CORRESPONDENCE

Comments on the paper 'Fission-track dating of British Ordovician and Silurian stratotypes' by R. J. Ross and others

SIR – Fission track ages of British Ordovician and Silurian stratotypes were first published in abbreviated form by Ross *et al.* (1978); now that they have been fully published (Ross *et al.* 1982) it is possible to assess their significance more carefully.

The earlier brief account of their data was hailed by some (e.g. Compston, 1979; McKerrow, Lambert & Chamberlain, 1980) as providing a considerable advance in the numerical calibration of the Phanerozoic time scale. This is an opinion not shared by fission track experts (e.g. Hurford & Green, 1982; Storzer & Wagner, 1982). Though the stratigraphy of the horizons which Ross *et al.* (1982) attempted to date by the fission track method is unexceptionable it is necessary to take account of Hurford & Green's (1982) warning that adequate safeguards must be taken against the addition of misleading data resulting from the related problems of uncertainties in both λ_f (the 238 U fission track decay constant) and neutron dosimetry. Storzer & Wagner (1982), though suggesting that future improvements in neutron dosimetry and age standards may eventually reduce errors in the accuracy of fission track ages below the present realistic figure of ±10%, commented that Ross *et al.* were apparently unaware of the efficiency problems in the external detector technique for zircons, that they did not consider adequately the possibility of fossil-track fading in zircon, and expressed surprise that they quoted fission track ages with errors as small as ±2%.

Ross *et al.* (1982) consistently and seriously underestimated the errors to be attached to their fission track ages. Apart from apparently unassessed errors due to flux perturbation (see Storzer & Wagner, 1982, pp. 213–14), both Storzer & Wagner (1982) and Hurford & Green (1982) stressed the difficulty in the fission track method of accurate measurement of the neutron fluence, even when this is attempted by use of the National Bureau of Standards standard glasses SRM 961–4. The only effective way to avoid this inaccuracy, together with the important remaining uncertainties in the fission decay constant and the fission cross section, is to use an age-standard which is irradiated simultaneously with each batch of samples of unknown age.

Apart from the fact that there is as yet no fission track age standard which meets all the necessary criteria of reliability for comparison with other radiometric dating schemes (see Storzer & Wagner, 1982, p. 214), Ross *et al.* did not follow this procedure. Instead they attempted to relate their fission track ages to the K–Ar age of a standard via neutron fluence measurement made by including in each run their laboratory standard glass, itself calibrated against SRM 962 and SRM 963 using the Cu calibration. Their procedure for relating fission track ages to the K–Ar age of a standard is given by Naeser, Hurford & Gleadow (1977). As was demonstrated by Hurford & Green (1982), this procedure introduces an extra component of at least ±3% into the absolute error to be attached to each fission track age quoted by Ross *et al.* (1982). As an example, the error for their Ludlovian Sample 76 Sh 25 cannot be as low as the quoted ±9 Ma; on an absolute basis the compounded error must be at least as large as ±15 Ma (1σ) for the quoted age of 407 Ma. The lack of a suitable K–Ar standard caused Ross *et al.* (1982) to write: 'It is possible, therefore, that fission track ages in the early Palaeozoic may differ by a per cent or two from K–Ar'.

More serious is the fact that in their statistical computation of errors Ross *et al.* (1982) used a statistical formula, given by Naeser, Johnson & McGee (1978), which few believe to be applicable to fission track data. Green (1981) criticized the restatement of this approach by Johnson, McGee & Naeser (1979), who in our view failed in their reply (Johnson, McGee & Naeser, 1982) to establish the correctness of their procedure. Briefly, the crux of the matter is that Johnson, McGee & Naeser (1979) proposed a formula which reduced the estimate of the standard deviation of the ratio ρ_s/ρ_i, used to compute a fission track age (ρ_s is the spontaneous track density in the mineral to be dated, ρ_i is the thermal neutron induced track density), by introducing an extra negative term depending on an assumed statistical correlation between ρ_s and ρ_i. In their defence of this procedure Johnson, McGee & Naeser (1982) stated correctly that both ρ_s and ρ_i are functions of the uranium concentration in the mineral to be dated and deduce that ρ_s and ρ_i are correlated, and are physically dependent

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on each other. This is unexceptionable, though it might be clearer to state that ρ_s and ρ_i are functionally related (for the equations relating them, see Faure, 1977). However it is implicit in the development of their formula for $\sigma\ (\rho_s/\rho_i)$ – the standard deviation of ρ_s/ρ_i – that Johnson, McGee & Naeser (1979) assumed that the measurements of ρ_s and ρ_i are statistically dependent; this is explicitly stated in Johnson, McGee & Naeser (1982). They are not. The fact that there is a functional relationship between two quantities ρ_s and ρ_i does not necessarily imply that the measurements of ρ_s and ρ_i are *statistically* dependent, as is lucidly explained by Mandel (1964). Functional dependence relates to the expected values of statistical populations, whereas statistical dependence relates to the fluctuating parts of the measurements, that is, to the deviation of observations from their expected values. Since the measurements of ρ_s and ρ_i (as track densities) are made quite independently of each other in two separate observations, $\sigma(\rho_s)$ and $\sigma(\rho_i)$ are necessarily statistically independent with zero correlation coefficient, although the expected values of ρ_s and ρ_i are highly correlated through the uranium concentration. What Johnson, McGee & Naeser (1982) stigmatized as the 'early practice' is, in fact, the correct practice. The errors quoted in Ross *et al.* (1982) are consequently too low, and should be recalculated according to the conventional statistics outlined by Green (1981).

That this is not an unimportant quibble may be illustrated by one example. The age quoted by Ross *et al.* (1982) of 434 ± 12 (1σ) Ma for sample 76 DL 39 for the Ashgillian Upper Hartfell Shale becomes 434 ± 20 (1σ) Ma for the *precision* alone if conventional statistics (Green, 1981) are used; on an *absolute* basis, compounding the error due to the method of neutron fluence measurement, this becomes 434 ± 24 (1σ) Ma. Note in passing that this fission track age agrees within error with the Ashgillian Stockdale Rhyolite age of 421 ± 5 (2σ) Ma.

Even were one to neglect all of the foregoing factors, it cannot be too strongly stressed that Ross *et al.* (1982) quoted their errors at the 1σ level. Even the intercomparison between themselves of the fission track ages requires at least 2σ errors to be employed, and this is yet more necessary if comparisons are to be made between fission track ages and ages based on other radiometric dating methods. As a result, even the most precise fission track age quoted by Ross *et al.* (1982, their Table 1) has an associated analytical error of at least ± 18 Ma, ranging up to ± 42 Ma in the worst case. Even these errors should in fact be considerably increased to include the additional uncertainties mentioned above.

One is left with the clear impression that the true 95% absolute error to be associated with these fission track dates is about ± 10% or more than the duration of the Silurian Period, which makes them of little value for the numerical calibration of the Phanerozoic time scale. This conclusion is confirmed by Hurford (private comm., 1982) on the basis of attempts to reproduce the ages of putative standards. Storzer & Wagner (1982) took an even more pessimistic view, setting the 68% accuracy even of fission track ages obtained by using age-standards at ± 10% and pointing to the large variations in the estimates by fission track dating of the age of the KBS Tuff in northern Kenya. The fission track ages of Ross *et al.* (1982) cannot bear comparison with other geochronological methods, which have yielded ages with 95% accuracies of ± 2% in the Phanerozoic, but at the same time their work has demonstrated the potential contribution which fission track dating could make to stratigraphical studies in the future.

Ross *et al.* (1982) went to considerable length to demonstrate the incorrectness of the revised fission track ages given by Gale, Beckinsale & Wadge (1979*a*). That revision was certainly incorrect because we based it directly on the account of the principles of fission track dating given by Naeser (1979) and because Ross *et al.* (1978) did not state that their fission track ages were calibrated against K–Ar ages. However, we corrected our mistake in our later paper (Gale, Beckinsale & Wadge, 1980 a paper quoted by Ross *et al.* in their list of references). Nevertheless Ross *et al.* (1982), two years later, criticized our initial error even to the extent of reproducing as their Table 4 a table which originally appeared in almost identical form on page 13 of Gale, Beckinsale & Wadge (1980).

In their discussion of other results pertinent to the Palaeozoic time scale Ross *et al.* (1982) concentrated considerable attention on the discussion in Gale, Beckinsale & Wadge (1979*a*) and failed to note the revised discussion in Gale, Beckinsale & Wadge (1980), which not only took account of 34 radiometric dates relevant to the numerical calibration of the Ordovician, Silurian and Devonian time scales but also demonstrated how poor a constraint the present fission track ages provide for that calibration. Now that it is known that the published errors for the fission track ages are underestimated, the constraint becomes even poorer.

There is an unfortunate emphasis in Ross *et al.* (1982) on the Rb–Sr whole rock isochron date for the Stockdale Rhyolite (Gale, Beckinsale & Wadge, 1979*a*). There is no radiometric date yet reported which has been proved to be so completely reliable that it can be used as an anchor point in calibrating the Palaeozoic time scale. Such a calibration must instead be based on all available reliable data, an approach taken by Gale, Beckinsale & Wadge (1980), by McKerrow, Lambert & Chamberlain (1980) and by Gale (1982).

Though undue weight should not be given to the Stockdale Rhyolite age of 421 ± 5 Ma (2σ error) for the Ashgill, nevertheless Ross *et al.* have presented no data which refutes it. Their own fission track age for the Rawtheyan Upper Hartfell Shale is 434 ± 24 Ma (2σ) even if the authors' own low error estimate is used; it has been shown earlier in this paper that this age should really be quoted as 434 ± 40 Ma (2σ). This overlaps with the age for the Stockdale Rhyolite whichever error estimate is used, so there is no conflict here. Neither are the two Lower Silurian fission track dates of 437 ± 20 Ma and 422 ± 20 Ma for the Birkhill Shale and the Buildwas Formation in conflict with the Stockdale Rhyolite age. Moreover the Lower Llandoverian age of 431 ± 7 (2σ) Ma obtained by Lanphere *et al.* (see Item NDS 128 in Odin, 1982) for Esquibel Island, though questioned by Rundle on both geochronological and stratigraphical grounds (see Odin, 1982, p. 478), is now recognized not to be in conflict with the Stockdale Rhyolite data (Gale, 1983). Finally, the data quoted by Ross *et al.* (1982) for the Lower Ludlovian Middle Elton Formation are a fission track age of 407 ± 18 (2σ) Ma and a K–Ar age of 419 ± 10 (2σ) Ma; when we note that the more precise K–Ar age spans a range of 409 to 429 Ma and note that the duration of the Silurian Period is no longer than 25 Ma we again see that this presents no conflict with the Stockdale Rhyolite age. There is thus no direct evidence for the statement by Ross *et al.* (1982) that Gale Beckinsale & Wadge (1979*a*) 'determined *precisely the wrong number* as a measure of the age of emplacement for the Stockdale Rhyolite', whilst there is evidence that Ross *et al.* (1982) determined *very imprecisely* the ages of a number of formations whose stratigraphy is precisely established.

Ross *et al.* (1982) are, therefore, left merely with their prejudice against Rb–Sr whole rock isochron ages on acid rocks. Gale, Beckinsale & Wadge (1979*b*), complemented by Gale, Beckinsale & Wadge (1980), presented a body of evidence showing that, although the Rb–Sr system is easily disturbed in acid pyroclastics, Rb–Sr whole rock isochron ages for rhyolite lavas can often reliably date their time of extrusion. An excellent recent example is the work by Williams *et al.* (1982) on the Cerberean Volcanics in Australia; they obtained a mean Rb–Sr biotite-whole rock age of 367 ± 3 Ma and a mean K–Ar biotite age of 366 ± 5 Ma for the biotite rhyodacite, whilst the contemporaneous basal rhyolite yielded a Rb–Sr isochron age for whole rocks and feldspars of 369 ± 3 Ma.

Against this evidence Ross *et al.* advanced merely a statement, given apparently the status of dogma, by Van Schmus, Thurman & Peterman (1975) which had already been examined by Gale, Beckinsale & Wadge (1979*b*, 1980). First, we may note that this statement questioned the acceptance not only of Rb–Sr whole rock isochrons for acid volcanics but also for granites; if this were to be accepted as a general rule it would eliminate many of the data usually accepted as reliable for time-scale calibration and would ignore excess argon or resetting problems with K–Ar dates, problems with U–Pb dates due to inherited zircons, etc. Second, Van Schmus, Thurman & Peterman (1975) based their statement merely on a comparison between U–Pb zircon dates and Rb–Sr whole rock isochron dates for Middle Precambrian rocks in Wisconsin; they provided no evidence that their problem could not instead have been explained in terms of the zircon age being inherited from the source region of the rocks, as for instance in the case documented by Pankhurst & Pidgeon (1976). Third, in a later refinement of their position Van Schmus & Bickford (1976) stressed the view that Rb–Sr whole rock isochron ages can sometimes be 10–20% too young for epizonal or fine-grained supracrustal Precambrian rocks which have low total Sr concentrations and high Rb/Sr ratios. None of these characteristics appertain to the Stockdale Rhyolite, which was moreover proved by Gale, Beckinsale & Wadge (1979*a*) to be extrusive and not of ignimbritic or ash flow tuff origin.

Perhaps the most convincing demonstration that Rb–Sr whole rock isochron ages for rhyolites are not incompatible with other types of radiometric dates used for calibrating the time scale is to list those ages within the Ordovician, Silurian and Devonian periods which appear to be based on sound stratigraphy and reliable geochronology; this is done in Table 1. In Figure 1 these ages are plotted for illustrative and comparative purposes against a stratigraphic axis in a way similar to that adopted by Boucot (1975), McKerrow, Lambert & Chamberlain (1980) and others. It is clear that a line drawn so as to pass through all items passes also through the Rb–Sr isochron ages for acid rocks, items 7, 9, 13, 15 and 32. Figure 1 also demonstrates that the Stockdale Rhyolite age is compatible with

Table 1. Critical radiometric dates for the Palaeozoic time scale

Item	Locality	Geochronological scheme	Ma ± 2σ	Stratigraphy	Reference*
1	Kelso Lavas, Scottish Borders	K–Ar basalt	361 ± 7	Pre Early Tournaisian, post Late Devonian	NDS 165
2	Post-cauldron intrusions, SE Australia	K – Ar biotite, hornblende, muscovite	362 ± 3†	Famennian	NDS 235
3	Cerberean Volcanics, SE Australia	K–Ar biotite	367 ± 4†	Frasnian	NDS 234
4	Mt Buller granodiorites and Woods Pt dyke swarms, SE Australia	K–Ar, biotite, hornblende	381 ± 4†	Eifelian–Givetian	NDS 233
5	Shap Granite, English Lake District	Rb–Sr, WR, biotite	394 ± 4†	Gedinnian-Givetian	NDS 241
6	Skiddaw Granite, English Lake District	K–Ar, biotite	398 ± 8	Post Pridoli	NDS 192
7	Pembroke Volcanics, Appalachians, USA	Rb–Sr, WR	393 ± 7	Early Gedinnian – Lower Emsian	NDS 237
8	Lorne Lavas	Rb–Sr	399 ± 5	Gedinnian	A
9	Hedgehog Volcanics, Appalachians, USA	Rb–Sr, WR	400 ± 10‡	Late Gedinnian	NDS 223
10	Gocup Granite, Australia	K–Ar, muscovite	409 ± 5§	Post Wenlock, pre Siegen	NDS 210
11	Laidlaw Volcanics, Australia	K–Ar, sanidine K–Ar, biotite Rb–Sr, WR	409 ± 5 420 ± 5 425 ± 17	Ludlow *nilssoni* zone	B
12	Middle Elton Formation, Shropshire	K–Ar, biotite; fissiontrack, zircons	415 ± 12§	Gorstian, Ludlow	C
13	Quoddy Volcanics, Appalachians, USA	Rb–Sr, WR	408 ± 8	Late Llandovery	NDS 238
14	Descon Formation, SE Alaska	40_{Ar}–39_{Ar}, hornblende	431 ± 7	Llandovery, Rhuddanian	NDS 128
15	Stockdale Rhyolite, English Lake District	Rb–Sr, WR	421 ± 5†	Ashgillian	NDS 243
16	Eskdale Granite, English Lake District	Rb–Sr, WR	429 ± 4	Late Caradoc	NDS 189
17	Oliverian Syenite	Rb–Sr, WR	441 ± 5	Caradoc, post lower *clingani*?	D
18	Carters Limestone, Alabama, USA	K–Ar, biotite, sanidine	455 ± 10	Early to Middle Caradoc	NDS 129
19	Tyrone Limestone, Kentucky, USA	K–Ar, biotite	443 ± 10	Middle Caradoc	NDS 161
20	Tyrone Limestone, Kentucky, USA	^{39}Ar–^{40}Ar	433 ± 5	Middle Caradoc	E

21	Kinnekulle, Sweden	Rb–Sr, biotite K–Ar, biotite	445 ± 4 450 ± 6	Post *gracilis*, pre *clingani*	F
22	Borrowdale Volcanics, English Lake District	Sm–Nd	457 ± 5	Llandeilo to Early Caradoc	G
23	Bail Hill Volcanics, Scotland	K–Ar, biotite	455 ± 15[§]	*gracilis* zone	H
24	Benan Conglomerate, Scotland	Rb–Sr	470 ± 5	Pre *gracilis* zone	NDS 135
25	Colmonell Gabbro, Scotland	K–Ar	484 ± 10	Post mid-Arenig, pre Late Llanvirn	H
26	Gt Cockup Picrite, English Lake District	K–Ar, biotite, hornblende	468 ± 10	Lower Llanvirn	NDS 191
27	Hare Bay Ophiolite, Newfoundland	^{40}Ar–^{39}Ar	480 ± 5	Mid Arenig to Mid Llanvirn	I
28	Byne Hill, Scotland	U–Pb, zircons	484 ± 4	Mid Arenig[‖]	NDS 134
29	Bay of Islands gabbro, Newfoundland	^{40}Ar–^{39}Ar	460 ± 5	Mid Arenig *or gracilis* zone	J
30	Twt Hill Granite	Rb–Sr	498 ± 7	Pre Arenig	K
31	Rhobell Fawr, Wales	K–Ar	508 ± 17[§]	Late Tremadoc	L
32	Krivoklat-Rokycany, Bohemia	Rb–Sr, WR	491 ± 14	Late Cambrian to pre Early Tremadoc	NDS 130
33	Mandar Granite, Sinai	Rb–Sr, WR	529 ± 8	Pre Early Cambrian?	NDS 251
34	Amram Quartz Pôrphyry, Sinai	Rb–Sr, WR	548 ± 5	Pre Early Cambrian?	NDS 251
35	Vires-Carolles Granite, Normandy	U–Pb, monazite	540 ± 10	Precambrian–Cambrian	NDS 121
36	Tregór, Massif Armoricain	Rb–Sr, WR, granites Rb–Sr, WR, ignimbrites	554 ± 19 547 ± 12	Precambrian–Cambrian	NDS 249
37	Syenite, Morocco	U–Pb, zircon	534 ± 10	Pre Vendian	M
38	Meltsen Granite, Morocco	U–Pb, zircon	563 ± 20	Precambrian III	N
39	Tiyourhzz Granite, Morocco	U–Pb, zircon	560 ± 8	Precambrian III	0
40	Tiouine Ignimbrite, Morocco	U–Pb, zircon	563 ± 5	Precambrian III	NDS 250
41	Ercall Granophyre, Central England	Rb–Sr, WR	533 ± 12	Pre basal Cambrian	NDS 242
42	Rushton Schist, Central England	Rb–Sr, WR + biotite	536 ± 8	Pre basal Cambrian	NDS 242
43	S. Uplands Basalt, Scotland	Sm–Nd	490 ± 14	Approximatus zone	G

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[*] NDS, *Abstracts in Numerical Dating in Stratigraphy* (1982). A, Brown & Pankhurst (1982), B, Wyborn *et al.* (1982). C, Ross *et al.* (1982). D, Foland & Loiselle (1981). E, Quoted in Gale *et al.* (1979). F, Williams *et al.* (1982). G, Thirlwell & Fitton (1982). H, Harris *et al.* (1965). I, Dallmeyer (1977). J, Dallmeyer & Williams (1975). K, Beckinsale (1982). L, Kokelaar, Fitch & Hooker (1982). M, Ducrot & Lancelot (1977). N, Juery (1976). O, Charlot (1978).

[†] Errors include an estimate of systematic errors due to spike calibrations, etc.

[‡] Age and error from my own least squares regression of the data given in NDS 223.

[§] Errors recalculated from authors' original data.

[‖] Stratigraphy from W. S. McKerrow.

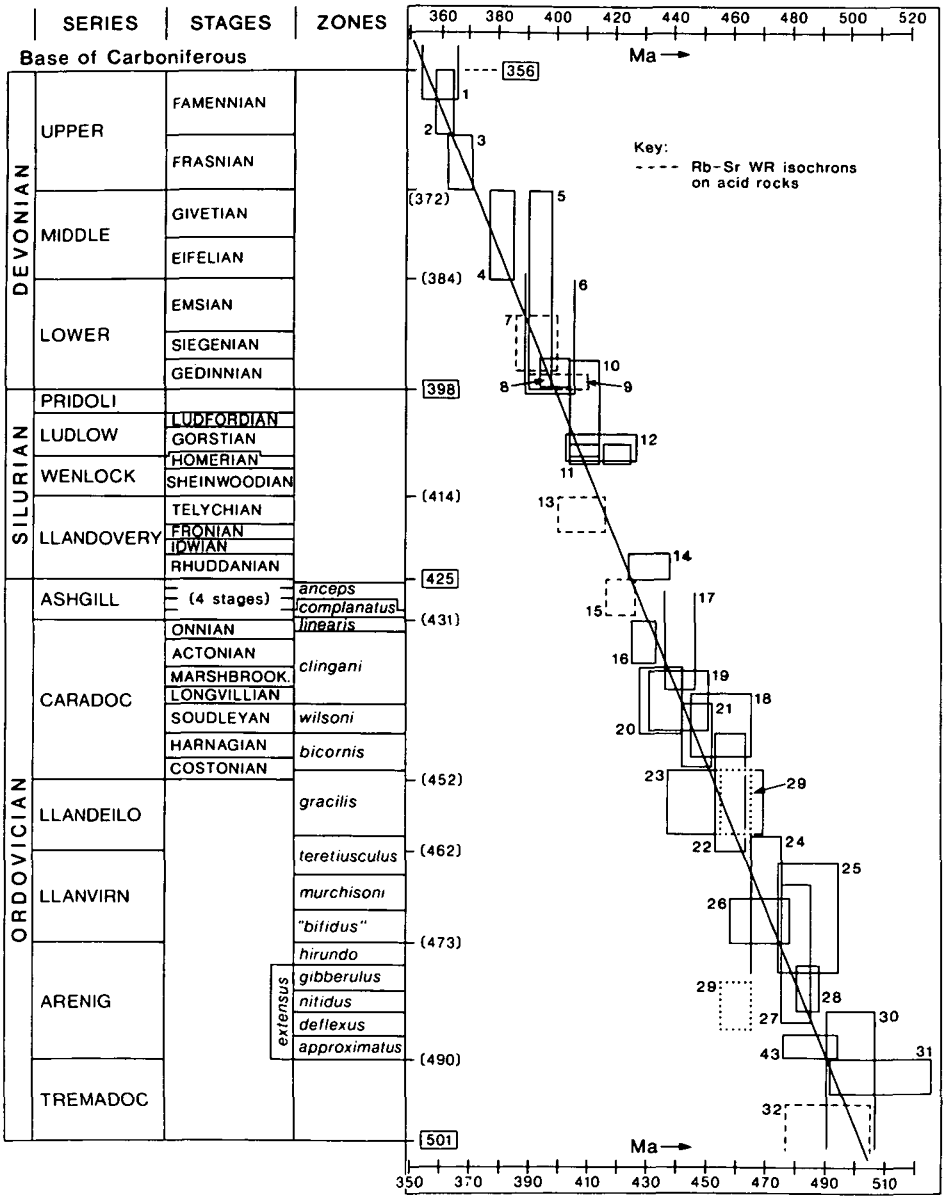

Figure 1. Plot of critical radiometric ages against a stratigraphic axis where the relative lengths of the stages and zones have been chosen to be consistent with the rather subjective estimates made by palaeontologists and stratigraphers. The numbers of the items correspond with the list given in Table 1. Two sigma errors for the ages are used throughout. Rb–Sr isochron ages on acid volcanics are distinguished by a broken line. The stratigraphic evidence for the Bay of Islands gabbro, item 29, places it *either* in the mid Arenig *or* in the gracilis zone; the correlation with other data shows that it must be placed unequivocally in the gracilis zone.

those few other ages near the Silurian/Ordovician boundary. The estimates for the bases of the Carboniferous, Devonian and Silurian periods given in Figure 1 are uncertain within an error of about ±5 Ma. The Ordovician base, given in Figure 1 as 501 Ma, is less well established; the base of the Tremadoc in Figure 1 could be moved down (without destroying the fit to the line of Items 31 and 32) as far as about 509 Ma. No great significance should be attached to the estimates placed in brackets in Figure 1 for the bases of the series, but the estimates for the beginnings of the periods are rather more soundly based than those advanced by Ross *et al.* (1982).

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Department of Geology and Mineralogy N. H. GALE
Parks Road.
Oxford, OX1 3PR
Institute of Geological Sciences, (NERC) R. D. BECKINSALE
Exhibition Road
London, SW7.
(who publishes with the approval of the Director, Institute of Geological Sciences (NERC).)
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