Field and petrographic evidence for partial melting of TTG gneisses from the central region of the mainland Lewisian complex, NW Scotland

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Abstract: The central region of the mainland Lewisian complex is dominated by granulite-facies tonalite-trondhjemite-granodiorite (TTG) gneisses that are highly depleted in some mobile trace elements (Cs, Rb, Th and U) relative to amphibolite-facies TTG gneisses elsewhere in the Lewisian complex and to the average composition of TTG gneisses worldwide. Over almost half a century of research there has been vigorous debate as to the origin of this depletion, in particular with respect to the role of partial melting and melt loss. Here we provide field and petrographic evidence that TTG gneisses across the central region partially melted during granulite-facies (Badcallian) metamorphism. Partial melting occurred largely by fluid-absent incongruent reactions consuming plagioclase, quartz, hornblende and biotite to produce melt and peritectic clinno- and orthopyroxene. The preservation of dry, granulite-facies assemblages requires loss of melt, consistent with the presence of an interconnected network of leucosomes and larger felsic sheets that probably record segregation and transfer of melt to higher crustal levels. Regardless of whether or not partial melting and melt loss can explain fully the unusual geochemical signature of the central region TTG gneisses, these fundamental processes did occur.

Supplementary material: Figure S1, showing additional field photographs of boulders from Poll Eòrna, is available at www.geolsoc.org.uk/SUP18580.

The Archaean Lewisian complex of NW Scotland (Fig. 1) is a small fragment of the North Atlantic craton, yet its size belies its importance to our understanding of the origin and evolution of Earth’s early continental crust. In particular, the granulite-facies central region of the mainland Lewisian complex has been important to our understanding of deep crustal processes (e.g. Peach et al. 1888, 1907; Sutton & Watson 1951; Moorbath et al. 1969; Weaver & Tarney 1980; Wheeler et al. 2010), even though fundamental questions concerning its evolution remain unresolved. For example, it is unclear to what extent the unusual geochemistry of the rocks reflects the characteristics of their source region at depth, and/or records modification by high-grade metamorphic processes, in particular partial melting and melt loss, at the level of their emplacement (Rollinson 2012). In addition, there is little consensus on the number and timing of metamorphic events and the P–T conditions they record (e.g. Love et al. 2004; Kinny et al. 2005; Whitehouse & Kemp 2010).

The rocks of the Lewisian complex are dominated by felsic orthogneisses of the tonalite–trondhjemite–granodiorite (TTG) suite that are typical of exposed deep Archaean crust worldwide. However, the granulite-facies TTG gneisses of the central region differ from most other TTG gneisses, including amphibolite-facies gneisses exposed in the northern and southern regions of the Lewisian complex, in exhibiting a marked depletion in the mobile elements Cs, Rb, Th and U, and, to a lesser extent, K (e.g. Evans 1965; Moorbath et al. 1969; Sheraton et al. 1973; Rudnick et al. 1985; Fig. 2). This geochemical signature has been used as evidence to support alternative hypotheses, as follows: (1) an original depletion of these mobile elements in the basaltic source region for the TTG gneisses (e.g. Park & Tarney 1987; Tarney & Weaver 1987; Rollinson 1996; Rollinson & Tarney 2005); (2) partial melting of the rocks during granulite-facies metamorphism, with loss of melt purging them of these elements (Moorbath et al. 1969; Fyne 1973; O’Hara & Yarwood 1978; Pride & Muecke 1980; Barnicoat 1983; Cartwright & Barnicoat 1987); or (3) removal of these elements by a (CO2-rich) volatile phase during high-grade metamorphism but in the absence of any partial melting (Tarney & Windley 1977; Weaver & Tarney 1980, 1981). Clearly, a key factor in the resolution of this debate lies in establishing whether or not the TTG gneisses melted, a fundamentally important process for which little convincing field evidence has been advanced to date (Wheeler et al. 2010).

Migmatites are rocks that partially melted. Although highly complex in detail, migmatites essentially comprise two main components: ‘leucosome’, those portions of the rock representing the melt-related products, and ‘residuum’, those formerly melt-bearing portions of the original (pre-anatectic) rock from which melt was extracted (see Sawyer 2008, and references therein). In many crustal migmatites (e.g. those with metapelitic, metagreywacke and metabasic protoliths), the residuum is enriched in mafic minerals (and termed ‘melanosome’), and is easy to distinguish from quartzofeldspathic leucosome. However, for other common crustal rock types that have undergone anatexis, most notably migmatized felsic plutonic rocks and impure quartzites, the colour contrast between leucosome and residuum, which are both quartzofeldspathic, may be subtle or non-existent, and clear migmatitic features indicative of partial melting become much harder to recognize (e.g. Sawyer 1998, 2010).

Leucosomes may be classified as in situ, in source or injected (Sawyer 2008). Injected leucosomes are the products of crystallization of melt derived from a source foreign to the rocks in which they occur, and their presence cannot be used as evidence for localized partial melting. Localized partial melting requires evidence based on the recognition in single outcrops of both former melt-related products (leucosome) and the residue from which melt was extracted (residuum). In the majority of cases, crustal rocks will melt via
fluid-absent incongruent reactions, in which hydrous phases react with quartz and/or feldspar to produce melt and an anhydrous solid (peritectic) phase (e.g. Sawyer et al. 2011). In such cases, evidence for in situ melting is provided by the spatial association of both the solid and liquid reaction products, in the form of peritectic phases located within the leucosome (e.g. Powell & Downes 1990; White et al. 2004), and/or the occurrence of leucosome surrounding (commonly porphyroblastic) reactant phases (e.g. White 2008). Incongruent fluid-absent partial melting of TTG gneisses will produce melts of broadly granitic composition with peritectic clinopyroxene, orthopyroxene and/or, at higher pressures, garnet via the breakdown of plagioclase, quartz and hornblende and/or biotite (see Watkins et al. 2007, and references therein).

Johnson et al. (2012) provided evidence to demonstrate that mafic rocks throughout the central region underwent partial melting during granulite-facies metamorphism. Field and petrographic evidence in support of in situ partial melting of the TTG gneisses is the focus of this contribution.

Regional geology

The Lewisian complex is dominated by felsic to mafic orthogneiss and rarer mica-rich supracrustal rocks that are cut by numerous dykes of mafic to ultramafic composition (Scourie dykes). Early work proposed a simple threefold subdivision of the mainland Lewisian complex, with a granulite-facies central region bounded by amphibolite-facies southern and northern regions (Peach et al. 1907; Sutton & Watson 1951; Fig. 1). As a result, the central region has been interpreted as exposing a deeper level of a once continuous piece of Archaean crust (Park & Tarney 1987). The advent of high-precision in situ dating techniques has led to the development of a terrane model, in which a more complex subdivision into discrete crustal blocks has been proposed (Friend & Kinny 2001; Kinny et al. 2005). However, debate continues regarding the number of terranes, the position of their boundaries, and the nature and timing of terrane accretion (Friend & Kinny 2001; Kinny et al. 2005; Mason & Brewer 2005; Park 2005; Goodenough et al. 2010, 2013; Love et al. 2010).

The rocks of the central region record polyphase deformation and metamorphism that occurred both prior to and after the intrusion of the Scourie dykes (Sutton & Watson 1951). Two pre-Scourie dyke (Scourian) metamorphic episodes are recognized, an early granulite-facies event termed the Badcallian (Park 1970) and a later amphibolite-facies event termed the Inverian (Evans 1965). All deformation and metamorphism that occurred after the intrusion of the Scourie dykes is termed Laxfordian (Sutton & Watson 1951). This paper deals with Scourian events; the complex and protracted Palaeoproterozoic Laxfordian events have been described in detail elsewhere (Kinny et al. 2005; Goodenough et al. 2010, 2013).

Granulite-facies mineral assemblages developed during the Badcallian event record peak conditions of 875–975 °C, 8.5–11.5 kbar (Johnson & White 2011), with metamorphism generally dated at c. 2.8–2.7 Ga (Corfu et al. 1994; Zhu et al. 1997). Inverian metamorphism resulted in the overprinting of Badcallian mineral assemblages and was driven by an influx of H2O-rich fluids concentrated within shear zones (Evans & Lambert 1974; Beach 1976; Zirkler et al. 2012). Inverian assemblages record a range of temperatures from 520 °C to 625 °C at pressures of 5–6 kbar (Cartwright & Barnicoat 1986; Zirkler et al. 2012), with metamorphism dated at c. 2490–2480 Ma (Corfu et al. 1994; Friend & Kinny 1995; Kinny & Friend 1997; Zhu et al. 1997). However, U–Pb zircon ages from central region gneisses, including data from homogeneous grains and overgrowths interpreted to have grown during high-grade metamorphism, show a continuous spread along concordia from c. 2.8 to 2.5 Ga (e.g. Whitehouse & Kemp 2010; Zirkler et al. 2012; Goodenough et al. 2013). As the errors on the measured U–Pb ratios are of the same magnitude as any discordance owing to Pb loss resulting from resetting during the Archaean or Palaeoproterozoic, these data have proven difficult to interpret (Whitehouse & Kemp 2010).

Varially deformed felsic sheets centimetres to several metres thick and of Scourian (pre-Scourie dyke) age occur throughout the central region. The felsic sheets range in composition from tonalite...
Fig. 3. Field evidence for partial melting of TTG gneisses in the central region of the Lewisian complex. (a) Typical TTG gneiss containing coarse-grained stromatic leucosome within a darker residuum (melanosome). (b) Stromatic leucosomes in petrographic continuity with a coarse-grained cross-cutting leucosome within a shear band. The cross-cutting leucosome contains abundant peritectic pyroxene consistent with the incongruent breakdown of hornblende and plagioclase. (c) Leucosome containing peritectic pyroxene within a vein that cross-cuts the foliation in the TTG gneiss at a high angle. Stromatic leucosomes are abundant within the residuum. (d) Small coarse-grained leucosome patch in an interboudin partition within an intermediate to felsic TTG residuum. (e) Schollen of TTG gneiss within a larger patch of coarse-grained leucosome. (f) Massive felsic sheet in contact with foliated TTG gneiss. The contact is marked by a diffuse melanosome or selvedge that is enriched in mafic minerals, predominantly hornblende and biotite.
Fig. 4. Evidence for partial melting of TTG gneisses within boulders around the high-tide mark at Poll Eörna, around British Grid reference [NC 150 456]. (a) Stromatic leucosome containing peritectic pyroxene within a mafic residuum. (b) Thin stromatic leucosomes feed into a thin (c. 1 cm) leucosome containing peritectic pyroxene that is concentrated along a small shear band. (c) Small leucosome veins containing peritectic pyroxene cross-cutting the distinct foliation of the TTG gneiss. (d) Larger leucosome vein containing peritectic pyroxene. The contact between leucosome and gneiss is diffuse. (e) Weakly cross-cutting leucosome containing peritectic pyroxene and small schollen of melanosome. (f) Diatexitic TTG gneiss with a peritectic pyroxene-bearing leucosome (middle of the boulder). (The lens cap for scale is 67 mm in diameter).
to granite and many preserve granulite-facies mineral assemblages, consistent with their formation at or close to the Badcallian metamorphic peak (Rollinson & Windley 1980; Cartwright & Barnicoat 1987; Rollinson 1994). The origin of these felsic sheets has been a long-standing debate (Cartwright & Rollinson 1995). Based largely on geochemistry, some researchers have suggested that they were derived locally from partial melting of the host TTG gneisses (Pride & Muecke 1982; Barnicoat 1983; Cartwright 1990; Cohen et al. 1991), whereas others have argued that they were derived from partial melting of a large ion lithophile element (LILE)-depleted mafic source at depth and are unrelated to the high-grade metamorphism (Rollinson & Windley 1980; Rollinson & Fowler 1987; Rollinson 1996; Rollinson & Tarney 2005). Although age data are scarce, the felsic sheets have a range of U–Pb zircon ages similar to those recorded by their host TTG gneisses (e.g. Corfu et al. 1994; Goodenough et al. 2013).

Field evidence

Outcrop evidence

Although in situ exposures of TTG gneiss throughout the central region of the mainland Lewisian complex preserve evidence for partial melting, in most cases outcrops are distinctly unphotogenic owing to the ubiquity of lichen on inland exposures. Clean wave-washed exposures are rare. Identifying field evidence for partial melting requires fresh faces, as the residual portions of the rocks are commonly leucocratic and similar in colour to leucosome. The features described below are most clearly shown in the Scourie–Badcall and Drumbeg areas (Fig. 1), where the gneissosity has a shallow to moderate dip and the rocks are relatively unaffected by subsequent Inverian and Laxfordian metamorphism and deformation.

Central region TTGs are layered on a millimetre to centimetre scale, in which single layers are distinguished on the basis of mineral assemblage, colour and grain size. Quartzofeldspathic leucosomes generally are aligned subparallel to the gneissosity, form the coarsest and most quartz-rich portions of the migmatitic gneiss, and are the only parts of the migmatite that may contain a significant amount (>5 vol.% of K-feldspar. The residuum may be darker in colour owing to a higher concentration of mafic minerals (predominantly clinopyroxene and hornblende replacing clinopyroxene), although commonly it is intermediate to leucocratic in colour. The TTG residuum does not contain conspicuous grains of K-feldspar.

Leucosome commonly forms stromatic veins that are coarser-grained than their host residuum and oriented parallel to the foliation (Fig. 3a). In many cases stromatic leucosomes are not associated with conspicuous mafic minerals or any obvious mafic selvedge. Stromatic leucosomes interconnect, and are in petrographic continuity (i.e. merge into each other without any discernible contact), with coarse-grained cross-cutting leucosomes that are commonly concentrated within shear bands (Fig. 3b) or form more irregular veins (Fig. 3c). The cross-cutting leucosomes may or may not contain K-feldspar, and their contact with the residuum is generally more diffuse than in stromatic variants. Most cross-cutting leucosomes contain orthopyroxene and/or clinopyroxene grains that are significantly larger than pyroxene grains within the residuum (Fig. 3b and c). Orthopyroxene is commonly concentrated within leucosome, although overall clinopyroxene is an order of magnitude more abundant than orthopyroxene. In rare instances, coarse-grained leucosome is concentrated within interboudin partitions (Fig. 3d). In some cases the migmatites are locally diatexitic, containing schollen of residual TTG gneiss located within more extensive areas of coarse-grained leucosome (Fig. 3e). Large felsic sheets, some tens of metres in width (Fig. 3f), may be laterally continuous for many tens of metres or more. The contact between the felsic sheets and TTG gneiss may be associated with a discrete hornblende-rich melanosome or selvedge that is a few centimetres in width (Fig. 3f).

Evidence from boulders

The clearest (i.e. most photogenic) evidence for in situ partial melting of the TTG gneisses is preserved within rounded wave-washed boulders, which show identical features to those described above. Particularly good examples occur close to the high water mark at the head of Poll Eòrna, the bay containing the original Scourie dyke (Teall 1885). Here, the boulders (i.e. those particles with a grain size

![Fig. 5. Petrographic evidence for partial melting. (a–c) Cross-polarized photomicrographs with 1-3-3 quartz-accessory plate inserted showing near-pristine granulite-facies residual TTG samples from close to the village of Scourie, around British Grid reference [NC 160 433]. Thin irregularly shaped films of K-feldspar (a, b) and quartz (c) with cuspatelike outlines (arrowed) occur between rounded grains of reactant quartz and plagioclase. These microstructures are interpreted as trapped melt pockets that crystallized within the residual melanosome and provide strong evidence for in situ partial melting. Partially retrogressed grains of ortho- and clinopyroxene (a, b) in contact with the films may represent the peritectic melting products. The K-feldspar in these residual TTG gneisses occurs only as these cuspatelike films; it does not occur as subhedral grains similar to quartz and plagioclase. Myrmekites are commonly developed where the former melt films are in contact with plagioclase (b). (d) Strongly recrystallized granitic (K-feldspar-rich) leucosome with serrated grain boundaries and containing a rounded grain of apatite. Such leucosomes are interpreted to be rich in crystallized segregated melt. Long dimension of (a) and (d) is 2.75 mm, and of (b) and (c) is 1.44 mm.](image-url)
Myrmekite is commonly developed at the sites of these films of quartz and plagioclase (see Sawyer 2000, 2001; Fig. 5a–c). K-feldspar, quartz and, rarely, plagioclase between rounded grains of TTG gneiss, preserved within residual TTG gneiss, predominantly hornblende. The clear microstructural evidence for partial melting is preserved where thin interstitial films of quartz, plagioclase and/or hornblende are indicated. The grey box shows the constraints on peak metamorphic conditions for granulite-facies (Badcallian) metamorphism determined from phase equilibria modelling (Johnson & White 2011). The high-T segment of a possible Scourian P–T–t path consistent with the combined data is shown (dashed curve). Bad., Badcallian; Inv., Inverian.

>200 mm) are up to a metre or more in diameter. Greater than 99% of boulders are of gabbroic Scourie dyke, clinopyroxene-rich mafic gneiss (commonly garnet-bearing) and layered TTG gneiss, the last of which is by far the most abundant lithology. No boulders of other common rock types occurring in NW Scotland (T. E. JOHNSON Fig. 4a). The clearest evidence is again preserved where thin stromatic leucosomes interconnect (with petrographic continuity) with pyroxene-bearing leucosomes that cut the foliation and are located within dilational structures such as shear bands (Fig. 4b), oblique interboudin partitions (Fig. 4c) and more irregular veins (Fig. 4d and e). In some instances melting has led to disruption of melanosome and the formation of partly disaggregated schollen (Fig. 4e). Near complete disruption of the pre-migmatitic fabrics locally gives rise to patches of diatectite (Fig. 4f). In all cases, pyroxene within the leucosome is significantly coarser-grained than that within the residuum or melanosome.

Petrographic evidence

Unequivocal microstructural evidence for partial melting in thin section (see Sawyer 2008, pp. 23–34 and references therein) is rare owing to extensive deformation-driven recrystallization during protracted cooling of the rocks from the granulite-facies peak (e.g. Johnson & White 2011). The clearest microstructural evidence for partial melting is preserved within residual TTG gneiss, predominantly in the form of irregular, optically continuous films of K-feldspar, quartz and, rarely, plagioclase between rounded grains of quartz and plagioclase (see Sawyer 2000, 2001; Fig. 5a–c). The films are commonly in contact with ortho- or clinopyroxene that are partially retrogressed to fine-grained biotite or hornblende respectively (Fig. 5a and b). Myrmekite is commonly developed where these films are in direct contact with subhedral plagioclase (Fig. 5b). Larger subhedral grains of K-feldspar do not occur within the residuum, and the thin interstitial films are the only K-feldspar present. Leucosomes are generally coarser-grained, and contain more quartz and a lower proportion of mafic minerals (dominantly pyroxene in fresh samples) compared with the residuum. Some of the cross-cutting leucosomes contain abundant subhedral grains of K-feldspar (Fig. 5d).

Discussion

Evidence for partial melting

Field evidence for partial melting of mafic rocks within the central region of the Lewisian complex is clear (Johnson et al. 2012), owing largely to the stark colour contrast between the pale quartzofeldspathic melt products (leucosome) and the dark mafic residuum (melanosome). Evidence for partial melting of the TTG gneisses is less obvious owing to more subtle colour contrasts between the various migmatitic components and the scarcity of clean outcrop faces. Although the clearest evidence is preserved within wave-washed boulders, evidence for in situ partial melting of the TTG gneisses exists in outcrops throughout the central region.

The clearest field evidence is provided by cross-cutting leucosomes that are coarser-grained and generally contain more quartz than the surrounding residuum. These may be granitic in composition, containing conspicuous grains of anhedral K-feldspar, consistent with these leucosomes containing a significant proportion of crystallized melt. However, many contain little or no K-feldspar, suggesting that they are rich in cumulus minerals, predominantly plagioclase. Most cross-cutting leucosomes contain coarse-grained orthopyroxene and/or clinopyroxene that are interpreted as the peritectic products of incongruent melting reactions consuming hornblende, biotite, plagioclase and quartz. The inferred coexistence of both the solid and (formerly) liquid products of incongruent melting within the cross-cutting leucosomes and the truncation of the fabric within the melanosome provide the clearest evidence for in situ partial melting and mobility of melt.

Stromatic leucosomes are in petrographic continuity with cross-cutting leucosomes, which we interpret to record movement of segregated melt along the foliation into dilatant sites represented by asymmetrical shear bands, interboudin partitions and more irregular veins (i.e. the stromatic leucosomes feed into the cross-cutting leucosomes). These relationships are consistent with movement of melt down gradients in pressure and away from its site of generation (e.g. Brown 1994, 2010). Several of the structures are consistent with ductile collapse owing to loss of melt from formerly melt-filled dilatant structures (compare Fig. 3b and d with figs 1c, d and 2 of Bons et al. 2008).

Although there is debate as to the origin of Scourian felsic sheets within the central region (e.g. Cartwright & Rollinson 1995; Fig. 3f), we suggest that melt ultimately fed into such bodies and escaped to higher (now eroded) crustal levels. Although most of the felsic sheets do not represent melt compositions (Rollinson 1994, 2012) and some were derived from accumulation and crystallization of melt largely derived from the metabasalts (Johnson et al. 2012), some record major accumulation and transfer to higher crustal levels of melt predominantly derived from the TTG gneisses. The preservation of anhydrous, granulite-facies assemblages in rocks that partially melted by reactions consuming hydrous phases requires melt loss on some scale (White & Powell 2002).

The best evidence for partial melting in thin section consists of thin cuspatate interstitial films of quartz, plagioclase and/or K-feldspar within the TTG residuum (e.g. Sawyer 2000, 2001, 2008; Marchildon & Brown 2002; Holness & Sawyer 2008;
Fig. 5a–c). These are interpreted as crystallized pockets of melt (or melt pseudomorphs) that remained trapped within the residuum following migration of most of the melt away from its source. Partially retrogressed pyroxene crystals in contact with former melt films (Fig. 5a and b) may represent the peritectic products of incongruent melting that have reacted with hydrous melt as it crystallized. Clear microstructures indicative of crystallized melt are generally not preserved within the leucosomes owing to extensive recrystallization, although granitic leucosomes containing abundant K-feldspar (Fig. 5d) are interpreted to represent areas dominated by segregated crystallized melt.

Conditions of partial melting and constraints on the Scourian P–T–t path

Temperatures during anatexis may be constrained using the study of Watkins et al. (2007), who performed partial melting experiments at 6–12 kbar on two natural amphibolite-facies sodic TTGs (one hornblende-bearing and the other biotite-bearing) from the northern region of the Lewisian complex. Figure 6 combines data from experiments on both starting compositions and shows the interpreted positions of the H₂O-saturated and undersaturated solidi, the prograde appearance of orthopyroxene, and the upper temperature stability of biotite and hornblende (Watkins et al. 2007). Also shown are the conditions of the Badcallian metamorphic peak constrained via phase equilibria modelling of metagabbro and metamorphosed ultramafic rocks from the Scourie area (Johnson & White 2011).

On heating, a small quantity of melt (less than or much less than 1 vol.%) may be formed at the H₂O-saturated solidi at 650–700°C proportional to the amount of intergranular H₂O. There is no evidence for the presence of significant volumes of H₂O-rich volatiles during granulite-facies metamorphism (Barnicoat 1983; Cartwright & Valley 1992). The onset of fluid-absent melting is constrained to 750–800°C. The formation of orthopyroxene, which is ubiquitous in fresh granulite-facies TTG gneisses of the central region, requires temperatures in excess of 800°C. The absence of both prograde hornblende and biotite implies peak temperatures in excess of 950°C. The P–T conditions for the peak metamorphic mineral assemblages preserved within the central region TTG gneisses based on the experimental constraints are consistent with those of Johnson & White (2011), albeit at the upper temperature range proposed by those workers. The presence of unretrogressed orthopyroxene in the leucosomes is indicative of partial melting having occurred during the high-P prograde segment of the Badcallian metamorphic event at pressures of around 10 kbar, and cannot be attributed to the Inverian event.

The development of coronae of plagioclase, orthopyroxene and magnetite replacing garnet within garnetiferous metagabbros is consistent with a segment of post-peak near-isothermal decompression to pressures of 7–9 kbar (Johnson & White 2011). Thereafter, the retrograde P–T evolution and rates of uplift and cooling between the Badcallian peak and subsequent Inverian metamorphism are largely unconstrained.

Conclusions

Partial melting and melt loss are the fundamental processes driving the irreversible differentiation of Earth’s crust. Rocks within the central region of the Lewisian complex probably reached temperatures in excess of 950°C at pressures corresponding to the deep continental crust, conditions under which both mafic (metagabbro) and felsic (TTG) gneisses underwent fluid-absent partial melting. Field observations provide the best criteria for determining whether rocks have partially melted or not.

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