1000 m
500 m
0
1 km



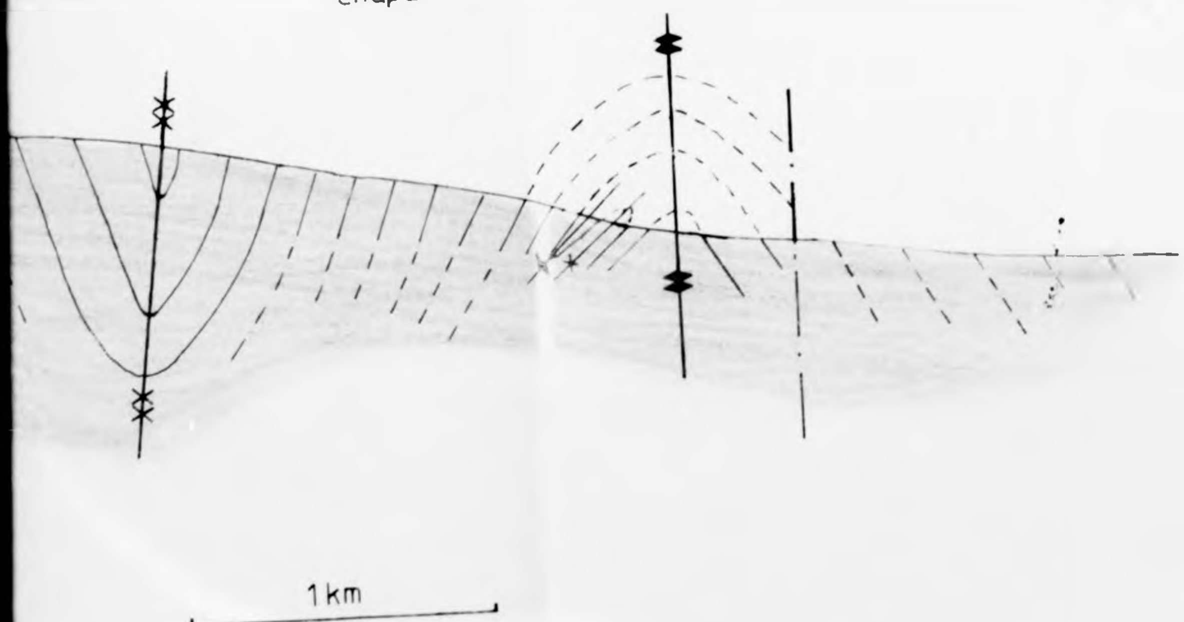
Stratigraphy as on Map 1

Location of sections shown on Map 2

Key as on Map 2

SE

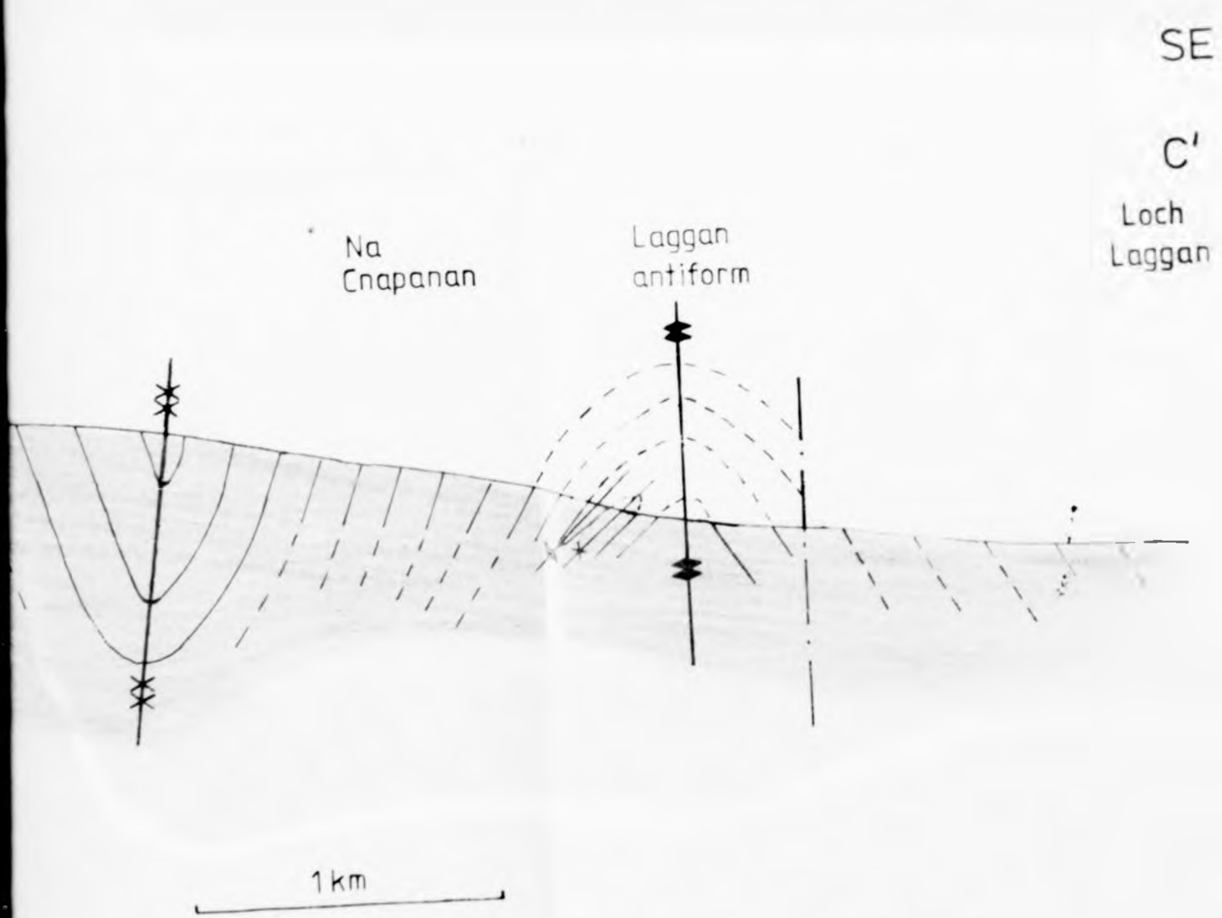
C′



Stratigraphy as on Map 1

Location of sections shown on Map 2

Key as on Map 2



Stratigraphy as on Map 1

Location of sections shown on Map 2

Key as on Map 2