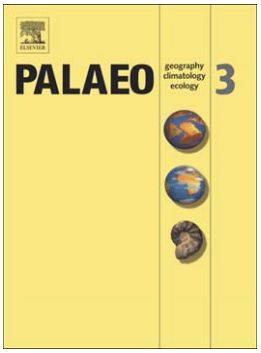


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# The terrestrial landscapes of tetrapod evolution in earliest Carboniferous seasonal wetlands of SE Scotland

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## ABSTRACT

The Lower Mississippian (Tournaisian) Ballagan Formation in SE Scotland yields tetrapod fossils that provide fresh insights into the critical period when these animals first moved onto land. The key to understanding the palaeoenvironments where they lived is a detailed analysis of the sedimentary architecture of this formation, one of the thickest and most completely documented examples of a coastal floodplain and marginal marine succession from this important transitional time anywhere in the world. Palaeosols are abundant, providing a unique insight into the early Carboniferous habitats and climate.

More than 200 separate palaeosols are described from three sections through the formation. The palaeosols range in thickness from 0.02 to 1.85 m and are diverse: most are Entisols and Inceptisols (63%), indicating relatively brief periods of soil development. Gleyed Inseptisols and Vertisols are less common (37%). Vertisols are the thickest palaeosols (up to 185 cm) in the Ballagan Formation and have common vertic cracks. Roots are abundant through all the palaeosols, from shallow mats and thin hair-like traces to sporadic thicker root traces typical of arborescent lycopods.

Geochemical, isotope and clay mineralogical analyses of the palaeosols indicate a range in soil alkalinity and amount of water logging. Estimates of mean annual rainfall from palaeosol compositions are 1000 –1500 mm per year. The high mean annual rainfall and variable soil alkalinities contrast markedly with dry periods that developed deep penetrating cracks and evaporite deposits. It is concluded that during the early Carboniferous, this region experienced a sharply contrasting seasonal climate and that the floodplain hosted a mosaic of closely juxtaposed but distinct habitats in which the tetrapods lived. The diversification of

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coastal floodplain environments identified here may link to the evolution and movement of tetrapods into the terrestrial realm.

Keywords:

Paleosol, Tournaisian, terrestrialization, monsoon, palaeoenvironment, floodplain

## 1. Introduction

The terrestrialization of vertebrates is one of the most important events in the evolution of life on Earth. Fundamental to understanding what drove evolution along this pathway is characterization of the subaerial environment in which the first dominantly terrestrial tetrapods lived. Around the world a wide range of Mid to Late Devonian taxa and trackways document the earliest phases of limbed vertebrate evolution from fishes (Clack, 1997; Narkiewicz and Ahlberg, 2010; Pierce et al. 2012; Narkiewicz et al., 2015; Lucas, 2015). In Poland, the occurrence of Mid Devonian tetrapod trackways suggests this change may have been driven by the development of novel habitats such as woodlands (Retallack, 2011) and intertidal and lagoonal environments (Niedzwiedzki et al., 2010). However, these early forms of limbed vertebrates have been shown to be mainly aquatic or semi-aquatic, with primitive features (Clack, 2009; Pierce et al., 2012; Smithson et al., 2012) and the trackways were formed underwater (Narkiewicz et al., 2015). This suggests that the Mid to Late Devonian tetrapods lacked terrestrial capability (Lucas, 2015). By the mid-Visean, the first evidence of fully terrestrial tetrapods is found in the Midland Valley of Scotland (Paton et al., 1999). The time between the mid-Visean tetrapod discoveries and Devonian tetrapods has been termed ‘Romer’s Gap’ due to the lack of tetrapod fossil material found during this interval (Clack, 2002). The cause of this gap has been attributed to environmental factors such as a low atmospheric oxygen content in the Tournaisian (Ward et al., 2006) or the move of tetrapods to woodlands with poor preservation potential (Retallack, 2011).

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Recent discoveries from the Tournaisian of SE Scotland and Nova Scotia have started to fill Romer's Gap (Smithson et al., 2012; Anderson et al., 2015). Tetrapods from these localities include both terrestrial and aquatic forms suggesting that full terrestrialization of tetrapods occurred soon after the Late-Devonian mass-extinction event (Kaiser et al., 2015). Garcia et al. (2006) have suggested that one of the factors that may have driven tetrapod diversification was the evolution in the early Carboniferous of a wealth of new habitats, and by implication palaeosols, suitable for continental organisms.

Palaeosols are one of the few direct indicators of the subaerial part of the floodplain (Retallack, 1993; Sheldon and Tabor, 2009) and provide a direct record of changes in climate and landscape architecture. Furthermore, they can also be used as proxies for estimating palaeo-rainfall and atmospheric variability (Sheldon and Tabor, 2009; Nordt and Driese, 2010; Retallack and Huang, 2011). Both Anderton (1985) and Williams et al. (2005) identified palaeosols in the Tournaisian Ballagan Formation in SE Scotland which hosts the new tetrapod discoveries (Smithson et al., 2012). They did not, however, provide a detailed nor systematic description and thus under-estimated palaeosol frequency and diversity. Here we describe and interpret for the first time the palaeosols found in the Ballagan Formation, in order to understand the range of habitats available to the earliest terrestrial tetrapods.

## 2. Geological setting

The Ballagan Formation crops out through the Midland Valley of Scotland and in the north of England (Figs. 1, 2). Previously known as the lower part of the Calciferous Sandstone Measures in the Midland Valley and as the Cementstone Group in northern England, the Ballagan Formation overlies the Kinnesswood Formation, a succession of fluvial sandstone beds with many rhizocretions (Browne et al., 1999; Scott, 1986). Previous studies have suggested that the Ballagan Formation was deposited on a low-lying coastal

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floodplain (Anderton, 1985; Andrews and Nabi, 1998; Andrews et al., 1991; Scott, 1986; Stephenson et al., 2002, 2004a; Turner, 1991). The formation comprises grey siltstone which is reddened in parts, along with sporadic nodules and many thin beds of ferroan dolostone, averaging 30 cm thick, and locally known as 'cementstones' (Belt et al., 1967). Bennett et al. (2016) identified ten facies and three facies associations, the latter comprising a fluvial facies association, an overbank facies association and a saline-hypersaline lake facies association. Parts of the Ballagan Formation, where ferroan dolostone beds are common, also contain thin beds or nodules of gypsum and/or anhydrite and, in some sections, rare siltstone pseudomorphs after halite (Scott, 1986). All the fine-grained sedimentary rocks in the Ballagan Formation also contain desiccation cracks indicating periodic drying out of the substrate.

In SE Scotland and neighbouring northern England the succession includes units, 5-30 m thick, of fine- and medium-grained sandstone, containing trough cross-bedding and lateral accretion surfaces. Thin, conglomerate lags commonly occur at the base of units interpreted as meandering fluvial channel systems (Scott, 1986). Palaeosols and rooted horizons have been identified previously in the Ballagan Formation, some of which appear to be associated with the cementstone units (Anderton, 1985; Andrews et al., 1991; Scott, 1986; Turner, 1991). Pedogenic calcrete occurs in the uppermost part of the formation in the Cockburnspath outlier near Dunbar on the East Lothian coast (Andrews and Nabi, 1998) although it has not been identified elsewhere.

The Ballagan Formation is predominantly Tournaisian in age and falls mostly in the CM palynozone (Stephenson et al., 2002; Stephenson et al., 2004a, b; Williams et al., 2005). At Burnmouth the lowest beds in the formation have yielded miospores of the VI palynozone at the base of the Tournaisian (Smithson et al., 2012) (Fig. 2).

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## 3. Materials and methods

### *3.1. Localities*

In SE Scotland the Ballagan Formation is generally very poorly exposed, except for coastal sections such as the foreshore at Burnmouth, which forms the first of three sections considered here (Fig. 1). The foreshore and cliff section at Burnmouth (British National Grid NT 95797 60944) is a 520 m thick section of vertically dipping strata that extends from the base to the top of the Ballagan Formation. The sedimentology of this section was logged at a scale of 1 m = 2 cm and is summarized in Figure 3.

A 500 m core through gently dipping Ballagan Formation strata was obtained from a borehole at Norham West Mains Farm (Norham borehole), about 8 km SW of Berwick-upon-Tweed (NT 91589 48135, BGS borehole ID: NT94NW20). The base of the Ballagan Formation was not reached and the only direct correlation between the borehole and coastal section is near the top of the succession (Fig. 3). The cores were transferred to the UK's National Geological Repository at the British Geological Survey in Keyworth, Nottingham, where they were cut in half lengthways and photographed. One half of the core is an archive reference and the other half was sampled for this study. The core was logged at a scale of 1 m = 8 cm (Fig. 3).

The third section is the 46 m thick succession near to the base of the Ballagan Formation exposed in a river cliff at Crumble Edge near Duns (NT 79276 56412). This section was logged at a scale of 1 m = 2 cm (Fig. 3).

### *3.2. Field techniques*

Palaeosols were identified in the sections, initially by the presence of root traces or pedogenic changes to the sediment such as the development of palaeosol horizons (Retallack, 1993, 1997). The palaeosols were numbered sequentially, and prefixed by a three-letter

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locality code (i.e., NOR = Norham and BUR = Burnmouth). Profile descriptions include horizonation, horizon thickness, nature of the contact between horizons, Munsell colour, reaction to acid, carbonate features using the classification scheme of Machette (1985), trace fossils present and gleys (Appendix A). Standard-sized, polished thin sections (20 µm thick) were made of selected samples of the palaeosol, including desiccation surfaces and carbonate nodules. Thin sections were examined using an Olympus petrographic microscope.

The palaeosols were divided into 'pedotypes'; where palaeosols are mapped based on a reference profile for definition (Bown and Kraus, 1987; Retallack, 1994). This approach focuses on the local environmental conditions that formed the palaeosol, rather than focusing on the lateral extent of a particular palaeosol as in the pedofacies approach proposed by Kraus (1999). The pedotype approach is more applicable in this study because it is not possible to trace a single palaeosol between the core and sections.

*3.3. Analytical techniques*

Palaeosols were sampled at 10 cm vertical intervals. This sampling interval was chosen because it is typical for detailed elemental redistribution studies in soils (Adams et al., 2011; Driese, 2004). Thirty-five samples from six palaeosols, representing the best preserved examples of the palaeosols described below, were analyzed for their major element composition using X-ray fluorescence spectrometry (XRFS). The samples were milled to a homogeneous fine powder (<32 µm), dried overnight at 105°C and pre-ignited at 1050°C before fusion using a pre-fused mixture of lithium tetraborate and lithium metaborate (66/34 percent ratio). The fusion melt was cast into a 40 mm diameter bead which was analysed using a PANalytical Axios sequential, fully automatic, wavelength-dispersive X-ray fluorescence spectrometer, fitted with a 60 kV generator and 4 kW rhodium (Super Sharp)

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end-window X-ray tube. The PANalytical calibration algorithm was used to fit calibration curves and inter-element effects were corrected by fundamental parameter coefficients. The analytical method is accredited to ISO 17025 and calibrations have been validated by analysis of a wide range of reference materials. Data were reported in weight percent and have been converted to molar concentrations from which the characteristic parameter ratios hydrolysis, leaching, provenance (acidification), salinization, and chemical affinity are calculated (for results see Appendix B). Palaeosol weathering ratios were calculated using CIA-K (Eq. 1, of Sheldon et al., 2002) and CALMAG weathering ratios (Eq. 2, of Sheldon et al., 2002):

$$\mathrm{CIA-K} = [\mathrm{Al_2O_3}/(\mathrm{AL_2O_3} + \mathrm{CaO} + \mathrm{Na_2O})] \times 100 \tag{1}$$

$$\mathrm{CALMAG} = [\mathrm{Al_2O_3}/(\mathrm{AL_2O_3} + \mathrm{CaO} + \mathrm{MgO})] \times 100 \tag{2}$$

The clay mineralogy of 78 samples from 13 palaeosols selected to represent each of the pedotypes was analysed using X-ray diffraction (XRD) techniques. Samples were included from the sedimentary unit above the soil where this appears unaltered by pedogenesis, to provide a reference for the background lithology of the overbank deposits prior to pedogenesis. Less than 2 µm fractions were isolated, orientated mounts prepared and analysed using a PANalytical X'Pert Pro series diffractometer equipped with a cobalt-target tube, X'Celerator detector and operated at 45 kV and 40 mA. Mounts were scanned from 2 - 40°2θ at 1.02°2θ/minute after air-drying, ethylene glycol-solvation and heating at 550°C for 2 hours. Clay mineral species were then identified and quantified from their characteristic peak positions, their reaction to the diagnostic testing program and modelling of the <2 µm glycol-solvated XRD profiles using Newmod II™ (Reynolds and Reynolds, 2013) software. Full

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details of the methodology employed are given in Harrington et al. (2004) (for results see Appendix B).

For stable isotope analysis, the calcite was hand sampled with a microdrill. The calcite was ground finer in agate and the equivalent of 10 mg of carbonate was reacted with anhydrous phosphoric acid *in vacuo* overnight at a constant 25°C. The $CO_2$ liberated was separated from water vapour under vacuum and collected for analysis. Measurements were made on a VG Optima mass spectrometer. Overall analytical reproducibility for these samples is normally better than 0.2‰ for $\delta^{13}C$ and $\delta^{18}O$ (2σ). Isotope values ($\delta^{13}C$, $\delta^{18}O$) are reported as per mil (‰) deviations of the isotopic ratios ($^{13}C/^{12}C$, $^{18}O/^{16}O$), calculated to the VPDB scale using a within-run laboratory standard calibrated against NBS standards (for results see Appendix B).

## 4. Results

### *4.1. Palaeosol facies*

In the section at Burnmouth 64 palaeosols were identified, compared with 216 in the Norham core (Fig. 3) even though these two sections are of similar thickness and thought to represent approximately the same period of time. The range of palaeosol thickness is similar: 0.02 - 1.85 m at Burnmouth and 0.02 - 1.58 m in the Norham Borehole (Appendix A). The thinnest palaeosols are identified by the presence of thin root mats (Fig. 4A) whereas the thicker palaeosols show many more pedogenic features (e.g. Fig. 4D). Comparing the two successions, there are similar numbers of palaeosols thicker than 0.60 m, but there are significantly fewer palaeosols thinner than 0.60 m recorded at Burnmouth compared with the Norham Borehole (Fig. 3). It seems likely that the number of palaeosols identified at Burnmouth is an underestimate, probably because much of the exposure of the fine-grained

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rocks is degraded by weathering and it is hard to see fine detail such as root traces. The number of palaeosols recorded in the borehole is probably a truer representation of the frequency of palaeosols developed in the Ballagan Formation. The short section of the Ballagan Formation from near its base at Crumble Edge contains 18 palaeosols with a thickness range of 0.05 - 0.40 m.

The palaeosols identified in these sections have been classified into four pedotypes based on the features found such as pedogenic slickensides, nature of the gleys and development of B horizons. These are labelled Pe, Pi, Pg, Pv (Table 1, Fig. 4).

*4.2. Pedotype Pe*

This pedotype is present in beds of sandstone and siltstone where roots occur at the top of the unit (A horizon). No other subsurface pedogenesis is evident, as the rock shows primary sedimentary lamination (such as cross-bedding) and is thus classified as a C horizon (Fig. 4A). Individual examples of this pedotype are 2 - 35 cm thick, although stacked packages up to 54 cm thick occur where repeated flooding events have formed a compound profile (cf. Kraus, 1999). In stacked sequences, root traces cover 5 - 25 % of the bed which can be overlain by more developed palaeosols. The root traces vary from single tapering structures to branching and interlocking mats (Fig. 5B). Most of the root traces are similar to small rootlets and tap roots (cf. Retallack, 1988) or Type C rooting structures described by Pfefferkorn and Fuch (1991).

*4.3. Pedotype Pi*

This pedotype shows some development of a reddened pedogenic B horizon where sedimentary lamination has been destroyed by soil formation processes (Fig. 4B). The thickness is 4 - 63 cm. At the top of approximately 50% of this pedotype is a 1 - 30 cm thick gleyed horizon (Eg) which is greenish grey to greyish green (5GY 5/1 to 5G 4/2) in colour.

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This horizon is internally homogenous, although it is commonly disrupted by carbonized roots and polygonal cracks. In the rest of the paleosols the E horizon is not seen. The B horizon is 3 - 63 cm thick and light reddish brown to red (2.5YR 6/3 to 10R 5/6). This horizon lacks sedimentary lamination, shows an increase in clay content and contains drab root halos. This pedotype also has sporadic yellow (2.5Y 8/6) mottles and iron oxide spots 1 - 2 mm diameter (Fig. 4B photograph). Some of this pedotype passes down into laminated units, 5 - 40 cm thick, with a small amount of pedogenic alteration (C horizon).

Root traces in this pedotype are preserved as carbon films in the gleyed horizons or either drab root halos or filamentous root traces below. The most common are tapering tubes, but root mats, lateral roots and sinuous filaments were also observed.

*4.4. Pedotype Pg*

Pedotype Pg is defined by the presence of a gleyed (10G 8/1 - 10B 8/1) B horizon and the absence of reddening in any horizon (Fig. 4C). The pedotype is 2 - 80 cm thick. The uppermost horizon, 5 - 15 cm thick, in 11% of examples of this pedotype is black in colour (N1) and has a total organic carbon content (TOC) of 0.5 - 4.7 % compared with the average of c. 0.1% for other siltstones in the succession. This horizon is interpreted to be an O horizon. The other examples of Pedotype Pg have a 2 - 45 cm thick, light greenish grey (5BG 7/1 - 10BG 8/1) horizon at the top.

The gleyed B horizon horizon is 10 - 73 cm thick and commonly contains yellow (2.5Y 7/6) mottles and ferro-siderite nodules 0.2 - 1 cm in diameter. Roots are less common than in upper horizons, but where found are preserved as carbonized films which tend to be vertical with sporadic branches. This pedotype becomes less massive below the gleyed horizon and starts to show primary sedimentary lamination, though root traces are still

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present. This is a C horizon, 3 - 23 cm thick and rests on pedogenically unaltered sedimentary rock.

The top of pedotype Pg with an O horizon is brecciated (Fig. 6A) in zones up to 25 cm, but more commonly 2 - 5 cm, thick. Cracks initiated deep in the profile broaden upwards and grade into the area of brecciation. At first the blocks are 2 - 3 cm across and have a jig-saw fit. The blocks become increasingly smaller upwards and their edges more irregular as the proportion of the overlying sediment between the blocks increases. There is no evidence of rounding or internal fracturing of the blocks. This may be alteration of the original ped structure of the soil.

*4.5. Pedotype Pv*

Examples of this pedotype are 0.32 - 1.85 m thick. They are defined by the red colour throughout the Bt horizon and by the presence of deeply penetrating vertic cracks (Table 1, Fig. 4D). Over 60% of this pedotype have a gleyed top, 10 - 30 cm thick which is dark greenish grey to pale green (5G 4/1 to 5G 6.2) in colour. This layer has filamentous root traces which are preserved as carbon films. The main horizon below is 35 - 123 cm thick and dusky red to red (2.5YR 3/2 to 10R 5/6). This layer contains minor pale green (5G 4/1) mottles and root traces preserved as drab root halos. In the thicker units these have an affinity with tap rooting structures (cf. Type H, Pfefferkorn and Fuch, 1991). Some of the better developed examples of this pedotype contain bands up to 15 cm thick of pedogenic carbonate nodules at depths of more than 1 m. The nodules are 0.5 - 2 cm in diameter and are of stage II calcrete development (cf. Machette, 1985). The carbonate nodules are indicative of a Bk horizon; where carbonate is absent this is the Bt horizon. Low-angle pedogenic slickensides may also be present in the Bt horizon outcrop but due to weathering cannot be confirmed. Below this the pedotype passes down into reddened, laminated mudstone (C horizon).

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The Pv pedotype is commonly overlain by beds of flood-generated sandy siltstone (Bennett et al., 2016). These beds mostly have a gley colour and also fill cracks in the top of the pedotype (Fig. 6B). The downward-tapering cracks are up to 38 cm long and 2 cm wide at the top. Most cracks are near vertical although there are horizontal and oblique examples, some of which radiate from the larger cracks (Fig. 6B). The margins of the cracks are irregular with finer cracks penetrating into the adjacent pedotype. Also, angular clasts of siltstone up to 1 mm appear broken off from the crack margin and have a jig-saw fit with the unfractured crack margin. There is commonly a zone of pale green gley (5G 4/1) up to 1 cm from the cracks (Fig. 6B). There are also rare examples of cracks filled with fine-grained sandstone.

*4.6. Root traces*

The diverse root traces found in the palaeosols of the Ballagan Formation range from 1 to 80 cm long. The simplest of these traces occurs in very fine-grained sandstone and siltstone beds less than 10 cm thick. They taper downward and have sinuous sides (Fig. 5A). These features are most similar to fibrous root systems (Retallack, 1988) or Type D rooting structures described by Pfefferkorn and Fuch (1991) and may be plug roots, but are often hard to distinguish from *Planolites*. In pedotype Pe rootmats are common (Fig. 5B). These root traces typically penetrate less than 1 cm into the sand unit and are preserved as carbon infills. Rooting associated with the more developed Pi pedotype commonly exhibits downward penetrating single fibres with sporadic branches 0.1 - 0.5 cm diameter. Individual roots penetrate 5 - 15 cm into the palaeosol. In the reddened horizons they are preserved as drab root halos (Fig. 5E). These have most affinity with simple fibrous vertical roots with occasional branches (Type D rooting structures described by Pfefferkorn and Fuch, 1991).

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The root traces of pedotype Pg are preserved as carbon films (Fig. 5C). This type of root is mostly vertical, 2 - 4 cm long, with sporadic branches and concentrated in the top 20 - 30 cm of the palaeosol. There are some horizontal root traces at the top of the pedotype and these appear to form root mats. Roots are only sporadically preserved lower down in the profile. These roots are similar to tabular root systems with sporadic lateral roots (Retallack 1988; Type G roots of Pfefferkorn and Fuch, 1991).

A lycopsid root is preserved in one example of pedotype Pi at Crumble Edge (Fig. 5D). The root is 38 cm long and 8 cm wide, tapers to a point and has lines of pits along its surface. Sediment is disrupted around the root which appears to be in situ. The root is filled with sand which probably infilled once the woody material within the root decayed, a mechanism suggested by Gastaldo (1986).

In pedotypes Pi and Pv which have a developed Bt or Bk horizon roots penetrate to depths of up to 80 cm (Fig. 5F, G). The roots are preserved as drab root halos and comprise a linear trace with sporadic bifurcation. Some of these root traces appear to have tapering tips and may be similar to adventitious roots (Retallack, 1988). A second set of horizontal, tubular root traces 0.5 - 2 cm diameter occurs in the thickest of pedotype Pv at depths of 100 cm (Fig. 5F). It is unclear whether these are connected to the vertical drab root halos above or are a separate rooting structure.

*4.7. Polygonal cracks*

In addition to the vertic cracks of pedotype Pv and the fractured and brecciated pedotype Pg, minor polygonal cracks are found at the top of pedotypes Pi, Pg and Pv. The cracks are 5 - 8 cm deep and originate from the top of the palaeosol. They mostly taper downwards and have irregular, sharp edges. When viewed on a bedding plane these cracks form polygons (Fig. 6C). Silt-grade sediment containing a large percentage of angular, 0.2 -

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0.5 mm organic fragments along with muscovite grains and subangular quartz fragments fills the cracks. In most cases this sediment is flood-generated sandy siltstone and identical to the overlying bed (see Bennett et al., 2016). Small (0.2 mm), angular clasts of the palaeosol may be present in the sediment filling the crack (Fig. 6D). The polygonal cracks are identified as prismatic peds (Retallack, 1988).

*4.8. Carbonate morphology and isotope composition*

Three palaeosols of pedotype Pi and Pv in the section at Burnmouth contain carbonate nodules 2 - 15 cm in diameter, and are of stage II calcrete development (cf. Machette, 1985). In the Norham Borehole eighteen palaeosols contain carbonate nodules 0.2 - 3 cm in diameter. Some nodules occur in discrete (Bk) horizons, but most others are found throughout the palaeosol.

The boundary of the nodule with the surrounding sediment is commonly diffuse (Fig. 7A), although in some there is an indication of mineral alignment around the carbonate nodule, suggesting they may have been affected by vertic movements in the soils (Fig. 7B). The carbonate nodules are mostly micritic calcite (crystal size 5 - 18 μm), with sparry calcitic centres, possibly filling a void (Fig. 7A). There are also examples of carbonate concretions forming around and within, root traces. These comprise a rim of micritic calcite which forms around the root trace and commonly a centre of larger (30 μm) calcite crystals filling a central void in the root (Fig. 7C). A further type of carbonate nodule, again with diffuse margins (Fig. 7B), comprises an aggregate of 20-μm rhomb-shaped dolomite crystals surrounded by larger crystals of calcite. All of these carbonate accumulations contain floating grains of sub-rounded quartz.

Only two palaeosols (BUR 59 and NOR 37) contain nodules that were formed of calcite rather than dolomite. The calcitic parts of these carbonates were handpicked and

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crushed to a powder. The micritic calcite parts of the nodule have isotope values within the range of $\delta^{13}C$ of –5.65 ‰ to –6.85‰ and $\delta^{18}O$ –6.85 ‰ to –7.14 ‰ (Fig. 7E). The late vein fills and the coarser, sparry core of nodules have a similar range of isotope values for $\delta^{13}C$ of –5.65‰ to –6.56 ‰ and $\delta^{18}O$ of –6.83 ‰ to –11.39 ‰ (Fig. 7E, Appendix B).

*4.9. Clay mineralogy*

In general terms, all palaeosols analysed show a similar clay mineral assemblage and are predominantly composed of illite/smectite (I/S) and illite with minor amounts of chlorite ± traces of kaolinite. NEWMOD-modelling of the XRD traces enabled the precise speciation of the I/S present (from an evolved, 92 % illite, *R*3-ordered species to a less evolved, more smectitic 80 % illite, *R*1-ordered species) and enabled traces of kaolinite to be distinguished in the presence of chlorite (Fig. 8, Appendix B). The <2 µm analyses also reveal the presence of non-clay minerals, principally quartz, plagioclase feldspar, hematite, goethite and sporadic calcite, dolomite, jarosite and siderite.

*4.10. Major element geochemistry*

All of the palaeosols show a broad increase in the Al/Si ratio with depth, reflecting the growth of clay minerals during pedogenesis (Fig. 9, Appendix B). This is most evident in the pedotype Pv, before passing into the more silica-rich C horizon. The thicker palaeosols at the top of the section (Fig. 9: NOR5, NOR6) also show an increase in Al/Si ratio in the top 40 cm. This may be due to the inclusion of flood-generated sandy siltstone filling many of the vertic cracks present in the top 40 cm of these profiles. The increase in clay content with the more developed palaeosols indicates the development of Bt horizons of pedotypes Pv and Pi. However, these have relatively elevated Al/Si ratio values compared with the average for palaeosols in general (cf. Retallack, 1997).

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(Ca + Mg)/Al is a proxy for the amount of carbonate in the soils (Retallack, 1997). From this, the Ballagan Formation palaeosols have very low carbonate values, possibly because of their relative immaturity, although there is an increase in the amount of Ca + Mg in one of the thicker palaeosols of pedotype Pv, reflecting the presence of carbonate accumulation in that palaeosol (Fig. 9: NOR5). Fe/Al varies little between the palaeosols (Fig. 9), but the redox state of the iron was not determined in this study.

Salinization ((Na+K)/Al) tracks the amount of alkali elements accumulated in the soil (Sheldon and Tabor, 2009). This separates the higher ratios of the more waterlogged pedotypes Pg and Pi, from the drier pedotype Pv (Fig. 9).

The Ti/Al ratio is used to assess potential changes in provenance in the parent material (Myers et al., 2014; Sheldon and Tabor, 2009). The molar ratios are 0.02 - 0.04 with a median value of 0.03. There is no variation with stratigraphic depth, suggesting there has been no major change in provenance of the source material throughout the Ballagan Formation.

## 5. Discussion

### *5.1. Pedotype interpretation*

The simplified interpretation of USDA Soil Taxonomy can be used to relate the pedotypes found in the Ballagan Formation to modern soil types (Retallack, 1993, 1994; Soil Survey Staff, 1999). There is debate about how far a classification scheme created for modern soils can be applied to palaeosols and other classification schemes have been suggested (Mack et al., 1993; Mack and James, 1994; Retallack, 1993, 1994; Krasilnikov and Calderón, 2006; Nettleton et al., 1998, 2000). However, comparison with modern soil types is useful to inform interpretations of the environment in which the palaeosols formed.

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Pedotype Pe shows an absence of subsurface pedogenic horizons which indicates that the palaeosols formed quickly before sediment buried them. This is characteristic of the more active areas of the floodplain of many fluvial systems today, for example on river sand bars which have been stable long enough for plants to become established. Based on the shallow rooting depths and absence of subsurface pedogenic horizons, this pedotype is most likely to be an Entisol, as suggested by Retallack (1993, 1994) (Table 1). Using the classification of Mack et al. (1993) these are Protosols (Table 1).

Pedotype Pi shows greater development of subsurface pedogenic horizons than pedotype Pe. The root networks in the Bt horizons are poorly preserved, but appear filamentous and branching. Pedogenic processes have removed any primary depositional structures in the horizon which is distinctly reddened and interpreted to be a cambic horizon as defined by Retallack (1994).

The presence of a gleyed surface horizon (Eg) and a cambic horizon (Bt) below are characteristic of Inceptisols as suggested by Retallack (1993, 1994) (Table 1). This suggests that they formed further away from the active river system than the Entisols; episodic flooding deposited new sediment on top of the palaeosols thus preventing further development. Using the classification of Mack et al. (1993) these would also be classified as Protosols.

The gleyed colour of the Pedotype Pg, along with root traces preserved as carbon films and the occurrence of ferro-siderite nodules all suggest permanent water logging (Retallack, 1994; Kraus and Hasiotis, 2006). The TOC content of the O horizon is too low for these palaeosols to be classified as Histosols and they are therefore more likely to be gleyed Inceptisols following Retallack (1993, 1994) or Gleysols, using the classification of Mack et al. (1993).

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Palaeosols with similar features to pedotype Pg have been described from Devonian sedimentary rocks in New York, USA by Retallack and Huang (2011). The lack of a peaty horizon in those palaeosols led to their classification as gleyed Inceptisols. However, it is evident that some of the palaeosols seen in the Ballagan Formation have an organic horizon preserved whereas others do not; yet they share most other features. The absence of an O horizon may be because it has been eroded, or did not have time to form.

Brecciation of the top of some of these palaeosols is unique to pedotype Pg and most likely formed in situ (Fig. 6A). The brecciation may be caused by disaggregation of the peds on the top of the palaeosol, but this occurs only in permanently water-logged palaeosols, and soils formed under water-logged swampy conditions typically lack soil ped structure (Retallack, 1988). However, this feature resembles soil crusts and vesicular surface horizons seen in modern saline-sodic wetland soils (Joeckel and Clement, 2005). Unlike desiccation or vertic cracks, these form in permanently water-logged soils and are confined to the very top of the soil. They form on a daily to seasonal time scale by repeated cycles of salt development, microbial activity and microrelief genesis, controlled by regular wetting and drying cycles interacting with ponded surface- and ground-waters (Joeckel and Clement, 2005). The palaeosols were dynamic and over time created surface soil textures which are extensively slaked or flaked.

Compared with other pedotypes from the Ballagan Formation, the Pv palaeosols are thicker and better developed. Any original, internal sedimentary structure in the siltstone has been overprinted completely by pedogenic processes. They are characterised by deep cracks, putative pedogenic slickensides, thick clayey horizon (Bt) and sporadic carbonate nodules indicating that these palaeosols are Vertisols, using either the USDA Soil Taxonomy or classification of Mack et al. (1993). They represent periods of relative stability on the

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floodplain where areas remained above the water table long enough for the thick profiles to develop (cf. Kraus, 1999).

The deep penetrating cracks (Fig. 6B) are similar to those reported from modern floodplain soils by Rust and Nanson (1989) and to the vertical cracks identified by Caudill et al. (1996) in late Mississippian palaeosols from Tennessee. The latter are associated with gilgai micro-topography, with the cracks forming at the centre of vertic 'pseudo-anticlines' on micro-highs. However, as only single deep penetrating cracks have been identified in individual palaeosols in the cores from the Ballagan Formation, it is impossible to measure the distance between putative micro-highs and micro-lows. The depth of cracking and the poorer preservation potential of micro-highs (Driese et al., 2000) may indicate that these palaeosols are micro-lows, probably formed in low topographic areas. The gleyed colour associated with these cracks is probably a surface water gley caused by rapidly deposited flood waters which deposited the flood-generated sandy siltstone in the cracks (Bennett et al., 2016).

The carbonate nodules found in palaeosols of this pedotype have two potential origins: they may indicate that the palaeosol dried out during periods of high evaporation (Breecker et al., 2009), or they may have formed during groundwater movement. A few of the nodules examined show evidence of neomorphic replacement. According to Wright and Tucker (1991) this is common within soil carbonate even when the soil is still part of the active vadose zone. However, it can also be a later diagenetic fabric in which the crystal contacts are characteristically concavo-convex (Fig. 7C), and enclose smaller patches of microcrystalline dolomite (Quast et al., 2006). Most of the carbonate found in the palaeosols in the Ballagan Formation exhibits alpha textures, although the calcified root traces (Fig. 7A - D) could be attributed to beta textures as defined by Alonso-Zarza and Wright (2010) and

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Wright and Tucker (1991). The presence of neomorphic replacement with calcite suggests a degree of alteration after the nodules formed.

The isotopic results from the calcitic nodules show more negative $\delta^{13}C$ and $\delta^{18}O$ values than ferroan dolostone beds found in the same sections (Fig. 7E). This is a similar pattern to that seen between paludal dolomites and calcretes from the Late Mississippian of Kentucky, USA (Barnett et al., 2012). In that locality it was suggested that the relative offsets were due to the calcretes forming from meteoric water while the paludal dolomites formed in brackish water conditions. A similar relationship has beens seen elsewhere in the Ballagan Formation in central Scotland (Williams et al., 2005). However, the isotopic results from the calcitic nodules in this study, overlap with the values from late vein fills and coarser, recrystallized core of nodule (Section 4.8). Turner (1991) and has recorded similar isotope values from phreatic calcite cement in sandstones in study of carbonates from the Ballagan Formation (Fig. 7E) suggesting palaeosol carbonate has been diagenetically altered.

*5.2. Clay minerals*

Pedogenesis tends to alter detrital clays to smectite (Sheldon and Tabor, 2009). Though smectite was not detected in any of the samples, some clay assemblages are composed of more than 55 % I/S and, given the burial depth, it seems likely that this was derived from the original pedogenic smectite. I/S increases proportionally with depth in the palaeosols, especially in the Vertisols (Fig. 8), suggesting that original pedogenic trends are retained.

Illite and chlorite are generally considered to have been inherited from parent rock or other material (Wilson, 1999). However, Joeckel and Clement (2005) showed that repeated wetting and drying cycles caused illitization in modern saline-sodic wetland soils, resulting in illite dominating the basin surface of the soil, with smectite becoming dominant at depth. In

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the gleyed Inceptisols with brecciated tops, the uppermost 10 cm are dominated by illite (and more illitic I/S) and the lower parts are dominated by more smectitic I/S suggesting that illitization may have occurred here in the Ballagan Formation palaeosols (Fig. 8). Alternatively, this may be because the floodplain material on which the palaeosols were forming was illite-rich.

Kaolinite forms a minor-trace component of the clay assemblages present in all palaeosols, but is more prevalent in the Inceptisols and Entisols. Kaolinite forms under acid soil conditions and is often cited as a proxy for more arid palaeoclimatic conditions (Sheldon and Tabor, 2009).

Hematite and/or goethite are also present in all of the palaeosols. In the Vertisols only hematite is present in the Bt horizon, whereas hematite and goethite are present in the Eg horizon. Inceptisols and gleyed Inceptisols, by contrast, contain both hematite and goethite throughout the palaeosol. Goethite is known to form in permanently water-logged environments (Sheldon and Tabor, 2009; Tabor et al., 2004) and this supports the link between the gleyed horizons in the palaeosols and water logging.

I/S species are transitory phases and do not typically persist in soil profiles. In addition, there is little published evidence for long-range ordered (*R*3) I/S or precursor randomly interstratified (*R*0) I/S forming stable phases in soils (Wilson, 1999). The presence of I/S and absence of discrete smectite in the Ballagan Formation palaeosols therefore suggests that the detected clay mineral assemblages have developed through burial diagenesis of original pedogenic smectite.

From the range of I/S compositions detected, the maximum burial depth of between 3 and 6 km is suggested, assuming a 30 °C/km geothermal gradient (Merriman and Kemp, 1996). A vitrinite reflectance value (Rv) of 0.54 was determined on coal-like samples from

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the Norham borehole (D. Carpenter, pers. comm. 2015). Comparing this value with the Rv gradient for Fife obtained by Marshall et al. (1994), predicts a burial depth of about 2.5 km, in broad agreement with that predicted by the least evolved I/S compositions. The deeper burial depths suggested by the more evolved I/S most likely reflect more advanced diagenetic progression hosted by slightly different palaeosol compositions.

*5.3. Palaeosol floodplain associations*

The diversity of palaeosols in the Ballagan Formation indicates a dynamic floodplain. The most common palaeosol in the three sections examined is Inceptisol (Pi), with 49 % at Burnmouth, 42 % at Norham (Fig. 10) and 67 % at Crumble Edge. This palaeosol represents a relatively short period of soil development, long enough for clay-rich sub-horizons to develop, but not long enough to develop any other pedogenic structures; they are thought to take 100s to 1000s of years to form (Retallack, 1998; Kraus, 1999). They may have formed near to fluvial channels.

The next most common palaeosol in the Norham core is gleyed Inceptisol (Pg) (27 %: Fig. 10), but its low frequency in the two field sections probably results from the difficulty of identification in weathered 'shale' sections. The gleyed character of these palaeosols, preservation of roots as carbon, and brecciation, suggest that these soils formed in wetlands, although none is capped by coal. The root traces in these palaeosols are vertical with sporadic lateral branches (Fig. 5C), reminiscent of fibrous rooting systems (Pfefferkorn and Fuch, 1991; Retallack, 1988). This suggests that they represent marshland, defined as wetland dominated by herbaceous or shrub-like vegetation on a mineral (non-peat) substrate (Greb et al., 2006). The presence of a thin O horizon in 11 % of the gleyed Inceptisols implies that small mires developed locally.

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Vertisols represent only 9 % of the palaeosols identified in the Norham core, suggesting that they probably developed above the water table on relatively small and isolated areas on the floodplain (Fig. 10). At 23 % Vertisols are considered to be proportionally over-represented in the Burnmouth section, probably because they are easier to identify than the other, generally thinner palaeosols. However, approximately similar numbers (19 and 15 respectively) were recorded.

Although no direct correlation between root length and the size of the plant above ground has been found (Raven and Edwards, 2001), rooting depths of 80 - 100 cm seen here have been considered by Algeo and Scheckler (1998) to be associated with arborescent plants from the Famennian onward. We did not find any tree stumps from the Vertisols. However, examples at the base of some of the beds overlying Inceptisols (Fig. 5H), are similar to those reported from the Tournaisian Horton Group in eastern Canada by Rygel et al. (2006). The trunks in the Horton Group have diameters of 10 - 110 cm, whereas those found at Burnmouth in the gleyed Inceptisols range from 6 to 14 cm. Using the relationship of tree width to its height (Eq. 3) proposed by Niklas (1994); where *H* is tree height in meters and *B* is the diameter of the trunk in meters ($R^2$ = 0.95 and S.E. = ±0.9 m):

$$H = 21.9B^{0.889} \tag{3}$$

The trees in the gleyed Inceptisols at Burnmouth were no taller than 3.8 m. It is known from other Ballagan Formation sections near Foulden, just 6 km SSW of Burnmouth, that the gleyed Inceptisols were dominated by small shrubby ferns such as *Lyrasperma scotica* (Retallack and Dilcher, 1988). At this locality tall forest trees have also been found, such as *Stamnostoma huttonense*, which have trunk diameters of 1.4 m and are thought to have been up to 25 m tall. These are interpreted by Retallack and Dilcher (1988) to have

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grown on the better drained palaeosols. This suggests that the forests were restricted to those areas where thick, better drained palaeosols were present.

Vertisols are only present in the uppermost 200 - 300 m of both the section at Burnmouth and in the Norham core (Fig. 10). This could indicate that there is increasing aridity later in the Tournaisian. However, this is not corroborated by any of the other palaeosols, such as the gleyed Inceptisols which are generally constant through the section. Alternatively, the abrupt appearance of Vertisols may be due to palaeosol progradation rather than climatic change.

In the Norham core 29 % of the palaeosols preserve polygonal or vertic cracks. Although this result could not be replicated at Burnmouth due to poor exposure of many of the palaeosols tops, this suggests that the floodplain was frequently exposed to periods of evaporation and desiccation. High evaporation rates are also implied by the presence of thin evaporite beds in the Norham core and in other sections by sporadic siltstone pseudomorphs after halite (Andrews et al., 1991; Turner, 1991; Williams et al., 2005).

More than half of the Inceptisols, gleyed Inceptisols and Vertisols have a gleyed surface horizon (Eg), commonly overlying a reddened Bt or Bk horizon. The presence of drab root halos, together with the gley horizon, but absence of siderite nodules implies that the soils may have been flooded by surface water (Retallack, 1994). Flood-generated sandy siltstone beds overlying many of these palaeosols have been interpreted to result from low-energy flooding events, supporting this hypothesis (Bennett et al., 2016). The preservation of roots as carbon films, rather than as drab root halos, in the uppermost part of the palaeosol and within the flood-generated sandy siltstones, indicates that the flood waters were poorly oxygenated or that deposition was rapid. Retallack et al. (1985) and Retallack and Huang (2011) have described similar palaeosols from upper Devonian strata in New York State, as

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have Caudill et al. (1996) and Bashforth et al. (2014) from the Carboniferous of New Brunswick, Canada. They are interpreted to be surface water gleys where stagnant water has filled root channels (Kraus and Hasiotis, 2006).

The picture that emerges is of a floodplain where bodies of standing water are juxtaposed with areas of developing soils (Fig. 11). Pedogenesis was regularly interrupted by low-energy flooding events (Bennett et al., 2016). By contrast, the thick Vertisols represent parts of the floodplain that were less affected by flooding as, based on their thickness and level of development, these soils could have taken thousands of years to develop (cf. Retallack, 1994). Overall, the palaeosols suggest that the Ballagan Formation floodplain was a diverse seasonal wetland (Fig. 12). It is not possible to determine the lateral extent of the different palaeosol types from the core and sections at Burnmouth and Crumble Edge. It is also not possible to trace any particular palaeosol between the sections. However, the occurrence of all the palaeosols throughout both sections suggests that a mosaic of environments co-existed.

Andrews et al. (1991) and Stephenson et al. (2002) have suggested that the Ballagan Formation contains evidence of marine incursions which Andrews et al. (1991) envisaged as short-lived events, possibly storm surges. The high frequency of palaeosols throughout the Ballagan Formation (Fig. 10) suggests that at no time was there a prolonged marine flooding event in the Tweed Basin.

*5.4. Palaeoprecipitation and seasonality*

The CIA-K and CALMAG weathering ratios of palaeosols with a Bw or Bt horizon (Fig. 9) can be used to determine mean annual precipitation (MAP) (Adams et al., 2011; Nordt and Driese, 2010; Sheldon and Tabor, 2009). Many of the palaeosols in this study do not show readily distinguishable chemical enrichments in the lower horizons (Fig. 9)

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precluding the use of such proxies. Typically this is caused by reworking of palaeosol material on the floodplain; however, reworked palaeosol material only makes up a minor component of the parent overbank material (Bennett et al., 2016). To ensure that the palaeosols have undergone significant phyllosilicate weathering Sheldon and Tabor (2009) proposed that only samples with a difference of 5 - 8 units in the CIA-K ratio between the B horizon and the parent material are used in the calculation. Many palaeosols in our study overlie, and are overlain by sediments that have undergone some pedogenesis, and therefore samples without rooting and with primary lamination were selected to act as the closest proxy to the parent material of the palaeosols. As a result of this screening, only palaeosols NOR148, NOR6, and NOR5 were different enough from the parent material to be used to estimate palaeoprecipitation.

The screened palaeosols are all Vertisols. Adams et al. (2011) and Nordt and Driese (2010) have claimed that the standard relationship between CIA-K and MAP is not accurate for Vertisols and either a variant of the CIA-K MAP relationship or the CALMAG MAP relationship should be used. The standard CIA-K -MAP relationship gives an estimated average precipitation of 1370 mm per year (max 1501 mm, min 988 mm) through the Ballagan Formation, whereas the CIA-K MAP modified for use with Vertisols gives an estimated average of 1368 mm per year (max 1458 mm, min 1064 mm); a similar estimated average of 1037 mm per year (max 1103 mm, min 811 mm) is obtained from the CALMAG MAP relationship. Stratigraphically, the difference between the average MAP estimates of 74 - 112 mm is within experimental error (CIA-K = ±181 mm; CALMAG = ±108 mm) (Nordt and Driese, 2010; Sheldon and Tabor, 2009).

The MAP estimates, along with the previously determined palaeolatitude at this time of 4ºS of the equator (Scotese and McKerrow, 1990), enable us to conclude that the northern UK lay within the tropical climate regime (Peel et al., 2007). A monsoonal climate has been

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proposed for the early Carboniferous of northern Britain based on a study of tree rings by Falcon-Lang (1999) and on Arundian palaeosols in South Wales by Wright et al. (1991). This is supported by plate reconstructions which suggest that the British Isles would be under the Intertropical Convergence Zone, where the highest tropical rainfall occurs. During the southern hemisphere summer it is predicted that a large area of low atmospheric pressure would have formed over Gondwana drawing these rains south and causing a dry season over southern Laurussia (Falcon-Lang, 1999; Wright, 1990).

Based on Tournaisian and Visean sections in the south of England, Wright (1990) suggested a semi-arid climate with monsoonal rain. While our study gives palaeoprecipitation values within the modern monsoonal range and provides plentiful evidence of high evaporation rates, we have not confirmed the tendency towards more semi-arid conditions towards the top of the Tournaisian that he demonstrated. This may be related to local floodplain palaeogeography, though in the western Midland Valley of Scotland the Ballagan Formation is overlain conformably by the lower Visean (Chadian) Clyde Sandstone Formation, comprising stacked fluvial sandstone bodies with common calcretes (Andrews and Nabi, 1998; Browne et al., 1999) suggesting a return to semi-arid conditions.

The highly variable water table demonstrated by the palaeosols in the Ballagan Formation is illustrated in Figure 11 by the inverse relationship shown between the thickness of palaeosols and that of grey laminated siltstone. In those parts of the sections where palaeosols dominate there is a reduced thickness of grey laminated siltstone. Deposited in a range of settings, from lacustrine to marine, the grey laminated siltstones can be used as a proxy for relatively stable sub-aqueous deposition. This suggests that some parts of the flood plain were under water for long periods and others switched back and forth between palaeosol and bodies of standing water caused by a degree of micro-topography on the floodplain (Fig. 12).

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Thin evaporite deposits, associated with ferroan dolostones and some with laminated grey siltstones are found throughout the section. Evaporites in seasonal tropical climates have been reported from the Pennsylvanian of New Mexico by Falcon-Lang et al. (2011). In the British Virgin Islands and in wetlands in Ghana that experience a seasonal tropical climate today (similar to that proposed for the Ballagan Formation) salinity in pools, ponds and lagoons varies greatly depending on the degree of connection to the sea (e.g. Jarecki and Walkey, 2006; Gordon et al., 2000). Evaporites such as gypsum crusts form during the dry season when seawater seeps into ponds continuously supplying salts, without introducing sufficient seawater to cause flushing of the deposit (Jarecki and Walkey, 2006).

*5.5. Comparison between Famennian and Tournaisian tetrapod sites*

Retallack (2011) proposed that the overlap between the intertidal zone and woodlands within brackish mangrove communities is a likely environment in which the transition of tetrapods on to land would occur. By contrast, the Upper Devonian strata of East Greenland, where the largely aquatic tetrapods *Ichthyostega* and *Acanthostega* were found, has been interpreted as an arid, low-sinuosity fluvial and lacustrine system (Astin et al., 2010). The sections there include a 460 m thick, stacked succession of Vertisols. Frasnian to Famennian tetrapods from New South Wales, Australia, are associated with fluvial sandstones and reddened overbank deposits including palaeosols indicative of fairly dry conditions (Campbell and Bell, 1977; Young, 2006). By contrast, Frasnian and Famennian rocks from Red Hill and other localities in Pennsylvania record evidence of lycopsid wetlands and abundant Vertisols and Aridisols with carbonate nodules thought to represent a sub-humid floodplain (Retallack et al., 2009; Cressler et al., 2010; Daeschler and Cressler, 2011). There, tetrapod bones are found in oxbow lake margins. Other tetrapod-bearing sections have shown that in the Famennian tetrapods inhabited environments from brackish lagoons to lakes and woodland-dominated fluvial systems (Retallack, 2011).

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There are few Tournaisian localities worldwide from which palaeosols have been described, and only one of those – Blue Beach, Nova Scotia – has so far yielded tetrapod fossils (Anderson et al., 2015; Falcon-Lang, 2004; Graham, 1981; Moore and Nilsen, 1984; Rygel et al., 2006). The Horton Group in Nova Scotia and the Albert Formation (part of the Horton Group) in New Brunswick contain palaeosols similar to those recorded here in the Ballagan Formation (Falcon-Lang, 2004; Rygel et al., 2006). The palaeosols in the Albert Formation are described as "grey vegetated wetlands, red desiccated mudstone beds are interpreted as well-drained, Entisols and Inceptisols on a vegetated flood basins that formed under a seasonally dry climate as indicated by pedogenic carbonate nodules" (Falcon-Lang, 2004). Whereas the palaeosols are similar in both formations, the Albert Formation lacks the cementstone beds that are abundant in the Ballagan Formation. The Horton Group in Nova Scotia contains “nodular and stratified dolomite” and “green rooted mudstones” with abundant tree stump casts (Rygel et al., 2006). However, these sections lack reddened claystones or vertic cracks characteristic of the Ballagan Formation. The broad similarities between the sections in the Horton Group and those in this study suggest that the overall terrestrial palaeoenviroment represented in the Ballagan Formation may have been extensive, but local variations controlled the types of palaeosol that formed.

There is evidence that salinity in the Ballagan Formation sediments varied. Evaporite beds and the brecciated gleyed Inceptisols have elevated [Na+K]/Al ratios. Morphologically, the gleyed Inceptisols are similar to the marsh palaeosols reported from the Devonian of New York, USA by Retallack and Huang (2011). However, those soils have [Na+K]/Al ratios identical to the dryland palaeosols in the same section (wetland 0.23 - 0.25; dryland 0.23 - 0.28). In our study, the gleyed Inceptisols have [Na+K]/Al ratios of 0.34 - 0.41 compared with 0.25 - 0.37 for the dryland Vertisols. Interpretation of this difference must be cautious because K in particular, can be redistributed during diagenesis and burial (Sheldon and

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Tabor, 2009). However, the brecciation seen on the top of some of the gleyed Inceptisols, interpreted in to have formed by salt development in the top of the soil, suggests that these palaeosols formed in saline-sodic wetlands (cf. Joeckel and Clement, 2005). Therefore it can be inferred that the vegetation found on these palaeosols must have been halophytic. Furthermore, lycopsid roots are also indicative of very shallow water, and a potentially saline wetland or salt marsh environment (Rygel et al., 2006; Raymond et al., 2010). By contrast, the terrestrial to aquatic vertebrate, arthropod and mollusc fauna present within sandy siltstones that overlie palaeosol beds indicates that floodplain pools and lakes were mostly freshwater to brackish (Bennett et al., 2016).

From the Visean onwards tetrapods seem to have preferred swamp woodlands and forest habitats (Retallack, 2011). While the Ballagan Formation does not contain any coal mires or 'swamp' palaeosols (e.g. Sproul pedotype of Retallack et al., 2009 and Retallack, 2011), there is a significant increase in the proportion of gleyed palaeosols compared with Famennian sections (e.g. Astin et al., 2010; Retallack et al., 2009; Retallack and Huang, 2011). The Tournaisian Ballagan Formation comprises 40 % more grey siltstones than red, compared with the Famennian tetrapod-bearing sections of Red Hills and Pennsylvania (Retallack et al., 2009; Retallack and Huang, 2011; Retallack, 2011) where there are 46 - 63 % more red siltstones. Whereas reddened palaeosols cannot be used to indicate aridity (Sheldon, 2005), the comparison suggests that the permanent ground-water table was higher in the Tournaisian sections. This might have been advantageous to tetrapods by providing a diversity of different floodplain water-bodies, such as marshes, pools and lakes, aside from fluvial systems and subaerial habitats. Other animals may have also benefited from the seasonal wetland environment: ostracods, bivalves and shrimp-like arthropods (Pygocephalomorpha) first adapted to freshwater in the early Carboniferous (Gray, 1988; Bennett, 2008; Bennett et al., 2012) and were a key part of the food chain. Actinopterygians,

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rhizodonts, dipnoans, tetrapods, acanthodians and elasmobranch chondrichthyans also thrived in these early Carboniferous freshwater-brackish environments (Friedman and Sallan, 2012; Gray, 1988).

The extinction of plant groups including trees such as *Archaeopteris* at the Hangenberg event affected the terrestrial landscape (Decombeix et al., 2011) and may have driven the tetrapods from more fluvially dominated upper Famennian environments into the Tournaisian seasonal wetland environments. The seasonal variability of such environments and close juxtaposition of different habitats may have produced the conditions in which previously aquatic tetrapods adapted to the more terrestrial realm.

## 6. Conclusions

The Ballagan Formation of northern Britain provides a window into an environment soon after the Late-Devonian mass extinction, where early Carboniferous tetrapods were known to have been living. The formation comprises a 500 m thick sandstone – siltstone – cementstone succession containing 298 palaeosols described from three sites. The palaeosols are divided into four pedotypes, interpreted to be: Entisols, Inceptisols, gleyed Inceptisols and Vertisols. This study records in detail one of the thickest and most complete successions of palaeosols from the Tournaisian. Rooting is abundant through all the palaeosols, from shallow root mats and thin hair-like root traces to the thicker root traces typical of arborescent lycopods. A floodplain with diverse soil types and vegetation is inferred.

The groundwater table varied widely as shown by the different palaeosols and their geochemistry and was affected by high evaporation rates. The presence of deep vertic cracks and evaporite deposits are indicative of high mean annual rainfall and variable soil alkalinities alternating with periods of wetting and drying. This wet to dry switching suggests a sharply contrasting seasonal climate.

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The palaeosols provide a unique insight into an early Carboniferous tropical coastal floodplain and its tetrapod habitats. The move of tetrapods from the uppermost Famennian aquatic forms to the more terrestrially capable Tournaisian forms occurred in a seasonally changeable environment. The close juxtaposition of a diverse array of habitats may have been a driver in the evolution and radiation of tetrapods into the terrestrial realm.

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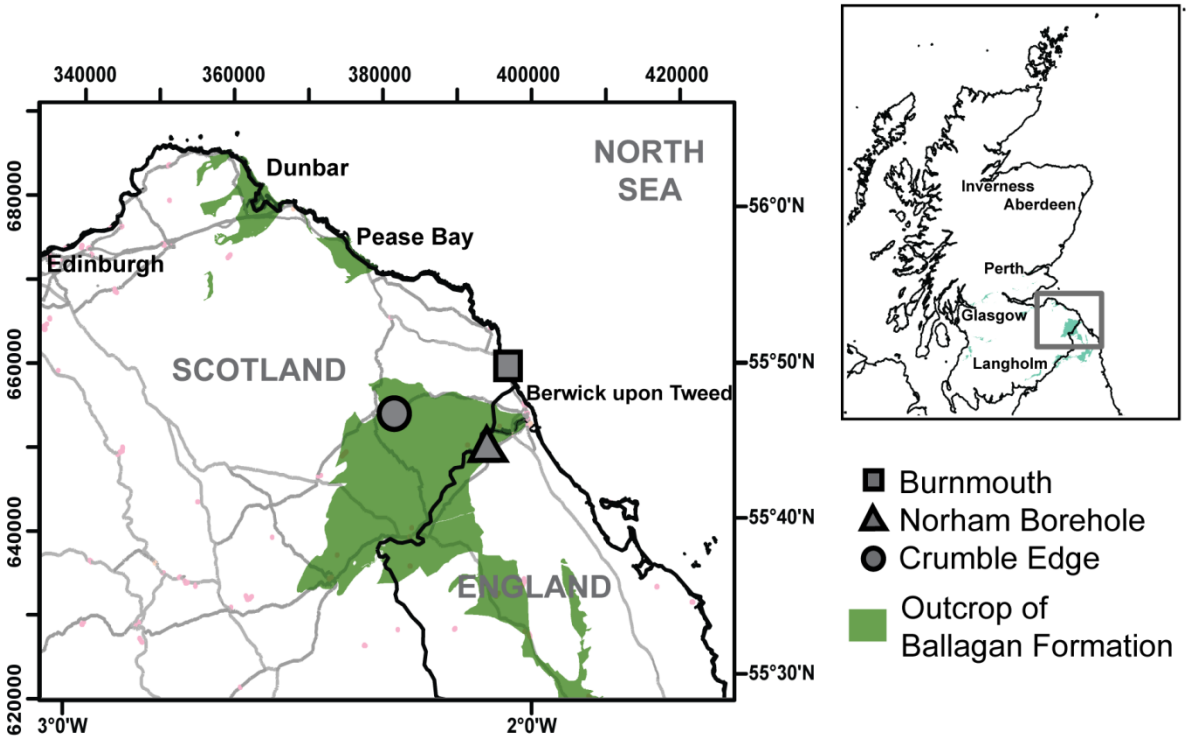
**Figure 1**

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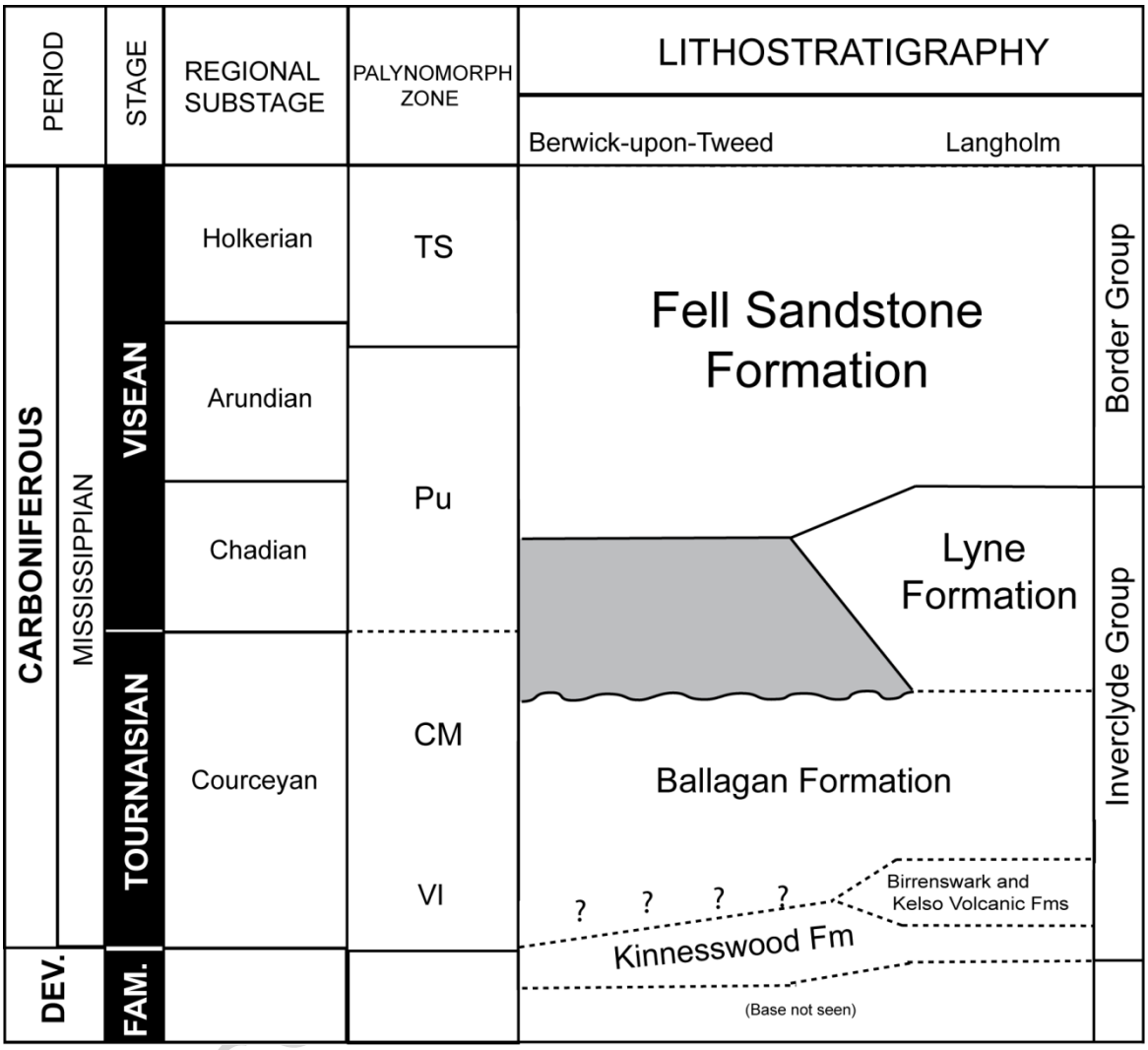

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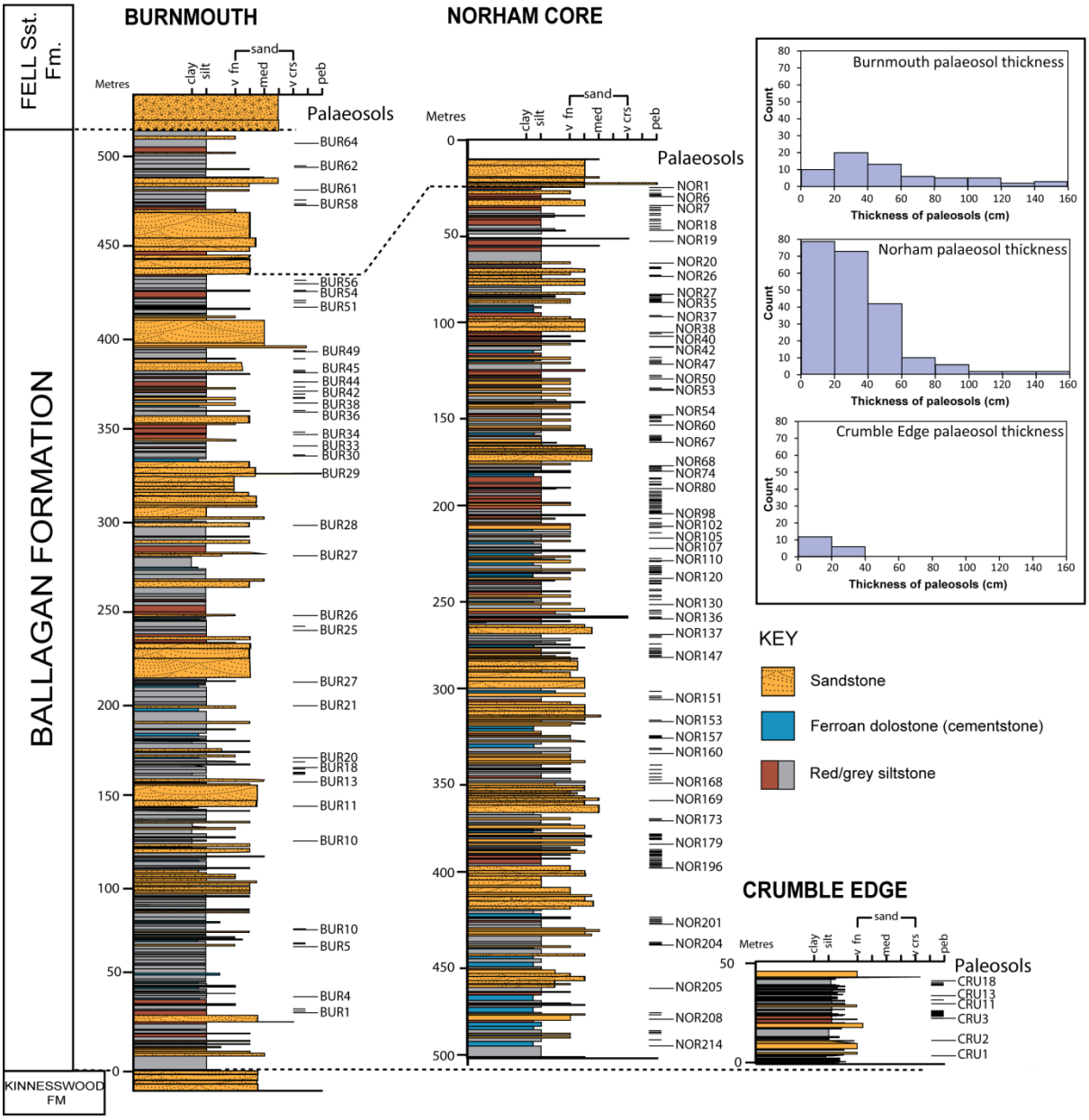

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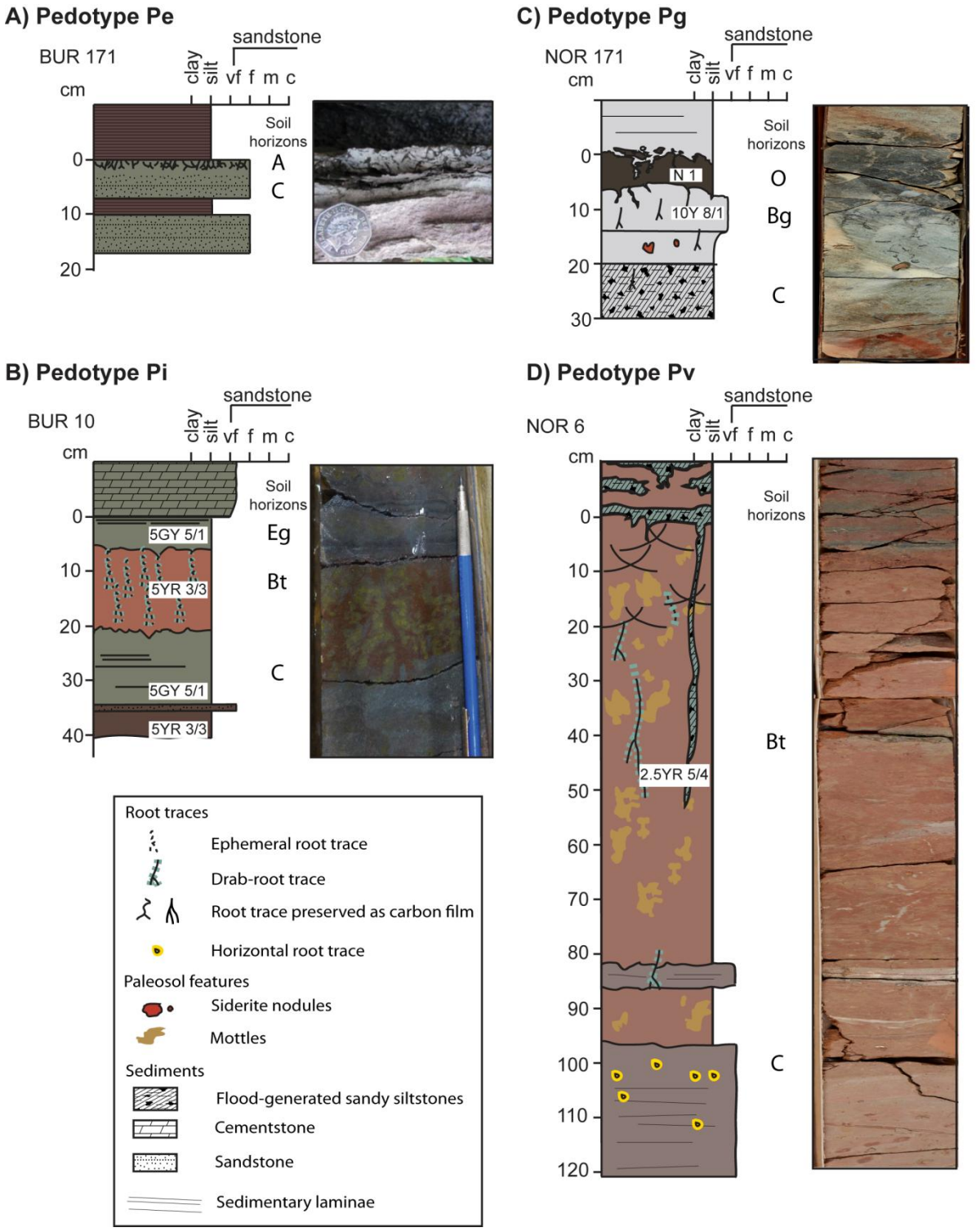

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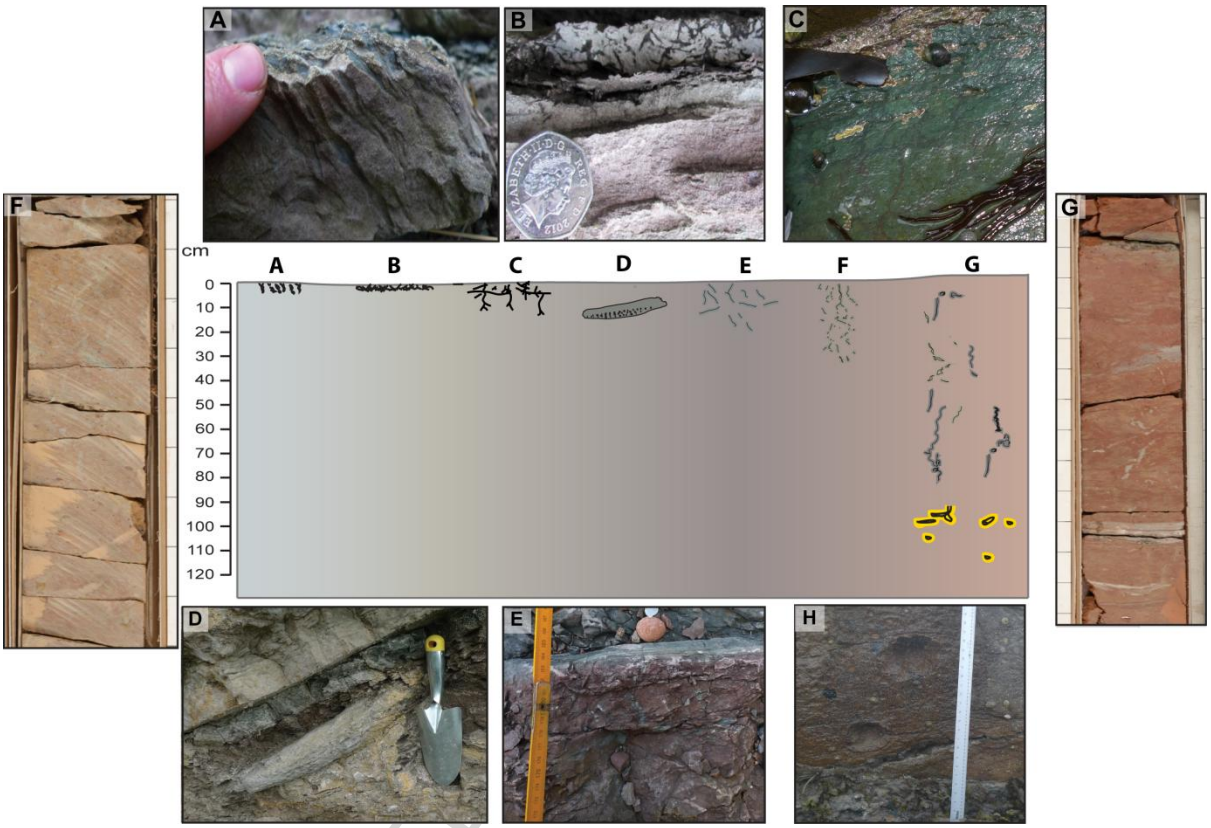


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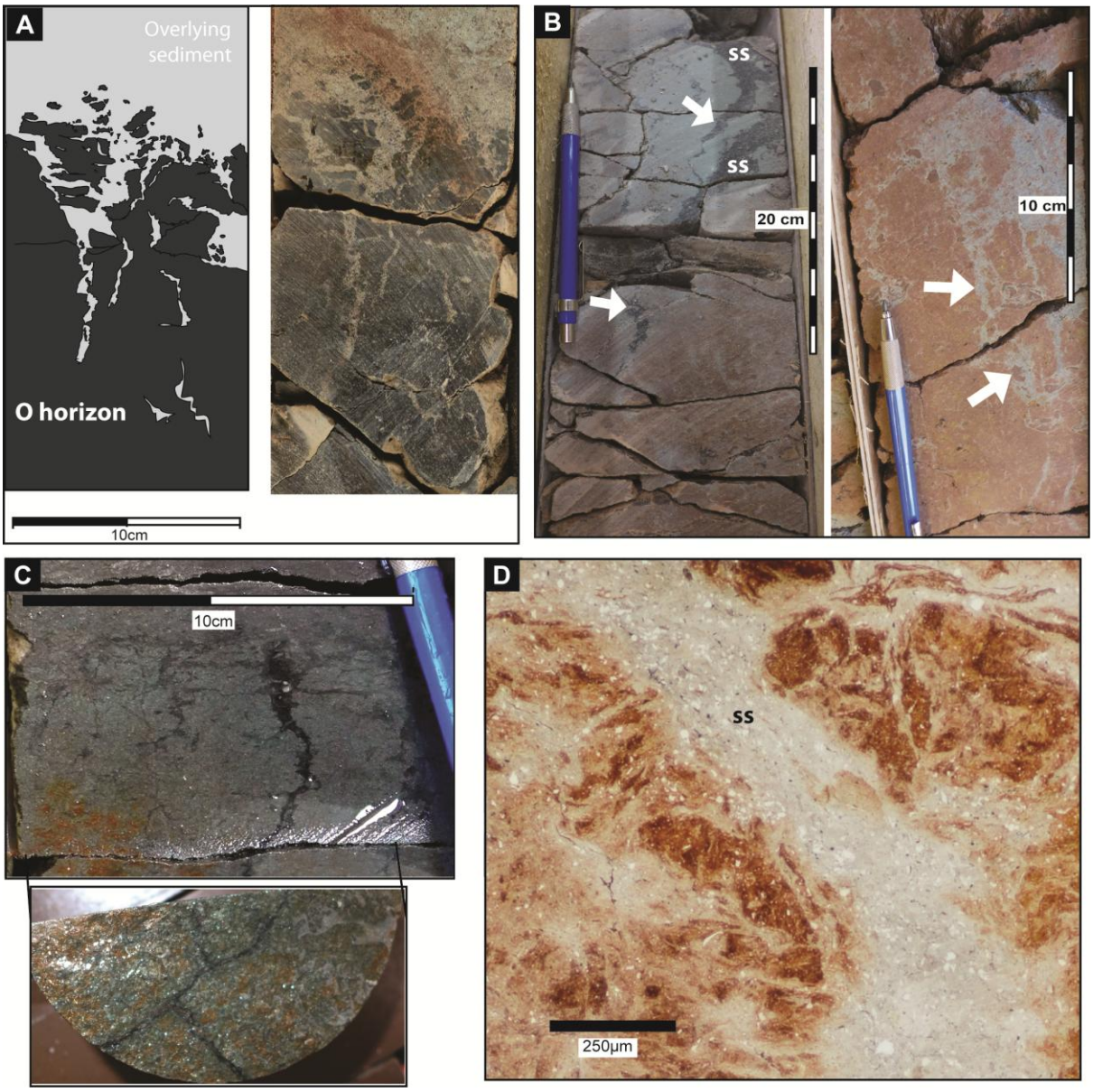

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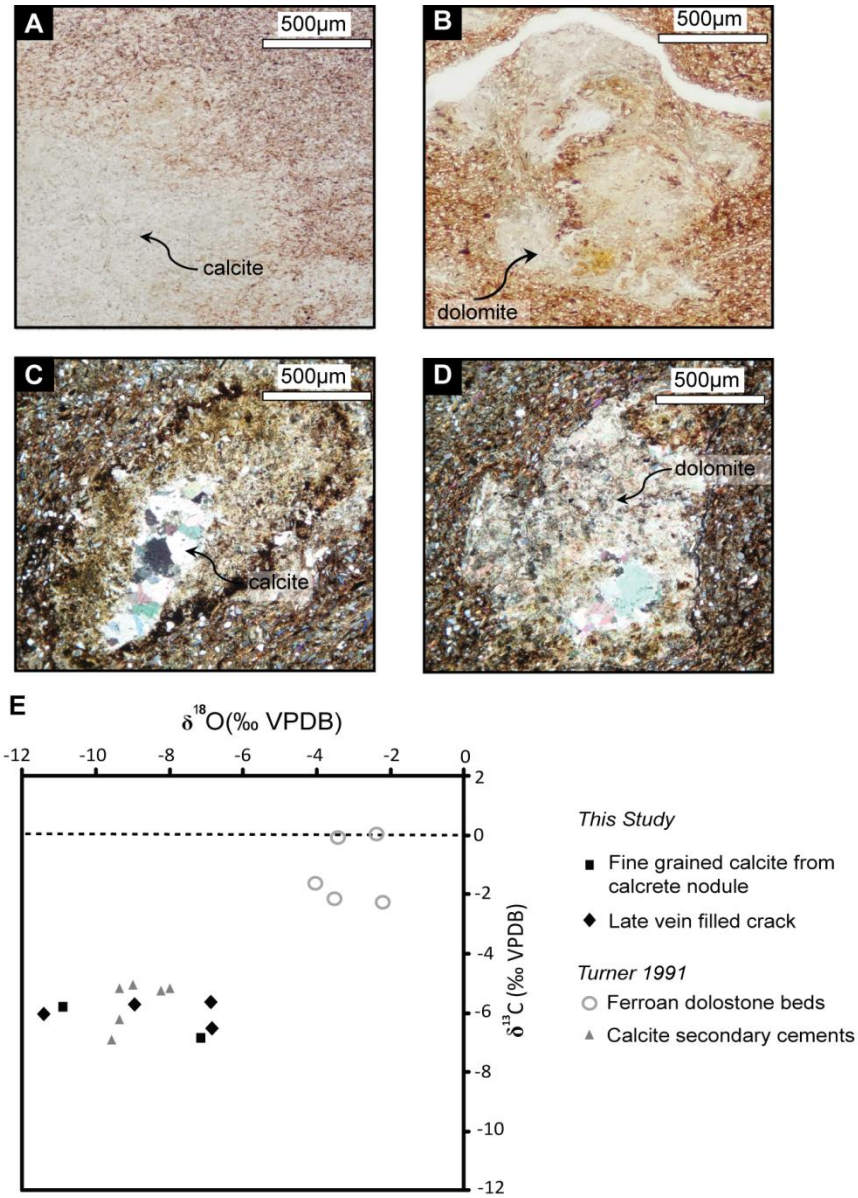

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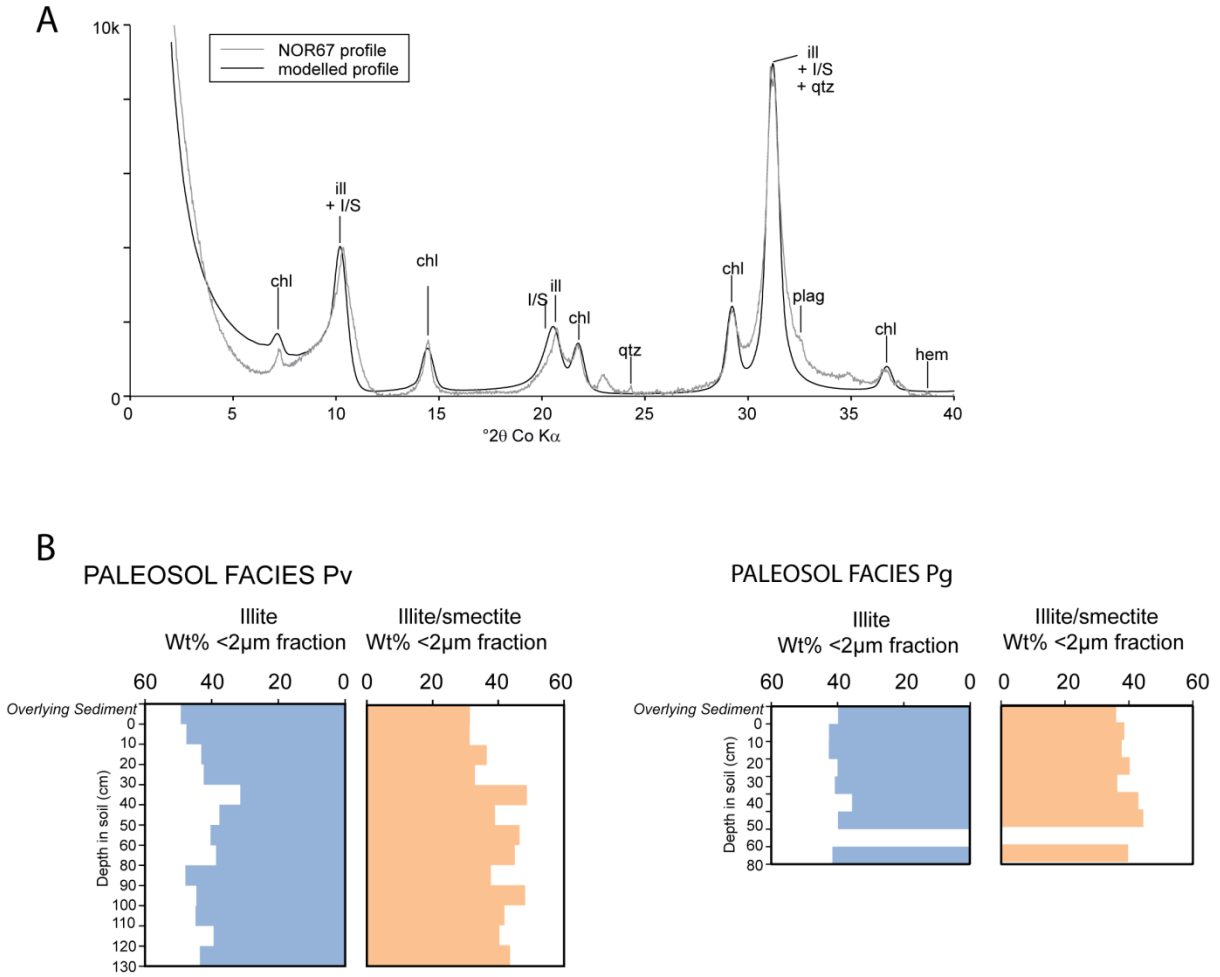

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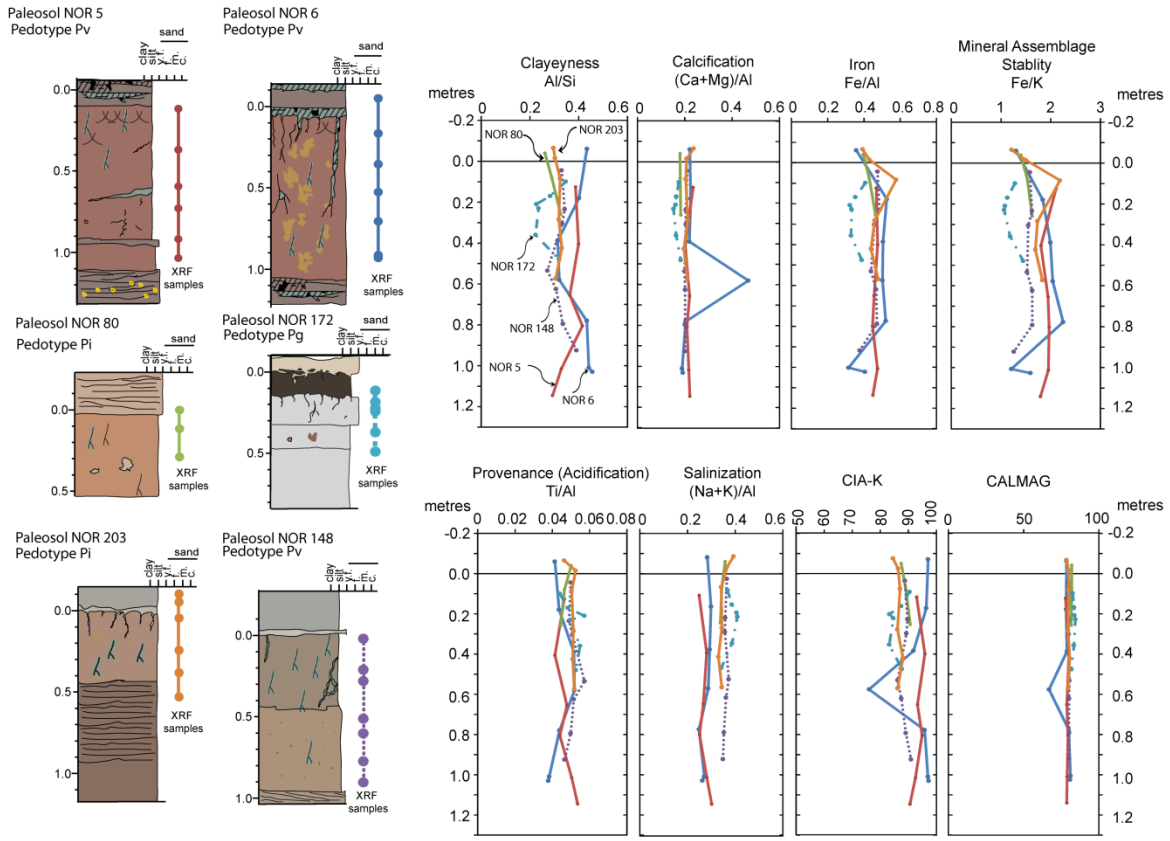

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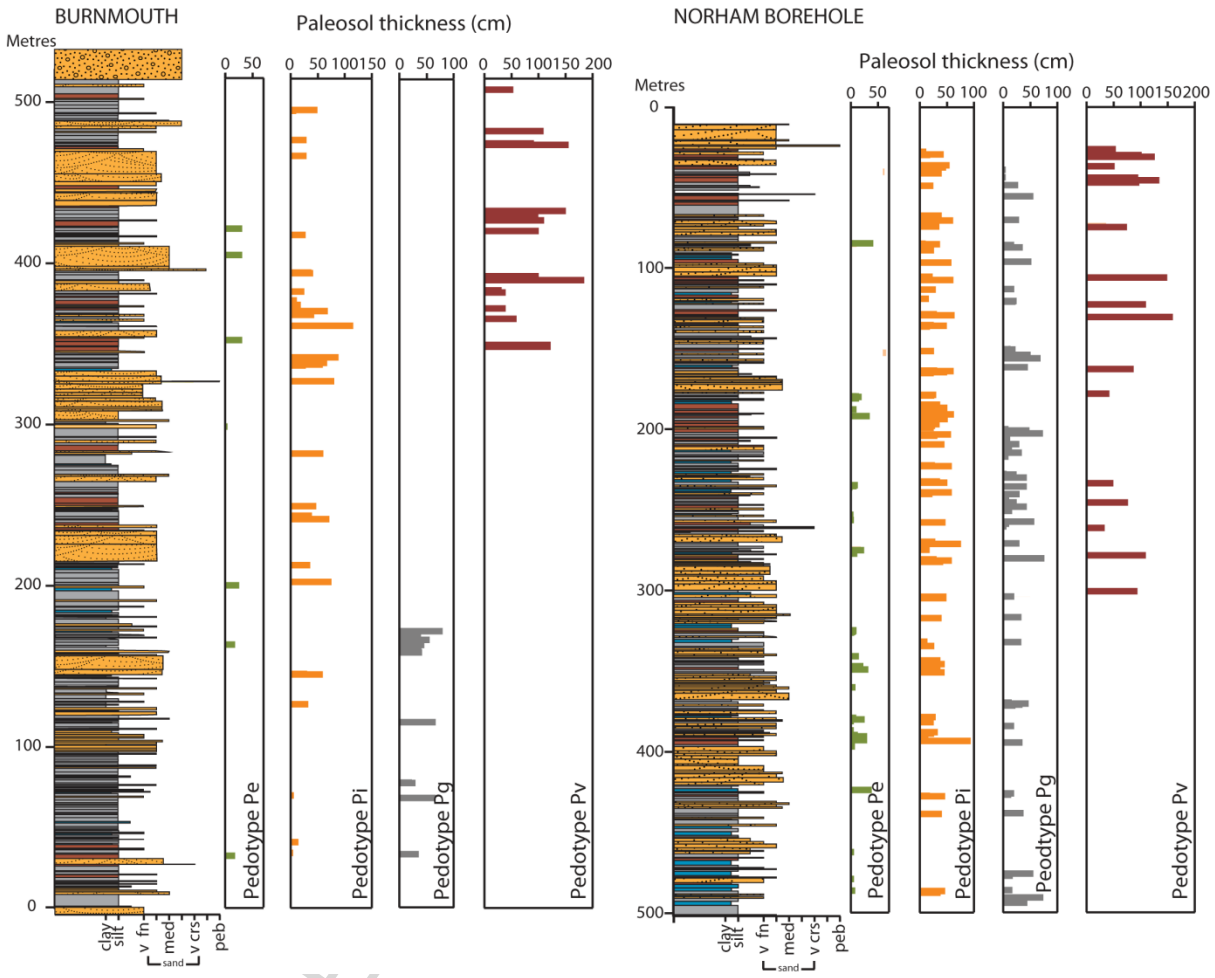

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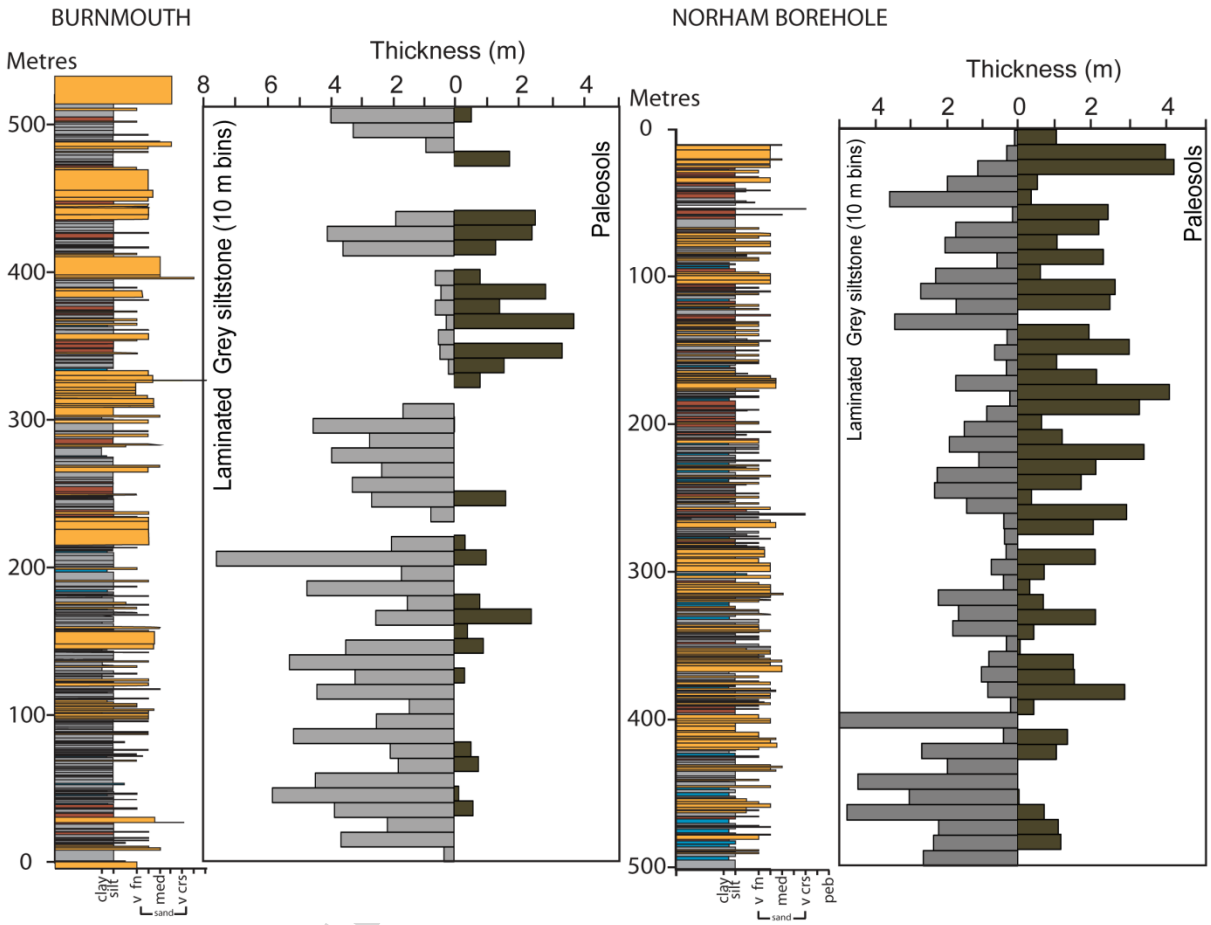

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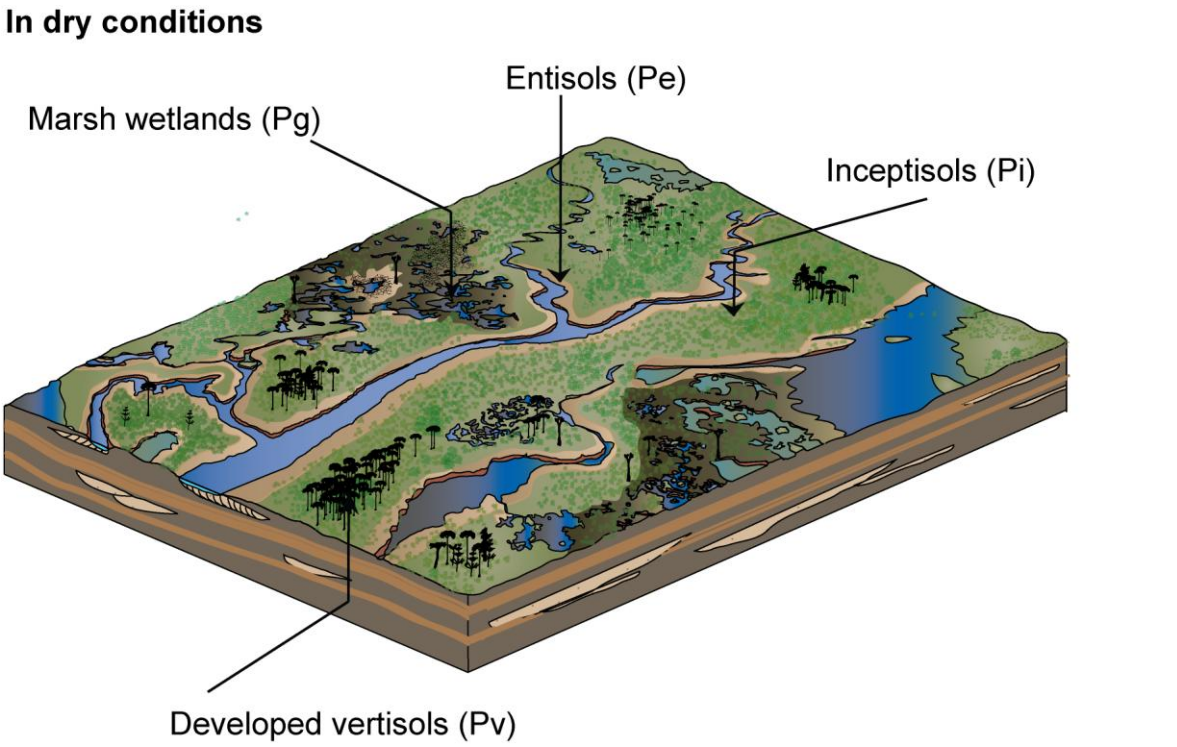


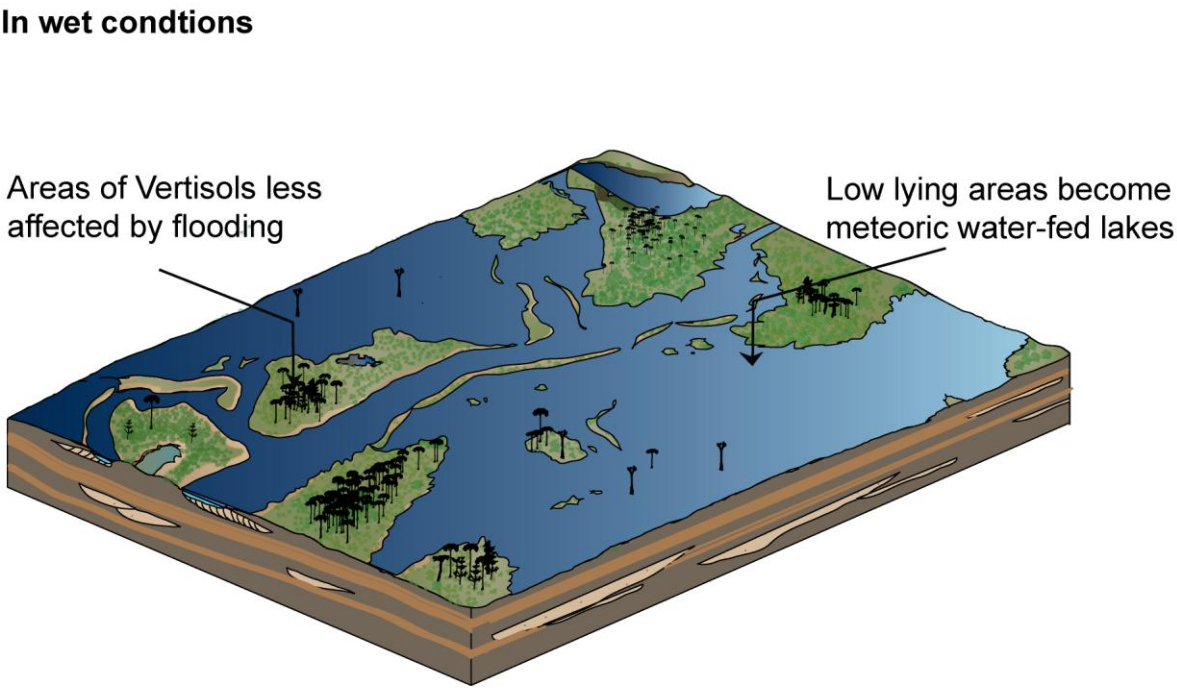

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Fig. 1. Location of the field sections and borehole in this study; Burnmouth, Norham borehole, Crumble Edge. The green area shows the outcrop of the Ballagan Formation, from British Geological Survey DiGMapGB © NERC 2015. (contains Ordnance Survey data © Crown copyright and database right 2016).

Fig. 2. Stratigraphic framework of the Scottish Borders and Northumberland basin (adapted from Waters, 2011). The zonal palynomorphs are VI = *Vallatisporites vallatus, Retusotriletes incohatus*; CM = *Schopfites claviger, Auroraspora macra*; Pu = *Lycospora pusilla*; TS = *Knoxisporites triradiatus, Knoxisporites stephanephorus.*

Fig. 3. Sedimentary logs of sections in this study with locations of palaeosols marked. The box on the right shows histograms of the thickness of palaeosols at each section.

Fig. 4. Examples of the four pedotypes Pe, Pi, Pg and Pv. The core and field photos (on right in each example) illustrate the features recorded in the sedimentary logs (on left in each example). The numbers above the palaeosol (e.g., NOR 6) refer to the specific palaeosol being used to typify that pedotype (see Appendix A). The soil horizons to the right of the logs are explained in the text. Munsell colours of each horizon are shown on the logs. Width of the core in photographs for B, C, D is 100 mm. Scale start at the top of the palaeosol.

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Fig. 5. Root traces found in the Ballagan Formation palaeosols. A) plug roots, B) rootmats, C) carbonized root traces with some lateral branches, D) lycopsid roots, E) drab root traces with some lateral branches, F) drab root linear traces with some bifurcation, G) linear traces with some bifurcation and horizontal roots at depth. H) in-situ tree stumps. The grey shade represents the degree to which the soil is gleyed.

Fig. 6. Observed palaeosol crack types. A) Brecciation is observed to be associated only with, Pg: drawing (left) and core photograph (right). B) Deep penetrating cracks (arrowed) infilled with flood-generated sandy siltstones (ss) in pedotype Pv interpreted to be associated with gilgai micro-topography; C) Polygonal cracks in section (top) and plan view (bottom); D) Polygonal crack infilled with flood-generated sandy siltstone (ss) in a thin section photomicrograph of the same bed illustrated in C.

Fig. 7. Carbonate nodule micromorphology. A) Diffuse carbonate boundary of a nodule; B) fine mass of dolomite crystals surrounding larger crystals of calcite; C) Neomorphic replacement textures in centre of nodule; D) Carbonate nodule with diffuse boundaries in cross-polarised light showing sparry calcite core: E) Calcite isotope plot from palaeosol nodules from this study compared with results from Turner (1991) a representative data set of lacustrine dolomitic cementstones (homogeneous cementstone) and secondary calcite cements from Burnmouth.

Fig. 8. A) Comparison of <2 µm ethylene glycol-solvated X-ray diffraction traces with NEWMOD II-modelled profile to illustrate excellent fit. B) The wt% values for illite and illite/smectite for all palaeosols of pedotype Pv and Pg analysed plotted against depth in soil in 10 cm bins (for results see Appendix B).

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Fig. 9. Geochemical profiles for six palaeosols from the Norham core. Palaeosols NOR5, NOR6 and NOR149 are of pedotype Pv; NOR80 and NOR203 are of pedotype Pi and palaeosol NOR172 is of pedotype Pg (for key to sedimentary logs see Fig.4, (for results see Appendix B).

Fig. 10. Variation in thickness and distribution of the four pedotypes through the Burnmouth and in the Norham core sections (for key to sedimentary logs see Fig. 3).

Fig. 11. The thickness of laminated grey siltstones compared with palaeosols graphed in 10 m thickness intervals. If the grey laminated siltstones are deposited in standing bodies of water this plot can be used as a proxy for the position of the watertable on the floodplain.

Fig. 12. A reconstruction of the Ballagan Formation palaeoenvironment in ‘dry’ conditions when palaeosols are dominant, and in wet conditions when large bodies of standing water dominate. Topographically higher areas of vertisols less affected by flooding.

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**Table 1. Ballagan Formation pedotype classification**

| Palaeosol pedotype | Palaeosol horizon and thickness (cm) | Macromorphology | Classification | |
|---|---|---|---|---|
| | | | after USDA Soil Taxonomy | after Mack et al (1993) |
| Pe | A (5 - 35 cm) | Contains single tapering structures to branching and interlocking mats. | Entisol | Protosol |
| Pi | C (2-18 cm) | Primary sedimentary lamination (cross bedding) | Inceptisol | Protosol |
| | (Eg) (1 – 30 cm) Present in 50% of this pedotype | Greenish grey to greyish green (5GY 5/1 to 5G 4/2). Internally massive and has an irregular boundary with the horizon below. Sinuous filamentous root traces and polygonal fractures. | | |
| | Bt (4-63 cm) | Reddish brown to red (2.5YR 6/3 to 10R 5/6). Extensive root traces which are preserved as drab root halos. | | |
| | C (12-20 cm) | Bluish grey to dark reddish brown (10B 8/1 to 5YR 3/3). Disrupted primary sedimentary lamination. | | |
| Pg | (O) (5 - 15 cm ) Present in 11% of this pedotype | Black (N1), internally massive horizon with elevated TOC compared with rest of profile. Top surfaces commonly broken and brecciated. | gleyed Inceptisol | Gleysol |
| | (Eg) (2 - 45 cm) | Light greenish grey to light bluish grey (5BG 7/1 - 10BG 8/1). Internally massive and has an irregular boundary with the horizon below. Carbonised root traces and polygonal fractures. | | |
| | Bg (10 - 73 cm) | Light greenish grey to Light bluish grey (10G 8/1 - 10B 8/1). Yellow (2.5Y 7/6) mottles and contains nodules of ferro-siderite between 0.2 – 1 cm in diameter. Carbonised root traces. | | |
| | C (3 - 23 cm) | Primary sedimentary lamination (cross-bedding). Some carbonised root traces. | | |
| Pv | Eg (10 - 30 cm) | Dark greenish grey to pale green (5G 4/1 to 5G 6.2). Filamentous root traces preserved as carbon films. | Vertisol | Vertisol |
| | Bt (35 - 123 cm) | Dusky red to red (2.5YR 3/2 to 10R 5/6). Type H rooting structures preserved as drab root halos and minor pale green (5G 4/1) mottles. | | |
| | (Bk) (5 - 15 cm) | Dusky red to red (2.5YR 3/2 to 10R 5/6). 0.5- 2cm in diameter and are of stage II carbonate nodules. | | |
| | C (10 - 20 cm) | Dusky red (2.5YR 3/2). Primary sedimentary lamination. | | |

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**Highlights**

- Paleosols of Tournaisian tetrapod-bearing strata in Scotland are described.
- Four pedotypes identified: Entisols, Inseptisols, gleyed Inseptisols, Vertisols.
- Coastal floodplain with diverse mosaic of habitats include marsh and forest.
- Tetrapods lived in tropical seasonal wetland with rainfall of 1000–1500 mm/year.
- Increased terrestriality in tetrapods may be driven by move to seasonal wetlands.

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