



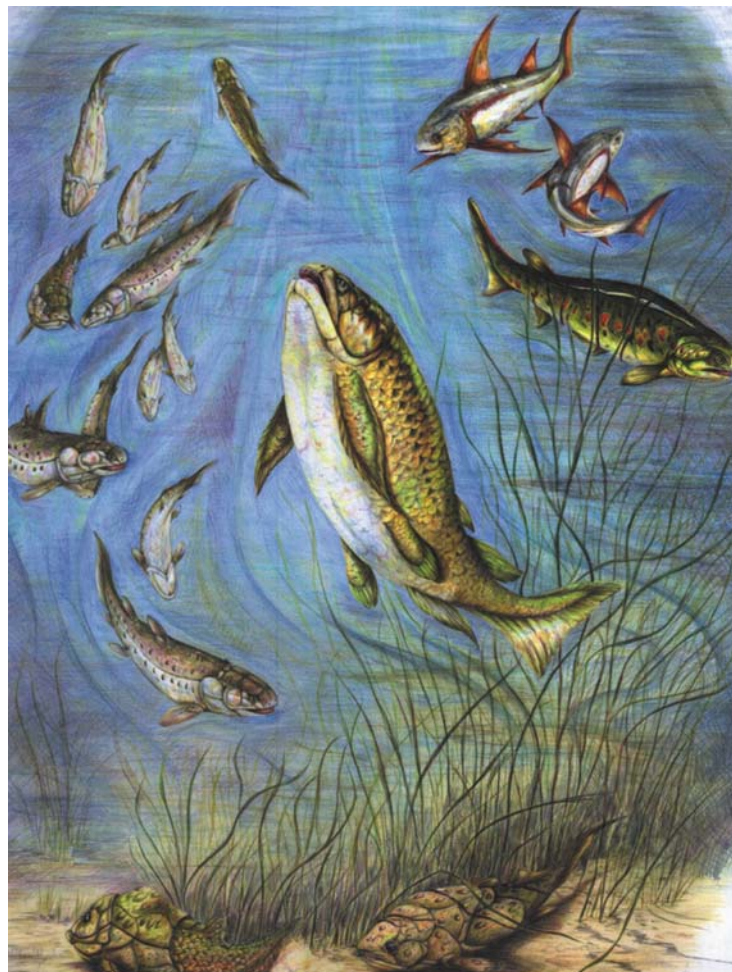
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A biostratigraphical framework for geological correlation of the Middle Devonian strata in the Moray-Ness Basin Project area

Geology and Landscape Northern Britain Programme

Internal Report IR/05/160



BRITISH GEOLOGICAL SURVEY

GEOLOGY AND LANDSCAPE NORTHERN BRITAIN PROGRAMME
INTERNAL REPORT IR/05/160

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Fish typical of the Achanarras
Fish Bed

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Foreword

This report summarises the progress that has been made in establishing a robust biostratigraphical framework for correlation of the onshore Devonian sequences of the western margin of the Orcadian Basin. The research has concentrated on establishing the stratigraphical ranges of zonal fossils of three orders of fish found within the lacustrine successions of the Middle Devonian in Caithness, on the northern mainland of Scotland. Although focused on Caithness and eastern Sutherland the study has also included parts of the succession on the Orkney islands and has also involved examination of museum collections containing material from the remainder of the Orcadian Basin and beyond. It has resulted in a new biostratigraphical framework, based on the distribution of fossil fish faunas, that provides a regional correlation of the Middle Devonian strata of Caithness. It can be used as a template for correlating the Middle Devonian successions in the adjacent Cromarty-Inverness-Nairn portion of the Orcadian Basin and has refined the correlation of the Caithness sequence with that on Orkney.

The work was principally undertaken by M J Newman under a two year contract to the British Geological Survey (BGS). It was initiated as part of the Integrated Geoscience Surveys North Programme in April 2004 and continues as part of the Geology and Landscape, Northern Britain Programme. It is due to be completed in March 2006.

M T Dean (BGS Edinburgh) collaborated in and supervised the contracted research, first as part of the Caithness Project, and subsequently as part of the Moray-Ness Basin Project, under the leadership of C A Auton (BGS, Edinburgh). M J Newman was accompanied in the field sampling and museum research by Jan den Blaauwen (University of Amsterdam). Both were accompanied on some occasions in the field (in Caithness and on Orkney) by U McL Michie (Consultant for UKAEA Dounreay).

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In addition to the BGS staff acknowledged in the Foreword, E R Phillips (BGS, Edinburgh) contributed to the production of this report by drafting the reconstruction of the fish of the 'Achanarras fauna' shown on the front cover, and by advising in the production of other posters and reports associated with these studies. The authors also gratefully acknowledge R Jones and C Moore for permission to reproduce Figures 2, 6, 7, 10, 12, 13, 14 and 15 from photographs of their fossil fish collections. This report was reviewed by C A Auton.

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Summary

This report presents an up dated biostratigraphical framework for correlation of the Middle Devonian strata exposed in onshore areas on the western margin of the Orcadian Basin. It focuses on the fossil fish faunas from Caithness and Orkney. The research has involved taxonomical and stratigraphical revision of key fossil fish specimens and whole assemblages held in museums and in private collections , together with targeted new field collecting in Caithness and on Orkney. This has enabled a robust pattern of distribution to be established for indicator species, based on faunas identified from large collections of individual species, so that presence/absence data are of significance in determining a more fully representative stratigraphical range for each species than was available hitherto.

This approach has enabled detailed biostratigraphical correlations to be made within the Middle Devonian of the Reay area and on adjacent ground. It also provides new constraints on the regional biostratigraphical correlation between the flagstone sequences in Caithness and on Orkney. The importance of fossil fish assemblages that have been examined in collections from the Middle Devonian on the southern margin of the Moray Firth are currently being re-evaluated in terms of their ability to constrain new and existing regional and local stratigraphical correlations. The eventual aim of this work is to provide a consistent means of correlating all of the onshore Middle Devonian strata in the Moray-Ness Project area.

1 Introduction

The stratigraphical correlation of the Devonian successions in the Orcadian Basin has been a focus of continuing research for more than a century (see Trewin and Thirlwall, 2002 and Barclay *et al*, 2005 and references therein). For most of this time correlation has been based on recognising the distribution of fossil fish assemblages within the lacustrine facies and the recognition of ‘fish bed laminites’ within well exposed coastal sections, particularly in Caithness and Orkney. This has been supplemented by the study of collections of fish fossils from working and abandoned flagstone quarries, notably at Achanarras [ND 150 545] and Spittal [ND 160 543] in Caithness and at Hill of Cruday [HY 247 217] and Gairsty [HY 257 205] on Mainland Orkney. Unfortunately, poor inland exposure of the flagstone sequences across the western margin of the Orcadian Basin has commonly hindered adequate characterisation of the lithostratigraphical units, established by geological mapping and also by inconsistent identification of their fish faunas.

In order to address this difficulty, most modern studies have concentrated on the identification of fossil miospore assemblages collected from coastal and inland exposures, as well as from samples collected from boreholes drilled for oil exploration within the offshore area (see Marshall, and Hewett, 2003 and references therein). Spore assemblages can commonly be recovered from small rock samples and have the potential to enable correlation of small isolated exposures with continuous sequences proved in boreholes (Stephenson, 2002, 2004). However, spores are by no means ubiquitous, their preservation, particularly within the type successions in Caithness, is often poor and their large stratigraphical ranges enable only very broad correlations to be established (Stephenson, 2005).

Several of the original stratigraphical correlations of the lacustrine sequences by means of their fish fossils have proved erroneous by latter geological mapping, principally due to the misidentification of the fossils and inadequate locality information for the specimens (particularly those in museum collections). Partly as a consequence of this, most modern work on the fossil fish has concentrated principally on taxonomy with little emphasis on stratigraphical range or correlation. The emphasis on taxonomy has, however, enabled confident new identifications to be made of misidentified specimens in museum collections and also of accurately located specimens collected as part of this current study. All of the important accurately located fossil specimens examined in this study, have been digitally photographed and the images placed into the BGS corporate ImageBase. Representative examples of most of the stratigraphically important species are also presented here (Figures 2-15).

This report details the progress made, to date, in enabling the use of the fossil fish from Caithness and Orkney to constrain stratigraphical correlation of the Middle Devonian sequence in Caithness and north east Sutherland, and provides a framework for correlation of these rocks with those from the remainder of the Moray-Ness Project area.

2 The initial focus of the study

2.1 COLLECTIONS AND DATABASING

The present work commenced in the spring of 2004 by examining the major fossil fish collections from the Orcadian sequence that are held in museums (notably the National Museum of Scotland in Edinburgh and the Hunterian Museum, in Glasgow), at BGS Murchison House

and in many private collections. The taxonomy was updated and verified and, where possible, locality data established. The datasets produced were then entered into the GIS for the Caithness/Moray-Ness projects (del Rio and Auton, 2004). This will enable comparisons to be made with datasets of palynological assemblages collected as part of the studies commissioned by UKAEA Dounreay, and also with the Bedrock geology of the Moray-Ness project area, held as DigMap 50 and DigMap10 tiles.

2.2 FIELD SAMPLING

In order to focus the outcomes of the research, it was decided to commence field sampling within the recently mapped ground on Scotland Sheet 115E (BGS, 2003) to build upon the detailed collecting undertaken for biostratigraphical studies in the vicinity of Dounreay, commissioned by UKAEA (den Blaauwen *et al*, 2000). In this area, the Orcadian Basin of east Sutherland and Caithness is divided at the Bridge of Forss Fault Zone into eastern and western portions. In central Caithness, to the east of the fault zone, a thicker Devonian succession with a more complete sequence of fish faunas is present than in the western (marginal) portion of the basin. A paucity of large inland exposures has hindered correlations. The new field visits to small exposures across the area, principally within active and disused quarries, and the study of numerous borehole cores in the vicinity of Dounreay have now provided new insights into the differences and similarities between the sequences on either side of the fault zone. Differences in composition, thickness and faunal character, between the sequences in both areas, are explained by the effects of synsedimentary movement along the fault zone.

3 Stratigraphically important fish fossils

Despite difficulties in their identification, the most useful forms are species of osteolepids (Class Sarcopterygii). Here the term osteolepid is used informally to include the families Osteolepidae and Tristichopteridae as both belong to order Osteolepidida. The coccosteids (Class Placodermi) are also useful biostratigraphically, but their known occurrence remains sporadic. The distribution of dipnoans (Class Sarcopterygii) are also useful indicators, despite their long stratigraphical ranges.

4 Faunal distribution in eastern and central Caithness

In Section 4 the stratigraphical ranges of the fossil fish are related to the Devonian lithostratigraphy recently established for Sheet 115E and on the Dounreay Bedrock Special Sheet.

4.1 LYBSTER FLAGSTONE FORMATION

In eastern Caithness (Table 1) the Lybster Flagstone Formation contains the osteolepid *Thursius macrolepidotus* (Sedgwick and Murchison), which is here considered synonymous with *Thursius moythomasi* (Jarvik). It is the only fish present in the lower and middle parts of the formation. Previous mentions of the dipnoan *Dipterus valenciennesi* (Sedgwick and Murchison) at, for example, South Head Wick and Westerdale Quarry were in fact misidentifications of *Thursius macrolepidotus* lacking cosmine, or indeterminate specimens. At higher stratigraphical intervals in the Lybster Flagstone Formation, *Thursius macrolepidotus* is joined by the coccosteid *Coccosteus cuspidatus* (Miller ex Agassiz MS), the newly described dipnoan *Pinnalongus saxoni* nom. nud. (Newman and den Blaauwen), and the very rare acanthodian *Mesacanthus pusillus* (Agassiz), which is here considered to be synonymous with *Mesacanthus peachi* (Egerton).

T. macrolepidotus and *P. saxoni* are confined to the Lybster Flagstone Formation, below the Achanarras Fish Bed Member, but *C. cuspidatus* extends into the Achanarras Fish Bed Member (which is also where *D. valenciennesi* is first noted).

4.2 ACHANARRAS FISH BED MEMBER

The Achanarras Fish Bed is a thick mudstone sequence containing a very diverse fish fauna. It is an important biostratigraphical marker, which can be correlated with contemporaneous beds in Orkney (the Sandwick Fish Bed), Shetland (Melby Fish Beds) and in offshore boreholes throughout much of the Orcadian Basin (Johnstone and Mykura, 1989, Marshall and Hewett, 2003). These particular ‘fish beds’ mark a uniquely extensive and deep phase of lake development within the basin. Consequently, they are crucial in correlating local and regional stratigraphies.

The position of the Achanarras Fish Bed within the Devonian stratigraphy of the Reay area has been subject to minor changes in recent years. It was placed at the base of the Achscrabster Flagstone in Nirex (1992) and at the base of the Spital Flagstone Formation in Auton (2003) and BGS (2003). It is probably more correctly regarded as the uppermost unit of the Lower Caithness Flagstone ‘Subgroup’, as it was by Westoll (1977). Donovan, *et al* (1974) defined the top of their Lower Caithness Flagstone ‘Group’ as the top of the Niandt Limestone Member, an equivalent to the ‘Achanarras Limestone Member’. However, most recent publications (e.g. Trewin, 1993, Marshall, 2000, Trewin and Thirlwall, 2002, Barclay *et al*, 2005) avoid the issue, by placing the Achanarras Fish Bed/Niandt Limestone between the Upper and Lower Caithness Flagstones and within neither. In Auton *et al.* (2005), and in this report, it is regarded as lying at (or just below) the top of the Calder Mudstone (i.e. at the top of the Lybster Flagstone Formation); It marks the top of the Robbery Head and Lybster ‘subgroup’ of the Caithness regional stratigraphical framework.

Within the Devonian sequence of Caithness, the faunal assemblages of the Achanarras Fish Bed are unique, both in terms of the number of different species recorded and the in their excellent state of preservation. The fauna includes *Achanarella treweni* (Newman), *Cheiracanthus grandispinus* (M’Coy), *Cheirolepis trailli* (Agassiz), *Coccosteus cuspidatus*, *Cornovichthys blaauweni* (Newman and Trewin), *Diplacanthus crassisimus* (Duff), *Diplacanthus longispinus* (Agassiz), *Diplacanthus tenuistriatus* (Traquair), *Dipterus valenciennesi*, *Glyptolepis paucidens* (Agassiz), *Homosteus milleri* (Traquair), *Mesacanthus pusillus*, *Osteolepis macrolepidotus* (Agassiz), *Palaeospondylus gunni* (Traquair), *Pterichthyodes milleri* (Miller ex Agassiz MS), and *Rhamphodopsis threiplandi* (Watson).

Of the biostratigraphically important species mentioned in Table 1, the osteolepid *O. macrolepidotus* seems to be confined to the Achanarras interval, though exposure is poor between the Achanarras Fish Bed Member at Achanarras Quarry and the succeeding fish beds, which are exposed at Spittal [ND 160 543] and Banniskirk [ND 167 567] quarries. The coccosteid *C. cuspidatus* is also found at the top of the Lybster Flagstone Formation, as is the dipnoan *D. valenciennesi*, which makes its first appearance here, but continues up through the Spital and Mey Flagstone formations.

A. treweni and *C. blaauweni* (both Class Monorhina) are only found at Achanarras Quarry, probably due to the exceptional preservation there. They are soft bodied organisms and their real distribution is strictly unknown. *P. gunni* (Class uncertain) is slightly more common and is found at Achanarras Quarry and Niandt. Elsewhere it is very rare (for example, only two specimens are known from this stratigraphical level in Orkney). *R. threiplandi* (Class Placodermi) is also confined to this level. It is only known from Achanarras Quarry and nodules at Black Park, Edderton. It is therefore of little use as a zone fossil. *C. trailli* (Class Osteichthyes) and *Pterichthyodes milleri* (Class Placodermi) are apparently widespread as articulated fish and confined to the Achanarras Fish Bed. However, some disarticulated remains of both species have

been found just above this horizon in Orkney (Jan den Blaauwen, pers. comm. 2005). The acanthodians include *C. grandispinus*, *D. crassissimus*, *D. longispinus*, *D. tenuistriatus*, and *M. pusillus*. Other species of *Cheiracanthus* are present in the Sandwick Fish Bed on Orkney and also in the Moray Firth area, but in Caithness only *C. grandispinus* has been recorded. Some acanthodians continue into higher stratigraphical units, but whilst their taxonomy and stratigraphy remains confused they are of little use as zone fossils. *H. milleri* (Class Placodermi) continues into higher strata, but in the Achanarras Fish Bed Member it is only present at Achanarras Quarry (and even then only rarely). The taxonomy of *Glyptolepis* is unresolved. The genus continues into higher strata, but it is not known how many species are present.

4.3 SPITAL FLAGSTONE FORMATION¹

The Spital Flagstone Formation largely lacks articulated fossil fish, except at Banniskirk Quarry. The fauna includes *Asperocephalus milleri* nom. nud. (Ahlberg) and *Cheiracanthus murchisoni*. The biostratigraphically important species in this part of the formation mentioned in Table 1 include the osteolepid *Gyroptychius milleri*, the coccosteid *Dickosteus threiplandi*, and the dipnoan *Dipterus valenciennesi*. *G. milleri* apparently replaces *Osteolepis macrolepidotus*, whilst *D. threiplandi* substitutes for *Coccosteus cuspidatus*. Poor exposure makes it uncertain if *D. threiplandi* occurs at the bottom of the sequence (possibly mirroring the situation in the western Orcadian Basin). After becoming progressively less common upwards it disappears altogether in the middle of the Spital Flagstones, depriving the formation of a coccosteid in its upper part. It may be the case that *D. threiplandi* occupies a much narrower zone than previously thought.

At least two, generally disarticulated, porolepiformes (Class Sarcopterygii) are present including *Glyptolepis* sp. and *A. milleri*. *Homosteus milleri* is now much more abundant than in the Achanarras Fish-bed Member, but it is rarely articulated. The acanthodian *C. murchisoni* (Agassiz) is found, but whether *Cheiracanthus grandispinus* continues above the Achanarras Fish-bed Member is uncertain. Both *Diplacanthus crassissimus* and *Diplacanthus longispinus* are seen at this level, but it is not clear if *Diplacanthus tenuistriatus* is present. It is found in equivalent sedimentary rocks in Orkney. Two specimens of *Trewinia magnifica* (Class Monorhina) are known from Spittal Quarry.

4.4 MEY FLAGSTONE FORMATION

The fauna of the Mey Flagstone Formation includes *Cheiracanthus* sp., *Cheiracanthus* sp. {juvenile form}, *Dipterus valenciennesi*, *Glyptolepis* sp., *Homosteus milleri*, *Mesacanthus pusillus*, *Millerosteus minor* (Miller), *Osteolepis panderi* (Pander), and *Thursius pholidotus* (Traquair).

The biostratigraphically important species in this formation include the osteolepid *Thursius pholidotus*, the coccosteid *Millerosteus minor*, and the dipnoan *Dipterus valenciennesi*. The lowest strata where *Thursius pholidotus* is seen are exposed in quarries at Weydale [ND 145 655] and Cairnfield [ND 155 655], south east of Thurso. *M. minor* appears towards the top of the formation and is widespread across most of the Orcadian Basin. *D. valenciennesi* also continues to the top of the Mey 'beds' (Mey 'subgroup' of the regional succession).

Glyptolepis sp. and *H. milleri* are present throughout the whole sequence, but the osteolepid *Osteolepis panderi* appears to be confined to a 'mass mortality horizon' (the *Osteolepis panderi* Zone). This occurs across most of the Orcadian Basin and is present as far north as the Isle of Rousay in Orkney. *O. panderi* is almost the only species present at this level, though

¹ The spelling of 'Spital' follows the precedent set by Crampton & Carruthers (1914) and is followed in most subsequent published geological accounts; as opposed to 'Spittal', which is the name of the village and associated quarries (given on current OS topographic maps) which are the type locality of the Spital Formation.

Cheiracanthus sp. {juvenile form} and *Mesacanthus pusillus* occur in small numbers and another *Cheiracanthus* sp. occurs stratigraphically above the *Osteolepis panderi* Zone.

4.5 JOHN O' GROATS SANDSTONE FORMATION

The fauna of the John o' Groats Sandstone in Caithness is restricted to just four species, but in Orkney and Shetland a number of others are present in comparable strata. The small antiarch (Class Placodermi) *Microbrachius dicki* (Traquair) is present, in Caithness, but it is only found at John o' Groats itself. The other three are the dipnoan *Pentlandia macroptera* (Traquair), the tristichopterid (Class Sarcopterygii) *Tristichopterus alatus* (Egerton), and the coccosteid *Watsonosteus fletti* (Watson).

5 Faunal distribution in eastern Sutherland and western Caithness

In Section 5 the stratigraphical ranges of the fossil fish are related to the Devonian lithostratigraphy recently established in Auton *et al*, (2005) and on the Dounreay Bedrock Special Sheet.

5.1 BIGHOUSE AND SANDSIDE BAY FORMATIONS

In eastern Sutherland and western Caithness (Table 2) the Bighouse Formation contains the osteolepid *Thursius macrolepidotus*, the coccosteid *Coccosteus cuspidatus*, the dipnoan *Pinnalongus saxoni* and the acanthodians *Mesacanthus pusillus* and *Cheiracanthus* sp. *Thursius macrolepidotus* is seen in the Portserra Conglomerate Member, at base of the formation, whilst remains of *Pinnalongus saxoni* first occur in the Baligill Limestone Member (at Baligill [NC 655 660] together with *Coccosteus cuspidatus*, and *Mesacanthus pusillus* and poorly preserved *Cheiracanthus* sp. *C. cuspidatus* is also present in the equivalent limestones at Bighouse [NC 891 653]. *M. pusillus* and *Cheiracanthus* sp. are present in the Baligill Limestone Member at Baligill. The *Cheiracanthus* specimens found so far are too poorly preserved to determine to species level, but the presence of acanthodians is important as they are very rarely found in the basin-margin facies.

This fauna continues into the overlying Sandside Bay Formation. Consequently, rocks of the Bighouse and Sandside Bay formations cannot be distinguished from one another by their fossil fish assemblages. A single specimen of *Diplacanthus crassisimus* (Duff) has been found in the Sandside Bay Formation, but its rarity precludes its use as a biostratigraphical marker.

5.2 DOUNREAY SHORE FORMATION

Fossils are very rare and mostly fragmentary in the Dounreay Shore Formation. The fauna includes the acanthodian *Diplacanthus tenuistriatus*, the porolepiform *Glyptolepis* sp., the osteolepids *Gyroptychius milleri*, and ?*Osteolepis macrolepidotus*, and the dipnoan ?*Pinnalongus saxoni*. The biostratigraphically important species include *Gyroptychius milleri*, which apparently replaces *Thursius macrolepidotus* in the stratigraphical sequence. No coccosteid remains have been discovered to date. A fish-bed adjacent to the Dounreay Site has so far yielded fully articulated *G. milleri* specimens and badly preserved remains that may belong to *P. saxoni* and *O. macrolepidotus*

Whilst no unequivocal dipnoan remains have been confirmed in the Dounreay Shore Formation, this is probably due to the difficulty of recognizing disarticulated dipnoan fragments and poor preservation rather than their absence. The lack of coccosteid remains is more significant, as

these are recognizable in the most fragmentary state, even if they cannot be identified to species level. Away from the fish-bed, *Glyptolepis* sp. is present and a single specimen of *D. tenuistriatus* has been found.

5.3 CROSSKIRK BAY FORMATION

The fauna of the Crosskirk Bay Formation includes *Cheiracanthus* sp., *Dickosteus threiplandi*, *Diplacanthus?* sp., *Dipterus valenciennesi*, *Gyroptychius milleri*, *Homosteus milleri*, *Mesacanthus pusillus*, *Osteolepis macrolepidotus*, and *Pinnalongus saxoni*.

The biostratigraphically important species include the osteolepid *G. milleri*, which continues stratigraphically upward from the underlying Dounreay Shore Formation, the coccosteid *D. threiplandi*, and the dipnoan *P. saxoni*.

Fully articulated *D. threiplandi*, *G. milleri*, *O. macrolepidotus* and *P. saxoni* are all found in the Crosskirk Bay Formation, whilst the acanthodians *M. pusillus* and *Cheiracanthus* sp. are poorly preserved. *H. milleri* has been reported and *Diplacanthus?* sp. may be present. In the lower part of the formation, a fish-bed rich with complete but juvenile *D. valenciennesi* and *M. pusillus* has been discovered; the occurrence of *D. valenciennesi* was apparently short-lived with the previous faunal assemblage being re-established before the top of the accessible outcrops is reached.

6 Initial correlations in the Reay Sheet area

The initial studies in the Reay Sheet area, in 2004, indicated that the Lybster Flagstone Formation to the east of the Bridge of Forss Fault Zone correlates with, and is probably equivalent to both the Bighouse and Sandside Bay formations in the west (which are generally indistinguishable on faunal grounds alone). The osteolepid *Thursius macrolepidotus* is present from the base of the succession in both sequences and is joined at higher stratigraphical levels by the coccosteid *Cocosteus cuspidatus*, the dipnoan *Pinnalongus saxoni* and acanthodians.

The faunal differences between the eastern basinal facies and the western marginal facies become more apparent in the overlying upper part of the Caithness Flagstones. A direct equivalent (in terms of lithofacies and the characteristic fauna) of the Achanarras Fish-bed Member to the east of the fault zone was not present in the Dounreay Shore Formation to the west, and poor exposure of the basal parts of the Spital Flagstone Formation precluded a direct correlation with the Dounreay Shore Formation. However, the fauna of the lower part (the Achscrabster Flagstone Member) of the Spital Flagstone Formation, to the east of the fault zone, is apparently equivalent to the fauna within the upper part of the Crosskirk Bay Formation, to the west, since both include the osteolepid *Gyroptychius milleri* and the coccosteid *Dickosteus threiplandi*.

No further correlation is possible, since the upper part of the Crosskirk Bay Formation forms the top of the accessible onshore exposures to the west of the Bridge of Forss Fault Zone.

7 Biostratigraphical data from field studies in 2005

Fieldwork conducted in June 2005 in Caithness and Orkney by M J Newman, U McL Michie and J L den Blauwen has advanced the knowledge of the fish biostratigraphy of Caithness and Orkney, so that several of the initial correlations presented in Section 6 were revised.

7.1 NEW OBJECTIVES

The major objective of the 2005 fieldwork was to examine the strata above the 'mass mortality horizon' (the *Osteolepis panderi* Zone) that had been recorded at various sites, above the level of the Achanarras/Sandwick Fish Bed, in Caithness and Orkney. In Caithness the *O. panderi* Zone had only been recognised at locations near the tops of the exposed succession (on hill tops) or in fault-bounded blocks, none of which provided sequences where the thickness of strata above the '*Osteolepis panderi* mass mortality bed' were sufficient to allow its position relative to the fish-bearing strata higher in the sequence to be determined unequivocally.

This objective was achieved on the island of Rousay, where a significant thickness of strata above the *Osteolepis. panderi* horizon was examined. In the initial investigation of the faunas within the Dounreay Shore Formation, it was suggested that the osteolepid *Gyroptychius milleri* apparently replaced *Thursius macrolepidotus* in the stratigraphical sequence. It was also suggested that this 'replacement' occurred prior to deposition of the *O. panderi* 'mass mortality bed'. This apparent substitution of *T. pholidotus* by *G. milleri* was based on the presence of the former and the absence of the latter in all of the "good" fish beds (i.e. those containing numbers of well-preserved fossil fish) within the Upper Caithness Flagstone sequence. These "good" fish beds comprise not only the mass-mortality fish beds with *O. panderi*, but also the limited number of fish beds with *Millerosteus minor* that have been recorded a higher levels (near the top of the Upper Caithness Flagstones) in Caithness.

During the field work on Rousay, however, *G. milleri* was found to be present in a fish bed at Scara Taing in western Rousay above the *O. panderi* horizon, which occurs in the south west of the island. This higher fish bed, at Scara Taing, is that identified by Astin (1990) as occurring at the base of his revised Rousay Formation. Astin also classified the strata beneath the Scara Taing Fish Bed, which formed part of the Rousay Beds of Wilson, *et al* (1935), as being equivalent to the Upper Stromness Flagstone, a change that is not supported by its fossil fish faunas.

The Scara Taing Fish Bed lies to the south of and below the fish beds at Sacquoy Head. These contain *Millerosteus minor* and *Thursius pholidotus*. The strata above the Scara Taing Fish Bed were not examined due to the inaccessible nature of the exposures in the cliffs, but *G. milleri* may continue upwards to close to the level of the fish beds at Sacquoy Head.

7.2 A NEW EXPLANATION FOR THE PATTERN OF DISTRIBUTION OF FISH SPECIES

The pattern of apparent local "extinction" of certain fish species in the lacustrine cycles within the Orcadian Basin, but then their re-appearance at higher stratigraphical levels, is best explained by replenishment of the fish from extant populations beyond the Basin. The cyclic pattern of sedimentation in the lacustrine sequence was not only influenced by longer-term cyclic climatic changes, that commonly affected several contiguous sedimentary cycles (with "fish bed" type laminites developed in each), but also by changing rates of tectonic subsidence, which altered the depositional environments in different parts of the basin.

During dry climatic phases, the level of the Orcadian lake would fall, cutting overflow river connection to other rivers and to the sea. At these times, events such as toxic algal blooms, anoxic overturns, increased salinity and reduction of the lake to isolated bodies of water could cause extinction of many species in the increasingly-arid, closed Basin, but there could be no replenishment from outside the Basin. Only a few tolerant species, such as *Dipterus*, could survive in the limited number of semi-permanent inflowing rivers or groundwater-fed pools during dry periods.

When the climate became wetter, the Basin gradually refilled and a "permanent" deeper-water lake developed. However, the fossil-fish fauna in the fish beds of this infilling-phase was initially limited to the long-lasting tolerant species. Only when the level of the permanent lake

recovered to the overspill level (during the culmination of a wet-climate phase) would an outflow river be established that allowed the entry of new species, some of which would be the fish that had previously become "extinct" in the Basin. These new species could come directly from the sea, but also from other permanent rivers or lakes to which the overflow river connected. For instance, the disappearance and reappearance of *T. pholidotus* and *G. milleri* and several other fish species from the lacustrine basinal sequence can be explained in this way, as outlined below.

Following the expansion of Lake Orcadia to its greatest extent, which resulted in the deposition of the Achanarras Fish Bed Member, the Spital Flagstone Formation, containing both *Gyroptychius milleri* and *Dickosteus threiplandi*, was laid down. In general, the extent of the lake began to decrease as the Spital Flagstones accumulated, until it slowly dried up. *Dickosteus threiplandi* became extinct and very shortly afterwards *Gyroptychius milleri* disappeared from the basinal successions.

When the lake refilled, it was restocked by an influx of *Osteolepis panderi* and *Thursius pholidotus* that migrated into the basin from the Baltic marine environment, to the east. However, very shortly after this, the lake again shrank, causing the mass extinction of *O. panderi* and *T. pholidotus*.

Again a deeper lake became re-established. Upon its reinstatement, the lake had a fauna derived from the western rivers, including *Gyroptychius milleri*, which finally became extinct when the lake shrank once more.

The deeper lake became re-established once again and it was then occupied by a fish fauna derived from the Baltic, to the east. This fauna includes *Thursius pholidotus* and *Millerosteus minor*, specimens of which are known from the Middle Devonian of Estonia.

8 Conclusions

Table 3 provides a revised biostratigraphical framework for the Orcadian sequences of Caithness, which it is hoped will form the basis for biostratigraphical correlations of the Middle Devonian sequence across the whole basin. It supersedes the correlations presented in Tables 1 and 2 that were only applicable to the sequences known from the Reay Sheet area and adjacent ground (and have required modification based on the results of the 2005 field work).

As the work since 2004 has been more regional in its focus, and because much of the regional stratigraphy remains to be placed into accepted modern lithostratigraphical terminology, most of the biostratigraphical 'zones' are applied here in relation to broad stratigraphical terms that have been used across both Caithness and Orkney (see Trewin and Thirlwall, 2002, figure 8.17). The 'subgroups' of the regional correlations have been largely retained (Table 4) but, in several instances, they have been combined (for example, Robbery Head Subgroup and the Lybster Subgroup have been combined and changed to the Robbery Head and Lybster 'subgroup') or modified (for example, the Ham Skarfskerry Subgroup is changed to Scarfskerry 'subgroup'). This reflects the fact that much of the basinal sequence in Caithness has not been subjected to modern resurvey that would be necessary to place the succession in to an acceptable lithostratigraphical hierarchy (Group, Subgroup Formation, Member etc).

The Scarfskerry 'subgroup' has been reinstated above the '*Osteolepis panderi* mass mortality bed' and between the Latheron and Mey 'subgroups' of the regional succession (ie. it may include parts of the Scarden and Shops Sandstone members of the Mey Flagstone Formation of the Reay Sheet area). It also correlates with the lower and middle part of the Rousay Beds on Orkney (of the original Geological Survey usage, Wilson, *et al*, 1935). Both have the '*Osteolepis panderi* mass mortality bed' close to their bases.

As mentioned in Section 7, the portion of the flagstone succession included within the Rousay Beds of Wilson, *et al.*, (1935) differs from that included within the Rousay Formation of Astin (1990, table 1). However, the latter was termed the Rousay Flagstone Member and included within the 'Upper Stromness Flagstone Formation' on the Orkney Islands 1:100 000 scale Special Sheet (BGS, 1999).

The fish assemblages of the Mey 'subgroup' of the regional succession can be correlated with those of the upper part of the Rousay Beds of Wilson *et al.* (1935). The fossils characteristic of the Latheron 'subgroup' of the regional succession (which is now taken as including the Spital Flagstone Formation and most of the Mey Flagstone Formation as shown on Sheet 115E (Reay) can now be directly correlated with the assemblages from the Upper Stromness Flagstones of Wilson, *et al.* (1935), whilst the 'Rousay Beds' are considered to be a separate overlying unit.

The Sandwich Fish Bed sequence is known to be at least 50 m thick on Orkney. It incorporates strata that equate with those of the Achanarras Fish Bed in the Caithness succession. Both fish beds include many of the same faunal elements although the relative proportions of individual species is different in each assemblage. The Sandwich/Achanarras unit should, perhaps, in future be raised to formational status not only to resolve the present stratigraphical ambiguities outlined in Section 4.2, but also because (where it is developed) the fish bed sequence constitutes a distinctive, relatively thick, mudstone-dominated, mappable unit. If applicable, it should be placed as a new formation, between the Spital and Lybster formations.

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Age	Group/subgroup	Formation/ Member	Vertebrate Biostratigraphical Zones		
			Osteolepid Zone	Coccosteid Zone	Dipnoan Zone
GIVE- TIAN	UPPER CAITHNESS FLAGSTONE SUBGROUP	MEY FLAGSTONE FORMATION	<i>Thursius pholidotus</i>	<i>Millerosteus minor</i>	<i>Dipterus valenciennesi</i>
		SPITAL FLAGSTONE FORMATION	<i>Gyroptychius milleri</i>	No arthrodires found to date	
EIFELIAN	LOWER CAITHNESS FLAGSTONE SUBGROUP	Achanarras Fish Bed Member	<i>Osteolepis macrolepidotus</i>	<i>Coccosteus cuspidatus</i>	<i>Pinnalongus saxoni</i>
		LYBSTER FLAGSTONE FORMATION	<i>Thursius macrolepidotus</i>	No arthrodires found to date	No dipnoans found to date
EMSIAN	SARCLET GROUP	No biostratigraphically useful fish fossils			

Table 1. Biostratigraphy of the Devonian sequence east of the Bridge of Forss Fault Zone on Sheet 155E (Reay) and the adjacent area.

Age	Group/subgroup	Formation	Vertebrate Biostratigraphical Zones		
			Osteolepid Zone	Coccosteid Zone	Dipnoan Zone
EIFELIAN	UPPER CAITHNESS FLAGSTONE SUBGROUP	CROSSKIRK BAY FORMATION	↑ <i>Gyroptychus milleri</i>	↑ <i>Dickosteus threiplandi</i>	↑ <i>Dipterus valenciennesi</i>
	----- ? -----	DOUNREAY SHORE FORMATION	No osteolepids found to date	No arthrodires found to date	
	LOWER CAITHNESS FLAGSTONE SUBGROUP	SANDSIDE BAY FORMATION	<i>Thursius macrolepidotus</i>	<i>Coccosteus cuspidatus</i>	<i>Pinnakongus saxoni</i>
		BIGHOUSE FORMATION			No arthrodires found to date
EMSIAIAN	SARCLET GROUP	No biostratigraphically useful fish fossils			

NOTE: Arrows associated with a named fossil indicate that it has not, to date, been recorded from lower stratigraphical intervals (within the formation)

Table 2. Biostratigraphy of the Devonian sequence west of the Bridge of Fors Fault Zone on Sheet 155E (Reay) and the adjacent area.

Stratigraphical Unit		Vertebrate biostratigraphical Zones		
		Osteolepids	Coccosteids	Dipnoans
John o' Groats Sandstone Group		<i>Tristichopterus alatus</i>	<i>Watsonosteus fletti</i>	<i>Pentlandia macroptera</i>
Upper Caithness Flagstone	Mey 'subgroup'	<i>Thursius pholidotus</i>	<i>Millerosteus minor</i>	<i>Dipterus valenciennesi</i>
	Scarfskerry 'subgroup'	<i>Gyroptychius milleri</i>	No arthrodires discovered to date	
	<i>Osteolepis panderi</i> mass mortality bed	<i>Thursius pholidotus</i>		
	Latheron 'subgroup'	<i>Gyroptychius milleri</i>	<i>Dickosteus threiplandi</i>	
Lower Caithness Flagstone	Achanarras Fish Bed	<i>Osteolepis macrolepidotus</i>	<i>Coccosteus cuspidatus</i>	<i>Pinnalongus saxoni</i>
	Robbery Head and Lybster 'subgroup'	<i>Thursius macrolepidotus</i>		No arthrodires discovered to date
	Clyth 'subgroup'	No osteolepids found to date		

Table 3. Biostratigraphical zonation of the Middle Devonian of Caithness

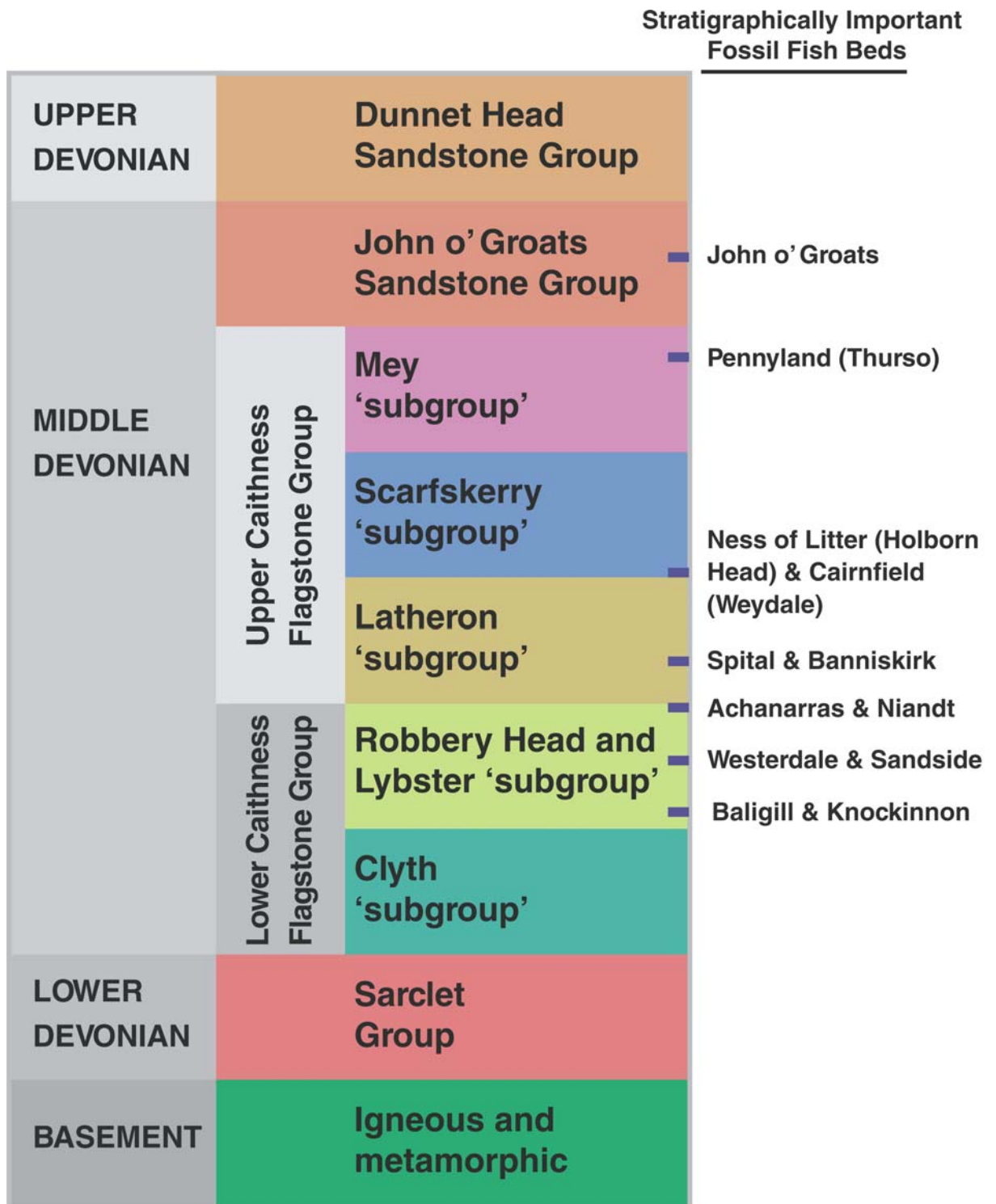


Table 4. Regional stratigraphical framework for the Orcadian sequence in Caithness showing the positions of the principal fish beds.

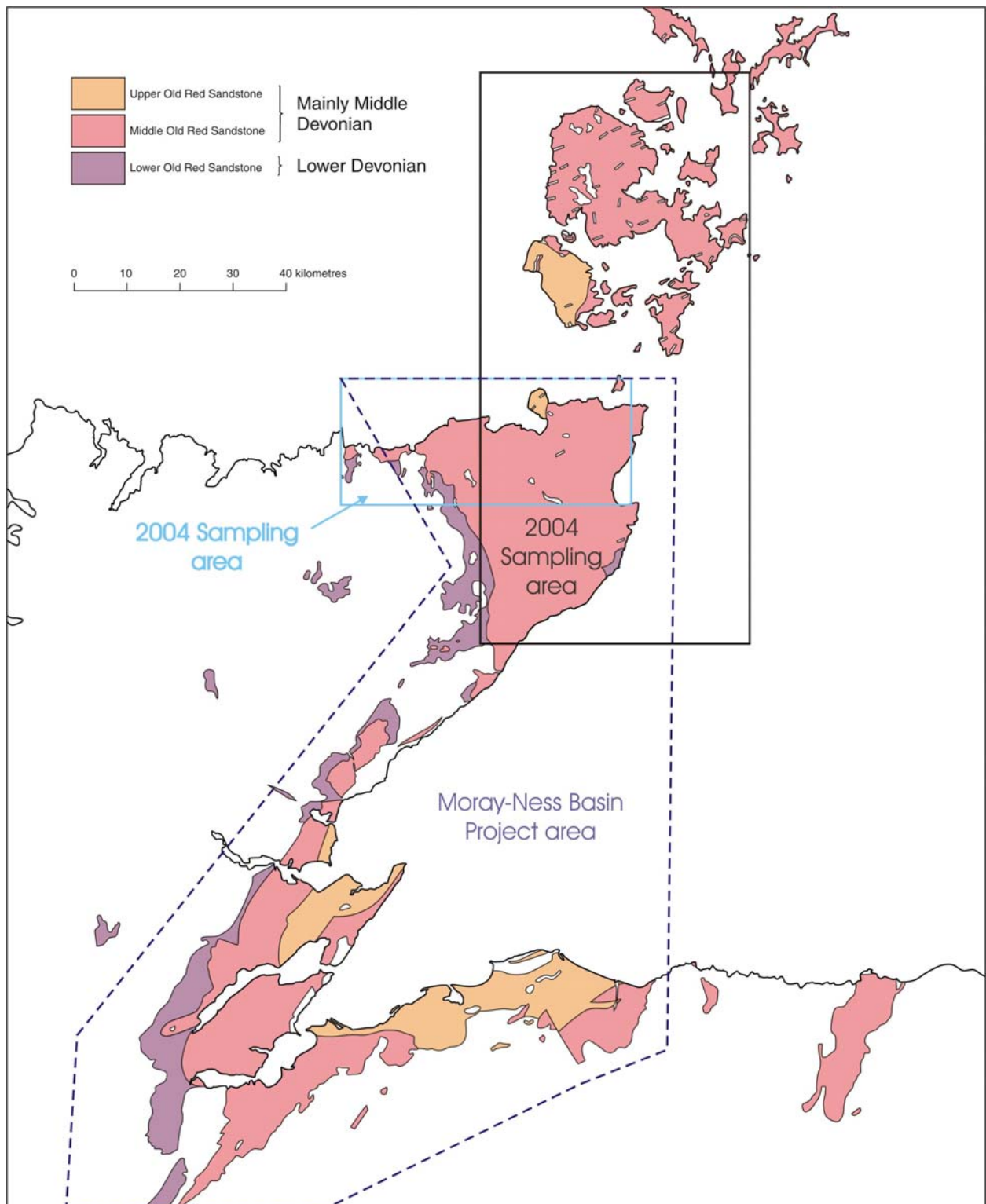


Figure 1. The Devonian strata on the western margin of the Orcadian Basin and the position of study areas.



Figure 2. *Tristichopterus alatus*. Eday Flagstone/John o' Groats Sandstone Group of South Ronaldsay, Orkney. Specimen RJ1. Roger Jones Collection.



Figure 3. *Osteolepis panderi*. Mey 'subgroup', Cairnfield Quarry, Caithness. National Grid Reference ND 152 651. Specimen MJN299. Michael Newman Collection.



Figure 4. *Thursius pholidotus*. Mey 'subgroup', East Murkle Bay, Caithness. National Grid Reference ND 178 692. Specimen MJN215. Michael Newman Collection.

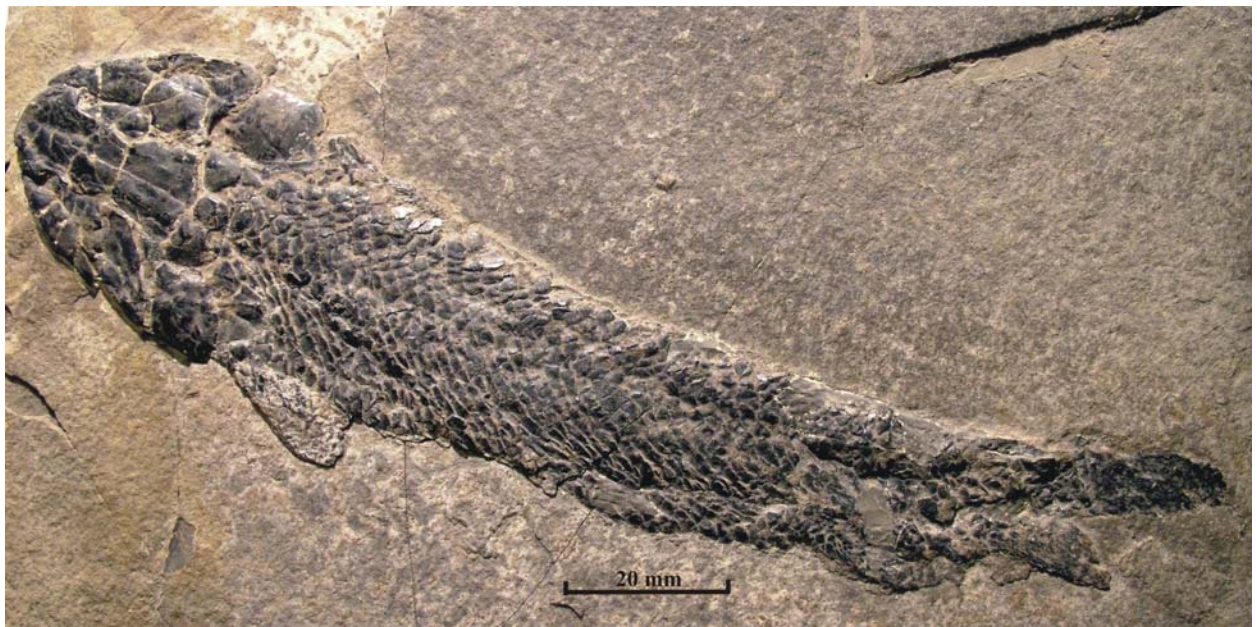


Figure 5. *Gyroptychius milleri*. Latheron 'subgroup', western Caithness. Specimen JdB20052. Jan den Blaauwen Collection.

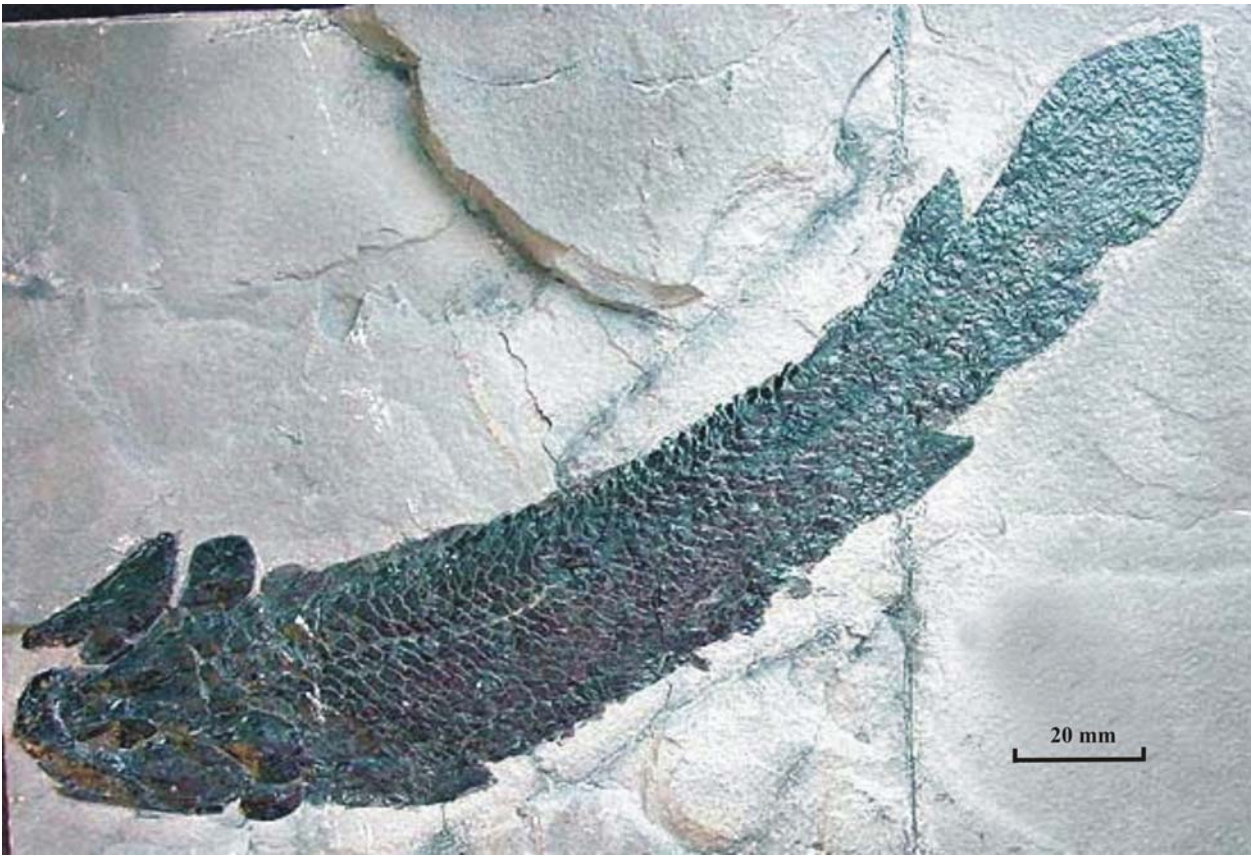


Figure 6. *Gyroptychius agassizi*. Sandwich Fish Bed, Cruday Quarry, Orkney Mainland. National Grid Reference HY 246 215. Specimen RJ2. Roger Jones Collection.

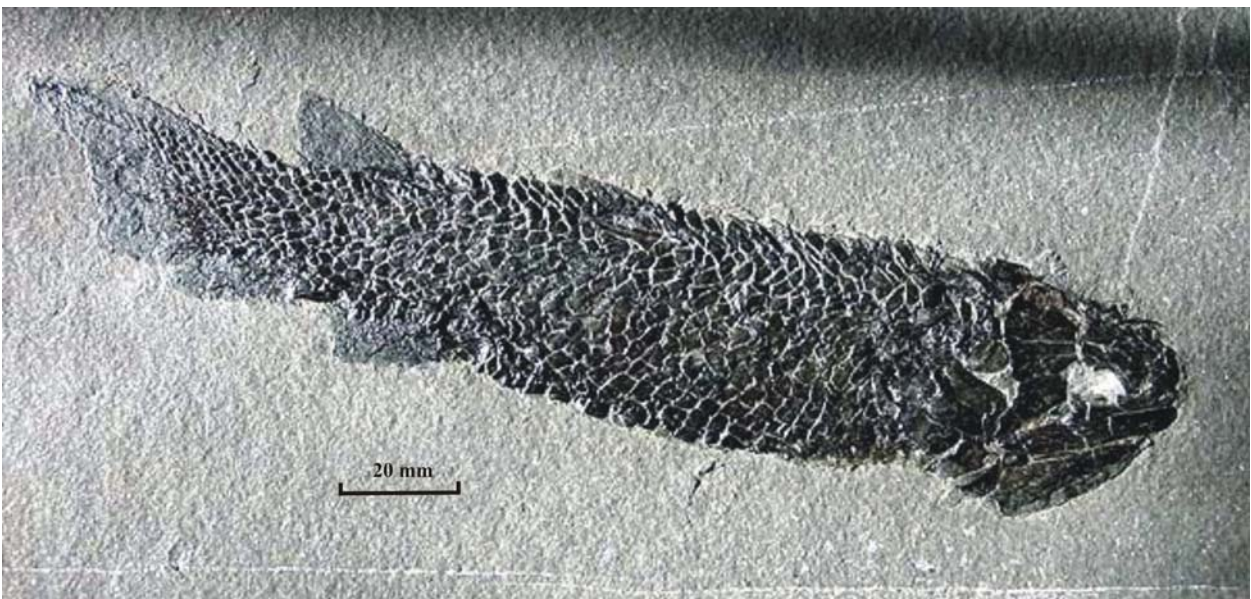


Figure 7. *Osteolepis macrolepidotus*. Sandwich Fish Bed, Cruday Quarry, Orkney Mainland. National Grid Reference HY 246 215. Specimen RJ3. Roger Jones Collection.

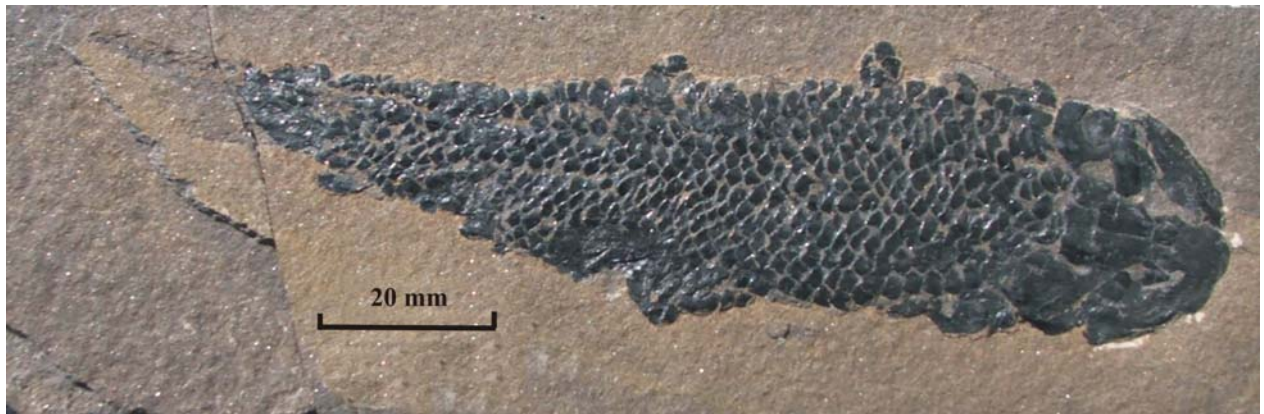


Figure 8. *Thursius macrolepidotus*. Robbery Head and Lybster 'subgroup' [Sandside Bay Formation], eastern side of Sandside Bay, Caithness. National Grid Reference NC 967 662. Specimen MJN997a. Michael Newman Collection.



Figure 9. *Watsonosteus fletti*. Eday Flagstone/John o' Groats Sandstone Group of South Ronaldsay, Orkney. Specimen JdB20051. Jan den Blaauwen Collection.



Figure 10. *Millerosteus minor*. Mey 'subgroup', East Mey, Caithness. National Grid Reference ND 292 747. Specimen RJ4. Roger Jones Collection.



Figure 11. *Dickosteus threiplandi*. Latheron 'subgroup', Banniskirk Quarry, Caithness. National Grid Reference ND 167 567. Specimen CM1. Chris Moore Collection.

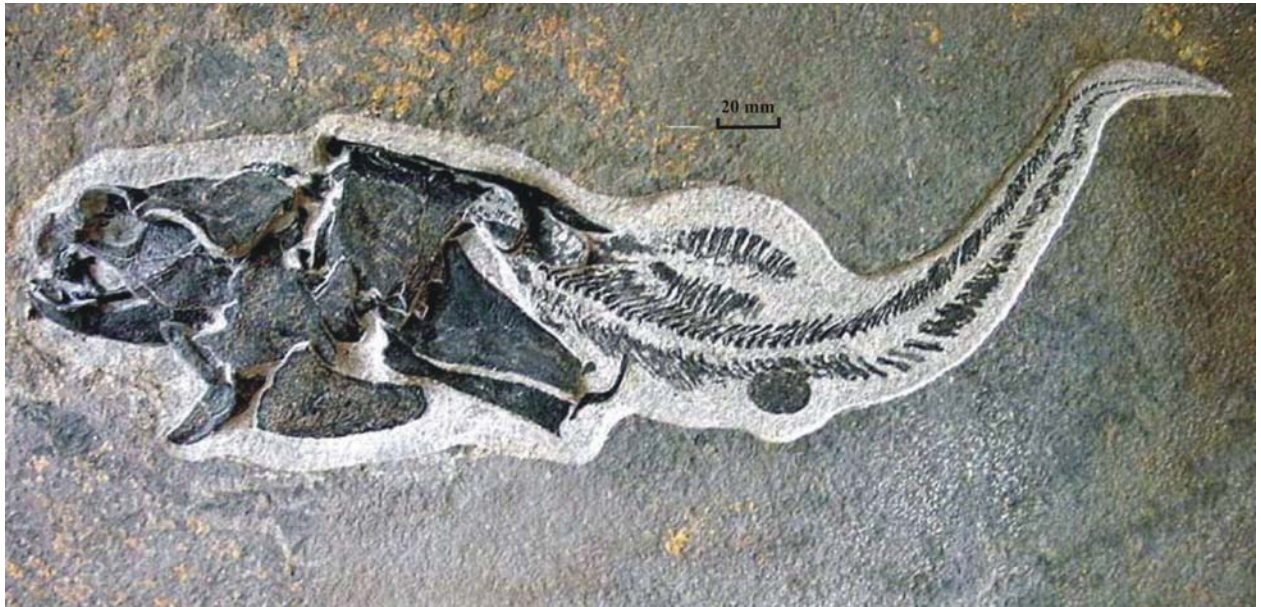


Figure 12. *Coccosteus cuspidatus*. Achanarras Fish Bed, Achanarras Quarry, Caithness. National Grid Reference ND 150 545. Specimen RJ5. Roger Jones Collection.



Figure 13. *Pentlandia macroptera*. Eday Flags/John o' Groats Sandstone Group, South Ronaldsay, Orkney. Specimen RJ9. Roger Jones Collection.

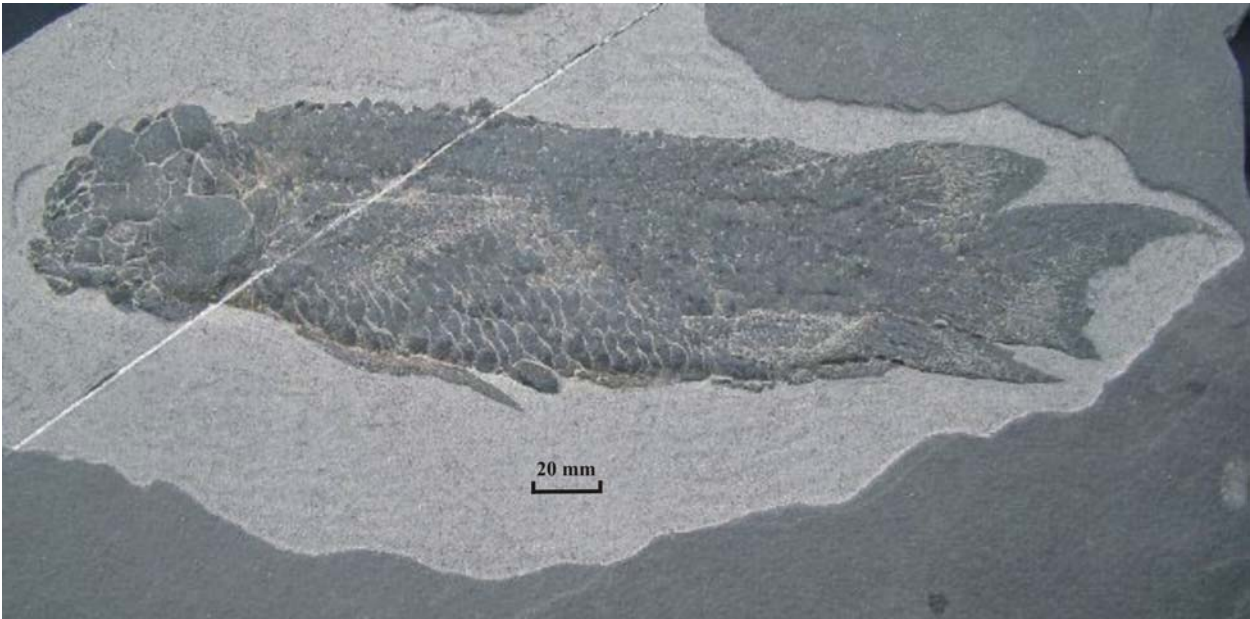


Figure 14. *Dipterus valenciennesi*. Achanarras Fish Bed, Achanarras Quarry, Caithness. National Grid Reference ND 150 545. Specimen CM2. Chris Moore Collection.

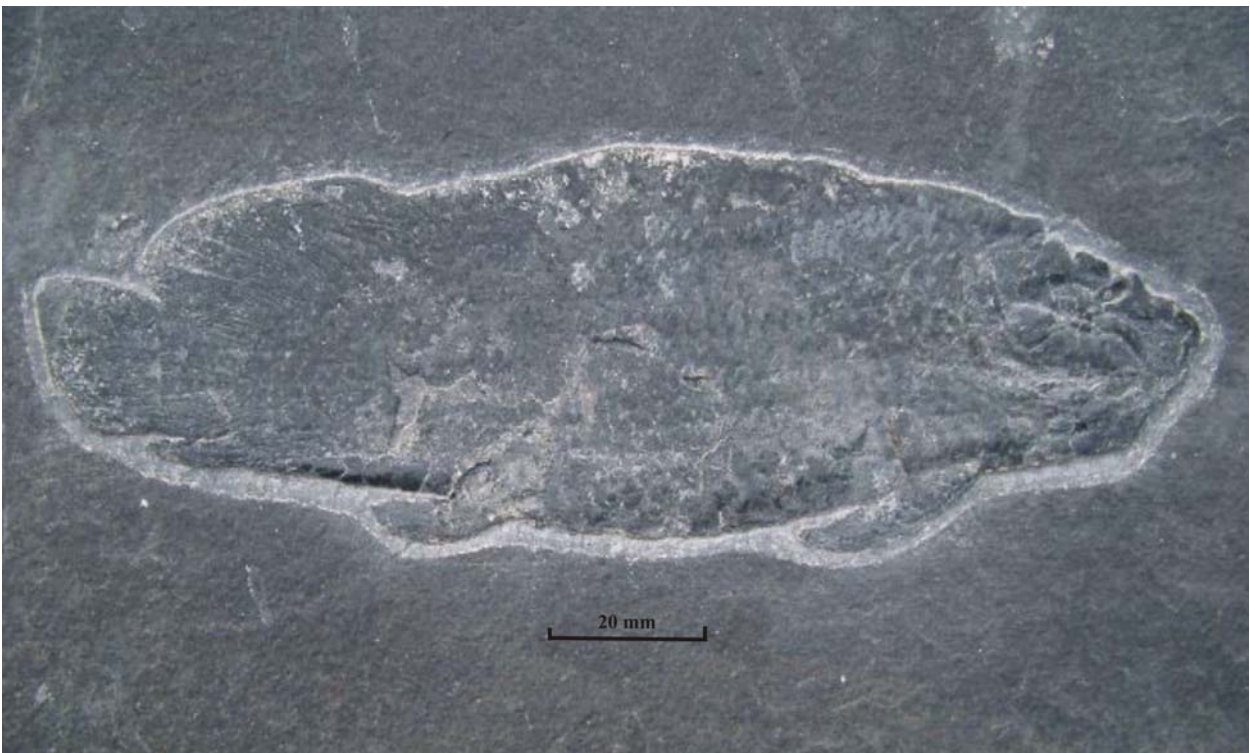


Figure 15. *Pinnalongus saxoni*. Robbery Head and Lybster 'subgroup' [Bighouse Formation], Baligill Burn, Sutherland. National Grid Reference NC 855 659. Specimen CM3. Chris Moore Collection.