Journal of the Geological Society, *London*, Vol. **168**, 2011, pp. 705–716. doi: 10.1144/0016-76492010-031.

A refined chronology for the Cambrian succession of southern Britain

THOMAS H. P. HARVEY[1,2]*, MARK WILLIAMS[1], DANIEL J. CONDON[3], PHILIP R. WILBY[4], DAVID J. SIVETER[1], ADRIAN W. A. RUSHTON[4], MELANIE J. LENG[3] & SARAH E. GABBOTT[1]

[1]*Department of Geology, University of Leicester, Leicester LE1 7RH, UK*

[2]*Present address: Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK*

[3]*NERC Isotope Geosciences Laboratory, British Geological Survey, Keyworth, Nottingham NG12 5GG, UK*

[4]*British Geological Survey, Keyworth, Nottingham NG12 5GG, UK*

**Corresponding author (email thp.harvey@cantab.net)*

Abstract: Three dated (U–Pb, zircon) ash beds from biostratigraphically constrained Avalonian successions of Shropshire (England) and Pembrokeshire (Wales) delimit the traditional 'Lower'–'Middle' Cambrian boundary and resolve a problematic regional correlation. In Shropshire, a date of 514.45 ± 0.36 [0.81 including tracer calibration and ^{238}U decay constant errors] Ma from near the top of the Lower Comley Sandstone Formation provides a maximum age for the boundary between Cambrian Stages 3 and 4, and a date of 509.10 ± 0.22 [0.77 including tracer calibration and ^{238}U decay constant errors] Ma from the basal Quarry Ridge Grits, Upper Comley Sandstone Formation, provides a minimum age for the boundary between Cambrian Stages 4 and 5 (and thus Series 2 and 3). These dates offer a calibration of early metazoan evolution by directly constraining the age of the intervening Comley Limestones, which contain diverse small shelly fossils in addition to trilobites, and also a key early occurrence of exceptional, three-dimensionally preserved arthropods. In Pembrokeshire, an ash bed from the Caerfai Bay Shales Formation dates to 519.30 ± 0.23 [0.77 including tracer calibration and ^{238}U decay constant errors] Ma, equivalent to a horizon low in the Lower Comley Sandstone Formation of Shropshire, possibly around the level at which trilobites make their first local appearance.

Supplementary material: Appendix 1, a table of isotope data, is available at http://www.geolsoc.org.uk/SUP18444.

The Cambrian Period marks a time of profound biological and geological change, not least the conspicuous expansion in the diversity, abundance and ecologies of large multicellular organisms (e.g. Butterfield 2007) concurrent with rapid fluctuations in carbon cycling (Saltzman *et al.* 1998; Maloof *et al.* 2005). Understanding the potential linkages between biological and environmental change and determining the exact ordering of events, rates and durations of processes requires a robust chronology. Radiometric dates obtained from uranium-bearing minerals from volcanic rocks are crucial in providing absolute dates that can be tied directly to bio-, litho- and/or chemostratigraphic information, and thus can test correlations based on more widely applicable, but often controversial, stratigraphies derived from fossil ranges and isotope excursions.

The Cambrian System will be divided into four series (Fig. 1), of which only the lowest and highest have been formalized (Shergold & Cooper 2004). Furthermore, of the 10 proposed stages within this framework, only the first (lowest), sixth, seventh and eighth have so far been defined (Peng & Babcock 2008). The base of the Cambrian now has a well-established date of *c.* 542 Ma (Bowring *et al.* 2007; also see Peng & Babcock 2008), and the base of the Ordovician of *c.* 488 Ma (Landing *et al.* 2000), but a highly resolved geochronology has yet to emerge, although work on this has been progressing (reviewed by Shergold & Cooper 2004). Although there exist numerous radio-isotopic dates for Cambrian-age strata, only a small number can be considered suitably robust (i.e. based on U–Pb isotope dilution thermal ionization mass spectrometry (ID-TIMS) zircon dates) and sufficiently well constrained biostratigraphically to be used for calibrating epoch and stage boundaries (Shergold & Cooper 2004). At present, key U–Pb (zircon) dates from trilobite-bearing strata in New Brunswick (Avalonia) and Morocco (Gondwana) (Landing *et al.* 1998) provide the basis for subdivision of absolute time within the Cambrian, although assigning ages to epoch and/or stage boundaries has often necessitated interpolation, and thus an increase in uncertainty.

Cambrian ash-bearing successions in Wales and England (Fig. 2) offer opportunities for obtaining radiometric ages from strata that are well calibrated biostratigraphically and can thus be correlated with the emerging global standard. Geochronological work on the fossiliferous successions of north Wales has given reliable radiometric ages for strata near the Cambrian–Ordovician boundary (Davidek *et al.* 1998; Landing *et al.* 2000) and an additional date has been recorded from the early Cambrian of south Wales (Landing *et al.* 1998). These results were based on ID-TIMS ^{206}Pb/^{238}U dates (zircons, and predominantly from single crystals) (Davidek *et al.* 1998; Landing *et al.* 1998, 2000). Continuing fieldwork is identifying additional ash beds dating from the earlier part of the Cambrian. Here we present new ^{206}Pb/^{238}U zircon dates for two volcanic ash beds from a key locality in Shropshire, England, the older one from near the top of the Lower Comley Sandstone Formation and the younger one from the base of the Upper Comley Sandstone Formation (Figs 3 and 4). We have also sampled an ash bed from a single locality in the lower Cambrian Caerfai Bay Shales Formation of Pembrokeshire, south Wales (Fig. 4).

The ash beds of the Shropshire succession straddle a hiatus between the local Comley Series and St. David's Series of earlier

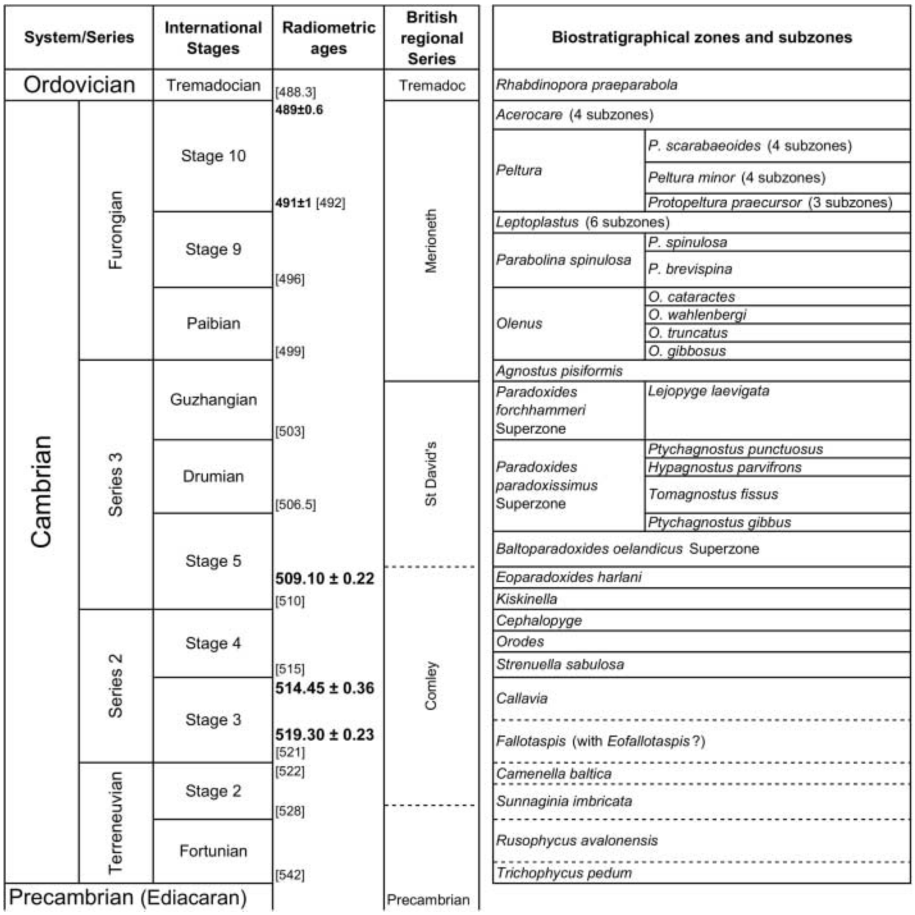

Fig. 1. Chronostratigraphical and biostratigraphical divisions of the Cambrian System (after Rushton *et al.* 2011). Series and stages that are numbered rather than named have not been ratified internationally. The British regional stages of former usage (Cowie *et al.* 1972) and the chief macrofossil biozones are shown. Radiometric ages shown in bold type and without brackets are based on British records including those from the late Cambrian of north Wales (Davidek *et al.* 1998; Landing *et al.* 2000); those in larger type are dates recovered in the present study. Dates in brackets are those summarized by Peng & Babcock (2008).

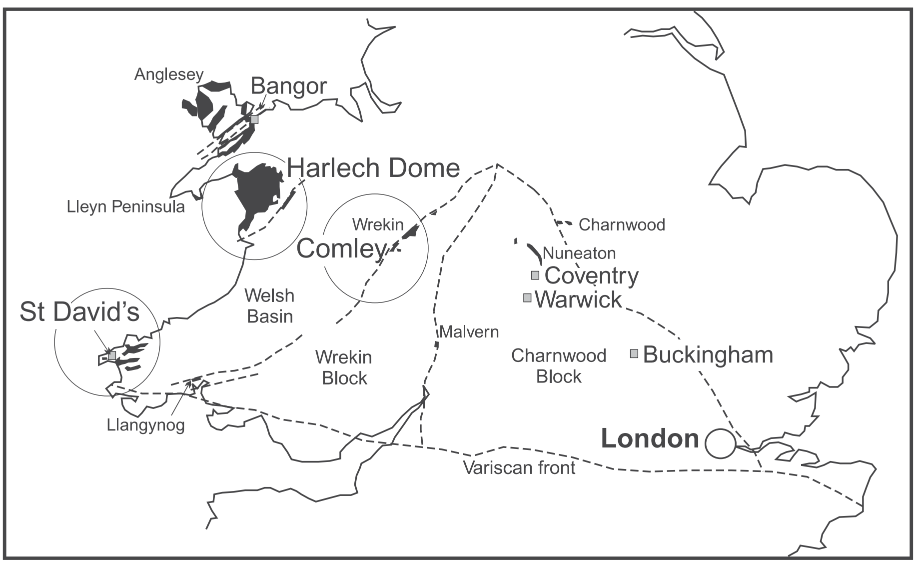

Fig. 2. Distribution of Cambrian and Tremadocian (lower Ordovician) rocks in England and Wales (from Brenchley *et al.* 2007; Rushton *et al.* 2011). New U–Pb zircon dates are from the Cambrian successions of Comley and St. David's. Ash beds of late Cambrian age have also been dated from the Harlech Dome (Davidek *et al.* 1998; Landing *et al.* 2000). Structural lineaments are shown with dashed lines.

British usage (Fig. 1), effectively the 'Lower'–'Middle' Cambrian boundary as previously recognized (Cowie *et al.* 1972). In the current scheme our results from Shropshire encompass approximately the limits that have been mooted for Cambrian Stage 4 and the lowermost part of Stage 5 (Fig. 1). We therefore offer a biostratigraphical correlation that allows us to limit the age of Stage 4 as provisionally recognized in Avalonia, and provide a minimum age for the base of Stage 5 of Series 3. The intervening succession in Shropshire consists of the Comley Limestones, which contain rich assemblages of small shelly fossils in addition to diverse trilobites, and have yielded some of the world's oldest known fossil arthropods to be preserved in

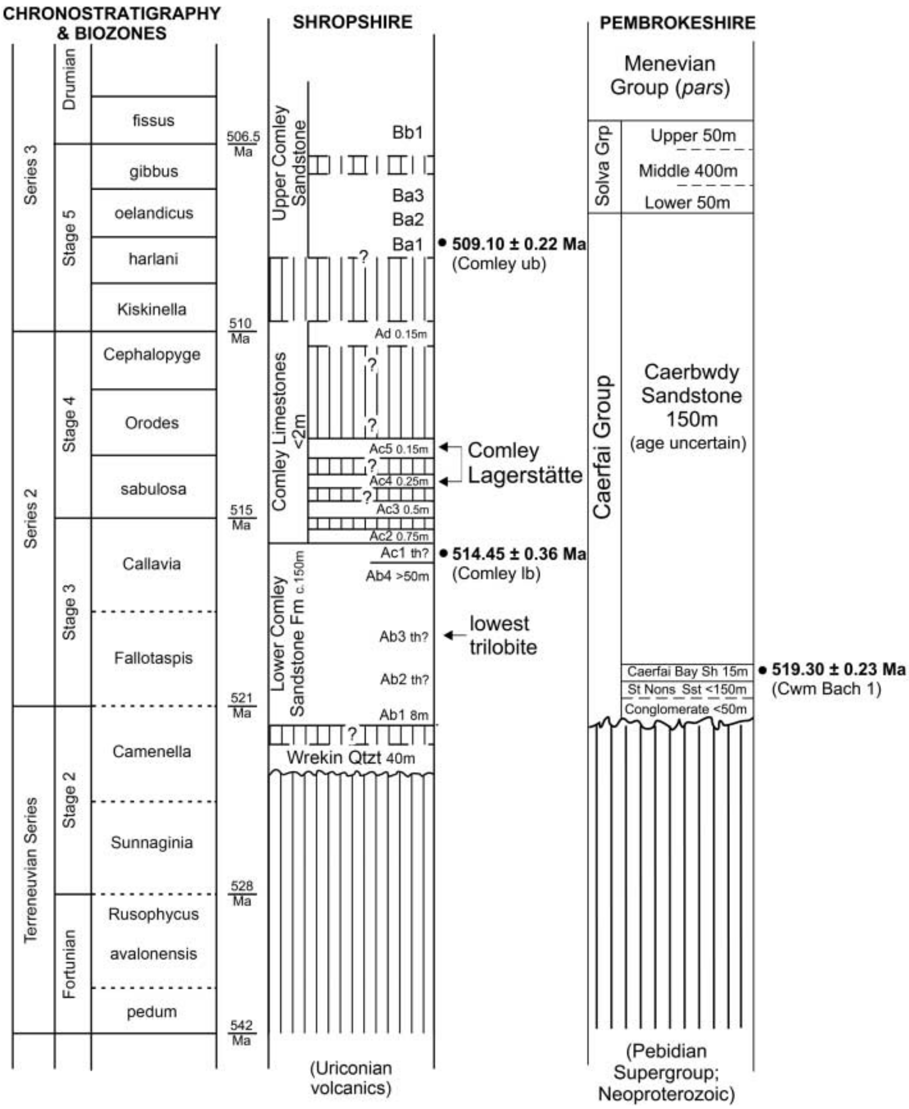

Fig. 3. Correlation of the lower Cambrian successions of Shropshire and Pembrokeshire, based on the new U–Pb zircon dates (after Rushton *et al.* 2011; thickness after Rushton *et al.* 1999 and references therein).

three dimensions with soft anatomy (Siveter *et al.* 2001, 2003). The new radiometric dates thus provide maximum and minimum ages by which to establish the durations of trilobite biozones, test the biostratigraphic potential of small shelly fossils, and constrain the chronology of an important fossil-Lagerstätte. In addition to the radio-isotopic study we attempt correlation with some of the major carbon isotope excursions (CIEs) recognized for the early and middle Cambrian via analyses of the Comley Limestones for their carbon and oxygen isotope signatures.

Sampled localities and horizons

We sampled ash beds from two localities in the Cambrian succession of southern Britain. The first locality is a small trench excavated *c.* 200 m south of Comley Quarry [National Grid Reference (NGR) SO 484 962], Comley village, Shropshire, England (Fig. 4). The succession exposed in the trench consists of, from base to top, the Lower Comley Sandstone Formation (uppermost part), the Comley Limestones, and the Upper Comley Sandstone Formation (lowermost part). In referring to horizons in this succession we use established names alongside alphanumeric notations as applied by Cobbold (1921). We sampled two thin soft ash beds exposed in the trench: they are up to 10 cm thick, but discontinuous. The lower bentonite (sample 'Comley lb') is from a few centimetres below the top of the Green Callavia Sandstone (Ac1 of Cobbold 1921) in the uppermost part of the Lower Comley Sandstone Formation, and the upper bentonite (sample 'Comley ub') is from the basal Quarry Ridge Grits (Ba1); that is, the basal unit of the Upper Comley Sandstone Formation. The more calcareous strata bracketed by the two ash beds, known collectively as the Comley Limestones, were sampled for stable isotope analysis. At the sampled locality, the Comley Limestones succession is relatively thin, about 0.8 m thick, and only four of a possible five units of Cobbold (1921) can be identified. The horizons sampled for stable isotopes in the present study are the Red Callavia Sandstone (Ac2), the Strenuella Limestone (Ac4), the Protolenus Limestone (Ac5) and the Lapworthella Limestone (Ad). The Bellimarginatus Limestone (Ac3) appears to be absent. At no other locality, however, could we have obtained samples from an unweathered and *in situ* succession.

The second locality sampled is a small outcrop at Cwm Bach [NGR SM 841 230], near Newgale, Pembrokeshire, south Wales. Here the Caerfai Bay Shales Formation contains a number of

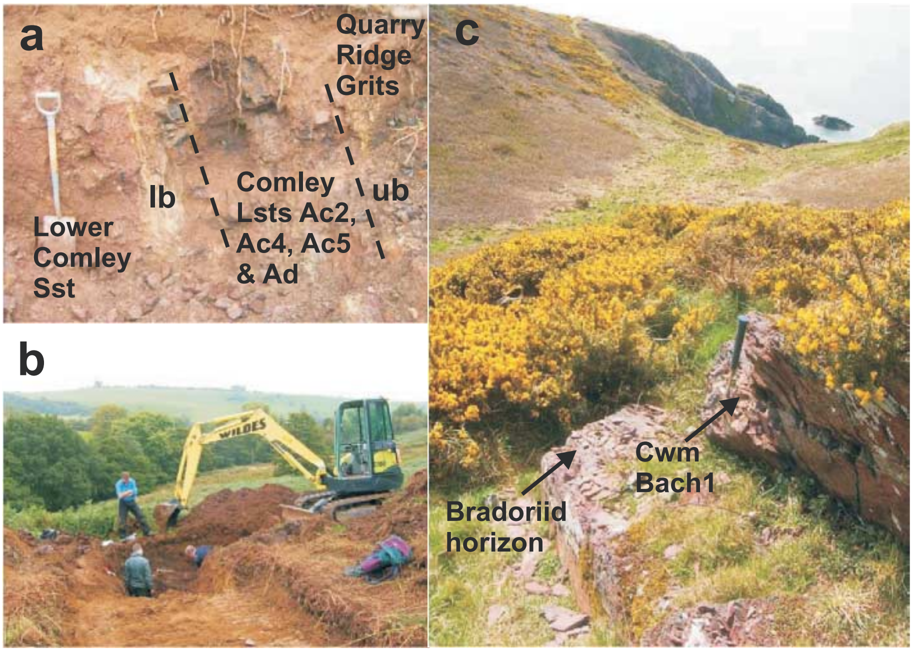

Fig. 4. Field localities for sampled ash beds. (**a**, **b**) Trench exposing the Comley Limestones and adjacent strata, south of Comley Quarry, Comley, Shropshire. (**a**) Sampled ash beds labeled lb (lower bentonite) and ub (upper bentonite) (note spade for scale). (**c**) Coastal hillside outcrop of Caerfai Bay Shales Formation at Cwm Bach, near Newgale, Pembrokeshire, south Wales. The sampled ash bed (Cwm Bach 1) and underlying bradoriid-bearing horizon (see Siveter & Williams 1995) are indicated.

thin ash beds. One of these, sample 'Cwm Bach 1' (see Fig. 4), lies closely above the only known fossiliferous horizon, which bears bradoriid arthropods (reported by Siveter & Williams 1995).

Analytical methods and isotope sampling strategy

Zircons were separated from three *c.* 2 kg samples of volcanic ash (Comley lb, Comley ub, and Cwm Bach 1) using conventional mineral separation techniques. Prior to ID-TIMS analysis zircons were subject to a modified version of the chemical abrasion technique (Mattinson 2005). Details of sample pretreatment, dissolution and anion exchange chemistry are similar to those described by Bowring *et al.* (2007). U–Pb ID-TIMS analyses herein utilized the EARTHTIME ^{205}Pb–^{233}U–^{235}U (ET535) tracer solution. Measurements at the NERC Isotope Geosciences Laboratory (NIGL) were performed on a Thermo Triton TIMS system. Lead analyses were made in dynamic mode on a MassCom SEM detector and corrected for $0.16 \pm 0.04\%$ per a.m.u. mass fractionation. Linearity and dead-time corrections on the SEM were monitored using repeated analyses of NBS 982, NBS 981 and U500. Uranium was measured in static Faraday mode on 10^{11} ohm resistors or, for signal intensities <15 mV, in dynamic mode on the SEM detector. Uranium was run as the oxide and corrected for isobaric interferences with an ^{18}O/^{16}O composition of 0.00205 (determined through direct measurement at NIGL). U–Pb dates and uncertainties were calculated using the algorithms of Schmitz & Schoene (2007) and a ^{235}U/^{205}Pb ratio for ET535 of $100.21 \pm 0.1\%$. All common Pb in the analyses was attributed to blank and subtracted based on the isotopic composition and associated uncertainties analysed over time. The ^{206}Pb/^{238}U ratios and dates were corrected for initial ^{230}Th disequilibrium using a $Th/U_{[magma]}$ of 3 ± 1, resulting in an increase in the ^{206}Pb/^{238}U dates of *c.* 100 ka. Errors for U–Pb dates are reported in the following format: $\pm X(Y)[Z]$, where X is the internal or analytical uncertainty in the absence of all systematic error (tracer calibration and decay constants), Y includes the tracer calibration error (using a conservative estimate of the 2σ standard deviation of 0.1% for the Pb/U ratio in the tracer), and Z includes the additional ^{238}U decay constant errors of Jaffey *et al.* (1971). These systematic errors are added, in quadrature, to the weighted mean internal error. All analytical uncertainties are calculated at the 95% confidence interval. We have attempted to include all sources of uncertainty including the systematic error from tracer calibration and ^{238}U decay constant. In many previous studies (Davidek *et al.* 1998; Landing *et al.* 1998, 2000) these systematic sources of uncertainty have not been included because analytical sources of uncertainty (e.g. correction for laboratory Pb blank) dominate the uncertainty budget. However, in the past decade improvements in analytical techniques have resulted in a decrease in analytical sources of uncertainty, and the relative importance of the systematic sources of uncertainty (i.e. decay constant errors) has become more apparent (Bowring *et al.* 2006). The current Cambrian time scale depends largely on ID-TIMS U–Pb (zircon) dates, although the development of alternative techniques that exploit other decay radio-isotope schemes (such as Re–Os dating of organic-rich sediments) may mean that future time scales are based on more diverse data. A consideration of decay constant uncertainties would then be required for comparison of all dates. For completeness, therefore, we have included all sources of uncertainty, although for most practical purposes the Y level of uncertainty (analytical plus U/Pb tracer calibration) may be most appropriate for comparison of these new dates with future and previously published ^{206}Pb/^{238}U dates, including those for other Avalonian and Gondwanan successions (Davidek *et al.* 1998; Landing *et al.* 1998, 2000).

For stable isotope analysis, we drilled small volumes of powder from localized sample points (*c.* 4 mm diameter centred 8 mm apart) along vertical transects of unweathered slabs cut through each of the four stratigraphic units of the Comley Limestones succession that we have sampled. For one of the units (the Lapworthella Limestone, Ad), we replicated sample points along a parallel transect, to test for consistency. With reference to petrographic thin sections, we focused on fine-grained sub-lithologies avoiding intraclasts, bioclasts, phosphatic hardgrounds, and areas of extensive carbonate recrystallization, translating sample points laterally by up to a few centimetres where necessary. To test diagenetic alteration trajectories, we collected control samples from pervasive calcite veins, and sampled a region of coarse crystallization. The sample material was ground in an agate mortar and an equivalent of 10 mg of carbonate was reacted with anhydrous phosphoric acid *in vacuo* overnight at a constant 25 °C. The CO_2 liberated was separated from water vapour under vacuum and collected for analysis. Measurements were made on a VG Optima mass spectrometer. Overall analytical reproducibility for these samples is normally better than 0.2‰ for $\delta^{13}C$ and $\delta^{18}O$ (1σ). Isotope values ($\delta^{13}C$, $\delta^{18}O$) are reported as per mil (‰) deviations of the isotopic ratios ($^{13}C/^{12}C$, $^{18}O/^{16}O$) calculated to the VPDB scale using a within-run laboratory standard calibrated against NBS standards.

Results from zircon dating

Zircons separated from the three ash bed samples were small (<50 μm), with aspect ratios of *c.* 3 to *c.* 7, and without the signs of abrasion that would indicate a detrital component. Samples Comley ub and Cwm Bach 1 contained single morphological populations in terms of crystal size, shape, colour and presence of medial melt inclusions, which is typical for zircons from volcanic ash beds. Sample Comley lb contained a more varied population in terms of colour and shape, and zircons were smaller than those recovered from the other two samples. In total, seven fractions (single grains or fragments) were analysed from sample Cwm Bach 1, six from sample Comley ub and seven from Comley lb, and the resulting data are presented in Table 1 and Figure 5.

Six of seven analyses of sample Cwm Bach 1 yield a weighted mean $^{206}Pb/^{238}U$ date of 519.30 ± 0.23(0.57)[0.77] Ma (MSWD = 1.1), which is interpreted as being the best estimate for the age of this sample. The sixth analysis (z9) from Cwm Bach 1 yielded a slightly younger date (*c.* 516 Ma), which is interpreted as reflecting residual Pb loss. Sample Comley lb yielded a more varied zircon population based upon external morphology compared with samples Comley ub and Cwm Bach 1. Seven analyses of single zircons yielded ages of *c.* 600 Ma, *c.* 550 Ma, *c.* 517 Ma and *c.* 514 Ma. The older component (*c.* 600 Ma and *c.* 550 Ma and *c.* 517 Ma) is interpreted as reflecting inheritance and/or xenocrystic incorporation during sedimentation. The remaining two grains yield $^{206}Pb/^{238}U$ dates that overlap within the quoted uncertainties and provide a weighted average of 514.45 ± 0.36(0.63)[0.81] Ma (MSWD = 2.0). Based upon the concordance of these two analyses and their overlapping uncertainties, they are interpreted as reflecting the age of the rock rather than Pb loss, and suggest an age of 514.5 Ma for this level. Seven analyses of sample Comley ub yield a weighted mean $^{206}Pb/^{238}U$ date of 509.10 ± 0.22(0.56)[0.77] Ma (MSWD = 0.51), which is interpreted as being the best age estimate for this sample. One additional analysis from Comley ub yielded an older date (*c.* 530 Ma) which is interpreted here as a spurious result attributable to xenocrystic contamination.

Petrographic context of stable isotope analysis of the Comley Limestones

The succession at the sampled locality consists of four distinct limestone units, each bounded by conspicuous erosional disconformities (Fig. 3). The lithology varies from calcareous glauconitic sandstone at the base (the Red Callavia Sandstone, Ac2), through a pair of internally heterogeneous but increasingly calcareous sandy limestones (the Strenuella and Protolenus Limestones, Ac4 and Ac5), to a more homogeneous and less sandy limestone at the top (the Lapworthella Limestone, Ad). Adjacent samples are unlikely to represent strictly sequential lithological horizons: the rocks are not bedded at the scale of sample spacing (8 mm), and the degree of bioturbation may be high throughout (although discrete burrow traces have not been observed). Petrographic thin sections show that all four units contain widely distributed calcareous bioclasts and intraclasts at a scale too fine to be excluded from isotope powder samples (Fig. 6), although we were able to avoid sampling from concentrations of coarser trilobite and echinoderm debris (which also tend to be sites of coarse recrystallization (Fig. 6a and b)) as well as from larger (>3 mm) intraclasts. Microscopic examination also reveals a distinctive 'rice-like' microstructure for much of the finer-grained carbonate matrix throughout the Comley Limestones succession (Fig. 6c and d). This feature is more or less pervasive, and grades into regions of coarser crystallization with conspicuous radiating crystal fans (Fig. 6d).

Results of stable isotope analysis of the Comley Limestones

More than 80 samples from the Comley Limestones interval have been analysed for their $\delta^{13}C$ and $\delta^{18}O$ signatures (Fig. 7). The values for $\delta^{18}O$ range from −9.7 to −4.5‰, and those for $\delta^{13}C$ from −5.5 to +0.8‰, with variation through the succession creating the appearance of several apparent 'excursions'. There is a conspicuous co-variation in oxygen and carbon isotope ratios ($r^2 = 0.82$, which includes samples from the vein calcite), and the most pronounced negative carbon isotope 'excursions' (of magnitudes *c.* −5‰) in the Red Callavia Sandstone (Ac2) and Lapworthella Limestone (Ad) are associated with the most negative $\delta^{18}O$ values (down to −9.7‰). However, the oxygen isotope values from the limestones are not as low as those from calcite veins that pervade the rock ($\delta^{18}O$ of −12.7‰). In contrast, carbon isotope values from these veins (−5.5‰) are very similar to the most negative values from the limestone. A replication of 14 pairs of $\delta^{13}C$ and $\delta^{18}O$ analyses via a parallel transect through the Lapworthella Limestone (Ad) reveals an apparent 'excursion' that is approximately parallel to, but less pronounced than, the original. In contrast, a replication of four pairs of $\delta^{13}C$ and $\delta^{18}O$ analyses through a lateral lithological variant within the Strenuella Limestone (Ac4), which samples a more coarsely crystalline region with abundant trilobite debris, shows trends in a direction opposite to the original, with relatively higher isotope values.

A refined and integrated stratigraphy for the Cambrian of Shropshire

The Cambrian of Shropshire is an important source of trilobites and other fossils that were used to recognize the traditional 'Lower' and 'Middle' Cambrian in southern Britain (Cobbold 1921, 1927, 1933; Cobbold & Pocock 1934; Raw 1936, summarized by Rushton 1974; see Rushton *et al.* 1999, p. 74–78). Here we summarize the biostratigraphic succession in relation to our new chronometric dates and to the emerging global standard.

The lower Cambrian in Shropshire comprises three units: (1) the Wrekin Quartzite, which unconformably overlies late Precambrian Uriconian volcanic rocks; (2) the Lower Comley Sandstone Formation; (3) the Comley Limestones (Fig. 3). Together these form the Lower Comley Group (Rushton 1974; Brenchley *et al.* 2007). In the lower part of the Group, the Wrekin Quartzite and the lower 60 m of the Lower Comley Sandstone Formation are devoid of trilobites, but are characterized by burrows and a

Table 1. *U–Th–Pb isotopic data for zircon analyses*

Sample							Radiogenic isotope ratios								Isotopic ages					
	Th/U	^{206}Pb* $\times 10^{-13}$ mol	mol% ^{206}Pb*	Pb*/Pbc	Pho (pg)	^{206}Pb/^{204}Pb	^{208}Pb/^{206}Pb	^{207}Pb/^{206}Pb	% err	^{207}Pb/^{235}U	% err	^{206}Pb/^{238}U	% err	corr. coef.	^{207}Pb/^{206}Pb	±	^{207}Pb/^{235}U	±	^{206}Pb/^{238}U	±
(a)	(b)	(c)	(c)	(c)	(c)	(d)	(e)	(e)	(f)	(e)	(f)	(e)	(f)		(g)	(f)	(g)	(f)	(g)	(f)
Comley lb																				
z1	0.694	0.3541	98.80	26.3	0.35	1536	0.216	0.059957	0.291	0.815655	0.368	0.098666	0.138	0.688	601.72	6.31	605.62	1.68	606.66	0.80
z2	1.344	0.3180	96.84	11	0.85	585	0.419	0.058578	0.534	0.719916	0.640	0.089134	0.111	0.960	551.22	11.66	550.62	2.72	550.47	0.59
z3	0.710	1.0256	99.53	68.5	0.40	3961	0.222	0.057657	0.149	0.660598	0.218	0.083097	0.093	0.841	516.41	3.26	514.98	0.88	514.66	0.46
z4	0.791	0.6957	99.12	37	0.51	2111	0.247	0.057640	0.267	0.659722	0.323	0.083011	0.114	0.626	515.78	5.87	514.44	1.30	514.14	0.56
z5	0.948	0.3509	97.59	14	0.71	767	0.296	0.058665	0.479	0.721408	0.566	0.089187	0.158	0.644	554.40	10.46	551.50	2.41	550.80	0.84
z6	0.589	0.5716	99.11	35	0.42	2075	0.184	0.058637	0.196	0.724551	0.274	0.089617	0.110	0.810	553.33	4.28	553.35	1.17	553.35	0.58
z7	0.536	0.5657	99.27	42	0.34	2523	0.167	0.057640	0.181	0.663469	0.253	0.083483	0.102	0.810	515.74	3.97	516.73	1.02	516.96	0.51
z8	0.487	0.3023	93.45	4	1.75	279	0.151	0.058069	0.808	0.715234	0.924	0.089331	0.206	0.638	532.03	17.70	547.85	3.91	551.66	1.09
Comley ub																				
z1	2.365	2.3284	98.84	38	2.26	1568	0.739	0.057430	0.175	0.650088	0.297	0.082097	0.189	0.831	508.00	3.85	508.53	1.19	508.65	0.92
z2	2.033	7.9318	99.60	104	2.68	4475	0.636	0.057502	0.098	0.651241	0.186	0.082140	0.098	0.949	510.71	2.15	509.24	0.74	508.92	0.48
z3	2.295	2.3721	99.48	86	1.01	3588	0.718	0.057539	0.139	0.651931	0.234	0.082174	0.135	0.850	512.15	3.06	509.67	0.94	509.11	0.66
z4	1.857	5.5204	99.84	260	0.72	11683	0.581	0.057552	0.097	0.651966	0.194	0.082161	0.121	0.915	512.56	2.13	509.69	0.78	509.05	0.59
z5	0.720	4.7545	99.74	124	1.02	7104	0.225	0.057981	0.103	0.684895	0.362	0.085672	0.325	0.960	528.70	2.26	529.73	1.49	529.97	1.65
z6	2.456	3.2758	99.86	317	0.39	12774	0.768	0.057518	0.096	0.651648	0.183	0.082169	0.103	0.924	511.36	2.12	509.49	0.73	509.08	0.51
z7	3.046	0.6924	98.13	27	1.09	987	0.952	0.057443	0.338	0.651253	0.414	0.082226	0.121	0.714	508.59	7.44	509.25	1.66	509.40	0.59
z8	2.109	0.7192	98.47	28	0.92	1212	0.660	0.057535	0.349	0.652145	0.411	0.082207	0.122	0.616	511.98	7.67	509.80	1.65	509.31	0.60
Cwm Bach 1																				
z7	0.782	1.0548	98.38	20	1.43	1133	0.244	0.057627	0.247	0.666114	0.318	0.083835	0.099	0.795	515.27	5.42	518.35	1.29	519.05	0.50
z8	0.740	1.5871	96.16	8	5.28	469	0.231	0.057736	0.298	0.668074	0.372	0.083922	0.109	0.755	519.44	6.55	519.54	1.51	519.56	0.54
z9	0.773	1.3373	98.83	27	1.31	1565	0.242	0.057759	0.301	0.663866	0.364	0.083360	0.126	0.633	520.32	6.60	516.98	1.48	516.22	0.63
z11	0.702	2.4887	99.49	62	1.05	3606	0.219	0.057739	0.132	0.668058	0.224	0.083916	0.125	0.864	519.52	2.90	519.53	0.91	519.53	0.62
z12	0.769	2.0838	98.83	27	2.05	1549	0.240	0.057626	0.178	0.666114	0.261	0.083836	0.120	0.810	515.25	3.91	518.35	1.06	519.05	0.60
z13	0.718	0.8413	98.74	25	0.88	1464	0.224	0.057706	0.178	0.667890	0.379	0.083942	0.120	0.618	518.30	7.00	519.43	1.54	519.69	0.60
z14	0.787	0.7711	97.96	16	1.32	899	0.246	0.057754	0.319	0.668078	0.399	0.083896	0.104	0.743	520.12	7.22	519.54	1.62	519.41	0.52

(a) z1, z2, etc. are labels for fractions composed of single zircon grains or fragments; all fractions annealed and chemically abraded after Mattinson (2005). (b) Model Th/U ratio calculated from radiogenic ^{208}Pb/^{206}Pb ratio and ^{207}Pb/^{235}U age. (c) Pb* and Pbc represent radiogenic and common Pb, respectively; mol% ^{206}Pb* with respect to radiogenic, blank and initial common Pb. (d) Measured ratio corrected for spike and fractionation only. (e) Corrected for fractionation, spike, and common Pb; up to 1 pg of common Pb was assumed to be procedural blank: ^{206}Pb/^{204}Pb = 18.50 ± 0.50%; ^{207}Pb/^{204}Pb = 15.8 ± 0.5%; ^{208}Pb/^{204}Pb = 38.02 ± 0.75% (all uncertainties 1σ). Excess over blank was assigned to initial common Pb. (f) Errors are 2σ, propagated using the algorithms of Crowley *et al.* (2007) and Schmitz & Schoene (2007). (g) Calculations are based on the decay constants of Jaffey *et al.* (1971). ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb ages corrected for initial disequilibrium in ^{230}Th/^{238}U using Th/U [magma] = 3.

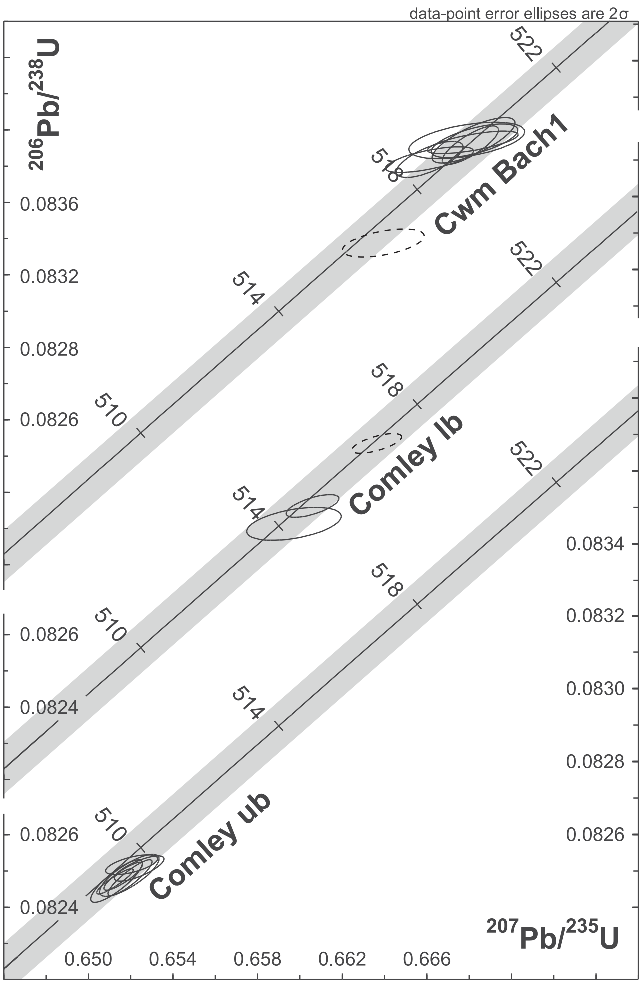

Fig. 5. Conventional U–Pb concordia plot of zircons from ash beds from the Caerfai Bay Shales Formation (Cwm Bach 1), Lower Comley Sandstone Formation (Comley lb), and Upper Comley Sandstone Formation (Comley ub). The grey band reflects the uncertainty in the ^{238}U and ^{235}U decay constants (Jaffey *et al.* 1971). Dashed ellipses represent analyses disregarded in calculation of final date.

fauna of 'small shelly fossils' in basal unit 'Ab1' of the Lower Comley Sandstone (Fig. 3). These suggest an assignment to the Terreneuvian Series of the Cambrian (Figs 1 and 3), probably to the upper part of Stage 2, and are referable to the *Camenella baltica* shelly faunal Biozone (Brasier 1989*a*). The lowest trilobite recorded from the Lower Comley Sandstone Formation was from midway through the succession (horizon Ab3 of Cobbold 1921, p. 369) and is a small form (Raw 1936, p. 269, plate 20, fig. 3; Lake 1936, plate 33, fig. 9) that has been assigned to *Holmia* or *Fallotaspis*, but which Bergström (1973, p. 304) thought was more probably a juvenile *Kjerulfia*. Its biostratigraphical significance is uncertain, but it is taken to represent a level above the base of the projected Cambrian Stage 3, because the earliest trilobites are expected to be an important criterion for the recognition of that stage (Babcock *et al.* 2005). The trilobite from Ab3 originated from strata that underlie, by perhaps 70 m, a part of the *Callavia* Biozone, as discussed below, and it has not been recognized from that or any higher level in the Lower Comley Sandstone. It may represent the *Fallotaspis* Biozone, but might lie in the lower part of the *Callavia* Biozone (Fig. 3). The downward extension of the *Callavia* Biozone and its relation to the *Camenella baltica* Biozone remains doubtful, both in the Comley area and in the Nuneaton Inlier in the English Midlands. At Nuneaton, Brasier (1986, 1989*a*) collected a large fauna of the *C. baltica* Biozone from the Home Farm Member of the Hartshill Formation. The overlying sandstones of the Woodlands Member contain very few fossils, and the basal part of the overlying Purley Shale Formation has yielded fragments of trilobites, implying equivalence with Stage 3 of Cambrian Series 2. Although these fragments have been compared to *Callavia* they are not strictly identifiable (Rushton 1966, p. 37) and their biostratigraphical age is uncertain. The next highest recognizable stratigraphical horizon in the Purley Shale Formation, about 70 m higher in the succession, is Rushton's (1966, p. 4) Locality 1 with *Strenuella sabulosa*, considered here to be at the base of Stage 4 in Cambrian Series 2. In SE Newfoundland the *Camenella* Biozone is seen to underlie the *Callavia* Biozone in the Smith Point Formation, but Landing *et al.* (1989) and Fletcher (2006) have recognized a hiatus between the lower unit (Fosters Point division, with *Camenella*) and the upper Broad Cove Member (Fletcher 2006, p. 45), with the lowest records of *Callavia*. Fletcher (2006) acknowledged that the Fosters Point *Camenella baltica* fauna, though underlying *Callavia* in Newfoundland, might be equivalent to strata with fallotaspid trilobites elsewhere (e.g. Morocco and the Siberian Platform).

The uppermost unit of the Lower Comley Sandstone, the Green Callavia Sandstone (Ac1), contains a fauna of the *Callavia* Biozone. Cobbold (1921) and Raw (1936) recorded *Callavia callavei* (which Fletcher synonymized with *C. broeggeri* from the Brigus Formation of Newfoundland), with other species of *Callavia*, a *Kjerulfia*? and *Wanneria*? *pennapyga*. Rushton (1974) transferred the last-named to *Judomia*?, a genus that characterizes upper Atdabanian and lower Botoman strata in Siberia (Palmer & Repina 1993), which approximate to the upper parts of Cambrian Stage 3. In addition, Cobbold (1931) described *Pagetia attleborensis* from beds Ac1, Ac2 and Ac3 of the Comley Limestones. Fletcher (2006) transferred this species to *Dipharus*, and noted that in Newfoundland *D. attleborensis* characterizes only the upper part of the range of *Callavia*. As *D. attleborensis* occurs in the lowest *Callavia*-bearing beds in Shropshire, it is likely that a lower portion of the *Callavia* Biozone is not sufficiently fossiliferous to allow it to be recognized at Comley.

The fauna from the Green Callavia Sandstone therefore favours correlation with the projected Stage 3 of Series 2 of the Cambrian (Fig. 1; see also Brenchley *et al.* 2007; Cocks *et al.* 2010). This biostratigraphic correlation may now be placed within a chronometric framework. Our lower ash bed sample, which we date to 514.45 ± 0.36 Ma, comes from a few centimetres below the top of the Green Callavia Sandstone (Figs 3 and 4), so this new date provides an age for the upper part of the *Callavia* Biozone, towards the top of Cambrian Stage 3, and thus a maximum age limit for the Stage 3–Stage 4 boundary (Fig. 1). The Lower Comley Sandstone Formation is succeeded by the thin and discontinuous Comley Limestones (Fig. 3). Where complete, they have a maximum thickness of *c.* 2 m, although they are only *c.* 0.8 m thick at the sampled locality. These comprise a succession of five stratigraphical units, each separated by a disconformity (and for the uppermost unit, an unconformity) and each with its own distinct faunal assemblage (Cobbold 1921). Like the underlying Green Callavia Sandstone (Ac1), the lowest division of the Comley Limestones, the Red Callavia Sandstone (Ac2), is assignable to the *Callavia* trilobite Biozone (Fig. 3). In contrast, the succeeding Bellimarginatus

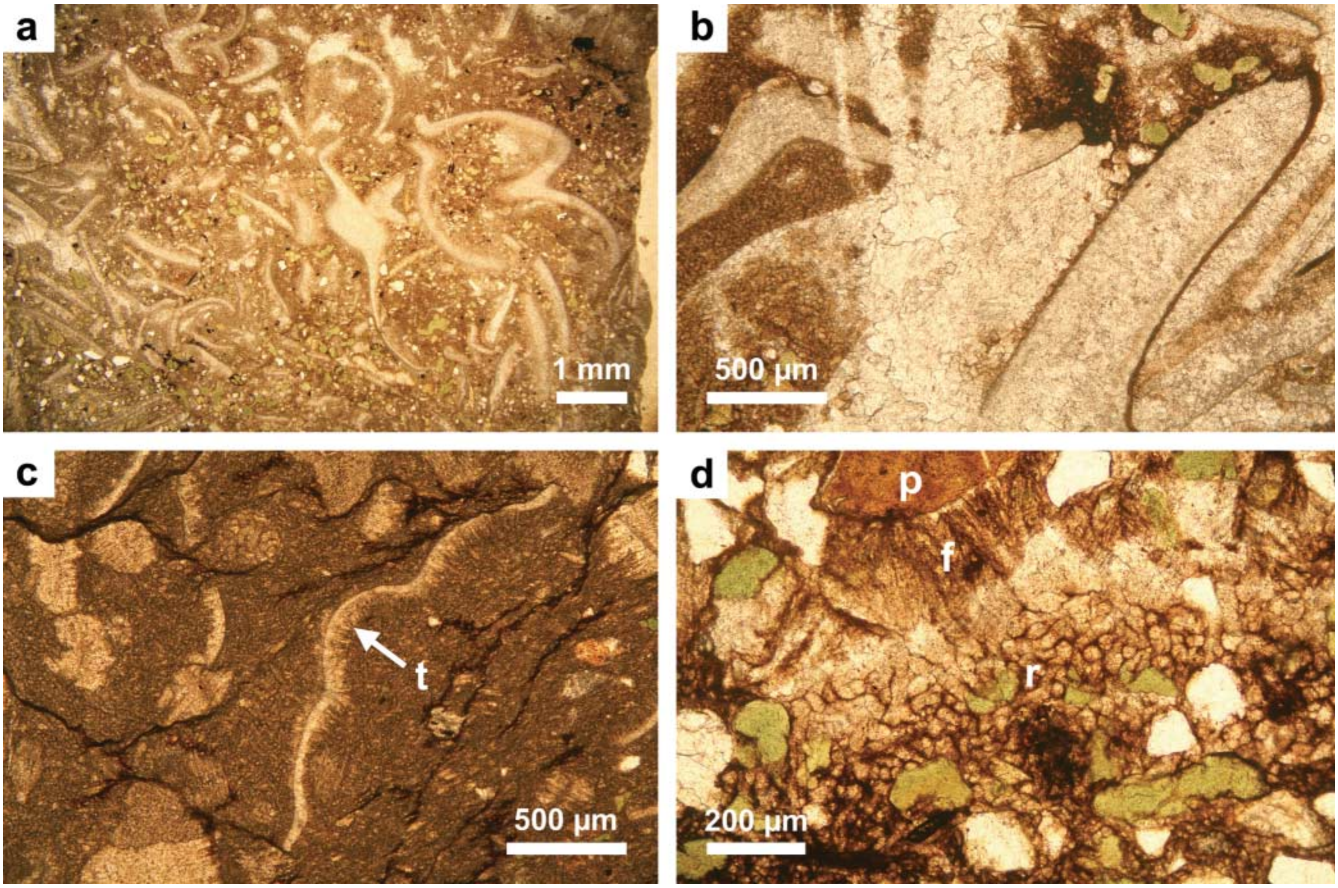

Fig. 6. Styles of carbonate crystallization in the Comley Limestones. (**a**) A coarse-grained sub-lithology of the Strenuella Limestone (Ac4) containing abundant bioclasts, predominantly trilobite debris. The boundaries of the bioclasts are diffuse through recrystallization, and the centres consist of crystalline spar. (**b**) A coarse-grained sub-lithology of the Red Callavia Sandstone (Ac2) exhibiting microveins and coarse recrystallization both of bioclasts (boundaries ghosted by iron-rich clay) and groundmass. (**c**) A typical lithology of the Lapworthella Limestone (Ad), with trilobite section ('t', arrowed) and abundant echinoderm debris. The overgrowth of acicular crystals on the trilobite should be noted. The groundmass exhibits a 'rice-like' texture that is too fine-grained to be discerned clearly in this image. (**d**) Detailed view of the Protolenus Limestone (Ac5), containing abundant grains of glauconite and quartz. It should be noted that the 'rice-like' texture ('r') of the groundmass is gradationally confluent with fan-like crystal bundles ('f'), which in this field of view abut a phosphatic bioclast ('p'), and thus is interpreted here as neomorphic in origin, rather than biological.

(Ac3) and Strenuella (Ac4) limestones can be correlated approximately to the *sabulosa* trilobite Biozone of Fletcher (2006, p. 42). Therefore, the Bellimarginatus Limestone is here treated as a proxy for the (as yet undefined) boundary between Stages 3 and 4, as adopted here (see Figs 1 and 3). The topmost unit of the Comley Limestones, the Lapworthella Limestone (Ad), oversteps the underlying carbonate units and is of uncertain early to middle Cambrian age (Brenchley *et al.* 2007). We suggest that it lies at or near the Series 2–Series 3 boundary of the Cambrian (Figs 1 and 3).

The Lapworthella Limestone (Ad), and thus the top of the Lower Comley Group, is succeeded unconformably by the Upper Comley Sandstone Formation, which has the Quarry Ridge Grits (Ba1) at its base (Figs 3 and 4). The Upper Comley Sandstone Formation contains paradoxidid trilobites that indicate its assignment to the St. David's Series, the traditional Middle Cambrian of Britain (see Cocks *et al.* 2010). The unconformity that separates the Lapworthella Limestone from the Quarry Ridge Grits is of uncertain duration; certainly there is no evidence in the Shropshire succession for the lowermost *Kiskinella* trilobite Biozone of SE Newfoundland (Fletcher 2006). The earliest trilobites of the Upper Comley Sandstone Formation include the local species *Bailiella longifrons* and *Kootenia lakei*, along with the more stratigraphically significant *Paradoxides groomi*, which Fletcher (2006) synonymized with *Paradoxides harlani*, a species that is assignable to the *harlani* trilobite Biozone in Newfoundland (Fletcher 2006; see Fig. 1). From immediately above the Lapworthella Limestone, within the lowermost Quarry Ridge Grits (Ba1), is the second sampled ash bed, 'Comley ub', which thus lies at the base of the local 'Middle' Cambrian (St. David's Series) in Shropshire (Fig. 4). As such, the date of 509.10 $\pm$ 0.22 Ma provides an upper age limit on the base of Series 3, and of Cambrian Stage 5. This complements the date of 511 $\pm$ 1 Ma from strata assigned to the *Protolenus howleyi* trilobite Biozone in the Hanford Brook Formation at Hanford Brook in New Brunswick, Canada, a little below the top of the Series 2 as employed there (Landing *et al.* 2008, fig. 9). The new date thus provides a precise younger constraint upon the age of 510 Ma for the Series 2–Series 3 boundary given by Peng & Babcock (2008).

Biostratigraphic significance of small shelly fossils

The Comley Limestones contain rich assemblages of 'small shelly fossils' (SSFs), which are particularly well known through

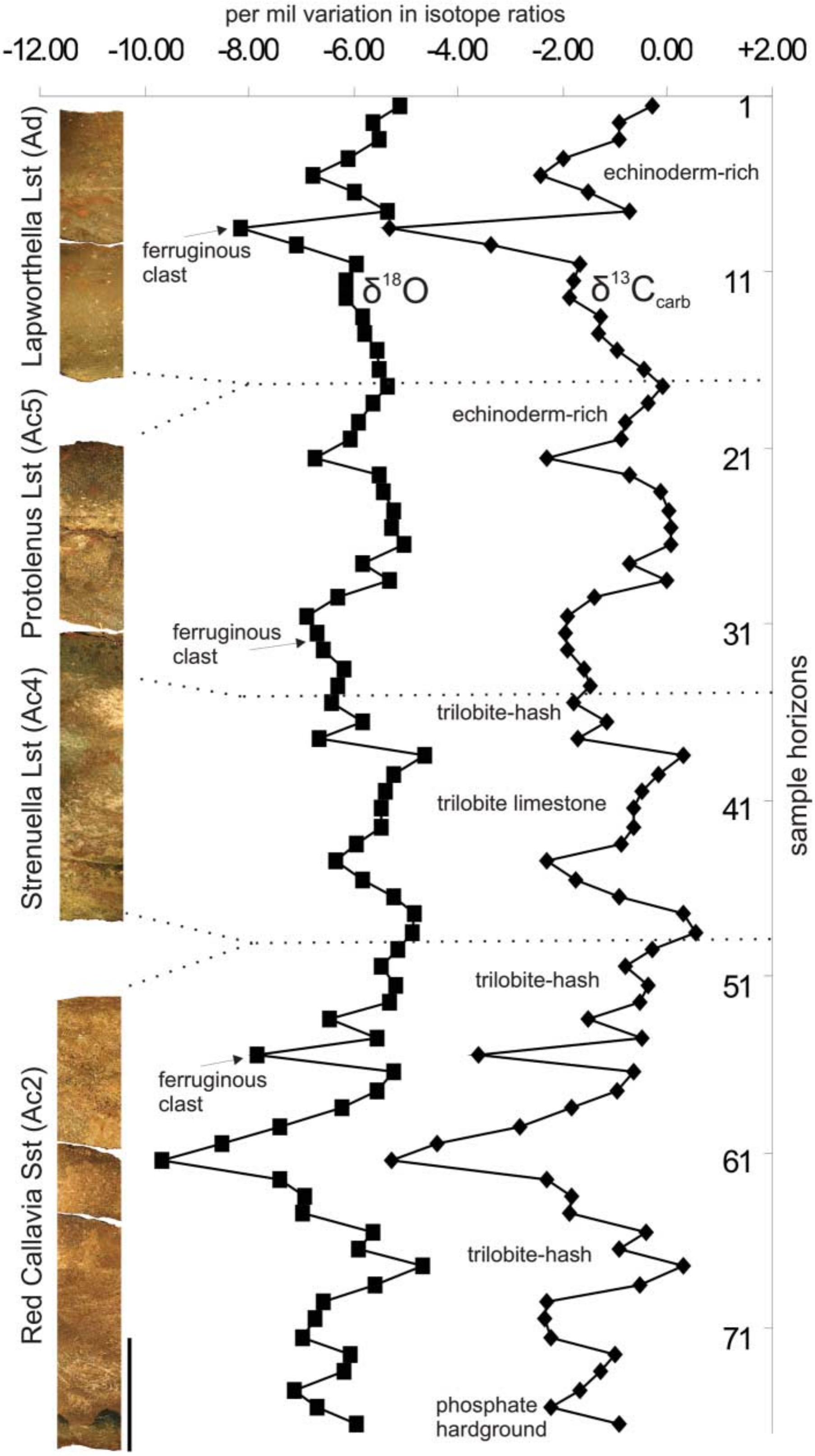

Fig. 7. $\delta^{13}C_{carb}$ and $\delta^{18}O$ plotted as per mil variation (VPDB) for the Comley Limestones in the trench section at Comley, Shropshire. The stable isotope data are aligned with a photographic log of the succession. Vertical scale bar, 5 cm.

a combination of early 'crack-out' collecting (e.g. Cobbold 1921; Cobbold & Pocock 1934) and, subsequently, extensive acid-preparation of limestones to recover microscopic specimens (e.g. Matthews 1973; Brasier 1986; Hinz 1987). Radiometric dates either side of this succession offer a test of biostratigraphic schemes based on SSF distribution, which are of interest because they potentially extend biostratigraphic correlation of the dates beyond the geographical range of comparable trilobites. According to Brasier (1989*a*,*b*), particular SSF taxa from the Comley Limestones characterize various more widespread assemblages. SSFs from the Red Callavia Sandstone (Ac2) are used to identify the *Rhombocorniculum cancellatum* Assemblage, supporting trilobite data (see above) through links to the *Judomia* Biozone of Siberia, whereas those from the Bellimarginatus (Ac3) and Strenuella (Ac4) Limestones are characteristic of the *Lapworthella cornu* Assemblage, with potential correlations to Siberia, Mongolia, southern Kazakhstan, Scania–Bornholm, and the Yangtze Platform of China (for more details see Brasier 1989*a*,*b*). Within the same scheme, SSFs from the overlying Protolenus Limestone (Ac5) have not been assigned to a formalized Assemblage, but are suggested to include forms of *Rhombocorniculum* and *Lapworthella* that provide potential correlations with Newfoundland and Siberia; the correlative significance of Lapworthella Limestone (Ad) SSFs is less well known. Our new radiometric dates provide a basis for rigorously testing the biostratigraphic utility of SSF ranges, for which the relative influences of evolutionary change versus ecophenotypic and facies-dependent factors remain to be elucidated (e.g. Landing 1992).

Dating the Comley Lagerstätte

The Comley Limestones have yielded specimens of a phosphatocopid crustacean, *Klausmuelleria salopensis*, in which 3D phosphatization has preserved even 'soft' cuticular structures including appendages (Hinz 1987; Siveter *et al.* 2001, 2003). These fossils, which derive specifically from the Strenuella Limestone (Ac4) and Protolenus Limestone (Ac5), provide one of the earliest occurrences of arthropods preserved in this mode (Maas *et al.* 2006). As a convincing total-group crustacean and thus a confirmed member of the euarthropod crown group, *K. salopensis* provides a key calibration point in metazoan evolution (Budd & Jensen 2003) and is advocated for use in calibrating and constraining molecular clocks (Benton *et al.* 2009). Although further examples have now come to light of early Cambrian crustaceans from approximately contemporaneous horizons in Canada (Harvey & Butterfield 2008) and slightly older horizons in China (Zhang *et al.* 2007), our dating of the Comley succession provides the only precise age brackets for this key evolutionary milestone.

Correlation of the Cambrian of Shropshire and Pembrokeshire

Correlation of the lower Cambrian succession of England with that of Pembrokeshire, south Wales, has long proven difficult, largely because the rock succession of Pembrokeshire is so poorly fossiliferous. However, Siveter & Williams (1995) presented evidence from bradoriid arthropods for correlation between the Red Callavia Sandstone (Ac2) of Shropshire and the Caerfai Bay Shales Formation of south Wales (Fig. 3). In Pembrokeshire, a thin ash bed analysed from the Caerfai Bay Shales Formation some 11 m above the top of the St. Non's Sandstone Formation at Caerfai Bay [NGR SM 7615 2436] has yielded an age of 519 ± 1 Ma (Landing *et al.* 1998; see Fig. 1). Landing *et al.* (1998) interpreted the contact between the St. Non's Sandstone and Caerfai Bay Shales Formations as unconformable (although the stratigraphy is complicated by a fault) and equated this with the horizon of the lowest occurrence of trilobites in Avalonia (Landing *et al.* 1998, p. 331). The date obtained from a sample of the Caerfai Bay Shales Formation has accordingly been used to support a minimum age of 521 Ma for the base of Cambrian Series 2 (see Peng & Babcock 2008). Records from Caerfai Bay of possible trilobite fragments reported by Landing *et al.* (1998, 2007) remain unconfirmed. However, a few kilometres to the east of Caerfai Bay, Siveter & Williams (1995) recovered the bradoriid arthropod *Indiana lentiformis* from the fault-bounded outcrop of Caerfai Bay Shales at Cwm Bach (Fig. 4). These bradoriids occur with a possible trilobite fragment and *Coleoloides*, all of which were illustrated by Siveter & Williams (1995). *Indiana lentiformis* was originally described from the fossil-rich succession of Shropshire, where it occurs in the Red Callavia Sandstone (Ac2), which may represent the upper levels of the *Callavia* Biozone. As mentioned above, the lower limit of the *Callavia* Biozone is not known in Shropshire or near Nuneaton. In both these areas the relationships of the SSF *Camenella baltica* Biozone and the overlying, or overlapping, trilobite zones of *Callavia* and *Fallotaspis* are uncertain. More generally, species of the bradoriid *Indiana* are characteristic of fossil assemblages containing the trilobites *Ellipsocephalus*, *Callavia* and *Protolenus* (see Siveter & Williams 1997; Williams & Siveter 1998; Williams *et al.* 2007), typical of strata assignable to the upper part of Cambrian Stage 3. The fossil-bearing horizon at Cwm Bach cannot be traced back into Caerfai Bay itself, but the newly dated ash bed at Cwm Bach (Fig. 4) acts as an upper bracket for the fossil horizon and provides a more refined age of 519.30 ± 0.23 Ma that is consistent with the date determined by Landing *et al.* (1998) from the same formation at Caerfai Bay. Therefore, a direct correlation between the upper part of the Caerfai Bay Shales Formation and Red Callavia Sandstone (Ac2) of Shropshire as suggested by Siveter & Williams (1995) cannot be sustained. Instead, the Caerfai Bay Shales Formation, although still falling within Cambrian Stage 3, correlates with a horizon low in the Lower Comley Sandstone Formation, possibly around the level in Shropshire where the lowest trilobite was found (Fig. 3). This lends indirect support, in the absence of an informative local fossil record, to the claim by Landing *et al.* (2007, p. 288) that the previously published Caerfai date may correspond to 'the earliest trilobite-bearing strata' (in Britain).

Carbon and oxygen isotope records from the Comley Limestones

The $\delta^{13}C_{carb}$ record of the lower Cambrian (used in the sense of the Terreneuvian and Series 2; see Fig. 1) displays several apparent positive (to +4‰) and negative (to −6‰) 'excursions' (Zhu *et al.* 2006, fig. 1; Kouchinsky *et al.* 2007, fig. 2). Carbon isotope excursions (CIEs) from the Late Proterozoic and Cambrian have been linked with major biotic or oceanographic events (e.g. Salzmann *et al.* 2004). Zhu *et al.* (2006) provided a synthesis of chronology, chronostratigraphy and carbon isotope stratigraphy for the Cambrian that displays a major negative (greater than −4‰) CIE in the uppermost part of Stage 4 and lowermost Stage 5, the Redlichiid–Olenellid or 'ROECE' event recorded in the trilobite faunas of palaeocontinental Laurentia, Gondwana and China (see also Guo *et al.* 2010).

Although very discontinuous, based on its stratigraphical correlation (Figs 1 and 3) the sampled interval of the Comley Limestones might include the interval of the ROECE event, perhaps at about the level of the Lapworthella Limestone (Ad) that we hypothesize straddles the Stage 4–Stage 5 boundary. Although most values for carbon isotopes are typically between about 0 and −2‰, there appear to be two negative $\delta^{13}C_{carb}$ excursions, the earlier one within the Red Callavia Sandstone (Ac2, peak −5.3‰) and the later one within the Lapworthella

Limestone (Ad, peak −5.3‰). As noted above, however, the stable isotope record through the Comley Limestones shows a marked co-variation in oxygen and carbon isotopes (including the vein calcite), with the most negative carbon isotope values coincident with the most negative oxygen isotope values (Fig. 7), and might therefore be associated with diagenetically altered parts of the Comley Limestones. This is strongly suggested by the stable isotope composition of vein calcite that pervades parts of the Comley Limestone succession, and that shows negative values for both oxygen (more negative than −12‰), and carbon (more negative than −5‰). Indeed, our petrological analysis of the rock shows extensive carbonate recrystallization. This is most obvious in the coarse-grained regions, where original and early diagenetic features such as discrete bioclast outlines and the overgrowth of bioclasts by radiating crystals (Fig. 6c) are largely obliterated by sparry crystal growth (Fig. 6b). However, even the finer-grained sub-lithologies that were preferentially selected for sampling may be extensively neomorphosed. The conspicuous 'rice-like' texture (Fig. 6c and d) has been described previously from localized regions within drill-core samples of Lapworthella Limestone, where it has been interpreted as biological in origin, specifically as calcareous cyanobacterial colonies referable to the form-genus *Bevocastria* (Danielli 1988). However, the pervasive distribution of this feature and its confluence with coarser-grained crystal fans suggest to us neomorphic recrystallization into a pseudospar-like texture (Fig. 6d). Where we tested the effect of lateral lithological variation on a centimetre scale, we found isotopic variation of a similar magnitude to that characterizing the apparent 'excursions', and furthermore that the degree and direction of variation is unpredictable: the data points from a more coarsely crystalline, conspicuously trilobite-rich region of Strenuella Limestone (Ac4) show relatively high isotope values, the opposite of what might be expected if a greater degree of diagenetic alteration (or stronger vital effects) had been in operation (compare Grant 1992). As a result, we cannot reliably correlate these Comley Limestone excursions with the global CIE record of the Cambrian.

That said, it is possible that the isotope composition of the Comley Limestones contains remnant oceanographic signatures. A preliminary comparative study of Cambrian Avalonian successions by Brasier *et al.* (1992) suggested that the Comley Limestones preserved the least altered oxygen isotope values analysed to date. Our expanded sampling of the Comley Limestones yields a range of δ^{18}O values (−4.7 to −9.7‰) that encompasses the values reported by Brasier *et al.* (1992), and furthermore finds correspondence in the isotope records of marine sediments of early and middle Cambrian age in China (δ^{18}O values −3.3 to −9.9‰; Guo *et al.* 2010) and of Botomian age in Siberia (δ^{18}O values about −5 to −9‰; Kouchinsky *et al.* 2007, fig. 2). These negative values might reflect warm Cambrian sea temperatures and the absence of extensive high-latitude ice sheets, or seawater more depleted in ^{18}O (see Shields *et al.* 2003). However, we cannot be sure of the diagenetic histories of the Chinese and Siberian carbonates, and negative values may also reflect recrystallization in warm pore waters during burial diagenesis and/or the influence of isotopically light meteoric waters.

Conclusions

Zircon ^{206}Pb/^{238}U dating of an ash bed near the top of the Green Callavia Sandstone (Ac1), Lower Comley Sandstone Formation at Comley, Shropshire provides a date of 514.45 ± 0.36 Ma. Through a chain of correlation, especially trilobite biostratigraphy, this suggests a maximum age for the Cambrian Stage 3–Stage 4 boundary (as adopted here). An ash bed from the basal Quarry Ridge Grits (Ba1) at the same locality yields a ^{206}Pb/^{238}U zircon age of 509.10 ± 0.22 Ma, providing a minimum age for the Series 2–Series 3 (Stage 4–Stage 5) boundary. These new high-precision dates are consistent with current estimates and time scales (Peng & Babcock 2008), and with their robust biostratigraphic context provide more accurate constraints for key biozones. Analysis of zircon from an ash bed from the Caerfai Bay Shales Formation at Cwm Bach, Pembrokeshire, south Wales, yields an age of 519.30 ± 0.23 Ma, consistent with dates obtained from an ash bed occurring within the same Formation, and now demonstrably along-strike, at Caerfai Bay. Thus, the Caerfai Bay Shales Formation, formerly correlated with the Comley Limestones, is now correlated with a low horizon within the Lower Comley Sandstone Formation, perhaps at the level where the lowest trilobite is reported in Shropshire. The new dates provide precise ages for bracketing the Comley Lagerstätte, one of the earliest occurrences of exceptional, three-dimensionally preserved fossil arthropods, and thus provide an absolute time constraint for a milestone within the Cambrian evolutionary explosion.

This research was supported by NERC Isotope Geosciences Facilities Steering Committee grant IP/1124/0509 and NERC grant NE/F010834/1. P.R.W. publishes with the permission of the Executive Director, BGS. We thank B. Pratt (Saskatchewan) and M. Brasier (Oxford) for discussion of Comley Limestone microstructures. We are most grateful to W. Beamond for his kind permission to excavate his land in Shropshire. The paper benefited from salient comments made by two referees.

References

Babcock, L.E., Peng, S.C., Geyer, G. & Shergold, J.H. 2005. Changing perspectives on Cambrian chronostratigraphy and progress toward subdivision of the Cambrian System. *Geosciences Journal*, **9**, 101–106.

Benton, M.J., Donoghue, P.C.J. & Asher, R.J. 2009. Calibrating and constraining molecular clocks. *In:* Hedges, S.B. & Kumar, S. (eds) *The Timetree of Life*. Oxford University Press, Oxford, 35–86.

Bergström, J. 1973. Classification of olenellid trilobites and some Balto-Scandian species. *Norsk Geologisk Tidsskrift*, **53**, 283–314.

Bowring, S.A., Schoene, B., Crowley, J.L., Ramezani, J. & Condon, D.J. 2006. High-precision U–Pb zircon geochronology and the stratigraphic record: progress and promise. *Palaeontological Society Papers*, **12**, 25–46.

Bowring, S.A., Grotzinger, J.P., Condon, D.J., Ramezani, J., Newall, M. & Allen, P.A. 2007. Geochronological constraints of the chronostratigraphic framework of the Neoproterozoic Huqf Supergroup, Sultanate of Oman. *American Journal of Science*, **307**, 1097–1145.

Brasier, M.D. 1986. The succession of small shelly fossils (especially conoidal microfossils) from English Precambrian–Cambrian boundary beds. *Geological Magazine*, **123**, 237–256.

Brasier, M.D. 1989*a*. Sections in England and their correlation. *In:* Cowie, J.W. & Brasier, M.D. (eds) *The Precambrian–Cambrian Boundary*. Clarendon Press, Oxford, 82–104.

Brasier, M.D. 1989*b*. Towards a biostratigraphy of the earliest skeletal biotas. *In:* Cowie, J.W. & Brasier, M.D. (eds) *The Precambrian–Cambrian Boundary*. Clarendon Press, Oxford, 117–165.

Brasier, M.D., Anderson, M.M. & Corfield, R.M. 1992. Oxygen and carbon isotope stratigraphy of early Cambrian carbonates in southeastern Newfoundland and England. *Geological Magazine*, **129**, 265–279.

Brenchley, P.J., Rushton, A.W.A., Howells, M. & Cave, R. 2007. Cambrian and Ordovician: the early Palaeozoic tectonostratigraphic evolution of the Welsh Basin, Midland and Monian terranes of eastern Avalonia. *In:* Brenchley, P.J. & Rawson, P.F. (eds) *The Geology of England and Wales*. Geological Society, London, 25–74.

Budd, G.E. & Jensen, S. 2003. The limitations of the fossil record and the dating of the origin of the Bilateria. *In:* Donoghue, P.C.J. & Smith, M.P. (eds) *Telling the Evolutionary Time: Molecular Clocks and the Fossil Record*. CRC Press, Boca Raton, FL, 166–189.

Butterfield, N.J. 2007. Macroevolution and macroecology through deep time. *Palaeontology*, **50**, 41–55.

Cobbold, E.S. 1921. The Cambrian horizons of Comley (Shropshire) and their Brachiopoda, Pteropoda, Gasteropoda and etc. *Quarterly Journal of the Geological Society of London*, **76**, 325–386.

Cobbold, E.S. 1927. The stratigraphy and geological structure of the Cambrian area of Comley (Shropshire). *Quarterly Journal of the Geological Society of London*, **83**, 551–573.

Cobbold, E.S. 1931. Additional fossils from the Cambrian rocks of Comley, Shropshire. *Quarterly Journal of the Geological Society of London*, **87**, 459–512.

Cobbold, E.S. 1933. Notes on Comley Quarry, near Church Stretton, Shropshire. *British Association Reports for 1933, Section C—Geology*, 473–476.

Cobbold, E.S. & Pocock, R.W. 1934. The Cambrian area of Rushton (Shropshire). *Philosophical Transactions of the Royal Society of London, Series B*, **223**, 305–409.

Cocks, L.R.M., Fortey, R.A. & Rushton, A.W.A. 2010. Correlation for the Lower Palaeozoic. *Geological Magazine*, **147**, 171–180.

Cowie, J.W., Rushton, A.W.A. & Stubblefield, C.J. 1972. *A Correlation of the Cambrian Rocks of the British Isles*. Geological Society, London, Special Reports, **2**.

Crowley, J.L., Schoene, B. & Bowring, S.A. 2007. U–Pb dating of zircon in the Bishop Tuff at the millennial scale. *Geology*, **35**, 1123–1126.

Danielli, H.M.C. 1988. The fossil alga *Bevocastria* Garwood (Cyanobacteria) in the *Lapworthella* Limestone. Appendix 1. *In:* Rushton, A.W.A., Hamblin, R.J.O. & Strong, G.E. (eds) *The Croft Borehole in the Lilleshall Inlier of north Shropshire*. British Geological Survey Report, **19**, 9–13.

Davidek, K., Landing, E., Bowring, S.A., Westrop, S.R., Rushton, A.W.A., Fortey, R.A. & Adrain, J.M. 1998. New uppermost Cambrian U–Pb date from Avalonian Wales and age of the Cambrian–Ordovician boundary. *Geological Magazine*, **135**, 305–309.

Fletcher, T. 2006. *Bedrock geology of the Cape St. Mary's Peninsula, southwest Avalon Peninsula, Newfoundland*. Government of Newfoundland and Labrador, Geological Survey, Department of Natural Resources, St. John's, Report, **06-02**.

Grant, S.W.F. 1992. Carbon isotopic vital effect and organic diagenesis, Lower Cambrian Forteau Formation, northwest Newfoundland; implications for δ^{13}C chemostratigraphy. *Geology*, **20**, 243–246.

Guo, Q.-J., Strauss, H., Liu, C.-Q., Zhao, Y.-L., Yang, X.-L., Peng, J. & Yang, H. 2010. A negative carbon isotope excursion defines the boundary from Cambrian Series 2 to Cambrian Series 3 on the Yangtze Platform, south China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **285**, 143–151.

Harvey, T.H.P. & Butterfield, N.J. 2008. Sophisticated particle-feeding in a large Early Cambrian crustacean. *Nature*, **452**, 868–871.

Hinz, I. 1987. The Lower Cambrian microfauna of Comley and Rushton, Shropshire/England. *Palaeontographica Abteilung A*, **198**, 41–100.

Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C. & Essling, A.M. 1971. Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U. *Physical Review C*, **4**, 1889–1906.

Kouchinsky, A., Bengtson, S., Pavlov, V., Runnegar, B., Torssander, P., Young, E. & Ziegler, K. 2007. Carbon isotope stratigraphy of the Precambrian–Cambrian Sukharikha River section, northwestern Siberian platform. *Geological Magazine*, **144**, 609–618.

Lake, P. 1936. *A Monograph of the British Cambrian Trilobites. Part 10*. Monographs of the Palaeontographical Society, London, 225–248, plates 32–35.

Landing, E. 1992. Lower Cambrian of southeastern Newfoundland: Epeirogeny and Lazarus faunas, lithofacies–biofacies linkages, and the myth of a global chronostratigraphy. *In:* Lipps, J.H. & Signor, P.W. (eds) *Origin and Early Evolution of the Metazoa*. Plenum, New York, 283–309.

Landing, E., Myrow, P., Benus, A.P. & Narbonne, G.M. 1989. The Placentian Series: appearance of the oldest skeletalized faunas in southeastern Newfoundland. *Journal of Paleontology*, **63**, 739–769.

Landing, E., Bowring, S.A., Davidek, K.L., Westrop, S.R., Geyer, G. & Heldmaier, W. 1998. Duration of the Early Cambrian: U–Pb ages of volcanic ashes from Avalon and Gondwana. *Canadian Journal of Earth Sciences*, **35**, 329–338.

Landing, E., Bowring, S.A., Davidek, K.L., Rushton, A.W.A., Fortey, R.A. & Wimbledon, W.A.P. 2000. Cambrian–Ordovician boundary age and duration of the lowest Ordovician Tremadoc Series based on U–Pb zircon dates from Avalonian Wales. *Geological Magazine*, **137**, 485–494.

Landing, E., Peng, S.-C., Babcock, L.E., Geyer, G. & Moczydlowska-Vidal, M. 2007. Global standard names for the lowermost Cambrian Series and Stage. *Episodes*, **30**, 287–289.

Landing, E., Johnson, S. & Geyer, G. 2008. Faunas and Cambrian volcanism on the Avalonian marginal platform, southern New Brunswick. *Journal of Paleontology*, **82**, 884–905.

Maas, A., Braun, A., *et al.* 2006. The 'Orsten'—more than a Cambrian Konservat-Lagerstätte yielding exceptional preservation. *Palaeoworld*, **15**, 266–282.

Maloof, A.C., Schrag, D.P., Crowley, J.L. & Bowring, S.A. 2005. An expanded record of Early Cambrian carbon cycling from the Anti-Atlas Margin, Morocco. *Canadian Journal of Earth Sciences*, **42**, 2195–2216.

Matthews, S.C. 1973. Lapworthellids from the Lower Cambrian *Strenuella* limestone at Comley, Shropshire. *Palaeontology*, **16**, 139–148.

Mattinson, J.M. 2005. Zircon U–Pb chemical abrasion ('CA-TIMS') method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages. *Chemical Geology*, **220**, 47–66.

Palmer, A.R. & Repina, L.N. 1993. Through a glass darkly: taxonomy, phylogeny, and biostratigraphy of the Olenellina. *University of Kansas, Paleontological Contributions, New Series*, **3**, 1–35.

Peng, S.-C. & Babcock, L.E. 2008. Cambrian Period. *In:* Ogg, J.G., Ogg, G. & Gradstein, F.M. (eds) *The Concise Geologic Time Scale*. Cambridge University Press, Cambridge, 37–46.

Raw, F. 1936. Mesonacidae of Comley in Shropshire, with a discussion of classification within the family. *Quarterly Journal of the Geological Society of London*, **92**, 236–293.

Rushton, A.W.A. 1966. *The Cambrian Trilobites from the Purley Shales of Warwickshire*. Monographs of the Palaeontographical Society, London, **511**.

Rushton, A.W.A. 1974. The Cambrian of Wales and England. *In:* Holland, C. H. (ed.) *Cambrian of the British Isles, Norden and Spitsbergen*. Wiley, London, 42–122.

Rushton, A.W.A., Brück, P., Molyneux, S.G., Williams, M. & Woodcock, N.H. 2011. A revised correlation of the Cambrian rocks in the British Isles. Geological Society, London, Special Report, **25**.

Rushton, A.W.A., Owen, A.W., Owens, R.M. & Prigmore, J.K. 1999. *British Cambrian to Ordovician Stratigraphy.* GCR Series, **18**. Joint Nature Conservation Committee, Peterborough.

Saltzman, M.R., Runnegar, B. & Lohmann, K.C. 1998. Carbon isotope stratigraphy of Upper Cambrian (Steptoean Stage) sequences of the eastern Great Basin: Record of a global oceanographic event. *Geological Society of America Bulletin*, **110**, 285–297.

Salzmann, M.R., Cowan, C.A., Runkel, A.C., Runnegar, B., Stewart, M.C. & Palmer, A.R. 2004. The Late Cambrian SPICE (δ^{13}C) event and the Sauk II–Sauk III regression: new evidence from Laurentian basins in Utah, Iowa, and Newfoundland. *Journal of Sedimentary Research*, **74**, 366–377.

Schmitz, M.D. & Schoene, B. 2007. Derivation of isotope ratios, errors, and error correlations for U–Pb geochronology using ^{205}Pb–^{235}U–(^{233}U)-spiked isotope dilution thermal ionization mass spectrometric data. *Geochemistry, Geophysics, Geosystems*, **8**, article 8, doi:10.1029/2006GC001492.

Shergold, J.H. & Cooper, R.A. 2004. The Cambrian Period. *In:* Gradstein, F.M., Ogg, J.G. & Smith, A.G. (eds) *A Geologic Time Scale 2004*. Cambridge University Press, Cambridge, 147–164.

Shields, G.A., Carden, G.A.F., Veizer, J., Miedla, T., Rong, J.-Y. & Rong, Y.-L. 2003. Sr, C, and O isotope geochemistry of Ordovician brachiopods: a major isotopic event around the Middle–Late Ordovician transition. *Geochimica et Cosmochimica Acta*, **67**, 2005–2025.

Siveter, D.J. & Williams, M. 1995. An early Cambrian assignment for the Caerfai Group of South Wales. *Journal of the Geological Society, London*, **152**, 221–224.

Siveter, D.J. & Williams, M. 1997. *Cambrian bradoriid and phosphatocopid arthropods of North America*. Special Papers in Palaeontology, **57**.

Siveter, D.J., Williams, M. & Waloszek, D. 2001. A phosphatocopid crustacean from the lower Cambrian of England. *Science*, **293**, 479–481.

Siveter, D.J., Waloszek, D. & Williams, M. 2003. Klausmuelleria salopensis *gen. et sp. nov., a phosphatocopid crustacean with preserved appendages from the lower Cambrian, England*. Special Papers in Palaeontology, **70**, 9–30.

Williams, M. & Siveter, D. J. 1998. *British Cambrian and Tremadoc bradoriid and phosphatocopid arthropods*. Monograph of the Palaeontographical Society, London, **607**.

Williams, M., Siveter, D.J., Popov, L.E. & Vannier, J.M.C. 2007. Biogeography and affinities of the bradoriid arthropods: cosmopolitan microbenthos of the Cambrian seas. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **248**, 202–232.

Zhang, X.-g., Siveter, D.J., Waloszek, D. & Maas, A. 2007. An epipodite-bearing crown-group crustacean from the Lower Cambrian. *Nature*, **449**, 595–598.

Zhu, M.-Y., Babcock, L.E. & Peng, S.-C. 2006. Advances in Cambrian stratigraphy and palaeontology: integrating correlation techniques, paleobiology, taphonomy and paleoenvironmental reconstruction. *Palaeoworld*, **15**, 217–222.

Received 17 February 2010; revised typescript accepted 5 October 2010.
Scientific editing by Martin Whitehouse.