

Heavy-mineral, mineral-chemical and zircon-age constraints on the provenance of Triassic sandstones from the Devon coast, southern Britain

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Abstract

An integrated heavy-mineral, mineral-chemical and zircon-dating study of the Triassic succession exposed on the south Devon coast, in the western part of the Wessex Basin, indicates derivation from a combination of granitic and metasedimentary lithologies of ages of mostly over 550 Ma. These sources were probably located at a relatively proximal location near the southern margin of the basin. Derivation from more distal sources in the Armorican Massif or local Variscan sources to the west appears unlikely in view of the scarcity of Permo-Carboniferous (Variscan-age) zircons. The Budleigh Salterton Pebble Bed Formation was derived from a different combination of source lithologies than the Otter Sandstone Formation, the former including staurolite-grade metasediments that were absent in the catchment area of the Otter Sandstone. The Devon coast succession has provenance characteristics that differ from equivalent sandstones further east in the Wessex Basin, and from sandstones in the East Irish Sea Basin to the north. These differences indicate that sediment supply patterns to the linked Triassic basin systems in southern Britain are complex, involving multiple distinct sub-catchment areas, and that heavy-mineral studies have considerable potential for unravelling these sub-catchment area sources.

Key words: heavy minerals, zircon, provenance, Triassic, Devon

1. Introduction

Triassic sediments in the southern UK were deposited in a series of linked basins, ranging from the Wessex Basin in the south, a number of basins in the English Midlands (Worcester, Stafford, Needwood, Knowle and Cheshire basins), to the East Irish Sea Basin and East Midlands Shelf in the north (Fig. 1). The Triassic sediments deposited in these basins can be broadly subdivided into the Sherwood Sandstone Group, which is of Early-Middle Triassic

(Olenekian-Anisian) age, overlain by the Mercia Mudstone Group, which is of Middle-Late Triassic (Anisian-Rhaetian) age (Hounslow & Ruffell, 2006). Most of the succession has a red-bed facies, deposited in a semi-arid climate with an annual summer monsoon, in a range of environments (ephemeral fluvial, aeolian and playa lacustrine) controlled by a complex interplay of climate and tectonics (Ruffell & Shelton, 1999; McKie & Williams, 2009; Preto et al., 2010).

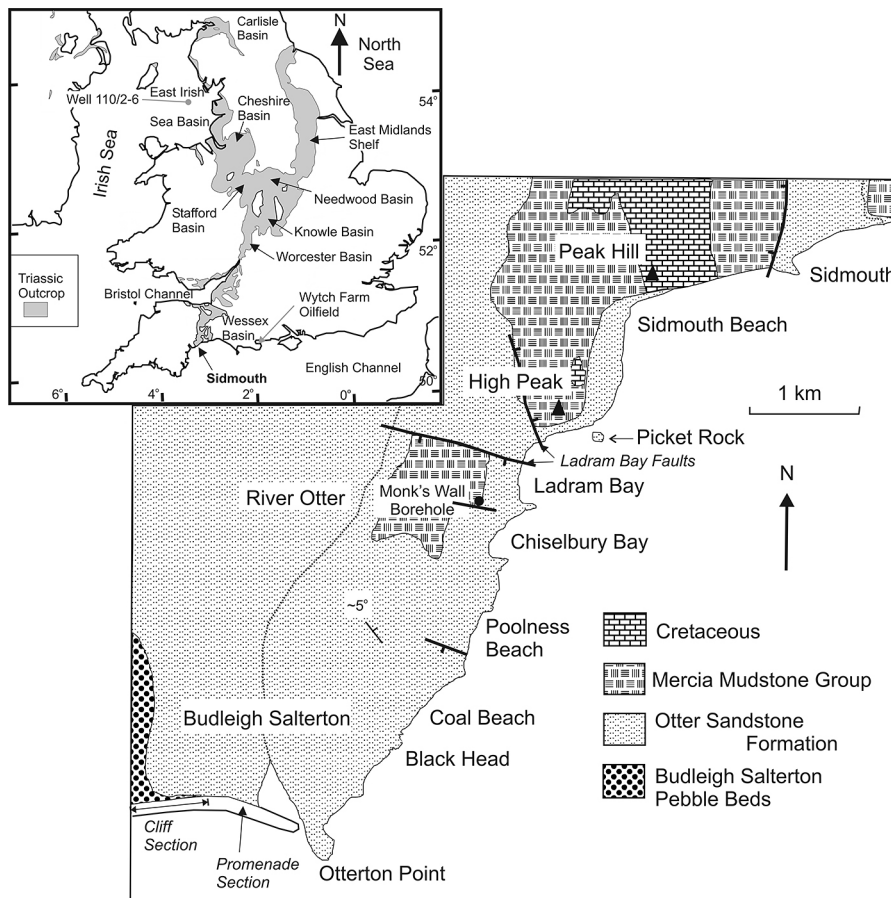


Fig. 1. Location of the Sherwood Sandstone Group outcrop on the Devon coast, southern UK, with inset showing the Wessex Basin in its regional context with the other Triassic outcrops of southern Britain. The inset map also shows the locations of the Wytch Farm oilfield (central Wessex Basin) and well 110/2-6 (East Irish Sea Basin). Adapted from Hounslow & McIntosh (2003).

Deposition in these linked basins is believed to have been dominated by a large axial fluvial drainage system, termed the 'Budleighensis River' (Wills, 1956), which flowed from south to north and drained the Variscan mountains of northern France. Evidence for this comes from a variety of data, including clast compositions, palaeocurrents, detrital-mica ages, and Pb-isotope compositions in feldspar.

Clasts in the conglomeratic lower part of the Sherwood Sandstone Group in the Wessex Basin (the Budleigh Salterton Pebble Beds Formation) include quartzites with an exotic Ordovician and Devonian brachiopod fauna similar to that found in Brittany and Normandy (Audley-Charles, 1970; Cocks, 1993, and references therein). The conglomeratic sediments at the base of the Sherwood Sandstone Group further north (Kidderminster Formation, Chester Pebble Beds) are also reported to contain fossiliferous quartzites of Armorican type (Audley-Charles, 1970, and references therein), together with igneous pebbles that have affinities

with rocks of SW England (Campbell-Smith, 1963), and clasts from more proximal sources (Wills, 1970).

Palaeocurrent data from the Budleigh Salterton Pebble Beds Formation indicate a palaeocurrent toward the north and north-east (Smith & Edwards, 1991), with a northward-directed palaeocurrent also recorded in the Sherwood Sandstone Group of the Cheshire Basin (Thompson, 1970; Steel & Thompson 1983). This northward palaeocurrent appears to extend northward even as far as the Cumbrian coast, on the NW margin of the East Irish Sea Basin (Jones & Ambrose, 1994).

K-Ar-isotopic analyses of bulk detrital muscovite and biotite separates from the Sherwood Sandstone Group of the Cheshire Basin indicate that the source area contained micas ranging in age from 280 to 300 Ma (Fitch et al., 1966), requiring that the mica provenance lay to the south, within the Variscan uplands. Pb-isotopic data from K-feldspars in the Sherwood Sandstone Group in the Wessex and East

Irish Sea Basins show that similar grain populations are present, and that their compositions can be matched with granites of Neoproterozoic-Cambrian (Cadomian) granites and Late Carboniferous-Permian (Variscan) granites in northern France, the French Massif Central, the Pyrenees and the Cornubian area of SW Britain (Tyrrell et al., 2012).

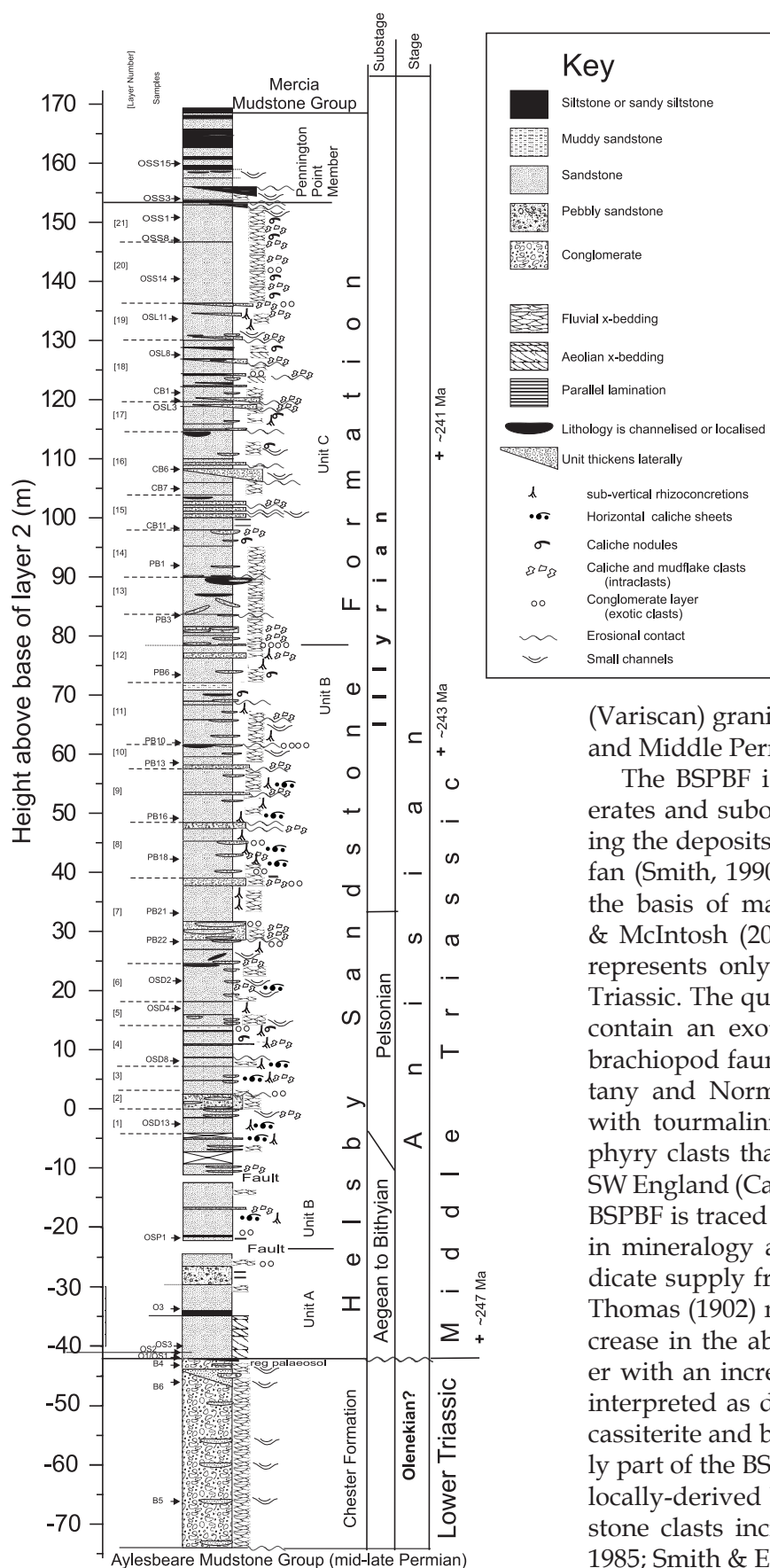
The Sherwood Sandstone Group of the Wessex Basin was the subject of some of the earliest heavy-mineral provenance studies ever undertaken in the UK (Thomas, 1902, 1909). Despite this long history, comparatively little modern quantitative heavy-mineral data have been collected on the Sherwood Sandstone Group from the linked basin system in order to test the 'Budleighensis River' concept. Morton & Hallsworth (1994) showed that the Sherwood Sandstone Group in the Wytch Farm oilfield (central part of the Wessex Basin; Fig. 1) has distinctly different heavy-mineral provenance characteristics to that in the East Irish Sea Basin. The Sherwood Sandstone in the latter basin was subsequently studied in detail by Mange et al. (1999), who argued that there was significant local input from a variety of areas bordering the basin, including the Welsh-Brabant Massif, the Ramsey-Whitehaven Ridge, the Isle of Man, and the Leinster Massif of Ireland. Mange et al. (1999) also noted the existence of abundant polycyclic detritus in the Sherwood Sandstone Group of the East Irish Sea Basin, implying widespread recycling from older sediments and metasediments. The heavy-mineral evidence for local input in the East Irish Sea Basin (Mange et al., 1999) would account for the differences in mineralogy between the Wytch Farm area and the East Irish Sea Basin recognised by Morton & Hallsworth (1994). Subsequent studies of heavy-mineral assemblages in the Sherwood Sandstone Group of the Cheshire Basin (Jones et al., 2000) showed that these also differ from those found in the Wytch Farm area, but are more comparable with those in the East Irish Sea Basin.

Although some quantitative heavy-mineral data are available from the Wytch Farm succession in the central part of the Wessex Basin (Morton & Hallsworth, 1994), equivalent data are not available from the outcrop sections of

the Sherwood Sandstone Group in Devon, in the western part of the basin (Fig. 1). Apart from the pioneering work on this area in the very early part of the last century (Thomas, 1902, 1909), the only data are general information on heavy-mineral abundances that were used in order to calibrate a chemostratigraphic study of the Otter Sandstone Formation by Svendsen & Hartley (2002), and similar information on a small number of samples collected as part of a regional provenance study by Jeans et al. (1993). In view of the importance of this section as a key point in evaluating the role of the 'Budleighensis River' system (Tyrrell et al., 2012), an integrated heavy-mineral study, combining determination of provenance-sensitive heavy-mineral ratios, mineral-chemical data on tourmaline and garnet, and detrital-zircon ages, has been undertaken in order to constrain the provenance of the sandstones and conglomerates in the succession and to provide a framework for comparison with equivalent sandstones in the linked basins to the north.

2. The Sherwood Sandstone Group of Devon

In the Wessex Basin, the Sherwood Sandstone Group is divided into a lower conglomeratic unit, the Budleigh Salterton Pebble Beds Formation (BSPBF), and an overlying sandstone-dominated unit, the Otter Sandstone Formation (OSF) (Fig. 2). The boundary between the BSPBF and the underlying Aylesbeare Mudstone Group (Early Triassic) is an unconformity (Holloway et al., 1989), which is most clearly apparent from seismic surveys and well data farther east in the Wessex Basin (Butler, 1998). The unconformity between the BSPBF and the OSF is considered to be equivalent to the Hardegsen Unconformity in the Germanic Basin (Holloway et al., 1989; Butler, 1998). However, magnetostratigraphy suggests that the base of the OSF in the outcrops of south Devon corresponds to a slightly younger level (Hounslow & McIntosh, 2003). Late Permian red-beds underlying the Aylesbeare Mudstone Group in the western part of the Wessex Basin clearly document the unroofing of the Permian



(Variscan) granites of SW England in the Early and Middle Permian (Edwards et al., 1997).

The BSPBF is composed of orthoconglomerates and subordinate sandstones, representing the deposits of a braidplain or wet alluvial fan (Smith, 1990; Smith & Edwards 1991). On the basis of magnetostratigraphy, Hounslow & McIntosh (2003) suggested that the BSPBF represents only a short interval of the Early Triassic. The quartzite clasts within the BSPBF contain an exotic Ordovician and Devonian brachiopod fauna probably derived from Brittany and Normandy (Cocks, 1993), together with tourmalinised hornfels and quartz-porphyry clasts that have affinities with rocks of SW England (Campbell-Smith, 1963). When the BSPBF is traced northwards, there are changes in mineralogy and clast composition that indicate supply from upland areas of Cornubia. Thomas (1902) noted a gradual northward decrease in the abundance of staurolite, together with an increase in abundance of minerals interpreted as derived from the west, such as cassiterite and blue tourmaline. In the northerly part of the BSPBF outcrop, the abundance of locally-derived Devonian sandstone and limestone clasts increases (Edmonds & Williams, 1985; Smith & Edwards, 1991).

A horizon of wind-faceted pebbles (ventifacts) is regionally important at the top of the BSPBF (Leonard et al., 1982; Smith & Edwards 1991). In the coastal section of southern Devon, this horizon is associated with a desert palaeosol (Fig. 2) estimated to have formed over a time-span of 50,000–100,000 years (Wright et al., 1991). This major hiatus represents the unconformity surface beneath the OSF. In the central and eastern parts of the Wessex Basin, the unconformity surface locally truncates faults in the underlying succession (Butler, 1998). Holloway et al. (1989) suggested that there was erosion at this time, in order to explain the absence of conglomerates below the OSF in the central parts of the Wessex Basin, although Smith & Edwards (1991) argued that this could equally well be due to non-deposition or to lateral facies changes.

The OSF, which forms the majority of the Sherwood Sandstone Group within the Wessex Basin, largely consists of stacked fluvial channel sandstones, with minor mudstones and aeolian sandstones. At outcrop in southern Devon (Fig. 2), the age of the OSF is believed to range from the latest Early Triassic to near the Anisian/Ladinian boundary (Hounslow & McIntosh, 2003). Farther east in the Wessex Basin, around the Wytch Farm oil field (Fig. 1), seismic evidence suggests that the upper part of the Sherwood Sandstone Group passes into the Mercia Mudstone Group, indicating that the upper boundary of the Sherwood Sandstone Group is probably diachronous (Butler, 1998).

In the coastal outcrop of southern Devon (Fig. 1), the OSF has been divided into four units, A, B, C and the Pennington Point Member (Hounslow & McIntosh 2003; Gallois, 2004). These loosely define an overall fining-upward succession, a feature that is also seen in the OSF of the Wytch Farm area (Lott & Strong 1982; Holloway et al., 1989; McKie et al. 1998; Svendsen & Hartley, 2001, 2002). In the coastal outcrops, the oldest part of the OSF (Unit A) is a ~20 m thick heterogeneous unit consisting of aeolian sandstones at the base overlain by fluvial channel sandstones that lack calcretes (Fig. 2). The overlying Unit B is characterised by multi-storey stacked channel sandstones, with a paucity of lacustrine or floodplain mud-

stones. In-situ calcretes are common in Unit B, in the form of both vertical rhizoconcretions and horizontal sheets (Purvis & Wright, 1991). The basal lags of the channel sandstones include abundant reworked calcrete and mudstone clasts.

Unit C of the OSF has more abundant mudstone- and sandstone-filled channels, with lesser amounts of calcrete (both in-situ and reworked), representing a higher-sinuosity river system (Svendsen & Hartley, 2001). Minor aeolian sandstones also occur in the upper part of the OSF at Wytch Farm (McKie et al., 1998; Edwards, 1999). The Pennington Point Member, which represents the uppermost unit of the OSF at outcrop (Fig. 2), is a succession of fluvial channel and sheetflood sandstones interbedded with numerous red mudstones. The sandstones in the Pennington Point Member lack reworked calcrete, and may be heavily channelised, similar in character to the uppermost units of the OSF at Wytch Farm, where they are interpreted as lacustrine (McKie et al., 1998).

Palaeocurrent directions have been measured on the sections at Chiselbury Bay and Ladram Bay (Unit C, beds 15–19 in Fig. 2). These indicate a shift from northwesterly- to northeasterly-directed palaeocurrents with time (Lorsong & Atkinson, 1995).

3. Analytical methods

3.1. Conventional (petrographic) analysis

Rock samples were gently disaggregated by use of a pestle and mortar, avoiding grinding action. Chemicals were not used in order to avoid the possibility of modifying assemblages in the laboratory. Following disaggregation, the samples were immersed in water and cleaned by ultrasonic probe to remove and disperse any clay adhering to grain surfaces. The samples were then washed through a 63 µm sieve and resubjected to ultrasonic treatment until no more clay passed into suspension. At this stage, the samples were wet-sieved through the 125 and 63 µm sieves, and the resulting >125 µm and 63–125 µm fractions

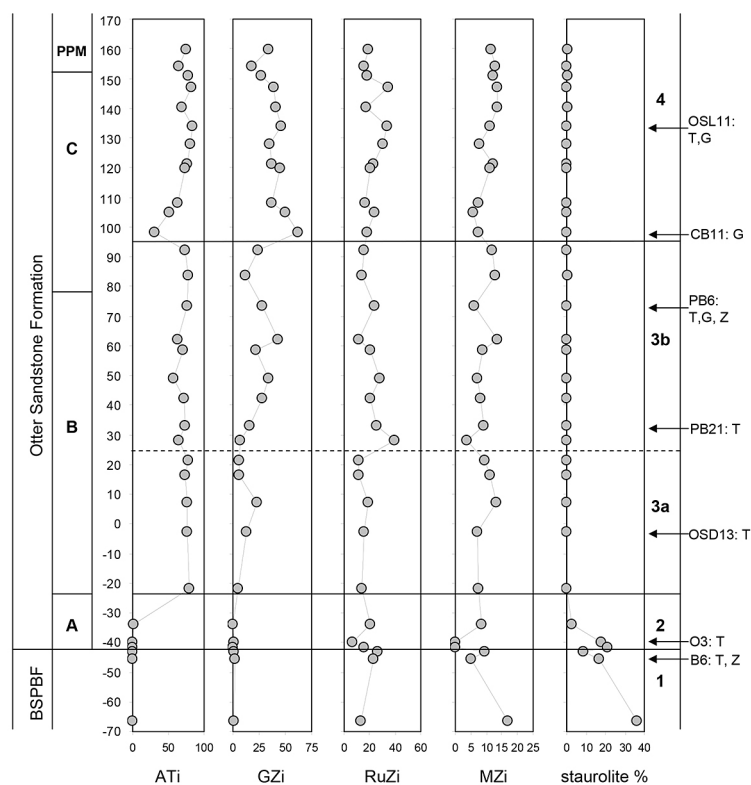


Fig. 3. Stratigraphic variations in key heavy-mineral parameters in the Sherwood Sandstone Group on the Devon coast. A, B and C are lithostratigraphic subdivisions, as shown in Figure 2. 1, 2, 3 and 4 are heavy-mineral zones (HM1–4) as discussed in the present contribution. ATi = apatite:tourmaline index; GZi = garnet:zircon index; RuZi = rutile:zircon index; MZi = monazite:zircon index (all as defined by Morton & Hallsworth, 1994). Samples chosen for tourmaline geochemical analysis, garnet geochemical analysis and zircon dating are indicated by T, G and Z, respectively.

were dried in an oven at 80°C. The 63–125 µm fraction was placed in bromoform with a measured specific gravity of 2.8. Heavy minerals were allowed to separate under gravity, with frequent stirring to ensure complete separation. The heavy-mineral residues were mounted under Canada balsam (cf. Marcinkowski & Mycielska-Dowgiałło, 2013) for optical study using a polarising microscope. Where possible, a split was retained for mineral-chemical and zircon-dating studies.

The heavy-mineral proportions were estimated by counting 200 non-opaque detrital grains using the ribbon method described by Galehouse (1971). Identification was made on the basis of optical properties, as described for grain mounts by Mange & Maurer (1992). A qualitative assessment was also made of other components, such as diagenetic minerals, opaques and mica. Determination of provenance-sensitive mineral ratios (Morton & Hallsworth, 1994) was ideally made on the basis of a 200-grain count per mineral pair, although this was not always possible because of the scarcity of some of the mineral phases. Stratigraphic variations in key mineral parameters are shown in Fig. 3. Light minerals and

opaque heavy minerals, although sometimes of interest for provenance studies (see Ludwikowska-Kędzia, 2013; Woronko et al., 2013), have not been investigated.

3.2. Garnet and tourmaline geochemistry by electron microprobe analysis (EMPA)

Samples for garnet and tourmaline geochemistry analysis by EMPA were selected on the basis of the results of the conventional optical analysis. The selected grains were analysed at Aberdeen University using a Link Systems AN10000 energy-dispersive X-ray analyser attached to a Cambridge Instruments Microscan V electron microprobe. The quality of each result was monitored to ensure that the stoichiometrically-determined formulae corresponded to ideal garnet and tourmaline compositions.

Garnet compositions are expressed in terms of the relative abundance of the Mg, Fe²⁺, Ca and Mn end members. The compositions of garnet assemblages are shown using ternary diagrams (Fig. 4) with relative proportions of Fe²⁺+Mn, Mg and Ca in the garnet molecule as poles, calculated assuming that all Fe is present as Fe²⁺.

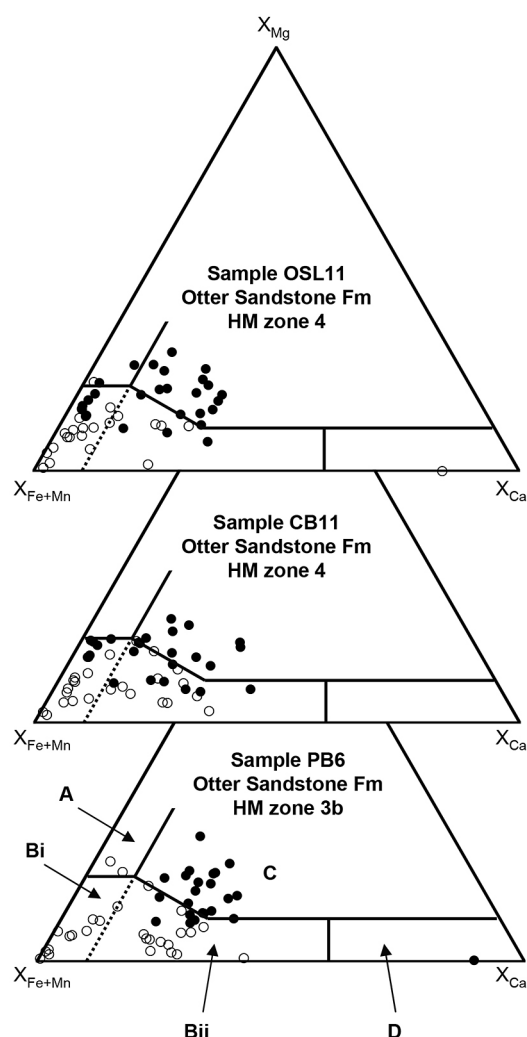


Fig. 4. Garnet compositions in the Sherwood Sandstone Group of the Devon coast. The stratigraphic locations of the samples are shown in Figure 3.

X_{Fe} , X_{Mg} , X_{Ca} , X_{Mn} = proportions of Fe, Mg, Ca and Mn in the garnet molecule. All Fe calculated as Fe^{2+} ; $\bullet$ = $X_{Mn} < 5\%$; $\circ$ = $X_{Mn} > 5\%$. Fields A, Bi, Bii, C and D are from Mange & Morton (2007).

The tourmaline compositions are expressed in terms of the relative abundances of Al, Fe and Mg, and are plotted on the provenance-discriminant $Al-Al_{50}Mg_{50}-Al_{50}Fe(tot)_{50}$ ternary diagram (Fig. 5) devised by Henry & Guidotti (1985).

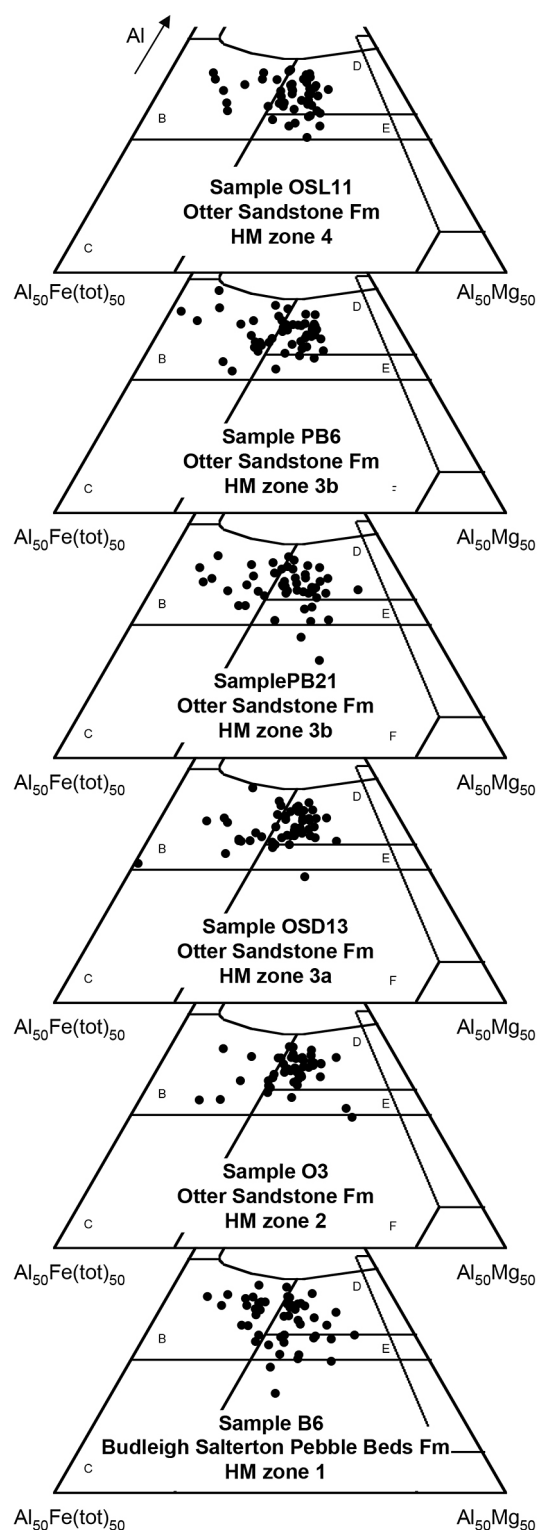


Fig. 5. Tourmaline compositions in the Sherwood Sandstone Group of the Devon coast, plotted on the provenance-discriminant $Al-Mg-Fe$ diagram of Henry & Guidotti (1985). The stratigraphic locations of the samples are shown in Figure 3.

Field A = Li-rich granitoids, pegmatites, aplites; Field B = Li-poor granitoids, pegmatites, aplites; Field C = hydrothermally-altered granitic rocks; Field D = metapelites, metapsammites (aluminous); Field E = metapelites and metapsammites (Al-poor); Field F = Fe^{3+} -rich quartz-tourmaline rocks, calc-silicates, metapelites.

3.3. Zircon dating

Zircons were separated from the bulk samples using conventional heavy-liquid and magnetic-separation methods. The final separation step was made by hand-picking individual zircon grains from the heavy and non-mag-

netic fraction using an optical microscope. The individual zircon grains were mounted on double-sided, transparent adhesive tape and subsequently embedded in 1-inch-diameter circular epoxy mounts for polishing. In order to study their internal structure, backscatter electron (BSE) images of all analysed zircon

Table 1. LA-SF-ICP-MS U-Th-Pb dating methodology employed at CAF, Stellenbosch University, South Africa.

Laboratory & sample preparation	
laboratory name	Central Analytical Facility, Stellenbosch University
sample type / mineral	detrital zircons
sample preparation	conventional mineral separation, 1 inch resin mount, 1 μm polish to finish
imaging	CL, LEO 1430 VP, 10 nA, 15 mm working distance
Laser ablation system	
make, model & type	ESI/New Wave Research, UP213, Nd:YAG
ablation cell & volume	Custom build low volume cell, volume approx. 3 cm^3
laser wavelength	213 nm
pulse width	3 ns
fluence	2.5 J/cm^2
repetition rate	10 Hz
spot size	30 μm
sampling mode / pattern	30 μm single spot analyses
carrier gas	100% He, Ar make-up gas combined using a T-connector close to sample cell
pre-ablation laser warm-up (background collection)	40 s
ablation duration	20 s
wash-out delay	30 s
cell carrier gas flow	0.3 l/minute He
ICP-MS instrument	
make, model & type	Thermo Finnigan Element2 single collector HR-SF-ICP-MS
sample introduction	via conventional tubing
RF power	1100 W
make-up gas flow	1.0 l/minute Ar
detection system	single collector secondary electron multiplier
masses measured	202, 204, 206, 207, 208, 232, 233, 235, 238
integration time per peak	4 ms
total integration time per reading	approx. 1 s
sensitivity	20000 cps/ppm Pb
dead time	16 ns
Data processing	
gas blank	40 s on-peak
calibration strategy	GJ-1 used as primary reference material, Plešovice & M127 used as secondary reference material (quality control)
reference material info	M127 (Nasdala et al., 2008; Mattinson, 2010); Plešovice (Slama et al., 2008); GJ-1 (Jackson et al., 2004)
data processing package used / correction for LIEF	in-house spreadsheet data processing using intercept method for laser-induced elemental fractionation (LIEF) correction
mass discrimination	standard-sample bracketing with $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ normalised to reference material GJ-1
common-Pb correction, composition and uncertainty	204-method, Stacey & Kramers (1975) composition at the projected age of the mineral, 5% uncertainty assigned
uncertainty level & propagation	ages are quoted at 2 σ absolute, propagation is by quadratic addition; reproducibility and age uncertainty of reference material and common-Pb composition uncertainty are propagated
quality control / validation	Plešovice: Wtd ave $^{206}\text{Pb}/^{238}\text{U}$ age = 337 ± 4 (2SD, MSWD = 0.2) M127: Wtd ave $^{206}\text{Pb}/^{238}\text{U}$ age = 520 ± 5 (2SD, MSWD = 0.8)
Other information	detailed method description reported by Frei & Gerdes (2009)

grains were obtained using a Philips XL 40 scanning electron microscope.

U-Pb ages were obtained at the Central Analytical Facility, Stellenbosch University, by laser ablation – single collector – magnetic sectorfield – inductively coupled plasma – mass spectrometry (LA-SF-ICP-MS) employing a Thermo Finnigan Element2 mass spectrometer coupled to a NewWave UP213 laser ablation system. All age data presented here were obtained by single-spot analyses with a spot diameter of 30 μm and a crater depth of approx. 15–20 μm , corresponding to an ablated zircon mass of approx. 150–200 ng. The methods employed for analysis and data processing have been described in detail by Gerdes & Zeh (2006) and Frei & Gerdes (2009). For quality control, the Plešovice (Sláma et al., 2008) and M127 (Nasdala et al. 2008; Mattinson 2010) zircon reference materials were analysed, and the results were consistently in excellent agreement with the published ID-TIMS ages. Full analytical details and the results for all quality control materials analysed are reported in Table 1.

The calculation of concordia ages and plotting of concordia diagrams were performed

using Isoplot/Ex 3.0 (Ludwig 2003). Stacked histogram – relative probability plots of the zircon-age populations have been plotted using AgeDisplay (Sircombe, 2004).

4. Heavy-mineral assemblages

The heavy-mineral assemblages in the BSP-BF and OSF comprise eleven non-opaque and non-micaceous detrital components (anatase, apatite, cassiterite, dumortierite, epidote, garnet, monazite, staurolite, titanite, tourmaline and zircon). Of these, cassiterite, dumortierite, epidote and titanite are present sporadically and in very minor amounts (< 0.5%). The range of minerals present is closely comparable to that recorded by Thomas (1902, 1909), who also recognised other minerals in very minor amounts (actinolite, kyanite, sillimanite, serpentine, topaz), but failed to identify apatite, owing to the use of hydrochloric acid during sample preparation. Jeans et al. (1993) identified common apatite, garnet, rutile, tourmaline, staurolite and zircon, together with minor titanite. Svendsen & Hartley (2002) recognised apatite, garnet, monazite, titanite, tourmaline

Table 2. Comparison of the main detrital heavy-mineral abundances in the Otter Sandstone Formation as determined in the present study with those determined by Jeans et al. (1993) and Svendsen & Hartley (2002). Abundance ranges are not shown for the Svendsen & Hartley data because their analyses included non-detrital components (carbonate and Fe-oxides). Data collected during this study are from the 63–125 μm size range, whereas those of Jeans et al. (1993) and Svendsen & Hartley (2002) are from 64–250 μm and 63–210 μm , respectively

	At	Ap	Gt	Mo	Ru	St	To	Zr
Otter Sandstone Fm.								
range (this study)*	2.5–13.5	11.0–64.0	<0.5–27.5	<0.5–5.5	0.5–7.0	0.0–0.5	9.5–31.0	5.0–32.5
mean (this study)*	7.1	44.2	7.9	1.9	4.0	0.1	17.8	16.9
range (Jeans et al., 1993)	n.i.	26–50	3–14	n.i.	2–6	0	22–43	11–35
mean (Jeans et al., 1993)	n.i.	35	10	n.i.	4	0	30	22
mean (Svendsen & Hartley, 2002)**	n.i.	37.1	9.6	2.9	n.i.	n.i.	29.1	12.5
Budleigh Salterton Pebble Beds Fm.								
range (this study)	5.5–15.5	0.0	<0.5–0.5	1.0–4.0	4.0–6.5	8.5–36.0	28.0–48.0	18.0–22.0
mean (this study)	10.8	0.0	0.3	2.7	5.5	20.5	40.5	19.7
range (Jeans et al., 1993)	n.i.	0–1	0–1	n.i.	1–4	9–27	45–71	2–40
mean (Jeans et al., 1993)	n.i.	1	<1	n.i.	2	19	60	18

At: anatase; Ap: apatite; Gt: garnet; Mo: monazite; Ru: rutile; St: staurolite; Zr: zircon;
n.i.: not identified.

*excludes basal Otter Sandstone (heavy-mineral zone 2), which has a mineralogy that is more comparable to that of the Budleigh Salterton Pebble Beds.

**mean values recalculated excluding carbonate and Fe-oxides.

and zircon, together with Fe-Ti oxides. A comparison of the range and mean values of the main heavy-mineral components found in this study and in those of Jeans et al. (1993) and Svendsen & Hartley (2002) is shown in Table 2. Variations in mineral parameters enable subdivision of the succession into four heavy-mineral zones, with zone 1 corresponding to the BSPBF and zones 2–4 to the OSF (Fig. 3).

The mineralogical constitution of the BSPBF (heavy-mineral zone 1) determined during this study is closely comparable to that of Jeans et al. (1993), the main differences being that Jeans et al. (1993) recorded higher tourmaline abundances, and that the ranges of both tourmaline and zircon are wider in the Jeans et al. (1993) data set. These differences are probably attributable to the fact that Jeans et al. (1993) analysed a wider grain-size range (64–250 μm) than the current study (63–125 μm). The OSF mineralogy determined during the present study is also closely comparable with the earlier data of Jeans et al. (1993) and Svendsen & Hartley (2002), the main discrepancies being partly attributable to differences in the grain-size ranges that were analysed and partly due to mineral categorisation: for example, Svendsen & Hartley (2002) did not specifically identify rutile, but included this mineral in the wider 'Fe-Ti oxides' category.

The data confirm the results of previous studies by Thomas (1902, 1909) and Jeans et al. (1993) for a distinct difference in mineralogy between the BSPBF and OSF, the main manifestation of the contrast being the abundance of staurolite in the BSPBF and its virtually complete absence higher in the stratigraphy (Fig. 3). The other main difference is the absence of apatite (measured as ATi, the apatite:tourmaline index) in the BSPBF and its relative abundance in the OSF (Fig. 3). Garnet (measured as GZi, the garnet:zircon index) is also absent in the BSPBF, but occurs in minor to moderate amounts in the OSF (Fig. 3). This major change in mineralogy does not take place at the boundary between the two formations, but slightly higher up, at the boundary between Unit A and Unit B in the lower part of the OSF (between heavy-mineral zones 2 and 3).

The heavy-mineral assemblages in the OSF are comparatively uniform, but there are some minor variations that can be used to subdivide the succession. The most significant change takes place near the base of Unit C, where there is a distinct but short-lived reduction in ATi accompanied by an increase of GZi. This event has been used to mark the boundary between heavy-mineral zones 3 and 4 (Fig. 3). In addition, there are relatively subtle upward increases in GZi and RuZi that have been used to subdivide zone 3 into a lower subzone 3a and a higher subzone 3b. It is likely that the boundary between zones 3 and 4 is coincident with the boundary between the upper and lower OSF as identified in the Devon coast section by Svendsen & Hartley (2002), which takes place some 50–60 m below the top of the formation (their Fig. 7), probably around the base of 'layer 15' as shown in Figure 2.

5. Mineral chemistry

Major-element mineral-chemical analyses of tourmaline and garnet have been undertaken on a limited number of samples (Figs 4 and 5), in order to provide additional information on the nature of the sediment sources. Tourmaline data have been acquired from the entire succession, but garnet analyses have been undertaken only for the upper part (heavy-mineral zones 3 and 4), owing to the scarcity of garnet in the BSPBF and lowest part of the OSF (zones 1 and 2).

The three garnet populations are closely comparable to one another, each having three main compositional groups (Fig. 4). A relatively large number of garnets are Mn-rich and Mg- and Ca-poor, and therefore plot in Field Bi as defined by Mange & Morton (2007). Garnets with these compositions are typically derived from granitic sources. The second group comprises high-Mg, high-Ca garnets (Field C of Mange & Morton, 2007), compositions that are generally associated with high-grade mafic rocks. The third group falls in Field Bii (low-Mg, variable Ca), and was probably derived from amphibolite-facies metasediments, although garnets of this composition are less

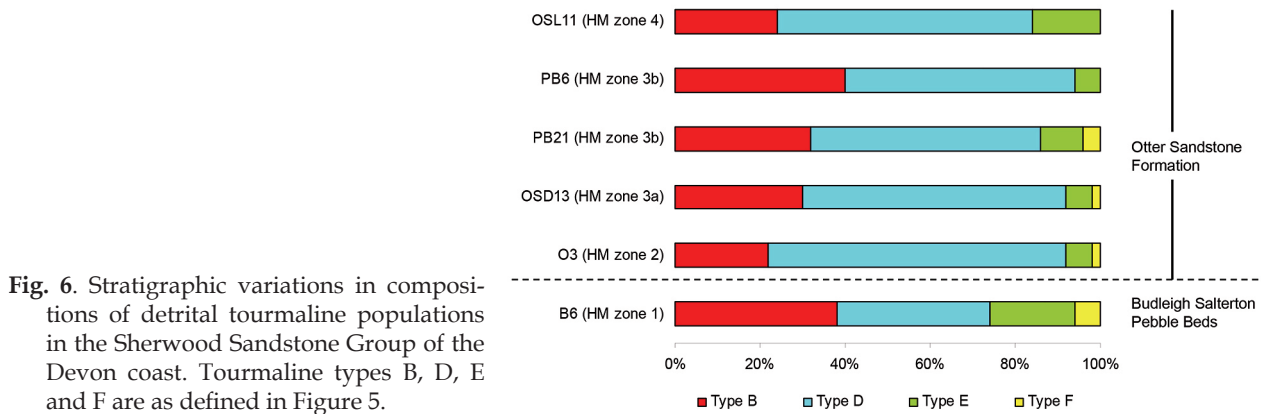


Fig. 6. Stratigraphic variations in compositions of detrital tourmaline populations in the Sherwood Sandstone Group of the Devon coast. Tourmaline types B, D, E and F are as defined in Figure 5.

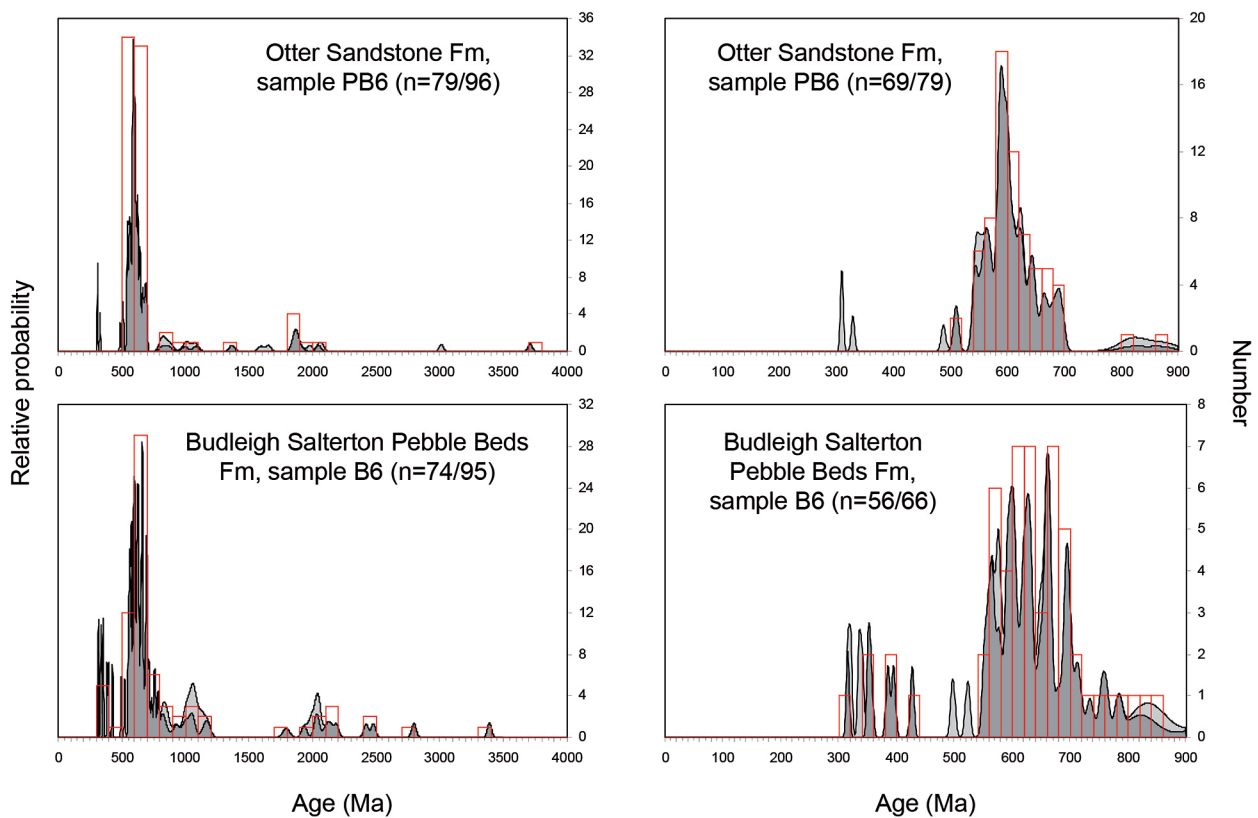


Fig. 7. Detrital-zircon ages in the Budleigh Salterton Pebble Beds Formation and Otter Sandstone Formation, displayed as combined histogram – relative probability diagrams generated using AgeDisplay (Sircombe, 2004). n denotes the number of zircons with 90–110% concordance and the total number of zircon analyses.

source-diagnostic than the other two groups. There does not appear to be any stratigraphic trend in garnet composition, despite the overall increase in abundance of garnet with time (increasing GZi).

Most of the tourmalines have compositions that correspond to Field D of Henry & Guidotti (1985), with variable proportions that fall in Field B (Fig. 5). Field D tourmalines form 36–70% of the populations, compared with 22–40%

in Field B (Fig. 6). Most of the samples have only minor representations of Fields E and F, but the sample from the BSPBF has higher proportions of these tourmalines than does the OSF (20% and 6%, respectively, compared with 6–16% and 0–4%). These data indicate that the tourmalines were derived principally from Al-rich metasediments (Field D) with subordinate input from Li-poor granitoids (Field B) and generally minor input from Al-poor metased-

iments (Fields E and F). The BSPBF appears to have a tourmaline population that slightly differs from the OSF (Fig. 6), with lower proportions falling in Field D and relatively large numbers in Fields B, E and F. This difference confirms the heavy-mineral evidence for a difference in provenance of the BSPBF and OSF.

6. Detrital-zircon ages

Zircon-age data have been acquired on two samples, one from the BSPBF (sample B6, heavy-mineral zone 1) and one from the OSF (sample PB6, zone 3b), in order to provide geochronological constraints on the provenance of these two formations. The age spectra are broadly similar, both having dominant Late Neoproterozoic groups in the ~540–700 Ma range, with subordinate older Precambrian zircons extending as far back as 3710 Ma (Fig. 7). The older Precambrian includes representation of earlier Neoproterozoic zircons (~700–860 Ma), a small group at ~1000–1200 Ma, and another small group at ~1800–2100 Ma, together with occasional zircons scattered through the earlier Palaeoproterozoic and Archaean. These older Precambrian zircons form a higher proportion of the BSPBF spectrum than of the OSF, but in both cases the abundance of zircons older than 700 Ma is low. The BSPBF and OSF also differ in that the Late Neoproterozoic in the BSPBF is represented by a broad zircon group, with distinct peaks at ~560 Ma, ~610 Ma, ~630 Ma, ~660 Ma and ~690 Ma, whereas the Late Neoproterozoic zircons in the OSF form essentially a group of similar ages, peaking in the ~580–600 Ma range. Although these differences are relatively minor, they nevertheless provide further evidence for a change in sediment source between the two units.

The most surprising feature of both spectra is the scarcity of younger, Variscan-age, zircons. The BSPBF spectrum contains four zircons with 90–110% concordance that correspond to the Late Devonian to Carboniferous (316 Ma, 351 Ma, 356 Ma and 385 Ma), but grains of this age are absent in the OSF samples, apart from 3 zircons with >10% discordance (Fig. 7).

7. Provenance of the Devon coast Triassic succession

The presence of distinct changes in mineralogy within the Devon coast Triassic succession indicates that the sediment provenance evolved with time. The BSPBF (heavy-mineral zone 1) is characterised by low apatite (low ATi), low garnet (low GZi), and relatively high staurolite contents. The overlying basal part of the OSF (zone 2) is generally similar to the BSPBF, but the overlying parts of the OSF (zones 3–4) have a contrasting mineralogy, with moderate to high ATi, low to moderate GZi, and a scarcity of staurolite. There are also differences in the tourmaline geochemistry within the succession, and although zircon-age spectra in the BSPBF and OSF are broadly comparable, they show some differences in detail. In addition, there are changes within the OSF, with an overall upward increase in relative abundance of garnet (higher GZi) and rutile (higher RuZi).

The lack of apatite and garnet in the BSPBF strongly suggests that the sediment has undergone extensive weathering (cf. Van Loon & Mange, 2007), since both minerals are unstable under such conditions (Morton, 2012). Furthermore, the presence of abundant staurolite indicates the source included moderate-grade metapelitic rocks, and such rocks would also be expected to supply garnet. The weathering could have occurred during alluvial storage prior to final deposition; alternatively, it could have taken place at the depositional site, or it could have been due to a combination of the two. The presence of a well-established desert palaeosol at the top of the BSPBF, estimated to have formed over a time span of 50,000–100,000 years (Wright et al., 1991), and the highly permeable nature of the BSPBF, suggests that the weathering took place at the depositional site, at least in part. In combination with the tourmaline data, which indicate the presence of a range of metapelitic rocks in association with Li-poor granitoids, the source region can be reconstructed as comprising metasediments at least up to staurolite grade (supplying staurolite, rutile and some of the tourmaline), in combination with granites that supplied zircon and the remaining tourmaline. Apatite and garnet

are also likely to have been supplied to the transport system, but have been lost through weathering at the depositional site, possibly as well as during periods of alluvial storage prior to final deposition.

The basal part of the OSF (heavy-mineral zone A) has similar characteristics to the BSPBF, with low ATi and GZi together with high staurolite abundances, although the latter decrease towards the top. These features suggest that the sediment was largely recycled from the BSPBF during the aeolian depositional phase that immediately followed the BSPBF and the palaeosol (Fig. 2). The decrease in staurolite towards the top may herald the appearance of typical fluvially-derived OSF detritus that characterises the rest of the formation.

The majority of the OSF (UM units 3 and 4) is typified by heavy-mineral assemblages that lack staurolite and have consistently moderate to high ATi. The sandstones show an evolution in certain features with time, notably increasing GZi and RuZi. The assemblage has a predominantly granitic aspect, on the basis of the high apatite and zircon contents, the presence of tourmalines of Li-poor granitoid origin, and garnets rich in Fe and Mn. Metasediments must also have been involved, in order to account for the remainder of the tourmaline population and for the high-Ca, low-Mg garnets, but unlike the BSPBF, these did not contain staurolite. The garnet data also suggest the presence of metamafic rocks in the source area. The overall increase in garnet and rutile with time suggests that granitic sources became less important, although they appear to have remained dominant throughout. The short-lived reduction in ATi at the base of heavy-mineral zone 4 is interpreted as representing a phase of increased weathering, possibly due to a reduction or temporary cessation in sediment supply. It is noteworthy that this event is coincident with a significant increase in GZi, possibly indicating a reorganisation of the sediment supply system.

The zircon-age data perhaps provide the most important constraints on the location of the source regions for both the BSPBF and OSF. Given that their sources lay to the south on the basis of a variety of other provenance

indicators, most notably the presence of fossiliferous pebbles of Armorican aspect, the dominance of the late Neoproterozoic group indicates that the Cadomian basement (as found, for example, in the Channel Islands and northern France) was the main source. The Cadomian granitoid basement rocks are believed to have formed in two phases from ~615 Ma to ~540 Ma (Samson et al., 2005). U-Pb zircon dating of the Cadomian granitoids of La Hague, Normandy, indicates two phases of magmatism, an earlier one between 620 Ma and 608 Ma and a later one between 583 Ma and 572 Ma (Samson et al., 2005). Granitoids and rhyolites from Jersey have been dated by zircon U-Pb as 580–583 Ma (Miller et al., 2001). The dominant peak in the OSF (~580–600 Ma) therefore corresponds to the range of Cadomian granitoids in northern Armorica. These granitoids are also likely to have supplied some of the zircons in the BSPBF, but the older Neoproterozoic zircons probably represent derivation from Brioverian (Neoproterozoic) metasediments, since these contain Neoproterozoic zircons dating back to ~760 Ma (Samson et al., 2005).

The small groups of zircon dated as ~1800–2100 Ma in both samples could correspond to the Palaeoproterozoic basement of northern Armorica (Calvez & Vidal, 1978; Vidal et al., 1981; Guerrot & Peucat, 1990; Samson & D'Lemos, 1998; Inglis et al., 2004). In addition to Neoproterozoic zircons, the Brioverian metasediments contain Palaeoproterozoic and Archaean grains as old as 3.1 Ga (Miller et al., 2001; Sansom et al., 2005), and it is therefore likely that these also supplied sediment to the Devon coast during the mid-Triassic, especially given the evidence for the presence of metasedimentary detritus as well as granitic material. The origin of the late Mesoproterozoic to early Neoproterozoic group is less certain, since the Brioverian metasediments do not contain this group (Miller et al., 2001; Samson et al., 2005), and crystalline rocks of this age do not appear to be present in the Armorican Massif (Roach et al., 1990). However, such zircons are found as detrital components of sediments in other parts of the Armorican Massif (Catalán et al., 2004; Dinis et al., 2012), and recycling from

pre-existing sediment is therefore considered their most likely origin.

Possibly the most important constraint on the location of the sources for the BSPBF and OSF is provided by the scarcity of Late Carboniferous to Early Permian zircons related to the Variscan orogenesis and associated magmatic activity. Variscan granites are widespread in the Armorican Massif of northern France and equivalent parts of the Variscan mountain belt in central Europe (Tischendorf et al., 1995; Brown & Dallmeyer, 1996; Ballèvre, 2009; Tyrrell et al., 2012). These granites are known to have been available as a sediment source as early as the Late Carboniferous, on the basis of the presence of detrital zircons in Westphalian sandstones of the UK (Hallsworth et al., 2000; Morton et al., 2010), and on the basis of evidence for rapid exhumation of such granites in the Variscan mountain belt (Schulmann et al., 2002). The scarcity of Late Carboniferous and Early Permian zircons in the Devon coast succession suggests that the catchment area did not extend into regions of Armorica that include widespread Variscan granites, and therefore implies that the source was more proximal, probably in the English Channel and possibly extending into the Channel Islands, the La Hague peninsula and the northern Brittany coast, where Variscan granites are comparatively minor (Brun et al., 2001; Sansom et al., 2005). Furthermore, the Early Permian Dartmoor granite is only some 25 km away from the Devon outcrop, and is known to have been unroofed in the Late Permian since it supplied a significant amount of clastic detritus to the Permian Exeter Group that underlies the Early-Middle Triassic Sherwood Sandstone Group and Early Triassic Aylesbeare Mudstone Group (Edwards et al., 1997). Derivation from the Cornubian area immediately to the west therefore also seems unlikely.

8. Implications regarding the 'Budleighensis River'

The heavy-mineral data acquired from the Devon coast Triassic succession are consistent with sourcing from the south, as indicated by

previous studies (especially the evidence from fossiliferous pebbles). The new data indicate that the source region had limited exposure of Late Carboniferous-Early Permian (Variscan) granites, and therefore must have been relatively proximal to the Wessex Basin, since such granites are widespread across most of Brittany apart from the northern coastal region. The source is therefore considered to have principally lain in the English Channel region, possibly extending into the Channel Isles, the La Hague peninsula and the northern Brittany coast. This evidence is consistent with the palaeogeographic reconstructions of Warrington & Ivimey-Cook (1992), which suggest relatively proximal sourcing (Fig. 8). The absence of Early Permian zircons in the BSPBF and OSF indicates that the Cornubian massif to the west had ceased to supply clastics into the western Wessex Basin by the mid-Triassic, even though it supplied clastic material during the Permian (Edwards et al., 1997). It also appears that the unconformity that separates the Sherwood Sandstone and Aylesbeare Mudstone Groups was not associated with sufficient uplift to rework the underlying Permian, at least in the south Devon area.

The scarcity of Late Carboniferous-Early Permian (Variscan) zircons indicates that the Devon coast succession was not supplied by a large river system draining the Massif Central, Brittany, Normandy and possibly the Pyrenees (Tyrrell et al., 2012) (Fig. 8). However, it is possible that a large river system draining these regions (as envisaged by Tyrrell et al., 2012) was responsible for the Sherwood Sandstone Group further east in the Wessex Basin, since the differences in heavy-mineral ratio characteristics between the Wytch Farm oilfield and the Devon coast (Fig. 9) indicate that the two areas were fed from different sources. The provenance relationships between the Sherwood Sandstone Group of the Devon coast and that in the central and eastern parts of the Wessex Basin require further investigation, to expand the heavy-mineral database and to acquire mineral-chemical and zircon-age data. Further work is also needed to investigate the reasons behind the marked

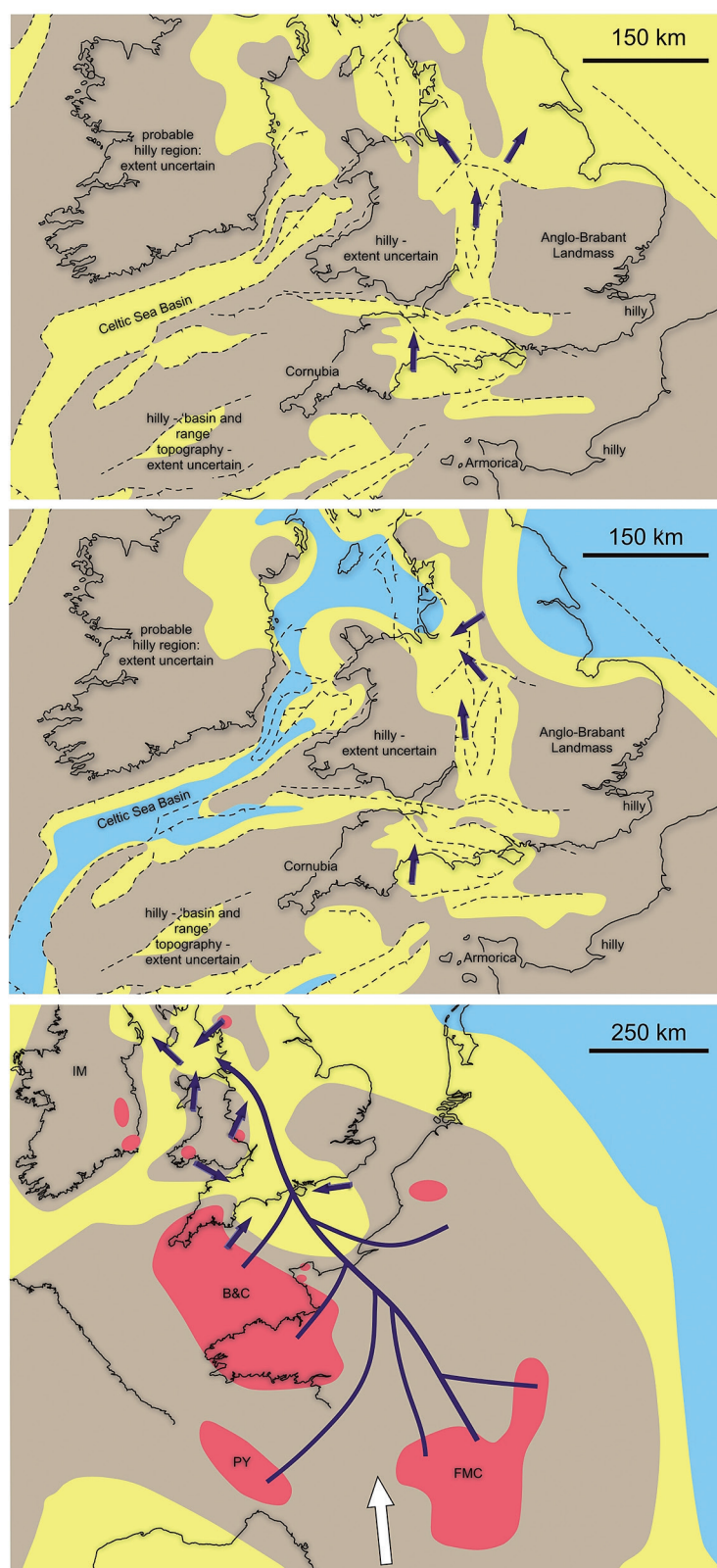


Fig. 8. Palaeogeographic reconstructions of the Sherwood Sandstone Group of southern Britain. Upper (Induan-Olenekian) and middle (Anisian) diagrams have been adapted from Warrington & Ivimey-Cook (1992). The lower diagram has been adapted from Tyrrell et al. (2012).

IM = Irish Massif; B&C = Brittany and Cornwall granites; FMC = French Massif Central granites; PY = Pyrenees granites. Brown = upland areas, yellow = non-marine basins, blue = marine basins, red = granites.

difference in heavy-mineral assemblages between the Wessex Basin and the East Irish Sea Basin, as illustrated by reductions in ATi (apa-

tite:tourmaline) and MZi (monazite:zircon) between the southern and northern parts of the 'Budleighensis River' system (Fig. 9).

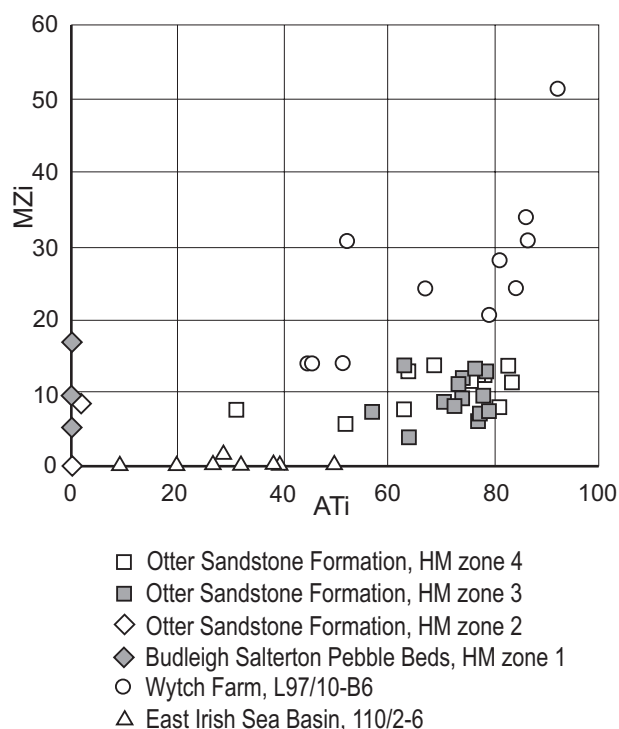


Fig. 9. Binary plot of the monazite:zircon index (Mzi) and the apatite:tourmaline index (Ati) comparing the Sherwood Sandstone of the Devon coast, the Wytch Farm oilfield (central Wessex Basin) and well 110/2-6 (East Irish Sea Basin). The plot demonstrates the presence of lateral differences in provenance across the Wessex Basin and the markedly different character of the sandstones towards the northern extent of the 'Budleighensis River' system. Locations of Wytch Farm and well 110/2-6 are shown in Figure 1.

9. Conclusions

An integrated heavy-mineral, mineral-chemical and zircon-dating study of the Triassic succession exposed on the south Devon coast on the western margin of the Wessex Basin confirms derivation from the Armorican Massif to the south, but indicates that the catchment area was relatively small and did not extend southwards or westwards into zones where Variscan granites are widespread. The Devon coast succession has different characteristics to stratigraphically equivalent sandstones further east in the Wessex Basin, indicating that the 'Budleighensis River' system is complex, and comprises at least two different systems draining different parts of the Armorican Massif. Available data indicate that there are marked contrasts in mineralogy between

the proximal (southern) part of the 'Budleighensis River' system and the distal (northern) region. Further heavy-mineral studies are required to investigate the causes of these mineralogical variations within the linked Triassic basins of southern Britain.

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