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Cambrian–Ordovician boundary age and duration of the lowest Ordovician Tremadoc Series based on U–Pb zircon dates from Avalonian Wales

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Abstract – Two thin volcaniclastic sandstone beds in the Bryn-llin-fawr road section in North Wales overlie an apparent sequence boundary within the uppermost Cambrian *Acerocare* Zone and are overlain by lowest Ordovician (lower Tremadoc) *Rhabdinopora* faunas. U–Pb geochronology of zircons from these sandstones yields a maximum Cambrian–Ordovician boundary age of 489 ± 0.6 Ma. This age indicates both that the Tremadoc Series (lowest Ordovician) may be shorter in duration than was previously thought and that the duration of the Middle and Late Cambrian (*c.* 22 Ma) was much less than that of the Early Cambrian (*c.* 33 Ma). Cambrian trilobite zones locally had an average duration as short as 1 Ma.

1. Introduction

In the 1990s, a precise geochronology based on U–Pb dating of volcanic zircons began to replace estimates on the lower and upper boundaries and on the higher-level chronostratigraphic divisions of the Cambrian that were based on glauconite and whole-rock analyses (compare Harland *et al.* 1990, pp. 134–8, with Bowring & Erwin, 1998, fig. 3). Among the key results of this more recent work are ages of the Proterozoic–Cambrian boundary (*c.* 543 Ma; Bowring *et al.* 1993; Grotzinger *et al.* 1995) and Lower–Middle Cambrian boundary interval (*c.* 511 Ma; Landing *et al.* 1998), and a date on the upper Upper Cambrian (491 ± 1 Ma; Davidek *et al.* 1998). These U–Pb dates place the Cambrian evolutionary radiation into the context of a pre-trilobitic Early Cambrian, which with a duration of approximately 24 Ma, was approximately half the length of the Cambrian. The rapid turnover of trilobite faunas in the later Early Cambrian to Late Cambrian allows a biostratigraphic resolution comparable to that of Ordovician graptolites or Mesozoic ammonites (Davidek *et al.* 1998).

The low diversity 'Cambrian fauna' persisted into the Early Ordovician (e.g. Sepkoski, 1995; the Ibexian fauna of Adrain, Fortey & Westrop, 1998). Dates on the lower and upper boundaries of the Tremadoc, which is the lowest Ordovician series in the historic Anglo-Welsh type area of the Cambrian and Ordovician systems (Fortey *et al.* 1991; Fortey, 1995), are needed to determine the rates of biotic turnover in the later stages of the 'Cambrian fauna', as well as to provide a basis for comparison with subsequent Phanerozoic biotic turnover events (e.g. Bowring *et al.* 1999). U–Pb zircon ages of volcanic ashes from the Anglo-Welsh, Maritime Canadian, and eastern Newfoundland sequences of the late Proterozoic–Middle Paleozoic Avalon continent (Landing, 1996) have been particularly important in the determination of precise dates through the Cambrian–Ordovician boundary interval. The new datum documented here allows by far the best determination of the age of the Cambrian–Ordovician boundary.

Davidek *et al.*'s (1998) U–Pb zircon age of 491 ± 1 Ma on a volcaniclastic sandstone in the lower *Peltura scarabaeoides* Zone at Ogof-ddû, 1.25 km east of Criccieth, North Wales (Fig. 1), supported Shergold's (1995, p. 4) estimate of a Cambrian–Ordovician boundary at an 'arbitrarily selected date of 490 Ma … with the acknowledgement that it is likely to be substantially younger'. Previous proposals on this systemic boundary ranged from 505 Ma (Harland *et al.* 1990) to 495 Ma (Tucker & McKerrow, 1995). An upper bracket on the Cambrian–Ordovician boundary is the 483 ± 1 Ma age on an ash in the upper Tremadoc (Hunneberg Stage) from Cape Breton Island, Nova Scotia (Landing *et al.* 1997).

The best section in Avalonia for determining a radiometric age on the Cambrian–Ordovician boundary

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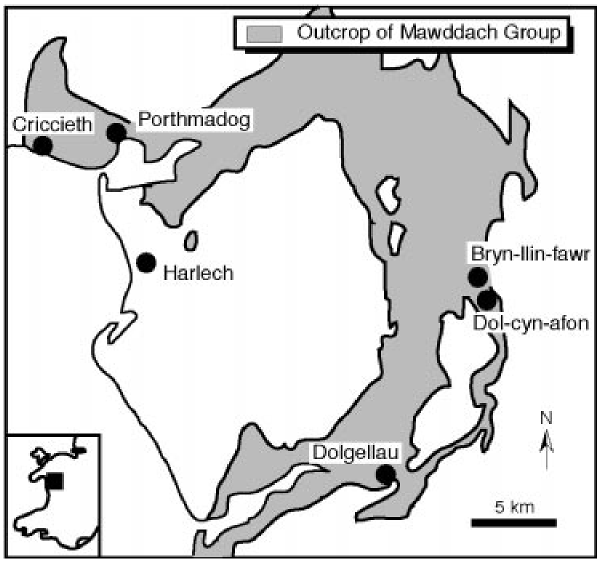

Figure 1. Map of Harlech Dome with outcrop belt of Mawddach Group (Middle Cambrian–lowest Ordovician) stippled. Location of Bryn-llin-fawr (B) and Dol-cyn-afon (D) sections shown.

is along the Bryn-llin-fawr forestry road on the east side of the Harlech Dome (Fig. 1). Thin volcaniclastic sandstones in a cut on Bryn-llin-fawr road (Rushton, 1982) lie just below the lowest fossils of the *Rhabdinopora flabelliformis* complex. These nema-bearing dendroid graptolites have been used through the twentieth century to identify the base of the Tremadoc Series and Ordovician System (Moberg, 1900; Skevington, 1966; Fortey *et al.* 1991). It should be noted that a global standard section and point (GSSP) has been ratified at Green Point, western Newfoundland, by the Ordovician Subcommission (December 1999: Cooper & Nowlan, 1999), but has yet to be ratified by the International Stratigraphic Commission. At Green Point, the lowest local occurrence of a new species of the conodont *Iapetognathus* Landing has been proposed as the index for the base of the Ordovician (Webby, 1998). Because this lowest occurrence of *Iapetognathus fluctivagus* Nicoll *et al.* 1999, occurs closely below the lowest specimens of *Rhabdinopora flabelliformis* (Nicoll *et al.* 1999) and conodont elements are very rare in the siliciclastic-dominated Cambrian–Ordovician boundary sequences in Avalon (Landing, 1993), the lowest occurrence of the *R. flabelliformis* complex provides a practical base of the Ordovician in Avalon and many other parts of the world.

2. Geological setting of Bryn-llin-fawr road

The Bryn-llin-fawr forestry road lies within the Harlech Dome, part of the area in which Sedgwick (1852) defined the Cambrian System. The road exposes an intermittent section through weakly cleaved, variably easterly dipping Upper Cambrian–Lower Ordovician siliciclastics that extend from the Ffestiniog Formation to the Allt Lwyd Formation (Arenig), the lowest unit of the Aran Volcanic Group (see Allen & Jackson, 1985*a*,*b*, Excursion 5).

Allen, Jackson & Rushton (1981, pp. 317–19) reported Cambrian–Ordovician boundary fossils at British national grid reference SH 7904 3068 in low outcrops on the south side of Bryn-llin-fawr forestry road (see British Geological Survey, 1982; Allen & Jackson, 1985*b*, Excursion 5, Stop 9). Allen, Jackson & Rushton (1981, p. 318) noted that the Merioneth Series (Upper Cambrian)–Tremadoc Series boundary in the eastern Harlech Dome is 'practically coincident' with the 'transitional junction' between very dark grey mudstones of the Dolgellau Member and somewhat paler grey mudstones with siltstone laminae of the overlying Dol-cyn-afon Member of the Cwmhesgen Formation. Both of these members were subsequently assigned formation-level status by Pratt, Woodhall & Howells (1995) and Howells & Smith (1997), who abandoned the term 'Cwmhesgen Formation' (Fig. 2).

3. Cambrian–Ordovician boundary biostratigraphy

Rushton (1982, p. 43, fig. 3) detailed the stratigraphic range of fossils through the Cambrian–Ordovician boundary interval on Bryn-linn-fawr road. He noted two 'tuffaceous' sandstone beds, each approximately 10 cm thick, at 180 m and 180.3 m in his measured section, that lie between definite uppermost Cambrian and definite lowest Ordovician (Tremadoc) faunas.

Rushton (1982, p. 43) recommended defining the base of the Tremadoc, which at that time was not necessarily regarded as coincident with the base of the Ordovician, at the lowest occurrence (184 m) of a *Rhabdinopora,* represented by a fragmentary rhabdosome. Three early subspecies of this genus (namely *R. flabelliformis desmograptoides, R. f. parabola, R. f. sociale*) appear slightly higher (185.8–186.2 m; see Fig. 3), and the uppermost Cambrian–earliest Tremadoc olenid trilobite *Boeckaspis hirsuta* (Brögger) was collected at 188 m. Underlying strata at 170–177 m have *Parabolina heres heres* Brögger, an olenid trilobite limited to the uppermost Cambrian *Acerocare* Zone in Scandinavia, *Parabolina heres heres* is associated with *P. (Neoparabolina) frequens* (Barrande), a widely distributed uppermost Cambrian–lower Tremadoc olenid (Nikolaisen & Henningsmoen, 1985, p. 9). Rushton (1982) extended the *Acerocare* Zone at least as low as 165 m in the Bryn-llin-fawr section, based on the lowest occurrence of the granulose olenid *Parabolinella contracta* Lu and Zhou, a species which is geographically widely distributed near the base of the Tremadoc (Rushton, 1988, p. 686). *Parabolinella contracta* is limited to the *Acerocare* Zone at Bryn-llin fawr and near Dol-cyn-afon, 2 km to the south (Fig. 1). The *Acerocare* Zone in the Bryn-llin-fawr section is estimated to be at least 20 m thick.

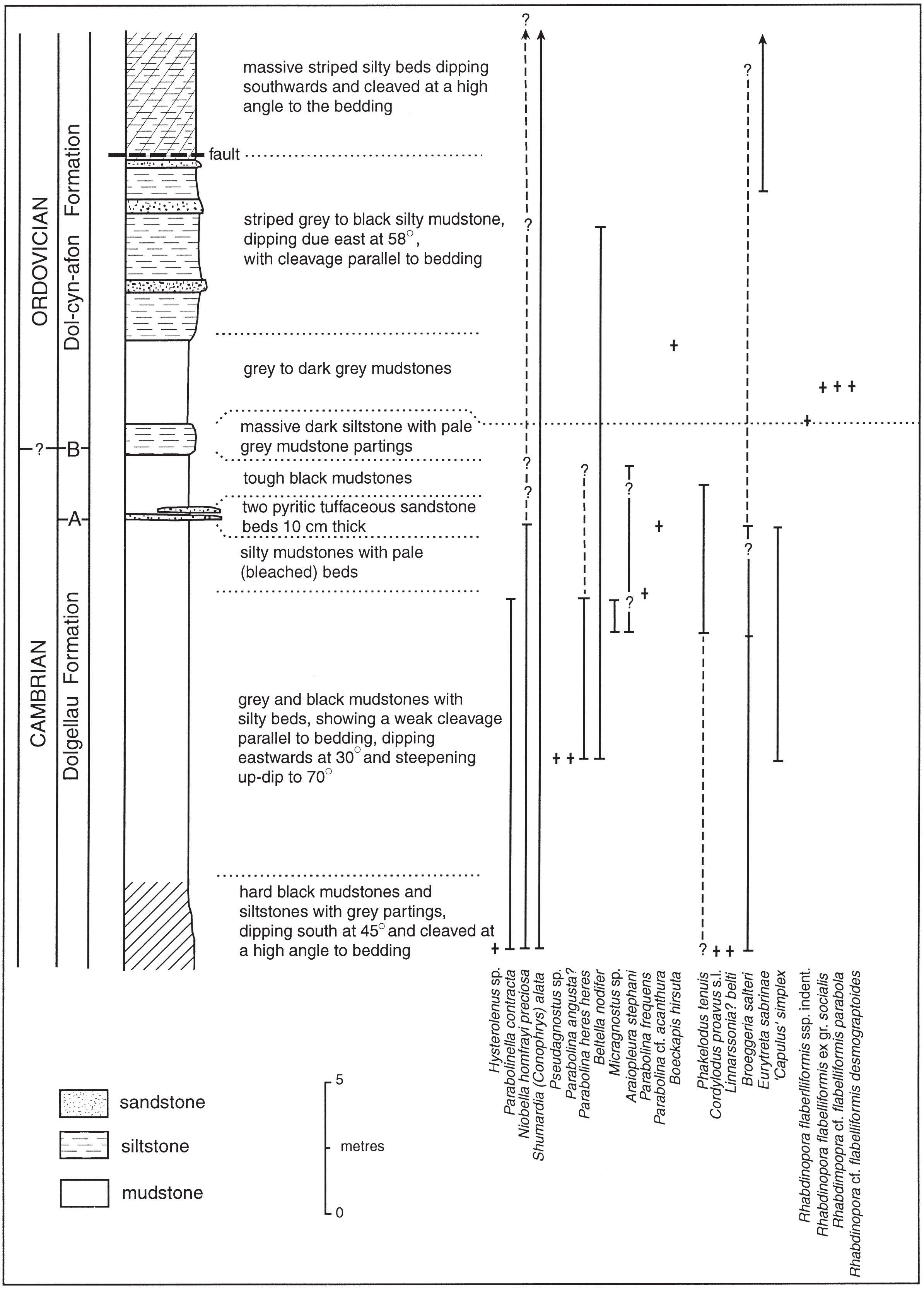

Figure 2. Cambrian–Ordovician boundary interval on Bryn-llin-fawr road, after Rushton *et al.* (2000). Faunal distribution updated from Rushton (1982). Alternative definitions of base of Dol-cyn-afon Formation from change to lighter-coloured siltstones (at B) (Rushton, 1982, upper boundary) or at sequence boundary defined by lower feldspathic sandstone (A, this report, lower contact). Diagonal ruling in lithological column emphasizes presence of slaty cleavage at high angle to bedding.

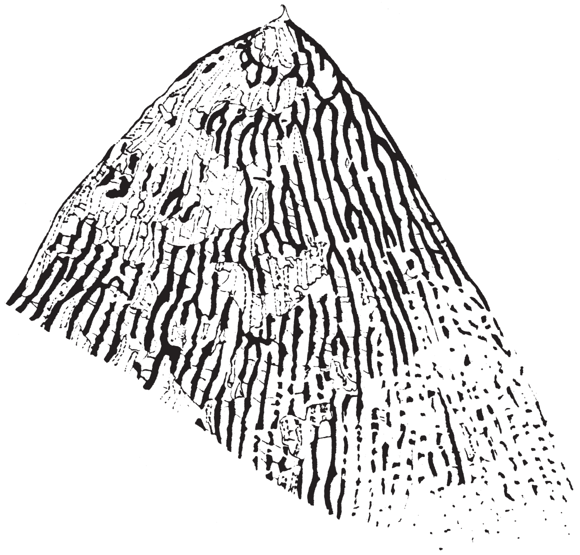

Figure 3. *Rhabdinopora flabelliformis parabola*, x2, from 185.8 m in the section at Bryn-llin-fawr. P. Legrande collection W98a1, drawing by P. Legrande.

In Rushton's (1982) paper, correlation of all of the strata at Bryn-llin-fawr between 177 m and 184 m remained problematical. However, re-examination of the specimens recorded therein as *P. heres heres?* at 182.5 m, just above the volcaniclastic sandstones and below the lowest *Rhabdinopora* (Rushton, 1982, fig. 3), confirms that they are referable to *Parabolina heres* subsp., and indicates that the *Acerocare* Zone extends above the sandstones (Fig. 2).

These data mean that the lowest occurrence of *Rhabdinopora* at 184 m defines the base of the Tremadoc and traditional base of the Ordovician at Bryn-llin-fawr. However, it is expected that the lowest occurrence of the conodont *Iapetognathus fluctivagus*, a species known to occur just below the lowest *Rhabdinopora* in western Newfoundland (Nicoll *et al.* 1999), will be accepted as the biostratigraphic criterion that defines the base of the Ordovician (e.g. Webby, 1998). In this case, the Cambrian–Ordovician boundary lies slightly below the lowest *Rhabdinopora* at Bryn-llin-fawr (Figs 2, 4).

4. Deposition and regional correlation of volcaniclastic sandstones

4.a. Deposition

The two tuffaceous sandstones represent a significant deviation in depositional environment from the sub- and superjacent low-energy, planar- and finely cross-laminated mudstones and siltstones, with sparse burrows in the overlying beds. The sandstones were described by Allen, Jackson & Rushton (1981, p. 313) as beds of 'reworked tuff, consisting mainly of subhedral albite with up to 15% of clear quartz, some with bipyramidal faces and clearly of volcanic origin'. The lower bed is cross-bedded and contains much euhedral pyrite, and the upper bed contains rhyolitic clasts. Allen & Jackson (1985*b*, p. 36) envisaged reworking of volcanic material that settled from an ash cloud. The two beds were seen to be 10 cm thick, with the upper one rapidly lensing out laterally, in exposures examined in 1978 (Rushton, 1982). Down-slope movement of colluvium tends to cover the Bryn-llin-fawr section, and the Countryside Council for Wales cleared the section with a front end loader in July 1997. When re-exposed, the upper bed was found to thicken to nearly 30 cm. Further study of slabs from both sandstones revealed grains derived from the underlying beds, including rounded phosphatic and mudstone granules. The sandstones range from medium- to locally coarse-grained, are well washed, show erosive bases, have parallel- and unidirectional cross-lamination with discontinuous mudflaser drapes, and are lenticular. Their sedimentological features suggest that they are amalgamated sandstones that may have resulted from the episodic appearance of high-energy waves in a deeper shelf environment (compare de Raaf, Boersma & van Gelder, 1977).

4.b. Correlation

At Bryn-llin-fawr, Rushton (1982, p. 43) placed the Dolgellau–Dol-cyn-afon formational contact at about 183 m with the change from very dark mudstones to the lowest grey siltstones ('B' in Fig. 2). This definition of the formational contact is about 3 m above the volcaniclastic sandstones and 1 m below the lowest *Rhabdinopora* ('A' in Fig. 2). However, as the sandstone beds mark an important change in sedimentary environment, they may provide a more appropriate formational base at Bryn-llin-fawr. Similar sandstones have not yet been found in contemporaneous strata at all other sections, and the Dolgellau–Dol-cyn-afon contact generally appears gradational, as was described for the basal stratotype in Dol-cyn-afon stream (Allen, Jackson & Rushton, 1981, p. 317; Rushton *et al.* 2000). There is, however, a lithological change at the base of the Dol-cyn-afon Formation at Ogof-ddû, on the northwest side of the Harlech Dome. The Dolgellau–Dol-cyn-afon contact is recognized at the base of a 25 cm thick phosphatic siltstone (Davidek *et al.* 1998, fig. 2) that is two metres above an upper *Peltura scarabaeoides* Zone fauna and 10 m below the lowest *Rhabdinopora flabelliformis*. The *Acerocare* Zone is not demonstrated at Ogof-ddû and must, if present, be considerably thinner than at Bryn-llin-fawr (Howells & Smith, 1997, p. 10). Sedimentation at Ogof-ddû is interpreted as condensed with non-sequences (that is, diastems and minor unconformities), and changes in oxygen tension created conditions suitable for the formation of *in situ* phosphates (J. K. Prigmore *in* Rushton *et al.* 2000).

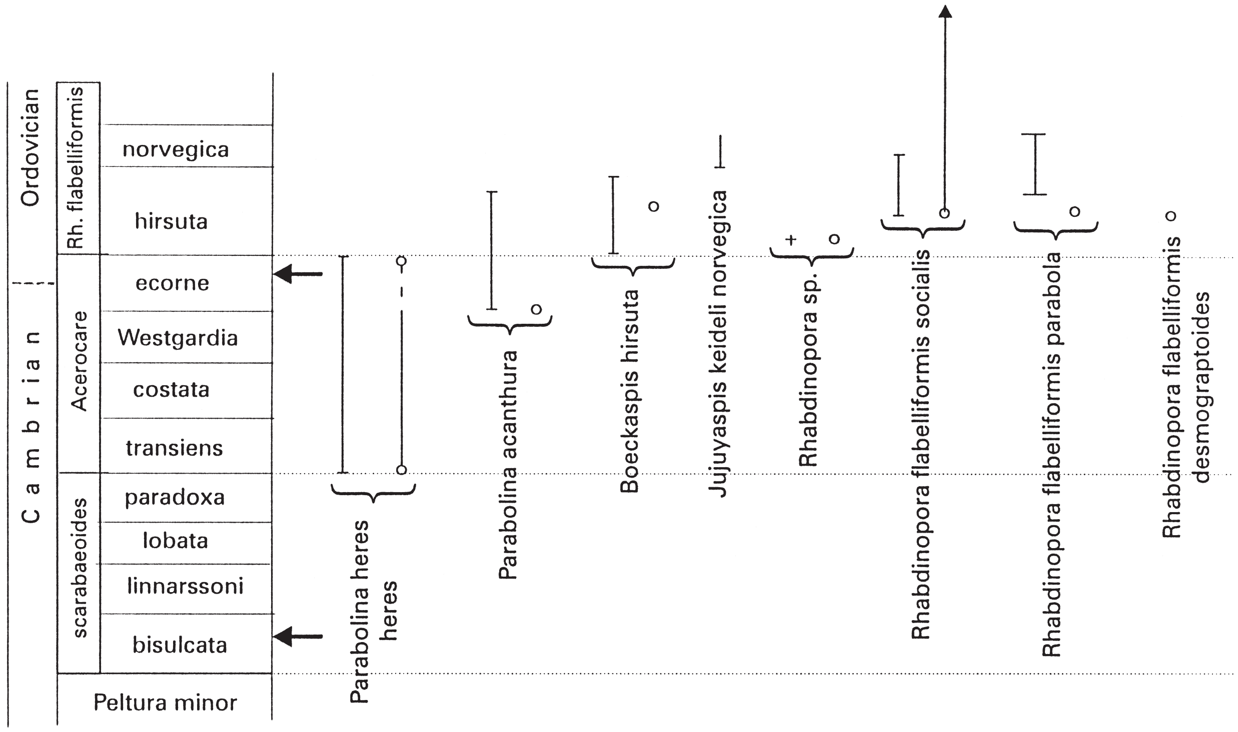

Figure 4. Key fossils through Cambrian-Ordovician boundary interval, based on the successions in the Oslo, Norway, area and North Wales; zonal scheme is that used in the Oslo region. Records at Oslo are shown by crossed-bars (+) to the left. Welsh records are shown by circles (o) on right. Thick arrows indicate levels at which Welsh tuffs have yielded U–Pb zircon dates: 491 ± 1 Ma at Ogof-ddû (Davidek *et al.* 1998) and 489 ± 1 Ma at Bryn-llin-fawr (this report). Approximate level of Cambrian-Ordovician boundary corresponds to that of proposed stratotype at Green Point, western Newfoundland.

4.c. Interpretation

In a sequence stratigraphic interpretation of the Welsh Basin, Woodcock (1990) proposed, without discussion of the evidence for its identification, his Id–Ie sequence boundary at the base of the Tremadoc. The sandstones at Bryn-llin-fawr and the phosphatic bed at Ogof-ddû are herein regarded as marking this sequence boundary in North Wales but are assigned to the uppermost Cambrian. The conformable contact observed between the Dolgellau and Dol-cyn-afon formations in other places in North Wales is seen as normal for a deep basinal setting (Woodcock, 1990, p. 538). On contemporary platform areas in many parts of the world, a marine regression close to the Cambrian–Ordovician boundary followed by an early Tremadoc eustatic rise have been proposed (Fortey, 1984; Landing, 1988, 1993). It is proposed herein that the two sandstones at Bryn-llin-fawr and the condensed phosphatic bed at Ogof-ddû are local expressions of these events and serve as markers of a sequence boundary. This sequence boundary provides a more unambiguous definition of the base of the Dol-cyn-afon Formation (‘A’ in Fig. 2) than the more subtle colour and lithological changes used by Rushton (1982) to define the base of the formation. The sandstones lie within the uppermost Cambrian, as indicated by the occurrence of *Parabolina heres* in overlying strata. Thus, if the sequence boundary is equated with the global ‘Tremadocian sea-level rise’, then the current evidence indicates that this eustatic rise actually began late in the *Acerocare* Chron. However, given the persistent tectonic instability of the North Welsh area during the Cambrian and Ordovician, it is best to be cautious before claiming that this sequence boundary is synchronous with that known from stable platforms.

The interpretation of the Bryn-llin-fawr sandstones as representing a sequence boundary would imply that the youngest U–Pb date determined on population(s) of zircons gives a maximum age for deposition, and it is possible that the zircons were reworked on the bottom for some time before their final deposition. However, the fact that such olenid species as *Parabolina heres, P. acanthura* and *Beltella nodifer* straddle the sequence boundary suggests that there was no major discontinuity in deposition in this basinal environment.

5. Zircon geochronology

U–Pb data were determined in the radiogenic isotope laboratory of the Massachusetts Institute of Technology. Zircon concentrates were obtained from samples collected from the feldspathic sandstones at 180 m and 180.3 m. Zircons were separated from the sandstone samples by the standard techniques of crushing and Wilfley table, magnetic and heavy liquid separation. Zircons were air-abraded (Krogh, 1982) and washed in warm 4N HNO_3 for one half hour prior to dissolution in HF and HNO_3 . The zircons were spiked with a mixed ^{205}Pb–^{233}U–^{238}U tracer solution, and dissolution took place in Teflon bombs maintained at 220°C for 48 hours. Lead and uranium were separated from the resulting solution by the use of standard anion exchange chemistry (Krogh, 1973). Total procedural blanks during the course of these analyses varied from < 1.0–3.0 pg for Pb and < 0.5 pg for U. Isotopes of Pb and U were measured with a VG Sector 54 thermal ionization mass spectrometer. Isotopes of Pb were analysed with a Daly detector in ion-counting mode. In general, an ion beam between 0.5 and 1.5 × 10^{-13} amps was maintained for ^{206}Pb during data acquisition. Uranium was loaded with phosphoric acid and colloidal graphite on rhenium filaments and was measured as metal ions in static mode utilizing three Faraday collectors and an average ^{235}U ion beam intensity of 2.5 × 10^{-13} amps. Errors in $^{238}U/^{206}Pb$, $^{235}U/^{207}Pb$ and $^{207}Pb/^{206}Pb$ ratios were estimated with Ludwig's (1989) algorithms, and all age uncertainties are quoted at the two sigma confidence level. Additional analytical details are in Figure 5 and Table 1.

Although it is reasonable to assume that both the upper and lower volcaniclastic sandstones are part of the same eruptive event, it was decided based on differences in grain size and appearance to sample and process them separately. The samples are distinguished as 'lower' and 'upper'. Zircons separated from both samples are very similar in appearance. In the lower unit, the zircons range in length from 50 to 300 microns and in the upper unit from 100 to 350 microns. The zircons are typically doubly terminated with no indication of sedimentary rounding in both samples. Many of the zircons are cracked and contain small opaque inclusions.

Thirteen zircon fractions were analysed from the lower unit, including seven single grains. There is evidence of a Lower Cambrian inherited component with two fractions having Pb–Pb dates of 529 and 523 Ma and two others that indicate a small inherited component. The majority of the analysed zircons appear to define a simple Pb-loss trajectory with upper and lower intercepts of 489.0 ± 1.1 Ma and 11.5 ± 16.4 Ma (MSWD = 0.84). The weighted mean of the Pb–Pb dates is 488.5 ± 1.0 Ma (MSWD = 0.97) and agrees very well with the upper intercept age.

Nine fractions of zircons separated from the upper unit were also analysed. Two fractions show elevated $^{207}Pb/^{206}Pb$ dates, which reflect an older component, but the rest define a simple Pb-loss trajectory. Seven fractions define upper and lower intercept dates of 489 ± 1.1 Ma and 4.1 ± 85.1 Ma, respectively (MSWD = 0.4). The weighted mean of the Pb–Pb dates is 489.0 ± 0.4 Ma (MSWD = 0.28).

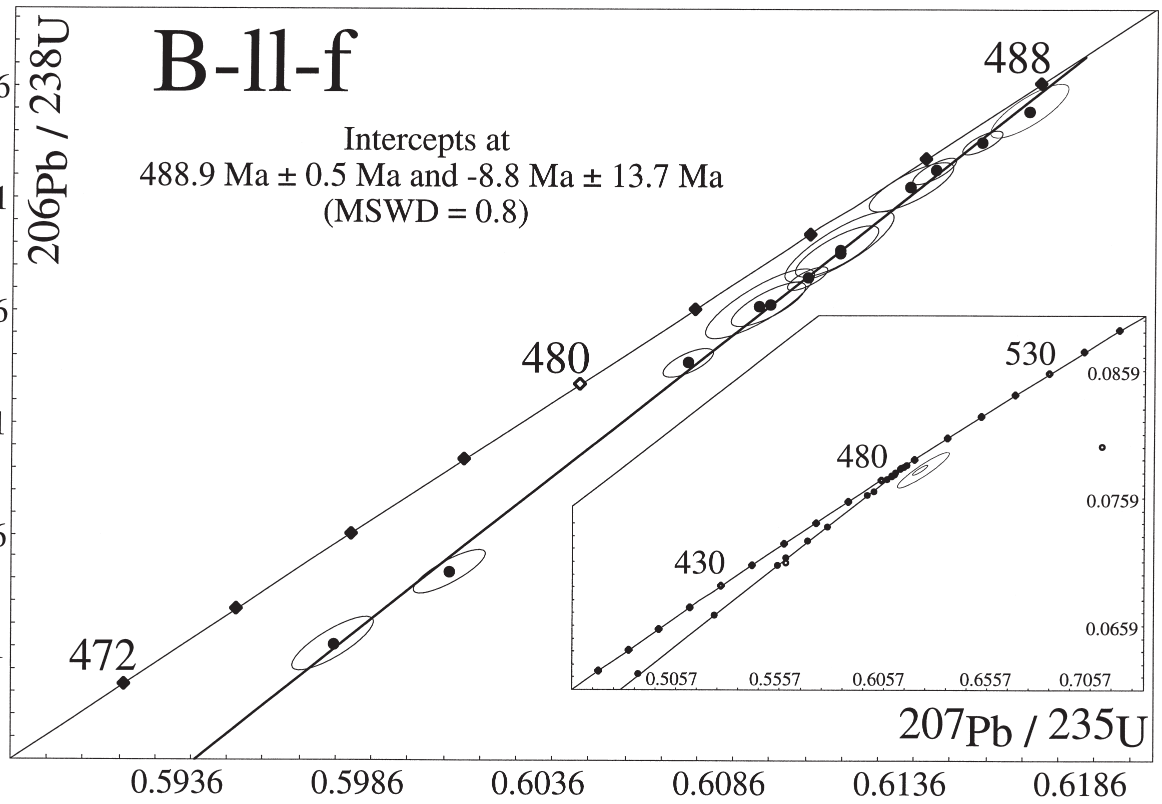

Figure 5. Concordia diagram for Bryn-llin-fawr volcaniclastic sandstones. Ages in millions of years are marked on the concordia curve. Individual analyses are depicted as 2 sigma error ellipses.

Table 1. U-Pb isotopic data for zircons for sample B-ll-f

		Concentration				Error 2 Sigma %						Age, Ma				
Fractions[a]	Weight, μg[b]	U, ppm	Pb, ppm	$^{206}Pb/^{204}Pb$[c]	$^{208}Pb/^{206}Pb$[d]	$^{206}Pb/^{238}U$[d]	Error	$^{207}Pb/^{235}U$[d]	Error	$207^{Pb}/^{206}Pb$[d]	Error	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Corr. Coef.	Pb, pg[e]
z5	5.0	531.1	45.6	5613.9	0.185	0.07984	(.08)	0.71246	(.15)	0.06472	(.12)	495.1	546.2	765.3	0.55	2.4
z6(6)	1.1	326.6	29.7	278.1	0.158	0.07814	(1.81)	0.62462	(2.00)	0.05798	(.78)	485.0	492.7	528.9	0.92	6.9
z7	4.1	326.9	27.8	1175.9	0.181	0.07813	(.51)	0.62295	(.59)	0.05783	(.28)	485.0	491.7	523.2	0.88	5.8
z8	3.8	505.2	42.3	4731.2	0.183	0.07852	(.15)	0.61675	(.18)	0.05696	(.09)	487.3	487.8	490.1	0.86	2.1
z14	5.8	543.1	43.6	4703.6	0.134	0.07838	(.06)	0.61544	(.09)	0.05695	(.06)	486.5	487.0	489.4	0.76	3.4
z6	5.0	470.8	39.1	6382.8	0.176	0.07825	(.08)	0.61414	(.10)	0.05692	(.06)	485.7	486.2	488.5	0.78	1.9
z15	1.6	600.9	51.6	1898.2	0.219	0.07819	(.14)	0.61349	(.18)	0.05691	(.12)	485.3	485.8	488.0	0.77	2.6
z10	2.2	474.8	39.5	1505.8	0.184	0.07790	(.15)	0.61148	(.19)	0.05693	(.11)	483.6	484.5	488.8	0.80	3.5
z13(5)	1.1	551.4	47.5	1048.1	0.228	0.07792	(.20)	0.61148	(.25)	0.05692	(.14)	483.7	484.5	488.3	0.82	3.0
z12	30.5	283.2	23.1	14578.2	0.164	0.07778	(.07)	0.61066	(.09)	0.05694	(.06)	482.8	484.0	489.3	0.77	3.0
z4	2.0	642.9	54.1	1888.8	0.203	0.07767	(.13)	0.60960	(.17)	0.05693	(.11)	482.2	483.3	488.7	0.75	3.4
z1	9.0	375.1	32.1	2418.0	0.208	0.07765	(.21)	0.60925	(.25)	0.05691	(.13)	482.1	483.1	487.9	0.86	6.9
z11	7.7	417.7	34.6	6023.2	0.187	0.07740	(.08)	0.60735	(.11)	0.05691	(.08)	480.6	481.9	488.1	0.73	2.7
z10	3.3	435.9	36.0	2675.8	0.202	0.07615	(.15)	0.59758	(.19)	0.05692	(.10)	473.1	475.7	488.3	0.83	2.7
z11	4.2	406.6	31.7	2013.6	0.171	0.07368	(.44)	0.57845	(.50)	0.05694	(.21)	458.3	463.5	489.1	0.90	4.0
z2(5)	2.4	505.7	37.2	3117.7	0.121	0.07253	(.11)	0.56891	(.23)	0.05689	(.20)	451.4	457.3	487.1	0.52	1.8
z12	3.0	339.9	25.4	1161.4	0.162	0.07123	(.20)	0.55879	(.38)	0.05689	(.31)	443.6	450.7	487.5	0.57	4.1
z14	1.9	583.1	44.5	1530.2	0.196	0.07082	(.15)	0.55860	(.27)	0.05721	(.22)	441.1	450.6	499.6	0.59	3.3
z1(6)	3.0	477.4	36.5	2216.8	0.200	0.07063	(.10)	0.55452	(.14)	0.05694	(.10)	439.9	448.0	489.3	0.73	3.0
z4	1.4	643.2	44.1	1900.5	0.138	0.06674	(.14)	0.52438	(.18)	0.05699	(.11)	416.5	428.1	491.0	0.79	2.1
z3	1.8	497.9	33.7	1921.5	0.208	0.06221	(.15)	0.48734	(.25)	0.05682	(.19)	389.0	403.1	484.5	0.64	1.9
z13	3.0	388.4	31.7	1712.5	0.182	0.07646	(.13)	0.60080	(.16)	0.05699	(.09)	475.0	477.7	491.1	0.82	3.4

Mass fractionation correction of 0.15% ± 0.04%/amu was applied to single collector Daly analyses.

Total procedural blank for Pb ranged from 0.65 to 3.5 pg and < 1.0 pg for U. Age calculations are based on the decay constants recommended by Steiger & Jäger (1977). Common-Pb corrections were calculated by using the model of Stacey & Kramers (1975) and the interpreted age of the sample. Corr. coef. = correlation coefficient for $^{206}Pb/^{238}U$-$^{207}Pb/^{235}U$.

a Sample chemistry follows procedures outlined in Bowring *et al.* (1998). All analyses represent single zircon grains, except where denoted by (#) which indicates number of zircon grains in analysis.

b Sample weights were estimated by using a videomonitor and are known to within 40%.

c Values are measured ratio corrected for spike and fractionation only.

Both layers of volcaniclastic sandstone yield the same date within error. When all analyses are combined, seventeen define an upper intercept date of 488.9 ± 0.6 Ma (MSWD = 0.57), and the weighted mean $^{207}Pb/^{206}Pb$ date is 489.1 ± 0.5 Ma (MSWD = 0.82). The best estimate of the age of the zircons in the volcaniclastic bed is 489 ± 0.6 Ma.

6. Age and correlation of Cambrian–Ordovician boundary

A maximum U–Pb age of 489 ± 0.6 Ma for the uppermost Cambrian of Avalon is consistent with a 491 ± 1 Ma age recently determined for older strata of the Dolgellau Formation (that is, lower *Peltura scarabaeoides* Zone) at Ogof-ddû on the northwest side of the Harlech Dome (Davidek *et al.* 1998). An age of 489 Ma must be strictly thought of as a maximum age as the zircons in the volcaniclastic sandstones were subject to reworking.

The dates from Ogof-ddu and Bryn-llin-fawr demonstrate that the interval spanned by the upper one and a half zones of the Olenid Series of Scandinavia (Henningsmoen, 1957), namely the upper *Peltura scarabaeoides* Zone through most of the *Acerocare* Zone, represents about 3 Ma. The Cambrian–Ordovician boundary beds at Bryn-llin-fawr are most readily correlated with those in the section at Nærsnes in the Oslo region, Norway (Bruton, Erdtmann & Koch, 1982). Both sections show the successive upward appearances of the olenid trilobites *Parabolina heres heres, P. acanthura*, and finally *Boeckaspis hirsuta*. In addition, the lowest occurrences of the dendroid graptolites *Rhabdinopora flabelliformis parabola* and *R. flabelliformis socialis* lie close to that of *B. hirsuta*. In sections on the Baltic (Norway) and Avalon continents (Wales and New Brunswick), *Parabolina heres* is limited to the *Acerocare* Zone and occurs throughout the zone. The highest appearances of *P. heres* are above the sandstones at Bryn-llin-fawr and in calcareous nodule 1N at the base of the Nærsnes succession. Bruton, Erdtmann & Koch (1982, pl. 1, figs 1–3) illustrated *P. heres* as *P. acanthura* at Nærsnes, but this identification was corrected by Nikolaisen & Henningsmoen (1985). Bruton, Erdtmann & Koch (1982) regarded the lowest occurrence of *B. hirsuta* as a local index for the base of the Ordovician, with the lowest *Rhabdinopora* specimen occurring 0.5 m higher and the lowest *R. flabelliformis parabola* 0.5 m higher still at Nærsnes (Bruton, Erdtmann & Koch, 1982). At Bryn-llin-fawr, *B. hirsuta* is known only from a horizon that is less than 2.0 m above the lowest occurrence of *R. flabelliformis parabola*.

The proposed Cambrian–Ordovician boundary global stratotype section and point at Green Point, western Newfoundland, defines the base of the Ordovician at the lowest occurrence of the conodont *Iapetognathus* sp. 1 (Webby, 1998: *I. fluctagavus* Nicoll *et al.* 1999). The lowest occurrences of *Rhabdinopora flabelliformis praeparabola* and *R. flabelliformis parabola* lie 4.8 and 6.4 m higher in the succession, respectively. Because few conodont elements have been recovered at Nærsnes or Bryn-llin-fawr, correlation with Green Point depends on the lowest occurrences of such *R. flabelliformis* subspecies as *R. flabelliformis parabola*. Although the trilobites have been illustrated from Bryn-llin-fawr (Rushton, 1982), few dendroid graptolites have been documented (see Rushton *et al.* 2000), so *R. flabelliformis parabola* is illustrated herein (Fig. 3). If the appearance of *R. flabelliformis parabola* is considered contemporaneous in all three localities, the base of the Ordovician as presently proposed (Webby, 1998) should lie slightly below the lowest local occurrence of *R. flabelliformis parabola* and close to the level of the volcaniclastic sandstones at Bryn-llin-fawr. A more precise correlation might be possible with the recovery of conodonts at Bryn-llin-fawr or olenids at Green Point.

7. Discussion

A determination of the upper boundary of the Cambrian is an important contribution to the progressive refinement of the geochronology of the lower Palaeozoic that has been taking place over the last decade. This new Cambrian–Ordovician boundary interval age combined with a 519 Ma date on the appearance of the oldest Avalonian trilobites (Landing *et al.* 1998) and definition of as many as 30–35 trilobite zones in various Lower–Upper Cambrian successions (Shergold, *in* Whittington *et al.* 1997) indicate that the duration of Cambrian trilobite zones locally averages about 1.0 Ma through an interval of 31 Ma.

Faunal replacements through the preceding 24 Ma of the Avalonian pre-trilobitic Lower Cambrian (Placentian Series) and equivalents seem to have been significantly slower. A relatively small number of successive trace- and body-fossil zones in this interval is indicated by the recognition of five or six zones in the Avalonian Placentian Series (Landing, 1992) and five zones in the Manykaian–Tommotian Stages of Siberia (Zhuravlev, 1995). It would appear that the 'Cambrian evolutionary radiation' gathered pace through the Placentian Epoch and achieved its 'explosive' character in an interval correlative with the Siberian Atdabanian–Botomian.

The relatively brief duration of trilobite biostratigraphic units seems to hold in the Upper Cambrian, where the 3 Ma interval at the top of the Upper Cambrian discussed here embraces six olenid subzones in the Scandinavian Upper Cambrian (Henningsmoen, 1957). This suggests a duration of as little as 0.5 Ma for olenid subzones in the uppermost Cambrian and affords some insight into the rate of origination of trilobite taxa. During the Late

Cambrian, comparatively uniform dysaerobic conditions prevailed in the sea covering much of Baltica, with minor fluctuations in the environment and their influence on olenid distribution discussed by Clarkson, Alhberg & Taylor (1998). The generally uniform conditions, undisturbed by major facies shifts, enabled Henningsmoen (1957) to develop a phylogeny of Baltic olenids, in which many taxa apparently evolved sympatrically or parapatrically. Within the 3 Ma represented by the upper part of the *Peltura scarabaeoides* Zone and the *Acerocare* Zone, five genera and seventeen species of olenids appeared in Scandinavian successions. These taxa comprise the Pelturinae (*Acerocarina* (with two species), *Westergardia* (three species), *Pelturina* (one species), and *Acerocare* (two species)) and the Oleninae (*Parabolina* with four subspecies of the *P. heres* group and the subgenus *Parabolina (Neoparabolina)* with two subspecies) (see Henningsmoen, 1957; Rushton, 1982; Nikolaisen & Henningsmoen, 1985).

The new date at Bryn-llin-fawr, taken with a 483 ± 1 Ma date within the upper Tremadoc of Nova Scotia (Landing *et al.* 1997) shortens previous estimates for the duration of the Tremadoc (Tucker & McKerrow, 1995). This change in estimated duration results from determination of a much younger age for the Cambrian–Ordovician boundary although the base of the Arenig is not yet precisely dated. Local biostratigraphic subdivision of the Tremadoc, whether done by trilobites, graptolites, or conodonts (e.g. Fortey, 1995; Cooper, 1999), typically features three to five zones in each faunal province, and may prove to be of a similar order of duration to Cambrian zonation.

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