7 Keltie Water, Callander

[NN 644 120]–[NN 633 131]

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7.1 Introduction

The Keltie Water is a spate stream whose rocky bed and low cliffs provide the most-complete and best-exposed section through the uppermost Dalradian sequence to be found in the Highland Border region. The rocks consist of an inverted succession of low metamorphic grade slaty pelites and gritty metasandstones, with subordinate metalimestones, which dip northwards at a low to moderate angle (Figure 4.20). They lie stratigraphically well above the Aberfoyle Slate Formation (see the *Duke's Pass* GCR site report), and the older part of the sequence is equated with the Ben Ledi Grit Formation of the Southern Highland Group. Structurally, the rocks lie on the south-east limb of the downward-facing F1 Aberfoyle Anticline, which is the local equivalent of the main closure of the Tay Nappe.

The geology of the Keltie Water section has aroused much interest and controversy since it was first examined in detail by Clough (in Geikie, 1897, p. 28); the early history of research has been reviewed by Tanner (1995). The most significant contributions were made by Clough, who concluded that it is not possible to make a clear distinction between undoubted Dalradian rocks in the north and other rocks farther south; by Stone (1957), who recognized a single southward-younging sequence, and disproved Anderson's (1947a) interpretation that the rocks now referred to as the Keltie Limestone and Shale Member (Figure 4.20) occupy a synclinal infold in the metasandstones; and by Harris (1962, 1969), who concluded that there is no evidence for a major stratigraphical or structural break within the Keltie Water section. The subsequent debate has focussed on whether or not there is stratigraphical and structural continuity between undoubted Dalradian rocks belonging to the Ben Ledi Grit Formation (which crop out in the northern part of the river section) and a younger group of rocks found farther south, named the Keltie Water Grit Formation (Tanner, 1995). A full understanding of the relationship between these two groups of rocks is vitally important, for the Keltie Water Grit Formation includes the fossiliferous Leny Limestone, which is of late Early Cambrian age (Pringle, 1940; Brasier *et al.,* 1992).

If stratigraphical and structural continuity between undoubted Dalradian rocks and the Keltie Water Grits can be demonstrated in the Keltie Water section, it follows that the deformation that has affected the southern part of the Dalradian block must be younger than Early Cambrian in age, specifically post 519 Ma (Tanner and Pringle, 1999); a conclusion that has profound implications for the age of the Grampian Event in the Scottish Caledonides. The alternative, strongly argued, viewpoint (Bluck and Ingham, 1997; but see Tanner, 1997) is that there is a major structural break between these two rock units, which is interpreted as a terrane boundary separating the Dalradian succession *sensu stricto* from the Keltie Water Grits (Brasier *et al.,* 1992). In this scenario, the Leny Limestone and Keltie Water Grits would be part of the Highland Border Complex, which is interpreted by those authors as an exotic terrane that docked with the Dalradian of the Grampian Terrane in late-Silurian to Devonian times. In this case, separation of the fossiliferous rocks from the Dalradian by a terrane boundary would remove any restriction on the maximum age of the deformation of the Dalradian rocks, and hence on the timing of the Grampian Event. The rocks exposed in the Keltie Water provide some of the key evidence for deciding between these two opposing hypotheses.

The other important feature of this site is the faulted contact of the Keltie Water Grits against Lower Old Red Sandstone conglomerate and volcanic rocks seen at the southern limit of the stream section. This fault has been referred to as the 'Highland Boundary Fault'.

7.2 Description

The emphasis in this account is upon the rocks exposed in the Keltie Water and the lower part of its tributary, the Allt Breac-nic (Figure 4.20). These rocks, referred to as the ‘Leny Grits’ by previous authors, were divided by Tanner (1995) into two main parts, from north to south:

(1) undisputed Dalradian rocks, mainly green gritty metasandstones, which are petrographically similar to those of the Ben Ledi Grit Formation in the classical Dalradian sequence farther north; and (2) the Keltie Water Grit Formation, which comprises a thick sequence of pale-coloured gritty metasandstones associated with grey and black slaty horizons, and includes a Transition Member of metasandstones and slaty pelites at the base.

All of the metasandstones in the *c.* 1.4 km-thick sequence exposed in the Keltie Water section are of turbidite facies and have a very similar field appearance. They preserve abundant way-up evidence from graded bedding, and less common cross-lamination, in beds that consistently preserve bottom structures, probably modified load-casts. This sequence is affected by faults and is cut by many, thick, irregularly shaped bodies of felsite (?late Caledonian) and two dolerite dykes of Palaeogene age.

7.2.1 Stratigraphy

Exposures in the upper part of the Allt Breac-nic are in massive gritty metasandstones with few minor structures or cleavages. The southern boundary of the Ben Ledi Grit Formation has been drawn at the southern limit of green and grey-green gritty metasandstones with abundant chlorite, detrital pink feldspar, and quartz (commonly pale blue). Workers familiar with the Southern Highland Group would confidently label these rocks as ‘Dalradian’. They almost certainly interdigitate with those of the Transition Member to the south, and include rare pale-coloured metasandstones similar to those commonly found in the main part of the Keltie Water Grit Formation.

The Transition Member comprises green, grey-green, brown and pale-coloured gritty metasandstones with green, grey and purple slaty pelites. The limit of the green-coloured rocks southwards marks the southern boundary of the transition and is accompanied by the incoming of grey and white metasandstones characteristic of the Keltie Water Grit Formation. The latter occur together with grey, black and variegated slaty pelites. The pale-coloured metasandstones are generally clast-supported, highly siliceous and have much Fe-rich carbonate in their matrix, so explaining why they are much more deeply weathered than the greenish coloured metasandstones to the north.

The Keltie Limestone and Slate Member appears to be a local facies development within a sequence of metasandstones that all young to the south-east. The black slaty pelites forming the middle unit contain numerous beds of orange-weathering, finely laminated carbonate rock, which contains abundant ferroan dolomite. A metre-sized lens of calcite metalimestone (the Keltie Limestone) is exposed in a small disused working at [NN 6468 1252]; major and trace element analyses show that it has the same overall composition as the Leny Limestone (Tanner and Pringle, 1999).

The black slaty pelites, which are part of the Leny Limestone and Slate Member, can be traced intermittently from Leny Quarry to the Keltie Water, and are correlated with the southernmost exposures of pelites found in the Keltie Water section. A full account of the setting, age, and correlation of the metalimestone, which is only exposed in Leny Quarry some 4 km south-west of the Keltie Water, is given in a GCR site report for that locality (in Rushton *et al.*, 1999) and in the paper by Tanner and Pringle (1999). The Leny Limestone and Slate Member consists of contorted and brecciated dull green to black slaty pelites with some chert bands, and grey and purple slaty pelites, intruded by 55 cm- and 15 m-thick dolerite dykes and by bodies of felsite; no metalimestone has been positively identified from these rocks in the Keltie Water section.

A detailed petrographical study of the entire sequence from the Ben Ledi Grit Formation to the southernmost exposure of the Keltie Water Grit Formation (Tanner and Pringle, 1999) has shown that the gritty metasandstones making up the bulk of this sequence have a distinctive detrital mineralogy throughout of quartz, plagioclase feldspar, white mica, biotite, tourmaline and zircon. K-feldspar is absent, and the amounts of detrital plagioclase and biotite decrease stratigrphically upwards. However, metasandstones of comparable grain size throughout this sequence show no discernable difference in petrographical features such as grain shape, strain fabrics and state of preservation of detrital micas (Figure 4.21).

7.2.2 Structure

Bedding throughout the section is generally inverted and dips to the north, except locally on the middle limbs of metre-scale minor folds where the beds are right way up and in places dip southwards. The main cleavage is a spaced cleavage in the metasandstones, with microlithons up to 2 cm thick (Figure 4.22). It appears, in exposures and under the hand-lens, to be a slaty cleavage in silty and argillaceous rocks. The cleavage is axial planar to the minor folds, or forms weak cleavage fans symmetrical to them; the folds have a variable plunge, which is gentle in the north but more variable and steep (up to 50° to either south-west or north-east) at the south end of the section. The main cleavage is invariably steeper than inverted bedding throughout the section.

In order to test for continuity in structural geometry across the boundary between the Ben Ledi Grit and the Keltie Water Grit formations, stereographic projections of the main cleavage were prepared for the southern part of the Ben Ledi Grit outcrop ((Figure 4.20), area A), the Transition Member (area B), and the northern part of the Keltie Water Grit outcrop (area C). These plots show that the mean orientation of the main cleavage in these three subareas is very similar and that it is not possible to separate the areas on the basis of structural geometry.

Harris (1969) recognized two main fabrics in these rocks, a penetrative slaty cleavage and a crenulation cleavage, which he correlated with similar structures in the adjoining Dalradian sequences. The crenulation cleavage is superimposed upon, and crenulates, the main cleavage described here and is most strongly developed in the argillaceous horizons such as the black slaty pelites above the waterfall at [NN 6458 1247]. The crenulation cleavage formed during a weak deformational event, which resulted in a gentle upright warping of beds in parts of the section. From a microscope study of the structural fabrics, Harris and Fettes (1972) subsequently identified an early cleavage in these rocks, which lies at a very low angle to bedding, and formed before the main cleavage. It is very difficult to see the early cleavage in the field.

The contact between the Keltie Water Grit Formation and the Lower Old Red Sandstone is seen as a fault at [NN 6451 1221], first described in detail by Harris (1969). The fault plane dips at 54° to the north-west (strike 048°) and is overlain by 40 cm of fault gouge and fragmented rock, followed by several metres of contorted and polished black slaty pelites. The exposed Old Red Sandstone succession commences with 5 m of conglomerate found in the stream bed immediately south of the fault, which is overlain by volcanic rocks dipping steeply to the south-east.

7.3 Interpretation

All previous workers, from Clough in 1897 to the present day, have agreed that the Ben Ledi Grit Formation and the overlying pale metasandstones and black slaty pelites of the Keltie Water Grit Formation form an essentially unbroken stratigraphical succession (i.e. Harris, 1962; Tanner, 1995). The transition beds, which occur between them, appear to be a normal stratigraphical part of the sequence and not to have arisen from tectonic interleaving. The rocks have all been affected by the same sequence of structural events, and are all at the same metamorphic grade (Tanner and Pringle, 1999). No evidence has been presented that contradicts any of these conclusions.

As has been demonstrated here, the main cleavage (S1) in the Keltie Water section maintains a consistent orientation and facing direction across the boundary between the Bed Ledi Grit and the Keltie Water Grit formations. Recent confirmation that there is evidence of a pre-D1 deformation phase in both the Bed Ledi Grit and the Keltie Water Grit formations, strengthens the structural correlation between these two units (Harris *et al.*, 1998; Tanner, 1998b). It is extremely unlikely that two sets of structural fabrics, which have formed at relatively low strains ((Figure 4.20) insets) and at low metamorphic grade, could have originated independently in two terranes of entirely different age and origin and then, upon amalgamation of the two terranes, become indistinguishable in their morphology, geometry, and facing direction. No alternative interpretation has been proposed to explain the structural data.

Recent work has also shown that that the metasandstones in the sequence have many petrographical features in common, despite the fact that burial diagenesis has almost certainly altered all of the detrital plagioclase to nearly pure albite (An_{1-3}), and caused dissolution of any pre-existing K-feldspar (Figure 4.21). The results of a whole-rock geochemical study of these metasandstones are consistent with the conclusion reached from the petrography, that the main vertical changes in composition reflect a progressive upward decline in amounts of detrital plagioclase and biotite

(Tanner and Pringle, 1999). In addition, electron-microprobe analysis of the detrital white micas from these rocks has shown that they have a comparable range in Si, Fe, Mg, and Ti contents at all levels of the sequence, with more-sodic micas occurring in the Transition Member and younger rocks. The wide range in chemistry suggests that they were derived from a complex source region.

$^{40}Ar/^{39}Ar$ laser fusion ages on detrital white micas from metasandstones at five different levels in the sequence gave age spectra which show a gradation from all old mica ages in the Ben Ledi Grit Formation (mainly 1600–1800 Ma, with a few at 2100 Ma) to a mixed population of old and younger white micas (507–886 Ma) in the Keltie Water Grit Formation. This work shows that none of the mica ages has been reset by Caledonian regional metamorphism, agreeing with the results of the petrographical work that the regional metamorphism was of low greenschist facies throughout, with no detectable metamorphic breaks, and maximum temperatures probably not exceeding 270oC.

The reported differences in whole-rock geochemistry, detrital mica composition and $^{40}Ar/^{39}Ar$ age upward in the succession are, as far as can be determined, progressive. Some of these changes may be linked to the establishment of a stable shelf environment, with the incoming upwards from the Ben Ledi Grits to the top of the Keltie Water Grit Formation of black muds, dark limestones, and dolostones, and an increase in the amount of possible detrital carbonate minerals in the turbidites (Tanner and Pringle, 1999). These data do not however preclude the possibility that an intraformational break may be present somewhere in the sequence.

The most illuminating finding from these investigations is that there is no suggestion from either the field observations or the various analytical data, of a major stratigraphical/structural break at a single, discrete level within the sequence that might be taken as positive evidence for the presence of a terrane boundary. Such a terrane boundary, if it existed, would have to be located between the southernmost exposure of undoubted Dalradian rocks (Ben Ledi Grit Formation), belonging to the Grampian Terrane, and the rocks farther south which include the Leny Limestone and were once considered to belong to an exotic terrane (the Highland Border Complex), which collided with the Grampian Terrane in late-Silurian to Devonian times (Brasier *et al.*, 1992; Bluck and Ingham, 1997). In view of the conclusion supported here that the rocks from the undoubted Dalradian Supergroup to the top of the Keltie Water Grit Formation are in their original stratigraphical sequence, this latter formation should be included logically within the Dalradian Supergroup. It is the lowest formation in the proposed Trossachs Group of Tanner and Sutherland (2007), which would include all units of the Highland Border Complex that crop out structurally below (i.e. north-west of) the Highland Border Ophiolite. This new Dalradian group would include strata containing fossils as young as Arenig in age.

It follows from the above relationships that the upper part of the Dalradian succession must have been deposited between 646 Ma (the youngest reliable detrital white mica age in the Keltie Water sequence and *c.* 517–509 Ma (the probable age range of upper Lower Cambrian rocks such as the trilobite-bearing Leny Limestone; Davidek *et al.,* 1998). This conclusion is compatible with the U-Pb age on zircon of 595 ± 4 Ma for the Tayvallich Volcanic Formation, which lies near the top of the Argyll Group (Halliday *et al.* 1989), and with the 590 ± 2 Ma age for the Ben Vuirich Granite (Rogers *et al.* 1989; Dempster *et al.*, 2002), which hornfelsed previously undeformed Dalradian rocks *prior* to the Grampian Event (Tanner and Leslie, 1994; Tanner, 1996; Tanner *et al.*, 2006).

In conclusion, as all of the rocks at this site can be shown to have shared the same structural history, then the Grampian Event where it affects the Southern Highland Group, is of post-Early Cambrian age (i.e. post 509 Ma). The Tay Nappe deformations (regional D1 and D2), and a possible earlier episode of deformation (Harris *et al.,* 1998; Tanner, 1998b) are also therefore of post-Cambrian age.

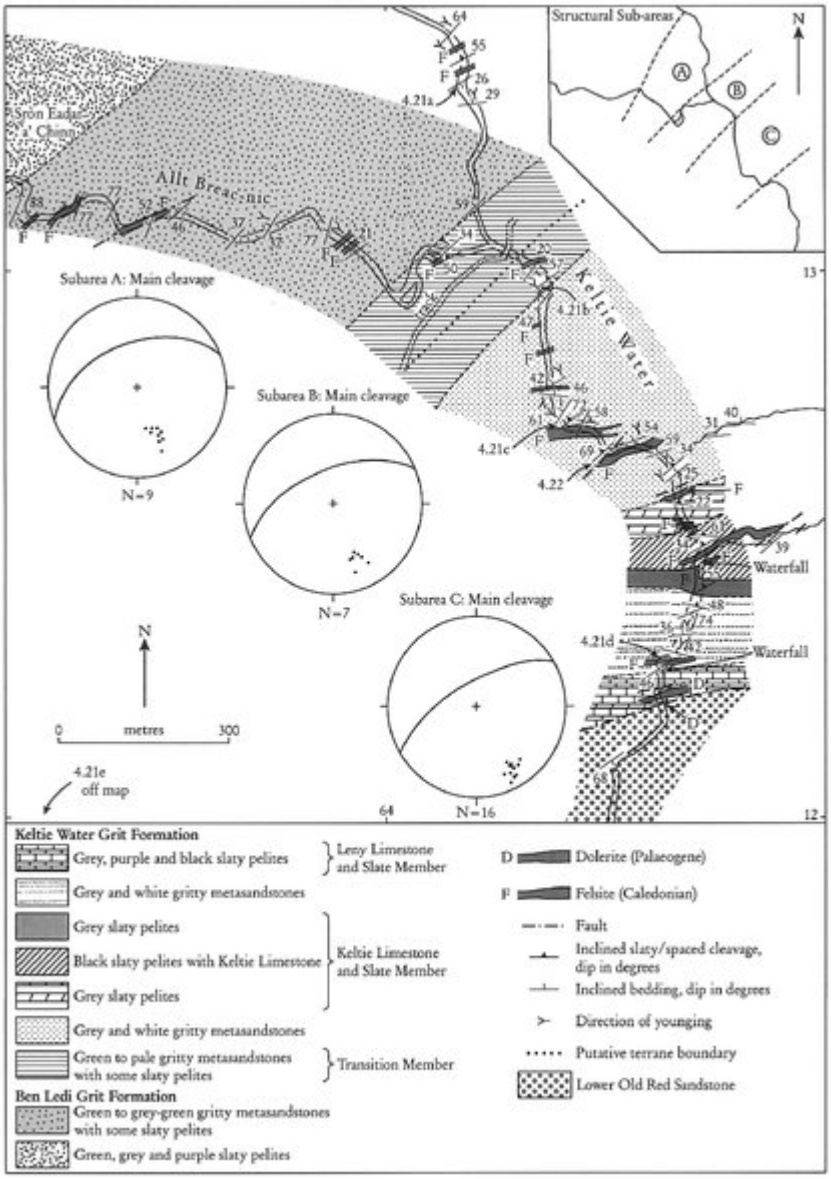
7.4 Conclusions

The Keltie Water provides a unique section of national importance through the uppermost Dalradian strata exposed in the Highland Border region. Its importance lies in the fact that it is the only place in the Grampian Terrane where there is an exposed section linking undoubted Dalradian rocks with fossiliferous rocks of known biostratigraphical age. Trilobites of Early Cambrian age have been reported from the Leny Limestone, which occurs at the nearby *Leny Quarry* GCR site (Rushton *et al.*, 1999). As the Dalradian rocks were once thought to be much older than this, the stratigraphical and structural relationship between undoubted Dalradian rocks and strata in the Keltie Water that are correlated with the

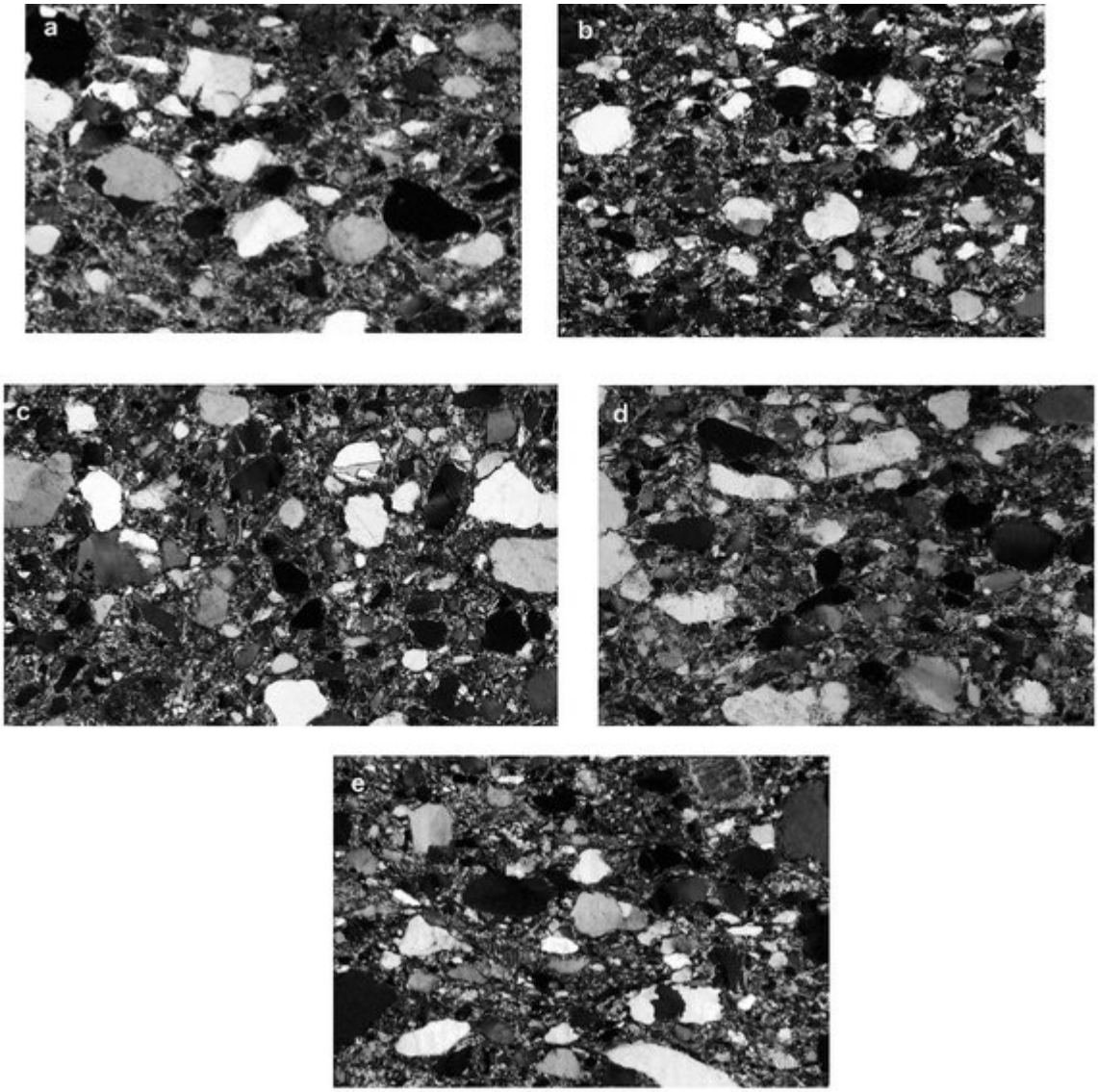
Cambrian rocks at Leny Quarry, has excited much scientific interest. Accordingly, the geological relationships seen at this GCR site have been the subject of much research and rigorous scientific debate in the past few decades.

Most geologists who have studied this GCR site now conclude that there is stratigraphical and structural continuity within the Keltie Water section, and a corresponding lack of evidence for a postulated terrane boundary between the undoubted Dalradian and the Cambrian rocks. The important corollary to this is that the Grampian Event, where it affects the upper part of the Dalradian sequence, commenced after the Early Cambrian, and that there is no evidence to support the hypothesis that a prior Precambrian orogenic event had affected the Dalradian rocks.

References



(Figure 4.20) Map of the Keltie Water, Callander GCR site. Locations of photomicrographs ((Figure 4.21), a–e) and the field photograph (Figure 4.22) are indicated. The position of the putative terrane boundary between the Grampian Terrane and the Highland Border 'exotic terrane' (Brasier et al., 1992) is also shown for reference. The inset map shows three structural sub-areas sited across the boundary between undoubted Dalradian rocks of the Ben Ledi Grit Formation (A), and the lower part of the Keltie Water Grit Formation, including the Transition Member (B). Sub-area C consists mainly of gritty metasandstones of the Keltie Water Grit Formation, comparable in lithology to the rocks in sub-area A. Equal-area stereographic projections for each of these sub-areas show the poles to the main cleavage, together with their computed mean orientation shown as a great circle (solid line).



(Figure 4.21) Photomicrographs of medium- to coarse-grained metagreywackes from the Keltie Water section, and a related exposure 5 km to the south-west. The photomicrographs illustrate the similarities in petrography and strain state of samples from (a) the Ben Ledi Grit Formation, (b) the Transition Member, (c) the lower part of the Keltie Water Grit Formation, above the Transition Member, (d) the Keltie Water Grit Formation above the Keltie Limestone and Slate Member and (e) the upper part of the Keltie Water Grit Formation above the Leny Limestone and Slate Member. The selected photomicrographs are representative examples chosen from over 100 thin sections and full details of the petrography were given by Tanner and Pringle (1999). Locations of samples are shown on (Figure 4.20), except for (e) which is located at [NN 6037 0858]. All photomicrographs are at the same scale with a width equivalent to approximately 4 mm. (Photos: P.W.G. Tanner.)

(Figure 4.22) Spaced S1 cleavage, with microlithons 1–3 cm thick, associated with a minor fold in gritty metasandstones of the Keltie Water Grit Formation. Section viewed to the north-east. This exposure (see (Figure 4.20) for location) was removed totally by a recent flood. (Photo: P.W.G. Tanner.)