# The position of the Permo-Triassic boundary in Devon, UK

*R.W. Gallois*

Gallois, R.W. 2014. The position of the Permo-Triassic boundary in Devon, UK.
*Geoscience in South-West England*, **13**, 328-338.

An almost complete Permo-Triassic succession over 3 km thick is exposed on the south Devon coast between Torbay and Lyme Regis. With the exception of the youngest (Rhaetian) part, the succession is in red-bed facies that includes breccias that were deposited in wadis and on fans, aeolian and fluviatile sandstones, and playa-lake and sabkha mudstones. Few of the formations can be dated with any certainty. Radiometric dates from contemporaneous igneous rocks in the older parts of the succession indicate Early Permian ages; a miospore from the middle part of the succession indicates an Early or Mid Permian age. A reptile track from younger strata also indicates an Early or Mid Permian age. This is overlain by up to >1,000 m of sediments, almost all of which are exposed in the coastal cliffs, for which there is no age-related evidence. A well documented vertebrate assemblage in the higher part of the succession indicates a Middle Triassic age which has been confirmed by magnetostratigraphy. In the absence of reliable age data for much of the succession it has been assumed that it contains unconformities that lasted for up to 10 million years. Re-examination of the field evidence has shown that there are few, if any, geologically important time breaks in the succession and that it is best interpreted as relatively continuous sedimentation punctuated by numerous hiatuses, many of which resulted from climatic changes and a few from tectonic events.

*92 Stoke Valley Rd., Exeter, EX4 5ER, U.K.*
*(E-mail: gallois@geologist.co.uk).*

**Keywords:** Permian, Triassic, Permo-Triassic boundary, stratigraphy, Devon.

## Introduction

A 3,000+ m thick Permo-Triassic succession of terrestrial sedimentary rocks, one of the most complete of its kind in Europe, is exposed on the Devon coast between Torbay and Lyme Regis (Figure 1). There have also, from time to time, been extensive inland exposures in quarries, road cuttings and marl pits. Notwithstanding the wealth of readily accessible exposures, the positions of the Permian-Triassic system boundary and most of the chronostratigraphical stage boundaries cannot be identified with any degree of certainty. This is principally because the sediments, which range from coarse breccias to mudstones, were almost all deposited in oxidising environments that left little palaeontological evidence other than trace fossils that are not age diagnostic. In addition, it is difficult in terrestrial sediments to differentiate local events such as flash floods, river avulsion or a change from a wetter to a drier climate which give rise to erosive lithological boundaries, from unconformities that represent significant time gaps in the sedimentary record.

The internationally agreed Global Boundary Stratotype Section and Point (GSSP) for the base of the Triassic is a section in marine sediments in Zhejiang Province in China where the boundary is taken at the incoming of the conodont *Hindeodus parvus*. Similarly, GSSPs have been agreed for six of the nine Permian stage boundaries, all based on the first appearance of a particular species of conodont, and three of the seven stage boundaries have been agreed for the Triassic, one based on the first appearance of a conodont species and two based on ammonite species. It should be noted, however, that the practicality and advisability of using conodont-based definitions has been questioned by Lucas (2013).

Vertebrate faunas, palynomorphs (spores and pollen), conchostracans (brine shrimps) and trace fossils have been used to correlate parts of non-marine Permo-Triassic successions with the standard marine successions in some areas in Europe. To date, this has not been possible at any levels in Devon. The most promising method of chronostratigraphical correlation described to date for unfossilferous sediments such as these is magnetostratigraphy. Polarity chrons, intervals between reversals of the earth's magnetic field, have been recorded from marine and terrestrial Permian and Triassic successions world wide, and some of these have been correlated with the successions at the GSSPs (Hounslow and Muttoni, 2010). However, in the absence of independent corroborative evidence of the age of the sediments such as that obtained from fossils or radiometric dates, the magnetic signatures still have limited potential.

In a review of the chronostratigraphy of the Devonian to Permian rocks of Great Britain, Warrington *et al.* (2012) concluded that the Permo-Triassic succession adjacent to the system boundary in South-West England includes three unconformities that represent breaks of several million years and that, although the position of the boundary was unresolved, there was sufficient evidence to place it at the base of the Budleigh Salterton Pebble Beds Formation (Figure 2). There is no reliable evidence for the positions of the Permian stage boundaries except for a few radiometric dates from close above the Carboniferous-Permian boundary. Re-examination of the field evidence has shown that one of the three unconformities is a conformable boundary, one may be a lesser sedimentary break and the third may not have lasted as long as

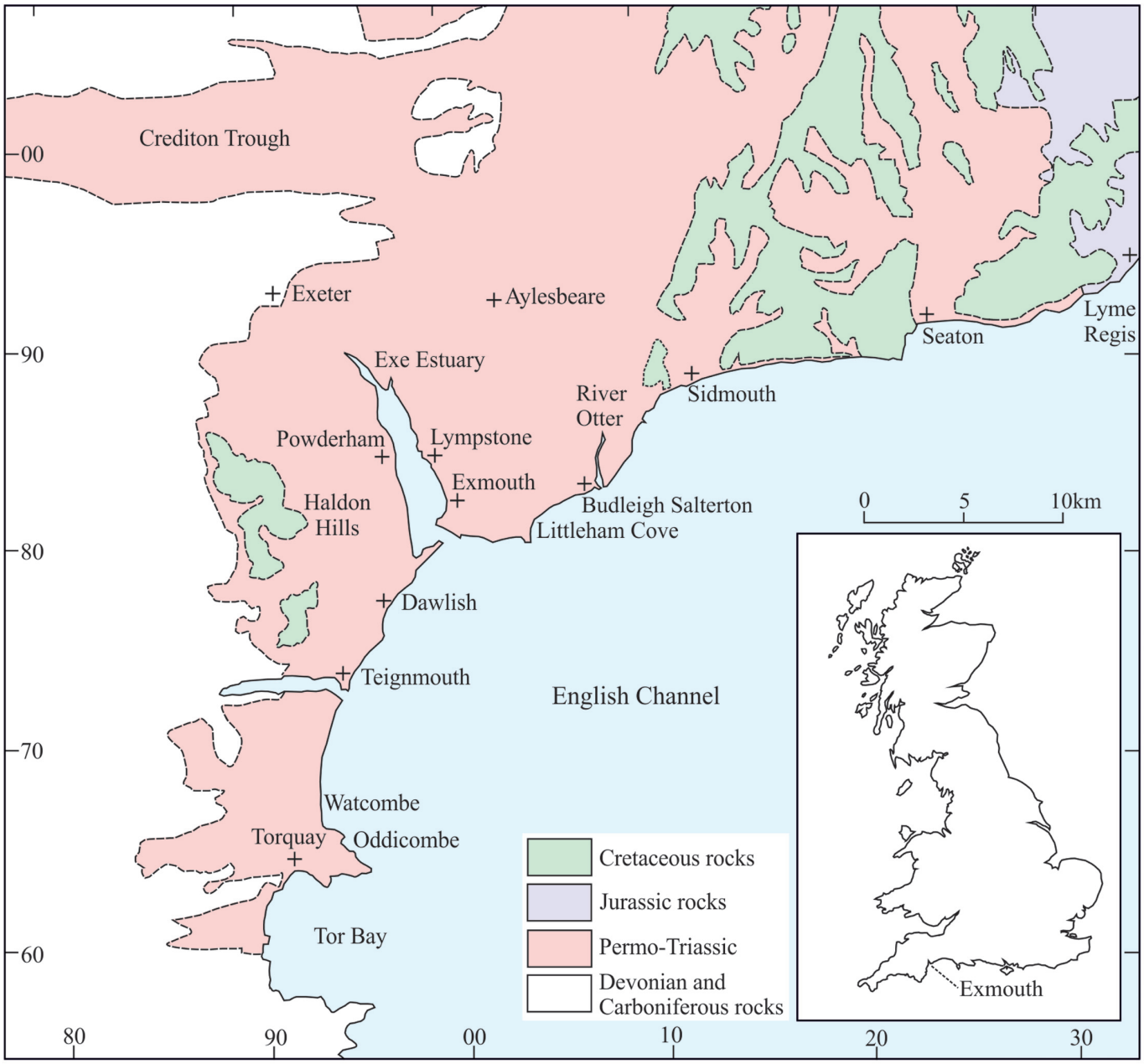


***Figure 1.*** *Geological sketch map of east Devon and the adjacent areas showing the positions of the localities referred to in the text. Drift deposits omitted for clarity.*

previously assumed. The position of the Permian-Triassic boundary remains uncertain somewhere within a succession of >1,000 m of sediments, almost all of which are well exposed.

## Radiometric, faunal and magnetostratigraphical evidence for the age of the Permo-Triassic in Devon

The only direct evidence for the absolute age of the Permian rocks in South-West England comes from radiometric dating. A rhyolite sill [SX 435 504] in the Kingsand Breccia at Kingsand, Plymouth, a correlative of the Torbay Breccia Formation, gave a K-Ar date of 290.7 ± 6 Ma (Leveridge *et al.*, 2002), and lavas in breccias in the Crediton Trough that have been correlated with the Torbay Breccia gave K-Ar and Ar-Ar dates ranging from 290.8 ± 0.8 to 283± 7 Ma (Edwards and Scrivener, 1999). All of these dates are indicative of the early Permian. Note that the error ranges refer to the accuracy of the laboratory measurements, not to the accuracy with which the radiometrically measured samples can be correlated with the agreed or candidate GSSPs that mark the stage boundaries. For example, the base of the Artinskian Stage was revised from 284.4 ± 0.7 Ma in 2004 (Gradstein *et al.*, 2005) to 290 ± 0.1 Ma in 2012 (Gradstein *et al.*, 2012). Similarly, the radiometric ages for the other Permian stage boundaries were revised by between -0.7 and +3.7 Ma during the same period. These revisions reflect in part the difficulty of finding rocks that are suitable for dating in the sedimentary successions that are used for the GSSPs or in successions that can be accurately correlated with those in the GSSPs.

There is no published body-fossil evidence for the ages of any of the formations shown in Figure 2 that are older than the Otter Sandstone Formation. The burrow-like trace fossil *Beaconites*, which has variously been attributed to a worm, a crustacean, an amphibian and a reptile, is relatively common in some of the sandstone lenses in the Torbay Breccia (Ridgeway, 1974; Pollard, 1976) and Watcombe Breccia (Laming, 1954) of the Torbay area, but is not age diagnostic. There is indirect evidence for the age of the Watcombe Formation which has been correlated on lithological grounds with the Whipton Formation of the Exeter area (Edwards and Scrivener, 1999). At

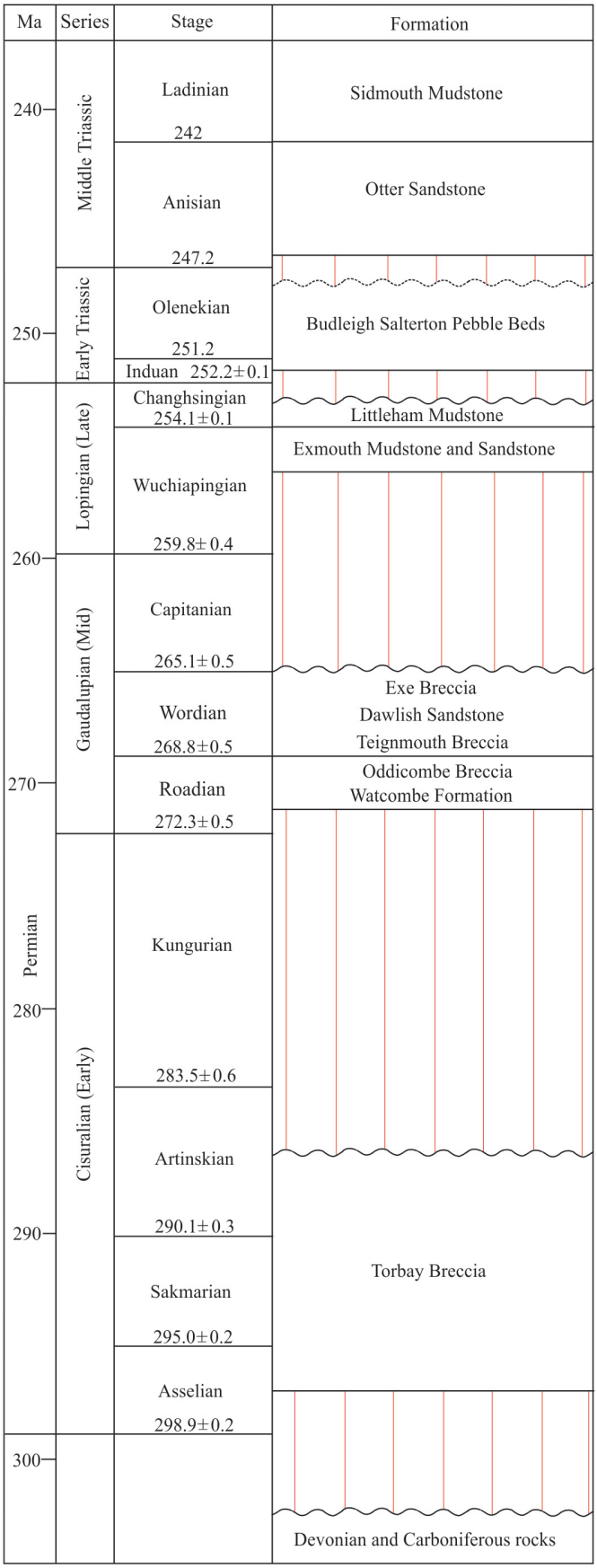


***Figure 2.*** *The presumed ages of the formations adjacent to the Permo-Triassic boundary exposed on the Devon coast. Permian succession and the base of the Budleigh Salterton Pebble Beds based on Warrington et al. (2012, figure 3); ages of younger formations based on Hounslow and McIntosh (2003). Ages of stage boundaries based on International Commission for Stratigraphy Timescale Version 2014-02 (International Commission on Stratigraphy, 2014).*

Exeter, pollen in the Whipton Formation includes the age-diagnostic form *Lueckisporites virkkiae* (Potonié and Klaus) which was attributed by Warrington and Scrivener (1988) to the Late Permian (Wuchiapingian Stage). The same species was subsequently defined by Souza and Marques-Toigo (2005) as the index fossil for the *L. virkkiae* Range Zone of late Cisularian to early Guadalupian age (Kungurian-Roadian Stages). Warrington *et al.* (2012, figure 3) showed the Whipton Formation as Roadian in age. There are no published age data for the Teignmouth Breccia.

The Dawlish Sandstone Formation contains rare trace fossils including crustacean tracks, and a single reported trackway of the mammal-like synapsid reptile *Cheilichnus bucklandi* (Jardine) from a quarry at Poltimore [SX 971 971] (Edwards and Scrivener, 1999, plate 3). The ichnogenus has been recorded in dune sands from widely spaced localities throughout the former Pangaean supercontinent, including the Hopeman Sandstone and related formations in Scotland (Grierson, 1828), the Cornberg Sandstein in Germany and from the USA, Argentina and South Africa (Lucas and Hunt, 2006). *C. bucklandi* is relatively common in the Coconino Sandstone in Arizona in aeolian sand dunes that have been dated as Early Permian (Kreiger, 1965) or Mid Permian (Hunt and Santucci, 1998) in age. In Scotland, the ichnogenus *Cheilichnus* has been recorded together with reptile remains that are indicative of a latest Permian age (Benton and Spencer, 1995).

There is no published evidence for the age of the Exe Breccia, Exmouth Mudstone and Sandstone, Littleham Mudstone or Budleigh Salterton Pebble Beds. In contrast, the age of the Otter Sandstone has been relatively accurately determined by two independent methods. A diverse vertebrate fauna, mostly from the upper part of the formation, is indicative of a Middle Triassic Anisian age (Benton, 1997). Correlation of the magnetostratigraphical signature of the Devon coastal section with that of normal and reversed polarity magnetozones in palaeontologically well documented successions elsewhere in Europe, has confirmed the Anisian age. The correlations indicate that the lower part of the Otter Sandstone is early and mid Anisian in age and that the upper part is late Anisian (Hounslow and McIntosh, 2003). Additional vertebrate finds in the highest part of the Otter Sandstone have confirmed the late Anisian age for this part of the formation (Benton, 2011).

Given the absence of age data for any of the sediments between the Watcombe Formation and the Otter Sandstone, except for the *C. bucklandi*, the positions of the stage boundaries have been based in part on presumed correlations with lithological successions and tectonic events elsewhere in NW Europe. In particular, the reported presence of unconformities at the bases of the Exmouth Mudstone and Sandstone, Budleigh Salterton Pebble Beds and Otter Sandstone are inferred to represent gaps in the sedimentary record of up to 10 Ma (Figure 2).

## Field evidence for the formation boundaries

The most comprehensive accounts of the Permo-Triassic succession of the Devon coastal zone are those of Laming (1954, 1968) and Henson (1971). The latter was summarised with additions in Selwood *et al.* (1984). The succession in the adjacent inland area around Exeter including the Crediton Trough was described by Edwards and Scrivener (1999).

### *Teignmouth Breccia-Dawlish Sandstone boundary*

The transitional boundary is well exposed in the cliffs on either side of Dawlish [SX 961 760 to SX 966 769] where breccias with minor interbeds of fluvial and aeolian sandstone pass up into fluvial and aeolian sandstones with minor breccia interbeds (Selwood *et al.*, 1984). Inland, in the Exeter area, the most prominent lithology in the Dawlish Sandstone is aeolian dune sandstone (Figure 4a). In the Crediton Trough, the

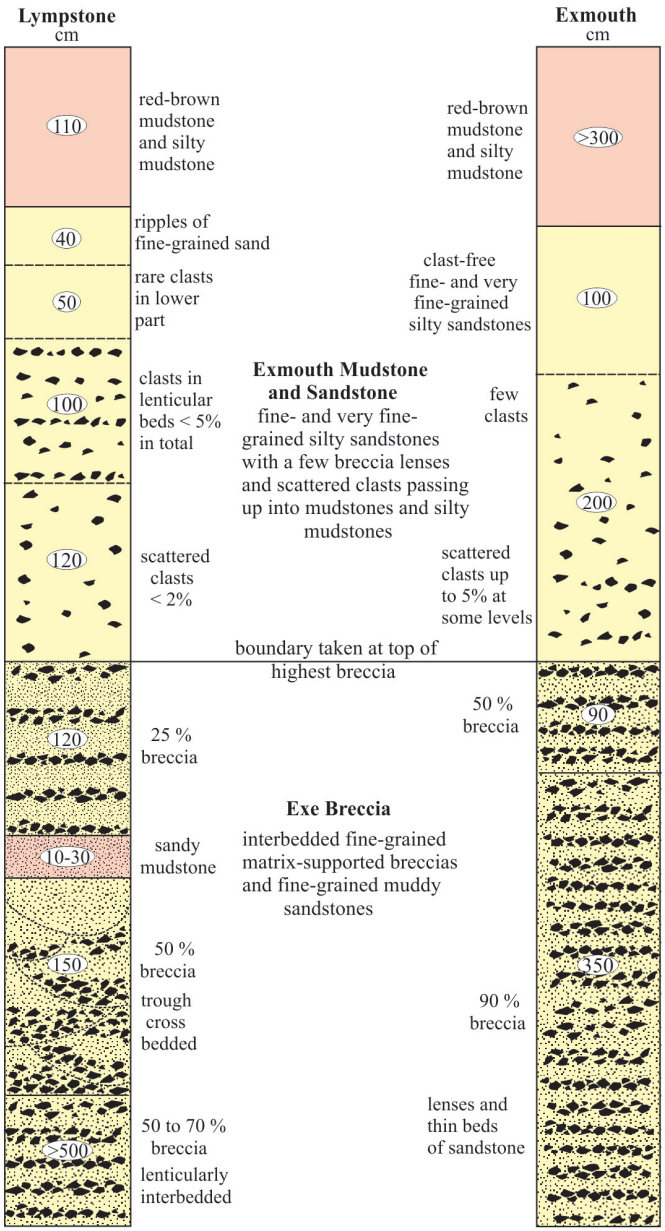


***Figure 3.*** *Graphic sections to illustrate the boundary of the Exe Breccia and Exmouth Mudstone and Sandstone exposed at Lympstone [SX 9901 8365] and Exmouth [SY 0021 8046].*

Dawlish Sandstone oversteps a variety of formations including the Newton St Cyres Breccia, the Shute Sandstone, the argillaceous Yellowford Formation and the Heavitree Breccia which are collectively presumed to be the correlatives of much of the Teignmouth Breccia, and locally rests on Pre-Permian rocks (Edwards and Scrivener, 1999).

## *Dawlish Sandstone-Exe Breccia boundary*

The junction of the Dawlish Sandstone and the Exe Breccia is well exposed in Langstone Cliffs [SX 977 778], 1 km east of Dawlish. There, aeolian sandstones are overlain by fluviatile sandstones with lenticular beds of breccia (Figure 4b) which pass up into interbedded breccias and fluviatile sandstones (Figure 4c), and breccias with sandstone partings and thin sandstone interbeds. The base of the Exe Breccia is taken at an arbitrary level at which breccia becomes the dominant lithology in this transitional succession (Selwood *et al.*, 1984). At Langstone Rock [SX 979 776], where the outcrop is separated from Langstone Cliffs by a fault, up to 8 m of breccia with a few sandstone lenses up to 0.1 m thick is overlain by 15 m of fine- and very fine-grained silty sandstones with scattered clasts and lenses of breccia up to 1 m thick (Figure 4d). Inland, the Exe Breccia is poorly exposed on the west side of the Exe Estuary. Exposures of breccias with sandstone interbeds in road cuttings in the Starcross area [SX 975 818] were mapped as Exe Breccia on the 1:50,000 Sheet 339 (Institute of Geological Sciences, 1976). Farther north, in the Powderham area [SX 951 855] where sandstones locally predominate, the breccias are interpreted as breccias in the Dawlish Sandstone. The only breccia >5 m thick recorded on the west side of the Exe Estuary is that seen at Langstone Rock. Selwood *et al.* (1984) referred to breccias in a reef [SX 999 780] at the mouth of the Exe Estuary that can only be seen at very low tides, but there is no published description of this exposure.

On the east side of the estuary the highest part of the Exe Breccia is exposed in cliffs at Lympstone [SX 9878 8437 to SX 9901 8365] and Exmouth [SY 0021 8046]. The continuous, actively eroding cliff sections at Lympstone are separated into a northern and southern section by a fault zone that passes beneath the harbour. The northern section exposes 22.5 m of interbedded breccias and sandstones in beds mostly 0.2 to 0.4 m thick, including two beds of fluviatile sandstone up to 1.3 m thick and a bed of aeolian sandstone 3.1 m thick (Figures 4e and 4f). The southern section exposes 6.2 m of interbedded breccias and sandstones cut by several small faults. It includes the junction with the overlying Exmouth Sandstone and Mudstone. Up to 3.5 m of breccia overlain by the Exmouth Mudstone and Sandstone is exposed in an abandoned cliff at Exmouth [SY 0021 8046].

The sections in the Exe Breccia on both sides of the estuary dip E or SE mostly at 5° to 10°. Assuming a steady dip of 5° and the absence of faults, the youngest bed exposed west of the estuary is separated from the oldest bed exposed at Lympstone by *c.* 100 m of unexposed strata. Part of the unexposed succession was recorded in the debris from a 1.7 km long gas-pipeline tunnel that ran beneath the estuary from Powderham to Lympstone (Laming and Roche, 2013). This proved sandstones and breccias that they correlated with the Dawlish Sandstone and Exe Breccia respectively, and mudstones that were correlated with the Exmouth Mudstone and Sandstone. The mudstones were proved in five locations along the tunnel: these were interpreted as due to step-normal faulting running approximately oriented parallel to the estuary (Laming and Roche, 2013).

In the current state of knowledge, the combined Dawlish Sandstone and Exe Breccia Formations are best regarded as a single formation comprised of interdigitating lithologies that become finer grained overall when traced northwards. The combined formation roughly equates with the Lower Sandstone of Ussher (1902). In the coastal area, it includes the aeolian and fluviatile sandstones of the Dawlish Sandstone, the Langstone Point and Exeter Shrubbery Breccias of Ussher (1913), the Kennford Breccias of Laming (1968), the Exminster Breccia of Smith *et al.* (1974) and the Exe Breccia of Selwood *et al.* (1984). In the Exeter area it comprises the Dawlish Sandstone including the argillaceous Bussell's Member and the Poltimore Mudstone Member (Edwards and Scrivener, 1999).

## *Exe Breccia-Exmouth Mudstone and Sandstone boundary*

Henson (1970) noted that the junction was exposed in Lympstone cliffs (see below) and described the boundary as a "*sharp contact existing between gravel-free sands and silts characteristic of the formation* [Exmouth Mudstone and Sandstone Formation] *and the underlying breccias* [Exe Breccia]". Selwood *et al.* (1984) referred to the junction as a hiatus (figure 16), a disconformity (table 7) and an unconformity (p.94), but did not supply evidence to support these descriptions. The junction of the two formations is well exposed in the section referred to above (Figure 5a) at the

***Figure 4.*** *(**a**) Dune sandstones in the Dawlish Sandstone. Entrance to the former Bishop's Court Quarry [SX 963 914], Exeter. The face is up to 8 m high. (**b**) Breccia lens resting on an irregular surface cut into aeolian sandstones and overlain by fluviatile sandstones with a few thin breccia lenses. Upper part of the Dawlish Sandstone, Langstone Cliffs [SX 9760 7778], Dawlish: face is 3.5 m high. (**c**) Interbedded breccias and fluviatile sandstones in the transitional boundary between the Dawlish Sandstone and the Exe Breccia, Langstone Cliffs [SX 9773 7787]: face is 7 m high. (**d**) Langstone Rock [SX 9787 7794], Dawlish, the presumed type section of the Exe Breccia. 1. Sandstones, 2. breccias. Cliff is 20 m high. (**e**) Lympstone Cliffs [SX 9875 8420]. 1. River Terrace gravels; 2. Breccias, 3. 3.2 m thick aeolian sandstone with scattered clasts in the lowest part, 4. breccia. (**f**) River cliff on the north side of Lympstone harbour [SX 9873 8417]. 1. River Terrace gravels; 2, 4 and 6 breccias; 3 and 5 sandstones with a few scattered clasts.*

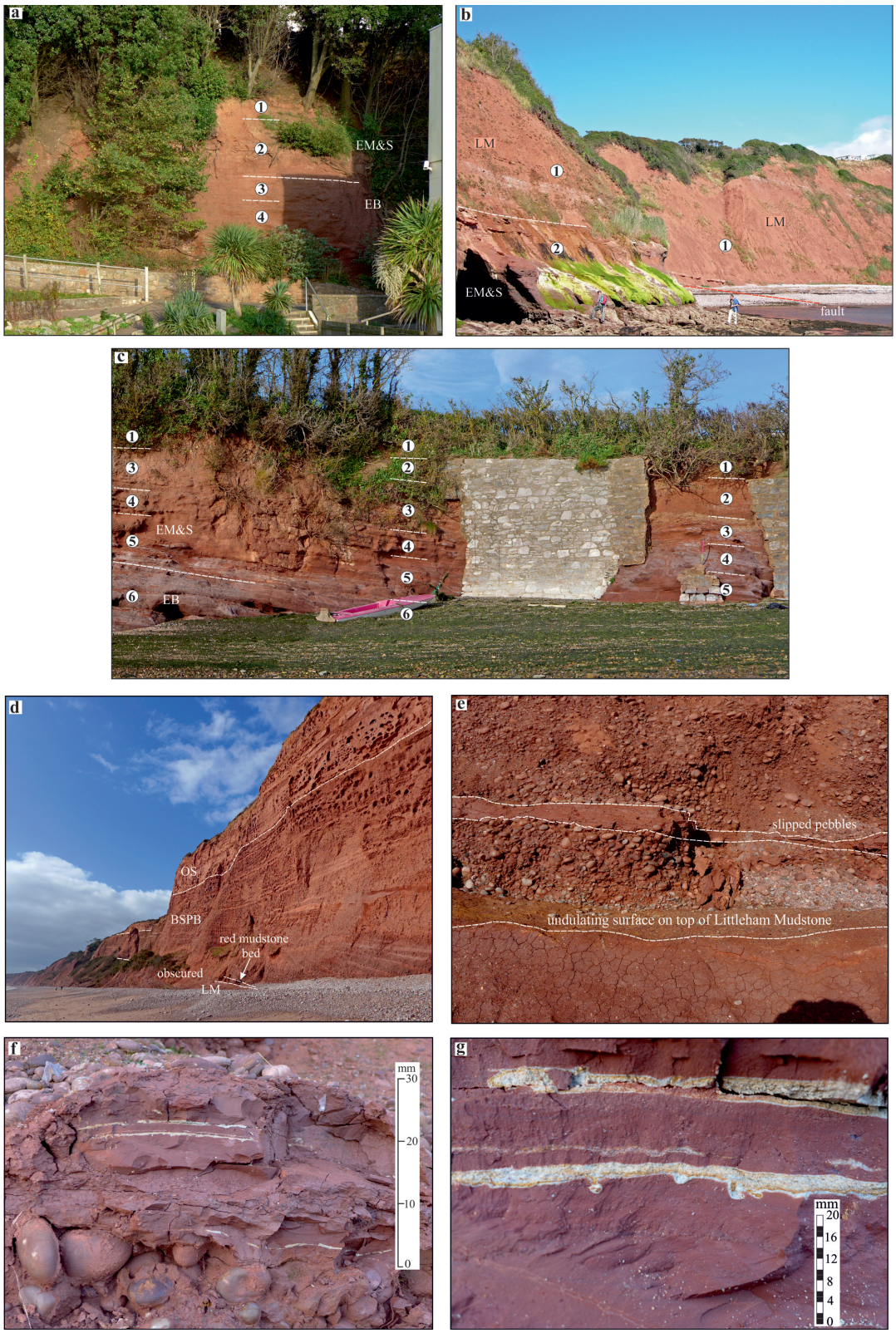


***Figure 5.*** *(**a**) Junction of the Exe Breccia (EB) and the Exmouth Mudstone and Sandstone (EM&S) at Exmouth [SY 0021 8046]. 1. Red-brown mudstone and silty mudstone. 2. Fine- and very fine-grained silty sandstones with scattered clasts in lower part. 3. Interbedded sandstones and breccias. 4. Breccia. (**b**) Junction of the Exmouth Mudstone and Sandstone (EM&S) and the Littleham Mudstone (LM) at the type section at Littleham Cove [SY 0397 8017]. The highest sandstone in the EM&S, a 9 m thick succession of stacked fluvial channels of fine-grained sandstone with a few breccia lenses, is overlain with sharp lithological contrast by red-brown mudstones with several thin (up to 1 m thick) lenticular sandstones in the lowest 20 m. (**c**) Junction of the Exe Breccia (EB) and the Exmouth Mudstone and Sandstone (EM&S), southern end of Lympstone cliffs [SX 9901 8365]. 1. River Terrace and Head deposits. 2. Red-brown mudstone and silty mudstone. 3. Fine- and very fine-grained silty sandstones with a few clasts. 4. Sandstone as above with breccia lenses and scattered clasts. 5. Sandstone as above but with few clasts. 6. Breccias with sandstone interbeds. (**d**) Junction of the Littleham Mudstone (LM) and Budleigh Salterton Pebble Beds (BSPB), west side of Budleigh Salterton [SY 0587 8156]. OS = Otter Sandstone. (**e**) Detail of the junction of the two formations and the bed of red-brown mudstone in the lower part of the BSPB. (**f**) Lamination in the thin mudstone bed picked out by thin (2 to 5 mm thick) siltstone beds. (**g**) Detail of bioturbation at the base of one of the siltstone beds showing that the bed is the right way up.*

southern end of the Lympstone cliffs [SX 9901 8365], and in a more deeply weathered state adjacent to the Esplanade at Exmouth (Figure 5c). Both successions show a similar upward transition from breccias with thin sandstone interbeds to mudstones via sandstones with scattered clasts and breccia lenses in the lower part. The base of the Exmouth Mudstone and Sandstone is taken at the top of the highest breccia bed (Figures 3, 5a and c). The successions, 4 km apart, are unusually similar in both lithology and thickness given the laterally variable nature of most of the rest of the local Permo-Triassic succession. Inland, the Exmouth Mudstone and Sandstone rests on the Dawlish Sandstone at Exton, and when traced northwards from there on progressively older strata until it comes to rest of the Carboniferous Crackington Formation on the south side of the Crediton Trough (Edwards and Scrivener, 1999).

### *Exmouth Mudstone and Sandstone-Littleham Mudstone boundary*

At the type section at Littleham Cove [SY 039 802] the base of the Littleham Mudstone rests with sharp lithological contrast on the higher of two cross-bedded fluviatile sandstones, 15 m and 9 m thick, which form the headland at Straight Point (Figure 5b). When traced inland, the sandstones have been shown to be lenticular beds that cannot be traced farther north than Aylesbeare (Edwards and Scrivener, 1999, figure 22).

### *Littleham Mudstone-Budleigh Salterton Pebble Beds boundary*

The base of the Budleigh Salterton Pebble Beds (BSPB) has been exposed from time to time in a small section (a few metres across) high in the cliff [SY 0575 8154] on the west side of Budleigh Salterton (Figure 5e) where the pebble beds rest on a gently undulating surface of red-brown mudstone at the top of the Littleham Mudstone. In January 2014, during a storm that coincided with a high spring tide, the vegetated scree at the foot of the cliff was washed away and the junction became exposed at beach level for the first time in many years over a distance of *c*. 25 m [SY 0589 8159]. At their base, the pebble beds rest on a similar gently undulating surface to that exposed in the cliff (Figure 5f). Above this, 0.7 to 0.8 m of pebbly sandstone is overlain by a 0.20 to 0.28 m thick bed of red-brown mudstone that is overlain by the full thickness of the BSPB, up to 25 m of pebble beds with sandstone partings and lenses (Figures 5e and g). The mudstone was visible over a distance of 20 m, being obscured by scree debris at the western end of the outcrop and by beach shingle at its eastern end. A prominent pair of green silt laminae (Figure 5g) could be traced through the full length of the outcrop of the bed. Although the bed could not be traced in the cliff west of the beach outcrop, the presence of right-way-up burrows in the lamina (Figure 5g) suggests that it is *in situ* and not an unusually large clast derived from the Littleham Mudstone.

In a study of the heavy-minerals of the BSPB of the Wessex Basin, Morton *et al*. (2013) observed that the almost all the zircons pre-date the Variscan Orogeny. The formation did not, therefore, receive input from the Dartmoor or other South-West England granites or from the Teignmouth and younger breccias that contain clasts derived from the granites. This suggests that these sources might at that time still have been concealed beneath the mudstones of the Aylesbeare Group, and that the base of the BSPB is not marked by a major unconformity at Budleigh Salterton. Smith and Edwards (1991) interpreted the BSPB as the deposits of northward-flowing, low sinuosity braided streams. The large size (up to 0.3 m across) of many of the well-rounded quartzitic pebbles at Budleigh Salterton suggests that they are remobilised pre-existing river deposits. The marked lithological contrast at the base of the pebble beds might, therefore, have been due to a rapid change to a wetter climate rather than to tectonic uplift and erosion.

### *Budleigh Salterton Pebble Beds-Otter Sandstone boundary*

At Budleigh Salterton, the cross-bedded, fine-grained sandstones of the Otter Sandstone rest with sharp lithological contrast on a 0.2 to 0.3 m thick reddish brown, pebbly, silty clay which rests on the BSPB (Figure 6a). The clay was interpreted by Wright *et al*. (1991) as a reg palaeosol (desert soil) that represents a break in sedimentation of 50 to 100 ka. Hounslow and Ruffell (2006) described this break as a disconformity/unconformity and suggested that it might be the correlative of the Hardegsen Unconformity (see below) of the North Sea and adjacent areas. Ventifacts, including zweikanter, dreikanter and multifaceted pebbles, are relatively common at the top of the clay (Leonard *et al*., 1982) which has been referred to as a ventifact surface and has been cited as further evidence of the presence of a major sedimentary break (e.g. Holloway *et al*., 1989). Ventifacts are also relatively common as scattered clasts in the underlying pebble beds (Figures 5b and c). Inland, at Beggar's Roost Quarry, West Hill [SY 061 941], the top of the BSPB is also marked by a ventifact horizon and the lowest part of the Otter Sandstone is pebbly with a second ventifact horizon 6 m above the base of the formation (Edwards and Scrivener, 1999). The presence of ventifacts is not necessarily an indication of long exposure to saltating and wind-blown sand. Knight and Burningham (2003) showed that rates of loss of surface material from ventifacts on a modern jetty in Oregon since 1930 due to erosion by beach sand had varied between 0.24 and 1.63 mm per annum.

When traced northwards from the Devon coast, Smith and Edwards (1991) recorded granitic and metamorphic-aureole clasts derived from South-West England in the basal Otter Sandstone. This marked difference between the provenance of the BSPB and the Otter Sandstone in that area might indicate a considerable time interval between the deposition of the two formations (Richard Edwards pers. comm.). Farther north, Edmonds and Williams (1985) observed that in the Taunton area of Somerset the boundary between the BSPB and Otter Sandstone was "*somewhat arbitrary*" in an upward passage from conglomerates to sandstones. When traced eastwards into the Wessex Basin, Holloway *et al*. (1989) noted that the BSPB was absent beneath a large part of the area and suggested that this might be due either to a lateral change in facies or to tectonic uplift and erosion prior to the deposition of the Otter Sandstone. In a study of seismic-reflection and borehole data from the same region, Butler (1998) concluded that there is a widespread unconformity at the base of the Otter Sandstone as the result of uplift and erosion of the BSPB and earlier Permo-Triassic rocks.

## TECTONIC AND CLIMATIC CONSIDERATIONS

The post-Variscan tectonic history of NW Europe is marked by a succession of extensional and compressional phases, the early Cimmerian Phase of Stille (1924). These have been well documented in the North Sea and adjacent areas where their role in hydrocarbons generation and migration is of economic importance. Four large-scale tectonic-stratigraphic successions (TR1 to TR4) have been recognised in the Triassic, each of which begins with a major regional unconformity followed by a transgressive succession which in many cases oversteps onto older rocks (Geluk, 2005; Hounslow and Ruffell, 2006). The base of TR1 corresponds approximately to the base of the Triassic System. Topographical changes that resulted from these tectonic events were at times intimately linked to climate changes. In the warm-arid to semi-arid climates that were present throughout this time interval, minor changes in rainfall or wind direction had marked effects on the sedimentation. For example, renewed uplift of parts of the Variscan uplands of South-West England, Wales and northern France was accompanied by sporadic heavy rainfall that gave rise to the flash floods that deposited the Budleigh Salterton Pebble Beds and their correlatives in the Midlands.

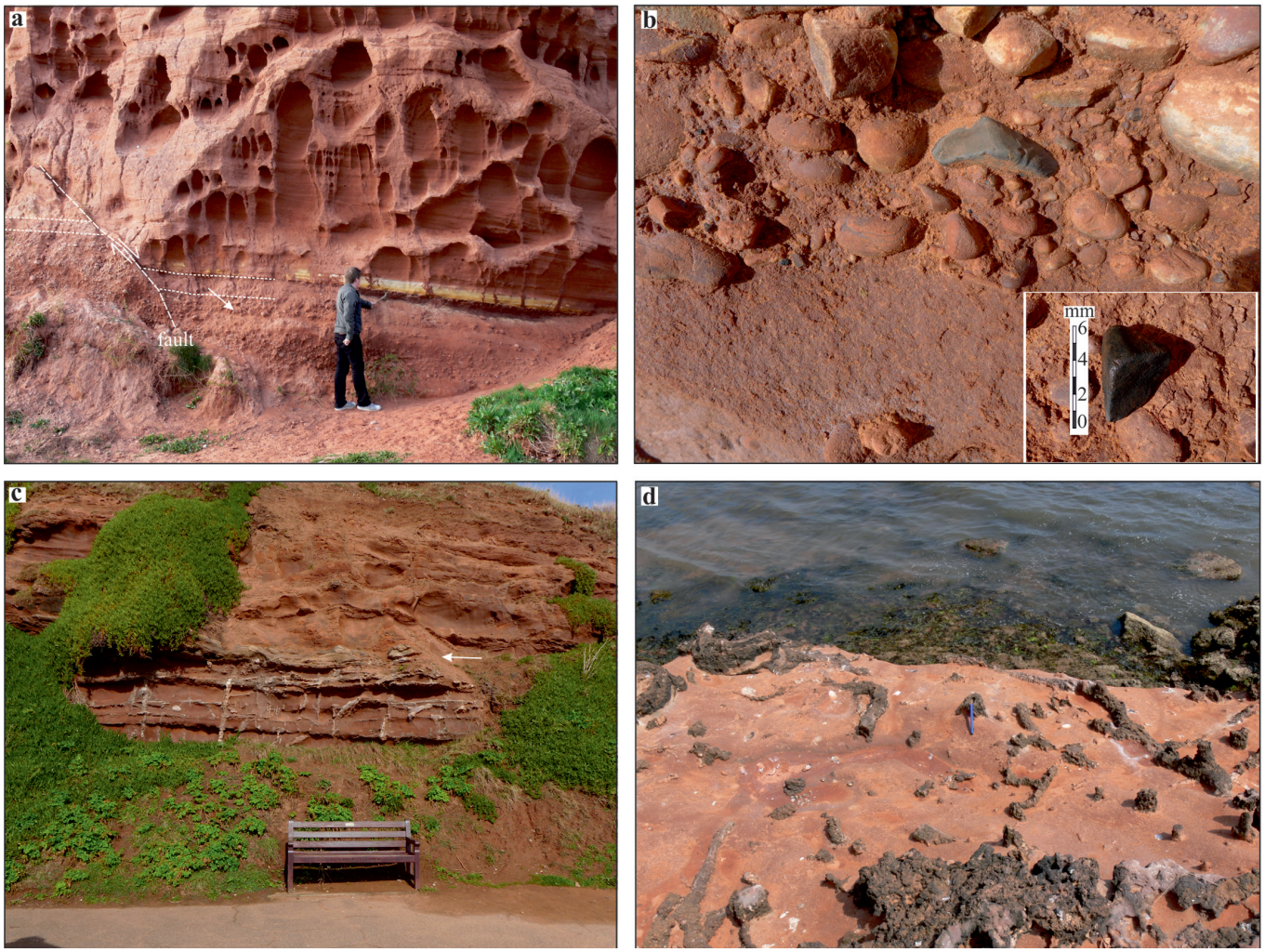


***Figure 6.*** *(**a**) Junction of the Otter Sandstone and the Budleigh Salterton Pebble Beds at the type section at Budleigh Salterton [SY 0624 8171]. The yellow groundwater-bleached horizon at the base of the sandstones rests on a ferruginously cemented bed at the top of a red mudstone (reg palaeosol) that is capped by the 'ventifact horizon'. (**b**) Detail of an in situ ventifact clast (arrowed in **c**) in the pebble beds: insert shows dreikanter shape, viewed from above. (**c**) Sedimentary hiatus marked by a caliche surface underlain by calcitised root systems. Otter Sandstone, the Esplanade [SY 0703 8195], Budleigh Salterton. (**d**) Eroded caliche surface and calcitised stem and root systems viewed from above. Otter Sandstone, Big Picket Rock [SY 1046 8573], Sidmouth. The surface marks a sudden upward change in lithofacies from cross-bedded sandstones with numerous caliche beds of the Otterton Point Member to stacked broad channels up to 100 m wide of the Ladram Bay Member (Gallois, 2013). Calcitised stem in foreground is 0.3 m diameter.*

The major sedimentary events in the Permo-Triassic succession in the beds above the Teignmouth Breccia in Devon are, in ascending order (Figure 7):

1) The change from the aeolian dune and fluviatile sands and fan breccias of the Dawlish Sandstone and Exe Breccia to the playa-lake/sabkha mudstones of the Exmouth Mudstone and Sandstone and Littleham Mudstone (collectively the Aylesbeare Group). In the coastal sections the boundary is a correlative conformity. This passes northwards into a disconformity in the Exeter area and an unconformity in the Crediton Trough.

2) The change from the argillaceous Aylesbeare Group to the fluviatile pebble beds and sands of the Budleigh Salterton Pebble Beds and Otter Sandstone (collectively the Sherwood Sandstone Group).

3) The change from the Sherwood Sandstone Group to the playa-lake/sabkha mudstones of the Sidmouth, Dunscombe, Branscombe Mudstone and Blue Anchor Formations (collectively the Mercia Mudstone Group). As with the base of the Aylesbeare Group, the boundary passes from a correlative conformity in the coastal sections to an unconformity when traced northwards.

4) The change from the Mercia Mudstone Group to the brackish and quasi-marine mudstones and limestones of the Westbury Mudstone, Cotham Formation and White Lias Formations (collectively the Penarth Group).

There is widespread agreement, based on palaeontological and magnetostratigraphical evidence, that the disconformity and transgression at the base of the Westbury Mudstone is the correlative of TR4 (e.g. Geluk, 2005; Hounslow and Ruffell, 2006). Below this, the most obvious transgressive event in the Triassic in southern England is the northward overstep of the Mercia Mudstone onto older-Permo Triassic rocks in Somerset and onto pre-Permian rocks along the southern edge of the Mendips-South Wales uplands. This was interpreted as the response to an extensional tectonic phase by Ruffell and Shelton (1999). The presence of latest Ladinian vertebrates in the youngest part of the Otter Sandstone (Benton, 2011) and the early Carnian conchostracan *Laxitextella multireticulata* (Reible) (Kozur in Gallois and Porter, 2006) in the lower part of the Dunscombe Mudstone is in accord with the

magnetostratigraphical conclusion that the base of the Mercia Mudstone is close to the Anisian-Ladinian boundary (Hounslow and Muttoni, 2010). In the Germanic Basin, the Anisian-Ladinian boundary is marked by a change from fluvial deposits to the open-marine sediments of the Muschelkalk Sea (Bourquin *et al.*, 2011). It is here suggested here that the transgression and tectonic pulse at the base of the Mercia Mudstone is the correlative of TR3.

Hounslow and Ruffell (2006) correlated the base of the Otter Sandstone (early Anisian) with TR2, the Hardegsen Unconformity of the North Sea and adjacent areas. However, the unconformity has been palaeontologically dated as Olenekian in Germany (Geluk, 2005) with the result that more recent authors (e.g. Hounslow and Muttoni, 2010) have correlated TR2 with the presumed unconformity at the base of the BSPB. If the transgression at the base of the Aylesbeare Group is the correlative of TR1, as suggested here, then the group is Induan to early Olenekian in age.

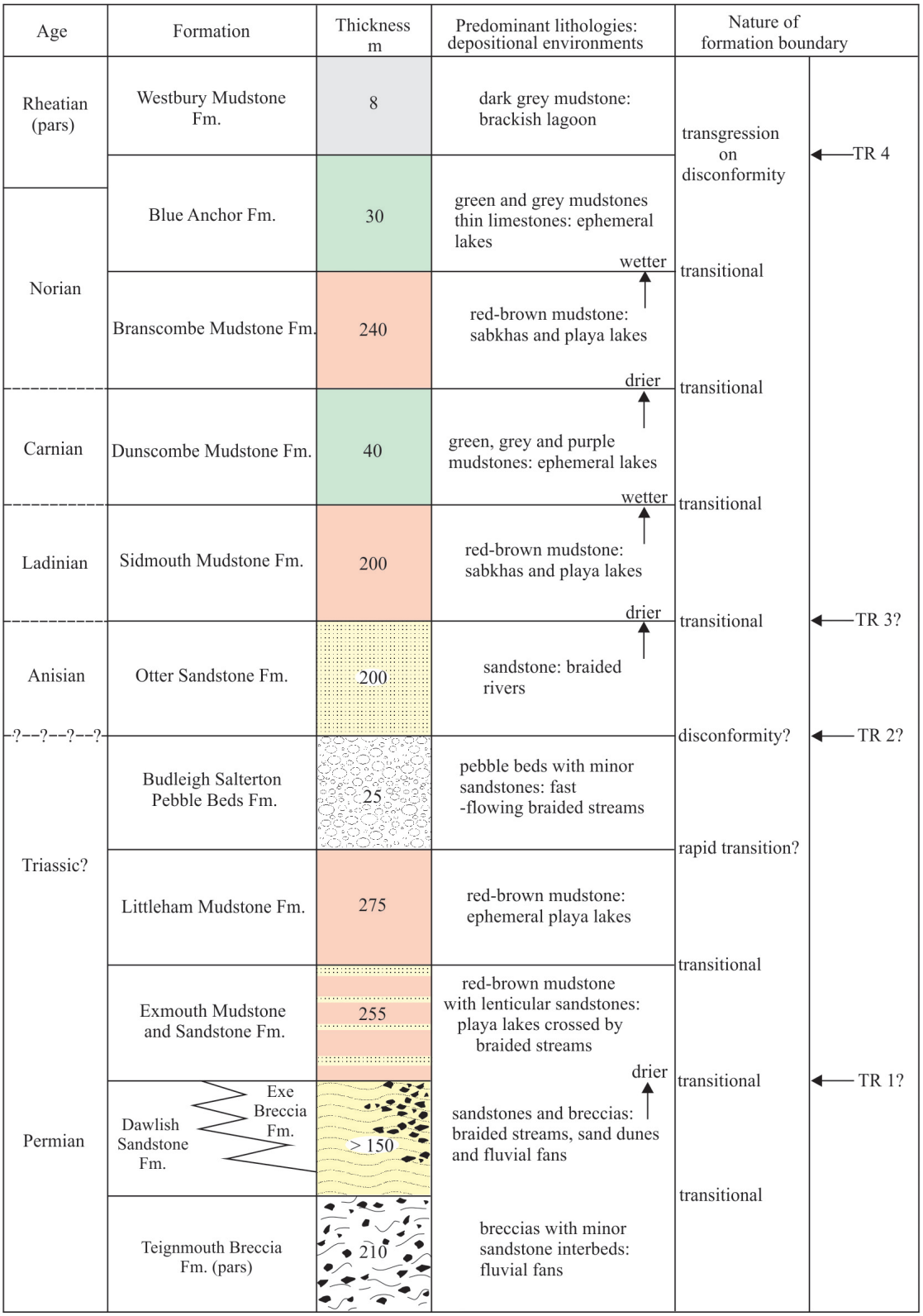


***Figure 7.*** *Summary of the mid/late Permian to late Triassic succession exposed on the Devon coast and its suggested correlation with sedimentary and tectonic events elsewhere in NW Europe.*

## Summary and conclusions

Over 1,000 m of terrestrial sediments including breccia fans, fluviatile and aeolian dune sandstones, and playa-lake mudstones that straddle the Permo-Triassic boundary are almost wholly exposed on the Devon coast. However, in the almost complete absence of palaeontological evidence, the position of the boundary cannot be placed with confidence anywhere within this part of the succession. Assuming that the trace fossil *Cheilichnus bucklandi* was confined to the Permian, then the base of the Permo-Triassic boundary lies somewhere between a level in the Dawlish Sandstone and a level in the lower part of the Otter Sandstone that has been determined as mid Triassic (early Anisian) on magnetostratigraphical grounds (Hounslow and McIntosh, 2003). In recent years, the Permo-Triassic boundary in Devon has been placed by most authors either at the base of the Exmouth Mudstone and Sandstone (e.g. Edwards and Scrivener, 1999) or at the base of the Budleigh Salterton Pebble Beds (e.g. Selwood *et al.*, 1984; Warrington *et al.*, 2012). In each case, the boundary has been taken at a presumed unconformity/disconformity that is assumed to represent a break in sedimentation of several million years. Re-examination of the well exposed sections through the junction of the Exe Breccia and Exmouth Mudstone and Sandstone at Lympstone and Exmouth has shown that the boundary is conformable transition at both localities (Figures 3 and 5a, c). The lithological change and presumed unconformity at the base of the Budleigh Salterton Pebble Beds might represent a climate change and not represent such a long period of time of time as previously assumed. Based on the evidence published to date, the sedimentary break at the base of the Otter Sandstone is the most likely to have been a regional unconformity, but the possibility cannot be excluded that the variations in the lithologies of the beds on which the sandstone rests are due to facies variations.

In the absence of proven major unconformities, the deposition of the Dawlish Sandstone to Otter Sandstone succession on the Devon coast can be considered to represent more or less continuous sedimentation during which there were numerous hiatuses of variable length accompanied by the reworking of older sediments. It is especially difficult in desert environments prone to flash floods and lateral variations in lithofacies over distances of a few kilometres, to differentiate between a regionally significant erosion surfaces and local breaks in sedimentation. As in most, if not all, sedimentary successions, the time represented by the sedimentary breaks far exceeds that represented by the sediments (Ager, 1993). For example, the BSPB at outcrop in Budleigh Salterton cliffs is made up of 10-12 units of pebble beds with sandstone lenses, each of which is separated by an omission surface. Each unit was deposited by one or more flash floods that may have lasted no more than a few days but which, taken together, are thought to represent much of the Olenekian Stage (*c.* 4 Ma). Similarly, most of the Otter Sandstone consists of cross-bedded sandstones that were deposited in river channels within single flood events. The formation comprises *c.* 200 m of sediment in which the numerous breaks in sedimentation represented by the caliche horizons and omission surfaces represent most of the 5.6 Ma attributed to the Anisian Stage. Comparison of the lithologically similar Aylesbeare Group (*c.* 530 m thick) and Mercia Mudstone Group (*c.* 510 m thick) on the Devon coast suggests that if, as suggested by the paleontological and magnetostratigraphical evidence, the Mercia Mudstone is earliest Ladinian to mid Norian in age (*c.* 24 Ma), the Aylesbeare Group is likely to have occupied more than the <4 Ma indicated by the late Wuchiapingian to early Changhsingian age proposed by Warrington *et al.* (2012).

In summary, there is still insufficient evidence at present to determine the position of the Permo-Triassic boundary in Devon. The field evidence described here suggests that there was more or less continuous sedimentation from the mid Permian to late Triassic punctuated by a large number of breaks of unknown duration. The best current interpretation is that TR1, the proxy for the boundary, is the correlative of the transgression at the base of the Aylesbeare Group based on a comparison of the sedimentary and tectonic history of the Devon succession with that of the North Sea and adjacent areas.

## Acknowledgements

The author is most grateful to Richards Edwards, Mark Hounslow and Deryck Laming whose thoughtful comments on an earlier draft led to many improvements.

## References

AGER, D.V. 1993. *The Nature of the Stratigraphical Record.* 3rd edition. John Wiley and Sons, Chichester.

BENTON, M.J. 1997. The Triassic reptiles from Devon. *Proceedings of the Ussher Society,* **9**, 141-52.

BENTON, M.J. 2011. Archosaur remains from the Otter Sandstone Formation (Middle Triassic, late Anisian) of Devon, southern UK. *Proceedings of the Geologists' Association,* **122**, 25-33.

BENTON, M.J. and SPENCER, P.S. 1995. *Fossil reptiles of Great Britain.* Geological Review Series **10**. Joint Nature Conservation Committee, Peterborough.

BOURQUIN, S., BERCOVICI, A., LÓPEZ-GÓMEZ, J., DIEZ, J.B., BROUTIN, J., RONCHI, A., DURAND, M., ARCHÉ, A., LINOL, B. and AMOUR, F. 2011. The Permian-Triassic transition and the onset of Mesozoic sedimentation at the northwestern peri-Tethyan domain scale: palaeogeographic maps and geodynamic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **299**, 265-280.

BUTLER, M. 1998. The geological history of the southern Wessex Basin - a review of new information from oil exploration. In: UNDERHILL, J.R. (Ed.), *The development, evolution and petroleum geology of the Wessex Basin.* Geological Society London, Special Publication, **133**, 67-86.

EDMONDS, E.A. and WILLIAMS, B.J. 1985. *Geology of the country around Taunton and the Quantock Hills.* Memoir for 1:50,000 geological sheet 339. H.M.S.O., London.

EDWARDS, R.A. and SCRIVENER, R.C. 1999. *The geology of the country around Exeter.* Memoir for 1:50,000 geological sheet 325. H.M.S.O., London.

GALLOIS, R.W. 2013. Possible tetrapod burrows in the Mid Triassic Otter Sandstone Formation at Sidmouth, Devon, U.K. *Geoscience in South-West England,* **13**, 208-215.

GALLOIS, R.W. and PORTER, R.J. 2006. The stratigraphy and sedimentology of the Dunscombe Mudstone Formation (late Triassic) of south-west England. *Geoscience in south-west England,* **11**, 174-182.

GELUK, M.G. 2005. *Stratigraphy and tectonics of Permian and Triassic basins in the Netherlands and surrounding areas.* Unpublished PhD thesis, University of Utrecht.

GRADSTEIN, F.M., OGG, J.G. and SMITH, G. (Eds) 2005. *A Geologic Time Scale 2004.* Cambridge University Press, Cambridge.

GRADSTEIN, F.M., OGG, J.G., SCHMITZ, M.D. and OGG, G.M. (Eds) 2012. *The geologic time scale.* Elsevier, New York.

GRIERSON, J. 1828. On footsteps before the flood, in a specimen of red sandstone. *Edinburgh Journal of Science,* **8**, 130-134.

HENSON, M.R. 1970. The Triassic rocks of south Devon. *Proceedings of the Ussher Society,* **2**, 172-177.

HENSON, M.R. 1971. *The Permo-Triassic rocks of south Devon.* Unpublished PhD thesis, University of Exeter.

HOLLOWAY, S., MILODOWSKI, A.E., STRONG G.E. and WARRINGTON, G. 1989. The Sherwood Sandstone Group (Triassic) of the Wessex Basin, southern England. *Proceedings of the Geologists' Association,* **100**, 383-94.

HOUNSLOW, M.W. and MCINTOSH, G. 2003. Magnetostratigraphy of the Sherwood Sandstone Group (Lower and Middle Triassic), south Devon, UK: detailed correlation of the marine and non-marine Anisian. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **193**, 325-348.

HOUNSLOW, M.W. and MUTTONI, G. 2010. The geomagnetic polarity timescale for the Triassic: linkage to stage boundary definitions. In: LUCAS, S.G. (Ed.), *The Triassic timescale.* Geological Society of London, London, 61-102.

HOUNSLOW, M.W. and RUFFELL, A.H. 2006. Triassic: seasonal rivers, dusty deserts and saline lakes. In: BRENCHLEY, P.J. and RAWSON, P.F. (Eds.), *Geology of England and Wales.* Geological Society of London, London, 295-324.

HUNT, A.P. and V.L. SANTUCCI, V.L. 1998. Taxonomy and ichnofacies of Permian tetrapod tracks from Grand Canyon National Park, Arizona. *National Park Service Paleontological Research*, Technical Report NPS/NRGRD/GRDTR-98/01, 94-96.

INSTITUTE OF GEOLOGICAL SCIENCES. 1976. Newton Abbot: 1:50,000 Sheet 339. Ordnance Survey, Southampton.

INTERNATIONAL COMMISSION FOR STRATIGRAPHY 2014. Timescale Version 2014-02. *http://www.stratigraphy.org/ICSchart/ChronostratChart2014-02.pdf*, last accessed on 14th December 2014.

KNIGHT, J. and BURNINGHAM, H. 2003. Recent ventifact development on the central Oregon coast, western USA. *Earth Surface Processes and Landforms,* **28**, 87-98.

KREIGER, H.H. 1965. Geology of the Prescott and Paulden quadrangles, Arizona. *Geological Survey Professional Paper* **476**. United States Government Printing Office, Washington.

LAMING, D.J.C. 1954. *Sedimentary processes in the formation of the New Red Sandstone of south Devonshire.* Unpublished PhD thesis, University of London.

LAMING, D.J.C. 1968. New Red Sandstone in Devon and west Somerset. *Proceedings of the Ussher Society,* **2**, 23-25.

LAMING, D.J.C. and ROCHE, D.P. 2013. Faulting in Permo-Triassic strata and buried channels revealed by excavation of the Lympstone-Powderham tunnel, Exe Estuary, Devon. *Geoscience in South-West England,* **13**, 244.

LEONARD, A.J., MOORE, A.G. and SELWOOD, E.B. 1982. Ventifacts from a deflation surface marking the top of the Budleigh Salterton Pebble Beds, east Devon. *Proceedings of the Ussher Society,* **5**, 333-339.

LEVERIDGE, B.E., HOLDER, M.T., GOODE, A.J.J., SCRIVENER, R.C., JONES, N. and MERRIMAN, R.J. 2002. *Geology of the Plymouth and the south-east Cornwall area.* Memoir for 1:50,000 geological sheet 348. British Geological Survey, Keyworth.

LUCAS, S.G. 2013. A new Triassic timescale. In LUCAS, S.G. (Ed.), *The Triassic timescale.* Geological Society of London, London, 366-374.

LUCAS, S.G. and HUNT, A.P. 2006. Permian tetrapod footprints: biostratigraphy and biochronology. *Geological Society of London, Special Publications,* **265**, 179-200.

MORTON, A., HOUNSLOW, M.W. and FREI, D. 2013. Heavy-mineral, mineral-chemical and zircon-age constraints on the provenance of Triassic sandstones from the Devon coast, southern Britain. *Geologos,* **19**, 67-85.

POLLARD, J.E. 1976. A problematic trace fossil from the Tor Bay Breccias of south Devon. *Proceedings of the Geologists' Association,* **87**, 105-108.

RIDGEWAY J.E.A. 1974. A problematical trace fossil from the New Red Sandstone of South Devon. *Proceedings of the Geologists' Association,* **85**, 511-517.

RUFFELL, A. and SHELTON, R. 1999. The control of sedimentary facies by climate during phases of crustal extension: examples from the Triassic of onshore and offshore England and Northern Ireland. *Journal of the Geological Society of London,* **156**, 779-789.

SELWOOD, E.B., EDWARDS, R.A., SIMPSON, S., CHESHER, J.A., HAMBLIN, R.J.O., HENSON, M.R., RIDDOLS, B.W. and WATERS, R.A. 1984. *Geology of the Country around Newton Abbot.* Memoir for 1:50,000 geological sheet 339. H.M.S.O., London.

SMITH, D.B, BRUNSTROM, R.G.W, MANNING, P.I, SIMPSON, S. and SHOTTON, F.W. 1974. A correlation of Permian rocks in the British Isles. *Special Report of the Geological Society of London* **5**.

SMITH, S.A. and EDWARDS, R.A. 1991. Regional sedimentological variations in Lower Triassic fluvial conglomerates (Budleigh Salterton Pebble Beds), southwest England: some implications for palaeogeography and basin evolution. *Geological Journal,* **26**, 65-83.

SOUZA, P.A. and MARQUES-TOIGO, M. 2005. Progress on the palynostratigraphy of the Permian strata in Rio Grande do Sul State, Paraná Basin, Brazil. *Anais da Academia Brasileira de Ciências,* **77**, 353-365.

STILLE, H. 1924. *Grundfragen der vergleichenden tetonik.* Borntraeger, Berlin.

USSHER, W.A.E. 1902. *The Geology of the country around Exeter.* Memoirs of the Geological Survey, Sheet 325. London, H.M.S.O.

USSHER, W.A.E. 1913. *Geology of the country around Newton Abbot.* Memoirs of the Geological Survey, Sheet 339. H.M.S.O., London.

WARRINGTON, G. and SCRIVENER, R.C. 1988. Late Permian fossils from Devon: regional geological implications. *Proceedings of the Ussher Society,* **6**, 95-96.

WARRINGTON, G., BARCLAY, W.J., LEVERIDGE, B.E. and WATERS, C.N. 2012. The Global Devonian, Carboniferous and Permian Correlation Project: a review of the contribution from Great Britain. *Geoscience in South-West England,* **13**, 47-51.

WRIGHT, V.P., MARRIOT, S.B. and VANSTONE, S.D. 1991. A reg palaeosol from the Lower Triassic of south Devon: stratigraphic and palaeoclimatic implications. *Geological Magazine,* **128**, 517-523.