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## Conodont biostratigraphy of the Crawford Group, Southern Uplands, Scotland

Howard A. Armstrong, Department of Geological Sciences, University of Durham,  
DH1 3LE, U. K.

James D. Floyd, British Geological Survey, Murchison House, Edinburgh, EH9 3LA,  
UK

Lu Tingqing, Institute of Petroleum Geology, Nanchong, P. R. China.

Hugh F. Barron, British Geological Survey, Murchison House, Edinburgh, EH9 3LA,  
UK

### Synopsis

Extensive new conodont collections from the Crawford Group, the oldest succession in the Southern Uplands of Scotland, support the previously documented biostratigraphical ages for the included formations. The Raven Gill Formation is lower Whitlandian, Arenig (comparable in age to the Dounans Limestone in the Highland Border Complex) and the Kirkton Formation is latest Llandeilian to Aurelucian, Llanvirn to Caradoc in age. It is concluded that there is a significant stratigraphical gap within the Crawford Group. The restricted and probably fault-bounded nature of the Raven Gill outcrops suggests that these may represent olistoliths within a *mélange* of Llandeilian to Aurelucian age. The chert-bearing succession of the Northern Belt of the Southern Uplands thus represents the juxtaposed sedimentary records of two entirely separate basins - the oldest pre-dates the Grampian assembly of the Laurentian margin, and the younger, the Northern Belt Basin *sensu stricto*, entirely post-dates this event.

**Keywords:** Conodont, Arenig, Llanvirn, Caradoc, Southern Uplands.

## **Introduction**

The Crawford Group is the oldest succession in the Northern Belt of the Southern Uplands. The historical but limited conodont biostratigraphical evidence suggests that there is a major stratigraphical gap between the Raven Gill Formation, of mid-Arenig age, and the Kirkton Formation of latest Llanvirn to early Caradoc age (Floyd, 2001 for a review). Remapping of the 1:50 000 Sheet 15E (Leadhills) by the British Geological Survey (BGS) over the last few years has brought to light a number of additional conodont-bearing chert localities within the Crawford Group that could potentially fill this stratigraphical gap. The aim of this study was to document the new collections, extend the historical dataset and test for stratigraphical continuity within the Crawford Group.

The thin, predominantly hemipelagic succession of the Crawford Group has provided the principal evidence for the Northern Belt forming part of a fore-arc accretionary prism (McKerrow *et al.* 1977; Leggett *et al.* 1979). This model relies on continuous accretion from the Arenig into the Silurian. Alternative models (see Smith *et al.* 2000 for a review), consider the Northern Belt as a back-arc basin (Hutton and Murphy 1987; Morris 1987; Stone *et al.* 1987) or as an extensional basin adjacent to the continental margin (Armstrong *et al.* 1996). The existence of a stratigraphical gap spanning much of the Lower Ordovician within the Crawford Group has significant implications for dating the onset of deposition in the Northern Belt Basin and, in particular, the accretionary prism model for the formation of the Southern Uplands.

## **Stratigraphical Context**

The Crawford Group crops out extensively within the structurally complex, 1.8 km wide Leadhills Imbricate Zone (LIZ), as faulted repetitions of volcanic rocks,

chert, black shale and greywacke (Hepworth 1981, Hepworth *et al.* 1982, Leggett 1978, Leggett and Casey 1982). The LIZ lies immediately to the north of the Leadhills Fault (Fig. 1, Leggett *et al.* 1979, Armstrong *et al.* 1999). At least some of the greywackes belong to the Kirkcolm Formation (= Abington Formation of Hepworth 1981, Hepworth *et al.* 1982) and the black shales are assumed to represent parts of the Moffat Shale Group either beneath or interleaved near the base of the Kirkcolm Formation.

Floyd (1996) proposed that the Raven Gill Formation should be restricted to rocks of proven Arenig age and followed Hepworth (1981) in assigning the more extensive development of grey and red cherts, red and green siliceous mudstones and lavas in the LIZ to the Kirkton Formation (Fig. 2).

### **Raven Gill Formation**

The Raven Gill Formation is known from only three closely grouped, probably fault-bounded, exposures within the LIZ (Figs 1 and 3, Table 1). Floyd (1996), following Hepworth (1981) and Hepworth *et al.* (1982), formally defined the Raven Gill Formation for the basaltic pillow lavas, basic sheets, brown mudstones and radiolarian cherts at the eponymous type locality (JF 176, Fig 3, Table 1). Floyd (1996, p. 157) noted the Arenig age of the conodonts from the type section in Raven Gill (*Oepikodus evae* Biozone - see also Lamont and Lindström 1957; Löfgren 1978, p. 38; Armstrong *et al.* 1990) but expressed uncertainty as to the unequivocal recognition of the Raven Gill Formation elsewhere along the LIZ. In addition to conodonts, radiolaria belonging to the family Inaniguttidae, spumellarian radiolaria and megascleres of hexactinellid sponges have been described from the Raven Gill Formation, but have limited biostratigraphical utility at present (Danelian and Floyd

2001). Brown mudstones interbedded with radiolarian cherts in the type section contain acrotretid brachiopods assigned to the genus *Paterula* by Lamont and Lindström (1957). Floyd (1996) further designated the red and green siliceous mudstones described by Hepworth (1981) in Glencaple Burn, near to its confluence with Raven Gill [NS 9252 1988], as a reference section in the type area. Other reference sections were designated further to the northeast.

The rocks of the Raven Gill Formation are also exposed on the hills to the north of Crawford (see Leggett and Casey 1982, fig. 5) where faulted repetitions of grey radiolarian chert, greywacke and pillow lavas, brown shales and red cherty mudstones occur. The latter unit of red mudstones (localities JF 166, 175, Fig 3, Table 1), now named the Castle Hill Member (Floyd 2001) has yielded conodonts of the *O. evae* Biozone (Armstrong and Dean 1996) and poorly preserved radiolaria (Danelian and Clarkson 1998; Danelian *et al.* 1999; Danelian and Floyd 2001). Danelian *et al.* (1999) and Danelian and Floyd (2001) also described the distinctive sponge *Konyrium varium* Nazarov and Popov 1976 from a loose block of red chert in the Southwood Burn (BGS locality JF 267, [NS 9400 2293]) in the Crawford area. This species has also been recorded in North America (Bergström 1979), and its type horizon in Kazakhstan is late Llanvirn in age (Nazarov and Popov 1976), suggesting that this block was derived from the Kirkton Formation (see also Armstrong & Owen 2001).

### **Kirkton Formation**

Hepworth (1981) proposed the ‘Kirkton Beds’ for the red, green and grey cherts and mudstones presumed to lie between the Raven Gill Formation and the Moffat Shale Group, along the LIZ. Floyd (1996) formalised the Kirkton Formation

and proposed the temporary exposure in the 1976 gas pipeline trench at Abington as the type section. In the type section approximately 70m of chert and siliceous mudstones overlie a lava succession up to 50m thick (Floyd 1996, p. 157). Reference sections in Glencaple Burn [NS 9252 1988; Hepworth 1981] within the type area, Normangill Burn [NS 971 241] and Hawkwood Burn [NS 976 254] were also defined. Lamont and Lindström (1957) described *Pygodus anserinus* from red chert sequences in Normangill Burn [NS 971 241], at Fardingmullach [NS 819 042] and also 11 km NW of Thornhill (see also Bergström and Orchard 1985, Armstrong *et al.* 1990 and Armstrong *et al.* 1996 for more recent identifications). Armstrong *et al.* (1990) described a conodont faunule from Hawkwood Burn, ascribing a Llanvirn age, though largely on negative evidence. The present study obtained *anserinus* Biozone conodont faunas from 12 localities in the Leadhills-Abington area. Their locations and conodont faunas are listed in Table 2.

Conodonts were first recorded from the Southern Uplands by Smith (1907) who reported conodonts in red siliceous mudstones of the Kirkton Formation at Morroch Bay [NX 017 524]. Subsequently, Lamont and Lindström (1957) described what would now be called *Spinodus spinatus* and *Periodon aculeatus* from red shales at the base of the succession. Lindström (1957) described coniform conodonts and *Periodon* (probably *P. grandis* see Löfgren 1978, p. 75) from black shales (Moffat Shale Group) with *Climacograptus wilsoni* Biozone graptolites (see also Bergström and Orchard 1985).

Graptolites of the *gracilis* Biozone are commonly found in the Glenkiln Shale Formation overlying or tectonically interleaved with the Kirkton Formation (Finney and Bergström 1986; Floyd 1996; Floyd 2001). The close association of *anserinus* Biozone conodonts and *gracilis* Biozone graptolites indicates a Llandeilian –

Aurelucian age for the Kirkton Formation in the type area. In the more southerly exposures in Morroch Bay, the red shales and mudstones could also be of this age.

Conodont species within the Kirkton Formation are representative of the *Protopanderodus-Periodon* Biofacies indicating a deep water continental margin setting (Armstrong 1990). The new collections add little additional biostratigraphical information though we record *P. anserinus* in samples from Hunt Law Cleugh (JF177) which were previously thought to be Arenig in age (Danelian *et al.* 1999).

### **Conodont specimens and curation**

In the Leadhills area, conodonts occur commonly as fragments and occasionally as demineralised moulds scattered on the bedding planes of red siliceous mudstones. Where original phosphate is preserved, the conodonts are black in colour, yielding a conodont colour alteration index (CAI) value of five, indicating heating to temperature in excess of 300°C (Epstein *et al.* 1977). White specimens could have a CAI value of 6 or higher indicating heating in excess of 480°C, but are more likely altered to clay minerals. The nature of the preservation is such that it is difficult to give specific names to many specimens, which can therefore only be *compared* to named species or tentatively identified at best. Species lists for the new localities are provided in Tables 1 and 2. Comprehensive faunal lists for samples from each locality are presented in Armstrong *et al.* (2001) and biostratigraphically useful taxa are illustrated in Figures 4 - 8. Sample numbers are for rock fragments bearing the conodont specimens, each locality can thus have multiple sample numbers. All material is housed in the collections of the British Geological Survey, Edinburgh.

### **Conodont biostratigraphy of the Raven Gill Formation**

In the Ordovician, two conodont realms have traditionally been distinguished, the temperate to cool water North Atlantic Realm (NAR) and the tropical, warm water Midcontinent Realm (MR). The NAR has been reported from Balto-Scandinavia, the Appalachians, South China, South America, the Nevada-Utah region of North America, and northwestern Australia (Bergström 1990; Bagnoli and Stouge 1991), the MR from cratonic North America, North China, eastern Australia and the Siberian Platform (see Ji and Barnes 1994 for a review). Provincial faunas can be delimited within the two major realms (Bergström and Sweet 1966; Lindström 1971; Bergström 1971, 1973; Sweet and Bergström 1972; Barnes and Poplawski 1973): the Midcontinent Realm included the Midcontinent and Chinese provinces; the North Atlantic Realm included the Baltic and Precordillera provinces. In addition to these, Bagnoli and Stouge (1991) further differentiated a “Pandemic Group” of conodonts including *Oepikodus* and *Periodon* that preferred cool temperate oceanic water, representing a group of cosmopolitan species. The “Pandemic Group” appeared on the East European Platform during the *Oepikodus evae* transgression in the early Arenig (Stouge and Bagnoli 1988; Nielsen 1992). Raven Gill Formation conodonts are referred to the “Pandemic Group” of the North Atlantic Realm and compared for biostratigraphical purposes with Lower Ordovician sections from Balto-Scandinavia. Interestingly however, the fauna also contains *Bergstroemognathus extensus*, found in the Lower Ordovician of New York State but absent from Balto-Scandinavia itself (see below).

Rasmussen and Stouge (1995) recognised four conodont biofacies in the Arenig-Llanvirn Stein Formation, Norway. From shallow to deep water these were:

the *Scalpellodus-Microzarkodina* Biofacies, the *Baltoniodus* Biofacies, the *Drepanoistodus* Biofacies and the *Protopanderodus-Periodon* Biofacies. Bagnoli and Stouge (1996) proposed an additional *Oepikodus* Biofacies, defined by the dominance of *O. evae* and subordinate *Periodon*, *Drepanoistodus*, *Protopanderodus* and *Oistodus*. They considered this to be a deep-water assemblage typical of slope deposits on palaeocontinental margins (Stouge and Bagnoli 1990). The fauna from the Raven Gill Formation is referred to the *Oepikodus* Biofacies.

#### *Oepikodus evae* Biozone fauna

The Raven Gill fauna is dominated by two species - *Oepikodus evae* (Lindström), the eponymous zonal species, and *Periodon flabellum* (Lindström), with subsidiary numbers of *Drepanoistodus forceps* (Lindström), *Drepanodus arcuatus* Pander, *Oistodus lanceolatus* Pander, *Paroistodus originalis* (Sergeeva), *Paroistodus parallelus* (Pander), *Paroistodus proteus* (Lindström), *Protopanderodus rectus* (Lindström) and *Paracordylodus gracilis* Lindström. All these species are typical of the *O. evae* Biozone in Balto-Scandinavia (Lindström 1960, 1971; van Wamel 1974; Stouge and Bagnoli 1988; Bagnoli and Stouge 1991, 1997; Löfgren 1978, 1993, 1994). In addition, the fauna contains two specimens tentatively assigned to *Bergstroemognathus extensus* Serpagli, a species absent from Balto-Scandinavia but found in coeval strata in New York State (Landing 1976).

In Balto-Scandinavia, *O. evae* and *P. flabellum* first appear in the *evae* Biozone (Löfgren 1978). Löfgren (1993, 1994) modified the original biozonation proposed by Lindström (1971) for the region, informally subdividing the *evae* Biozone into four sub-biozones. The lower *evae* Sub-biozone contains *O. evae* and reworked and *in situ* *Prioniodus elegans* (Löfgren 1978, 1993, 1994; Bergström 1988; Bagnoli and Stouge 1997). The lower–middle and middle–upper *evae* sub-biozones have the highest



diversity of taxa including the zonal index species. *O. evae* disappears in the upper *evae* Sub-biozone, leaving an impoverished coniform fauna including species of *Protopanderodus*, *Drepanoistodus* and *Paroistodus* (Kohut 1972; Löfgren 1978, 1993, 1994; Bagnoli and Stouge 1997).

The *evae* Biozone has also been reported from cratonic margin sections in North America. Landing (1976) described a fauna from the Deep Kill Shale in New York State including the zonal index species, *P. flabellum*, *Scolopodus rex*, *Paroistodus? gladius*, *Paracordylodus gracilis*, *Paroistodus originalis* and questionably *P. parallelus*, *Protopanderodus gradatus* (which appears to replace *P. rectus* in the North American faunas) and *Bergstroemognathus cf. extensus*. *Drepanoistodus forceps* and *Oistodus lanceolatus* are present in Balto-Scandinavia and Scotland but absent from the Deep Kill Shale. Bergström and Cooper (1973) described an *evae* Biozone fauna from the Upper Member of the Marathon Limestone, Texas, which contained *O. evae*, *Paroistodus parallelus* and *Protopanderodus rectus*. The *evae* Biozone in Argentina (Serpagli 1974) appears similar to that from the Deep Kill Shale and Löfgren (1978) compared this directly to the *evae* Biozone in Balto-Scandinavia.

The conodont fauna from the Raven Gill Formation therefore contains taxa typical of the *O. evae* Biozone, possibly the lower –middle and middle-upper sub-biozones, indicative of a lower Whitlandian, Arenig age (*sensu* Fortey *et al.* 1995). Samples from Glencaple Burn (JF175, 175A, 175B), contain an impoverished coniform fauna and lack the zonal index species. These samples could conceivably be from the upper part of the *evae* Biozone, but still within the lower Whitlandian.

In Britain, the *O. evae* Biozone is recorded only from the Raven Gill Formation in the Northern Belt of the Southern Uplands in Scotland (Bergström & Orchard

1985). However, conodonts of an equivalent age have been reported from the Dounans Limestone, Highland Border Complex (Ethington and Austin 1991). This fauna may have occupied a shelf-margin setting and includes representatives of both the North Atlantic and American Midcontinent realms. The presence of *Periodon flabellum* indicates that the Dounans Limestone can be correlated with the interval of the Ross/Hintze zone J through lower zone L, approximately equivalent to the *O. evae* and *B. triangularis* conodont biozones of the North Atlantic Realm (Ethington and Austin 1991).

Palaeogeographical reconstructions (Torsvik *et al.* 1996) indicate that the Highland Border and contiguous terranes to the south lay adjacent to Laurentia within tropical latitudes. Although there was significant tectonic re-organisation within the paratectonic Caledonides during the Grampian and subsequent Caledonian deformations, it is reasonable to consider that the conodont fauna of the Raven Gill Formation represents a deep-water slope environment, and is partly equivalent to that of the Dounans Limestone.

### **Implications**

The expanded conodont biostratigraphical dataset supports the presence of a major stratigraphical gap within the Crawford Group, the oldest part of the Northern Belt succession. Cherts and volcanic rocks occur at two distinct stratigraphical levels, in the Raven Gill Formation of Whitlandian, low to mid-Arenig age and the Llandeilian-Aurelucian, late Llanvirn to early Caradoc Kirkton Formation. The stratigraphical gap is thus equivalent to the upper Arenig to upper Llanvirn (Llandeilian), a period of approximately 10 million years (Fortey *et al.* 2000).

The existence of a large stratigraphical gap within the Crawford Group is inconsistent with the accretionary prism model for the Southern Uplands as this assumes continual accretion of Layer 1 sediments from the Arenig to Silurian (Leggett *et al.* 1979). Alternatively, Armstrong and Owen (2001) suggested that the Raven Gill Formation was part of a pre-Grampian ocean margin succession of Novantia, an Ordovician arc terrane now concealed beneath the Southern Uplands Allochthon and that the Raven Gill Formation was tectonically emplaced during the formation of the Southern Uplands (see also Leggett *et al.* 1979). This hypothesis is consistent with the Raven Gill Formation cherts having a continental margin Rare Earth Element geochemistry (Armstrong *et al.* 1999) and the presence of an *Oepikodus evae* Biofacies conodont assemblage.

The new mapping indicates that the Raven Gill Formation is restricted to geographically isolated and probably fault-controlled outcrops in the type area. A possible interpretation of these outcrop patterns is that the exposures of the Raven Gill Formation represent olistoliths in a mélangé within the lower Crawford Group. This reinterpretation implies that the Raven Gill Formation was exposed along the margin to the Northern Belt Basin in the early Middle Ordovician, albeit in a deep water setting.

The Kirkton Formation (and coeval Currarie Formation in the Ballantrae area) crops out in several tracts of the Northern Belt and clearly forms part of an extensive basal unit to the succeeding and prograding greywacke succession. Continental margin REE patterns for cherts within the Kirkton Formation (Owen *et al.* 1999) and the presence of conodonts of the *Protopanderodus-Periodon* Biofacies, indicate that the Northern Belt Basin succession was initiated in the latest Llanvirn, in a deep-water continental margin setting (Owen *et al.* 1999).

## Conclusions

Samples from the Raven Gill Formation, within the LIZ, contain conodonts of the *Oepikodus evae* Biozone and are of lower Whitlandian, Arenig age (*sensu* Fortey *et al.* 1995). The Raven Gill Formation is reinterpreted as a mélange of late Llanvirn to early Caradoc age, within the lower Crawford Group. The Kirkton Formation, though lithologically similar, can be distinguished on the widespread presence of Llandeilian - Aurelucian, *P. anserinus* Biozone conodonts, and forms the basal unit of the Northern Belt Basin succession. Despite extensive re-collecting, no conodonts representing the intervening upper Arenig and Llanvirn have been found. It is concluded, therefore, that there is a significant stratigraphical gap within the Crawford Group.

The chert-bearing succession of the Northern Belt of the Southern Uplands represents the juxtaposed sedimentary records of two entirely separate basins. The older pre-dates the Grampian assembly of the Laurentian margin while the younger Northern Belt Basin *sensu stricto* entirely post-dates this event. A stratigraphical gap of some 10 million years within the Crawford Group is incompatible with the model of progressive accretion of Layer 1 sediments to the leading edge of Laurentia, during the development of an accretionary prism over this period.

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#### Appendix - Systematic notes

Taxa from the Kirkton Formation are well known and have been recently described by Armstrong (1997, 2000). Taxa from the Raven Gill Formation have not been formally described. The nature of the preservation of this collection makes it difficult to contribute to the systematic palaeontology of the species recorded. Consequently *Oepikodus evae* Biozone species are listed below with authorisation and the most recent citation with which the authors agree. The *O. evae* Biozone fauna is dominated by prioniodinid and coniform species for which natural assemblages are not known. Rigorous hypotheses of topological homology cannot be easily inferred from secondary morphological criteria, and notational schemes proposed by Sweet (1988) and Sansom *et al.* (1994) are retained, indicating no firm topological homology (Purnell *et al.* 2000, p. 119). Specimens were photographed using a Wild photomicroscope and FP4 monochrome film.

*Bergstroemognathus extensus* (Graves and Ellison, 1941). Figure 8i. Barnes *et al.*,

1991, pl.1, figs 28-30. Only two S elements have been discovered.

*Drepanodus arcuatus* Pander, 1856. Figure 4g, i. Zhang, 1998, p. 59-60, pl.4, figs 7-11, 15-16.

*Drepanoistodus forceps* (Lindström, 1955). Figure 4a, b. Löfgren, 1996, text-figs 5:A-C.

*Oepikodus evae* (Lindström,1955). Figure 5a-j. Löfgren, 1996, text-figs 5:A-F. The distinction of P and S elements is difficult in our collection. S elements tend to have longer processes.

*Oistodus lanceolatus* Pander,1856. Figure 4e. Bergström, 1988, pl. 2, figs 17-19.

*Paracordylodus gracilis* Lindström, 1955. Figure 6b, c, e, f. Stouge and Bagnoli, 1988, pp.125-126, pl. 8, figs 16-19. S elements in this collection have a costa on each denticle of the posterior process.

*Paroistodus originalis* (Sergeeva, 1963). Figure 4c, h. Löfgren, 1996, text-figs 5:P-Q.

*Paroistodus parallelus* (Pander,1856). Figure 7a. Löfgren, 1996, text-figs 5:S-T. The species has a variably developed carina on the cusp.

*Periodon flabellum* (Lindström, 1955). Figure 6a, h-k. Löfgren, 1996, pp.174-175, text-figs 5:AK-AL. In our collection, S elements are significantly more abundant than P elements.

*Protopanderodus varicostatus* (Sweet & Bergström, 1962). Figure 4d. Figures 4 j and 4 k are only tentatively assigned to this species due to poor preservation.

*Protopanderodus rectus* (Lindström, 1955). Figure 4f. Stouge and Bagnoli, 1990, p.23, pl. 8, figs 1-5.

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## Figure Captions

**Figure 1.** Outline geology of the Leadhills - Crawford area in the Southern Uplands showing localities with *Oepikodus evae* Biozone faunas (white x) and those with *Pygodus anserinus* Biozone faunas (black +). Inset shows area of main map.

Geological units: KKF, Kirkcolm Formation; MCHB, Marchburn Formation; MFS, Moffat Shale Group and Crawford Group (undivided); PPF, Portpatrick Formation; SHIN, Shinnel Formation; LIZ, Leadhills Imbricate Zone.

**Figure 2.** Simplified stratigraphical diagram of early-mid Ordovician successions in the Southern Uplands, highlighting the established biozones recognised so far in the radiolarian cherts of the Crawford Group (after Danelian 1999). Lithostratigraphical terminology according to Floyd (1996, 2001). Chronostratigraphy and biostratigraphy from Fortey *et al.* (1995).

**Figure 3.** Outline stratigraphy at the three known exposures of Raven Gill Formation near Abington. Raven Gill (JF 176) is the type locality for the Raven Gill Formation; Castle Hill (JF 166) is the type locality for the Castle Hill Member (Floyd 1996, 2001).

**Figure 4. a, b.** *Drepanoistodus forceps* (Lindström, 1955). **a**, sample 17E111, x50.

**b**, sample 17E111, 100.

**c, h.** *Paroistodus originalis* (Sergeeva, 1963). **c**, sample 17E93, x50. **h**, sample 17E93, 100.



- d.** *Protopanderodus varicostatus* (Sweet and Bergström, 1962). Sample 17E171, x40.
- e.** *Oistodus lanceolatus* Pander, 1856. Sample 16E952, x50.
- f.** *Protopanderodus rectus* (Lindström, 1955). Sample 16E778, x25.
- g, i.** *Drepanodus arcuatus* Pander, 1856. **g**, sample 16E774, x14. **i**, sample 16E773, x14.
- j.** *Protopanderodus ?varicostatus* (Sweet and Bergström, 1962), sample 17E110, x50.
- k.** *Protopanderodus ?varicostatus* (Sweet and Bergström, 1962), sample 17E94, x50.

**Figure 5. a-j.** *Oepikodus evae* (Lindström, 1955). All specimens x50. **a**, 1, S element, sample 16E788. **b**, S element, sample 17E117. **c**, M element, sample 16E789. **d**, M element, sample 16E766. **e**, S element, sample 16E802. **f**, S element, 16E793. **g**, P element, sample 17E107. **h**, P element, sample 17E108. **i**, S element, sample 17E118. **j**, P element, sample 15E759.

**Figure 6. a, h-k.** *Periodon flabellum* (Lindström, 1955). All specimens x50. **a**, Pa element, sample 16E858. **h**, Pb element, sample 16E951. **i**, ?S element, sample 16E796. **j**, M element, sample 16E799. **k**, S element, sample 16E787.

**b, c, e, f.** *Paracordylodus gracilis* (Lindström, 1955). All specimens x50. **b**, S element, sample 17E107. **c**, M element, sample 16E798. **e**, S element, sample 17E124. **f**, S element, sample 16E794.

**d, g.** *Spinodus spinatus* (Hadding, 1913). Both specimens x50. **d**, S element, sample 17E174. **g**, S element, sample 17E177.

**Figure 7. a.** *Paroistodus parallelus* (Pander, 1856), sample 16E784, x45.

**b, c, e-h.** *Periodon aculeatus* (Hadding, 1913). All specimens x50. **b**, S element, sample 17E181. **c**, S element (mould), sample 17E267. **e**, Sc element (mould), sample 16E834. **f**, M element, sample 16E951. **g**, S element, sample 17E310. **h**, Pb element, sample 17E127.

**d.** *Spinodus spinatus* (Hadding, 1913), S element, sample 15E6586, x40.

**Figure 8. a, d.** *Periodon aculeatus* (Hadding, 1913). All specimens x50. **a**, S element, sample 17E272. **d**, S element, sample 17E309.

**b, c, e, f, k.** *Pygodus anserinus* Lamont and Lindström, 1957. All specimens x50. **b**, Pa element, sample 15E6592. **c**, Pa element, sample 15E6593. **e**, Pb element, sample 17E141. **f**, Pa element, sample 17E137. **k**, Pc element, sample 17E151.

**h.** *Periodon flabellum* (Lindström, 1955), S element, sample 17E108, x50.

**g, j.** *Periodon aculeatus* (Hadding, 1913). Both specimens x50. **g**, S element, sample 16E863. **j**, Pb element, sample 16E851.

**i.** *Bergstroemognathus extensus* (Graves and Ellison, 1941), P element, sample 16E862, x50.

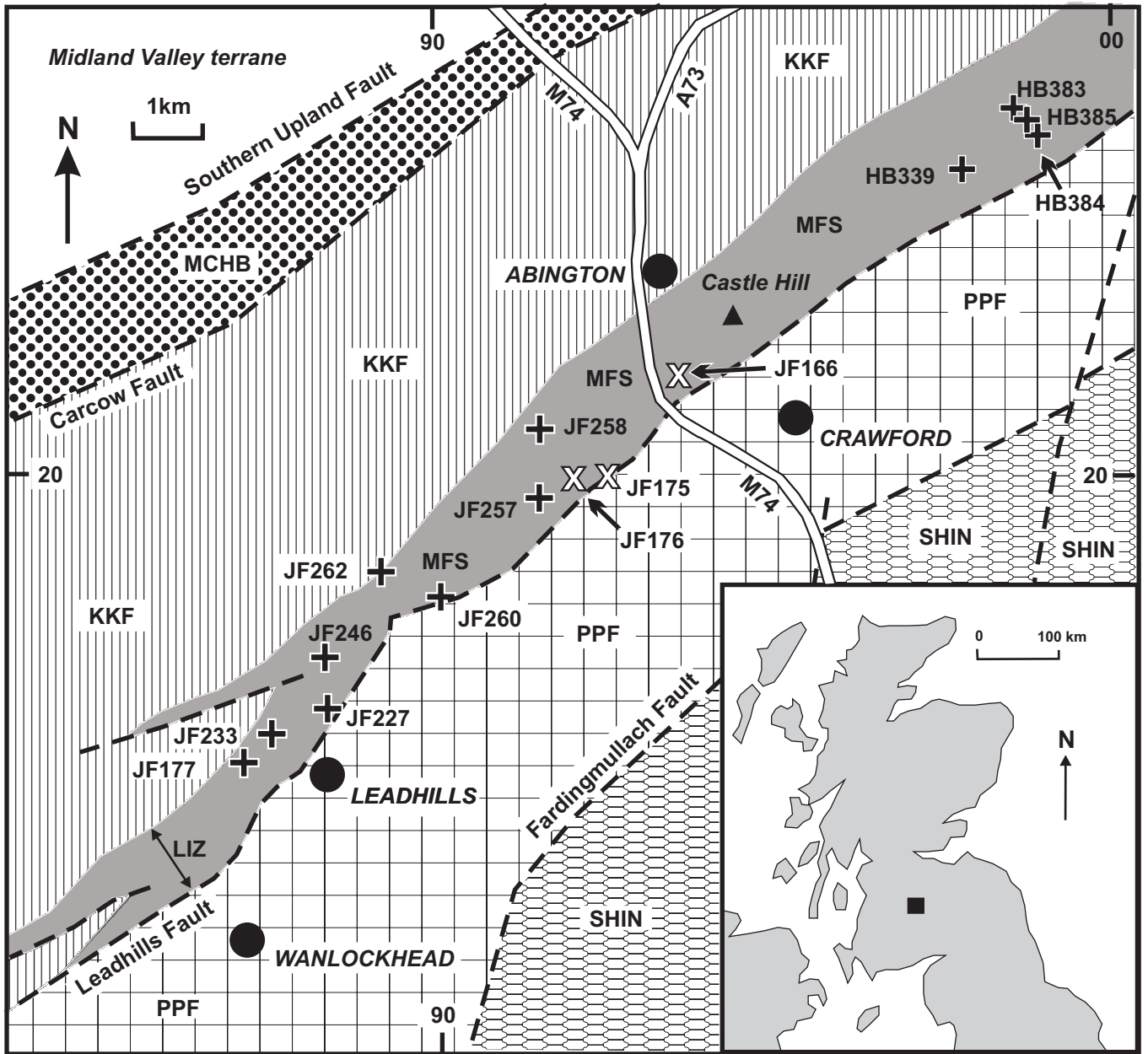
BGS locality	Grid Reference [NS]	Locality	? <i>Belodella</i> sp.	<i>Bergstroemognathus extensus</i>	<i>Drepanodus arcuatus</i>	<i>Drepanoistodus forceps</i>	<i>Microzarkodina ?flabellum</i>	<i>Oepikodus evae</i>	<i>Oistodus lanceolatus</i>	<i>Paracordylodus gracilis</i>	<i>Paraoistodus originalis</i>	<i>Paraoistodus parallelus</i>	<i>Parapanderodus</i> sp.	<i>Periodon flabellum</i>	<i>Protopanderodus gradatus</i>	<i>Protopanderodus rectus</i>	<i>Protopanderodus varicosatus</i>	<i>Spinodus spinatus</i>
JF176	9204 1989	Raven Gill, north branch		?	x	cf		x				x		cf		x	x	
JF176A	9204 1989	Raven Gill, NW side of gully						x		x	x			x	x			
JF176B	9204 1989	Raven Gill, NE side of gully				x		x		x				x				
JF176C	9204 1989	Raven Gill, SE side of gully								x				x				
JF175	9255 1989	Glencaple Burn, Abington	x	?			x		x	?				?				
JF175A	9255 1989	Glencaple Burn 'A', Abington						?					x	x				
JF175B	9255 1989	Glencaple Burn 'B', Abington								x	x			x				?
JF166	9373 2175	Castle Hill track, Crawford						x		x	cf			x				

Table 1. Localities yielding *Oepikodus evae* Biozone faunas, and the distribution of species recorded.



BGS locality	Grid Reference [NS]	Locality	<i>Drepanodus arcuatus</i>	<i>Periodon aculeatus</i>	<i>Protopanderodus liripipus</i>	<i>Protopanderodus varicosatus</i>	<i>Pygodus anserinus</i>	<i>Drepanoistodus suberectus</i>	<i>Spinodus spinatus</i>	<i>Strachanognathus parvus</i>
JF 177	8708 1568	Hunt Law Cleugh, Snar Water	cf	x		x	x	cf	?	
JF233	8752 1606	Glenkip Head, Leadhills	?	x				x	x	
JF227A	8843 1652	Gripps Shaft, Leadhills		x		x	x		x	
JF227B	8843 1652	Gripps Shaft, Leadhills	x	x		x		cf	x	x
JF227C	8843 1652	Gripps Shaft, Leadhills		x			x			
JF227D	8843 1652	Gripps Shaft, Leadhills		x		x		x		
JF227E	8843 1652	Gripps Shaft, Leadhills		x			x			
JF246B	8829 1713	Gripps Cleugh, Leadhills		x		x	x			
JF 262	8914 1845	Clow Gill (lower) , Leadhills		x			x			
JF260	8991 1815	Clow Gill (upper), Leadhills		x		x	x	sp.		
JF257	9151 1961	Kirk Gill Cleugh, Abington		x			x			
JF258	9150 2070	Kirk Gill, Abington		x			x			
HB339	9779 2460	Black Grain, Abington		x	cf	x	x			
HB383	9850 2533	Lead Burn, Abington		x			x			
HB384	9870 2516	Lead Burn, Abington		x			x		x	
HB385	9858 2528	Lead Burn, Abington					x			

Table 2. Localities yielding *Pygodus anserinus* Biozone faunas, and the distribution of species recorded



Armstrong et al. Figure 1

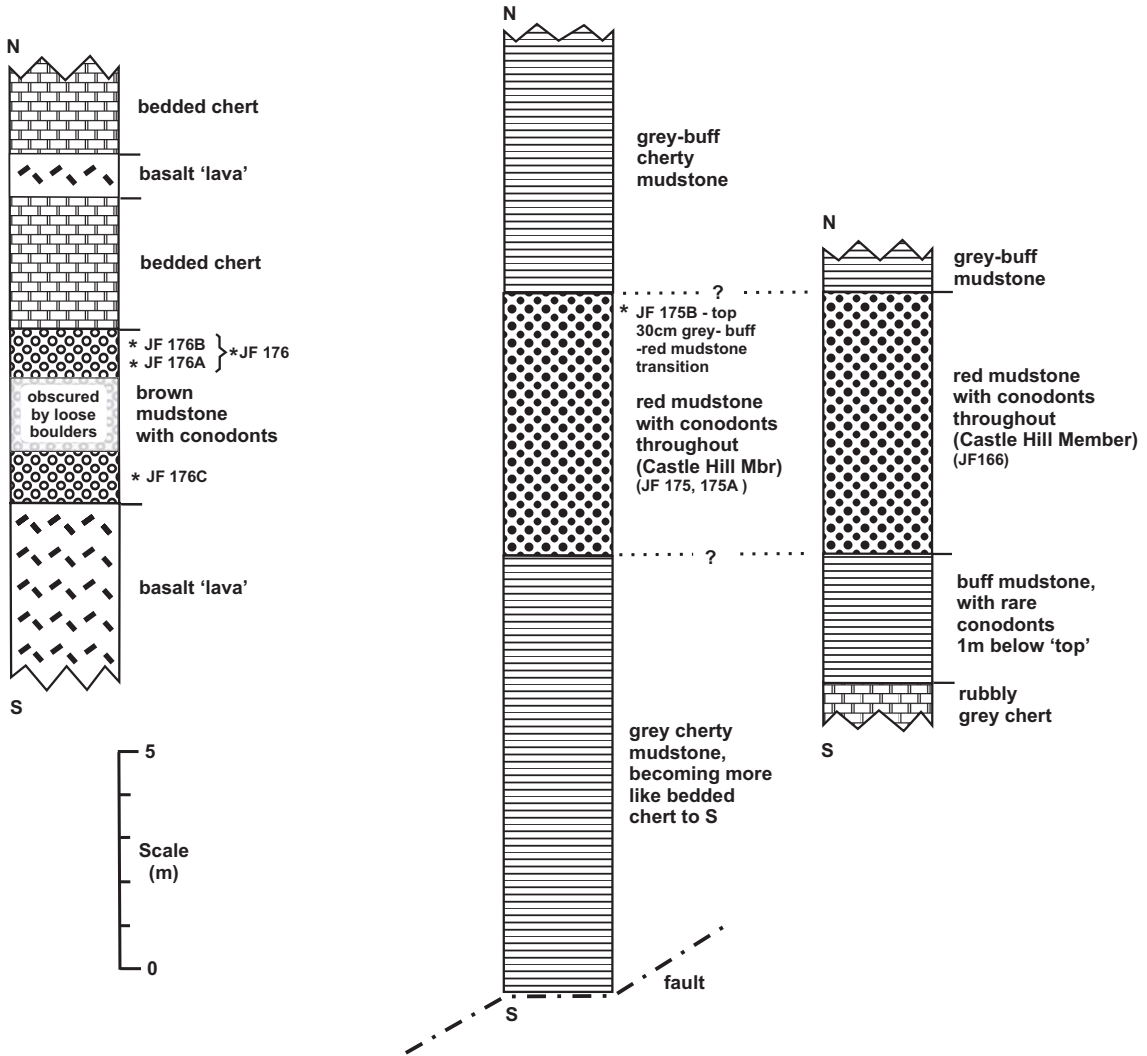
British chronostratigraphy		British biostratigraphy		Lithology	Lithostratigraphy	
Series	Stages	graptolite zones	conodont zones			
CARADOC	Burrellian			greywacke	LEADHILLS SUPERGROUP	
	Aurelucian	<i>gracilis</i>	<i>anserinus</i>	shale	MOFFAT SHALE GROUP	
LLANVIRN	Llandeilian			radiolarite	KIRKTON FORMATION	
	Abereiddian			lava		
ARENIG	Fennian			?		
	Whitlandian			?		
	Moridunian		<i>evae</i>	radiolarite	RAVEN GILL FORMATION	
				lava	CRAWFORD GROUP	

Armstrong et al. Figure 2

**Raven Gill**  
 (BGS locality JF 176)  
 [NS 9204 1989]

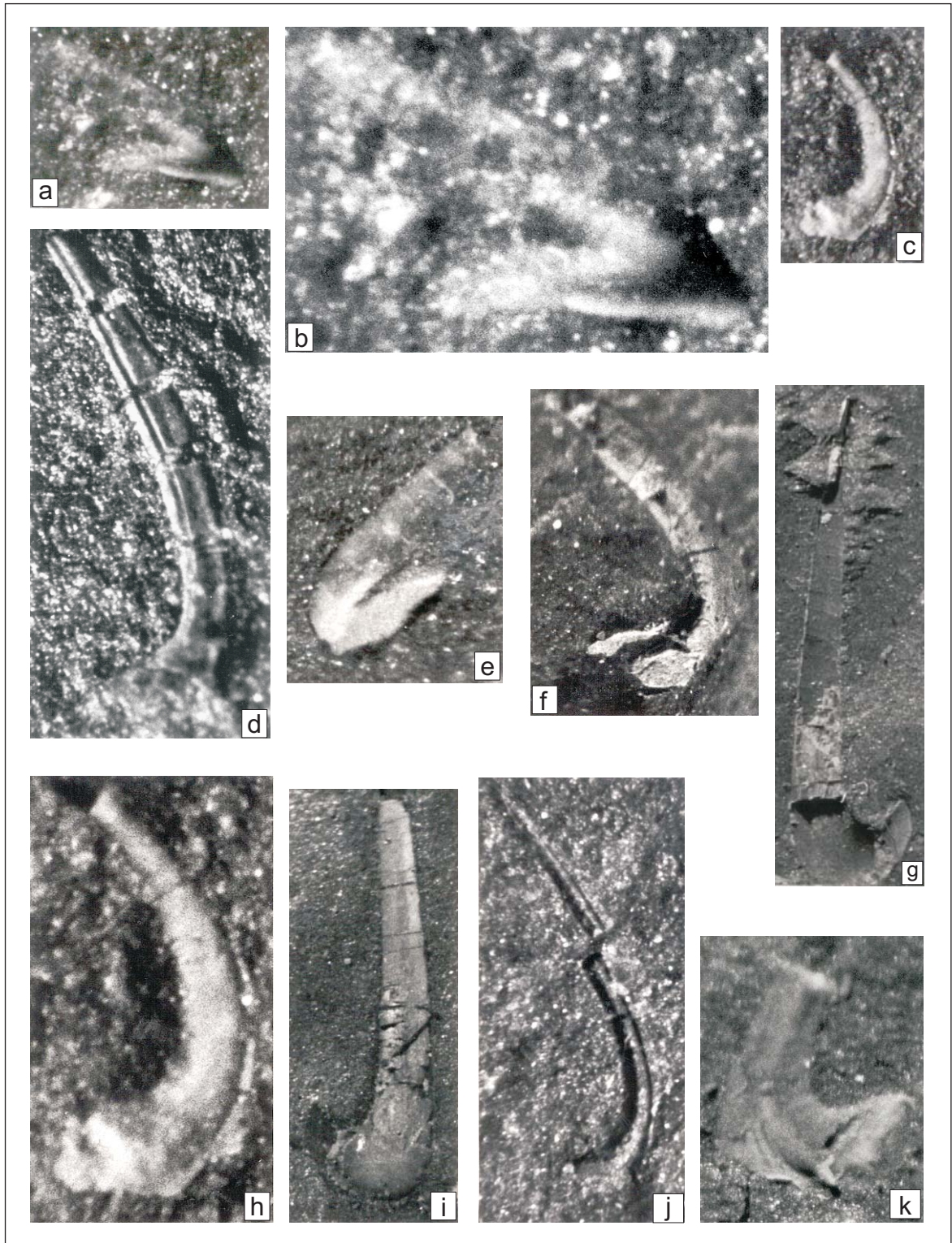
**Glencaple Burn**  
 (BGS locality JF 175)  
 [NS 9255 1989]

**Castle Hill**  
 (BGS locality JF 166)  
 [NS 9373 2175]



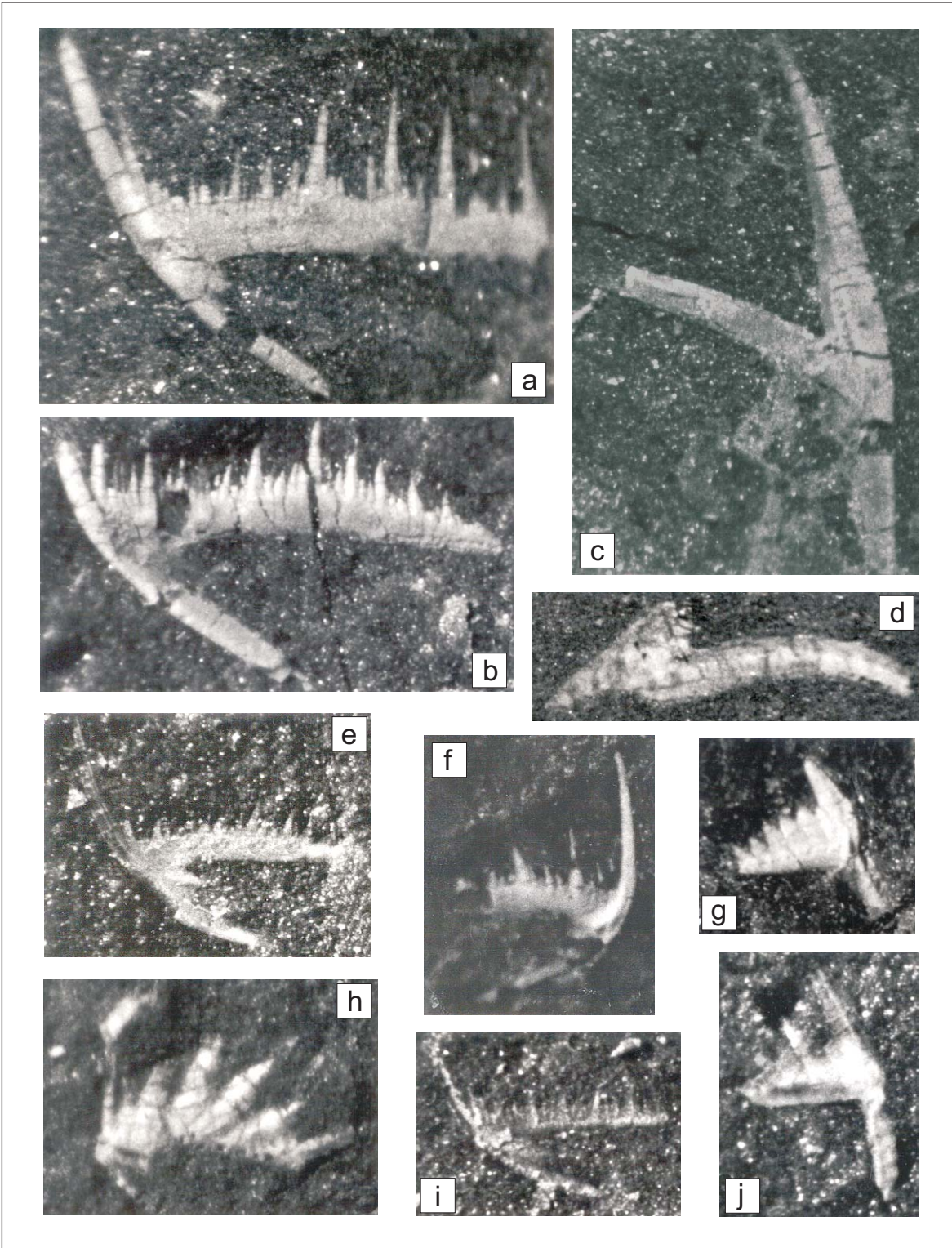
Armstrong et al. Figure 3





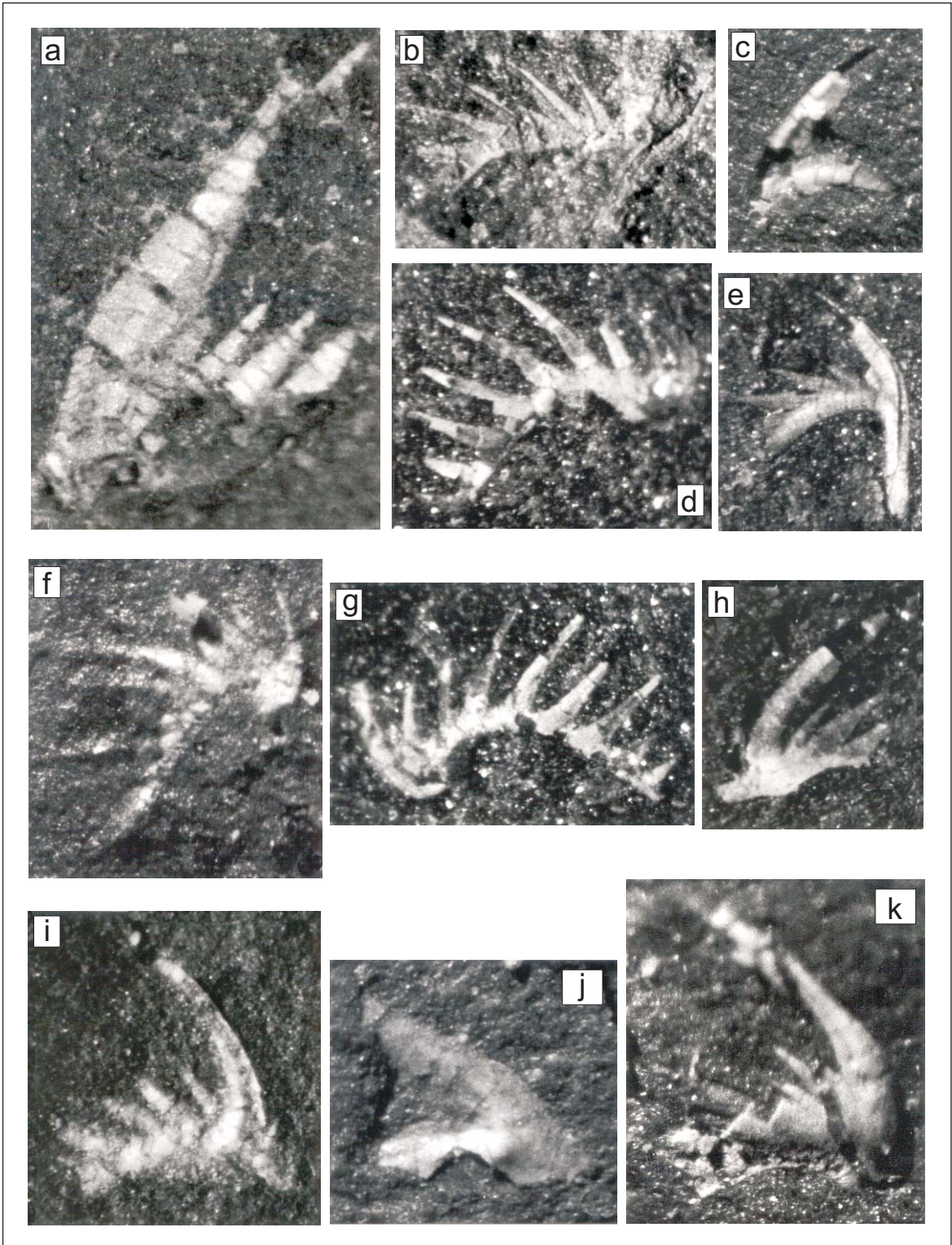
Armstrong et al. Figure 4





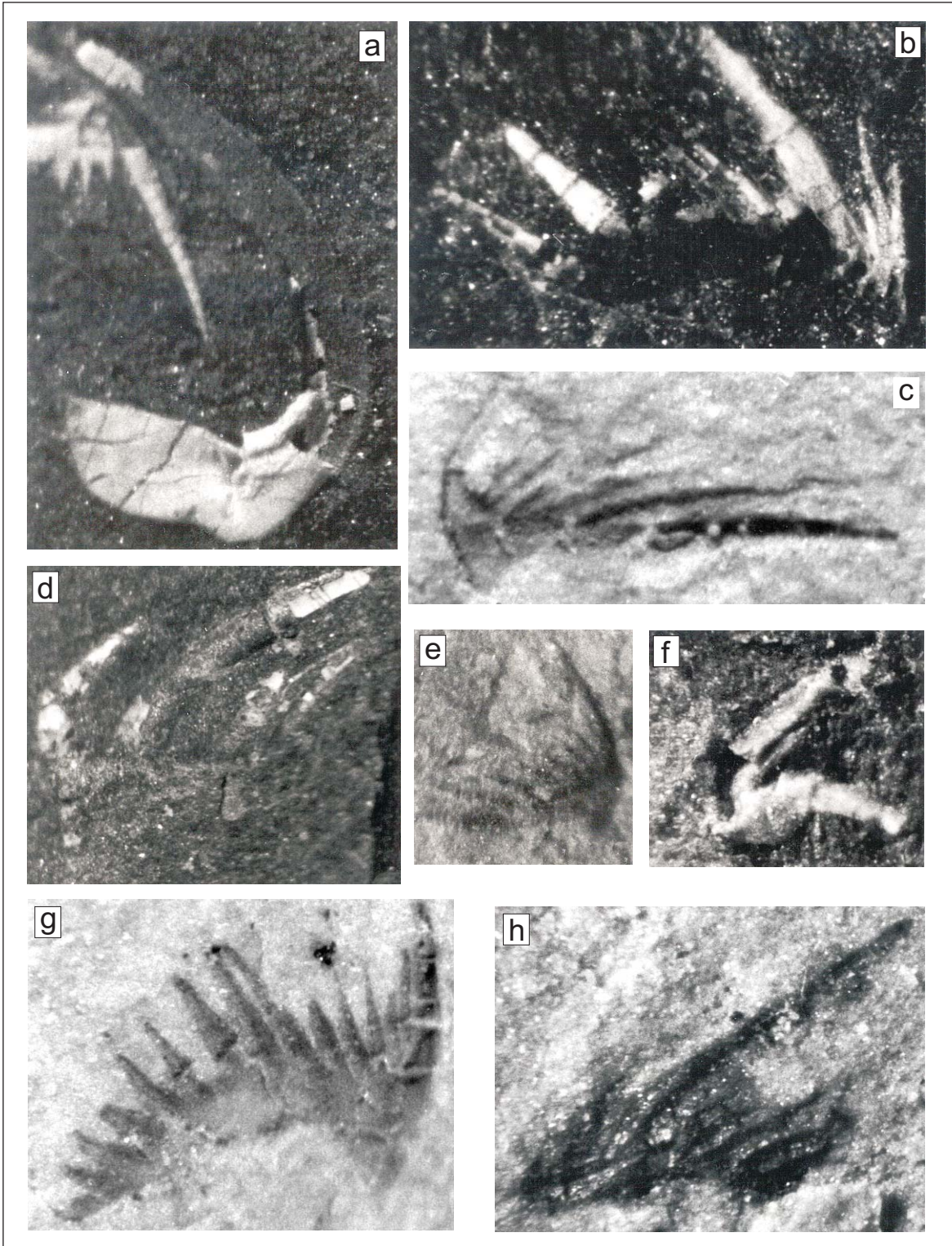
Armstrong et al. Figure 5





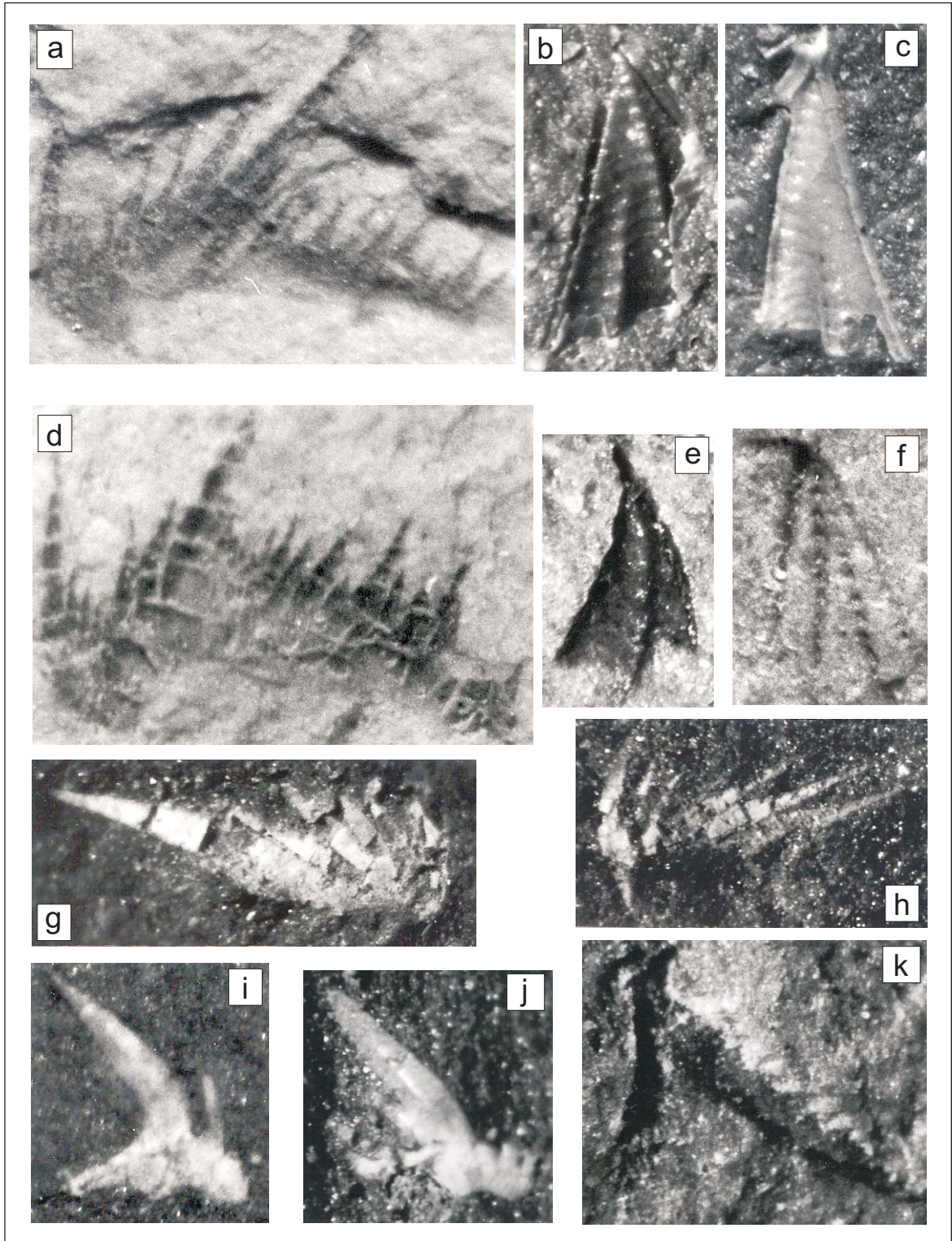
Armstrong et al. Figure 6





Armstrong et al. Figure 7





Armstrong et al. Figure 8