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# Stratigraphy and geochemistry of volcanic mass flows in the Stac Fada Member of the Stoer Group, Torridonian, NW Scotland

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ABSTRACT: The Stac Fada Member, which forms part of the Stoer Group, contains the only definitive evidence of volcanic activity within the thick Torridonian succession. At the type area in the Bay of Stoer, four volcanic-rich sandy mudstone units are recognised in the Stac Fada. An irregular erosional contact at the base of the main Stac Fada unit truncates two thinner layers of similar volcanic-rich material that were formerly interpreted as intrusions. Directional sedimentary structures associated with the Stac Fada mass flows, and the distribution and thickness of an accretionary or armoured lapilli tuff, support the existence of at least two volcanic sources. Geochemical evidence suggests that the thick Stac Fada unit at the Bay of Stoer and comparable units to the SW were derived from the same volcanic centre. The chemical composititon of volcanic fragments in the main Stac Fada unit indicates that their potassic nature is not a primary feature but is due to alteration and subsequent metasomatism.

KEY WORDS: Proterozoic, provenance, sedimentation, volcanism

The Torridonian of NW Scotland comprises a thick succession of sandstones, mudstones, conglomerate/breccias, minor limestones and volcanic rocks. It has been divided (Stewart 1991a) into three groups, the oldest of which is the Stoer Group. The age of the rocks of the Stoer Group is poorly constrained, but they are probably about 1·2 Ga (Turnbull *et al.* 1996). Locally preserved rocks of the Stoer Group are overlain by the much more widespread Torridon Group rocks, which have yielded Rb/Sr isochrons of about 1·0 Ga (Turnbull *et al.* 1996). The third group, the Sleat Group, is only known from a thrust panel, the Kishorn nappe, in the southern part of the Torridonian belt. Since the rocks of the Sleat Group appear to be conformable with the Torridon Group, they also are considered to be younger than the Stoer Group rocks, although contacts between the Stoer and Sleat Groups are not seen. The Stac Fada Member (Stewart 1990a,b) is of interest because it is the only Torridonian unit with a well-documented volcanic component. There has been considerable discussion as to the mode of emplacement of the Stac Fada (volcanic-influenced mass flow deposit or peperitic intrusion) and as to whether it constitutes a single correlatable unit along its *c.* 50 km strike length from the Stoer area to Poolewe (Fig.1). In this study, new field observations and geochemical data are used in an attempt to resolve some of these questions and to establish the provenance of the stratigraphic units that make up the Stac Fada Member.

Lawson (1972) provided the first detailed description and interpretation of the Stac Fada Member. He considered it to be an ash flow deposit that represents a single correlatable unit. Davison & Hambrey (1996) argued that there might be several volcanic horizons within the Stoer Group. Because the Stac Fada is commonly overlain by carbonate-bearing rocks, which are rare in the Stoer Group, Stewart (1997) favoured a single volcanic horizon, although he did describe it as a 'multi-storey' volcanic mudflow. Opinions differ as to the origin and mode of emplacement of the Stac Fada. Sanders & Johnston (1989) interpreted the unit as an extrusion that rose to the surface as a slurry generated by phreatomagmatic activity during the passage of mafic magma through still-wet sediments comprising the lower part of the Stoer Group.

## 1. Stratigraphic context

The Stoer Group is well exposed along the foreshore on the northern side of the Bay of Stoer (Figs 1, 2). In this area rocks of the Stoer Group strike in a northerly direction and dip at about 20° to the W (Stewart 1991b). To the NW, rocks of the Torridon Group unconformably overlie the Stoer Group. A schematic stratigraphic column (Fig. 3, after Stewart 1991b) shows that the Stac Fada Member occurs within a succession of mainly siliciclastic rocks, comprising basal breccias, conglomerates and sandstones, together with subordinate mudstones and limestones. It occurs at the transition between the sandstone-dominated part of the Bay of Stoer Formation and red and grey mudstones of the Poll a' Mhuilt Member, which forms the upper part of the same formation. At the type area near Stoer (Figs 2, 3) and also on the southern side of Enard Bay (Fig. 1) the Stac Fada is overlain by carbonate-rich mudstones.

## 2. Previous work

Lawson (1972) carried out petrographic examinations and described angular volcanic fragments including pumice, shards and devitrified glass palagonite. He considered the *c.* 12 m-thick Stac Fada Member to provide a marker horizon from Stoer to Poolewe in the SW (Fig. 1). Lawson (1972) considered the Stac Fada to be an ash flow resulting from a highly explosive phreatic eruption. Because of the presence of a relatively thick airfall lapilli tuff unit in the vicinity of Enard Bay, Lawson thought that the source of volcanic detritus may have been near that area.

Sanders & Johnston (1989) described a small, apparently stratigraphically lower body of volcanic-rich material at the

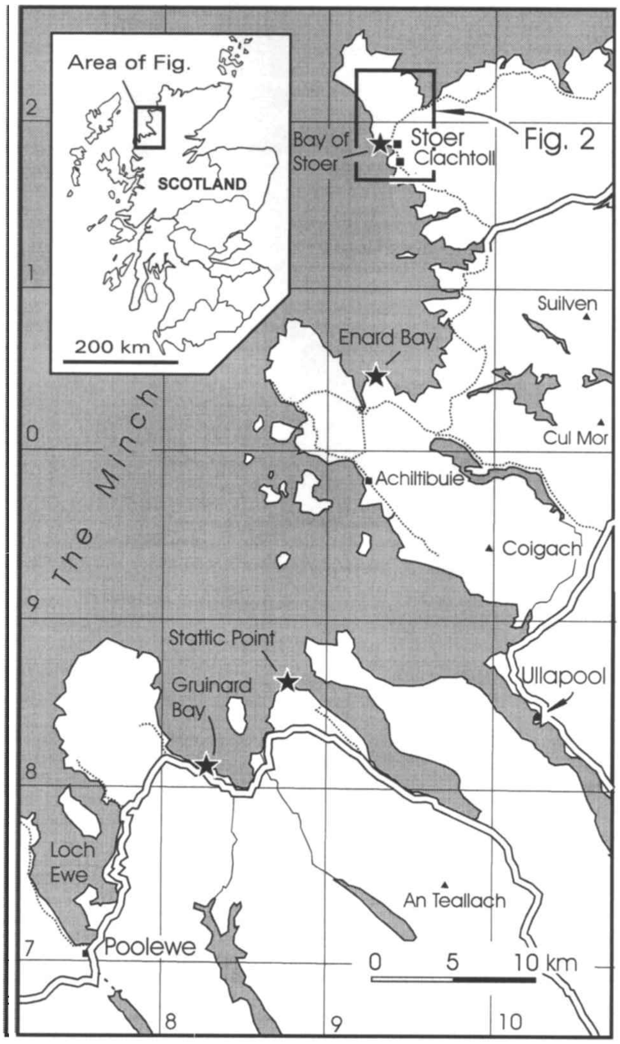

**Figure 1** Map to show the location of coastal outcrops of the Stac Fada Member referred to in the text (stars); the type area is at the Bay of Stoer, which is shown in more detail in Figure 2.

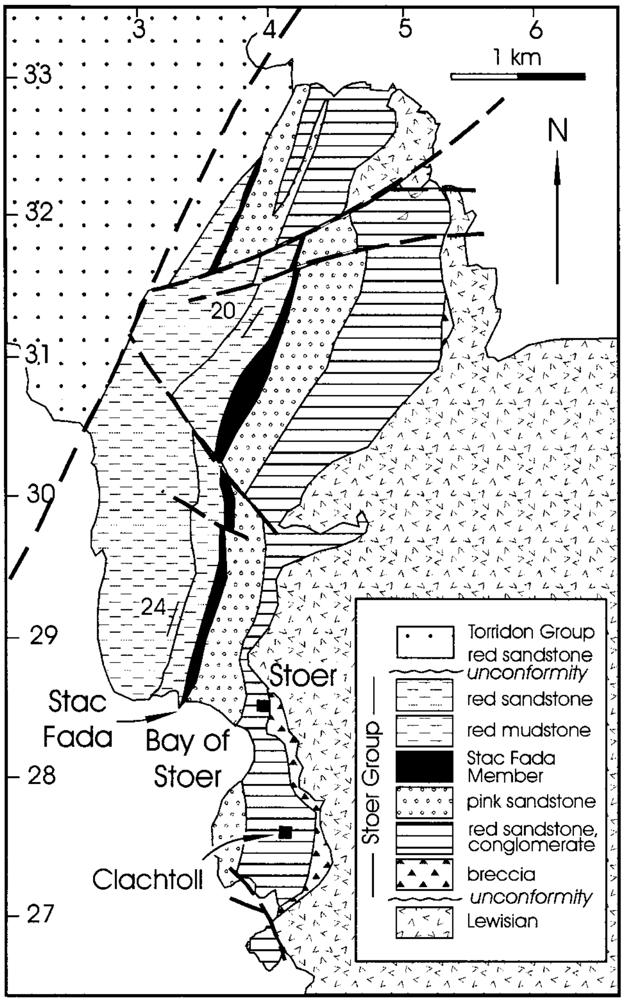

**Figure 2** Geological sketch map (after Stewart 1991b) to show the distribution of the Stac Fada Member (black ornament) in the type area of the Stoer Peninsula; the best exposures are at Stac Fada in the Bay of Stoer; note the angular unconformity between the rocks of the Torridon Group and the underlying Stoer Group in the northern part of the map.

Bay of Stoer locality. The small, more easterly body was interpreted as a feeder and the main, upper body, which contains some highly deformed sandstone 'rafts', was thought to be the updomed, ruptured and fragmented top of a laccolithic 'blister'. According to this model, the magma intruded the sedimentary rocks of the Stoer Group when they were still poorly consolidated. Rapid expansion of heated pore water was thought to have caused fluidisation, fragmentation of the volcanic material and development of a peperitic slurry.

Stewart (1990a) noted some chemical similarities between the Stac Fada and associated muddy sandstones and siltstones of the Stoer Group. A model age of *c.* 2·2 Ga for the materials making up the Stac Fada Member was interpreted as being due to mixing of young volcanic material with materials derived from the older Lewisian basement.

## 3. Description and reinterpretation of the Stac Fada Member at the Bay of Stoer

The Stac Fada Member is a mixture of generally small (millimetres to a few centimetres) dark-green volcanic fragments, rare gneiss clasts (some up to 50 cm across) and generally ragged-looking mudstone and sandstone fragments in a purple sandy-muddy matrix. In this investigation, the Stac Fada Member is divided into four units as shown in Figure 4. The stratigraphically lowest occurrence (SF1) corresponds to the lower of the two units described by Sanders & Johnston (1989). Their upper unit has been divided into three separate stratigraphic units called SF2, SF3 and SF4. In previous investigations (Lawson 1972; Stewart 1991b) units SF2 and SF3 were considered to be 'injections' from the main part of the Stac Fada into the associated sandstones and mudstones, but these are here interpreted as separate stratigraphic units and the main part of the Stac Fada Member, unit 4 of this study, is considered to have an erosive (as opposed to intrusive) contact with the subjacent units.

### 3.1. Stac Fada unit 1

The stratigraphically lowest occurrence of volcaniclastic material (Stac Fada of Fig. 4) is up to about 3 m thick. The contact on the E side of the outcrop is generally concordant but is locally erosive. Small fold structures are present in the underlying beds. The base of SF1 is a thin (*c.* 10 cm) granular and pebbly sandstone that passes upward into the typical volcanic fragment-rich material of the Stac Fada. The basal few centimetres contain many small sandstone and mudstone clasts and the main body includes bedded sandstone clasts up to 40 cm across. The western contact is more difficult to interpret, for the Stac Fada rocks appear to abut laterally against sandstones and mudstones. This contact was thought by Sanders & Johnston (1989) to be intrusive and they considered SF1 to

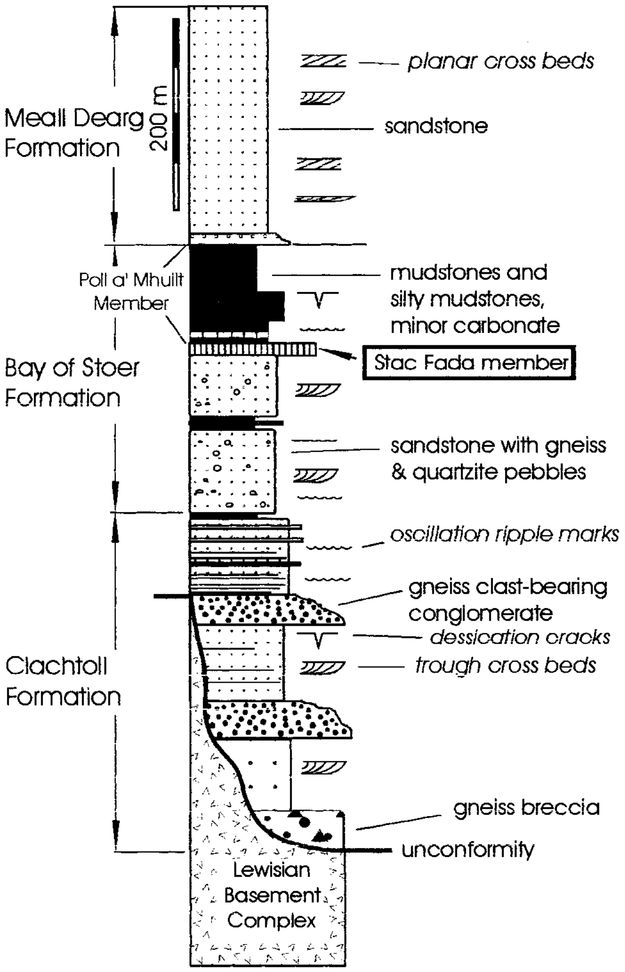

**Figure 3** Generalised stratigraphic column (after Stewart 1982; Stewart 1991b) to show the stratigraphy of the Stoer Group at the type locality for the Stac Fada Member at the Bay of Stoer..

be a feeder to the overlying unit. Stewart (1990b), in discussing Sanders & Johnston (1989), considered SF1 to be a strike fault repetition of the main Stac Fada (unit SF4 of this paper). Inspection of the critical relationships at low tide, indicates that this interpretation is correct. The age of the fault is unknown, but if it were considered to be an early structure then it might be interpreted as a southward-directed thrust.

### 3.2. Stac Fada unit 2

The stratigraphical interval between Stac Fada 1 and Stac Fada 2 comprises about 7 m of purple mudstones and pink sandstones. Oscillation ripple marks and desiccation cracks attest to a shallow-to-emergent depositional setting. Convolute bedding and cross-bedding are common in the sandstones. Some thin-bedded sandstone–mudstone couplets contain small gneiss pebbles and rip-up clasts of sandstone. The second volcanic-rich unit (SF2) is about 1·5 m thick at its southern end but thins to a few centimetres to the N, over a distance of about 10 m. Unit SF2 has a generally planar and conformable upper surface, but there is a locally erosive contact with the underlying sandstones. The basal contact locally displays small asymmetrical folds with slightly steeper dips on their S limb (Fig. 5a,b) and flame structures (Fig. 5c) that suggest transport towards the S. The fold axes trend between 84° and 140°. These folds are thought to be syn-sedimentary, for the rocks of the Stoer Group show little evidence of tectonic folding. To the S unit SF2 is erosionally truncated by the main body of the Stac Fada Member SF4, which contains many large contorted sandstone clasts (Fig. 5d). Thus unit SF2 is a wedge-shaped, southward-thickening body of volcanic-clast-bearing sedimentary material. Associated folds and flame structures suggest southwesterly transport. Thus unit SF2 is not an intrusive apophysis of the main Stac Fada unit (SF4), as previously thought (Lawson 1972; Sanders & Johnston 1989; Stewart 1990b) but was deposited as a discrete sedimentary unit before deposition of the main Stac Fada unit.

### 3.3. Stac Fada unit 3

This unit consists of a few centimetres of purple mudstone and granule conglomerate containing scattered well-rounded gneiss clasts up to 40 cm in diametre (Fig. 5e). Together with the enclosing sandstones SF3 is truncated at its southern end by the main Stac Fada unit, SF4 (Fig. 5e). Unit SF3 can be traced northwards for tens of metres where it is present in a sea cliff. Green volcanic shards, which are common in the muddy matrix material, establish its affinity with the Stac Fada Member. Large basement clasts (Fig. 5e) are underlain by muddy granule conglomerate and covered by a thin veneer of purple mudstone. This unit was noted by Sanders & Johnston (1989) but they did not offer an explanation of its origin. Stewart (1990b; 1991b) suggested that SF3, like the thicker underlying SF2 unit, was possibly emplaced as an injection or intrusion. Several gneiss clasts have dimensions that are much greater than the thickness of the associated bed. Intrusion of such large clasts would have presumably caused considerable disruption of the enclosing beds. The sandstones immediately underlying SF3 (but not above it) exhibit contorted bedding and flame structures (Fig. 5f). The flames verge towards the S, in the opposite direction to that expected from disturbance related to injection from the main SF4 unit. Rather than being an intrusion, unit SF3 is interpreted as a sedimentary layer produced by mixing of volcanic materials with mud, sand and gravel as part of a small-scale debris flow event. The large gneiss fragments attest to the initial strength of the current, but they were dropped and draped by mud during waning stages of the emplacement. The rounded nature of some of the clasts in the Stac Fada was interpreted by Sanders & Johnston (1989) to indicate that they were incorporated by vertical transportation from coarse gravels in the lower part of the Stoer Group as the magma rose through the unconsolidated sediment pile before erupting on the surface. Alternatively, they could have been incorporated into a flash flood as it traversed coarse gravels that formed marginal facies of the depositional basin (Stewart 1991b). Deformation structures in sandstones beneath SF3 (Fig. 5e) could indicate violent emplacement, or they could have been produced by contemporaneous seismic activity. The upper surface of a sandstone bed, about 20 cm above SF3, displays abundant flat purple mudstone clasts, indicating exposure and desiccation, so that a shallow water to subaerial depositional setting is indicated.

### 3.4. Stac Fada unit 4 on the northern shore of the Bay of Stoer

The distribution of unit 4, which constitutes the major mappable part of the Stac Fada Member, is shown in Figure 2 (after Stewart 1991b). The stratigraphic context is shown in Figure 3 and a more detailed stratigraphic column is illustrated in Figure 4. In the type exposures at the Bay of Stoer, the unit is about 12 m thick. It is mainly massive in appearance, consisting of scattered clasts of purple mudstone and sandstone, together with abundant, generally small, green, irregular-shaped volcanic clasts and rare gneiss clasts in a dark grey-green-weathering purple matrix of sand- and mud-sized particles, including small volcanic shards.

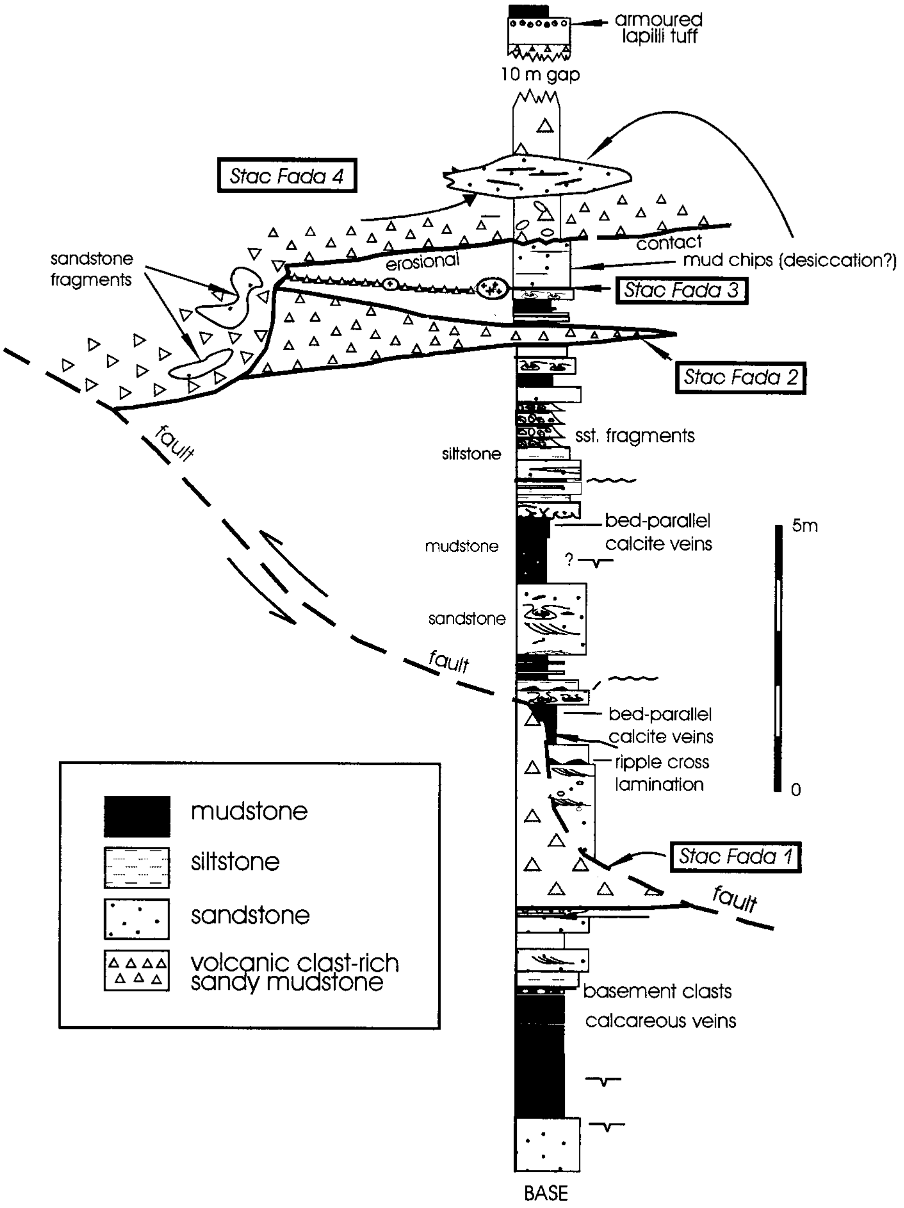

**Figure 4** Measured section of the Stac Fada Member and enclosing strata at the type area on the northern shore of the Bay of Stoer; inferred stratigraphic relationships among the four units of the Stac Fada Member are illustrated; see text for explanation.

In this area, the lower part of the main Stac Fada Member contains a number of large (up to 16 m×1 m) clasts of sandstones (Fig. 6). Some of these are obviously locally derived, since they show characteristics identical to those of underlying sandstones. Some of the sandstones and mudstones are chaotically deformed, but others display N-verging folds (Fig. 6). Others, such as the sandstone 'raft' labelled in Figure 6, are relatively undeformed and intact. The erosional nature of the base of SF4 is clearly shown in Figure 6, where it truncates the underlying sandstones and unit SF2. At Stoer Bay the top of SF4 is characterised by the presence of a fine-grained unit containing centimetre-sized spherical bodies interpreted as accretionary lapilli (Lawson 1972), formed due to airfall of ash and other materials through a water-rich atmosphere.

### 3.5. Summary of directional indicators in the Stac Fada

At the type locality at Stoer Bay unit 2 displays small-scale contemporaneous asymmetrical folds (axes trend between 84° and 140°) and flame structures suggesting transport towards the S. In the same area sandstones below unit 3 exhibit S-verging flame structures. The main body of the Stac Fada (unit 4), however, contains chaotically folded sandstones and mudstones, but some of the folds are N-verging as shown in Figure 6. No directional structures were noted in the same unit at the Enard Bay locality, but at Stattic Point near Badluchrach Lawson reported penecontemporaneously deformed sandstones that he interpreted to indicate transport to the SW. These data are interpreted in Section 6.

## 4. The Enard Bay (Coigach) locality

On the southern side of Enard Bay (Fig. 1) the Stac Fada Member is over 20 m in thickness. In this area the Stac Fada directly overlies basin-marginal breccias and conglomerates of the Stoer Group, whereas in the type locality at Stoer a thick succession of sandstones and minor mudstones intervenes (Fig. 3). The lower part includes some large sandstone rafts and

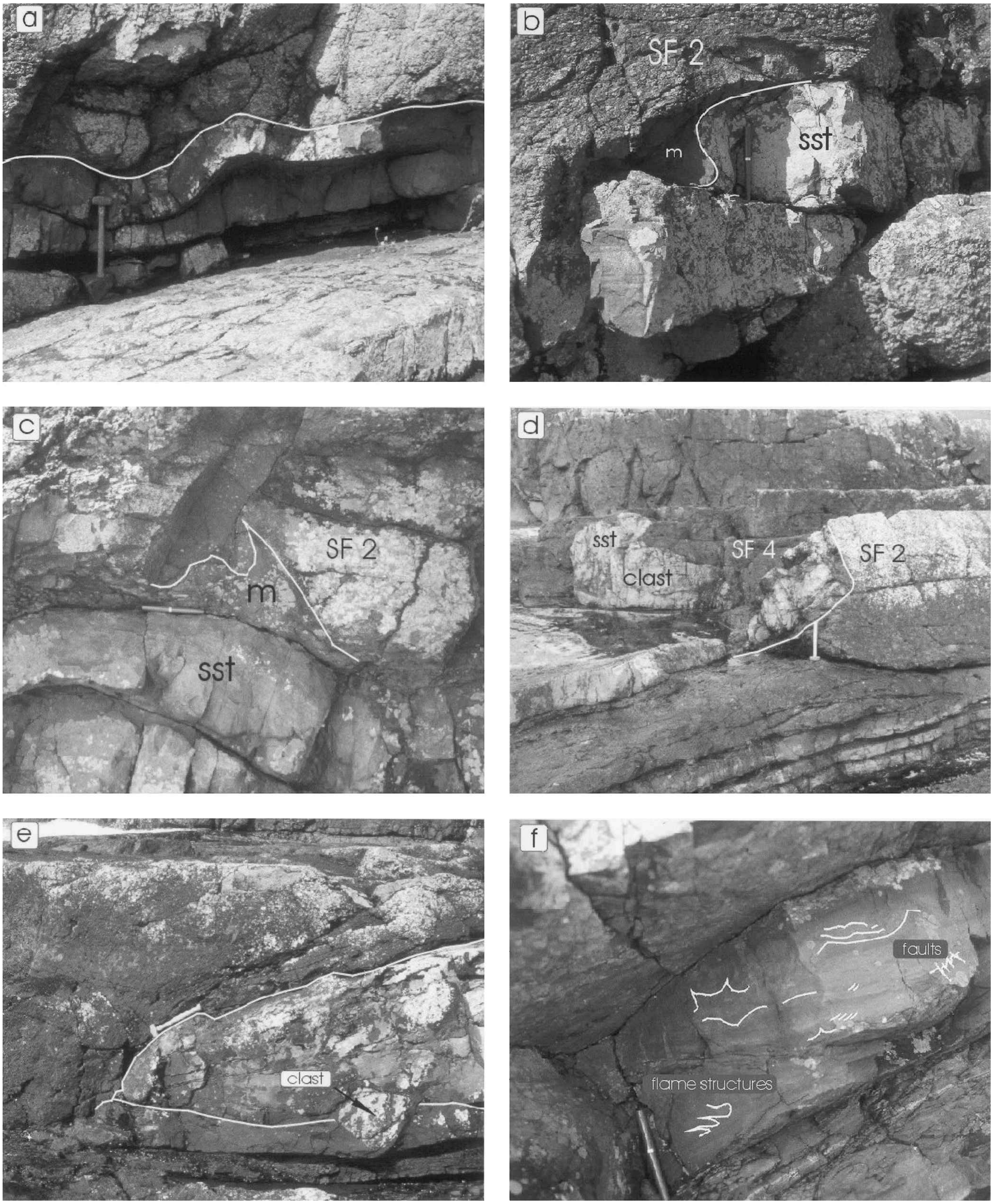

**Figure 5** Photographs (all taken looking to the W) of features exhibited by the Stac Fada Member at Stac Fada in Stoer Bay: (a) Asymmetrical folds at the contact (white line) between sandstones and the overlying SF2; these folds are considered to be contemporaneous with emplacement of the SF2 and are thought to indicate movement to the S (left); hammer is about 35 cm long. (b) Asymmetrical S-verging fold (highlighted by white line) at the contact between SF2 and underlying sandstones (sst) and mudstone (m); pen is about 10 cm long. (c) Flame structure (outlined by white line) developed at the contact between sandstones (sst) and mudstone (m) and unit SF2; pen is about 10 cm in length. (d) Contact between units SF4 and SF2; SF4 contains many large sandstone clasts (e.g. sst clast) which help in delineating the erosional contact (white line) with unit SF2, which does not contain such clasts; hammer is about 35 cm long. (e) Erosional contact between unit SF4 (top and left) and sandstone beds (below hammer, which is *c*. 30 cm in length) containing thin volcanic-rich sandstone and mudstone of unit SF3 (indicated by the horizontal white line) and a large clast. (f) Disturbed bedding (outlined in white) beneath unit SF3; disturbance of the substrate may have occurred during emplacement of SF3; flame structures suggest southwesterly transport; pen is about 10 cm long.

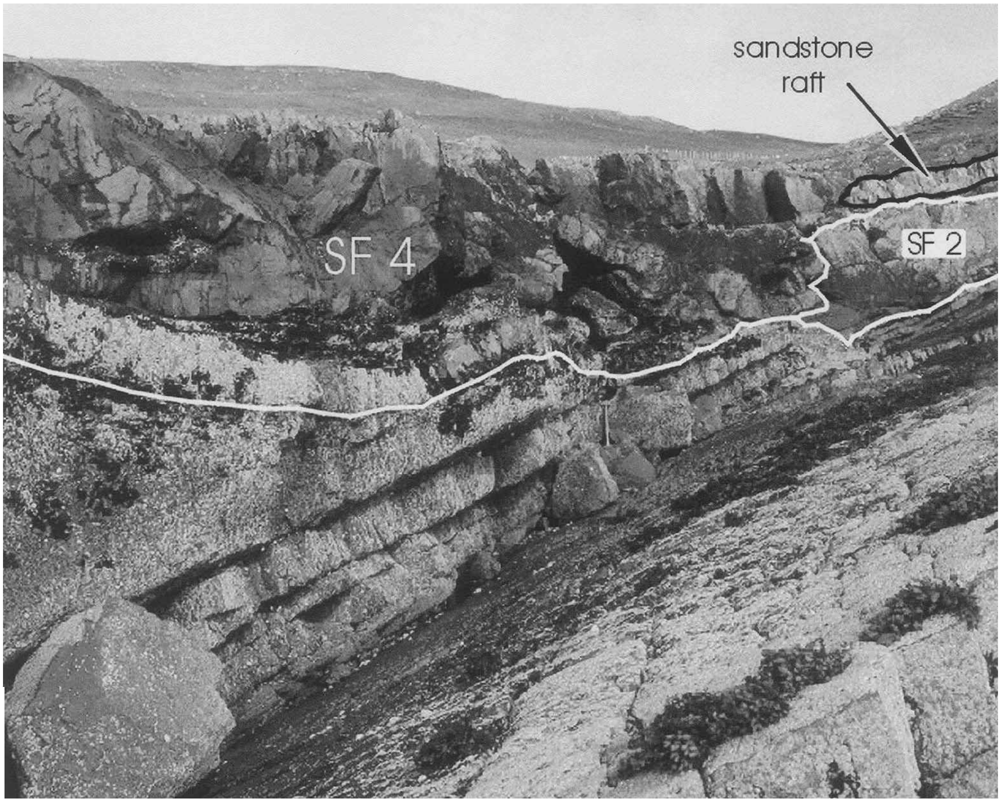

**Figure 6** Erosional contact (top white line) between SF4, the thickest unit of the Stac Fada Member, and underlying sandstones and mudstones and unit SF2; note the highly contorted sandstone bodies included in the lower part of SF4, including N-verging folds just above the hammer (centre of photo); at top right there is a large, relatively undeformed sandstone raft that is included in SF4; note that the sandstone (light) unit (left side of photo) is displaced and included within the Stac Fada Member; hammer is about 30 cm long.

also exhibits some channel-like bodies filled with pebble to boulder-size clasts. Near the top of the Stac Fada member, the accretionary lapilli unit noted at the top of SF4 in the Bay of Stoer area reappears. It is thicker in this area (2–3 m) than elsewhere. This unit may be more accurately described as 'armoured lapilli tuff' for many of the lapilli have a core of rock material, as opposed to being composed entirely of accreted fine-grained volcanic debris (Fisher & Schmincke 1984). The tuff is overlain by several metres of parallel-bedded sandstones containing scattered volcanic fragments. As in the type area at the Bay of Stoer, the Stac Fada Member is overlain by carbonate-rich mudstone.

## 5. Stattic Point, near Badluchrach

Stattic Point is about 35 km SSW of the type area at Stoer. In this area the stratigraphy of the Stac Fada is relatively simple, comprising about 13 m of volcanic-rich muddy sandstones within a succession of pink sandstones, some of which display large-scale (several metres thick) cross-bedding. Lawson (1972, p. 359) noted that deformation of sandstone beds in the upper part of the Stac Fada at the Stattic Point locality indicates transport to the SW. The absence of accretionary lapilli at this locality and elsewhere to the S (the Stac Fada occurs as far S as Poolewe, Fig. 1) suggests that these regions were farther removed than the Coigach or Bay of Stoer localities from the source of the material that formed the armoured or accretionary lapilli. Alternatively, the southern region may have been 'upwind' of the volcanic area at the time of eruption.

## 6. Interpretation of the physical stratigraphy of the Stac Fada Member

Since the volcanic component of the Stac Fada Member was first described (Lawson 1972) various interpretations of its origin and emplacement have been proposed. Lawson (1972) and Sanders & Johnston (1989) interpreted parts of the Stac Fada Member as intrusive. In this study, however, all four units making up the Stac Fada member are considered to have been emplaced as volcanic-rich sandy and muddy mass flows. A schematic interpretation of the relationships among the various units of the Stac Fada Member at the Bay of Stoer locality is shown in Figure 7. Injection of SF2 and SF3 from the main Stac Fada body (SF4) is precluded by the erosional nature of the contact between these units (Figs 5d,e; 6). Asymmetrical folds and flame structures at the base of units SF2 and SF3 suggest southward emplacement, in the direction of thickening, rather than injection towards the N, as might be expected, had the unit originated as an apophysis of the main Stac Fada unit. Unit SF2 abuts against similar material of unit SF4 but the contact is erosional (Figs 5d, 6). SF4 and SF2 can be differentiated by the abundant sandstone clasts in the former and their absence in SF2.

Emplacement of unit SF3 was also interpreted as a lateral injection, but it is difficult to envisage a mechanism that would permit injection of gneiss clasts, up to 40 cm in diametre, into the enclosing sandstones without significant disturbance and disruption both above and below the injected material. Underlying sandstones do exhibit contorted laminations and small-scale faults, but flame structures suggest movement to the S, in the direction from which the putative injection was thought to have come (Fig. 5f). The thin SF3 unit is interpreted

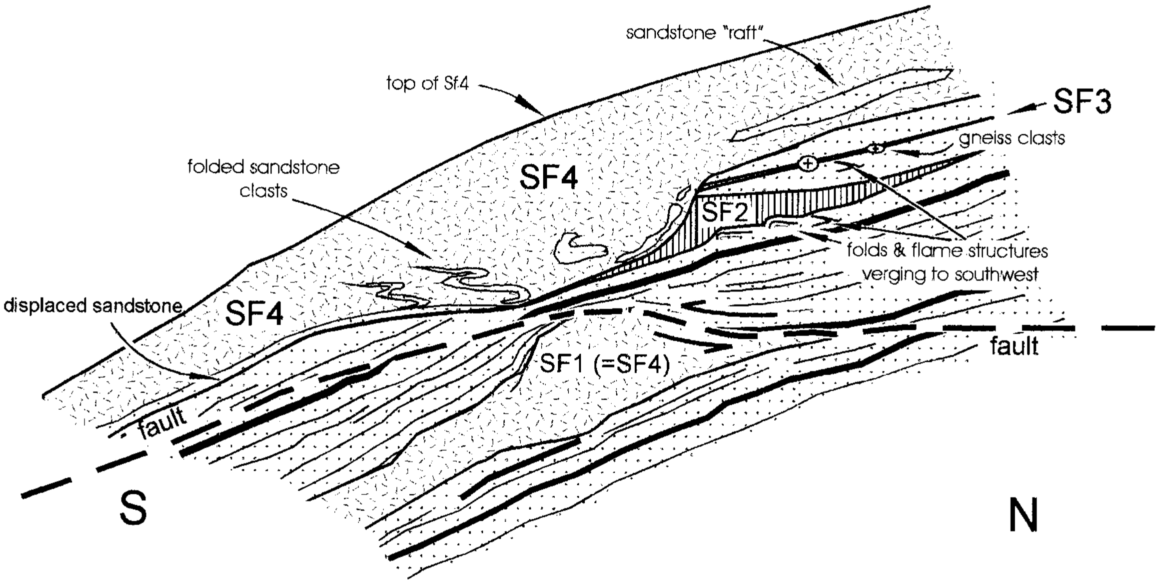

**Figure 7** Interpretive sketch to show the relationships among the various units of the Stac Fada Member at the type area at Stoer Bay; units SF2 and SF3(?) are thought to have been derived from the NE, whereas SF4 is thought to have been emplaced from the SW (see Fig. 6); unit SF2 has a maximum thickness of about 2 m; unit SF1 is a fault repetition of unit SF4 as suggested by Stewart (1990b); not to scale.

as the deposit of a flash flood event that displaced volcanic materials (from volcano slopes?) and picked up large basement clasts from coarse gravels forming a marginal facies to the depositional basin. As proposed by Sanders & Johnston (1989) the Stac Fada may have originated, at least in part, as a peperitic slurry but the available exposures are interpreted as a succession of volcanic-influenced debris flows. Forceful and violent emplacement is indicated by the erosive nature of the base of the SF4 unit at Stoer and the displacement and deformation of many large sandstone rafts. There is no evidence for an intrusive origin for any of the Stac Fada units at the Bay of Stoer or elsewhere. Unit SF1, which was considered by Sanders & Johnston (1989) to be a feeder pipe for the other parts of the Stac Fada Member, is here interpreted, following Stewart (1990b), as a fault repetition of SF4.

The three Stac Fada units described in this paper (SF1 is a fault repetition of SF4) are interpreted as deposits from volcanic debris flows or mudflows carried from steep volcanic slopes and/or fault scarps out over a sand and mud plain, fringed by bouldery debris. The volcanic materials were possibly derived from at least two separate centres, as shown in Figure 8. Various structures, such as asymmetrical folds and flame structures associated with SF2 and SF3, suggest that emplacement involved movement in a southerly direction, whereas an intrusive origin would have involved emplacement to the N, away from the main body of SF4. Differences between upper (generally smooth and planar) and lower contacts (commonly erosive and irregular) of SF2 also support a sedimentary rather than intrusive emplacement. Many folds involving sandstone and mudstone clasts in SF4 in the Bay of Stoer area have a relatively chaotic disposition, but some suggest transport toward the NE (Fig. 6). Because the greatest thickness of the Stac Fada is developed at southern Enard Bay, Lawson (1972) suggested that this area was close to the volcanic source. No clear directional criteria were noted in this area but farther to the SW, at Stattic Point, contorted sandstone beds in the upper part of the Stac Fada were interpreted by Lawson (1972, p. 359) as indicating transport to the SW. Lawson (1972) also reported a NW–SE preferred alignment of elongate lapilli in this area. Assuming that the undifferentiated Stac Fada units at southern Enard Bay (Coigach locality of Lawson 1972) and at Stattic Point are equivalent to the thick SF4 unit at the Bay of Stoer (Fig. 9), then all of these materials may have been derived from a volcanic centre that lay a few kilometres to the NW of Enard Bay. Units SF2 and SF3 were probably derived from a separate centre that lay to the N of the Bay of Stoer locality. This interpretation is also supported by the thickness variations of lapilli tuff in the upper part of the Stac Fada Member. The airfall tuff unit is several metres thick at Enard Bay, but is represented by a few tens of centimetres at the Bay of Stoer. As pointed out by Lawson (1972), and supported by data provided in Fisher & Schmincke (1984, p. 155), such airfall tuffs probably indicate fairly close proximity to a volcanic vent. The thick development of lapilli tuff at Enard Bay, its thin expression at the Bay of Stoer locality and its absence from Stattic Point all support the suggested source locality shown in Figure 8.

Units SF2 and SF3 were probably derived from a source to the NE of the type locality at the Bay of Stoer. Although there are no unequivocal directional features to indicate the provenance of SF4 (and its fault-repeated equivalent, SF1) at the Bay of Stoer locality, thickness variations (in particular the thickness distribution of an armoured lapilli tuff) suggest that the material making up the Stac Fada Member may have been transported to the NE. At southern Enard Bay and at Stattic Point, transport appears to have been in a southerly direction so that all of these deposits may have originated from a 'point source' located to the NW of Enard Bay (Fig. 8).

The triggering mechanism for deposition of the Stac Fada Member is not known. A possible analogue may, however, be provided by Quaternary giant landslides (both onshore and offshore) described by Carracedo *et al.* (1999) from La Palma and El Hierro in the Canary Islands. These deposits involve 400–500 km$^3$ of volcanic and sedimentary material and extend over distances greater than 100 km. These landslides have been attributed to gravitational collapse of volcanic edifices, but contemporaneous rift-faulting (Stewart 1991a) may also have played a role in emplacement of the Stac Fada. Because of the linear nature of the Stac Fada outcrop, it is impossible to calculate the original volume of material involved, but an

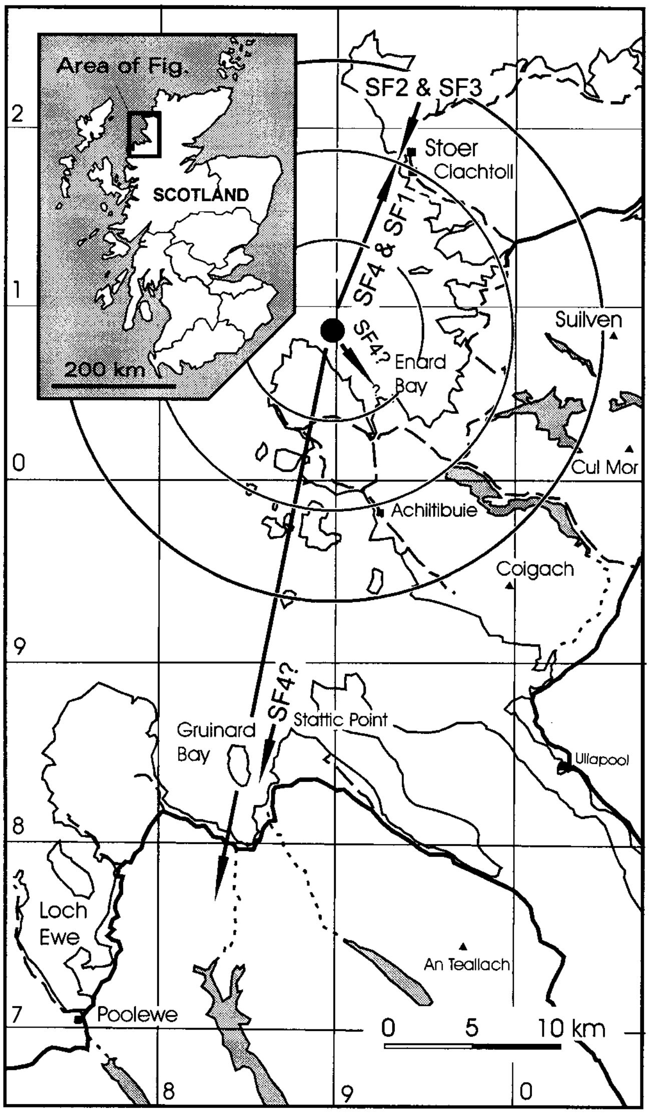

**Figure 8** Possible sources for the volcanic materials in the Stac Fada Member; the interpretation is based on directional sedimentary structures observed by the author and reported by Lawson (1972), and on thickness variations of an armoured lapilli tuff horizon in the upper part of the Stac Fada; circles around suggested source area of volcanic material in SF4 (black dot) have radii of 5, 10 and 15 km; see text for explanation.

estimate, based on the observed thicknesses in outcrop and the putative source position (Fig. 8), suggests a figure in the order of tens of cubic kilometres. Alternatively, the distribution of such a relatively thin layer consisting of a mixture of volcanic debris and siliciclastic sedimentary materials may have been due to amalgamation of flood-related lahars that descended from volcanoes and/or contemporaneous fault scarps (e.g. Pareschi *et al.* 2000).

## 7. Geochemistry

Some aspects of the geochemical composition of the Stac Fada Member were investigated by Lawson (1972) and Stewart (1990a). Most of the samples analysed for this study were collected from the type area at the Bay of Stoer, but some were collected from the southern coast of Enard Bay and at Gruinard Bay (Fig. 1). Twenty-two samples were analysed for major and trace elements, including REE. Most samples were taken from massive, volcanic-rich units of the Stac Fada Member, but some stratified materials were also collected from the upper part of the member at Enard Bay and two samples of lapilli tuff and two volcanic clasts were also analysed.

The main objectives of the geochemical investigation were to compare the composition of the various units of the Stac Fada Member in the type area at Stoer, and to carry out geochemical comparisons among Stac Fada samples from several outcrop areas. These investigations were directed towards elucidating stratigraphical relationships in the type area at Stoer and establishing possible correlations with outcrop areas to the SW. A second objective was to make comparisons with geochemical results from other volcanic rocks of known tectonic setting.

### 7.1 Sampling and analytical techniques

Most of the analysed samples were bulk samples comprising a mixture of volcanic materials and ‘normal’ siliciclastic sedimentary material. Because of the fine grain-size of most of the volcanic fragments, it is difficult to separate them for analysis. Lawson (1972) provided a partial analysis of such material. In this study, samples from two large volcanic fragments (*c.* 10 cm across) were separated from the matrix with a hammer and chisel. One such sample was obtained from the Stattic Point area and one from the SF4 unit at the Bay of Stoer. All samples were taken from fresh outcrops with minimal visible signs of weathering. Prior to analysis, any surficial materials were removed using a diamond saw. The samples were washed in distilled water to remove any possible contaminants such as salts from sea water. Analyses were carried out at Activation Laboratories Ltd. in Ancaster, Ontario. Major and trace elements were determined by fusion ICP/MS techniques. Standard and duplicate analyses were performed in order to ascertain precision and accuracy, which were $< 10\%$ for all elements and $< 5\%$ for many. Normalising factors used for REE are from Masuda *et al.* (1973) and Taylor & McLennan (1985).

### 7.2. Major elements

The major element compositions of the analysed samples are listed in Table 1. Nesbitt & Young (1982, 1984) proposed a way of investigating weathering profiles, sediments and rocks in terms of their degree of chemical alteration, using a Chemical Index of Alteration (CIA). The CIA is calculated according to the formula:

$$\mathrm{CIA} = [\mathrm{Al_2O_3}/(\mathrm{Al_2O_3} + \mathrm{CaO}^* + \mathrm{Na_2O} + \mathrm{K_2O})] \times 100.$$

For the calculation of CIA, the oxides are converted to molar proportions and $\mathrm{CaO}^*$ ideally represents CaO associated with silicates only, excluding that associated with phosphates or carbonates. The details of calculations and corrections are given in Fedo *et al.* (1995). The CIA can be expressed as a dimensionless number, usually between about 50 (for fresh crystalline rocks) and 100 (materials composed entirely of secondary aluminous clay minerals such as gibbsite/kaolinite). Thus the CIA provides a measure of the ratio of primary silicate minerals to secondary aluminous products such as clay minerals. Nesbitt & Young (1984, 1989) proposed a second, more informative method of portraying variations among the elements portrayed in the CIA calculation. This involves plotting the proportions of the oxides in an equilateral triangle with $\mathrm{Al_2O_3}$, $\mathrm{CaO}^* + \mathrm{Na_2O}$ and $\mathrm{K_2O}$ at the apices (the A–CN–K triangle). The CIA value is represented by the height above the base of the triangle, with the feldspar join representing a CIA value of 50 and the Al-apex representing 100. This triangle can also provide additional information regarding provenance and possible metasomatic alteration (Fedo *et al.* 1995).

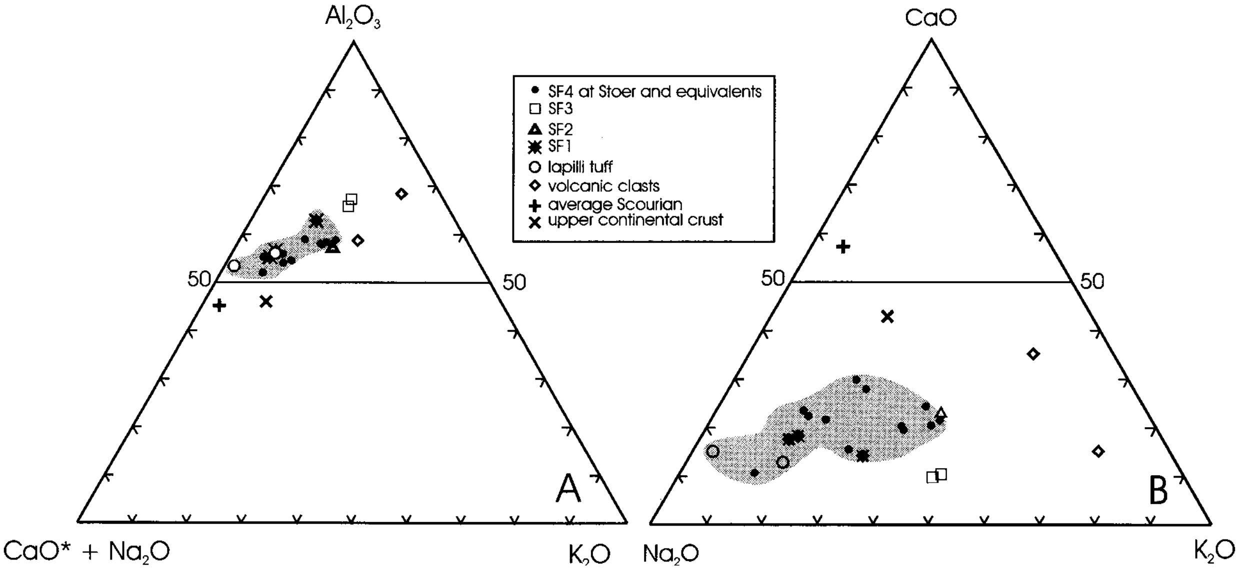

**Figure 9** (A) A–CN–K triangle showing low CIA values for samples of the SF1 and SF4 and equivalent units (shaded area), in contrast to higher values for SF2 and SF3 samples and two analysed volcanic clasts; see text for explanation. (B) CaO–$Na_2O$–$K_2O$ plot (molar proportions) to show the similarity of analysed samples from SF1 and SF4 (shaded area) and the slightly more K-rich nature of the SF2 and SF3 samples; note the K-rich nature of the analysed volcanic clasts.

The analysed samples are plotted in A–CN-K space in Figure 9A, together with an estimate of the Scourian basement composition (Tarney 1973; Tarney & Weaver 1987) and an upper crustal estimate (Taylor & McLennan 1985). On this triangle (Fig. 9A) samples from units SF1 and SF4 at Stoer and from the undifferentiated Stac Fada in other areas, all plot in a fairly tight cluster with relatively low CIA values between 50 and 60. Two lapilli tuff samples have similar values but samples from SF3 plot higher on the diagram. Two samples representing volcanic fragments plot to the right of the Stac Fada field, indicating that they are richer in K. A sample from SF2 lies on the edge of the SF4 field. These results indicate that all of the Stac Fada samples except for those from SF3 are composed mainly of relatively unweathered materials. In this plot, units SF1 and SF2 appear to be similar. The volcanic samples are K-rich and one of them appears to be moderately weathered. The geochemical similarities among SF1, SF4 and the Stac Fada samples from areas to the SW are also shown by the shaded area in Figure 9B, which is a plot (molar proportions) of CaO, $Na_2O$ and $K_2O$. The K-rich nature of the analysed volcanic fragments (diamonds) and the SF2 and SF3 samples are also illustrated.

Some aspects of the major element geochemistry of the Stac Fada units are compared in parts A to D of Figure 10, which shows the stratigraphic distribution of Si, K, Al and Ca (expressed as major oxides in weight percent). These plots show the individual values obtained from each unit. Variations in mean values are shown by the heavy lines and the thinner lines show one standard deviation on each side of the mean. Unit 2 is represented by only one point and is therefore excluded from the statistical treatment. These diagrams serve to show the similarity between units 1 and 4 (which are thought to be the same stratigraphic unit) and illustrate differences between these and unit 3.

### 7.3. Trace elements

Comparisons of the trace-element compositions of the various Stac Fada units indicate strong similarities between SF4 and SF1 and less strong affinities between SF2 and SF3. These similarities and differences are shown in Figure 10E and F, which illustrate comparison of the Cr and Ni contents of the various units. The generally higher Cr and particularly Ni contents of unit 4 (and 1) may reflect a stronger mafic igneous contribution to these rocks.

Th:Sc ratios have been used by previous authors (e.g. Taylor & McLennan 1985; Fedo *et al.* 1997) as a provenance indicator. This ratio is thought to have increased in siliciclastic sediments throughout geological time as the crust became more differentiated. A scatter plot of these elements for the analysed rocks (Fig. 11a) shows that samples from SF1 and SF4 at Stoer, together with samples from the Stac Fada at other localities to the SW, all show a fairly tight clustering with relatively low Th/Sc ratios, near 0.5. The volcanic clasts have higher Sc contents than the Stac Fada samples. This grouping suggests homogeneity of all of the Stac Fada samples, except for the SF1 and SF2 units which show a high degree of scatter and generally have somewhat higher Sc values.

The distribution of Ni and Cr in the analysed samples is shown in Figure 11B. Stac Fada samples from SF1 and SF4 at Stoer have much lower values for both elements than the analysed volcanic fragments but the ratios are similar. SF2 and SF3 are less enriched in these elements and have slightly higher Cr:Ni ratios. Samples from the Stattic Point and Gruinard Bay areas lie on a quite different trend and are relatively enriched in Ni. When the Cr/Ni ratio is plotted against distance from the proposed volcanic source area (Fig. 8), there is a strong correlation, with much decreased ratios in more distal settings (Fig. 11C). Separate plots of Cr and Ni versus 'transport distance' show that this change is largely due to increased Ni content in the more 'distal' samples. The reason for this trend is not known, but one possibility is that it may be due to incorporation of Ni-rich sedimentary (?) material that was picked up as the mass flow moved towards the SE.

### 7.4. Rare earth elements

Rare earth elements (REE) are useful for provenance studies because their distribution in sedimentary rocks, particularly fine-grained siliciclastic rocks, is thought to reflect that of the source rocks. Some of these elements may be mobile in certain

**Table 1** Major and trace element compositions of samples of the Stac Fada Member

| Sample No. | GY-98-30 | GY-98-33 | GY-98-32 | GY-98-45 | GY-98-44 | GY-98-43 | GY-98-42 | GY-98-8 | GY-99-10 | GY-99-11 | GY-99-12 | GY-99-13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit/rock type | SF1 | SF1 | SF1 | SF4 | SF4 | SF4 | SF4 | SF4? | SF4? | SF4? | SF4? | SF4? |
| Location | Stoer | Stoer | Stoer | Stoer | Stoer | Stoer | Stoer | Enard Bay | Stattic Pt | Stattic Pt | Stattic Pt | Stattic Pt |
| Major Elements (wt%) | | | | | | | | | | | | |
| $SiO_2$ | 60·85 | 65·60 | 65·74 | 67·76 | 67·22 | 67·21 | 62·81 | 67·29 | 66·42 | 66·92 | 67·79 | 69·23 |
| $TiO_2$ | 0·56 | 0·50 | 0·51 | 0·50 | 0·48 | 0·48 | 0·53 | 0·50 | 0·50 | 0·47 | 0·48 | 0·47 |
| $Al_2O_3$ | 15·20 | 13·61 | 13·72 | 13·06 | 13·36 | 13·26 | 14·37 | 12·83 | 12·87 | 11·85 | 12·72 | 12·56 |
| $Fe_2O_{3\{t\}}$ | 6·07 | 5·26 | 5·50 | 4·94 | 5·13 | 5·16 | 6·07 | 4·71 | 5·65 | 7·42 | 5·02 | 4·96 |
| MnO | 0·11 | 0·09 | 0·09 | 0·09 | 0·09 | 0·09 | 0·10 | 0·08 | 0·08 | 0·06 | 0·08 | 0·08 |
| MgO | 5·78 | 3·91 | 4·41 | 3·47 | 3·56 | 3·58 | 5·14 | 4·03 | 3·90 | 2·79 | 4·33 | 4·05 |
| CaO | 0·74 | 1·10 | 1·10 | 0·65 | 1·64 | 1·46 | 0·89 | 1·25 | 1·08 | 1·00 | 1·10 | 1·25 |
| $Na_2O$ | 3·12 | 4·55 | 4·24 | 5·02 | 4·65 | 4·33 | 3·56 | 3·66 | 2·62 | 2·12 | 2·10 | 2·17 |
| $K_2O$ | 2·65 | 1·65 | 1·71 | 1·32 | 1·79 | 1·84 | 2·62 | 1·96 | 3·06 | 3·23 | 3·46 | 3·15 |
| $P_2O_5$ | 0·16 | 0·13 | 0·14 | 0·15 | 0·13 | 0·50 | 0·15 | 0·15 | 0·14 | 0·10 | 0·14 | 0·14 |
| LOI | 4·34 | 2·97 | 3·13 | 2·11 | 2·73 | 2·76 | 3·50 | 2·95 | 2·98 | 2·62 | 2·95 | 2·81 |
| Total | 99·58 | 99·37 | 100·29 | 99·07 | 100·78 | 100·67 | 99·74 | 99·41 | 99·28 | 98·59 | 100·17 | 100·85 |
| CIA | 62·90 | 55·39 | 56·67 | 55·41 | 52·15 | 55·64 | 59·08 | 56·06 | 58·18 | 58·05 | 58·93 | 58·48 |
| Trace elements (ppm) | | | | | | | | | | | | |
| Cs | 1·1 | 0·5 | 0·5 | 0·6 | 0·4 | 0·3 | 0·6 | 0·4 | 1·1 | 1·0 | 1·0 | 1·0 |
| Rb | 79 | 38 | 48 | 35 | 46 | 52 | 76 | 47 | 92 | 113 | 104 | 104 |
| Ba | 1350 | 515 | 622 | 433 | 572 | 597 | 1460 | 825 | 1460 | 1950 | 3220 | 1580 |
| Th | 5·93 | 4·13 | 4·82 | 4·25 | 4·20 | 4·37 | 5·55 | 4·00 | 4·24 | 3·77 | 3·87 | 3·86 |
| U | 1·44 | 0·73 | 0·85 | 0·79 | 0·73 | 0·90 | 1·00 | 1·01 | 1·05 | 0·91 | 0·74 | 0·67 |
| La | 28·9 | 30·5 | 34·4 | 35·7 | 31·6 | 40·6 | 36·0 | 33·3 | 35·7 | 33·9 | 26·7 | 32·6 |
| Ce | 65·8 | 66·5 | 69·4 | 67·9 | 61·6 | 70·8 | 61·3 | 63·0 | 67·3 | 61·1 | 51·9 | 62·4 |
| Nd | 30·0 | 25·6 | 31·2 | 28·1 | 24·0 | 30·0 | 30·6 | 29·4 | 27·6 | 26·3 | 22·1 | 26·4 |
| Nb | 5·2 | 4·0 | 4·9 | 5·7 | 5·3 | 5·6 | 5·7 | 4·4 | 4·7 | 3·9 | 4·6 | 4·4 |
| Zr | 168 | 212 | 161 | 149 | 169 | 142 | 150 | 154 | 179 | 150 | 176 | 153 |
| Hf | 4·3 | 3·5 | ·40 | 3·7 | 3·9 | 3·6 | 3·8 | 4·0 | 4·5 | 3·7 | 4·4 | 3·8 |
| Sr | 189 | 221 | 227 | 170 | 190 | 229 | 189 | 242 | 210 | 227 | 313 | 223 |
| Sm | 4·77 | 4·16 | 4·50 | 4·49 | 4·07 | 5·01 | 5·01 | 4·45 | 4·73 | 4·92 | 3·81 | 4·22 |
| Gd | 4·41 | 3·66 | 4·13 | 3·96 | 3·54 | 3·92 | 4·20 | 3·75 | 3·62 | 4·20 | 3·00 | 3·08 |
| Tb | 0·56 | 0·38 | 0·46 | 0·44 | 0·40 | 0·46 | 0·52 | 0·45 | 0·56 | 0·62 | 0·46 | 0·41 |
| Eu | 1·21 | 1·12 | 1·12 | 1·14 | 1·10 | 1·19 | 1·14 | 1·13 | 1·28 | 1·36 | 1·07 | 1·11 |
| Lu | 0·198 | 0·146 | 0·151 | 0·146 | 0·135 | 0·148 | 0·157 | 0·156 | 0·172 | 0·147 | 0·157 | 0·142 |
| Yb | 1·29 | 0·87 | 0·95 | 0·97 | 0·87 | 1·03 | 1·08 | 1·03 | 1·22 | 1·04 | 1·04 | 0·92 |
| Ga | 16 | 13 | 15 | 16 | 14 | 15 | 16 | 12 | 16 | 14 | 17 | 17 |
| Y | 17·0 | 11·0 | 12·0 | 13·0 | 11·0 | 12·0 | 14·0 | 12·0 | 16·3 | 14·3 | 12·5 | 10·9 |
| Zn | 65 | 19 | 89 | 62 | 74 | 55 | 59 | 16 | 60 | 66 | 66 | 40 |
| Sc | 10 | 8 | 9 | 8 | 8 | 8 | 9 | 8 | 9 | 8 | 8 | 8 |
| Co | 36 | 26 | 37 | 27 | 32 | 35 | 38 | 24 | 31 | 13 | 33 | 29 |
| Cr | 264 | 203 | 251 | 186 | 233 | 229 | 265 | 175 | 201 | 209 | 209 | 194 |
| Ni | 185 | 146 | 197 | 135 | 194 | 206 | 226 | 115 | 366 | 180 | 376 | 322 |

| Sample No.<br>Unit/rock type<br>Location | GY-99-15<br>SF4?<br>Stattic Pt. | GY-99-16<br>SF4?<br>Stattic Pt. | GY-96-53<br>SF4?<br>Gruinard | GY98-40<br>SF2<br>Stoer | GY-98-21<br>SF3<br>Stoer | GY-98-20<br>SF3<br>Stoer | GY-98-9<br>Lapilli tuff<br>Enard Bay | GY-98-49<br>Lapilli tuff<br>Stattic Pt. | GY-99-20<br>Volc. Clast<br>Stattic Pt. | GY-99-32<br>Volc. Clast<br>Stoer | Avg. Scour,<br>Avg. Scour. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Major Elements (wt%) | | | | | | | | | | | |
| $SiO_2$ | 67·52 | 69·51 | 67·59 | 62·43 | 55·43 | 47·76 | 69·69 | 67·52 | 55·14 | 50·32 | 60·06 |
| $TiO_2$ | 0·48 | 0·45 | 0·51 | 0·63 | 0·64 | 1·12 | 0·52 | 0·56 | 0·89 | 1·16 | 0·66 |
| $Al_2O_3$ | 12·83 | 12·35 | 12·70 | 14·31 | 16·33 | 19·41 | 13·77 | 13·55 | 16·95 | 19·30 | 15·25 |
| $Fe_2O_{3\,\{t\}}$ | 5·01 | 4·37 | 5·37 | 6·81 | 9·11 | 10·97 | 5·42 | 5·04 | 4·60 | 7·42 | 6·87 |
| MnO | 0·07 | 0·07 | 0·10 | 0·08 | 0·14 | 0·14 | 0·05 | 0·08 | 0·14 | 0·11 | 0·09 |
| MgO | 3·44 | 3·40 | 4·22 | 3·32 | 6·71 | 6·55 | 1·82 | 3·32 | 6·14 | 6·82 | 3·66 |
| CaO | 1·70 | 1·78 | 1·04 | 1·40 | 0·49 | 0·58 | 1·04 | 0·79 | 2·38 | 0·81 | 6·00 |
| $Na_2O$ | 3·17 | 3·16 | 2·61 | 2·41 | 2·17 | 2·86 | 6·11 | 4·67 | 1·05 | 0·73 | 4·20 |
| $K_2O$ | 2·48 | 2·16 | 3·12 | 4·03 | 3·58 | 4·40 | 0·40 | 1·74 | 5·71 | 6·38 | 0·97 |
| $P_2O_5$ | 0·15 | 0·14 | 0·15 | 0·13 | 0·18 | 0·20 | 0·18 | 0·18 | 0·15 | 0·30 | 0·18 |
| LOI | 2·51 | 2·55 | 2·51 | 4·49 | 4·90 | 4·97 | 1·70 | 1·76 | 5·70 | 6·39 | – |
| Total | 99·36 | 99·95 | 99·93 | 100·04 | 99·68 | 98·96 | 100·70 | 99·21 | 98·86 | 99·74 | – |
| CIA | 54·68 | 54·19 | 57·98 | 57·53 | 67·38 | 65·90 | 53·55 | 56·17 | 58·80 | 68·53 | 45·29 |
| Trace elements (ppm) | | | | | | | | | | | |
| Cs | 0·7 | 0·8 | 0·9 | 3·9 | 1·4 | 2·3 | 0·2 | 0·5 | 1·9 | 2·8 | – |
| Rb | 74 | 66 | 96 | 167 | 99 | 121 | 8 | 52 | 223 | 288 | 11 |
| Ba | 688 | 743 | 1062 | 494 | 853 | 604 | 111 | 436 | 3720 | 754 | 711 |
| Th | 4·05 | 3·74 | 4·64 | 7·41 | 7·13 | 15·60 | 4·40 | 5·36 | 6·88 | 8·66 | – |
| U | 0·72 | 0·63 | 0·83 | 2·11 | 1·83 | 3·82 | 1·40 | 1·12 | 1·03 | 1·67 | – |
| La | 33·0 | 31·1 | 34·1 | 33·5 | 37·0 | 34·9 | 37·6 | 53·6 | 23·7 | 53·9 | 22·0 |
| Ce | 63·5 | 59·7 | 68·1 | 62·6 | 54·9 | 97·9 | 70·5 | 87·5 | 45·5 | 100·0 | 43·2 |
| Nd | 26·3 | 25·3 | 26·6 | 27·9 | 39·9 | 29·8 | 30·3 | 37·9 | 23·3 | 43·6 | 18·5 |
| Nb | 4·5 | 4·2 | 4·7 | 9·3 | 6·1 | 12·0 | 4·6 | 7·3 | 8·2 | 10·7 | 5·0 |
| Zr | 176 | 187 | 139 | 149 | 226 | 228 | 143 | 171 | 300 | 396 | 195 |
| Hf | 4·3 | 4·5 | 3·6 | 4·1 | 6·3 | 6·1 | 3·9 | 4·4 | 7·6 | 10·1 | 3·6 |
| Sr | 245 | 232 | 242 | 114 | 152 | 96 | 185 | 182 | 168 | 46 | 533 |
| Sm | 4·23 | 3·91 | 4·40 | 5·24 | 6·29 | 5·34 | 4·80 | 5·92 | 5·01 | 7·75 | 3·3 |
| Gd | 3·05 | 2·93 | 2·71 | 4·41 | 6·09 | 4·74 | 3·76 | 4·81 | 5·12 | 7·28 | – |
| Tb | 0·43 | 0·40 | 0·41 | 0·65 | 0·80 | 0·66 | 0·46 | 0·56 | 0·89 | 1·07 | 0·5 |
| Eu | 1·14 | 1·12 | 1·12 | 1·10 | 1·59 | 1·27 | 1·18 | 1·30 | 1·53 | 2·01 | 1·2 |
| Lu | 0·159 | 0·145 | 0·131 | 0·278 | 0·385 | 0·498 | 0·160 | 0·184 | 0·386 | 0·416 | 0·2 |
| Yb | 1·00 | 0·95 | 0·91 | 2·00 | 2·42 | 2·91 | 1·08 | 1·32 | 2·57 | 2·99 | 1·3 |
| Ga | 18 | 17 | 15 | 20 | 25 | 29 | 13 | 18 | 21 | 30 | – |
| Y | 11·6 | 11·0 | 9·9 | 20·0 | 27·0 | 23·0 | 12·0 | 14·0 | 29·7 | 38·2 | 10·6 |
| Zn | 42 | 39 | 72 | 85 | 68 | 19 | 42 | 182 | 46 | 85 | – |
| Sc | 9 | 8 | 8 | 13 | 10 | 25 | 9 | 10 | 14 | 21 | – |
| Co | 26 | 26 | 33 | 26 | 40 | 41 | 24 | 24 | 34 | 42 | – |
| Cr | 171 | 166 | 202 | 117 | 227 | 149 | 162 | 149 | 423 | 590 | 94 |
| Ni | 292 | 296 | 494 | 52 | 121 | 80 | 154 | 245 | 424 | 558 | 62·6 |

Average Scourian values are from Tarney (1973) and Tarney & Weaver (1987)

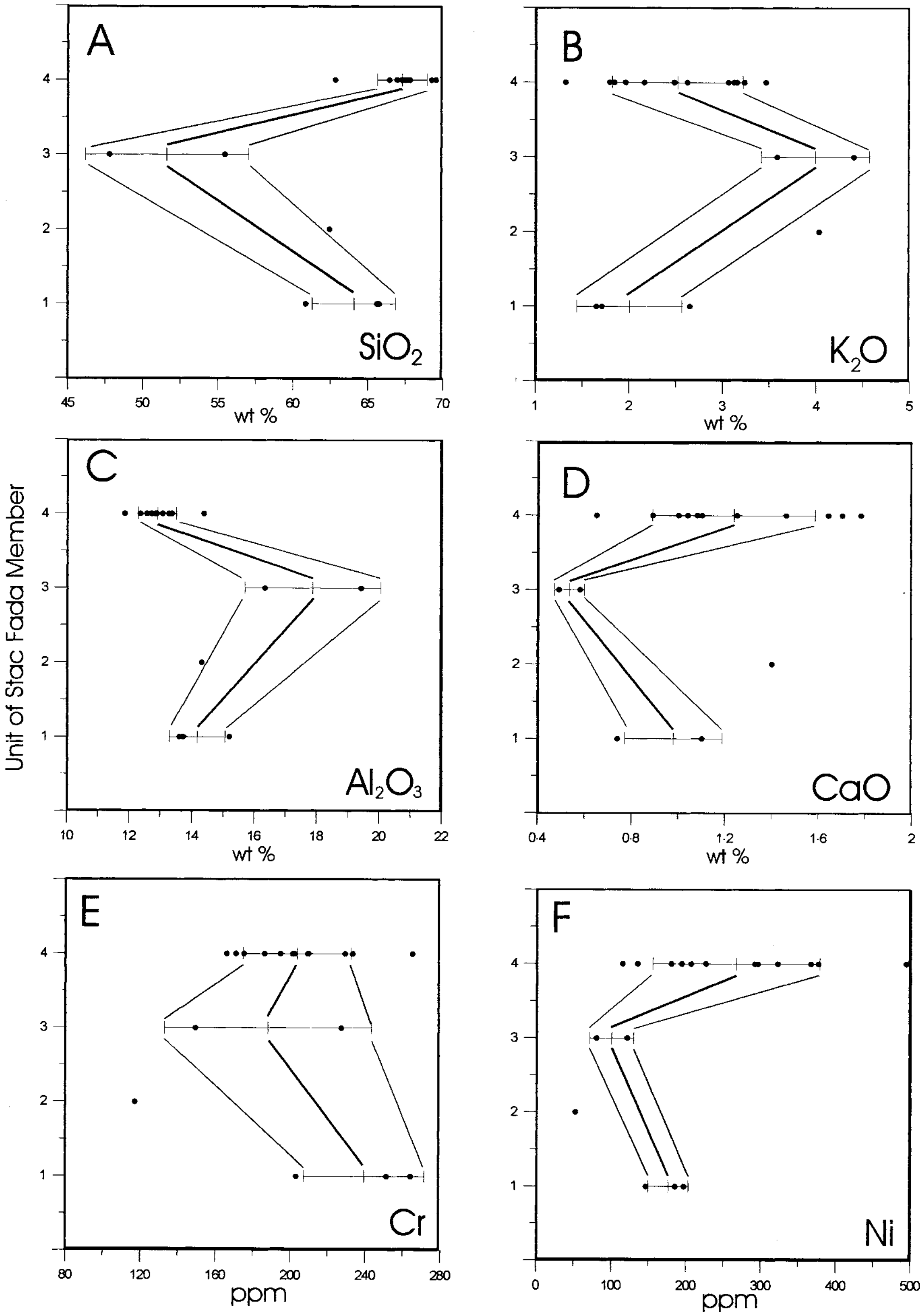

**Figure 10** (A)Variations in $SiO_2$ content of the SF2 units differentiated in the text; for all diagrams on this figure the dots represent individual analyses; heavy lines are average values and the lighter lines enclose two standard deviations from the mean. Note the similarity between units 1 and 4 and the different character of samples from unit 3 in (A–D), which relate respectively to $SiO_2$, $K_2O$, $Al_2O_3$ and CaO; (E, F) are similar plots for Cr and Ni, respectively, in parts per million (ppm), showing the relative enrichment of units 1 and 4 in these elements, which are typically common in mafic igneous rocks; see text for discussion.

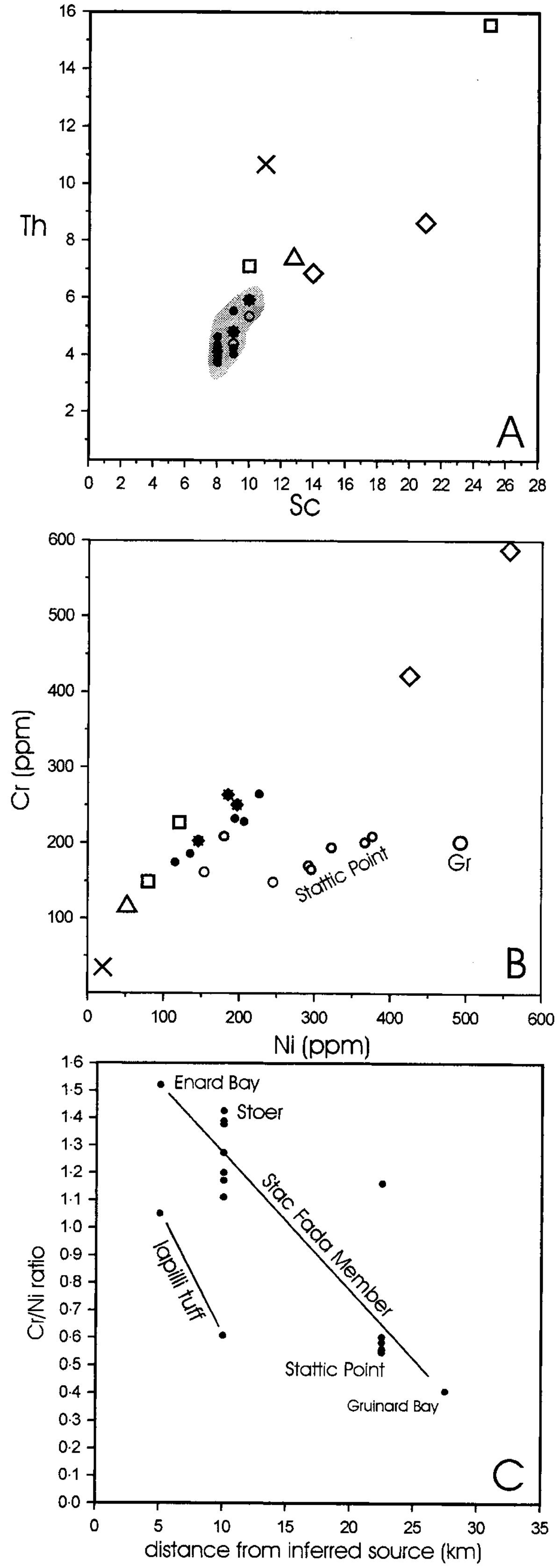

**Figure 11** (A) Th vs Sc plot to show the small field (shaded area) defined by the SF4 and SF1 samples, compared to the analysed SF2 and SF3 samples and volcanic clasts; symbols as in Figure 9. (B) Cr vs Ni plot to show the linear relationship between the volcanic samples (diamonds) and most of the analysed Stac Fada samples; samples from the Stattic Point area fall on a different trend, with a higher Ni content; see text for discussion; symbols as in Figure 9. (C) Plot of Cr/Ni ratio versus distance from inferred source (see Fig. 8 for the proposed position of the volcanic centre); note that the Cr/Ni ratio is much lower in areas considered more distal to the volcanic centre; see text for discussion.

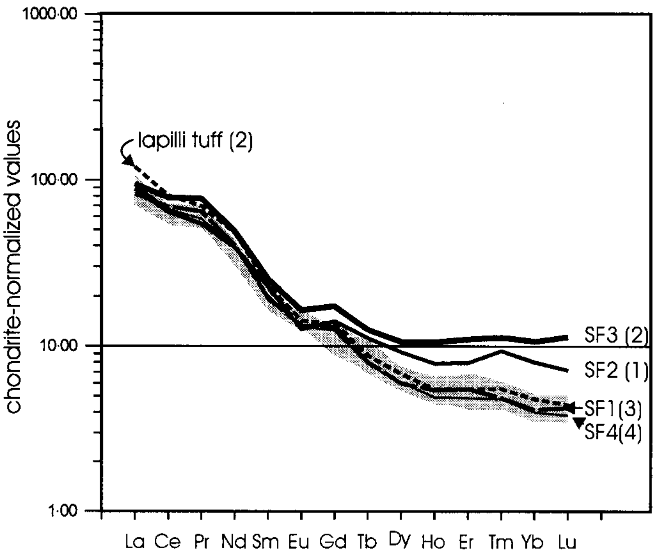

**Figure 12** Average chondrite-normalised values for the rare earth elements in various Stac Fada units at the type area at the Bay of Stoer; note the similar patterns for SF1, SF4 and the two analysed lapilli tuff samples; shaded area includes patterns from all the analysed samples from SF1, SF4 and the analysed tuff samples; SF2 and SF3 samples have a flatter heavy REE pattern; numbers of analysed samples are shown in parentheses.

weathering environments (Nesbitt 1979; Duddy 1980; Nesbitt & Markovics 1997), but because of the generally large size of drainage networks involved in filling sedimentary basins and because of the homogenising effects of mixing, the REE distributions are nevertheless taken as representative of the source areas (McLennan 1982; McLennan & Taylor 1991; McLennan *et al.* 1993). These elements are also considered to be relatively immobile during diagenetic and metamorphic processes.

Chondrite-normalised REE plots for samples from SF1 and SF4 at the Bay of Stoer are shown in Figure 12. The average values and that of the associated lapilli tuffs are very similar, with high LREE (light rare earth element) values and relatively low HREE (heavy rate earth element) values. Samples from SF3 and SF2 have similar chondrite-normalised LREE values, but the HREE shows a much flatter pattern. These compositional differences support field evidence and other geochemical data, suggesting that SF2 and SF3 are not intrusive apophyses of the main Stac Fada unit but are separate units that were derived from a different source area.

## 8. Nature of the volcanic rocks

Stewart (1990a,b) suggested that the volcanic rocks incorporated into the Stac Fada Member were similar to potassic rift-related lavas from eastern Africa. Because the fragments within the Stac Fada Member are mostly small ( < 1 cm) it is difficult to isolate the volcanic materials but two large volcanic fragments were sampled and analysed. An A–CN–K triangle, showing these volcanic clasts, together with a partial analysis of the volcanic rocks reported by Lawson (1972), is shown in Figure 13A. The volcanic fragments from the Stac Fada are different from all of the average igneous rocks shown in the diagram (Nockolds 1954) and from the eastern African rift volcanics (Higazy 1954; Bell & Powell 1969; Edgar 1996), to which they have been compared. Because fresh igneous rocks fall close to the 50–50 join on this diagram (Nesbitt & Young 1982, 1984; Fedo *et al.* 1995), the relatively high position

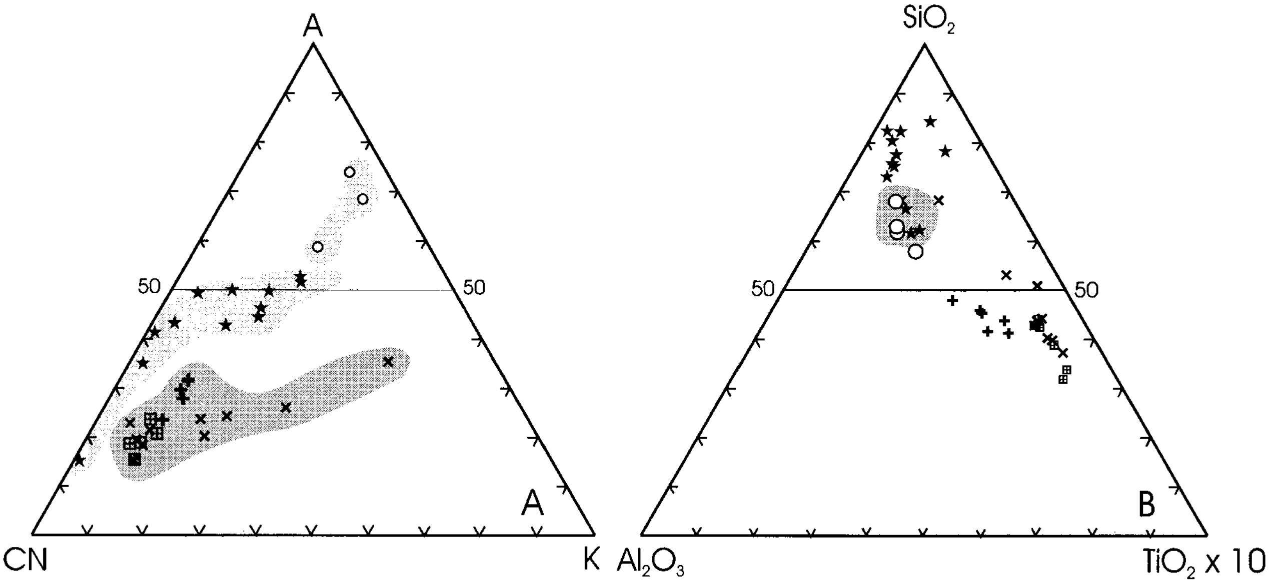

**Figure 13** (A) A–CN-K plot; stars show the distribution of the estimated compositions of average fresh igneous rocks (after Nockolds 1954); lower shaded area on the diagram represents various alkaline rocks from eastern Africa; crosses indicate potassic rocks from eastern Africa (Bell & Powell 1969). 'x' symbols are based on data from Edgar (1996) and squares with crosses are from Higazy (1954); circles represent volcanic clasts analysed for this study and a partial analysis from Lawson (1972); note that the volcanic samples from the Stac Fada Member differ markedly from the alkalic eastern African lavas and from all average igneous rock compositions, indicating that they have undergone alteration (weathering and K-metasomatism). (B) $SiO_2$–$Al_2O_3$–$TiO_2$ × 10 plot to illustrate the difference between various potassic rocks from eastern Africa (symbols and sources as in (A)) and the analysed volcanic fragments from the Stac Fada (open circles); shaded area indicates the field occupied by the Stac Fada samples and average mafic igneous rocks from Nockolds (1954).

of the analysed volcanic fragments indicates that they are quite highly altered (weathered and/or metasomatised). This finding provides an explanation for their relatively potassic nature, for like many weathered rocks they appear to have undergone potassium metasomatism (Rainbird *et al.* 1990; Fedo *et al.* 1995). A triangular plot of $SiO_2$–$Al_2O_3$–$TiO_2$, which are thought to be relatively stable during weathering and metasomatism (Nesbitt & Young 1984), also illustrates differences between the Stac Fada volcanic fragments and potassic lavas from the eastern African rift (Fig. 13B). The average igneous rocks that plot near to the Stac Fada samples are gabbro, and associated mafic rocks from Nockolds (1954). The potassic nature of the Stac Fada volcanic samples is attributed to their weathered nature and subsequent K-metasomatism rather than being a primary magmatic feature.

The limited distribution of volcanic rocks in what is widely considered to be a rift environment is puzzling. One possibility, however, is that the linear exposure of the Stac Fada Member is just the 'distal end' of much more significant volcanism that occurred to the W in the vicinity of major faults such as the Minch Fault. Such volcanic rocks, if they exist, are currently under water and their exploration would only be possible as a result of drilling.

## 9. Conclusions

Field observations, mainly in the type area of the Stac Fada Member at the Bay of Stoer, but also on the southern shore of Enard Bay, at Stattic Point and at Gruinard Bay, support interpretation of the member as a series of volcanic-rich mass flows. Two thin volcanic-rich units (SF2 and SF3) at the Bay of Stoer locality were formerly interpreted as intrusive apophyses of SF4, but are here considered to be separate volcanic mud flows derived from a source to the NE. The reason for the irregular thickness expressed by SF2 is not known. These thickness variations could represent the original depositional configuration, if the material were strongly cohesive, or the thickness could have been modified by post-depositional reworking or 'soft sediment' deformation. The main Stac Fada Member (SF4) was probably emplaced by transport in the opposite direction, towards the NE. In the type area the base of SF4 is erosive into the SF2 and SF4 units and enclosing sedimentary rocks. The lowest unit of the Stac Fada (SF1) is a fault repetition of unit SF4. Evidence from regional thickness variations of the Stac Fada Member, directional sedimentary structures, and thickness variations of accretionary or armoured lapilli tuffs at or near the top of the main Stac Fada unit suggest that there were at least two volcanic sources, one to the N of the Enard Bay outcrops, which is thought to have been the source for most of the volcanic material preserved in the Stac Fada Member, and a second volcanic center NE of the Bay of Stoer locality. Emplacement of the volcanic-rich debris flows was probably the result of gravity-induced mass flow (possibly triggered by seismic activity and/or flash floods) resulting from the build up and faulting(?) of contemporaneous volcanic edifices. The volcanic mass flows appear to have been emplaced violently, at least in the type area at the Bay of Stoer, for large sandstone and mudstone masses were contorted and displaced during the process. Distorted sandstones are also reported from the Stattic Point area, but the Bay of Stoer area appears to have been the site of greatest disruption and incorporation of underlying sediments. The reason for this is unknown, but one possibility is that slopes (volcanic and/or fault-related) were steeper in the vicinity of the Stoer locality.

Both major and trace element analyses indicate strong similarities among the SF1 and SF4 units at the Bay of Stoer and the Stac Fada Member in areas to the SW of the type area. Geochemical data from the thin SF2 and SF3 units at Stoer support the suggestion that these units have a different composition and were not formed as intrusions from unit SF4.

Two volcanic fragments from the Stac Fada Member are K-rich, as previously noted by Stewart (1990a). An A–CN–K plot (Fig. 13A), however, shows that the K-enrichment is a secondary feature The analysed fragments appear to be basaltic(?) materials that underwent significant K-metasomatism.

The Stac Fada Member was emplaced as a series of volcanic mass flows from at least two centres. Most of the volcanic debris was probably derived form an area just N of the southern Enard Bay locality. Two thin volcanic-rich units, SF2 and SF3, known only from the Bay of Stoer area, appear to have been derived from a different source that lay to the NE of this locality. The dearth of volcanism in the supposed rift setting for the Stoer and Torridon Groups is puzzling, but it is possible that magmatic rocks are much more abundant to the W in sea-covered areas in the proximity of major faults such as the Minch Fault.

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