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Fish and tetrapod communities across a marine to brackish salinity gradient in the Pennsylvanian (early Moscovian) Minto Formation of New Brunswick, Canada, and their palaeoecological and palaeogeographical implications

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Abstract: Euryhaline adaptations in Pennsylvanian vertebrates allowed them to inhabit the marine to freshwater spectrum. This is illustrated by new assemblages of fish and tetrapods from the early Moscovian Minto Formation of New Brunswick, Canada. Fish include chondrichthyans (xenacanthids~~,~~ and the enigmatic *Ageleodus*), acanthodians (gyracanthids and acanthodiforms), sarcopterygians (rhizodontids, megalichthyids and dipnoans), and actinopterygians (eurynotiforms). Tetrapods include ~~small~~ small- to medium-sized, and largely aquatic, stem tetrapods (colosteids) and anthracosaurs (embolomeres). A key finding is that the parautochthonous fossil assemblages are preserved across a salinity gradient, with diversity (measured by the Simpson Index) declining from open marine environments, through brackish embayments, and reaching a nadir in tidal estuaries. Chondrichthyans dominate the entire salinity spectrum (65% of fossils), a distribution that demonstrates a euryhaline mode of life, and one large predatory chondrichthyan, *Orthacanthus*, may have practised filial cannibalism in coastal nurseries because its heteropolar coprolites contain juvenile xenacanthid teeth. In contrast, other fish communities were more common in open marine settings while tetrapods were more common in coastal brackish waters. While all these faunas were~~,~~ also~~,~~ likely~~,~~ euryhaline, their osmoregulation was, perhaps, less versatile. The demonstration of widespread euryhalinity among fish and aquatic tetrapods explains why Pennsylvanian faunas generally show a cosmopolitan biogeography because taxa were able to disperse via seaways. It also resolves the paradox of enriched strontium isotopic signatures observed in these faunas because organisms would have been, at times, exposed to continental water bodies as well. Therefore, our new findings contribute to the long-running debates about the ecology of Pennsylvanian fishes and tetrapods.

Key words: Pennsylvanian, fish communities, salinity gradient, euryhaline, cosmopolitan, New Brunswick.

EURYHALINE animals are relatively rare in modern ecosystems (Edwards and Marshall 2013; McCormick *et al.* 2013), with less than 10% of organisms adopting this osmoregulatory strategy (Schultz and McCormick 2013). In contrast, euryhaline adaptations appear to have been much more widespread at certain times in the geological past (Minter *et al.* 2016), and, in fact, may have played a critical transitional role in the Palaeozoic colonisation of continental freshwater ecospace (Buatois *et al.* 1998; Miller and Labandeira 2002; Park and Gierlowski-Kordesch 2007; Falcon-Lang *et al.* 2015*a*). Adaptation to lower and more variably saline (brackish to fresh) water bodies commenced as early as the Ordovician (MacNaughton *et al.* 2002; Davies and Sansom 2009; Sansom *et al.* 2009), and the abundance and complexity of these ecosystems steadily ~~increasing~~ increased through the Silurian–Carboniferous (Jones and Dixon 1977; Buatois *et al.* 2005; Kennedy *et al.* 2012). Colonisation patterns closely parallel the Ordovician rise of hepatophytes and the Silurian–Carboniferous diversification of tracheophytes (Gensel and Edwards 2001), indicating co-evolutionary teleconnections between land plants, terrestrial-marine nutrient export patterns (Algeo and Scheckler 1998), and the carrying capacity of ‘non-marine’ coastal environments (Prescott *et al.* 2014).

Adoption of euryhalinity appears to have peaked during a “mid-Carboniferous diversification” when this mode of life, temporarily, became dominant (Davies and Gibling 2013; Falcon-Lang *et al.* 2015*a*) among organisms as diverse as microconchids, ostracodes, xiphosurans and fish (Anderson and Shuster 2003; Carpenter *et al.* 2011; Bennett *et al.* 2012; Gierlowski-Kordesch and Cassle 2015; Gierlowski-Kordesch *et al.* 2016), ~~perhaps,~~ in order, perhaps, to utilise depauperate non-marine coastal ecospace for feeding and breeding (Williams *et al.* 2006; Carpenter *et al.* 2014). Rapid diversification coincided with the sharp growth of Gondwanan ice sheets and the onset of significant Milankovitch-driven glacio-eustatic fluctuations (Fielding *et al.* 2008; Montañez and Poulsen 2013). These marine transgressions, with magnitudes up to 120 m (Rygel *et al.* 2008)~~-~~, repeatedly flooded continental margins, creating extensive epicontinental microtidal seaways (Wells *et al.* 2005), whose salinity slowly decreased in a landward direction over many hundreds of kilometres (Falcon-Lang 2005; Falcon-Lang *et al.* 2015*b*), similar to the present-day Baltic Sea (Andersson *et al.* 1992 1994). This palaeo-oceanographic context probably provided optimum conditions for euryhaline organisms to exploit brackish environments.

In this paper, we describe euryhalinity in Late Palaeozoic vertebrate communities. Facies analysis suggests that a wide range of fish, including gyracanthids, elasmobranchs, dipnoans, rhizodonts and megalichthyids, as well as tetrapods, existed in freshwater to brackish environments in Devonian–Carboniferous times (Friedman and Sallan 2012; Schultze 2013), and much recent attention has been given to the apparent dominance of a euryhaline mode of life among mid-Carboniferous vertebrate communities (Schultze 2009; Carpenter *et al.* 2011, 2014, 2015). However, consensus regarding ecology is currently lacking, with some researchers arguing on palaeogeographical, sedimentological and geochemical grounds that fish taxa, especially xenacanthid sharks (Masson and Rust 1984)~~,~~ and tetrapods, may have been obligate freshwater organisms (Johnson, 1979, 1999; Śtamberg and Zajíc 2008; Fischer *et al.* 2011, 2013; Montañez and Cecil 2013). In this paper, we describe a new fauna of fish and tetrapods from the Carboniferous (Pennsylvanian; early Moscovian) of New Brunswick, Canada (Fig. 1A), and demonstrate – based on independent indicators of palaeo-salinity – that certain fish and tetrapod taxa existed across a brackish to marine gradient, and that communities must therefore have been euryhaline. We discuss how these new findings improve understanding of Carboniferous fish and tetrapod ecology.

GEOLOGICAL CONTEXT

The fish and tetrapod fossils reported here were obtained from opencast mine sites (now reclaimed) within the Minto Coalfield, Queens County, New Brunswick, Canada (Fig. 1A–C). The rocks of the Minto Coalfield are of historical interest, having been the first place in North America where coal was mined, beginning in 1639, and they are mentioned in a 1667 entry of Samuel Pepys' famous diary (Smith 1989; Falcon-Lang 2009; Quann *et al.* 2010).

Stratigraphy, age and basin analysis

Rocks of the Minto Coalfield belong to the Pennsylvanian Minto Formation (*sensu* St Peter and Johnson 2009), the lowest unit of the Pictou Group. They were deposited on the New Brunswick Platform (Fig. 1B–C), a stable cratonic region that lay to the north of the oblique collisional zone between Laurasia and Gondwana (Gibling *et al.* 2008). Based on combined megafloral and palynofloral biostratigraphy, the Minto Formation is thought to be latest Duckmantian to Bolsovian in age (Hacquebard and Barss 1970; St Peter 1997, 2000), with the economically important Minto Coal specifically dated as early Bolsovian (Kalkreuth *et al.* 2000). Radiometric ages recently obtained from immediately below and above the Aegiranum Marine Band, which marks the Duckmantian–Bolsovian in western Europe (Pointon *et al.* 2012; Waters and Condon 2012), suggest an age of c. 314 Ma for this boundary. The Minto Formation therefore correlates with the early part of the Moscovian Stage (Peterson 2011; Richards 2013; Fig. 2A).

Within the Minto Coalfield, sediments of the Minto Formation were deposited unconformably over the top of basement rocks of Mississippian age and older, as the cratonic New Brunswick Platform underwent thermal subsidence (Gibling *et al.* 2008; Fig. 2B). Extensive borehole arrays indicate that this basal unconformity is marked by a major silcrete palaeosol, up to 9 m thick in places (Sullivan 1981; St Peter 2000), which mantles the basement complex and indicates seasonally dry-climate weathering over the preceding several million years of depositional hiatus (St Peter and Johnson 2009). In the course of this lengthy episode of landscape degradation, a NE-SW-trending valley system, c. 16 km wide, was cut into the basement, forming an erosional 'container' (degradational depocentre) in which younger sediments of the Minto Formation accumulated (Hacquebard and Barss 1970).

This bedrock palaeovalley was bordered on either side by slates and lavas that formed subdued topographical highs with a palaeo-elevation of a few tens of metres above base level (Hacquebard and Barss 1970; Gray *et al.* 2012; Fig. 3A). Two lines of evidence suggest that the valley drained towards the southwest (Hacquebard and Barss 1970): (1) the thickness of the lower part of the formation, as measured from the basement contact to the base of the Minto Coal (a prominent chronostratigraphic marker bed) gradually increases from c. 15 m in the northeast to > 90 m in the southwest (Fig. 3A), implying that the basin deepened towards the southwest, and sediment progressively onlapped towards the northeast; and (2) NE-SW-orientated ribbons of channelized sandstone, 1–1.5 km wide, in the 'roof rock' of the Minto Coal, fine towards the southwest (Fig. 3B) and suggest sediment transport in that direction. We note, however, that this inferred palaeoflow direction opposes regional patterns of sediment dispersal, which are directed towards the ENE (van de Poll 1973; Gibling *et al.* 1992). This suggests that either drainage in the Minto Coalfield was strongly influenced by local bedrock topography, or that palaeoflow inferences based on grain size and isopachytes are incorrect. More reliable palaeoflow indicators, such as cross-bed arrays, have not been obtained to date due to poor surface exposure.

Palaeoenvironments

Despite its long history of geological study (Gesner 1841; Robb 1850; Bailey and Matthew 1873), there have been no comprehensive studies of the sedimentary facies of the Minto Formation (St Peter 2000; Clark 2004; St Peter and Johnson 2009). Three units are generally recognised, and their lithologies are described below, based on our own studies of borehole cores (DH62-1 to 3) accessioned at the New Brunswick Department of Energy and Mines, Geological Surveys Branch, Fredericton (Fig. 4A).

The lowest unit, up to 60 m thick (uppermost part only is shown in Fig. 4A), comprises quartz pebble and intraclast conglomerate, fine- to very coarse-grained trough cross-bedded sandstone, and grey siltstone arranged in fining-upward successions, with intermittent silcrete palaeosols. These beds resemble the broadly coeval (early Moscovian) South Bar Formation of Nova Scotia, which formed under braided fluvial conditions (Rust and Gibling 1990), and the early Moscovian Waddens Cove Formation of Nova Scotia, which shows similar silcrete palaeosols (Gibling and Rust 1992). The beds are interpreted as the fluvial channel deposits of a poorly- to well-drained coastal plain.

The middle unit, up to 15 m thick (Fig. 4A), comprises grey laminated shale with distinctive ‘pinstripe’ laminations of very fine-grained to fine-grained sandstone. Sedimentary structures include ripple cross-lamination showing mud drape pairs, flaser bedding, and symmetrical ripples (Fig. 4B–C). At one level is developed the < 0.8 m thick Minto Coal, underlain by a seat earth, 1 m thick (rooted, bleached palaeosol). These beds resemble those of the broadly coeval (early Moscovian) Malagash Formation of Nova Scotia, interpreted as tidal deposits (Naylor *et al.* 1998; Costain 2000), with the coal being formed in a calamite-dominated coastal peat mire (Kalkreuth *et al.* 2000). Proximity of the peat mire to an open brackish-marine embayment is supported by the relatively high (5–9%) sulphur content of the Minto Coal, which increases towards the southwest and the basin centre (Fig. 3A; Hacquebard and Barss 1970). Sandstone ribbons, up to 1.5 km wide, that have been mapped in the succession overlying the Minto Coal, and locally ‘wash out’ the coal (Fig. 3B) may represent incised valleys, flooded to form tidal estuaries; however, this interpretation cannot be confirmed because the boreholes do not intersect this facies.

The uppermost unit, c. 100 m thick (lowermost part only shown in Fig. 4A), comprises units of pebbly sandstone, thin sandstone sheets, and relatively thick intervals of massive, red mudrock, locally showing slickensides and small, scattered carbonate nodules. These beds were formerly assigned to the Hurley Creek Formation, but were amalgamated into the Minto Formation by St Peter (2000), based on regional mapping. The succession probably represents the deposits of a relatively well-drained alluvial plain (cf. Davies and Gibling 2003), but borehole characteristics are insufficient for detailed analysis.

Fish- and tetrapod-bearing lithologies

Fish and tetrapod assemblages reported here were not collected *in situ* within a logged succession, but obtained from the tip heap piles of opencast mines exploiting the Minto Coal at relatively shallow depth, and must have come from the overburden of the coal. A careful review of all fossiliferous specimens shows that the fossils occur in four different lithologies, and can be related to the logged section, with varying degrees of confidence. All fossils are inferred to have come from the middle unit (tidal/estuarine facies), as shown on Fig. 4A.

Lithology 1 comprises a medium grey limestone bed, up to 24 mm thick, which shows abundant fish skeletal fragments throughout. In petrographic thin section, the lithology comprises a wackestone containing scattered bioclasts of punctate brachiopods (Fig. 5A, D), fish bones (Fig. 5B), ostracodes (Fig. 5C), putative sponge spicules (Fig. 5D), spirorbiform microconchids (Fig. 5E), echinoid spines (Fig. 5F), and putative forams (Fig. 5G). An early diagenetic phase of framboidal pyrite (Fig. 5F) commonly infills voids, followed by a later phase of sparry calcite (Fig. 5C, E, G). The only macroscopic invertebrate fossils that are visible in hand specimen are rare spirorbiform microconchids. The invertebrate assemblage, together with the presence of framboidal pyrite, indicates deposition under fully marine conditions (Maliva 1989; Tucker and Wright 1990; Schieber 2002). The high micrite content indicates quiet bottom waters, and the absence of siliciclastic grains suggests that the marine embayment was relatively extensive (Gibling and Kalkreuth 1991). Similar marine limestone beds have been documented elsewhere in the Maritimes Basin, in the Pennsylvanian (Langsettian) Joggins Formation (Grey *et al.* 2011) and Tynemouth Creek Formation (Falcon-Lang *et al.* 2015*a*).

Lithology 2 comprises dark grey, bituminous limestone, up to 28 mm thick, showing abundant fragments and rare articulated examples of the bivalve *Naiadites* (Fig. 6A), spirorbiform microconchids (Fig. 6B-C), and a large quantity of comminuted fossil plant debris. In petrographic thin section, these lithologies comprise bivalve-dominated packstone with minimal micrite matrix (Fig. 5H–I), rare fish fragments (Fig. 5I) and spirorbiform microconchids. Calver (1968) interpreted *Naiadites* as a mostly brackish bivalve, and it is known also from identical lithologies in the Pennsylvanian Joggins, Port Hood, Parrsboro~~,~~ and Sydney Mines Formations of nearby Nova Scotia, where they have been interpreted as the deposits of extensive brackish embayments (Gibling and Kalkreuth 1991; Calder 1998; Falcon-Lang *et al.* 2006). The environment was probably shallow and wave-agitated given that the micrite matrix has largely been winnowed away and bivalves are commonly fragmented (Davies and Gibling 2003; Falcon-Lang 2005; Carpenter *et al.* 2015).

Neither limestone lithology was observed in the logged boreholes. However, in the Joggins Formation of Nova Scotia, such thin limestone beds form the roof of coal seams (Davies and Gibling 2003; Falcon-Lang 2005), and represent brackish-marine flooding surfaces, possibly triggered by glacio-eustatic or tectonic factors (Falcon-Lang *et al.* 2006). In all the boreholes that we studied, the interval containing the Minto Coal has been removed for coal petrographic analysis, and possibly with it, evidence for the stratigraphic position of overlying limestone beds. Clearly, the two limestone lithologies represent open-water facies, and the presence of comminuted plant debris in Lithology 2 suggests proximity to coastal vegetation. Based on fossil content and lithology, we infer that Lithology 1 was formed in the offshore marine part of the embayment and Lithology 2 represents the coastal embayed zone where fluvial discharge led to lower and most variable salinities.

Lithology 3 comprises thinly bedded, pale grey siltstone to very fine-grained sandstone showing symmetrical ripple marks with mud drapes (Fig. 7A). In thin section, it shows a poorly developed micritic matrix. Fish skeletal fragments, included xenacanthid teeth, are particularly concentrated within the mud-rich ripple troughs (Fig. 7B). Lithology 4 comprises a medium- to dark-grey, laminated mudstone, with thin partings of very fine-grained sandstone, and isolated fish fragments. These latter two lithologies are identical to those found in the tidal/estuarine facies reported from the borehole core overlying the Minto Coal, and therefore can be directly related to the logged succession with a high degree of confidence. These clastic beds probably represent the most proximal of the fossiliferous lithologies, probably deposited within a tidal estuary developed on the coast of the brackish-marine epicontinental sea represented by the limestone beds.

MATERIAL AND METHOD

All fossil material reported here was obtained by surface prospecting on weathered tip heaps adjacent to back-filled opencast coal mines within the Minto Coalfield (Fig. 8), and no material was directly obtained in a sedimentary context.

~~*Institutional abbreviation.* NBMG, New Brunswick Museum (Geology), Saint John, New Brunswick, Canada.~~

Localities, collections and collections history

Fossil material was collected in four phases. Prior to 1988, William H. Forbes obtained 28 specimens from various sites in the Minto Coalfield, but without detailed locality data (Miller and Forbes 2001). Between c. 1991 and 2000, amateur palaeontologist Michael Lee obtained a much larger collection at Iron Bound Cove (Latitude 46°08.67'N; Longitude 65°58.10'W) and Coal Creek (Latitude 46°06.09'N; Longitude 65°53.39'W) on the Northeast Arm of Grand Lake, c. 10 km NE of Minto, Queens County (Fig. 1B–C). Those collections were augmented by one of us (RFM) in collaboration with Michael Lee, at Iron Bound Cove in 2002, and by three of us (AÓG, RFM, MRS) at Iron Bound Cove in 2015. There are 404 catalogued hand specimens from Iron Bound Cove and 60 catalogued hand specimens from Coal Creek, together with a further 230 specimens from Coal Creek that are currently uncatalogued but show indeterminate fish skeletal material only.

Specimen preparation and imaging

Fossils visible on bedding surfaces were prepared through a combination of mechanical and chemical removal of surrounding matrix. Mechanical preparation was by means of a pin-vice, assorted fine-tipped brushes, and tweezers. Where the matrix was too hard for this to work, specimens were immersed in a 5% acetic acid solution, buffered with calcium acetate, following the approach of Jeppsson *et al.* (1985). To minimise risk of fracture and to provide a barrier against acid attack, fossils were coated with a weak, ethanol-based contact adhesive ('Mowital') before acid digestion. Specimens prepared in this way were photographed with a Nikon D700 digital SLR camera with a Nikon 60 mm macro lens. Other specimens were photographed using a Panasonic Lumix DMC-ZS3 digital camera or a Canon Eos 40D digital camera using a Canon Ultrasonic 100 mm macro lens or mounted on a Leica MS5 microscope. Figures were prepared with Adobe Photoshop Illustrator in Creative Suite 5.

Institutional abbreviation. NBMG, New Brunswick Museum (Geology), Saint John, New Brunswick, Canada.

SYSTEMATIC PALAEONTOLOGY

A comprehensive review of 722 hand specimens containing > 2692 individual fish skeletal fragments in the NBMG collections from the Minto Formation is given in the supplementary material (see Ó Gogáin *et al*. 2016, S1). Miller (1999) published a preliminary list of taxa known up to that date, but no detailed study of the material has been undertaken hitherto. We present the materials in the sequence Chondrichthyes, Acanthodii, Sarcopterygii, Actinopterygii (Table 1).

Class CHONDRICHTHYES Huxley, 1880

Subclass ELASMOBRANCHII Bonaparte, 1838

Superorder XENACANTHIMORPHA Nelson, 1976

Order XENACANTHIFORMES Berg, 1937

Family DIPLODOSELACHIDAE Dick, 1981

Genus *ORTHACANTHUS* Agassiz, 1843*a*

Type species. Orthacanthus cylindricus Agassiz, 1843*a*

-*Orthacanthus compressus* Newberry, 1856

Figure 9A–D

Material. 71 specimens bearing isolated teeth (NBMG 9948, 10740 (juvenile specimen attached to *Ctenodus* tooth plate), 10746–10748, 10757, 14953–14965, 14967–14968, 14983–14984, 14991–14993, 14996, 15823, 15825, 15832–15834, 15836, 15838, 15841, 15843, 15846–15847, 15849, 15902–15903, 15905–15910, 15916, 16088, 16090, 16093, 16095, 19614–19626, 19850, 19852–19854, 19856).

Diagnosis. Teeth bi- or tricuspid, with two lateral cusps flanking a median cusp in tricuspid teeth. Where present, the median cusp is smaller than the lateral cusps. Carinae may be present on the edges of the lateral cusps. Tooth base is thin with a round to oval shape. A coronal button is present which does not contact any cusps. A median foramen is present on the labial side of the coronal button. A basal tubercle may be present, which extends in a labial direction and has a bulbous shape.

Description. Teeth range in height, as measured from the basal surface to the apex of the largest cusp, from 0.5 to 11.0 mm (Fig. 10A). In larger teeth (> 1 mm) one lateral cusp is typically larger than the other with both showing a degree of lateral divergence; the 'major cusp' tends to diverge more than the 'minor cusps' (Fig. 9A–C), with some 'minor cusps' having near vertical orientations. Lateral cusps have a lanceolate ~~cross-~~cross-section. Carinae are present on lateral cusps ≥ 1 mm. Serration is absent from all specimens. Median cusps, although present in the majority of specimens, are absent in several teeth. The median cusps of teeth > 0.5 mm high are on average less than 1/3 the height of associated lateral cusps, whereas the median cusps of teeth ≤ 0.5 mm high are roughly the same height as the lateral cusps. A median foramen is present in all specimens. The shape of the coronal button is variable, and may be rounded, oval or heart-shaped (Fig. 9D), and oval coronal buttons are elongated along the labial-lingual axis. Lingual to the coronal button are 1–4 nutritive foramina except in one specimen where the button is absent; the precise placement of the nutritive foramina varies between teeth. The bases of the teeth vary in shape from circular to oval and have a 'scarred' appearance. Oval bases may be either elongated along the labial-lingual axis or along the lateral axis. Base thickness shows a positive linear correlation with base length and tooth height ($R^2 = 0.8132, 0.816$ respectively). A convex basal tubercle is present in some specimens and forms a bulbous shape, which protrudes beyond the labial margin of the base.

Remarks. Tooth size is unimodal (Fig. 10A), suggesting we have a single population and a single species. Assigning small teeth and teeth which lack serration to the genus *Orthacanthus* has been argued against by Hampe (1988). Johnson (1999), on the other hand, shows that *Orthacanthus* teeth can lack serration and have small sizes. It is difficult to distinguish *Orthacanthus compressus* from *Orthacanthus texensis*; *O. texensis* has been ruled out as a possible identity here, as teeth of this species typically have thicker bases, whereas *O. compressus* teeth are characterised by having thin bases, although this is not always the case (Johnson 1999). Also our specimens lack serration, whereas serration has been recorded in thin-based teeth of *O. texensis* (Johnson 1999). Based on the placement of teeth within the jaw for *O. texensis* (Johnson 1999), it is reasonable to assume a posterior curvature of the 'major cusp' in the teeth of *O. compressus*.

Xenacanthiformes indet.

Figure 9E

Material. 32 specimens containing isolated teeth (NBMG 14966, 14985–14987, 14994, 15835, 15837–15838, 15842, 15848, 16082, 16089, 18613, 19628–19645).

Diagnosis. Bicuspid or tricuspid teeth with a base that extends lingually.

Description. Bi- or tricuspid teeth with a base that extends in a lingual to anterio-lingual direction. Cusps are lanceolate to oval in ~~cross~~ cross-section and lateral cusps larger than 1 mm often have carinae on their lateral edges. Serration is absent in all specimens. A sub-circular coronal button is present in specimens with intact bases. In specimens not obscured by sediment there is no median foramen. A convex basal tubercle is present except where it has been broken off (Fig. 9E).

Remarks. The specimens are too fragmentary to identify beyond ordinal level. Some show individual features consistent with *Orthacanthus compressus*, such as the presence of carinae, but have not been included within *O. compressus* as these characteristics are shared by *Xenacanthus* (Johnson 1999).

Elasmobranchii indet.

Figure 9F–G

Material. 32 specimens containing 607 isolated scales (NBMG 19646–19677). Note that some of these specimens were obtained through the destructive dissolution of NBMG 14984, 15834, and 15901, and then assigned new collection numbers.

Diagnosis. Scales with thin bases and cusps extending out from the free-face. Scales vary from polycuspid to fused cusps.

Description. Scales range from ≤ 0.5 mm to ≤ 0.2 mm in both diameter and height (height measured from the base outwards along the denticles). The base of the scales is thin and tends to be dotted with holes, which are likely to be a result of post-mortem degradation, as hole morphology is highly variable. Cusps range from polycuspid to fused cusps, which form a robust structure (Fig. 9F). The cusps of the polycuspid scales tend to have a degree of curvature, and all curve in the same direction.

Remarks. Elasmobranch scales from the Palaeozoic have been shown to have a high degree of morphological variability, depending on which part of the body they are from (Dick 1981). This variability can be more pronounced than that seen between species, making the assignment of scales a difficult task. The Minto specimens show similarities to denticles depicted by Lebedev (1996, fig 6d–f), characterised there as "*Ctenacanthus*" type denticles (Karatajute-Talimaa 1992; Lebedev 1996).

Order *incertae sedis*

Family *incertae sedis*

Genus *AGELEODUS* Owen, 1867

Type species. Ageleodus pectinatus Agassiz, 1843*a*

Ageleodus pectinatus Agassiz, 1843*a*

Figure 9H–J

Material. 67 specimens containing isolated teeth (NBMG 9973b, 10800, 12067, 14965, 14969–14982, 14995, 14997–15004, 15175, 15806, 15838, 15858–15861, 15863, 15868, 15890–15893, 15895, 15897–15900, 16070–16072, 16095, 19600–19613, 19717, 19851).

Diagnosis. Mesio-distally elongated teeth with multiple sharp-conical cusps arranged in a row along the crown. The base is long, narrow and deep, and lacks imbrications.

Description. The teeth are mesio-distally elongated, giving an impression of anterior-posterior compression: the crown is bulbous on one side and flattened on the opposite side (Fig. 9H–J). The number of cusps on the crown varies from 9–18 (Fig. 10B) in complete specimens, with the exception of NBMG 15715, which has 35 (Fig. 9J). The cusps are sharp-conical, except where rounded by abrasion, and are situated along the crown, with 1–2 marginal cusps in a slightly ventral position at each edge. The root of the tooth is compressed and is punctuated by nutritive channels.

Remarks. As *A. pectinatus* is known only from disarticulated teeth, the arrangement of dentition within the jaws is unknown; we follow the terminology established by Downs and Daeschler (2001). Cusp count appears to be continuous and unimodal within the sample, with a mean of 14, and all specimens lie within the first standard deviation except for NBMG 15175 (Fig. 10B). This is similar to the variation in other samples (e.g. Downs and Daeschler 2001, fig. 3); in that example, the majority of specimens had 3 to 16 cusps, though rare teeth with as many as 33 cusps were found. Given the much smaller sample size here, the fact that specimens from Minto show less variation than those from Red Hill is not surprising; nonetheless, all specimens except NBMG 15715 fall within the range of variation established by Downs and Daeschler (2001) for *A. pectinatus*. Controversy continues to surround the interpretation and affinity of *Ageleodus* (Turner 2013). Here we have followed the conservative view that these features represent the teeth of a basal elasmobranch of uncertain placement; however, we note that Lebedev (1996) proposed a rather different hypothesis, i.e., that they are not teeth at all, but rather specialised branchial denticles.

Class ACANTHODII Owen, 1846

Order *incertae sedis*

Family GYRACANTHIDAE Woodward, 1906 emend. Warren *et al.,* 2000

Genus *GYRACANTHIDES* Woodward, 1906

Type species. Gyracanthides murrayi Woodward, 1906.

Gyracanthides sp.

Figure 11A–F

Material. One specimen containing 11 individual spine fragments (NBMG 10739/1–11) and two further specimens containing single spines (NBMG 10736, 15173, 15826, 19969, 19970).

Diagnosis. Laterally compressed spines with a V- to U-shaped ~~cross~~ cross-section. Striated insertion area with an exsertion area covered by tubercles that form ornament ridges. Ornament ridges intersect in a chevron arrangement along the leading edge. Ridges are oblique to the long axis near the insertion area, but become parallel to the long axis towards the distal end in pectoral spines. This is not seen in dorsal and pelvic spines, where tubercle ridges are consistently oblique towards the distal end.

Description. NBMG 15173 is a partially exposed spine 84 mm long. The long axis shows a very small degree of curvature (Fig. 11A). The ~~cross~~ cross-section of the spine does not show curvature, but this may be a result of the sediment obscuring parts of the spine. The insertion/ exsertion boundary (IEB; Fig. 11A) is hard to distinguish due to the high degree of abrasion on the ornament ridges. There is an angle of 42° between the IEB and the ornamented ridges and 25° between the IEB and the striae. Ornament ridges more distal to the IEB show less abrasion, allowing individual ridges to be traced, but the damage is still sufficient that individual tubercles on the ridges are heavily worn and difficult to discern. Seven ridges cross a line drawn perpendicular to the leading edge at the posterior limit of the insertion area (Fig. 11A, cf. Turner *et al.* 2005, fig. 2a).

NBMG 10739 is composed of 11 fragments from several different spines. In NBMG 10739/1–2 the ornament ridges of the exsertion area are pinched out by the insertion area along the leading line (Fig 11B–C). Specimens NBMG 10739/1–2 measure 46 mm and 44 mm along their long axes respectively, with broken surfaces on the distal and proximal ends. The cross-sectional shape of NBMG 10739/1–2 is difficult to determine because it is fragmentary. The insertion area is covered by parallel to sub-parallel incomplete striae that branch and converge in places and taper off both distally and proximally (Fig. 11D). There is a c. 20^o angle between the striae and the IEB. The exsertion area is covered by tubercles, which are arranged en échelon on the ornament ridges of NBMG 10739/1 and 4 (Fig. 11E), and as near-straight ridges in NBMG 10739/2 and 5. The tubercles are elongated along the long axis and intersect as even chevrons along the leading edge (Fig. 11C, E). The lengths of the elongated tubercles vary from 400 to 910 µm in different spine fragments. Any ornamentation originally present on the tubercles has been lost to abrasion. The angle between the ornament ridges and the IEB varies from c. 81^o (Fig. 11B–C) in NBMG 10739/1–2 to c. 52^o in NBMG 10739/4 with the latter having more longitudinal elongate ridges to the long axis, suggesting that it is part of the distal end of a pelvic spine (Turner *et al.* 2005). Spines with varying levels of abrasion along their length may be indicative of wear during life (Turner *et al.* 2005); if abrasion was caused by post-mortem transportation, then a more even distribution of abrasion along the spine would be expected.

NBMG 10739/3–5, 7 and 10 are the only fragments complete enough for the cross-sectional shape to be determined; all are elliptical (Fig. 11F). Only a single ridge is visible on the trailing edge of NBMG 10739/3, as the surface is damaged where a second ridge would be expected in *Gyracanthides* (Turner *et al.* 2005). There is an infilled circular hollow in NBMG 10739/4 that narrows distally in proportion with the narrowing of the spine. This hollow represents the pulp cavity. All spine fragments are too small to show any distal curvature.

Remarks. Gyracanthid material from the Minto Formation has been reported previously as *Gyracanthus* cf. *G. duplicatus* (Gardiner 1966; Miller 1999), but since Dawson's *Gyracanthus duplicatus* is now known to be invalid (Carpenter *et al.* 2015), the Minto material merits re-classification. Specimens NBMG 10736, NBMG 15173, NBMG 15826, NBMG 10739/1–11, NBMG 19969 and NBMG 19970 have been removed from the genus *Gyracanthus* based on having spines with ellipsoid ~~cross-~~cross-sections, open grooved hollows and ornament ridges showing a change in angle from oblique to parallel along the long axis of the pectoral spines. These features are not characteristic of *Gyracanthus*, the spines of which have circular ~~cross~~ cross-sections and ornament ridges that are consistently oblique, but are characteristic of *Gyracanthides* (Turner *et al.* 2005; Snyder 2011), to which we assign our specimens. Species-level classification of *Gyracanthides* is based on tubercle orientation, ornamentation and arrangement along the ornament ridges (Warren *et al.* 2000; Turner *et al.* 2005). As NBMG 15173 is highly abraded, this specimen cannot be assigned to a species. NBMG 10739/1 and NBMG 10739/2 (Fig. 11B–C) show a much lesser degree of abrasion, yet no striae on the tubercles can be seen, as in *Gyracanthides murrayi* (Warren *et al.* 2000, fig. 8e–f), indicating that these spines still underwent a small degree of abrasion. The en échelon packaging of tubercles on the ornament ridges better fits *Gyracanthides hawkinsi* than the straight ornament ridges of *G. murrayi*, but ornamented ridges in *G. hawkinsi* meet along the leading edge in uneven chevrons, which is not seen in specimen NBMG 10739/1–11, and tubercles have three projections which converge towards the apex, again not seen in this specimen. Therefore we assign all specimens to *Gyracanthides* sp.

Order ACANTHODIDA Berg, 1940

Family ACANTHODIDAE Huxley, 1861

Genus *ACANTHODES* Agassiz, 1843*b*

Type species. *Acanthodes bronni* Agassiz, 1843*b*.

Acanthodes sp.

Figure 11G–H

Material. Four isolated spines (NBMG 15174, 15852, 15869, 15913).

Diagnosis. Slender, gently curving spines with a rounded anterior rib; lateral surfaces smooth except for a single longitudinal groove on each side.

Description. Isolated, incomplete spines 10 to 32.5 mm in length and 0.5 to 2.5 mm wide, exposed in lateral view. A rounded rib runs along the anterior surface, and is flanked on each side by a prominent longitudinal groove; this is visible as an external mould in the matrix where parts of the spine have been lost, confirming its presence on both sides. The spines are otherwise smooth.

Remarks. The Acanthodidae were a highly cosmopolitan mid to late Palaeozoic group, representatives of which have been found on every continent except South America (Denison 1979; Long 1986; Burrow *et al*. 2008; Sallan and Coates 2010). First appearing in the Middle Devonian, this was the only acanthodiform family to persist into the Carboniferous and Permian (Beznosov 2009; Sallan and Coates 2010). The best known acanthodidid genus, *Acanthodes*, was widely distributed, occurring in Australia, South Africa, Europe, North America, Greenland~~,~~ and Siberia from the Middle Devonian to the late Permian (Denison 1979; Sallan and Coates 2010). However, the earliest known articulated specimens (*Acanthodes lopatini* Rohon, 1889) are from the Tournaisian of south-central Siberia (Beznosov 2009) and many earlier isolated scales and ichthyoliths assigned to *Acanthodes* sp. are considered doubtful (Burrow *et al*. 2010).

Though other acanthodiforms were common in the Maritimes Basin of eastern Canada during the Devonian (Gardiner 1966; Denison 1979; Kennedy *et al*. 2012), the only previously reported occurrence of Acanthodidae is from the Tournaisian Horton Bluff Formation of Nova Scotia (Zidek 1977; Mansky and Lucas 2013, fig. 13A), identified as Acanthodidae indet. Thus, the four isolated spines (NBMG 15174, 15852, 15869, 15913), reported here, are the first Canadian example of *Acanthodes* and extend the known range of the Acanthodidae in Canada by some 35 million years. The acanthodid remains in the Horton Bluff Formation are tantalising, because if they are in fact referable to *Acanthodes* this would indicate a substantial ghost lineage, and suggest the lack of specimens from this interval is the result of collection failure or taphonomic bias; it is to be hoped that further investigations in the Horton Bluff Formation will provide determinable material which will resolve this issue.

Acanthodidae indet.

Material. Ten specimens containing multiple isolated spines (NBMG 15822, 15835, 15838, 15844, 15873, 16082, 16094, 16095, 20013, 20016).

Diagnosis. Slender, gently curving spines, unornamented except for a single prominent longitudinal groove.

Description. Isolated, incomplete spines 5 to 25 mm long and 0.5 to 1.75 mm wide, exposed in various aspects. Several have been crushed and badly damaged, so no further diagnostic features can be discerned.

Class OSTEICHTHYES Huxley, 1880

Subclass SARCOPTERYGII Romer, 1955

Infraclass DIPNOMORPHA Ahlberg, 1991

Order DIPNOI Müller, 1845

Family *incertae sedis*

Genus *CTENODUS* Agassiz, 1843*a*

Type species. Ctenodus cristatus Agassiz, 1843*a*.

Ctenodus interruptus Barkas, 1869

Figure 12A–B

Material. Two incomplete tooth-plates (NBMG 10740, 15822).

Diagnosis. Subtriangular tooth-plate with ridges that are near-parallel to one another. The ridges are equipped with prominent, longitudinally compressed teeth with rounded apices.

Description. NBMG 10740 is a broken fragment of a tooth-plate. Only four near-parallel ridges are present (Fig. 12A) with lengths of 9 to 31 mm, but these measurements do not represent the original length of the ridges, as they are broken at both ends. There is a space of 5 mm between ridges (measured from between the apices). Individual apex height reduces along each ridge from the centre out in both directions. Ridges are relatively straight. There is a prominent depression between two apices on one side of the specimen (Fig. 12A), seen in three of the ridges (not observable in the fourth ridge as this section of the ridge is not preserved). Apices vary randomly along the ridge between conical and rounded (Fig. 12A); rounded apices are likely a result of abrasion. All apices are laterally compressed towards the apex. The basal surface is encased in sediment.

Remarks. Only two species of *Ctenodus* have been reported from the North American continent: *C. cristatus* and *C. interruptus*, with *C. murchisoni* from Nova Scotia being assigned to *Conchodus plicatus* (Baird 1978). NBMG 10740 shows more prominent separated apices than *C. cristatus* (Sharp and Clack 2013, fig. 2) and *C. murchisoni* (Sternberg 1941, fig~~.~~s 1–3). These prominent apices are similar to *C. interruptus* (see Sharp and Clack 2013, fig~~.~~s 5, 14). Therefore NBMG 10740 has been assigned to *C. interruptus*. Ahlberg *et al.* (2006), in their review of the development of lungfish dentitions, convincingly argue that these apices are teeth and not denticles, as described in older literature. The dental plate bears some very small xenacanthid teeth on the occlusal surfaces (Fig. 12B).

Dipnoi indet.

Figure 12C–D

Material. Six specimens, each comprising isolated tooth-plate fragments (NBMG 18609, 19698–19701, 19833).

Diagnosis. Triangular tooth-plates equipped with ridges of teeth.

Description. Fragmentary tooth-plates, each bearing two ridges, converging at an angle of c. 20° (Fig. 12C). There is no evidence that any other ridges were originally present. Teeth are laterally compressed, and this is consistently more pronounced in one ridge than the other (Fig. 12D). Tooth-plates show broken surfaces near the edges.

Remarks. Dipnoan tooth-plates show substantial variation attributed to tooth wear (Schultze and Chorn 1997) and to developmental anomalies (Kemp 1996, 2003), making the identification of isolated specimens difficult. Most diagnostic characters are associated with cranial bones rather than tooth-plates (Sharp and Clack 2013), although isolated tooth-plates can often be identified to species level when complete (Sharp and Clack 2013). Due to the fragmentary nature of the specimens they have been assigned to Dipnoi indet.

Infraclass TETRAPODOMORPHA Ahlberg, 1991

Order RHIZODONTIDA Andrews and Westoll, 1970 emend. Johanson and Ahlberg, 2001

Family RHIZODONTIDAE Traquair, 1881*a* emend. Andrews and Westoll, 1970

Genus STREPSODUS Huxley, *in* Huxley and Etheridge, 1865

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Type species. Strepsodus sauroides Binney, 1841.

Strepsodus sauroides Binney, 1841

Figure 13A

Material. Nine isolated teeth (NBMG 9969, 15005, 15007, 15788, 15815, 15820, 15829–15830, 19688).

Diagnosis. Tall, slender teeth that are recurved lingually. Teeth are oval in ~~cross~~ cross-section. Reversed curvature is present towards the apex of the crown. Raised parallel striae are present on the lingual side and on the lingual portions of the distal and mesial sides of the teeth. Striae are longitudinal and show minor to no degree of curvature.

Description. Incomplete teeth varying in length from 7 mm in NBMG 9969 to 17 mm in NBMG 15820. Teeth have an oval ~~cross~~ cross-section. Teeth are recurved and show reverse-curvature near the apex (Fig. 13A), giving them a sigmoidal shape. Raised striae are longitudinal and some show minor curvature, particularly towards the apex, causing individual striae to cross from the lingual surface to the mesial/distal sides. Striae subside near the apex and are absent on the apex itself. Striae may appear to converge apically as a result of recurvature, yet they never come into direct contact. Instead a stria caught between two converging striae will taper out. Striae show a maximum spacing of 0.1 mm prior to convergence. This distance is consistent irrespective of tooth size; larger teeth simply bear more striae. The base of the crown is absent in all specimens.

Remarks. Reverse curvature seen in NBMG 9969 and possibly present in NBMG 15820 suggests that these may be symphysial tusks, but the small size of NBMG 9969 and the lack of well-preserved *Strepsodus* mandibles makes this uncertain (Jeffery 2003, 2006).

Genus *ARCHICHTHYS* Hancock and Atthey, 1870

Type species. Archichthys portlocki Portlock, 1843 ex Agassiz MS.

Archichthys portlocki Portlock, 1843 ex Agassiz MS

Figure 13B–C

Material. Three isolated teeth (NBMG 15799, 15818, 19972).

Diagnosis. Robust, gently curved teeth with 11 plications around the base. A ‘woven’ pattern of striation is present above the plications.

Description. NBMG 19972 is a robust tooth 14 mm long. Teeth show gentle lingual curvature (Fig. 13B) with an oval ~~cross-~~cross-section, and are equipped with 11 basal plications (Fig. 13C). Striations on the exposed parts of the tooth surface form a “woven” texture; these are most pronounced at the base of the teeth, and become fainter apically, disappearing completely at the apex. Although the labial surface of NBMG 19972 is partially covered in sediment, an exposed part lacks striations.

Remarks. The 11 plications reported from NBMG 19972 are fewer than the 16 to 18 recorded by Jeffery (2006). This does not rule out assigning NBMG 19972 to *Archichthys portlocki*, as the plication count did not form part of the diagnosis of the species by Jeffery (2006). A plication count of 11 agrees with the estimated 10 to 12 for *A. portlocki* in Carpenter *et al.* (2015). Although the striations in NBMG 15799, NBMG 15818 and NBMG 19972 are similar to those of *Letognathus* (Brazeau 2005), this assignment has been ruled out because, unlike *Letognathus*, striations are absent from the labial surface of all three teeth, as expected for *A. portlocki* (Jeffery 2006). The teeth of *Letognathus* are long and slender (Brazeau 2005), unlike the robust teeth of NBMG 15799, NBMG 15818 and NBMG 19972, again supporting our identification.

cf. *Archichthys portlocki* Portlock, 1843 ex Agassiz MS

Figure 13D–E

Material. Two isolated scales (NBMG 15831, 19689).

Diagnosis. Sub-hexagonal scales with concentric growth lines becoming more prominent towards the periphery of the scale. Median boss on the inner surface.

Description. Two incomplete sub-hexagonal scales with the inner surface exposed. NBMG 19689 has a diameter of 25 mm (Fig. 13D) and NBMG 15831 has a length of 16 mm and a width of 24 mm (Fig. 13E). Concentric growth rings are most prominent at the periphery of the scale and diminish towards the centre. NBMG 19689 has an elongated median boss 4 mm long and 2 mm wide. NBMG 15831 has a pentagon-shaped median boss 1 mm across.

Remarks. NBMG 15831 and NBMG 19689 resemble scales, which formed part of the type series for *Archichthys portlocki* (Portlock 1843, reproduced in Jeffery 2006, fig. 1). Surface detail is partially obscured by a light coating of very fine sediment which proved impossible to remove without damaging the scale.

Genus *RHIZODUS* Owen, 1840

Type species. Rhizodus hibberti Owen, 1840.

Rhizodontidae cf. *Rhizodus hibberti* Owen, 1840

Figure 13F

Material. 15 specimens comprising isolated tusks (NBMG 15787, 15789-15791, 15795, 15798, 15809-15810, 15812-15813, 15816-15817, 15862, 15866, 16074).

Diagnosis. Large tusks with lenticulate cross-section. Approximately 24 plications.

Description. NBMG 15809 is a single robust tusk partially covered in matrix. The exposed portion is 29 mm long. The apex of the crown is either covered in matrix or absent. The exposed surface of the base of the crown is equipped with 12 plications. Recurvature, if any, cannot be observed due to matrix cover. The tusk is slightly compressed which has resulted in longitudinal fractures.

Remarks. Based on the number of plications (n = 12) visible on the exposed portion of NBMG 15809, it is likely that the tooth bears 22 to 26 in total. Similar tusk morphotypes from different genera of rhizodont are differentiated based on the number of plications (Jeffery 2003). This tusk cannot be *Archichthys portlocki* or *Letognathus hardingi* because they bear 16 to 18 and around 14 plications, respectively (Brazeau 2005; Jeffery 2006). *Strepsodus sauroides* is also excluded because it lacks striations. An estimated plication count of 22 to 26 is consistent with *Rhizodus hibberti* (20 to 22) and *Barameda decipiens* (20 to 26) (Jeffery 2003; Holland *et al.* 2007). As *B. decipiens* is known mostly from Australia, whilst *R. hibberti* is found in North American and European localities, this is more likely *R. hibberti*. Isolated tusks of *R. hibberti* and *Screbinodus ornatus* are only distinguishable based on size (Jeffery 2003); with a minimum crown height of 26 mm, we assign NBMG 15809 to Rhizodontidae cf. *Rhizodus hibberti*.

Order *incertae sedis*

Family MEGALICHTHYIDAE Hay, 1902

Genus RHIZODOPSIS Young, 1866 ex Huxley MS emend. Traquair, 1881*b*

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Type species. Rhizodopsis sauroides Williamson, 1849.

Tetrapodomorpha indet.~~,~~ cf. *Rhizodopsis sauroides* Williamson, 1849

Figure 13G

Material. One specimen comprising a single isolated scale (NBMG 15901).

Diagnosis. Ovoid scale, divided into four quadrants. Concentric growth lines present in all quadrants. Radial striae present in only the posterior and anterior quadrants. A median boss and concentric growth lines are present on the inner surface.

Description. Elongated ovoid scale with a length of 26.5 mm and a maximum width of 14 mm. The scale is embedded in the matrix with the inner surface exposed. The scale is fractured, but almost complete, with only a small section of the outer edge broken off (Fig. 13G). Quadrants can be identified, but with great difficulty, and concentric growth lines can be seen only along the very edges. Radial striae can be seen in parts only along the outer edge. There is a median boss on the inner surface, elongated along the long axis. The median boss is 4 mm long and 1 mm thick. The scale is marked by punctae, 400 µm in diameter.

Remarks. The placement of *Rhizodopsis* as a sister-taxon to *Megalichthys* (Friedman *et al.* 2007) has led to its transferal from Rhizodopsidae Berg (1940) to Megalichthyidae Hay

(1902) and thus it has been referred to as a megalichthyid (Coates *et al*. 2008). Detail on the surface of NBMG 15901 has been lost, seen in the lack of concentric growth lines towards the centre of the scale, making identification uncertain. Overall scale morphology looks similar to that illustrated by Williamson (1837, fig~~.~~s 1, 4), with NMBG 15901 being slightly more ovoid. This less rhombic morphology is seen in other *Rhizodopsis sauroides* scales (e.g. Holland *et al*. 2010, fig. 6f, reproduced from Woodward 1891). The median boss of NBMG 15901 resembles the median boss illustrated by Williamson (1837, fig~~.~~s 1, 4). *Megalichthys* scales with the cosmine removed have been misidentified as the scales of *Rhizodopsis* (Holland *et al*. 2010), but as the scales of *Megalichthys* lack a median boss (Andrew and Westoll 1970) it is certain that NBMG 15901 does not belong to *Megalichthys*. For the present, NBMG 15901 is placed in Tetrapodomorpha indet. cf. *Rhizodopsis sauroides*.

Order Sarcopterygii *incertae sedis*

Family MEGALICHTHYIDAE Hay, 1902

Genus *MEGALICHTHYS* Agassiz, 1843*b*

Type species. *Megalichthys hibberti* Agassiz, 1843*b*.

Megalichthys sp.

Figure 13H–J

Material. Four specimens (NBMG 10741 in two parts, 15794, 19974). One of these blocks contains up to 11 identifiable fragmented scales (NBMG 10741/1) and seven complete scales in the other part (NBMG 10741/2–7).

Diagnosis. Sub-rhombic scales with a cosmine-covered outer surface.

Description. Fractured rhombic scales c. 25 mm in length where complete (Fig. 13H). Cosmine-covered outer surface with very low relief ripple-like ornamentation (Fig. 13I). There is a cosmine-free ridge at the margin of the cosmine-covered outer surface, which gradually thins towards the outer edge of the scale. Where the cosmine covering has been worn away from the scales, the surface is covered by closely spaced punctae. On the inner surface is a prominent ridge, which follows the line of contact between the cosmine-covered portion and the ridge on the free field. The ridge on the inner surface does not extend to the margins and tapers off sharply in a stepwise fashion (Fig. 13J). This gives the ridge an elongated rectangular shape.

Remarks. Genus- and species-level identification of megalichthyids is based on cranial characters (Thompson 1964; Andrews 1985, Fox *et al*. 1995), but as *Megalichthys* is common throughout the Carboniferous Maritime Basin it is reasonable to associate these rhombic scales with the genus (e.g., Carpenter *et al.* 2015).

cf. *Megalichthys* sp.

Figure 13K–L

Material. One specimen, a single isolated centrum (NBMG 19958).

Diagnosis. Annular centrum with a relatively large notochordal canal.

Description. NBMG 19958 is a single annular centrum with an outer diameter of 27 mm (Fig. 13K) and a thickness of 5.5 mm (Fig. 13L). The inner surface tapers to form a ridge-like structure, and a relatively large notochordal canal (diameter 16 mm) is inferred. Therefore the inner/outer diameter ratio is 1.69. The inner and outer surface is rough and has a worn appearance. There is no evidence of a neural arch or spine.

Remarks. The worn texture of the centrum suggests that smooth or wrinkled periosteal bone is absent, which may be the reason why triangular areas over the posteroventral regions are absent (see Andrews and Westoll 1970, fig. 7d). The inner/outer diameter ratio of NBMG 19958 is slightly larger than the typical ratio seen in *Megalichthys hibberti*, but ratios in excess of 1.6 have been noted (Andrews and Westoll 1970). Based on its size, this centrum would have been from the trunk of the fish. Neural arches are present in some, but not all, megalichthyid trunk vertebrae, meaning that the lack of a neural arch does not exclude this specimen from the trunk (Andrews and Westoll 1970). The higher outer/inner diameter ratio of NBMG 19958 compared to *Megalichthys hibberti*, along with the difficulty of assigning a single isolated worn centrum to a species, means we assign it to cf. *Megalichthys* sp.

Tetrapodomorpha indet.

Figure 13M–N

Material. Thirteen specimens, comprising incomplete, isolated teeth (NBMG 9968, 10776, 10777, 10783, 10785, 19691-19697) and scales (NBMG 20014).

Diagnosis. Recurved conical teeth with a smooth surface, lacking cutting edges.

Description. The teeth are conical teeth and very gently curved (Fig. 13M); however, NBMG 10785 has been flattened to such a degree that it is impossible to tell if the tooth was ever recurved. NBMG 19696 has a circular ~~cross ~~cross-section exposing a sediment-filled pulp cavity. NBMG 10777 (Fig. 13N) has a broken side exposing part of the pulp cavity that has likewise been filled with sediment. The crown base is absent in all specimens.

Remarks. Apical caps lacking acrodin exclude these teeth from Actinopterygii, so they are identified as sarcopterygians. Sediment-filled pulp cavities suggest that NBMG 19696 and NBMG 10777 had hollow pulp cavities, which are indicative of polyplocodont teeth, such as are present in *Megalichthys*, *Rhizodopsis*, *Rhizodus* and *Strepsodus* (Schultze 1970). Polyplocodont teeth are also present in primitive crown tetrapods, so a tetrapod affinity cannot be ruled out. Without further histological investigation and in the absence of a tooth base, plication folding cannot be determined and these teeth cannot be identified more precisely (Schultz 1970; Vorobyeva 1977; Jeffery 2003). Therefore we identify these teeth as Tetrapodomorpha indet.

Superclass TETRAPODA Goodrich, 1930

Figure 14–D

Material. Ten specimens, including partial jaws (NBMG 15821, 15853, 15872, 20019, 20020, 20021), vertebrae (NBMG 15783, 15784, 15870~~),~~) and possible limb bones (NBMG 15915).

Description. NBMG 15821 is the most complete of several jaw bones; it comprises a 14 mm long mandible, with at least 17 elongate, straight, bullet-shaped, pointed teeth that bear faint longitudinal striations confined to the basal one-third of the visible portion of the crown (Fig. 14A). The jaw bone, although somewhat damaged, appears to be narrow, barely as deep as the length of the tooth crowns, and it bears a shallow sculpture of longitudinal ridges. NMBG 15783 is a vertebra comprising a disc-shaped inter- or pleurocentrum, with nearly equidimensional measurements in articular view (Fig. 14B), and anteroposteriorly short (Fig. 14C), and with a central notochordal canal. In lateral view (Fig. 14C), the portion of the lateral surface between the projecting, rolled edges around the articular faces is depressed. NBMG 15915 is one of several small limb bones (Fig. 14D); it is 19 mm long, shows expanded articular ends, 5 mm across, and a narrow shaft, 2 mm wide at its narrowest. The expansions are more or less symmetrical at each end, forming a roller structure on one end and a shallow socket at the adjacent end, as illustrated.

Remarks. Material includes several small jaw bones, vertebra, and limb bones that do not appear to correspond to any of the fishes described above, but more closely resemble those of tetrapods. Jaw material shows similarities to those of stem tetrapods (colosteids) and anthracosaurs (embolomeres) (Carroll 2009); however, neither of these groups of tetrapods have maxillaries or dentary rows with diagnostic features that would allow attribution with confidence (Bolt and Lombard 2010). The vertebral centrum (NMBG 15783) is reminiscent of those of embolomerous anthracosaurs (e.g. ‘rolled up’ projections of the peripheral margins of its anterior and posterior surfaces; markedly arcuate dorsal and ventral profile of vertebral body in lateral view); however, some lungfish have similar disc-shaped centra (e.g.

Griphoganthus from the Devonian of Australia; Campbell & Barwick 2002) so a dipnoan affinity cannot be entirely discounted. These preliminary remarks do not allow us to make confident interpretations of the tetrapod fauna.

Subclass ACTINOPTERYGII Cope, 1887

Order EURYNOTIFORMES Sallan and Coates, 2013

EURYNOTIFORMES indet.

Fig. 15A

Material. Incomplete mandible with five attached teeth (NBMG 20021).

Diagnosis. Teeth smooth, bulbous and conical, with apical caps of acrodin.

Description. Isolated mandibular fragment c. 2 mm in length. The teeth are bulbous, conical, and unornamented; they are also very small, measuring only c. 0.75 mm.

Remarks. Durophagous actinopterygians first appeared during the Tournaisian (Sallan and Coates 2010), and are believed to have undergone at least two significant radiations in Euramerica during the Carboniferous; hence, they are a common component of Pennsylvanian fossil assemblages in North America and Europe (Zidek 1992; Mickle and Bader 2009; Sallan and Coates 2010). Although their systematic status is yet to be fully resolved, most genera can be placed into either Eurynotiformes Sallan and Coates, 2013 or the likely paraphyletic Bobasatraniiformes Berg, 1940 (Mickle and Bader 2009; Sallan and Coates 2013). The Eurynotiformes possessed a heterognathic dentition consisting of phyllodont tooth plates and a denticulated maxilla; anterior maxilliary teeth were tall and conical, while posterior teeth were much more tumid (Sallan and Coates 2013, fig. 14b). In contrast, the Bobasatraniiformes were equipped with similar tooth plates (Johnson and Zidek 1981; Zidek 1992) but otherwise appear to have been generally edentulous (Campbell and Le Duy Phuoc 1983; Zidek 1992; Mickle and Bader 2009).

Three eurynotiform genera (*Eurynotus*, *Mesolepis*~~,~~ and *Amphicentrum*) are known to have persisted into the Pennsylvanian (Sallan and Coates 2013), but isolated teeth of these taxa cannot be distinguished from one another.

Actinopterygii indet.

Figure 15B–E

Material. Eight specimens containing 25 isolated scales (NBMG 18608, 19678–19683, 20015), ten specimens containing 172 cranial bone fragments (NBMG 19799–19808), one isolated tooth (NBMG 19684), and four isolated centra (NBMG 19834, 19685–19687).

Diagnosis. Rhombic scales with a covering of ganoine, peg-and-socket articulation and asymmetrical serrations. Disc shaped cranial bone fragments with elongated ridges on the outer surface. Conical teeth with a distinct apical cap. Hour-glass shaped centra with concave depressions.

Description: scales~~. Scales:~~. Rhombic scales 0.5 to 1 mm in size. Four scales have asymmetrical serrations on the posterior margin (Fig. 15B–C). Dorsal and ventral margins are straight with slight curvature near the anterior and posterior margins. The anterior margins are slightly curved along their entire extent. Sockets from peg-and-socket articulation are present in seven of the scales (Fig. 15C).

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~~*Cranial* ~~*Description: cranial* ~~*Bone* ~~*bone* ~~*Fragments*~~*fragments*.~~:~~ Elongated sub-rectangular shaped bone plates with a maximum long axis of 2.5 mm. NBMG 19804 has closely packed, branching ridges present on the outer surface (Fig. 15D), which vary along the surface from longitudinal to curved. The inner surface is smooth lacking a peg-and-socket articulation.

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Tooth: NBMG 19684 is a slender, recurved conical tooth with translucent apical cap (Fig. 15E).

Description: c~~*C*~~*entra*.~~:~~ NBMG 19686 measures 1.22 mm from anterior to posterior margin and 0.5 mm in maximum height, giving a height:length ratio of 2.44. The centrum becomes

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constricted towards the centre (Fig. 15F) producing an ‘hour glass-shape’ (Schultz and Chorn 1986). Concave posterior and anterior margins form ‘cup’ shapes on either end that are infilled with sediment. On the dorsal surface there are two sockets elongated along the long axis and separated by a trough. These sockets would have housed the neural arches. A rounded attachment site is present only on one of the lateral sides, which extends laterally (Fig. 15F). On the other lateral side it is likely that an attachment site was present, but has been broken off. A thin ridge runs along the long axis of the ventral surface.

Remarks. The interrelationships of basal Actinopterygii are poorly understood (Patterson 1982; Gardiner 1984; Gardiner and Schaeffer 1989; Sallan 2014), and certain groups, such as the Palaeonisciformes, are certainly paraphyletic (Janvier 1996), making the placement of ichthyoliths in mid-level taxonomic groups problematic. Peg-and-socket articulation in NBMG 19679/1 is similar to that depicted by Schultze (1966, fig. 1a–b) and was previously thought characteristic of ganoid fishes, but the discovery of cladistian scales with peg-and-socket articulation suggests that it is plesiomorphic within the Actinopterygii (Schultze 1977; Patterson 1982). The ridge patterns on the cranial bone fragments, from the Minto specimen, resemble to a limited degree the pattern of ridges seen in the rostral and premaxilla of *Gogosardia coatesi* illustrated in Choo *et al*. (2009, fig. 8a-b) suggesting they are of palaeoniscoid-type. Wide variation in the ridges of cranial bones (Choo *et al.* 2009; Choo 2011, 2015) means that identification of fragmented cranial bones is problematic. Likewise, the high variability of scale morphologies in early Actinopterygii means that it is difficult to say whether the Minto Formation scales represent one or more species (Choo 2011). The apical cap of NBMG 19684 is composed of modified dentine called acrodin (Ørvig 1978), found only in the teeth of Actinopterygii, including cladistians, some palaeonisciformes, colobodonts and pycnodonts (Ørvig 1978; Patterson 1982), though it is absent in pachycormids, *Cheirolepis* and *Severnichthys* (Patterson 1982; Carpenter *et al*. 2014). The centra resemble those of palaeoniscoids illustrated by Schultz and Chorn (1986, fig 3.1–2). The presence of lateral attachment sites, which would have served as attachment points for the ribs, and a height:length ratio of 1:2.44 suggests that these centra formed part of the abdominal region (Schultz and Chorn 1986), although this is higher than a ratio of 1:1.5 recorded by Schultz and Chorn (1986).

BROMALITES

Heteropolar microspiral coprolites

Figure 16A–B, E

Material. Thirty-three specimens (NBMG 18789, 19975–19998, 20004–20011).

Diagnosis. Spiral coprolites, with coils concentrated at the posterior end, covering < 50% of the total length, and striae parallel to the long-axis at the anterior end.

Description. Spiral coprolites, dark grey to brown in colour, 12 to 37 mm long and 5 to 14 mm in diameter (Fig. 16A). Coprolites characterised by six to 12 coils, typically 1 to 2.5 mm wide, concentrated at the posterior end, and comprising up to 50% of the total length (Coprolite Type F3 of Hunt and Lucas 2012*a*). The anterior end is characterised by prominent striae, parallel to the long axis, but twisted into a corkscrew. In thin section, posterior coils are recognisable (Fig. 16B), and the bulk of the coprolites comprise amorphous to pelleted phosphatic grains. Abundant fish skeletal material is also present including recognisable bicupsid xenacantid teeth, although their very small size could indicate an origin in a juvenile shark (Fig. 16E).

Remarks. Heteropolar spiral coprolites were produced by fishes with valvular intestines (McAllister 1987), and represent fully evacuated coprolites rather than enterolites preserved *in situ* (Hunt *et al.* 2012; Hunt and Lucas 2012*a, b*). The phylogenetic distribution of this intestinal structure is not well understood, but it is generally considered to be a primitive feature, most characteristic of elasmobranchs; it is absent in more derived fishes such as actinopterygians and teleosts (Hunt and Lucas 2012*a*). Various authors have argued that xenacanthiform sharks were the most likely producers of spiral coprolites in the Pennsylvanian-Permian of U.S.A. (Williams 1972; McAllister 1985; Hampe 1988). Johnson (1999) and Hunt *et al.* (2012) described similar coprolites to those reported here from the Pennsylvanian-Permian of U.S.A. and related them to *Orthacanthus* sharks, in particular, based on quantitative co-occurrence data. Given the large size of our coprolites and the abundance of *Orthacanthus* teeth in the Coal Creek assemblages where the heteropolar coprolites co-occur, a biological association is considered very likely. Based on the occurrence of small xenacanthid teeth within the coprolite, *Orthacanthus* may have fed on juvenile sharks amongst other prey.

Short cylindrical coprolites

Figure 16C–D

Material. Four specimens (NBMG 19999–20002).

Diagnosis. Short cylindrical coprolites with the posterior end rounded, and the anterior end slightly to strongly tapered.

Description. Light grey, calcareous coprolites, comprising a short cylindrical morphology with two rounded ends or an anterior taper resulting in a tear-drop shape (Coprolite Types B1 and B2 of Hunt and Lucas 2012*a*). Coprolites are 20 to 60 mm long and 6 to 20 mm in diameter, and comprise a dense, solid posterior mass and a more diffuse anterior zone (Fig. 16D). Invertebrate fragments, < 1 mm in granularity, are abundant, especially at the anterior end and include recognisable microconchids and bivalve fragments, possibly of *Naiadites* type (Fig. 16C).

Remarks. The calcareous composition, and the presence of recognisable shelly fragments, indicates that the producer fed on invertebrates. The producer cannot be identified but the crushed shelly components suggest a durophagous habit facilitated by grinding tooth plates, most consistent with the lungfish *Ctenodus*. The size of the coprolite suggests that the fish that produced it was relatively large.

Subspherical coprolite

Figure 16F–G

Material. One specimen (NBMG 19824).

Diagnosis. Short coprolite, approximately as wide as tall, rounded in all dimensions, showing a bilobed external appearance.

Description. The specimen is somewhat nondescript, and can simply be termed ‘round’, or as a subrounded small pellet (category C1), using the shape scheme of Hunt and Lucas (2012*a*, *b*). The coprolite is bilobed, with two equal-sized subspherical portions largely overlapping, and presumably reflecting the original structure. It measures 19 x 22 mm, and is, at most, 7 mm thick. The thickness is probably reduced by compaction and by breakage; one side appears to be external, the other internal (Fig. 16F), showing numerous broken pieces of bone, scales, and teeth preserved. These fish skeletal fragments (Fig. 16G) include a portion of a ridged tooth, preserved shiny and black, possibly from a rhizodont, as well as unidentifiable portions of scales and bones.

Remarks. The coprolite is not especially distinctive; however, based on its size and its contents, it is assignable to a relatively large predatory animal, perhaps a xenacanth shark, rhizodont, or even an aquatic tetrapod.

DOMINANCE-DIVERSITY ANALYSIS

The taxonomic make-up of a total of 722 hand specimens, each containing at least one fish fragment, was analysed quantitatively, at order/class and generic level, with indeterminate material discarded (Table 2). At order/class level, the assemblage (n = 325 identifiable hand specimens) is dominated by chondrichthyans (64.3%), with common sarcopterygians (17.8%) and rare actinopterygians (8.0%), acanthodians (5.2%) and tetrapods (4.6%). At generic level (n = 182 identifiable hand specimens), chondrichthyans are even more dominant with *Ageleodus* (37.0%) and *Orthacanthus* (39.2%) comprising nearly ~~four~~ four-fifths of the assemblage, while four sarcopterygians, *Rhizodus* (8.8%), *Strepsodus* (5.0%), *Megalichthys* (2.8%), and *Archichthys* (2.8%) make up most of the rest of the total. Note that these figures represent raw totals, based on the fossils, and they take no account of the differing biology with regards tooth shedding rates between fish taxa ~~biology of the various taxa~~. In particular, the dominance by chondrichthyans may reflect, in part, the fact that these taxa, presumably, shed teeth at a relative high rate, throughout their lives, as do modern elasmobranchs. This would inflate the chondrichthyan sample by several multiples. There are no reliable adjustment factors that can be used to relate fossil assemblage data to original fish population pyramids.

In order to examine palaeoecological patterns, specimens were assigned to one of the four sedimentary facies (Ó Gogáin *et al*. 2016, Supplementary Dataset 1) and analysed in a palaeoenvironmental context: shallow marine facies (Lithology 1), brackish embayment facies (Lithology 2), or brackish tidal estuary facies (~~Lithology~~ Lithologies 3 and 4). Fish and tetrapod remains are considered parautochthonous to each facies in which they are found. This is based on the fact that ~~all~~ no material shows ~~no~~ signs of abrasion, with the exception of abrasion on the distal portions of the spines of *Gyracanthides*, which is attributed to wear during life, suggesting minimal transportation. However the possibility that fish and tetrapod remains washed in from other environments cannot be entirely ruled out and the disarticulated nature of the material indicates that there was at least some minimal washing.

We note that analysis of the facies distribution of fishes across this offshore to onshore salinity gradient is hampered by the fact that three-quarters of determinate specimens derive from the brackish embayment facies (Lithology 2) whereas fossils in the offshore shallow marine facies (Lithology 1) and onshore tidal estuary facies (~~Lithology~~ Lithologies 3 and 4) are relatively rare. Acknowledging this limitation, genus-level data was analysed using the inverse of the Simpson Index given by the equation:

$$D = 1 - \left(\sum \frac{n(n-1)}{N(N-1)} \right),$$

where n is the total number of specimens of a particular genus and N is the total number of specimens of all genera. This analysis shows that diversity, measured in terms of the total number of taxa and the evenness of the abundance distributions of those taxa, is highest in the shallow marine environment (D = 0.805) and progressively declines in the brackish embayment (D = 0.641) and tidal estuary (D = 0.428). Examining these data qualitatively also reveals patterns. It is noteworthy that both shark genera, *Ageleodus* and *Orthacanthus*, are distributed across the salinity gradient (~~Lithology~~ Lithologies 1 – 4) in relatively high proportions. Here, the equally high proportions of sharks across all facies may ~~help mitigate~~indicate biasing effects of their relative over-abundance because of tooth shedding. In contrast, dipnoans (*Ctenodus*), rhizodonts (*Archichthys*, *Strepsodus*) and *Megalichthys* occur in higher proportions in the marine facies (Lithology 1) while some other rhizodonts (*Rhizodus*) and *Rhizodopsis* are more common in brackish tidal estuaries.

DISCUSSION

In this paper~~,~~ we document a new, diverse assemblage of fish and tetrapods in a facies context from the Pennsylvanian (early Moscovian) Minto Formation of New Brunswick, Canada. Findings improve knowledge of the biodiversity, food webs, and ecology of fish and tetrapod communities during a critical evolutionary phase.

Biodiversity and food webs

Based on specimen counts, the dominant fish were chondrichthyans, comprising 64.3% of the assemblage based on class-level counts. As noted, this value is likely inflated by the common shedding of teeth by sharks. Two genera are co-dominant. Most common (39.2%) is *Orthacanthus*, a large predatory shark that reached its acme in Pennsylvanian times. The diet of *Orthacanthus* was catholic, including actinopterygians, acanthodians, dipnoans, xenacanthids, and tetrapods, based on analysis of coprolites (Williams 1972; Hampe 1988; Johnson 1999) and gut contents (Kriwet *et al.* 2008). However, the presence of possible juvenile xenacanthid remains in heteropolar microspiral coprolites, reported here, adds another dimension to our understanding of *Orthacanthus* behaviour. It suggests the genus was practising filial cannibalism of juvenile xenacanthids (as postulated at other sites; Hampe 1988; Soler-Gijon 1995; Heidke 1998; Johnson 1999; Beck *et al.* 2014). The ecology of the other abundant shark, *Ageleodus*, remains completely unknown, and it is even uncertain whether skeletal elements represent teeth or specialised branchial denticles (Lebedev 1996; Turner 2013).

The assemblage~~,~~ also~~,~~ contains common (17.8%) sarcopterygians (rhizodontids, megalichthyids, rhizodopsids) and rare aquatic tetrapods (4.6%), which were similar large predatory animals. Subspherical coprolites containing rhizodont and actinopterygian remains may have been derived from either of these groups. The dominance of large predators (secondary and tertiary consumers) is inconsistent with a normal trophic pyramid. However, this inverted structure is commonly reported for Pennsylvanian assemblages (e.g. Carpenter *et al.* 2015), and may simply reflect a much lower preservation potential of, mostly soft-bodied, producers and primary consumers.

Within the fish assemblage, the acanthodians (5.2%) had differing feeding habitats. *Acanthodes* was likely a suspension feeder (Brazeau and Winter 2015) filtering planktonic organisms, while *Gyracanthides*, which based upon abrasion on pelvic and pectoral spines

(Denison 1979) occupied a partial benthic habitat and possibly fe~~e~~d on small benthos. Also present were eurynotiforms and the dipnoan, *Ctenodus*, whose crushing/grinding dentition suggests a durophagous mode of life. Based on their size, dipnoans were the most likely producer of the short ellipsoid coprolites that contain fragmentary invertebrate remains (microconchids, bivalves) and rare fish fragments. Non-eurynotiform actinopterygians may have fed on a variety of organisms including zooplankton, arthropods or other fish but, due to the fragmentary nature of the associated material, this cannot be deduced with any certainty.

Euryhaline tolerances

The fish and tetrapod assemblages date from the early Moscovian acme of a major diversification event within brackish/freshwater environments (Falcon-Lang *et al.* 2015*a*). Acquisation of a euryhaline habitat within Carboniferous fish groups occurred prior to the diversification event (Sallan and Coates 2010, 2014; Friedman and Sallan 2012). However, there is considerable disagreement as to whether Carboniferous fish communities documented from continental facies were adapted for a euryhaline habitat. Some authors agree that fish communities were, indeed, temporary visitors from adjacent marine environments because their cosmopolitan distribution implies dispersal via marine seaways (Schultze 2009; Carpenter *et al.* 2011, 2014, 2015). In contrast, others have maintained that they comprised elements of an endemic freshwater ecosystem because the strontium isotope ratio (^{87}Sr/^{86}Sr) of apatite tooth enamel (0.70824 to 0.71216) suggests substantial contact with continental-influenced water bodies (Masson and Rust 1984; Śtamberg and Zajíc 2008; Fischer *et al.* 2011, 2013; Montañez and Cecil 2013).

Quantitative analysis of fish remains in a facies context, reported here, indicate that some fish taxa at least were euryhaline, but also reveals previously unsuspected ecological heterogeneity. Chondrichthyans appear to have been particularly successful in colonising the full salinity gradient, and both *Orthacanthus* and *Ageleodus* have been found in apparently freshwater fluviolacustrine facies upstream of the marine coast at other sites (Schneider *et al*. 2000; Hampe 2002; Carpenter *et al*. 2014). This is also the case for *Acanthodes*, which been reported from a variety of lacustrine, fluvial, estuarine/deltaic, and fully marine settings (Zidek 1976; Beznosov 2009; Burrow *et al*. 2010; Sallan and Coates 2010). In contrast, while also likely euryhaline, dipnoans (*Ctenodus*), rhizodonts (*Archichthys*, *Strepsodus*) and *Megalichthys* appear to have been better adapted to marine environments, while some other fishes (*Rhizodus*, *Rhizodopsis*) appear to be better suited to life in brackish tidal estuaries based on facies distribution data (Table 2). This heterogeneity is reflected by the Simpson Index, which shows that fish diversity declines from open marine environments towards more variably saline estuaries, suggesting that not all taxa were equally successful at infiltrating brackish water coastal tracts.

Aquatic tetrapod remains (embolomeres, colosteids), by contrast, are found only in brackish brackish-water facies and were probably euryhaline, hunting with in coastal brackish bays. This hypothesis has been raised, periodically, based on anecdotal facies associations across Euramerica (Milner 1987; Laurin and Soler-Gijon 2001; Schultze 2009), and is here supported, based on analysis of parautochthonous assemblages associated with a brackish water fauna. Embolomeres and colosteids have always been identified as primarily aquatic forms. The embolomeres, typically 1–4 m long, with their short limbs, elongate, laterally flexible trunks, and long flat-sided tails, have always been interpreted as largely aquatic predators on fishes of all sizes (Milner 1987). Likewise, colosteids were long-bodied, flat-headed predators up to 1 m in length, with reduced limbs and prominent lateral line systems, both indicators of a primarily aquatic lifestyle (Milner 1987). Further, Milner (1987) notes the prevalence of a tetrapod association comprising embolomeres, keraterpetontid nectrideans, lysorophians, and trimerorachoid temnospondyls in Pennsylvanian assemblages throughout

Europe and North America; these have been interpreted as salinity-tolerant organisms, indicating brackish conditions (Schultze~~,~~ 2009, 2013). Our findings suggest that early tetrapods, either retained the osmoregulatory systems of their sarcopterygian ancestors, or independently diversified back into brackish settings.

The inferred widespread euryhalinity of Carboniferous fish and tetrapods in the Minto Formation contributes to the long-running debate regarding ecology. If taxa were freely migrating beneath marine and freshwater settings, or even occupying brackish coastal settings, it is possible for them to both have a marine-based dispersal pattern, explaining the cosmopolitan nature of assemblages (Sahney *et al*. 2010; Carpenter *et al*. 2015). However, a euryhaline habit, also, explain how such fishes and tetrapods could show enriched strontium isotope values indicative of continental/freshwater influences (Fischer *et al.* 2011, 2013; Montañez and Cecil 2013).

Evolutionary implications

The Maritimes Basin of Canada is a particularly informative area for studying the evolution of fish populations within brackish coastal waters. This depocentre is positioned near the continental interior of Pangaea (Falcon-Lang *et al.* 2006) but was intermittently connected to marine water bodies in the course of glacio-eustatic and tectonic fluctuations (Gibing *et al.* 2008). Fully marine incursions occurred only during three brief intervals, during part of the Visean (Windsor Group), the Bashkirian (Joggins and Tynemouth Creek formations; Grey *et al.* 2011; Falcon-Lang *et al*. 2015*b*) and early Moscovian stages (Minto Formation; this paper). However, brackish incursions were far more common, spanning the entire Carboniferous interval (Archer *et al.* 1995; Tibert and Scott 1999; Falcon-Lang *et al.* 2006; McIlroy and Falcon-Lang 2006; Gibling *et al.* 2008), and reflecting the periodic development of a brackish epicontinental sea, in some ways, analogous to the present-day Baltic Sea

(Calder 1998; Falcon-Lang 2005). These brackish-marine incursions contain rich but fragmentary fish faunas (summarised in Fig. 17; see references in figure caption). A remarkable feature of these faunas in their conservative composition, with a consistent collection of taxa assembled by Serpukhovian times (Pomquet Formation) and persisting for 20 million years, with minimal variation, until late Moscovian times (Sydney Mines Formation). Conservative composition was probably maintained by euryhalinity, which kept populations well mixed, and suppressed allopatric speciation.

CONCLUSIONS

1. We describe a new fish and tetrapod assemblage from the Carboniferous (Pennsylvanian; early Moscovian) Minto Formation of New Brunswick, Canada.
2. The fish fauna includes chondrichthyans (xenacanthids, and the enigmatic *Ageleodus*), acanthodians (gyracanthids and acanthodiforms), sarcopterygians (rhizodontids, megalichthyids, rhizodopsids, dipnoans), and actinopterygians (eurynotiforms).
3. The tetrapod fauna includes small to medium-sized, and largely aquatic, forms of stem tetrapods (colosteids) and anthracosaurs (embolomeres).
4. Facies analysis of taxa across a brackish-marine palaeosalinity gradient demonstrates that almost all fish and tetrapod taxa were euryhaline, with chondrichthyans especially well equipped to traverse into non-marine environments.
5. Documentation of widespread euryhalinity in fish may explain how strontium isotope analyses of tooth enamel indicate continental influence when other data point to marine dispersal.
6. In the context of other rich Carboniferous fish faunas of the Maritimes Basin of Atlantic Canada, fossils show the assembly of a conservative range of euryhaline taxa over the 20 million year period coinciding with the mid-Carboniferous diversification.

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DATA ARCHIVING STATEMENT

Data for this study are available in the Dryad Digital Repository: http://dx.doi.org/10.5061/dryad.xxxx

REFERENCES

AGASSIZ, L. J. R. 1843*a* (1837–1843). *Recherches sur les poissons fossiles*, **3**. Petitpierre, Neuchâtel et Soleure, viii + 390 + 32 pp.

— 1843*b* (1837–1843). *Recherches sur les poissons fossiles*, **2**. Petitpierre, Neuchâtel et Soleure, xii + 310 + 336 pp.

AHLBERG, P. E. 1991. A re-examination of sarcopterygian interrelationships, with special reference to the Porolepiformes. *Zoological Journal of the Linnean Society*, **103**, 241–287.

ALGEO, T. J. and SCHECKLER, S. E. 1998. Terrestrial-marine telecommunications in the Devonian: Links between the evolution of land plants, weathering processes, and marine anoxic events. *Philosophical Transactions of the Royal Society, London, Series B*, **353**, 113–130.

ANDERSON, L. I. and SHUSTER, C. N. 2003. Throughout geological time: where have they lived. *In* SHUSTER, C. N., BARLOW, R. B., and BROCKMANN, H. J. (eds.), *The American Horseshoe Crab.* Harvard University Press, Cambridge, Massachusetts, 189–223.

ANDERSSON, P. S., WASSERBURG, G. J. and INGRI, J. 1992. The sources and transport of Sr and Nd isotopes in the Baltic Sea. *Earth and Planetary Science Letters*, **113**, 459–472.

— , — and STORDAL, M. C. 1994. Strontium, dissolved and particulate loads in fresh and brackish waters: the Baltic Sea and Mississippi Delta. *Earth and Planetary Science Letters*, **124**, 195–210.

ANDREWS, S. M. 1985. Rhizodont crossopterygian fish from the Dinantian of Foulden, Berwickshire, Scotland, with a re-evaluation of this group. *Transactions of the Royal Society of Edinburgh, Earth Sciences*, **76**, 67–95.

— and WESTOLL, T. S. 1970. The postcranial skeleton of rhipidistian fishes excluding *Eusthenopteron*. *Transactions of the Royal Society of Edinburgh*, **68**, 391–489.

ARCHER, A. W., CALDER, J. H., GIBLING, M. R., NAYLOR, R. D., REID, D. R. and WIGHTMAN, W. G. 1995. Invertebrate trace fossils and agglutinated foraminifera as indicators of marine influences within the classic Carboniferous section at Joggins, Nova Scotia, Canada. *Canadian Journal of Earth Sciences*, **32**, 2027–2039.

BAILEY, L.W. and MATTHEW, G. F. 1873. Report of observations on the Carboniferous system of New Brunswick in the counties of Queens, Sunbury and a portion of York. *Geological Survey of Canada, Report of Progress for 1872–1873*, Part 8, 180–230.

BAIRD, D. 1962. A haplolepid fish fauna in the Early Pennsylvanian of Nova Scotia. *Palaeontology*, **5**, 22–29.

— 1978. Studies on Carboniferous freshwater fishes. *American Museum Novitates*, **1641**, 1–22.

BALL, F. D., SULLIVAN, R. M. and PEACH, A. R. 1981. Carboniferous Drilling Project. Report Investigation 18. New Brunswick Department of Natural Resources, 109 pp.

BARKAS, T. P. 1869. *Ctenodus interruptus*. *Scientific Opinion*, **2**, 113–114.

BASHFORTH, A. R., CLEAL, C. J., GIBLING, M. R., FALCON-LANG, H. J., MILLER, R. F., 2014. Early Pennsylvanian plant communities on a seasonal tropical fluvial landscape (Tynemouth Creek Formation, New Brunswick, Canada). *Review of Palaeobotany and Palynology,* **200**, 229–263.

BECK, K. G., SOLER-GIJÓN, R., CARLUCCI, J. R. and WILLIS, R. E. 2014. Morphology and histology of dorsal spines of the xenacanthid shark *Orthacanthus platypternus* from the Lower Permian of Texas, USA: palaeobiological and palaeoenvironmental implications. *Acta Palaeontologica Polonica*, **61**, 97–117.

BENNETT, C. E., SIVETER, D.J., DAVIES, S. J., WILLIAMS, M., WILKINSON, I. P., BROWNE, M. and MILLER, C. G. 2012. Ostracods from freshwater and brackish environments of the Carboniferous of the Midland Valley of Scotland: the early colonization of terrestrial water bodies. *Geological Magazine*, **149**, 366–396.

BERG, L. S. 1937. A classification of fish-like vertebrates. *Bulletin de l'Académie des Sciences de l'URSS*, **20**, 1277–1280.

— 1940. Classification of fishes, both living and fossil. *Trudy Zoologicheskovo Instituta*, **5**, 85–517.

BEZNOSOV, P. 2009. A redescription of the Early Carboniferous acanthodian *Acanthodes lopatini* Rohon, 1889. *Acta Zoologica*, **90**, 183–193.

BINNEY, E. W. 1841. On the fossil fishes of the Pendleton coal field. *Transactions of the Manchester Geological Society*, **1**, 153–178.

BOLT, J. R. and LOMBARD, R. E. 2010. *Deltaherpeton hiemstrae*, a new colosteid tetrapod from the Mississippian of Iowa. Journal of Paleontology, **84**, 1135–1151.

BONAPARTE, C. L. 1838. *Iconografia della fauna Italiana per le quattro classi degli Animali Vertebrati, 3*. Salviucci, Rome, 266 pp.

BRAZEAU, M. D. 2005. A new genus of rhizodontid (Sarcopterygii, Tetrapodomorpha) from the Lower Carboniferous Horton Bluff Formation of Nova Scotia, and the evolution of the lower jaws in this group. *Canadian Journal of Earth Sciences*, **42**, 1481–1499.

— and WINTER, V. DE. 2015. The hyoid arch and braincase anatomy of *Acanthodes* support chondrichthyan affinity of “acanthodians”. *Proceedings of the Royal Society B*, **282**, 2015–2210.

BUATOIS, L. A., MÁNGANO, M. G., GENISE, J. F. and TAYLOR, T. N. 1998. The ichnological record of the continental invertebrate invasion: evolutionary trends, environmental expansion, ecospace utilization, and behavioral complexity. *Palaios*, **13**, 217–240.

—, GINGRAS, M. K., MACEACHERN, J., MÁNGANO, M. G., ZOONEVELD, J. P., PEMBERTON, S. G., NETTO, R. G., MARTIN, A., 2005. Colonization of brackish-water systems through time: evidence from the trace-fossil record. *Palaios*, **20**, 321–347.

BURROW, C. J., LONG, J. L. AND TRINAJSTIC, K. 2008. Disarticulated acanthodian and chondrichthyan remains from the upper Middle Devonian Aztec Siltstone, Southern Victoria Land, Antarctica. *Antarctic Science*, **21**, 71–88.

—, TURNER, S. and YOUNG, G. C. 2010. Middle Palaeozoic microvertebrate assemblages and biogeography of East Gondwana (Australasia, Antarctica). *Palaeoworld*, **19**, 37–54.

CALDER, J. H. 1998. The Carboniferous evolution of Nova Scotia. 261–302. *In* BLUNDELL, D. J. and SCOTT, A. C. (eds.). *Lyell: the past is the key to the present.* Geological Society of London, Special Publication, **143**, 376 pp.

CALVER, M. A. 1968. Invertebrate faunas. 147–177. *In* MURCHISON, D. and WESTOLL, T. S. (eds.) *Coal and coal-bearing strata*. Oliver and Boyd, Edinburgh, 418 pp.

CAMPBELL, K. S. W. and DUY PHUOC, L. 1983. A late Permian actinopterygian fish from Australia. *Palaeontology*, **26**, 33–70.

—, and BARWICK, R. E. 2002. The axial postcranial structure of *Griphognathus whitei* from Gogo. Records of the Western Australian Museum, 21, 167–201.

CARPENTER, D. K., FALCON-LANG, H. J., BENTON, M. J. and NELSON, W. J. 2011. Fishes and tetrapods from the Pennsylvanian (Kasimovian) Cohn Coal Member of the Mattoon Formation, Illinois, USA: systematics, palaeoecology and palaeoenvironments. *Palaios*, **26**, 639–658.

—, —, —, and HENDERSON, E. 2014. Carboniferous (late Tournaisian) fish assemblages from the Isle of Bute, Scotland: systematics and palaeoecology. *Palaeontology*, **57**, 1215–1240.

—, —, —, and GREY, M. 2015. Early Pennsylvanian (Langsettian) fish assemblages from the Joggins Formation, Canada, and their implications for palaeoecology and palaeogeography. *Palaeontology*, **58**, 661–690.

CARROLL, R. L., 2009. The Rise of Amphibians: 365 Million Years of Evolution. The Johns Hopkins University Press, 544 pp.

—, BELT, E. S., DINELEY, D. L., BAIRD, D. and MCGREGOR, D. C. 1972. *Field excursion A59, vertebrate paleontology of Eastern Canada*, *guidebook*. 24th International Geological Congress, Montreal, 113 pp.

CHOO. B. 2011. Revision of the actinopterygian genus *Mimipiscis* (=*Mimia*) from the Upper Devonian Gog formation of Western Australia and the interrelationships of the early Actinopterygii. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **102**, 77–104.

— 2015. A new species of the Devonian actinopterygian *Moythomasia* from Bergisch Gladbach, Germany, and fresh observations on *M. durgaringa* from the Gogo Formation of Western Australia. *Journal of Vertebrate Paleontology*, **35**, e952817 (doi: 10. 1080/02724634.2015.952817).

—, LONG, J.A. and TRINAJSTIC, K. 2009. A new genus and species of basal actinopterygian fish from the Upper Devonian Gogo Formation of Western Australia. *Acta Zoologica*, **90** (Suppl 1), 194–210.

CLARK, P. 2004. *The Sedimentology of Minto Salmon Harbour Mine site and its high sulfur coals*. Unpublished Honours thesis, University of New Brunswick, Fredericton, New Brunswick, 74 pp.

COATES, M. I., RUTA, R. and FRIEDMAN, M. 2008. Ever since Owen: changing perspectives on the early evolution of tetrapods. *Annual Review of Ecology, Evolution and Systematics*, **39**, 571–592.

COPE, E. D. 1887. Geology and palaeontology. *American Naturalist*, **1887**, 1014–1019.

COSTAIN, T. 2000. *Stratigraphic analysis and possible tidal influences in the Thorburn Member and Coal Brook Member, Stellarton Formation, Nova Scotia.* Unpublished BSc thesis, Dalhousie University, 77 pp.

DAVIES, N. S. and SANSOM, I. J. 2009. Ordovician Vertebrate Habitats: A Gondwanan Perspective. *Palaios*, **24**, 717–722.

— and GIBLING, M. R. 2013. The sedimentary record of Carboniferous rivers: continuing influence of land plant evolution on alluvial processes and Palaeozoic ecosystems. *Earth Science Reviews*, **120**, 40–79

DAVIES, S. J. and GIBLING, M. R. 2003. Architecture of coastal and alluvial deposits in an extensional basin: the Carboniferous Joggins Formation of eastern Canada. *Sedimentology*, 50, 415–439.

DAWSON, J. W. 1868. *Acadian Geology* or *The Geology of Nova Scotia, New Brunswick and Prince Edward Island*, 2nd Edition. Oliver and Boyd, Edinburgh, 694 p.

DENISON, R. 1979. Acanthodii. 1–62. *In* SCHULTZE, H-P. (ed.). *Handbook of Paleoichthyology Volume 5*. Gustav Fischer Verlag, Stuttgart and New York, 62 pp.

DICK, J. R. F. 1981. *Diplodoselache woodi* gen. et sp. nov., an early Carboniferous shark from the Midland Valley of Scotland. *Transactions of the Royal Society of Edinburgh, Earth Sciences*, **72**, 99–113.

DOWNS, J. P. and DAESCHLER, E. B. 2001. Variation within a large sample of *Ageleodus pectinatus* teeth (Chondrichthyes) from the late Devonian of Pennsylvania, USA. *Journal of Vertebrate Paleontology*, **21**, 811–814.

EDWARDS, S. L. and MARSHALL, W. S. 2013. Principles and patterns of osmoregulation and euryhalinity in fishes. 1–44. *In* McCORMICK, S. D., FARRELL, A.P., and BRAUNER, C.J. (eds.), *Fish Physiology, Vol. 32, Euryhaline Fishes*, Elsevier, New York.

FALCON-LANG, H. J. 2005. Small cordaitalean trees in a marine-influenced coastal habitat in the Pennsylvanian Joggins Formation, Nova Scotia, Canada. *Journal of the Geological Society, London*, **162**, 485–500.

— 2009. The earliest history of coal mining and grindstone quarrying at Joggins, Nova Scotia and its implications for the meaning of the place-name "Joggins". *Atlantic Geology*, **45**, 1–21.

— , BENTON, M. J., BRADDY, S. J. and DAVIES, S. J. 2006. The Pennsylvanian tropical biome reconstructed from the Joggins Formation of Canada. *Journal of the Geological Society, London*, **163**, 561–576.

— , MINTER, N. J., BASHFORTH, A. R., GIBLING, M. R., MILLER, R. F. 2015*a*. Mid-Carboniferous diversification of continental ecosystems inferred from trace fossil suites in the Tynemouth Creek Formation of New Brunswick, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **440**, 142–160.

— , PUFAHL, P. K., BASHFORTH, A. R., GIBLING, M. R., MILLER, R. F. and MINTER, N.J. 2015*b*. A marine incursion in the Lower Pennsylvanian Tynemouth Creek Formation, Canada: implications for paleogeography, stratigraphy and paleoecology. *Palaios*, **30**, 779–791.

FIELDING, C.R., FRANK, T.D., BIRGENHEIER, L.P., RYGEL, M.C., JONES, A.T. and ROBERTS, J. 2008. Stratigraphic imprint of the Late Palaeozoic Ice Age in eastern Australia: a record of alternating glacial and nonglacial climate regime. *Journal of the Geological Society*, **165**, 129–140.

FISCHER, J., VOIGT, S., SCHNEIDER, J.W., BUCHWITZ, M. and VOIGT, S. 2011. A selachian freshwater fauna from the Triassic of Kyrgyzstan and its implication for Mesozoic shark nurseries. *Journal of Vertebrate Paleontology*, **31**, 937-953.

—, SCHNEIDER, J. W., VOIGT. S., JOACHIMSKI, M. M., TICHOMIROWA, M., TUTKEN, T., GOTZE, J. and BERNER, U. 2013. Oxygen and strontium isotopes from fossil shark teeth: Environmental and ecological implications for Late Palaeozoic European basins. *Chemical Geology*, **342**, 44–62.

FOX, R. C., CAMPBELL, K. S. W., BARWICK, R. E. and LONG, J. A. 1995. A new osteolepiform fish from the Lower Carboniferous Raymond Formation, Drummond Basin, Queensland. *Memoirs of the Queensland Museum*, **38**, 99–221.

FRIEDMAN, M., COATES, M. I. and ANDERSON, P. 2007. First discovery of a primitive coelacanth fin fills a major gap in the evolution of lobed fins and limbs. *Evolution and Development*, **9**, 328–336.

— and SALLAN, L. C. 2012. Five hundred million years of extinction and recovery: a Phanerozoic survey of large-scale diversity patterns in fishes. *Palaeontology*, **55**, 707–742.

GAGNIER, P-Y. and WILSON, M. V. H. 1996. Early Devonian acanthodians from northern Canada. *Palaeontology*, **39**, 241–258.

GARDINER, B. G. 1966. *Catalogue of Canadian fossil fishes.* Contribution No. 68, Life Sciences. Royal Ontario Museum, University of Toronto, 154 pp.

— 1984. The relationship of the palaeoniscid fishes, a review based on new specimens of *Mimia* and *Moythomasia* from the Upper Devonian of western Australia. *Bulletin of the British Museum, Natural History (Geology)*, **37**, 173–428

— and SCHAEFFER, B. 1989. Interrelationships of lower actinopterygian fishes. *Zoological Journal of the Linnean Society*, **97**, 135–187.

GENSEL, P. G. and EDWARDS, D. 2001. *Plants invade the land*. Columbia University Press, New York, 304 pp.

GESNER, A. 1841. *Third report on the Geological Survey of the Province of New Brunswick*. Henry Chubb, Saint John, New Brunswick, 88 pp.

GIBLING, M. R. and KALKREUTH, W .D. 1991. Petrology of selected carbonaceous limestones and shales in Late Carboniferous coal basins of Atlantic Canada. *International Journal of Coal Geology*, **17**, 239–271.

— and RUST, B. R. 1992. Silica-cemented palaeosols (ganisters) in the Pennsylvanian Waddens Cove Formation, Nova Scotia, Canada. *In* WOLF, K. H. and CHILINGARIAN, G. V. (eds), *Diagenesis III: Developments in Sedimentology 47*, Amsterdam, Elsevier, p. 621–655.

— CALDER, J. H., RYAN, R., VAN DER POLL, H. W. and YEO, G. M. 1992. Late Carboniferous and Early Permian drainage patterns in Atlantic Canada. *Canadian Journal of Earth Sciences*, **29**, 338–352.

— CULSHAW, N., RYGEL, M. C. and PASCUCCI, V. 2008. The Maritimes Basin of Atlantic Canada: basin creation and destruction in the collisional zone of Pangea. 211–244. *In* MIALL, A. D. (ed.). *The sedimentary basins of the United States and Canada*. Elsevier, Oxford, 624 pp.

GIERLOWSKI-KORDESCH, E. H. and CASSLE, C. F. 2015. The "*Spirorbis*" problem revisited: sedimentology and biology of microconchids in marine-nonmarine transitions. *Earth-Science Reviews*, **148**, 209–227.

— FALCON-LANG, H. J. and CASSLE, C. F. 2016. Reply to comment on the paper of Gierlowski and Cassle, The "*Spirorbis*" problem revisited [Earth-Science Reviews, 148, 209–227]. *Earth-Science Reviews*, **152**, 201–204.

GOODRICH, E. S. 1930. Studies on the Structure and Development of Vertebrates. Macmillian and Co, London.

GRAY, T. R., DOSTAL, J., McLEOD, M., KEPPIE, D. and ZHANG, Y. 2012. Geochemistry of Carboniferous peralkaline felsic volcanic rocks, central New Brunswick, Canada: examination of uranium potential. *Atlantic Geology*, **46**, 173–184.

GREINER, H. 1977. Crossopterygian fauna from the Albert Formation, New Brunswick, Canada, and its stratigraphic-paleoecologic significance. *Journal of Paleontology*, **51**, 44–56.

GREY, M., PUFAHL, P. K. and AZIZ, A. A. 2011. Using multiple environmental proxies to determine degree of marine influence and paleogeographical position of the Joggins Fossil Cliffs UNESCO World Heritage Site. *Palaios*, **26**, 256–263.

HACQUEBARD, P. A. and BARSS, M. S. 1970. Paleogeography and facies aspects of the Minto Coal seam, New Brunswick, Canada, C.R. *Sixth International Congress of Carboniferous Stratigraphy and Geology*, **3**, 861–872.

HAMPE, O. 1988. Über die Bezahnung des *Orthacanthus* (Chondrichthyes: Xenacanthida; Oberkarbon-Unterperm). *Paläontologische Zeitschrift*, **62**, 285–296.

— 2002. Revision of the Xenacanthida (Chondrichthyes: Elasmobranchii) from the Carboniferous of the British Isles. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **93**, 191-237.

HANCOCK, A. and ATTHEY, T. 1870. Note on an undescribed fossil fish from the Newsham coal-shale near Newcastle-upon-Tyne. *Annals and Magazine of Natural History Series 4*, **5**, 266–268.

HANKE, G. F. 2008. *Promesacanthus eppleri* n. gen., n. sp., a mesacanthid (Acanthodii, Acanthodiformes) from the Lower Devonian of northern Canada. *Geodiversitas*, **30**, 287–302.

HAY, O. P. 1902. Bibliography and catalogue of the fossil Vertebrata of North America. *Bulletin of the United States Geological Survey*, **179**, 1–868.

HEIDKE, U. H. J. 1998. Revision of the genus *Orthacanthus* Agassiz 1843 (Chondrichthyes: Xenacanthida). *Paläontologische Zeitschrift*, **72**, 135–147.

HOLLAND, T., WARREN, A., JOHANSON, Z., LONG, J., PARKER, K. and GARVEY, J. 2007. A new species of *Barameda* (Rhizodontida) and heterochrony in the rhizodontid pectoral fin. *Journal of Vertebrate Paleontology*, **27**, 295–315.

— LONG, J. and SNITTING, D. 2010. New information on the enigmatic tetrapodomorph fish *Marsdenichthys longioccipitus* (Long 1985). *Journal of Vertebrate Paleontology*, **30**, 68–77.

HUNT, A. P. and LUCAS, S. G. 2012*a*. Descriptive terminology of coprolites and Recent feces. *New Mexico Museum of Natural History and Science, Bulletin*, **57**, 153–160.

— and — 2012*b*. Classification of vertebrate coprolites and related trace fossils. *New Mexico Museum of Natural History and Science, Bulletin*, **57**, 137–146.

—, —, SPIELMANN, J. A., CANTRELL, A., SUAZO, T. and LERNER, A. J. 2012. Bromalites from the Tinajas Lagerstätte (Late Pennsylvanian: Late Missourian), central New Mexico, USA. *New Mexico Museum of Natural History and Science, Bulletin*, **57**, 175–183.

HUXLEY, T. H. 1861. Preliminary essay on the systematic arrangement of the fishes of the Devonian epoch. Figures and descriptions illustrative of British organic remains. Decade 10. *Memoirs of the Geological Survey of the United Kingdom*, London, 1-40.

— 1880. On the application of the laws of evolution to the arrangement of the Vertebrata, and more particularly of the Mammalia. *Proceedings of the Zoological Society of London*, **1880**, 649–662.

— and ETHERIDGE, R. 1865. *A catalogue of the collection of fossils in the Museum of Practical Geology, with an explanatory introduction*. G. E. Eyre and W. Spottiswoode, London, 381 pp.

JANVIER, P. 1996. *Early vertebrates*. Oxford Monographs on Geology and Geophysics, **33**, 393 pp.

JEFFERY, J. E. 2003. Mandibles of rhizodontids: anatomy, function, and evolution within the tetrapod stem-group. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **93**, 255–276.

— 2006. The Carboniferous fish genera *Strepsodus* and *Archichthys* (Sarcopterygii: Rhizodontida): clarifying 150 years of confusion. *Palaeontology*, **49**, 113–132.

JEPPSSON, L., FREDHOLM, D. and MATTIASSON, B. 1985. Acetic acid and phosphatic fossils – a warning. *Journal of Paleontology*, **59**, 952–956.

JOHANSON, Z. and AHLBERG, P. E. 2001. Devonian rhizodontids and tristichopterids (Sarcopterygii; Tetrapodomorpha) from East Gondwana. *Transactions of the Royal Society of Edinburgh, Earth Sciences*, **92**, 43–74.

JOHNSON, G. D. 1979. *Early Permian vertebrates from Texas: Actinopterygii (Schaefferichthys), Chondrichthyes (including North American Pennsylvanian and Triassic Xenacanthodii, and Acanthodii).* Unpublished Ph.D. thesis, Southern Methodist University, Dallas, Texas, 653 pp.

— 1999. Dentitions of Late Palaeozoic *Orthacanthus* species and new species of ?*Xenacanthus* (Chondrichthyes: Xenacanthiformes) from North America. *Acta Geologica Polonica*, **49**, 215–266

— and ZIDEK, J. 1981. Late Paleozoic phyllodont tooth plates. *Journal of Paleontology*, **1981**, 524–536.

JONES, B. and DIXON, O. A. 1977. Stratigraphy and sedimentology of upper Silurian rocks, northern Somerset Island, Arctic Canada. *Canadian Journal of Earth Sciences*, **14**, 1427–1452.

KALKREUTH, W. MARCHIONI, D. and UTTING, J. 2000. Petrology, palynology, coal facies, and depositional environments of an Upper Carboniferous coal seam, Minto Coalfield, New Brunswick, Canada. *Canadian Journal of Earth Sciences*, **37**, 1209–1228.

KARATAJUTE-TALIMAA, V. N. 1992. The early stages of the dermal skeleton formation in chondrichthyans. *In* MARK-KURIK, E. (ed.) *Fossil Fishes as Living Animals.* Proceedings of the II International Colloquium on the study of Palaeozoic fishes, Tallinn, 1898. *Academia*, **1**, 223–231.

KEMP, A. 1996. *Sagenodus* (*Proceratodus*) *carlinvillensis* (Romer and Smith 1934), (Osteichthyes: Dipnoi), short ridge anomaly and classification of dipnoans. *Journal of Vertebrate Paleontology*, **16**, 16–19.

— 2003. Development anomalies in the tooth plates and jaw bones of lungfish. *Journal of Vertebrate Paleontology*, **23**, 517–531.

KENNEDY, K. L., MILLER, R. F. and GIBLING, M. R. 2012. Palaeoenvironments of Early Devonian fish and other aquatic fauna of the Campbellton Formation, New Brunswick, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 361–362, 61–72.

KRIWET, J., WITZMANN, F., KLUG, S. and HEIDTKE, U. H. J. 2008. First direct evidence of a vertebrate three-level trophic chain in the fossil record. *Proceedings of the Royal Society B*, **275**, 181–186.

LAMBE, L. M. 1910. Palaeoniscid fishes from the Albert Shales of New Brunswick. *Geological Survery of Canada, Contributions to Canadian Paleontology, Memoir*, **3**, 1–69.

LEBEDEV, O. A. 1996. Fish assemblages in the Tournaisian – Viséan environments of the East European Platform. 387–415. *In* STROGEN, P., SOMERVILLE, I. D. and JONES, G. Ll. (eds.). *Recent advances in Lower Carboniferous geology*. Geological Society Special Publication **107**, The Geological Society Publishing House, Bath, 464 pp.

LEE, C. E. and BELL, M. A. 1999. Causes and consequences of recent freshwater invasions by saltwater animals. *Trends in Ecology and Evolution*, **14**, 284-288.

LONG, J. A. 1986. A new Late Devonian acanthodian fish from Mt. Howitt, Victoria, Australia, with remarks on acanthodian biogeography. *Proceedings of the Royal Society of Victoria*, **98**, 1–17.

MacNAUGHTON, R. B., COLE, J. M., DALRYMPLE, R. W., BRADDY, S. J., BRIGGS, D. E. G., and LUKIE, T. D. 2002. First steps on land: arthropod trackways in Cambrian-Ordovician eolian sandstone, southeastern Ontario, Canada. *Geology*, **30**, 391–394.

MALIVA, R. G. 1989. Displacive calcite syntaxial overgrowths in open marine limestones. *Journal of Sedimentary Research*, **59**, 397–403.

MANSKY, C. F. and LUCAS, S. G. 2013. Romer's Gap revisited: continental assemblages and ichno-assemblages from the basal Carboniferous of Blue Beach, Nova Scotia, Canada. *In* LUCAS, S. G., DiMICHELE, W. A., BARRICK, J. E., SCHNEIDER, J. W. and SPEILMAN, J. A. (eds.) *The Carboniferous–Permian Transition.* New Mexico Museum of Natural History and Science, **60**, 244–273.

MASSON, A. G. and RUST, B. R. 1984. Freshwater shark teeth as environmental indicators in the Upper Pennsylvanian coal-bearing succession near Sydney, Nova Scotia. *Canadian Journal of Earth Sciences*, **21**, 1151–1155.

McALLISTER, J. A. 1985. Reevaluation of the formation of spiral coprolites. *The University of Kansas Paleontological Contributions*, *Paper,* **114**, 1–12.

— 1987. Phylogenetic distribution and morphological reassessment (SIC) of the intestines of fossil and modern fishes. *Zoologische Jahrbücher. Abteilung für Anatomie und Ontogenie der Tiere*, **115**, 281–294.

McCORMICK, S. D., FARRELL, A. P. and BRAUNER, C. J. (eds) 2013. *Euryhaline fishes. Fish Physiology*, **32**, Elsevier, London, 594 pp.

McILROY, D. and FALCON-LANG, H. J. 2006. Discovery and paleoenvironmental implications of a *Zoophycos*-group trace fossil (? *Echinospira*) from the Middle Pennsylvanian Sydney Mines Formation of Nova Scotia. *Atlantic Canada*, **42**, 31–35.

MICKLE, K. E. and BADER, K. 2009. A new Platysomid from the Upper Carboniferous of Kansas (USA) and remarks on the systematics of deep-bodied lower actinopterygians. *Acta Zoologica*, **90**, 211–219.

MILLER, R. F. 1999. Report of *Gyracanthus* (Chordata: Acanthodii) and other Upper Carboniferous fish from the Minto Formation, New Brunswick (NTS 21 1/4). 37–43. *In* CARROLL, B. M. W. (ed.). *Current Research 1998*. New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Mineral Resource Report **99-4**, New Brunswick Department of Natural Resources and Energy, Fredericton, 163 pp.

— and FORBES, W. H. 2001. An Upper Carboniferous trigonotarbid, *Aphantomartus pustulatus* (Scudder 1884) from the Maritimes Basin (Euramerican Coal Province), New Brunswick, Canada. *Atlantic Geology*, **37**, 191–196.

— and McGOVERN, J. H. 1997. Preliminary report of fossil fish (Actinopterygii: Palaeonisciformes) from the Lower Carboniferous Albert Formation at Norton, New Brunswick (NTS 21 H/12). *In* CARROLL. B. M. W. (ed.) *Current Research 1996*. New Brunswick Department of Natural Resources, Resource Report, **97**, 191–200.

MILLER, M. F. and LABANDEIRA, C. C. 2002. Slow crawl across the salinity divide: delayed colonization of freshwater ecosystems by invertebrates. *GSA Today*, **12**, 4–10.

MILNER, A. R. 1987. The Westphalian tetrapod fauna; some aspects of its geography and ecology. *Journal of the Geological Society, London*, **144**, 495–506.

MINTER, N. J., BUATOIS, L. A., MÁNGANO, M. G., DAVIES, N. S., GIBLING, M. R. and LABANDEIRA, C. C. 2016. The establishment of terrestrial ecosystems. In:

MÁNGANO, M.G. and BUATOIS, L.A. (eds.), The trace-fossil record of major evolutionary events. Topics in Geobiology 39, xxx–xxx. Springer.

MONTAÑEZ, I. P. and CECIL, C. B. 2013. Paleoenvironmental clues archived in non-marine Pennsylvanian-lower Permian limestones of the Central Appalachian Basin, USA. *International Journal of Coal Geology*, **119**, 41–55.

— and POULSEN, C.J. 2013. The Late Paleozoic Ice Age: an evolving paradigm. *Annual Review of Earth and Planetary Sciences*, **41**, 629–656.

MOY-THOMAS, J. A. 1937. The Palaeoniscids from the Cement Stones of Tarras Waterfoot, Eskdale, Dumfriesshire. *Journal of Natural History*, **20**, 345–356.

MÜLLER, J. 1845. Über den Bau und die Grenzen der Ganoiden, und über das natürliche System der Fische. *Archiv für Naturgeschichte*, **1845**, 91–142.

NAYLOR, R. D., ARCHER, A. W., CHANDLER, F. W. and FRALICK, P. W. 1998. Fluvioestuarine sedimentation in the Late Carboniferous Malagash Formation of Nova Scotia, Canada. *Nova Scotia Department of Natural Resources, Report of Activities 1998*, Report ME 1999-1, p. 71–89.

NELSON, J. S. 1976. *Fishes of the world.* Wiley & Sons, New York, 416 pp.

NEWBERRY, J. S. 1856. Description of several new genera and species of fossil fishes, from the Carboniferous strata of Ohio. *Proceedings of the Academy of Natural Sciences of Philadelphia*, **8**, 96–100.

Ó GOGÁIN, A., FALCON-LANG, H. J., CARPENTER, D. K., MILLER, R. F., BENTON, M. J., PUFAHL, P. K., RUTA, M., DAVIES, T., HINDS, S. J. and STIMSON, M. R. 2016. Data from: Fish and tetrapod communities across a marine to brackish salinity gradient in the Pennsylvanian (early Moscovian) Minto Formation of New Brunswick, Canada, and their palaeoecological and palaeogeographic implications. *Dryad Digital Repository*. doi: 10.5061/dryad.xxxx

ØRVIG, T. 1978. Microstructure and growth of the dermal skeleton in fossil actinopterygian fishes: *Nephrotus* and *Colobodus*, with remarks on the dentition in other forms. *Zoologica Scripta*, **7**, 297–326.

OWEN, R. 1840. *Odontography; or, a treatise on the comparative anatomy of the teeth; their physiological relations, mode of development, and microscopic structure in the vertebrate animals. Volume 1, text*. Hippolyte Baillière, London, 655 pp.

— 1846. *Lectures on the comparative anatomy and physiology of the vertebrate animals delivered at the Royal College of Surgeons, England in 1844 and 1846*. Part 1, fishes. Longman, Brown, Green and Longmans, London, 304 pp.

— 1867. On the dental characters of genera and species, chiefly of fishes, from the Low Main Seam and shales of coal, Northumberland. *Transactions of the Odontological Society of Great Britain*, **1**, 323–391.

PAGEAU, Y. 1969. Nouvelle faune ichthyologique du Dévonien moyen dans les Grès de Gaspé (Québec). II. Morphologie et systématique. Première section: A. Euryptérides, B. Ostracodermes, C. Acanthodiens et Sélaciens. *Naturaliste Canadien*, **96**, 399–478.

PARK, L. E. and GIERLOWSKI-KORDESCH, E. H. 2007. Paleozoic lake faunas: establishing aquatic life on land. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **249**, 160–179.

PATTERSON, C. 1982. Morphology and interrelationship of primitive actinopterygian fishes. *American Zoologist*, **22**, 241–259.

PAWLEY, K. and WARREN, A. A. 2006. The appendicular skeleton of Eryops megacephalus Cope, 1877 (Temnospondyli: Eryopoidea) from the Lower Permian of North America. *Journal of Paleontology*, **80**, 561–580.

PETERSON, J. A. 2011. Better mathematical constraints on ages of Carboniferous stage boundaries using radiometric tuff dates and cyclostratigraphy. *Geochemistry, Geophysics, Geosystems*, **12**, Q0AA15, doi: 10.1029/2010GC003467.

POINTON, M. A., CHEW, D. M., OVTCHAROVA, M., SEVASTOPULO, G. D. and CROWLEY, Q. G. 2012. New high-precision U-Pb dates from western European Carboniferous tuffs; implications for time scale calibration, the periodicity of late Carboniferous cycles and stratigraphical correlation. *Journal of the Geological Society*, **169**, 713–721.

PORTLOCK, J. E. 1843. *Report on the geology of the County of Londonderry, and of parts of Tyrone and Fermanagh*. A. Milliken, Dublin, 784 pp.

PRESCOTT, Z., STIMSON, M. R., DEFOE, L. T., GIBLING, M. R., MACRAE, R. A., CALDER, J. H. and HEBERT, B. 2014. Microbial mats and ichnofauna of a fluvial-tidal channel in the Lower Pennsylvanian Joggins Formation, Canada. *Palaios*, **29**, 624–645.

QUANN, S., YOUNG, A., LAROQUE, C., FALCON-LANG, H. J. and GIBLING, M. R. 2010. Dendrochronologic dating of coal mine workings at the famous Joggins Fossil Cliffs of Nova Scotia, Canada. *Atlantic Geology*, **46**, 185**–**194.

RICHARDS, B. C. 2013. Current status of the international Carboniferous time scale. *New Mexico Museum of Natural History and Science, Bulletin*, **60**, 348–353.

ROBB, J. 1850. Report of coal in New Brunswick. 38–47. *In* JOHNSTON, J.F.W. (ed) *Report of the Agricultural Capabilities of the Province of New Brunswick.* Queen’s Printer, Fredericton, New Brunswick.

ROHON, J. V. 1889. Über fossile Fische vom oberen Jenissei. *Memoires de l’Académie Impériale des Sciences de St-Pétersbourg, VII Série*, **36**, 1–17.

ROMER, R. S. 1955. *Herpetichthys*, Amphiboidei, Choanichthyes or Sarcopterygii? *Nature*, **176**, 126–127.

RUST, B. R. and GIBLING, M. R. 1990. Braidplain evolution in the Pennsylvanian South Bar Formation, Sydney Basin, Nova Scotia, Canada. *Journal of Sedimentary Research*, **1**, 59–72.

RYGEL, M. C., FIELDING, C. R., FRANK, T. D. and BIRGENHEIER, L. P. 2008. The magnitude of Late Paleozoic glacioeustatic fluctuations: a synthesis. *Journal of Sedimentary Research*, **78**, 500–511.

SAHNEY, S., BENTON, M. J. and FALCON-LANG, H. J. 2010. Rainforest collapse triggered Carboniferous tetrapod diversification in Euramerica. *Geology*, **38**, 1079–1082.

SALLAN, L. C. 2014. Major issues in the origin of ray-finned fish (Actinopterygii) biodiversity. *Biological Reviews*, **89**, 950–971.

— and COATES, M. I. 2010. End-Devonian extinction and a bottleneck in the early evolution of modern jawed vertebrates. *Proceedings of the National Academy of Sciences, USA*, **107**, 10131–10135.

— , — 2013. Styracopterid (Actinopterygii) ontogeny and the multiple origins of post-Hangenburg deep-bodied fishes. *Zoological Journal of the Linnean Society*, **169**, 156–199.

— , — 2014. The long-rostrumed elasmobranch *Bandringa* Zangrel, 1969, and taphomomy within a Carboniferous shark nursery. *Journal of Vertebrate Paleontology*, **34**, 22–33.

SANSOM, I. J., MILLER, C. G., HEWARD, A., DAVIES, N.S., BOOTH, G. A., FORTEY, R. A., and PARIS, F. 2009.Ordovician fish from the Arabian Peninsula. *Palaeontology*, **52**, 337–342.

SCHIEBER, J. 2002, Sedimentary pyrite: a window into the microbial past. *Geology*, **30**, 531–534.

SCHMITZ, B., ABERG, G., WERDLIN, L., FOREY, P. and BENDIX-ALMGREEN, S. E. 1991. ^{87}Sr/^{86}Sr, Na, F, Sr, and La in skeletal fish debris as a measure of the paleosalinity of fossil–fish habitats. *Geological Society of America Bulletin*, **103,** 786–794.

SCHNEIDER, J. W., HAMPE, O. and SOLER-GIJÓN, R. 2000. The Late Carboniferous and Permian: Aquatic vertebrate zonation in southern Spain and German basins. *Courier Forschungsinstitut Senckenberg,* **223**, 543-61.

SCHULTZ, E.T. and McCORMICK, S.D. 2013. Euryhalinity in an evolutionary context. *EEB Articles*, Paper 29.

SCHULTZE, H.–P. 1966. Morphologische und histologische Untersuchungen an Schuppen mesozoischer Actinopterygier (Ubergang von Ganoid- zu Rund-Schuppen). *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen*, **126**, 232–314.

— 1970. Folded teeth and the monophyletic origin of tetrapods. *American Museum Novitates*, **2408**, 1–10

— 1977. Ausgangsform und Entwicklung der rhombischen Schuppen der Osteichthyes (Pisces). *Paläontologische Zeitschrift*, **51**, 152–168.

— 2009. Interpretation of marine and freshwater paleoenvironments in Permo-Carboniferous deposits*. Palaeogeography, Palaeoclimatology, Palaeoecology,* **281**, 126–136.

— and CHORN, J. 1986. Palaeoniscoid (Actinopterygii, Pisces) vertebrae from the Late Paleozoic of central North America. *Journal of Paleontology*, **60**, 744–757.

— and — 1997. The Permo-Carboniferous genus *Sagenodus* and the beginning of modern lungfish. *Contributions to Zoology*, **67**, 9–70.

SHARP, E. L. and CLACK, J. A. 2013. A review of the Carboniferous lungfish *Ctenodus* Agassiz, 1838 from the United Kingdom, with new data from an articulated specimen of *Ctenodus interruptus* Barkas, 1869. *Transactions of the Royal Society of Edinburgh: Earth and Environmental Sciences*, **104**, 169–204.

SMITH, G. 1989. Coal in Canada. *Geological Survey of Canada, Paper* 89-4.

SNYDER, D. 2011. Gyracanthid gnathostome remains from the Carboniferous of Illinois. *Journal of Vertebrate Paleontology*, **31**, 902–906.

SOLER-GIJÓN, R. 1995. Evidence of predator–prey relationship in xenacanth sharks of the Upper Carboniferous (Stephanian C) from Puertollano, Spain. *Geobios*, **19**, 151–156.

ST. PETER, C. 1997. Bedrock geology of the Chipman/Canaan River map area (NTS 21 I/04 and part of 21 H/13), Sunbury, Queens and Kings counties, New Brunswick. *New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division*, Plate 97-34.

— 2000. Carboniferous geology of the southwestern New Brunswick platform (Maugerville Subbasin). *New Brunswick Department of Natural Resources and Energy, Mineral Resources*, Plate 2000-16.

—, and JOHNSON, S.C. 2009. Stratigraphy and structural history of the late Paleozoic Maritimes Basin in southeastern New Brunswick, Canada. New Brunswick. *Department of Natural Resources; Minerals, Policy and Planning Division, Memoir*, **3**, 348 p.

ŚTAMBERG, S. and ZAJÍC, J. 2008. *Carboniferous and Permian faunas and their occurrence in the limnic basins of the Czech Republic*. Museum of Eastern Bohemia. 224 pp.

STERNBERG, R. M. 1941. Carboniferous dipnoans from Nova Scotia. *American Journal of Science*, **239**, 836–838.

SUES, H.-D., HOOK, R. W. and OLSEN, P. E. 2013. Donald Baird and his discoveries of Carboniferous and early Mesozoic vertebrates in Nova Scotia. *Atlantic Geology*, **49**, 90–103.

SULLIVAN, R.M. 1981. *A brief petrographic study of the rock stratigraphic unit Mississippian-Pennsylvanian felsic volcanics (MPfv) near Stanley, New Brunswick.* Supplementary Report No. 4 of the Carboniferous Drilling Project, New Brunswick Department of Natural Resources, Mineral Development Branch, Open File Report 81 3, 20 pp.

THOMPSON, K. S. 1964. Revised generic diagnoses of the fossil fishes *Megalichthys* and *Ectosteorhachis* (family Osteolepidae). *Bulletin of the Museum of Comparative Zoology*, **131**, 283–311.

TIBERT, N. E. and SCOTT, D. B. 1999. Ostracodes and agglutinated foraminifera as indicators of paleoenvironmental change in an Early Carboniferous brackish bay, Atlantic Canada. *Palaios*, **14**, 246–260.

TRAQUAIR, R. H. 1881*a*. Report on the fossil fishes collected by the Geological Survey of Scotland in Eskdale and Liddlesdale, part 1, Ganoidei. *Edinburgh Philosophical Transactions*, **30**, 15–71.

— 1881*b*. On the cranial osteology of *Rhizodopsis*. *Transactions of the Royal Society of Edinburgh*, **30**, 167–179.

— 1890. Observations on some fossil fishes from the Lower Carboniferous rocks of Eskdale, Dumfriesshire. *Annals and Magazine of Natural History (6th series)*, 6, 491–494.

TUCKER, M.E. and WRIGHT, V.P. 1990. *Carbonate Sedimentology*. Blackwell Scientific Publications, London, 482 pp.

TURNER, S. 2013. *Ageleodus*: widespread mid-Palaeozoic sharks known only from teeth. 61st Symposium on Vertebrate Palaeontology and Comparative Anatomy, Abstracts with Programme, Edinburgh, p. 43.

— , BURROW, C. and WARREN, A. 2005. *Gyracanthides hawkinsi* sp. nov. (Acanthodii, Gyracanthidae) from the Lower Carboniferous of Queensland, Australia, with a review of gyracanthid taxa. *Palaeontology*, **48**, 963–1006.

VAN DE POLL, H. W. 1973. Stratigraphy, sediment dispersal and facies analysis of the Pennsylvanian Pictou Group in New Brunswick. *Maritime Sediments*, **9**, 72–77.

VOROBYEVA, E. I. 1977. Evolutionary modifications of the teeth structure in the Palaeozoic Crossopterygii. *Journal of the Palaeontological Society of India*, **20**, 16-20

WARREN, A., CURRIE, B. P., BURROW, C. and TURNER, S. 2000. A redescription and reinterpretation of *Gyracanthides murrayi* Woodward 1906 (Acanthodii, Gyracanthidae) from the Lower Carboniferous of the Mansfield Basin, Victoria, Australia. *Journal of Vertebrate Paleontology*, **20**, 225–242.

WATERS, C. N. and CONDON, D. J. 2012. Nature and timing of Late Mississippian to Mid-Pennsylvanian glacio-eustatic sea-level changes of the Pennine Basin, UK. *Journal of the Geological Society of London*, **169**, 37–51.

WELLS, M. R., ALLISON, P. A., PIGGOTT, M. D., PAIN, C. C., HAMPSON, G. J. and DE OLIVIERA, C. R. E. 2005. Large sea, small tides: the Late Carboniferous seaway of NW Europe. *Journal of the Geological Society of London*, **162**, 417–420.

WILLIAMS, M., LENG, M. J., STEPHENSON, M. H., ANDREWS, J. E., WILKINSON, I. P., SIVETER, D. J., HORNE, D. J. and VANNIER, J. M. C. 2006. Evidence that Early Carboniferous ostracods colonised coastal flood plain brackish water environments. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **230**, 299–318.

WILLIAMS, M. E. 1972. The origin of “spiral coprolites.” *The University of Kansas Paleontological Contributions*, **59**, 1–19.

WILLIAMS, S. C. and LUCAS, S. L. 2013. Taphonomy and paleoecology of Pennsylvanian fishes from Kinney Brick Quarry, New Mexico, USA. *In* LUCAS, S. G., NELSON, W. J. , DiMICHELE, W. A., SPEILMAN, J. A., KRAINER, K., BARRICK, J. E., ELRICK, S., VOIGT, S. (eds.) *The Carboniferous–Permian Transition in Central New Mexico.* New Mexico Museum of Natural History and Science, **59**, 371–398.

WILLIAMSON, W. C. 1837. On the affinity of some fossil scales of fish from the Lancashire Coal Measures with those of the recent Salmonidæ. *Philosophical Magazine Series 3*, **11**, 300–301.

— 1849. On the microscopic structure of the scales and dermal teeth of some ganoid and placoid Fish. *Philosophical Transactions of the Royal Society of London*, **139**, 435–475.

WOODWARD, A. S. 1891. *Catalogue of the fossil fishes in the British Museum (Natural History). Part II. Containing the Elasmobranchii (Acanthodii), Holocephali, Ichthodorulites, Ostracodermi, Dipnoi and Teleostomi*. British Museum of Natural History, London, 553 pp.

— 1906. On a Carboniferous fish fauna from the Mansfield District, Victoria. *Memoirs of the National Museum of Victoria*, **1**, 1–32.

YOUNG, J. 1866. On the affinities of *Chondrosteus*, Ag. *Quarterly Journal of the Geological Society*, **22**, 569.

ZIDEK, J. 1976. Kansas Hamilton Quarry (Upper Pennsylvanian) *Acanthodes*, with remarks on the previously reported occurrences of the genus. *University of Kansas Paleontological Contributions*, **83**, 1–41.

— 1977. An acanthodid shoulder girdle from Lower Mississippian of Nova Scotia. *Journal of Paleontology*, **51**, 199–200.

— 1992. Late Pennsylvanian Chondrichthyes, Acanthodii, and deep-bodied Actinopterygii from the Kinney Quarry, Manzanita Mountains, New Mexico. *New Mexico Bureau of Mines and Mineral Resources Bulletin*, **138**, 145–182.

FIGURE CAPTIONS

FIG. 1. Location and geological context of the fossil sites. A, ~~The~~ the Late Pal~~a~~eozoic Maritimes Basin of Atlantic Canada, developed in the oblique convergence zone of Laurasia and Gondwana (modified from Gibling *et al.* 2008). Inset map gives location within Canada. B, ~~Geology~~ geology of southern New Brunswick and northwest Nova Scotia showing the fossil sites near Grand Lake, positioned on the stable craton, adjacent to the active Moncton and Cumberland basins (modified from Falcon-Lang *et al.* 2015*a*). Other Pennsylvanian sites with marine beds (Joggins, Emerson Creek) are also shown. C, ~~Geology~~ geology of the Pennsylvanian (early Moscovian) Minto Coalfield of New Brunswick (after Hacquebard and Barss 1970; Ball *et al.* 1981; St Peter 2000) showing the location of the two fossil sites, borehole DH62-1 illustrated in Fig. 4, and other boreholes (closed circles). Abbreviations: NB, New Brunswick; NS, Nova Scotia; PEI, Prince Edward Island. Fig. 1 set for double column (166 mm).

FIG. 2. Geochronology and stratigraphic context of the fossil sites. A, ~~The~~ the Pennsylvanian ~~Timescale~~ timescale (compiled from Peterson 2011; Waters and Condon 2012; Pointon *et al.* 2012; Richards 2013). B, ~~Stratigraphy~~ stratigraphy of the Pennsylvanian (Bashkirian) Cumberland Group and Pennsylvanian (Moscovian) Pictou Group of Atlantic Canada (modified from Gibling *et al.* 2008; Bashforth *et al.* 2014) showing the presence of Langsettian marine bands documented in the Joggins (Grey *et al.* 2011) and Tynemouth Creek (Falcon-Lang *et al.* 2015*b*) formations, and the new marine band (reported here) from the early to mid-Bolsovian part of the Minto Formation. Fig. 2 set for double column (166 mm).

FIG. 3. Geology of the Pennsylvanian (early Bolsovian) Minto Coalfield (modified from Hacquebard and Barss 1970). A, ~~Isopachytes~~ isopachytes for (i) the Minto Coal and (ii) coal to basement, the latter indicating onlap towards the northeast. B, ~~Sandstone~~sandstone/mudstone ratio in the roof rock of the Minto Coal showing NE-SW

trending drainage channels that, locally, ‘wash out’ the coal (i.e., areas where Minto Coal is eroded). Fig. 3 set for double column (166 mm).

FIG. 4. Sedimentary context of the fossil sites based on borehole core DH62-1. A, ~~Graphic~~ graphic log of a short section of borehole DH62-1 (core boxes 44–52; depth 196–231 m) illustrating the three units of the Minto Formation (see text for explanation). The Minto Coal is removed from the core and limestone beds are believed to represent a roof facies as seen in the Joggins Formation (Davies and Gibling 2003). B, ~~Erosive~~erosive-based fluvial channel conglomerate facies in lower unit. C, ~~Pin~~pin-stripe lamination in estuarine facies in middle unit. D, ~~Red~~ red mudrock with carbonate glaebules in upper unit. E, Close-up of paired mud-drapes in ripple cross-lamination in middle unit, a distinctive tidal indicator (cf. Naylor *et al.* 1998; Costain 2000). Scale bar is 30 mm (B–D), 4 mm (F). Fig. 4 set for double column (166 mm).

FIG. 5. Petrology of limestone Lithology 1 (shallow marine facies at Coal Creek: A–G, NBMG 18789) and Lithology 2 (brackish embayment facies at Iron Bound Cove: H–I, NBMG 18611). A, ~~Punctate~~ punctate brachiopods. B, fish skeletal fragments. C, ~~Ostracodes~~ostracodes. D, ~~Punctate~~ punctate brachiopods and possible sponge spicules. E, ~~Spirorbiform~~ spirorbiform microconchids. F, ~~Echinoderm~~ echinoderm spine mineralised with framboidal pyrite. G, putative foraminifera. H, ~~Bivalves~~bivalves. I~~.~~, ~~Bivalves~~ bivalves and phosphatic (francolite) nodule possibly of fish origin. Abbreviations: bv, bivalve fragment; es, echinoid spines; f, foraminifera test; fb, fish skeletal fragments; fp, framboidal pyrite; os, ostracode carapace; pb, punctate brachiopods; pn, phosphatic nodule, sp, spirorbiform microconchids; Scale bar is 1 mm (A–D, H–I), 0.5 mm (E–F), 0.25 mm (G). Fig. 5 set for double column (166 mm).

FIG. 6. Macroscopic invertebrates found in Lithology 2 (brackish embayment facies at Coal Creek). A, ~~Spirorbiform~~ spirorbiform microconchid, NBMG 15841. B, ~~Abundant~~ abundant

spirorbiform microconchids, NBMG 15815. C, ~~Articulated~~ articulated *Naiadites* bivalves, NBMG 19967. Abbreviations: sm, spirorbiform microconchids. Scale bar is 1 mm (A), 1.5 mm (B), 5 mm (C). Fig. 6 set for double column (166 mm).

FIG. 7. Sedimentary and fossil characteristics of Lithology 3 (tidal estuary facies). A, ~~Symmetrically~~symmetrically-rippled siltstone to very fine-grained sandstone showing fish skeletal fragments concentrated within mud-rich ripple troughs. NBMG 15901 (specimen dissolved to extract fish fauna). B, ~~Enlargement~~ enlargement of area in (A) showing *Orthacanthus* tooth and macerated skeletal debris. Abbreviation: xt, xenacanthid tooth. Scale bar as indicated (ruler divided into 10 mm intervals) for A; 10 mm for B. Fig. 7 set for double column (166 mm).

FIG. 8. Tip heaps adjacent to the former opencast mine at Iron Bound Cove (flooded area on the right; Latitude 46°08.67'N; Longitude 65°58.10'W), illustrating how material was collected by 'surface prospecting'. Fig. 8 set for single column (80 mm).

FIG. 9. Teeth of ~~Chondrichthyans~~ chondrichthyans from the Minto Formation (Pennsylvanian) of New Brunswick, Canada. A–D, ~~Tricuspid~~ tricuspid tooth of *Orthacanthus compressus*, NBMG 19617, in aboral (A), oral (B), dorso-aboral (C), and ventro-oral (D) views. E, ~~Tooth~~ tooth of Xenacanth indet., NBMG 19629. F, ~~Denticle~~ denticle of elasmobranch indet., NBMG 19667. G, ~~Denticle~~ denticle of elasmobranch indet., NBMG 19647. H–J, ~~Teeth~~ teeth of *Ageleodus pectinatus*: NBMG 19613 in aboral view (H), NBMG 19613 in oral view (I) and NBMG 15175 in aboral view (J). Abbreviations: cb, coronal button; nf, nutrient foramen; mf, median foramen. Scale bar is 2 mm (A–D), 1 mm (E), 0.25 mm (F–G), 0.5 mm (H–I), 2 mm (J). Fig. 9 set for double column (166 mm).

FIG. 10. Size ranges for Chondrichthyan teeth from the Minto Formation (Pennsylvanian), New Brunswick. A, ~~Range~~ range of heights and frequencies for teeth of *Orthacanthus*. B,

~~Cusp~~ cusp counts and frequencies for complete teeth of *Ageleodus*. Figure 10 set for single column (80 mm).

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FIG. 11. Spines of the Acanthodians from the Minto Formation (Pennsylvanian) of New Brunswick, Canada. A–F, *Gyracanthides* sp., G–H, *Acanthodes* sp. A–C, spines in lateral view: NBMG 15173 (A), NBMG 10739/1 (B), with indications of location of close-ups D and E, and NBMG 10739/2 (C). D, ~~Striae~~ striae on the insertion area and the angle between the striae and the exsertion area, NBMG 10739/1. E, ~~Chevron~~ chevron pattern in ornament ridges on the leading edge, NBMG 10739/2. F, cross-section of a spine, NBMG 10739/4. G, spine in lateral view, NMBG 15174. H, spine in lateral view, NBMG 15852. Line at r-s represents the insertion/exsertion boundary (IEB). Line at x-y represents a line perpendicular to the leading edge. Scale bar is 20 mm (B, C), 10 mm (A, G, and H), 2 mm (F), 1 mm (D and E). Fig. 11 set for double column (166 mm).

FIG. 12. Feeding plates of ~~Dipnoans~~ dipnoans from the Minto Formation (Pennsylvanian) of New Brunswick, Canada. A–B, ~~Feeding~~ feeding plate of *Ctenodus interruptus*, NBMG 10740 (A), with close-ups of isolated xenacanth teeth sitting on the surface (B). C–D, ~~Fragments~~ fragments of the feeding plates of Dipnoi indet., NBMG 18609 showing convergent ridges (C), and NBMG 19699, showing differential apical elongations (D). Scale bar is 4 mm (A), 1 mm (B–D). Fig. 12 set for 2/3 page width (110 mm).

FIG. 13. Teeth and scales of ~~Rhizodonts~~ rhizodonts and ~~Tetrapodomorphs~~ tetrapodomorphs from the Minto Formation (Pennsylvanian) of New Brunswick, Canada. A, ~~Tooth~~ tooth of *Strepsodus sauroides*: NBMG 15820 in lateral view. B, C, ~~Tooth~~ tooth of *Archichthys portlocki*, NBMG 19972, showing striations, in lateral view (B), and plication count on the base (C). D–E, ~~Scales~~ scales of cf. *Archichthys portlocki*, NBMG 19689 (D), NBMG 15831 (E). F, ~~Tooth~~ tooth of cf. *Rhizodus hibberti* NBMG 15809. G, ~~Scale~~ scale of cf. *Rhizodopsis sauroides* NBMG 15901 showing the attachment side. H–J, ~~Scales~~ scales of *Megalichthys*

indet.: NBMG 10741/1, showing the free field (H), and close-up image of the cosmine cover of the free field (I), and NBMG 19974a, showing the attached surface (J). K–L, ~~Centrum~~ centrum of *Megalichthys* sp. NBMG 19958, in articular (K) and lateral (L) views. M–N, ~~Teeth~~ teeth of Tetrapodomorpha indet., NBMG 10776 (M), and NBMG 10777 (N). Scale bar is 2 mm (A–C, M, and N); 20 mm (F), 10 mm (D–E, G, K, and L), 20 mm (H, J), separate 2 mm scale bar (I). Fig. 13 set for double column (166 mm).

FIG. 14. Tetrapod remains, with provisional identifications. A, ~~Small~~ small dentary of a possible ?colosteid bearing teeth, NBMG 15821. B, C, intecentrum of a possible embolomerous anthracosaur vertebra, in ?anterior (B) and lateral (C) views, NBMG 15783~~,~~ ~~and~~. D, small tetrapod limb bone (NBMG 15915). Scale bar is 80 mm (A), 10 mm (B–C), 7.5 mm (D). Fig. 14 set for 2/3 page width (110 mm).

FIG. 15. Actinopterygian remains from the Minto Formation (Pennsylvanian) of New Brunswick, Canada. A, ~~Eurynotiforme~~eurynotiform~~, B – E, indeterminate actinopterygians. A,~~; jaw fragment with five teeth, NBMG 20021. B – F, indeterminate actinopterygians. B–C, ~~Scale~~scale, NBMG 19679/1 showing the free field (B), and the attached surface (C). D, ~~Sculptured~~ sculptured scale or dermal skull bone, NBMG 19804a. E, ~~Tooth~~tooth, NBMG 19684. F, ~~Vertebra~~vertebra, NBMG 19686. Abbreviations: las, lateral attachment site; vr, ventral ridge. Scale bar is 0.4 mm (A, F), 0.5 mm (B–C, and E). Fig. 15 set for single (80 mm).

FIG. 16. Fish coprolites (bromalites). A, ~~Heteropolar~~ heteropolar microspiral coprolite, NBMG 19979. showing coils and posterior spire. B, ~~Thin~~ thin section of heteropolar microspiral coprolite containing fish skeletal fragments including probable juvenile xenacanthid tooth (box: F), NBMG 18789. C, ~~Large~~large, short cylindrical coprolite composed of calcareous material (box: E), NBMG 20000. D, ~~Rounded~~rounded, bilobed coprolite (box: G), NBMG 19824. E, ~~Expanded~~ expanded view of spirorbiform microconchids

and bivalve fragments in coprolite ~~shown~~ (C), NBMG 20000. F, ~~Expanded~~ expanded view of xenacanthid tooth in coprolite (B), NBMG 18789. G, ~~Expanded~~ expanded view of rhizodont tooth and actinopterygian scale (D), NBMG 18789. Abbreviations: as, actinoptergian scale; bf, bivalve fragments; ps, posterior spiral; rt, rhizodont tooth; sm, spirorbiform microconchids; xt, xenacanthid tooth. Scale bars are 4 mm (A–B, D), 6 mm (C), 1.5 mm (E), 1 mm (F, G). Fig. 16 set for single (80 mm).

FIG. 17. Summary of 10 fish faunas from brackish-marine facies in the Carboniferous Maritimes Basin of Atlantic Canada. Carboniferous timescale based on critical synthesis of recent papers (Peterson 2011; Waters and Condon 2012; Pointon *et al.* 2012; Richards 2013) and age of key formations in the Maritimes Basin based on various sources (e.g.~~,~~ Calder 1998; Gibling *et al.* 2008 for discussion). Faunas based on illustrations in published records, revised in light of modern nomenclature. Principal sources for the compilation (Dawson 1868; Gardiner 1966; Carroll *et al.* 1972; Calder 1998) were supplemented by the following additional sources (Lambe 1910; Baird 1962, 1978; Greiner 1977; Johnson 1979, 1999; Miller and McGovern 1997; Turner *et al.* 2005; Brazeau 2005; Jeffrey 2006; Sues *et al.* 2013; Mansky and Lucas 2013; Carpenter *et al.* 2015; this paper; Yale Peabody Museum collections database: http://collections.peabody.yale.edu/search/). Fig. 17 set for double column (166 mm).

TABLE CAPTIONS

Table 1. Summary of fish taxa from the Pennsylvanian (early Moscovian; early Bolsolvian) Minto Formation of New Brunswick, Canada (cf. Bashkirian fish fauna in Joggins Formation; Carpenter *et al.* 2015, fig. 5).

Table 2. Quantitative data for the facies distribution of fish specimen ranked at class/order and generic level. Note that the number of specimens at class/order level (n = 325) is higher

than at generic level (n = 181) because some specimens can be assigned to class/order but not to genus. Percentage values at class/order and genus level differ because of they are based on these different datasets. The inverse of the Simpson Index (1 – H) is calculated for generic level data only.

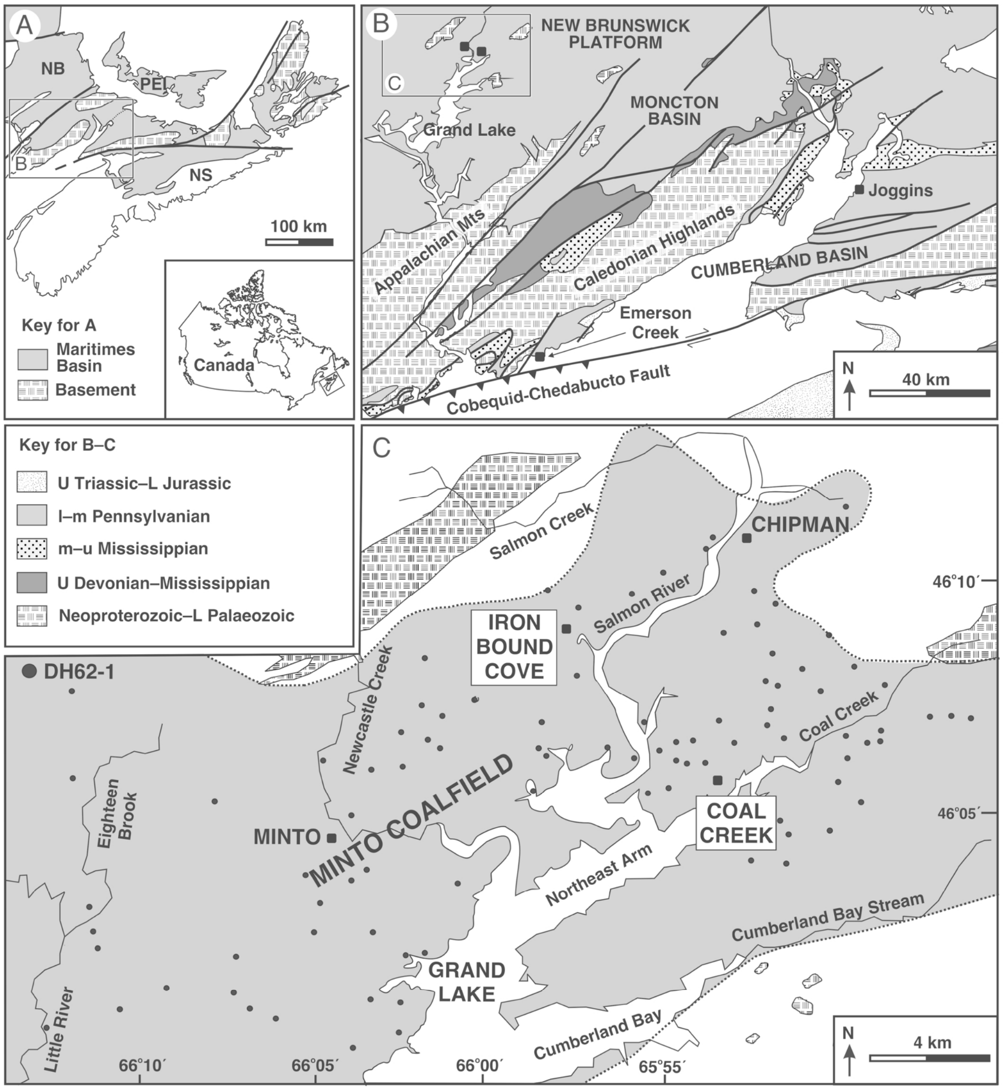

FIG. 1. Location and geological context of the fossil sites. A, The Late Paleozoic Maritimes Basin of Atlantic Canada, developed in the oblique convergence zone of Laurasia and Gondwana (modified from Gibling et al. 2008). Inset map gives location within Canada. B, Geology of southern New Brunswick and northwest Nova Scotia showing the fossil sites near Grand Lake, positioned on the stable craton, adjacent to the active Moncton and Cumberland basins (modified from Falcon-Lang et al. 2015a). Other Pennsylvanian sites with marine beds (Joggins, Emerson Creek) are also shown. C, Geology of the Pennsylvanian (early Moscovian) Minto Coalfield of New Brunswick (after Hacquebard and Barss 1970; Ball et al. 1981; St Peter 2000) showing the location of the two fossil sites, borehole DH62-1 illustrated in Fig. 4, and other boreholes (closed circles). Abbreviations: NB, New Brunswick; NS, Nova Scotia; PEI, Prince Edward Island.

178x193mm (300 x 300 DPI)

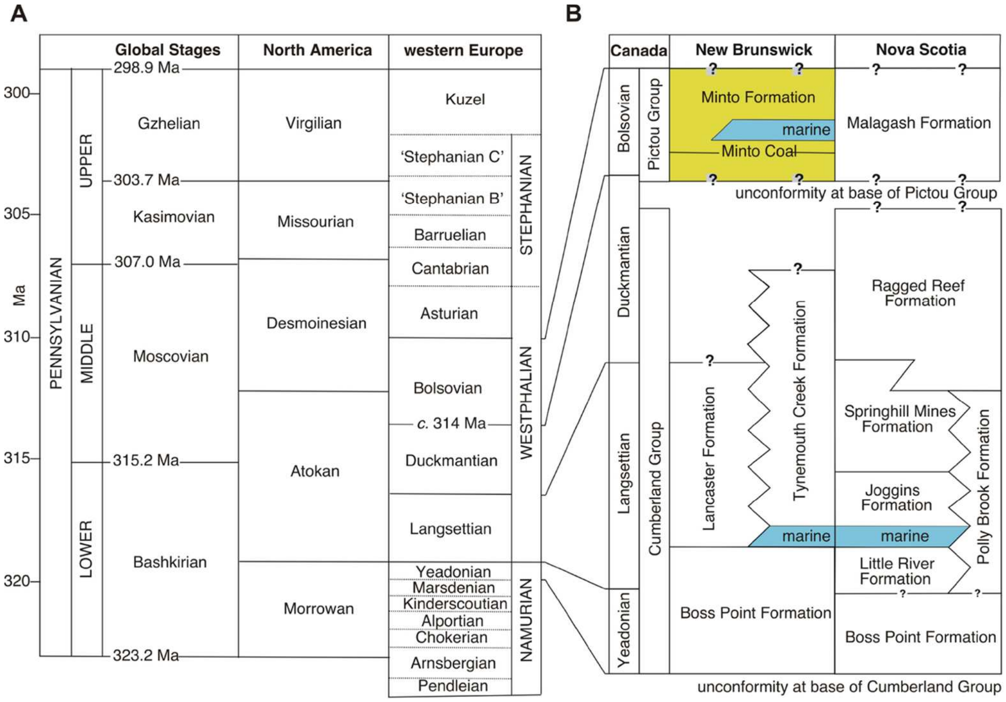

FIG. 2. Geochronology and stratigraphic context of the fossil sites. A, The Pennsylvanian Timescale (compiled from Peterson 2011; Waters and Condon 2012; Pointon et al. 2012; Richards 2013). B, Stratigraphy of the Pennsylvanian (Bashkirian) Cumberland Group and Pennsylvanian (Moscovian) Pictou Group of Atlantic Canada (modified from Gibling et al. 2008; Bashforth et al. 2014) showing the presence of Langsettian marine bands documented in the Joggins (Grey et al. 2011) and Tynemouth Creek (Falcon-Lang et al. 2015b) formations, and the new marine band (reported here) from the early to mid-Bolsovian part of the Minto Formation.
114x79mm (300 x 300 DPI)

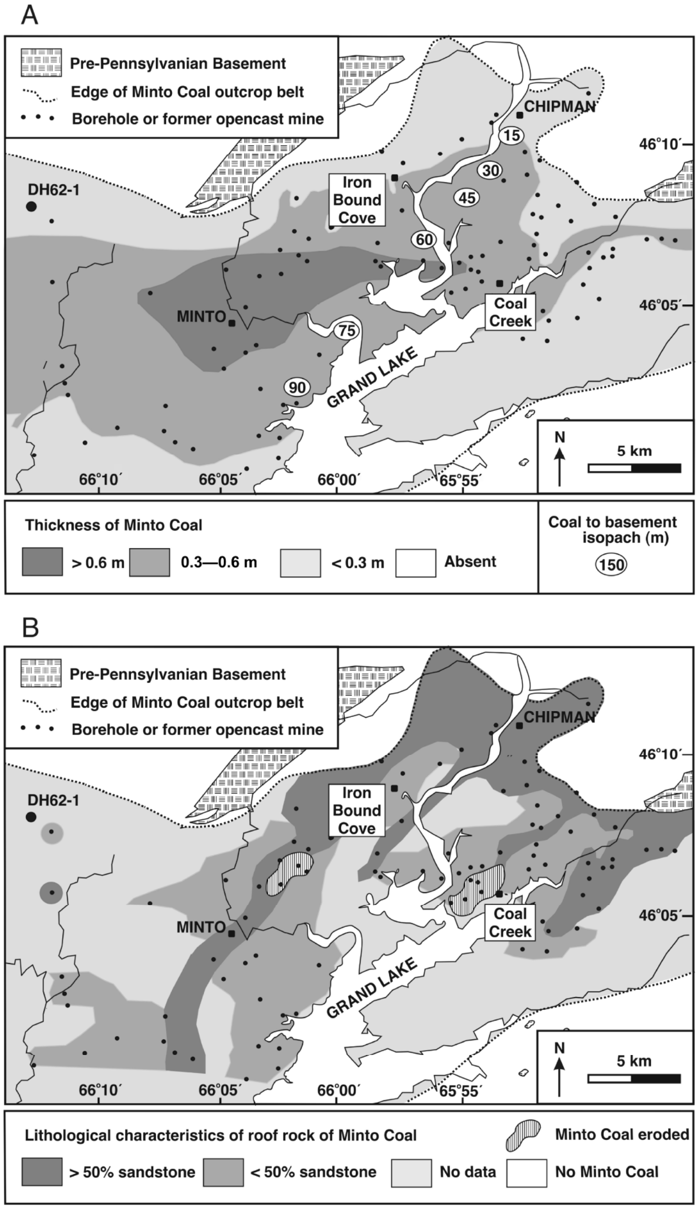

FIG. 3. Geology of the Pennsylvanian (early Bolsovian) Minto Coalfield (modified from Hacquebard and Barss 1970). A, Isopachytes for (i) the Minto Coal and (ii) coal to basement, the latter indicating onlap towards the northeast. B, Sandstone/mudstone ratio in the roof rock of the Minto Coal showing NE-SW trending drainage channels that, locally, 'wash out' the coal (i.e., areas where Minto Coal is eroded).
287x497mm (300 x 300 DPI)

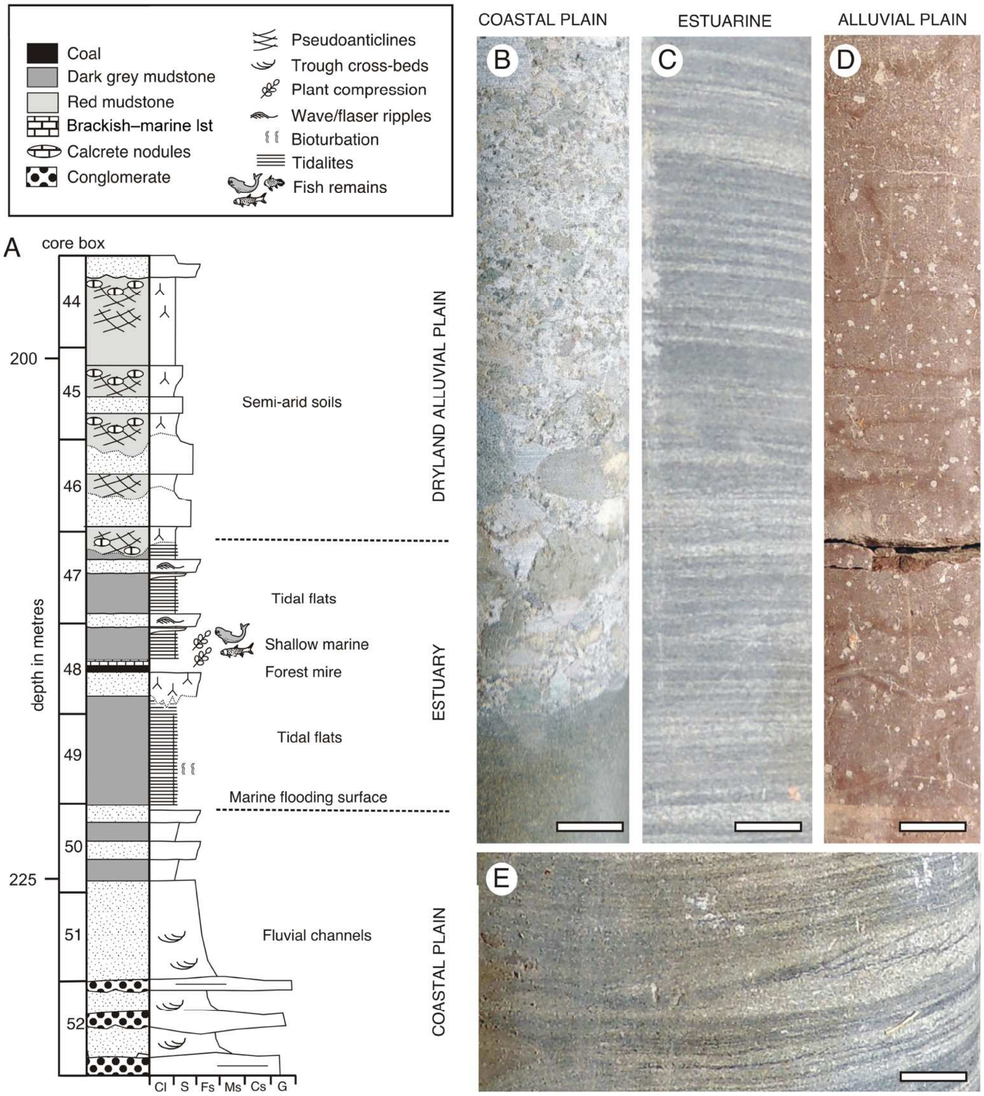

FIG. 4. Sedimentary context of the fossil sites based on borehole core DH62-1. A, Graphic log of a short section of borehole DH62-1 (core boxes 44–52; depth 196–231 m) illustrating the three units of the Minto Formation (see text for explanation). The Minto Coal is removed from the core and limestone beds are believed to represent a roof facies as seen in the Joggins Formation (Davies and Gibling 2003). B, Erosive-based fluvial channel conglomerate facies in lower unit. C, Pin-stripe lamination in estuarine facies in middle unit. D, Red mudrock with carbonate glaebules in upper unit. E, Close-up of paired mud-drapes in ripple cross-lamination in middle unit, a distinctive tidal indicator (cf. Naylor et al. 1998; Costain 2000). Scale bar is 30 mm (B–D), 4 mm (F).
185x208mm (300 x 300 DPI)

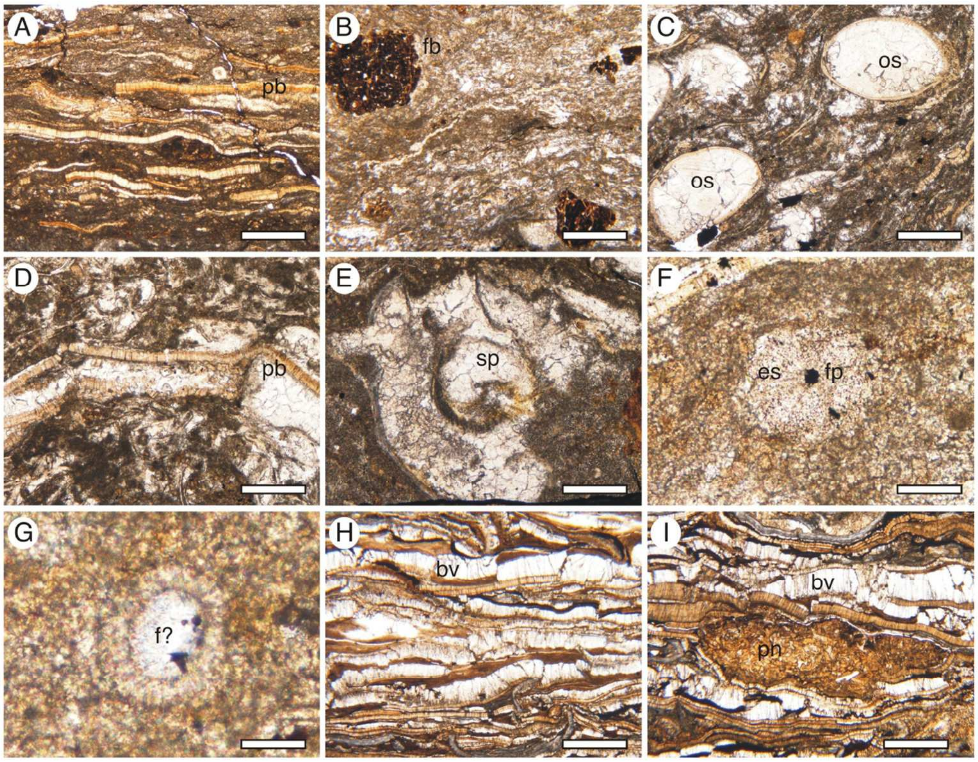

FIG. 5. Petrology of limestone Lithology 1 (shallow marine facies at Coal Creek: A–G, NBMG 18789) and Lithology 2 (brackish embayment facies at Iron Bound Cove: H–I, NBMG 18611). A, Punctate brachiopods. B, fish skeletal fragments. C, Ostracodes. D, Punctate brachiopods and possible sponge spicules. E, Spirorbiform microconchids. F, Echinoderm spine mineralised with framboidal pyrite. G, putative foraminifera. H, Bivalves. I. Bivalves and phosphatic (francolite) nodule possibly of fish origin. Abbreviations: bv, bivalve fragment; es, echinoid spines; f, foraminifera test; fb, fish skeletal fragments; fp, framboidal pyrite; os, ostracode carapace; pb, punctate brachiopods; pn, phosphatic nodule, sp, spirorbiform microconchids; Scale bar is 1 mm (A–D, H–I), 0.5 mm (E–F), 0.25 mm (G).
129x101mm (300 x 300 DPI)

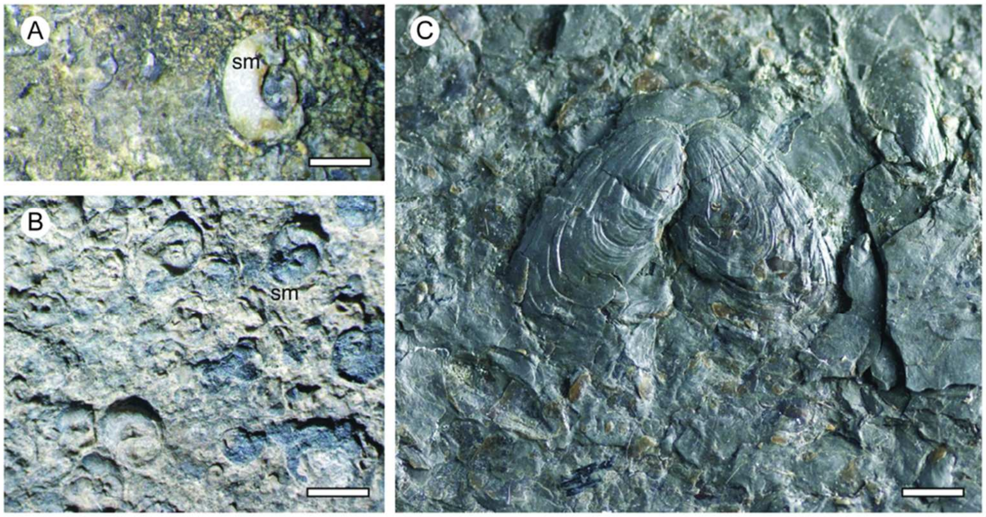

FIG. 6. Macroscopic invertebrates found in Lithology 2 (brackish embayment facies at Coal Creek). A, Spirorbiform microconchid, NBMG 15841. B, Abundant spirorbiform microconchids, NBMG 15815. C, Articulated Naiadites bivalves, NBMG 19967. Abbreviations: sm, spirorbiform microconchids. Scale bar is 1 mm (A), 1.5 mm (B), 5 mm (C).
87x45mm (300 x 300 DPI)

FIG. 7. Sedimentary and fossil characteristics of Lithology 3 (tidal estuary facies). A, Symmetrically-rippled siltstone to very fine-grained sandstone showing fish skeletal fragments concentrated within mud-rich ripple troughs. NBMG 15901 (specimen dissolved to extract fish fauna). B, Enlargement of area in (A) showing Orthacanthus tooth and macerated skeletal debris. Abbreviation: xt, xenacanthid tooth. Scale bar as indicated (ruler divided into 10 mm intervals) for A; 10 mm for B.
147x132mm (300 x 300 DPI)

FIG. 8. Tip heaps adjacent to the former opencast mine at Iron Bound Cove (flooded area on the right; Latitude 46°08.67’N; Longitude 65°58.10’W), illustrating how material was collected by ‘surface prospecting’.
56x41mm (300 x 300 DPI)

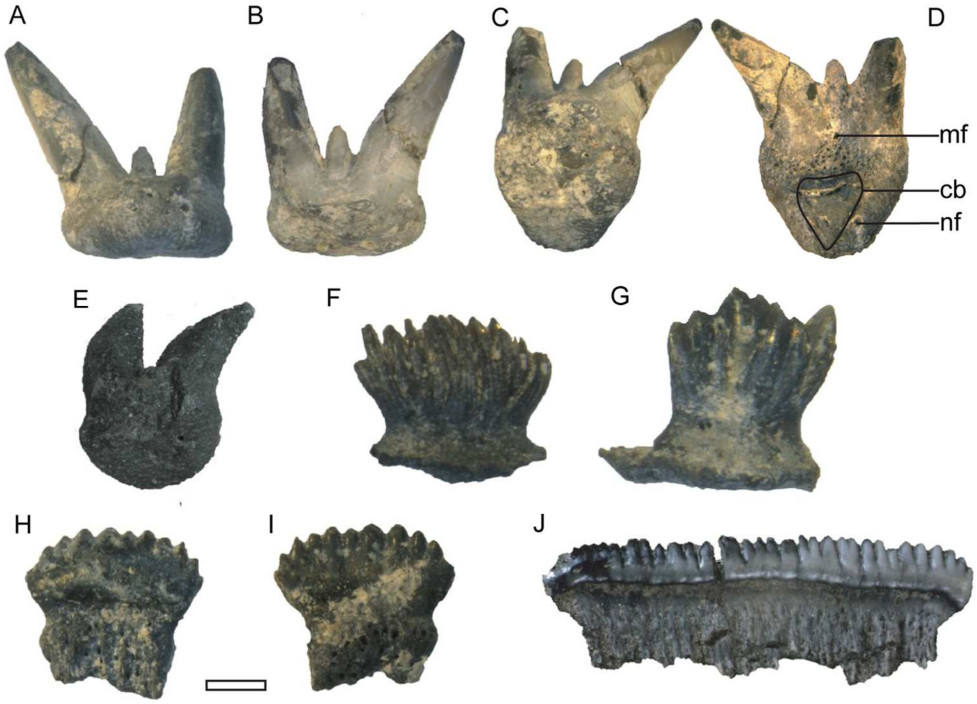

FIG. 9. Teeth of Chondrichthyans from the Minto Formation (Pennsylvanian) of New Brunswick, Canada. A–D, Tricuspid tooth of Orthacanthus compressus, NBMG 19617, in aboral (A), oral (B), dorso-aboral (C), and ventro-oral (D) views. E, Tooth of Xenacanth indet., NBMG 19629. F, Denticle of elasmobranch indet., NBMG 19667. G, Denticle of elasmobranch indet., NBMG 19647. H–J, Teeth of Ageleodus pectinatus: NBMG 19613 in aboral view (H), NBMG 19613 in oral view (I) and NBMG 15175 in aboral view (J). Abbreviations: cb, coronal button; nf, nutrient foramen; mf, median foramen. Scale bar is 2 mm (A–D), 1 mm (E), 0.25 mm (F–G), 0.5 mm (H–I), 2 mm (J).
119x86mm (300 x 300 DPI)

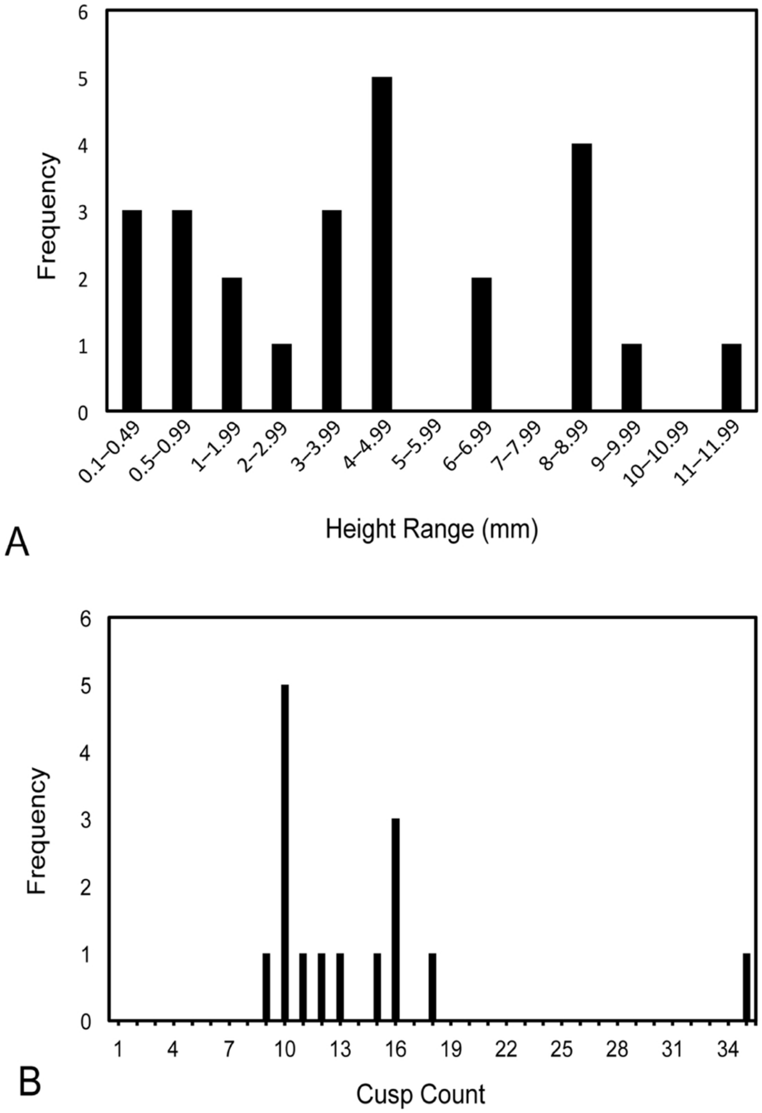

FIG. 10. Size ranges for Chondrichthyan teeth from the Minto Formation (Pennsylvanian), New Brunswick. A, Range of heights and frequencies for teeth of Orthacanthus. B, Cusp counts and frequencies for complete teeth of Ageleodus.
108x146mm (300 x 300 DPI)

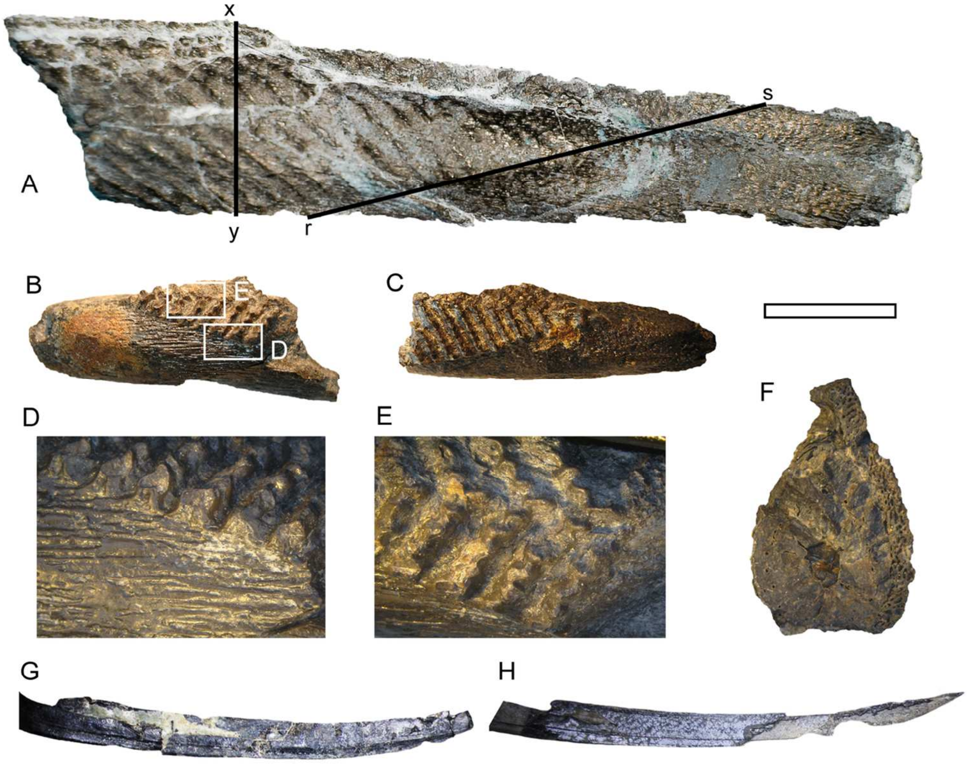

FIG. 11. Spines of the Acanthodians from the Minto Formation (Pennsylvanian) of New Brunswick, Canada. A–F, Gyracanthides sp., G–H, Acanthodes sp. A–C, spines in lateral view: NBMG 15173 (A), NBMG 10739/1 (B), with indications of location of close-ups D and E, and NBMG 10739/2 (C). D, Striae on the insertion area and the angle between the striae and the exsertion area, NBMG 10739/1. E, Chevron pattern in ornament ridges on the leading edge, NBMG 10739/2. F, cross-section of a spine, NBMG 10739/4. G, spine in lateral view, NMBG 15174. H, spine in lateral view, NBMG 15852. Line at r-s represents the insertion/exsertion boundary (IEB). Line at x-y represents a line perpendicular to the leading edge. Scale bar is 20 mm (B, C), 10 mm (A, G, and H), 2 mm (F), 1 mm (D and E).
130x103mm (300 x 300 DPI)

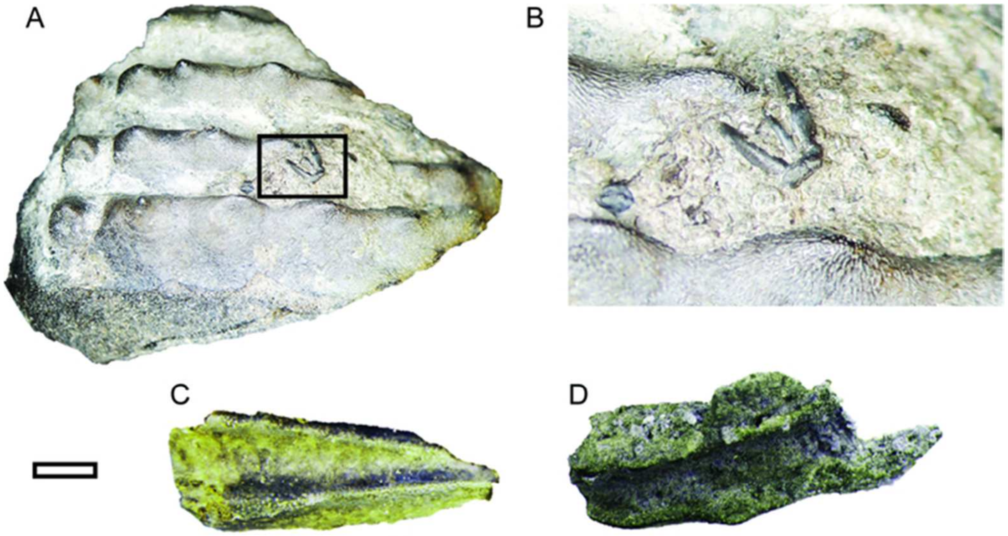

FIG. 12. Feeding plates of Dipnoans from the Minto Formation (Pennsylvanian) of New Brunswick, Canada. A–B, Feeding plate of Ctenodus interruptus, NBMG 10740 (A), with close-ups of isolated xenacanth teeth sitting on the surface (B). C–D, Fragments of the feeding plates of Dipnoi indet., NBMG 18609 showing convergent ridges (C), and NBMG 19699, showing differential apical elongations (D). Scale bar is 4 mm (A), 1 mm (B–D).

63x36mm (300 x 300 DPI)

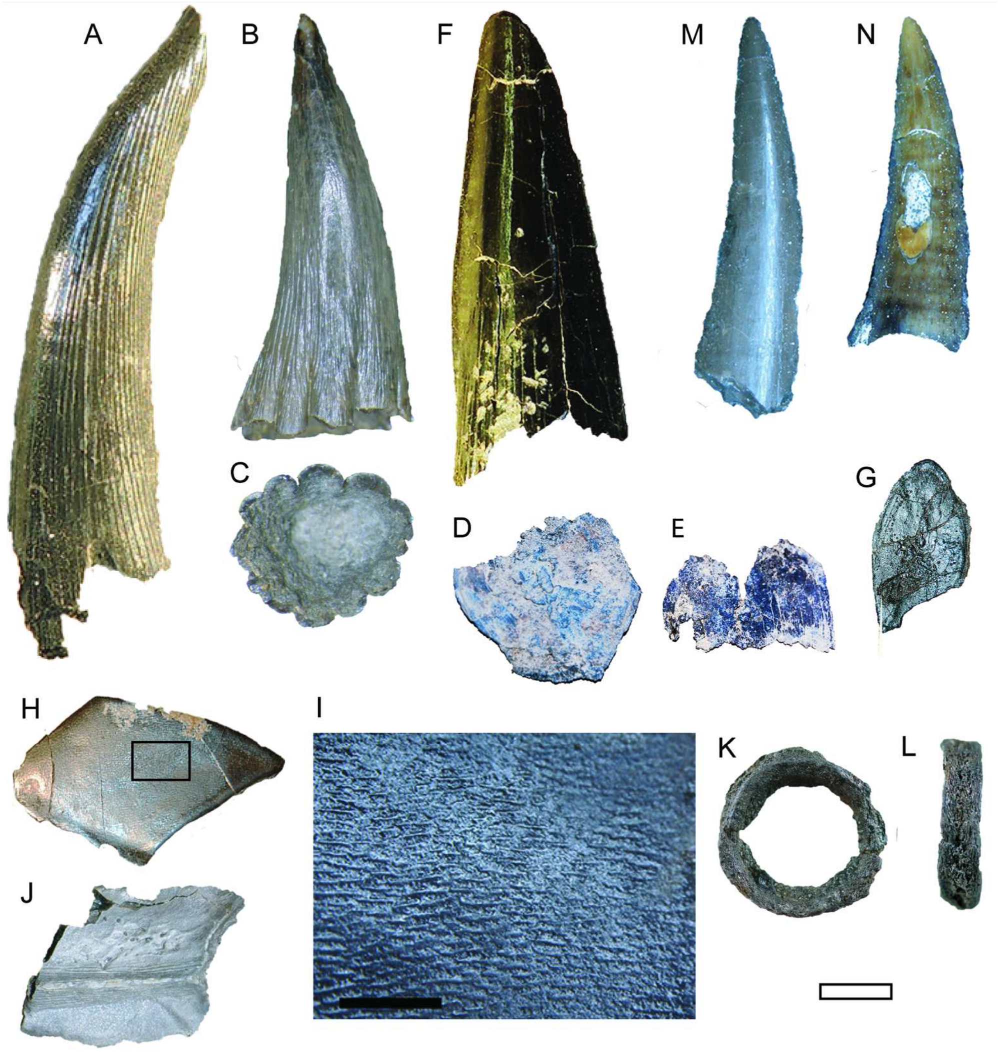

FIG. 13. Teeth and scales of Rhizodonts and Tetrapodomorphs from the Minto Formation (Pennsylvanian) of New Brunswick, Canada. A, Tooth of Strepsodus sauroides: NBMG 15820 in lateral view. B, C, Tooth of Archichthys portlocki, NBMG 19972, showing striations, in lateral view (B), and plication count on the base (C). D–E, Scales of cf. Archichthys portlocki, NBMG 19689 (D), NBMG 15831 (E). F, Tooth of cf. Rhizodus hibberti NBMG 15809. G, Scale of cf. Rhizodopsis sauroides NBMG 15901 showing the attachment side. H–J, Scales of Megalichthys indet.: NBMG 10741/1, showing the free field (H), and close-up image of the cosmine cover of the free field (I), and NBMG 19974a, showing the attached surface (J). K–L, Centrum of Megalichthys sp. NBMG 19958, in articular (K) and lateral (L) views. M–N, Teeth of Tetrapodomorpha indet., NBMG 10776 (M), and NBMG 10777 (N). Scale bar is 2 mm (A–C, M, and N); 20 mm (F), 10 mm (D–E, G, K, and L), 20 mm (H, J), separate 2 mm scale bar (I).
175x186mm (300 x 300 DPI)

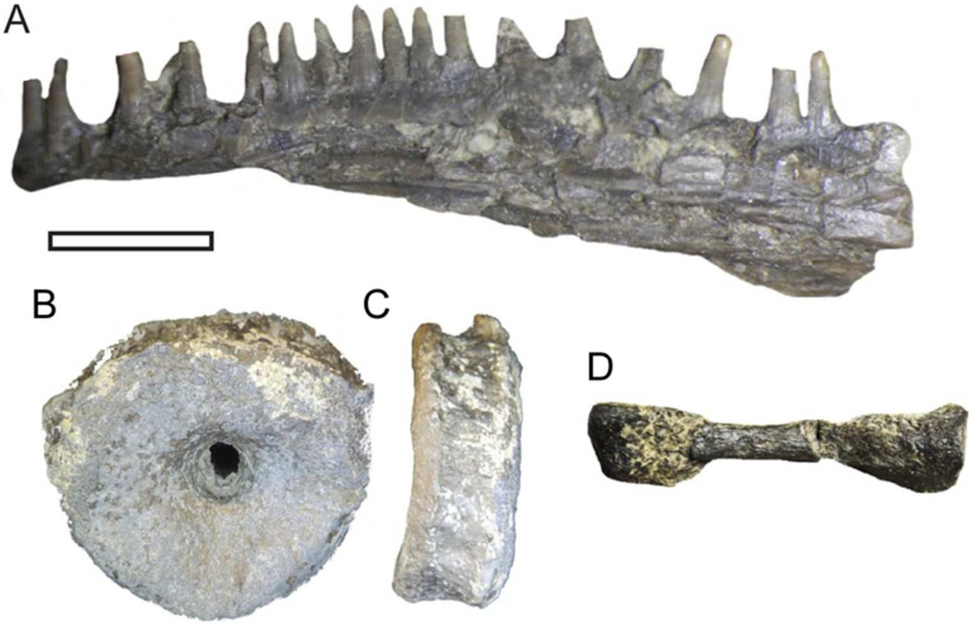

FIG. 14. Tetrapod remains, with provisional identifications. A, Small dentary of a possible ?colosteid bearing teeth, NBMG 15821. B, C, intecentrum of a possible embolomerous anthracosaur vertebra, in ?anterior (B) and lateral (C) views, NBMG 15783, and D, small tetrapod limb bone (NBMG 15915). Scale bar is 80 mm (A), 10 mm (B–C), 7.5 mm (D).
71x46mm (300 x 300 DPI)

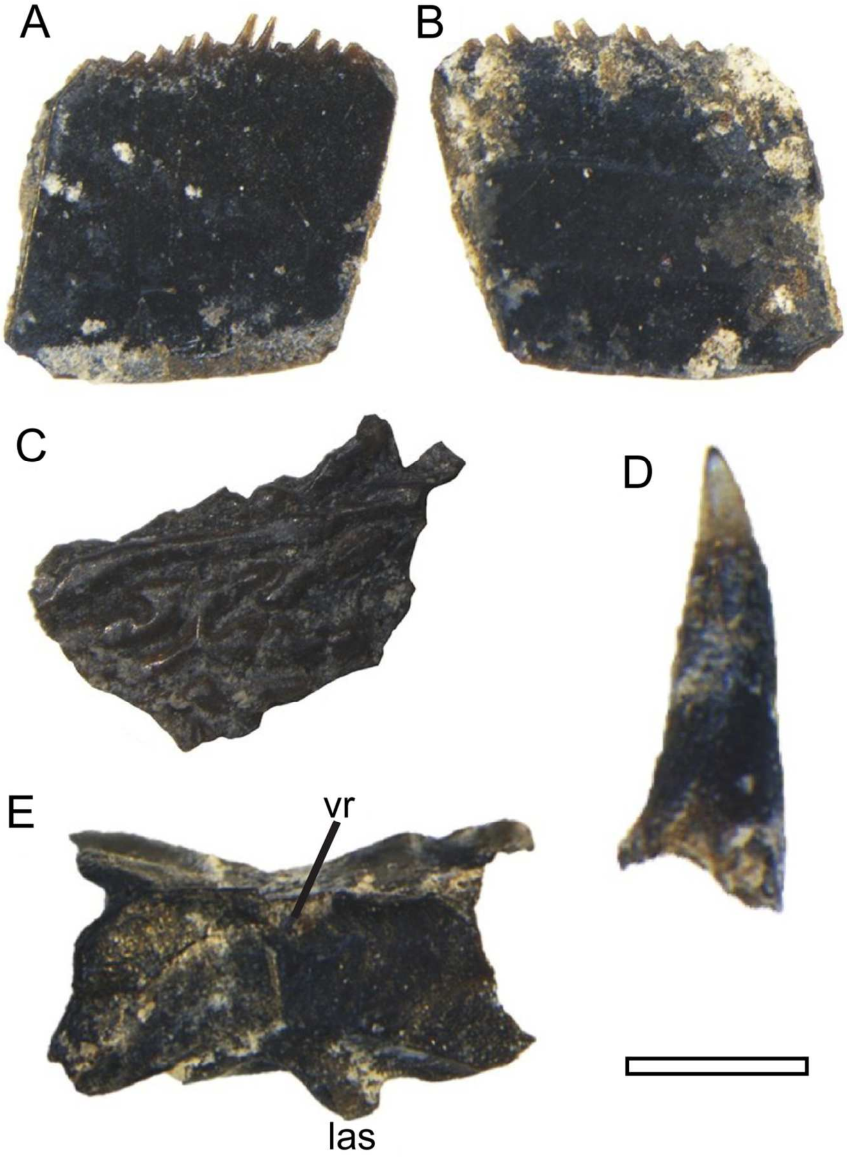

FIG. 15. Actinopterygian remains from the Minto Formation (Pennsylvanian) of New Brunswick, Canada. A, Eurynotiform, B – E, indeterminate actinopterygians. A, jaw fragment with five teeth, NBMG 20021. B–C, Scale, NBMG 19679/1 showing the free field (B), and the attached surface (C). D, Sculptured scale or dermal skull bone, NBMG 19804a. E, Tooth, NBMG 19684. F, Vertebra, NBMG 19686. Abbreviations: las, lateral attachment site; vr, ventral ridge. Scale bar is 0.4 mm (A, F), 0.5 mm (B–C, and E).
111x154mm (300 x 300 DPI)

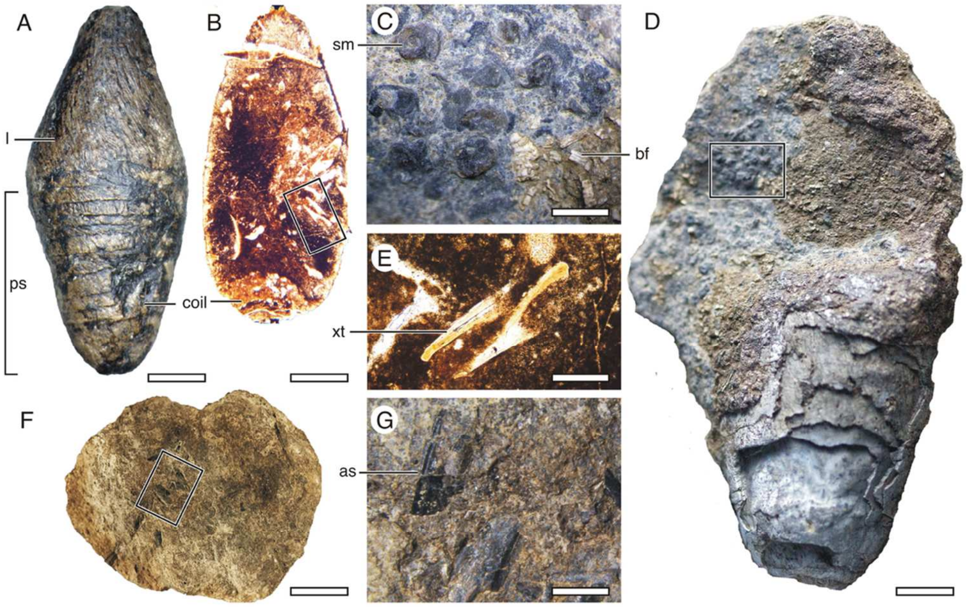

FIG. 16. Fish coprolites (bromalites). A, Heteropolar microspiral coprolite, NBMG 19979. showing coils and posterior spire. B, Thin section of heteropolar microspiral coprolite containing fish skeletal fragments including probable juvenile xenacanthid tooth (box: F), NBMG 18789. C, Large, short cylindrical coprolite composed of calcareous material (box: E), NBMG 20000. D, Rounded, bilobed coprolite (box: G), NBMG 19824. E, Expanded view of spirorbiform microconchids and bivalve fragments in coprolite shown (C), NBMG 20000. F, Expanded view of xenacanthid tooth in coprolite (B), NBMG 18789. G, Expanded view of rhizodont tooth and actinopterygian scale (D), NBMG 18789. Abbreviations: as, actinoptergian scale; bf, bivalve fragments; ps, posterior spiral; rt, rhizodont tooth; sm, spirorbiform microconchids; xt, xenacanthid tooth. Scale bars are 4 mm (A–B, D), 6 mm (C), 1.5 mm (E), 1 mm (F, G).
107x69mm (300 x 300 DPI)

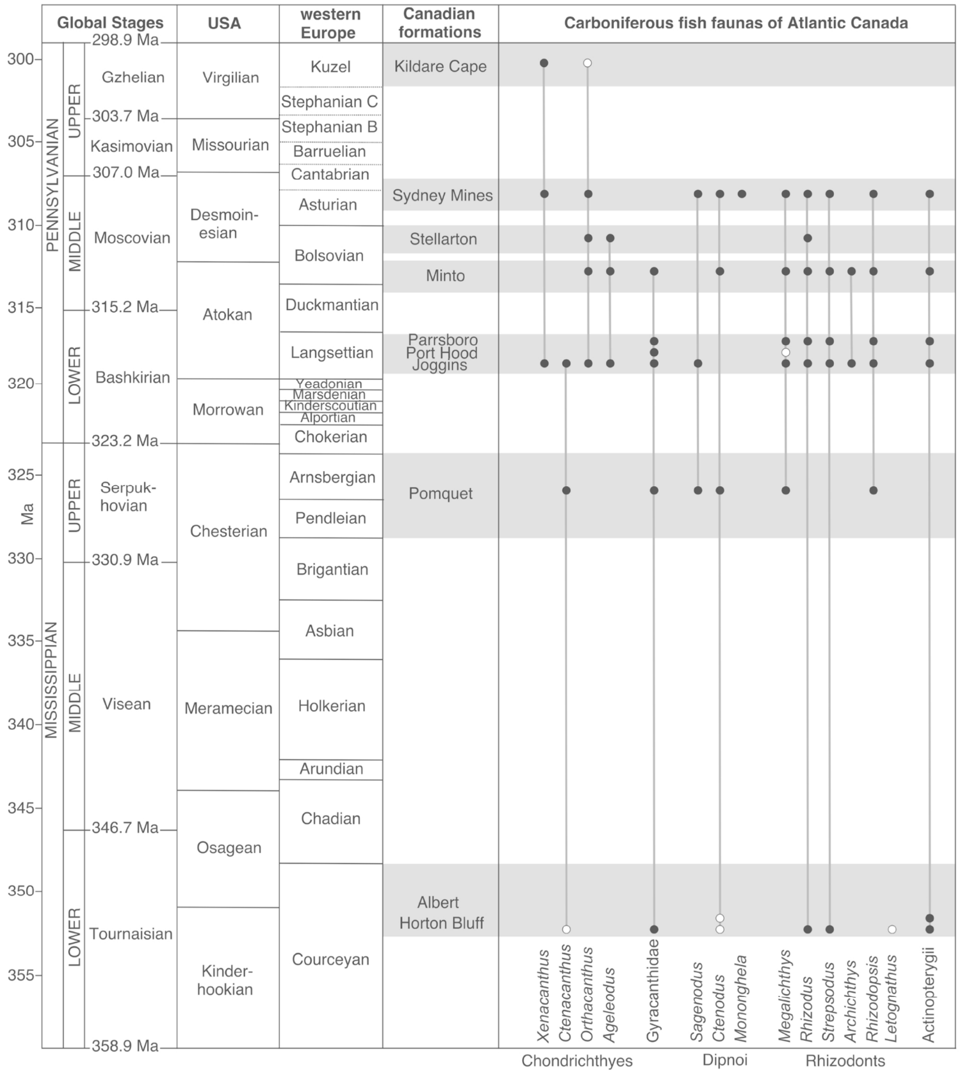

FIG. 17. Summary of 10 fish faunas from brackish-marine facies in the Carboniferous Maritimes Basin of Atlantic Canada. Carboniferous timescale based on critical synthesis of recent papers (Peterson 2011; Waters and Condon 2012; Pointon et al. 2012; Richards 2013) and age of key formations in the Maritimes Basin based on various sources (e.g., Calder 1998; Gibling et al. 2008 for discussion). Faunas based on illustrations in published records, revised in light of modern nomenclature. Principal sources for the compilation (Dawson 1868; Gardiner 1966; Carroll et al. 1972; Calder 1998) were supplemented by the following additional sources (Lambe 1910; Baird 1962, 1978; Greiner 1977; Johnson 1979, 1999; Miller and McGovern 1997; Turner et al. 2005; Brazeau 2005; Jeffrey 2006; Sues et al. 2013; Mansky and Lucas 2013; Carpenter et al. 2015; this paper; Yale Peabody Museum collections database: http://collections.peabody.yale.edu/search/).
185x207mm (300 x 300 DPI)

Class CHONDRICHTHYES
  Subclass ELASMOBRANCHII
    Superorder XENACANTHIMORPHA
      Order XENACANTHIFORMES
        Family DIPLODOSELACHIDAE
          Genus *ORTHACANTHUS*
            Orthacanthus compressus
      Order *incertae sedis*
        Family *incertae sedis*
          Genus *AGELEODUS*
            Ageleodus pectinatus
Class ACANTHODII Owen, 1846
      Order *incertae sedis*
        Family GYRACANTHIDAE
          Genus *GYRACANTHIDES*
            ***Gyracanthides* sp.**
      Order ACANTHODIDA
        Family ACANTHODIDAE
          Genus *ACANTHODES*
            ***Acanthodes* sp.**
Class OSTEICHTHYES
  Subclass SARCOPTERYGII
    Infraclass DIPNOMORPHA
      Order DIPNOI
        Family *incertae sedis*
          Genus *CTENODUS*
            Ctenodus interruptus
    Infraclass TETRAPODOMORPHA
      Order RHIZODONTIDA
        Family RHIZODONTIDAE
          Genus *STREPSODUS*
            Strepsodus sauroides
          Genus *ARCHICHTHYS*
            Archichthys portlocki
          Genus *RHIZODUS*
            cf. *Rhizodus hibberti*
      Order *incertae sedis*
        Family RHIZODOPSIDAE
          Genus *RHIZODOPSIS*
            cf. *Rhizodopsis sauroides*
      Order Sarcopterygii *incertae sedis*
        Family MEGALICHTHYIDAE
          Genus *MEGALICHTHYS*
            ***Megalichthys* sp.**
    Subclass ACTINOPTERYGII Cope, 1887
      Order EURYNOTIFORMES
            Actinopterygii indet.

Palaeoenvironment	**Number of specimens**	**Shallow marine**	**Brackish embayment**	**Brackish tidal estuary**	**All facies**
Lithology		1	2	3+4	
Orthacanthus compressus	71	25.0 %	39.2 %	53.3 %	39.2 %
Ageleodus pectinatus	67	18.8 %	44.8 %	23.3 %	37.0%
Chondrichthyes	**209**	**41.9 %**	**65.2 %**	**75.0 %**	**64.3 %**
Gyracanthides sp.	3	6.3 %	1.5 %	0.0 %	1.6 %
Acanthodes sp.	4	0.0 %	1.5 %	0.0 %	1.6 %
Acanthodians	**17**	**3.2 %**	**6.4 %**	**0.0 %**	**5.2 %**
Ctenodus interruptus	2	6.3 %	0.8 %	0.0 %	1.0 %
Archichthys portlocki	5	6.3 %	1.5 %	0.0 %	2.8 %
Strepsodus sauroides	9	6.3 %	5.4 %	3.3 %	5.0 %
cf. *Rhizodus hibberti*	16	6.3 %	5.4 %	16.7 %	8.8 %
cf. *Rhizodopsis sauroides*	1	0.0 %	0.0 %	3.3 %	0.6 %
Megalichthys sp.	5	25.0 %	0.8 %	0.0 %	2.8 %
Sarcopterygians	**59**	**48.4 %**	**13.6 %**	**20.5 %**	**17.8 %**
Actinopterygians	**26**	**6.5 %**	**8.8 %**	**4.5 %**	**8.0 %**
Tetrapods	**15**	**0%**	**6.0%**	**0%**	**4.6%**
1- H for genera		**0.805**	**0.641**	**0.428**	

NBMG Numl	**Class**	**Identification**	**Number of s**	**Material ext**
9948	Chondrichthyes	*Orthacanthu* s cf. *compressu*	1	
9968	Sarcopterygian	Tetrapodomorpha indet. too	1	
9969	Sarcopterygian	*Strepsodus sauroides*	1	
9973	Chondrichthyes	*Ageleodus pectinatus*	1	9973b
10739	Acanthodian	*Gyracanthides* sp.	11	
10740	Sarcopterygian	*Ctenodus interruptus* + xen	2	
10741.1	Sarcopterygian	*Megalichthyes* sp.	3	
10741.2	Sarcopterygian	*Megalichthyes* sp.	4	
10746	Chondrichthyes	*Orthacanthus compressus*	1	
10747	Chondrichthyes	*Orthacanthus compressus*	1	
10748	Chondrichthyes	*Orthacanthus compressus*	1	
10757	Chondrichthyes	*Orthacanthus compressus*	1	
10761	Chondrichthyes	cf. Elasmobranch indet.	1	
10776	Sarcopterygian	Tetrapodomorpha indet. too	1	
10777	Sarcopterygian	Tetrapodomorpha indet. too	1	
10783	Sarcopterygian	Tetrapodomorpha indet. too	1	
10785	Sarcopterygian	Tetrapodomorpha indet. too	1	
10798	Unknown	Unknown	1	
10800	Chondrichthyes	*Ageleodus pectinatus*	1	
12067	Chondrichthyes	*Ageleodus pectinatus*	1	
14953	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14954	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14955	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14956	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14957	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14958	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14959	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14960	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14961	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14962	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14963	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14964	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14965.1	Chondrichthyes	*Ageleodus pectinatus*	1	
14965.2	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14966	Chondrichthyes	Xenacanthiformes indet.	1	
14967	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14968	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
14969	Chondrichthyes	*Ageleodus pectinatus*	1	
14970	Chondrichthyes	*Ageleodus pectinatus*	1	
14971	Chondrichthyes	*Ageleodus pectinatus*	1	
14972	Chondrichthyes	*Ageleodus pectinatus*	1	
14973	Chondrichthyes	*Ageleodus pectinatus*	1	
14974	Chondrichthyes	*Ageleodus pectinatus*	1	
14975	Chondrichthyes	*Ageleodus pectinatus*	1	
14976	Chondrichthyes	*Ageleodus pectinatus*	1	
14977	Chondrichthyes	*Ageleodus pectinatus*	1	
14978	Chondrichthyes	*Ageleodus pectinatus*	1	
14979	Chondrichthyes	*Ageleodus pectinatus*	1	
14980	Chondrichthyes	*Ageleodus pectinatus*	1	

14981	Chondrichthyes	*Ageleodus pectinatus*	1
14982	Chondrichthyes	*Ageleodus pectinatus*	1
14983	Chondrichthyes	*Orthacanthus* cf. *compressu*	1
14984	Chondrichthyes	*Orthacanthus compressus*	1
14985	Chondrichthyes	*xenacanthiformes indet.*	1
14986	Chondrichthyes	Xenacanthiformes indet.	1
14987	Chondrichthyes	Xenacanthiformes indet.	1
14991	Chondrichthyes	*Orthacanthus compressus*	1
14992	Chondrichthyes	*Orthacanthus compressus*	1
14993	Chondrichthyes	*Orthacanthus* cf. *compressu*	1
14994	Chondrichthyes	Xenacanthiformes cf. Xenaca	1
14995	Chondrichthyes	*Ageleodus pectinatus*	1
14996	Chondrichthyes	*Orthacanthus* cf. *compressu*	1
14997	Chondrichthyes	*Ageleodus pectinatus*	1
14998	Chondrichthyes	*Ageleodus pectinatus*	1
14999.1	Chondrichthyes	*Ageleodus pectinatus*	1
14999.2	Chondrichthyes	*Ageleodus pectinatus*	1
15000	Chondrichthyes	*Ageleodus pectinatus*	1
15001	Chondrichthyes	Ageleodus cf. *pectinatus*	1
15002	Chondrichthyes	*Ageleodus pectinatus*	1
15003	Chondrichthyes	*Ageleodus pectinatus*	1
15004	Chondrichthyes	Ageleodus cf. *pectinatus*	1
15005	Sarcopterygian	cf. *Strepsodus sauroides*	1
15007	Sarcopterygian	cf. *Strepsodus sauroides*	1
15173	Acanthodian	*Gyracanthides* sp.	1
15174	Acanthodian	*Acanthodes* sp. spine	1
15175	Chondrichthyes	*Ageleodus pectinatus*	1
15786	Unknown	Coprolite	2
15787	Sarcopterygian	cf. *Rhizodus hibberti*	1
15788	Sarcopterygian	cf. *Strepsodus sauroides*	1
15789	Sarcopterygian	cf. *Rhizodus hibberti*	1
15790	Sarcopterygian	cf. *Rhizodus hibberti*	1
15791	Sarcopterygian	cf. *Rhizodus hibberti*	1
15794	Sarcopterygian	cf. *Megalichthys*	1
15795	Sarcopterygian	cf. *Rhizodus hibberti*	1
15798	Sarcopterygian	cf. *Rhizodus hibberti*	1
15799	Sarcopterygian	cf Archichthys portlocki	1
15806	Chondrichthyes	*Ageleodus pectinatus*	1
15809	Sarcopterygian	zodontidae cf. *Rhizodus hibb*	1
15810	Sarcopterygian	cf. *Rhizodus hibberti*	1
15812	Sarcopterygian	cf. *Rhizodus hibberti*	1
15813	Sarcopterygian	cf. *Rhizodus hibberti*	1
15815	Sarcopterygian	cf. *Strepsodus sauroides*	1
15816	Sarcopterygian	cf. *Rhizodus hibberti*	1
15817	Sarcopterygian	cf. *Rhizodus hibberti*	1
15818	Sarcopterygian	cf. *Archichthys portlocki*	1
15820	Sarcopterygian	*Strepsodus sauroides*	1
15821	Tetrapoda	jaw	
15822	Sarcopterygian	*Ctenodus interruptus,* Acant	2
15823	Chondrichthyes	*Orthacanthus* cf. *compressu*	1

15824	Unknown	Bone/spine fragments	4	15855, 1589
15825	Chondrichthyes	*Orthacanthus compressus*	1	15904, 1582
15826	Acanthodian	*Gyracanthides* sp. spine	1	
15829	Sarcopterygian	cf. *Strepsodus sauroides*	1	
15830	Sarcopterygian	cf. *Strepsodus sauroides*	1	
15831	Sarcopterygian	Tetrapodomorpha indet. cf.	1	15904, 1582
15832	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
15833	Chondrichthyes,	*Orthacanthus compressus,*	1	
15834	Chondrichthyes	*Orthacanthus compressus*	1	
15835	Chondrichthyes,	Xenacanthiformes indet., Ac	1	
15836	Chondrichthyes	*Orthacanthus compressus*	1	
15837	Chondrichthyes	Xenacanthiformes indet.	1	
15838.1	Chondrichthyes,	*Ageleodus pectinatus,* Acan	1	
15838.2	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
15838.3	Chondrichthyes	Xenacanthiformes indet.	1	
15838.4	Chondrichthyes	*Ageleodus pectinatus*	1	
15841	Chondrichthyes	*Orthacanthus compressus*	1	
15842	Chondrichthyes	Xenacanthiformes indet.	1	
15843	Chondrichthyes	*Orthacanthus compressus*	1	
15844	Acanthodian	Acanthodidae indet.	1	
15846	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
15847	Chondrichthyes	*Orthacanthus compressus*	1	
15848	Chondrichthyes	Xenacanthiformes indet.	1	
15849	Chondrichthyes	*Orthacanthus compressus*	1	
15852	Acanthodian	Acanthodidae indet.	1	
15855	Unknown	Bone fragments	1	
15858	Chondrichthyes	*Ageleodus pectinatus*	1	
15859	Chondrichthyes	*Ageleodus pectinatus*	1	
15860	Chondrichthyes	*Ageleodus pectinatus*	1	
15861	Chondrichthyes	*Ageleodus pectinatus?*	1	
15862	Sarcopterygian	cf. *Rhizodus hibberti*	1	
15863	Chondrichthyes	*Ageleodus pectinatus*	1	
15864	Unknown	Scale fragments	1	
15866	Sarcopterygian	cf. *Rhizodus hibberti*	1	
15868	Chondrichthyes	*Ageleodus pectinatus*	1	
15869	Acanthodian	Acanthodidae indet.	1	
15872	Tetrapoda	Jaw	1	
15873	Acanthodian	Acanthodidae indet. Spine	2	
15890	Chondrichthyes	*Ageleodus pectinatus*	1	
15891	Chondrichthyes	*Ageleodus pectinatus*	1	
15892	Chondrichthyes	*Ageleodus pectinatus*	1	
15893	Chondrichthyes	*Ageleodus pectinatus*	1	
15894	Unknown	Bone fragments	2	
15895	Chondrichthyes	*Ageleodus pectinatus*	1	
15897	Chondrichthyes	*Ageleodus pectinatus*	1	
15898	Chondrichthyes	*Ageleodus pectinatus*	1	
15899	Chondrichthyes	*Ageleodus pectinatus*	1	
15900	Chondrichthyes	*Ageleodus pectinatus*	1	
15901	Sarcopterygian	cf. *Rhizodopsis sauroides*	1	

15902	Chondrichthyes	*Orthacanthus* cf. *compressu*	1	
15903	Chondrichthyes	*Orthacanthus compressus*	1	
15904	Unknown	Bone Fragments	1	
15905	Chondrichthyes	*Orthacanthus compressus*	1	
15906	Chondrichthyes	*Orthacanthus compressus*	1	
15907	Chondrichthyes	*Orthacanthus compressus*	1	
15908	Chondrichthyes	*Orthacanthus compressus*	1	
15909	Chondrichthyes	*Orthacanthus compressus*	1	
15910	Chondrichthyes	*Orthacanthus compressus*	1	
15913	Acanthodian	Acanthodidae indet. Spine	1	
15916	Chondrichthyes	*Orthacanthus compressus*	1	
16070	Chondrichthyes	*Ageleodus pectinatus*	1	
16071	Chondrichthyes	*Ageleodus pectinatus*	1	
16072	Chondrichthyes	*Ageleodus pectinatus*	1	
16074	Sarcopterygian	cf. *Rhizodus hibberti*	1	
16082	Chondrichthyes,	Xenacanthiformes indet., Ac	1	
16087	Chondrichthye	Elasmobranchii indet.	1	
16088	Chondrichthyes	*Orthacanthus compressus*	1	
16089	Chondrichthyes	Xenacanthiformes indet.	1	
16090	Chondrichthyes	*Orthacanthus compressus*	1	
16093.1	Chondrichthyes	*Orthacanthus compressus*	1	
16093.2	Chondrichthyes	*Orthacanthus compressus*	1	
16094	Acanthodian	Acanthodidae indet. Spine	1	
16095.1	Chondrichthyes,	*Ageleodus pectinatus, Acant*	1	
16095.2	Chondrichthyes	*Orthacanthus compressus*	1	
18608	Actinopterygian	Actinopterygii scale	1	18608
18609	Sarcopterygian	Dipnoi indet.	1	18609
18613	Chondrichthyes	Xenacanthiformes indet.	1	
19599	Chondrichthyes	Scales (2) and *Ageleodus pe*	3	
19600	Chondrichthyes	*Ageleodus pectinatus*	1	
19601	Chondrichthyes	*Ageleodus pectinatus*	1	
19602	Chondrichthyes	*Ageleodus pectinatus*	2	
19603	Chondrichthyes	*Ageleodus pectinatus*	1	
19604	Chondrichthyes	*Ageleodus pectinatus*	1	15834, 1498
19605	Chondrichthyes	*Ageleodus pectinatus*	2	15855, 1589
19606	Chondrichthyes	*Ageleodus pectinatus*	1	
19607	Chondrichthyes	*Ageleodus pectinatus*	1	
19608	Chondrichthyes	*Ageleodus pectinatus*	1	
19609	Chondrichthyes	*Ageleodus pectinatus*	1	
19610	Chondrichthyes	*Ageleodus pectinatus*	1	
19611	Chondrichthyes	*Ageleodus pectinatus*	1	
19612	Chondrichthyes	*Ageleodus pectinatus*	4	15901
19613	Chondrichthyes	*Ageleodus pectinatus*	2	15901
19614	Chondrichthyes	*Orthacanthus compressus*	1	
19615	Chondrichthyes	*Orthacanthus compressus*	3	
19616	Chondrichthyes	*Orthacanthus compressus*	1	15834, 1498
19617	Chondrichthyes	*Orthacanthus compressus*	1	15904, 1582
19618	Chondrichthyes	*Orthacanthus compressus*	1	
19619	Chondrichthyes	*Orthacanthus compressus*	1	

19620	Chondrichthyes	*Orthacanthus compressus*	1	
19621	Chondrichthyes	*Orthacanthus compressus*	1	
19622	Chondrichthyes	*Orthacanthus compressus*	1	15901
19623	Chondrichthyes	*Orthacanthus compressus*	2	15901
19624	Chondrichthyes	*Orthacanthus compressus*	2	15901
19625	Chondrichthyes	*Orthacanthus compressus*	1	15901
19626	Chondrichthyes	*Orthacanthus compressus*	1	
19627	Chondrichthyes	Broken xenacanth cusps	6	
19628	Chondrichthyes	Xenacanthiformes indet.	4	
19629	Chondrichthyes	Xenacanthiformes indet.	1	15834, 1498
19630	Chondrichthyes	Xenacanthiformes indet.	1	15834, 1498
19631	Chondrichthyes	Xenacanthiformes indet.	1	
19632	Chondrichthyes	Xenacanthiformes indet.	2	
19633	Chondrichthyes	Xenacanthiformes indet.	1	
19634	Chondrichthyes	Xenacanthiformes indet.	1	
19635	Chondrichthyes	Xenacanthiformes indet.	1	
19636	Chondrichthyes	Xenacanthiformes indet.	1	
19637	Chondrichthyes	Xenacanthiformes indet.	1	15901
19638	Chondrichthyes	Xenacanthiformes indet.	2	15901
19639	Chondrichthyes	Xenacanthiformes indet.	1	15901
19640	Chondrichthyes	Xenacanthiformes indet.	1	15901
19641	Chondrichthyes	Xenacanthiformes indet.	1	15901
19642	Chondrichthyes	Xenacanthiformes indet.	1	15901
19643	Chondrichthyes	Xenacanthiformes indet.	1	
19644	Chondrichthyes	Xenacanthiformes indet.	1	
19645	Chondrichthyes	Xenacanthiformes indet.	1	
19646	Chondrichthyes	Elasmobranchii indet.	80	
19647	Chondrichthyes	Elasmobranchii indet.	112	
19648	Chondrichthyes	Elasmobranchii indet.	30	
19649	Chondrichthyes	Elasmobranchii indet.	2	
19650	Chondrichthyes	Elasmobranchii indet.	4	
19651	Chondrichthyes	Elasmobranchii indet.	7	
19652	Chondrichthyes	Elasmobranchii indet.	67	
19653	Chondrichthyes	Elasmobranchii indet.	7	
19654	Chondrichthyes	Elasmobranchii indet.	20	
19655	Chondrichthyes	Elasmobranchii indet.	27	
19656	Chondrichthyes	Elasmobranchii indet.	40	
19657	Chondrichthyes	Elasmobranchii indet.	15	
19658	Chondrichthyes	Elasmobranchii indet.	2	
19659	Chondrichthyes	Elasmobranchii indet.	3	15834, 1498
19660	Chondrichthyes	Elasmobranchii indet.	26	
19661	Chondrichthyes	Elasmobranchii indet.	2	
19662	Chondrichthyes	Elasmobranchii indet.	2	
19663	Chondrichthyes	Elasmobranchii indet.	1	
19664	Chondrichthyes	Elasmobranchii indet.	1	
19665	Chondrichthyes	Elasmobranchii indet.	1	
19666	Chondrichthyes	Elasmobranchii indet.	1	15901
19667	Chondrichthyes	Elasmobranchii indet.	21	15901
19668	Chondrichthyes	Elasmobranchii indet.	7	15901
19669	Chondrichthyes	Elasmobranchii indet.	12	15901

19670	Chondrichthyes	Elasmobranchii indet.	2	
19671	Chondrichthyes	Elasmobranchii indet.	2	
19672	Chondrichthyes	Elasmobranchii indet.	3	
19673	Chondrichthyes	Elasmobranchii indet.	30	
19674	Chondrichthyes	Elasmobranchii indet.	32	
19675	Chondrichthyes	Elasmobranchii indet.	3	
19676	Chondrichthyes	Elasmobranchii indet.	20	
19677	Chondrichthyes	Elasmobranchii indet.	25	15901
19678	Actinopterygian	Actinopterygii scale	6	
19679	Actinopterygian	Actinopterygii scale	6	
19680	Actinopterygian	Actinopterygii scale	1	
19681	Actinopterygian	Actinopterygii scale	6	
19682	Actinopterygian	Actinopterygii scale	3	
19683	Actinopterygian	Actinopterygii scale	1	
19684	Actinopterygian	Actinopterygii tooth	1	
19685	Actinopterygian	Actinopterygii vertebrate	1	
19686	Actinopterygian	Actinopterygii vertebrate	1	
19687	Actinopterygian	Actinopterygii vertebrate	1	15834, 1498
19688	Sarcopterygian	*Strepsodus sauroides*	1	
19689	Sarcopterygian	Tetrapodomorpha indet. cf.	1	15904, 1582
19690	Unknown	Broken cusp	1	15855, 1589
19691	Sarcopterygian	Tetrapodomorpha indet. sca	1	
19692	Sarcopterygian	Tetrapodomorpha indet. sca	1	
19693	Sarcopterygian	Tetrapodomorpha indet. bor	1	
19694	Sarcopterygian	Tetrapodomorpha indet. sca	1	
19695	Sarcopterygian	Tetrapodomorpha indet. sca	1	
19696	Sarcopterygian	Tetrapodomorph indet. toot	1	
19697	Sarcopterygian	Tetrapodomorph indet. toot	1	
19698	Sarcopterygian	Dipnoi indet.	1	
19699	Sarcopterygian	Dipnoi indet.	1	
19700	Sarcopterygian	Dipnoi indet.	1	19700
19701	Sarcopterygian	Dipnoi indet.	1	
19702	Unknown	Jaw bones and teeth	3	
19703	Unknown	Jaw bones and teeth	6	15901
19704	Unknown	Cusp	1	
19705	Unknown	Tooth	4	
19706	Unknown	Single cusps	11	
19707	Unknown	Cusps	5	
19708	Unknown	Cusps	2	
19709	Unknown	Teeth	4	
19710	Unknown	Cusps	1	
19711	Unknown	Bone fragments	10	
19712	Unknown	Cusps	1	
19713	Unknown	Cusps	4	
19714	Unknown	Cusps	5	
19715	Unknown	Cusps	3	
19716	Unknown	Tooth cusps	4	
19717	Chondrichthyes	cf. *Ageleodus pectinatus*	2	
19718	Unknown	Double cusped teeth	2	
19719	Unknown	Two cusped denticles	2	

19720	Unknown	Tooth cusps	2	
19721	Unknown	Tooth cusps	1	
19722	Unknown	Tooth cusps	3	
19723	Unknown	Tooth cusps	6	
19724	Unknown	Tooth cusps	5	
19725	Unknown	Curved cusps	3	
19726	Unknown	Single teeth	6	15901
19727	Unknown	Single teeth	2	15901
19728	Unknown	Cusps	4	15901
19729	Unknown	Tooth cusps	6	15901
19730	Chondrichthyes	Xenacanth like cusp	1	19730
19731	Sarcopterygian	Limb bone cf. tetrapodomor	1	
19732	Unknown	Bone fragments	1	
19733	Unknown	Bone fragments	25	
19734	Unknown	Spines/bones	30	
19735	Unknown	Spine in matrix	1	
19736	Unknown	Sperical bones with hollow c	6	
19737	Unknown	Bones with extended bases	4	
19738	Unknown	bones/spines with canals	10	
19739	Unknown	Bone fragments	43	
19740	Unknown	Spines	8	
19741	Unknown	Bone fragment	1	
19742	Unknown	Spines/bones	3	
19743	Unknown	Spines	5	
19744	Unknown	Spine/bone	1	
19745	Unknown	Spine/bone	1	
19746	Unknown	Spine/bone	1	
19747	Unknown	Bones/spines	43	
19748	Unknown	Bone fragments	2	
19749	Unknown	Bone fragments	6	
19750	Unknown	Bone fragments	20	
19751	Unknown	Bone fragments	1	15834, 1498
19752	Unknown	Bone fragments	1	
19753	Unknown	Bone fragment	3	
19754	Unknown	Bone fragments	1	
19755	Unknown	Bone fragments	2	
19756	Unknown	Bone fragments	20	15901
19757	Unknown	Bone fragments	10	15901
19758	Unknown	Bone with extended base	2	
19759	Unknown	bones with expanded bases	4	
19760	Unknown	Bones with expanded base	22	15901
19761	Unknown	Two fused bones	1	
19762	Unknown	Bone fragments	6	
19763	Unknown	Bone fragments	7	
19764	Unknown	Bone fragments	30	
19765	Unknown	Bone fragments	30	
19766	Unknown	Bone fragments	41	
19767	Unknown	Bone fragments	10	
19768	Unknown	Bone fragments	11	
19769	Unknown	Bone fragment	1	

19770	Unknown	Bone fragments	6	
19771	Unknown	Bone fragments	18	
19772	Unknown	Bone fragments	8	15901
19773	Unknown	Bone fragments	76	
19774	Unknown	End of long bones	3	
19775	Unknown	Bone with extended base	14	
19776	Unknown	Bone with extended base	2	15901
19777	Unknown	Bone fragments	2	15834, 14984
19778	Unknown	Bone fragments	4	15904, 15825
19779	Unknown	Spines	12	15901
19780	Unknown	Bone material	1	
19781	Unknown	Bone fragments	1	
19782	Unknown	Bone fragments	5	
19783	Unknown	?Bone fragments	7	
19784	Unknown	Bone fragments	1	
19785	Unknown	Bone or spine with canal	6	
19786	Unknown	Bone fragments	52	
19787	Unknown	Bones in sediment	2	
19788	Unknown	Bone fragments	34	
19789	Unknown	Bone fragments	30	
19790	Unknown	bone fragments	3	
19791	Unknown	Bone fragments	12	
19792	Unknown	Bone fragments	25	15901
19793	Unknown	Bone fragments	35	15901
19794	Unknown	Bone fragments	2	15901
19795	Unknown	Bones/spines with internal c	84	15901
19796	Unknown	Bone fragments	1	15901
19797	Unknown	Bone fragments	213	15901
19798	Unknown	End of long bones	3	15901
19799	Actinopterygian	Cranial bone fragments and	2	
19800	Actinopterygian	Cranial bone fragments and	2	
19801	Actinopterygian	Cranial bone fragments and	2	
19802	Actinopterygian	Cranial bone fragments and	28	
19803	Actinopterygian	Cranial bone fragments and	4	
19804	Actinopterygian	Cranial bone fragments and	35	
19805	Actinopterygian	Cranial bone fragments and	17	
19806	Actinopterygian	Cranial bone fragments and	6	
19807	Actinopterygian	Cranial bone fragments and	62	15901
19808	Actinopterygian	Cranial bone fragments and	14	15901
19809	Unknown	Scale fragments	8	
19810	Unknown	Small scales	1	
19811	Unknown	Scale fragments	9	
19812	Unknown	Scale fragments	6	
19813	Unknown	Scale fragmnets	4	
19814	Unknown	Scale fragments	1	
19815	Unknown	Small scales	1	
19816	Unknown	Scale fragments	6	
19817	Unknown	Scale fragment	1	
19818	Unknown	Small scale	1	
19819	Unknown	Scale fragment	6	

19820	Unknown	Small scale	1	
19821	Unknown	Scale fragments	3	
19822	Unknown	Scale Fragments	6	15901
19823	Unknown	Coprolite	1	
19824	Unknown	Coprolite	1	
19825	Unknown	Coprolite	4	
19826	Unknown	Unknown	1	
19827	Unknown	Unknown	25	
19828	Unknown	Unknown	2	
19829	Unknown	Unknown	14	
19830	Unknown	Unknown	23	
19831	Unknown	Unknown	11	
19832	Unknown	Coprolite	1	
19833	Sarcopterygian	Dipnoi indet.	1	
19834	Actinopterygian	Actinop Vertebrate	1	15904, 1582
19835	Sarcopterygian	Limb bone cf. tetrapodomor	1	
19836	Unknown	Unknown	1	15901
19837	Unknown	Unknown	1	15901
19838	Unknown	Unknown	1	15901
19839	Unknown	Unknown	1	15901
19840	Unknown	Unknown	1	15901
19841	Unknown	Unknown	1	15901
19842	Unknown	Unknown	1	15901
19843	Unknown	Unknown	1	15901
19844	Unknown	Unknown	1	15901
19845	Unknown	Unknown	1	15901
19846	Chondrichthyes	Xenacanthiformes indet.	1	
19847	Unknown	Bone/spine fragments	1	
19848.1	Unknown	Bone/spine fragments	1	
19848.2	Unknown	Bone/spine fragments	3	
19849	Chondrichthyes	cf. Elasmobranchii	1	
19850	Chondrichthyes	*Orthacanthus compressus*	1	15901
19851	Chondrichthyes	*Ageleodus pectinatus*	1	15901
19852	Chondrichthyes	*Orthacanthus compressus*	1	15901
19853	Chondrichthyes	*Orthacanthus compressus*	1	15901
19854	Chondrichthyes	*Orthacanthus compressus*	1	15901
19855	Unknown	Coprolite	1	15901
19856	Chondrichthyes	*Orthacanthus compressus*	1	15901
19958	Sarcopterygian	cf. *Megalichthyes* sp.	1	
19972	Sarcopterygian	*Archichthys portlocki*	1	
19974	Sarcopterygian	*Megalichthys* sp.	1	
19975	Chondrichthyes	Coprolite type 1 - spiral cf O	1	
19976		Coprolite type 1 - spiral cf O	1	
19977		Coprolite type 1 - spiral cf O	1	
19978		Coprolite type 1 - spiral cf O	1	
19979		Coprolite type 1 - spiral cf O	1	
19980		Coprolite type 1 - spiral cf O	1	
19981		Coprolite type 1 - spiral cf O	1	
19982		Coprolite type 1 - spiral cf O	1	
19983		Coprolite type 1 - spiral cf O	1	

19984		Coprolite type 1 - spiral cf O	1
19985		Coprolite type 1 - spiral cf O	1
19986		Coprolite type 1 - spiral cf O	1
19987		Coprolite type 1 - spiral cf O	1
19988		Coprolite type 1 - spiral cf O	1
19989		Coprolite type 1 - spiral cf O	1
19990		Coprolite type 1 - spiral cf O	1
19991		Coprolite type 1 - spiral cf O	1
19992		Coprolite type 1 - spiral cf O	1
19993		Coprolite type 1 - spiral cf O	1
19994		Coprolite type 1 - spiral cf O	1
19995		Coprolite type 1 - spiral cf O	1
19996		Coprolite type 1 - spiral cf O	1
19997		Coprolite type 1 - spiral cf O	1
19998		Coprolite type 1 - spiral cf O	1
19999		Coprolite type 2 - duraphago	1
20000		Coprolite type 2 - duraphago	1
20001		Coprolite type 2 - duraphago	1
20002		Coprolite type 2 - duraphago	1
20003	Chondrichthyes	xenacanth tooth	1
20004		Coprolite type 1 - spiral cf O	1
20005		Coprolite type 1 - spiral cf O	1
20006		Coprolite type 1 - spiral cf O	1
20007		Coprolite type 1 - spiral cf O	1
20008		Coprolite type 1 - spiral cf O	1
20009		Coprolite type 1 - spiral cf O	1
20010		Coprolite type 1 - spiral cf O	1
20011		Coprolite type 1 - spiral cf O	1
20013	Acanthodian	Acanthodidae indet.	
20014	Sarcopterygian	Scale fragment	
20015	Actinopterygian	Scale fragment	
20016	Actinopterygian	Acanthodidae indet., spine	
20019	Tetrapoda?	Jaw	
20020	Tetrapoda?	Jaw	
20021	Actinopterygian	Actinopterygii indet. (jaw)	
20028	Actinopterygian	Actinopterygii indet. (upper jaw)	

Locality	**Lithology**	**Remarks**
UNKNOWN SITE WIT	Lithology 4	
UNKNOWN SITE WIT	Lithology 4	
UNKNOWN SITE WIT	Lithology 4	
UNKNOWN SITE WIT	Lithology 4	
COAL CREEK	Lithology 1	Unsure of lithology as it was already extracted fr
COAL CREEK	Lithology 1	Unsure of lithology as it was already extracted fr
COAL CREEK	Lithology 1	Unsure of lithology as it was already extracted fr
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COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
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COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	Block of Lithology 1 labelled with Dipnoi but no d
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
IRON BOUND COVE	Lithology 3?	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 3?	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 3?	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 3?	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2a	

IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2 [indet] c	Coprolite is broken along the outher surface expo
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 1?	a few IBC look similar to Coal Creek lithology
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 3?	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2c	

IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	Identical to Howittacanthus kentoni Long, 1986
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 1?	a few IBC look like Coal Creek Lithology 1
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	Identical to Howittacanthus kentoni Long, 1986
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 1?	a few IBC look like Coal Creek Lithology 1
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 3	

IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	Similar to Acanthodes beecheri pelvic spine as ill
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2a	Denticles
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2c	
IRON BOUND COVE	Lithology 2c	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	

IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
UNKNOWN SITE WIT	Lithology 4	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 3	Denticles
IRON BOUND COVE	Lithology 3	Denticles
IRON BOUND COVE	Lithology 3	Denticles
IRON BOUND COVE	Lithology 3	Denticles

IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
COAL CREEK	Lithology 1	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 2 [indet]	Denticles
IRON BOUND COVE	Lithology 3	Denticles
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
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IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
COAL CREEK	Lithology 1	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2 [indet]	Cusp and base with no laterial cusps.
IRON BOUND COVE	Lithology 2 [indet]	Curved tooth with ridge along the curve
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	Cusp and base with ridge on the laterial side to t
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	Isoltaed teeth
IRON BOUND COVE	Lithology 2 [indet]	Tri-cusped "teeth". Not similar to xenacanthiform
IRON BOUND COVE	Lithology 2 [indet]	Sperical bones with hollow centres
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	Curved
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	Two morphotypes
IRON BOUND COVE	Lithology 2 [indet]	

IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	Broken
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	Main cusps with small laterial cusps
IRON BOUND COVE	Lithology 3	
COAL CREEK	Lithology 1	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
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IRON BOUND COVE	Lithology 2 [indet]	
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IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
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IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	

IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 3
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 3
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 3
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
COAL CREEK	Lithology 1
COAL CREEK	Lithology 1
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 3
IRON BOUND COVE	Lithology 3
IRON BOUND COVE	Lithology 3
IRON BOUND COVE	Lithology 3
IRON BOUND COVE	Lithology 3
IRON BOUND COVE	Lithology 3
IRON BOUND COVE	Lithology 3
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 3
IRON BOUND COVE	Lithology 3
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]
IRON BOUND COVE	Lithology 2 [indet]

IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	Spine fragment in coprolite
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	Fragmented
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	
IRON BOUND COVE	Lithology 2 [indet]	Isolated spine
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
IRON BOUND COVE	Lithology 3	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	

COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a or 2b	microconchids may all be in coprolite
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2a	
IRON BOUND COVE	Lithology 2a	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
COAL CREEK	Lithology 1	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 1	a few IBC look like Lithology 1
IRON BOUND COVE	Lithology 1	a few IBC look like Lithology 1
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2b	
IRON BOUND COVE	Lithology 2b	Can probably identify more precisely
IRON BOUND COVE	Lithology 2b	Teeth similar to those of NBMG 20021

om the matrix. Likely the Lithology 2

om the matrix. Likely the Lithology 2

om the matrix. Likely the Lithology 2

om the matrix. Likely the Lithology 2

ipnoi or other vertebrate material present.

osing bone fragments in the interior.

ustrated by Zidek 1976, fig. 8B

he curve

es.