ESSAY REVIEW

More time scales

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ODIN, G. S. (ed.). 1982. *Numerical Dating in Stratigraphy*, Part I (Chapters 1–34), pp. i–xxvii & 1–607; Part II (Chapters 35–37 bibliography and indexes), pp. i–xxvii & 633–1040. Wiley-Interscience: Chichester, New York, Brisbane, Toronto, Singapore.

This work is a major contribution to geochronology, it deserves not only very serious consideration for the conclusions on methodology and results but provides a new set of definitive papers and a data bank that should be available to every geochronologist. It starts from the premise that the Geological Society of London 1964 time scale and its 1971 sequel (Harland *et al.*) are by now thoroughly out of date and need replacing. The two volumes provide what is clearly a planned successor. It follows a somewhat similar design: there are a series of papers on methodology; there are 251 items or abstracts (new determinations, first published or abstracted) with full documentation; and there are important and systematic conclusions on the Phanerozoic time scale.

The work is in two parts bound separately. Part I contains 34 chapters each with distinct authorship under two main headings. The first is 'Methodology' in four sections and the second is 'Calibrating the time scale' in two sections. Part II contains chapters 35–37 and is entitled 'Abstracts for a revision of the Phanerozoic time scale'. There is also a bibliography and index. The physical separation is designed to make the 251 abstracts and other data easily accessible to the reader while engaged in any part of Volume I.

The work is truly international. Altogether 137 authors of the 37 chapters are listed, some needless to say, like Odin himself, being responsible for many chapters. Twenty laboratories participated and much of the work was part of I.G.C.P. Project No. 133 with the result that a major and comprehensive investigation is reported here.

1. Methodology

The 23 chapters on methodology comprise nearly half the work – 450 out of 960 pages of text – and each is an independent scientific paper except that the references are all in the second volume. Chapter 1 is an introduction on uncertainties in evaluating the numerical time scale which is perhaps the crux of the whole matter. Four sources of uncertainty are well known but their labels in this chapter will not avoid some ambiguity.

(1) *Stratigraphical* uncertainty relates the sample determined to the rock whose age may be interpreted via structural relations and correlation.

(2) *Genetic* uncertainty depends on the nature and origin of the chronometer used and in particular the time of closure of the system in relation to the time of formation of the rocks to be dated. It is thus petrogenesis in relation to primary formation and excludes secondary changes.

(3) *Historical* uncertainty (which might be thought to cover also 1 and 2) is taken to refer to secondary changes after initial formation and closure of the system. To combine uncertainties 2 and 3 (both of which are petrogenetic and commonly inseparable in their consideration) Odin oddly uses *geochemical* – a term which might be thought to include 4 as well as 2 and 3.

(4) *Analytical* uncertainty includes not only treatment of material, precision of measurement, systematic errors and repeatability, but differences if different constants are used. Generally a standard deviation is given as a $\pm$ which is the only value in this fourth class of uncertainties (commonly with 95% confidence level signified by 2σ).

In the following review little or no attention is paid to the errors or uncertainty of the values mentioned. This would be a serious defect in a definitive paper, but the object here is to draw attention briefly to a number of points and so encourage readers to go to the original publication where the fuller information is available.

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Although the first chapter of the book was written after the contributions had been seen by the Editor (Odin) and so serves to relate to a number of specialist papers, the matter of uncertainty is fundamental and a still more rigorous classification of components of uncertainty would have been useful because until all the main elements are identified, possibly with an agreed notation, the wide divergencies in the interpretation of apparent ages will continue to be the rather subjective affair that it has become.

Section 1 under methodology concerns correlation: after Chapter 1, discussed above, Chapter 2, biochronology; 3, geochemical events; 4, marine strontium geochronometry; 5, palaeomagnetic stratigraphy. The scheme is not exhaustive and presumably reflects the number of those willing to be authors. Of course correlation is vital. B. U. Haq and J. R. Worsley (Ch. 2) describe some of the limitations in the use of planktonic index fossils (first and last appearance datum – FAD, LAD etc.) especially sharpened from DSDP work. But as in other methodological studies in this type of symposium no new method is given, simply warnings against too naive an acceptance or application of correlation data. Indeed, as this is not a text book, readers are likely to be those who will not need the explanations. Those who do the naughty things that this chapter is set to avoid are probably those who will not bother with it.

Table 1. Some decay constants and corresponding half-lives

$$\lambda(^{238}\mathrm{U}) = 1.55125 \times 10^{-10}\ \mathrm{a}^{-1};\ T \sim 4.47\ \mathrm{Ga}$$
$$\lambda(^{235}\mathrm{U}) = 9.8485 \times 10^{-10}\ \mathrm{a}^{-1};\ T \sim 0.704\ \mathrm{Ga}$$
$$\lambda(^{232}\mathrm{Th}) = 4.9475 \times 10^{-11}\ \mathrm{a}^{-1};\ T \sim 14.0\ \mathrm{Ga}$$
$$\lambda(^{87}\mathrm{Rb}) = 1.42 \times 10^{-11}\ \mathrm{a}^{-1};\ T \sim 48.8\ \mathrm{Ga}$$
$$\left.\begin{aligned}\lambda_{\beta-}(^{40}\mathrm{K}) &= 4.962 \times 10^{-10}\ \mathrm{a}^{-1}\\ \lambda_e+\lambda'_e(^{40}\mathrm{K}) &= 0.581 \times 10^{-10}\ \mathrm{a}^{-1}\end{aligned}\right\}\ T \sim 1.25\ \mathrm{Ga}$$
$$\lambda(^{147}\mathrm{Sm}) = 6.539 \times 10^{-12}\ \mathrm{a}^{-1};\ T \sim 106.0\ \mathrm{Ga}$$
$$\lambda(^{14}\mathrm{C}) = 1.21 \times 10^{-4}\ \mathrm{a}^{-1};\ T \sim 5.730\ \mathrm{Ka}$$

Odin, Reynard and Grazzini review some geochemical events as a promising means of 'litho-stratigraphic' correlation. Sedimentological events (volcanic, erosional climatic, etc.) will generally only be effective for correlation within a basin or region. Trace element events, especially in sea water, are potentially powerful, but so far no general methods have been established. Promising cases of systematic fluctuations in manganese and strontium concentrations are known but relate to other aspects of the chemical environment. Stable isotope events are more promising especially ^{13}C; ^{18}O and ^{34}S because isotopes of the same element behave similarly in various chemical environments but may allow of some fractionation which if systematic is likely to be oceanwide. The pattern of ^{13}C and especially ^{18}O concentration is well established and relates *i.a.* to climatic cycles (e.g. relating the abstraction of the lighter ^{16}O into ice sheets). G. Faure describes the fluctuation of ^{87}Sr/^{86}Sr in sea water as determined from carbonates through Phanerozoic time. It is an empirical curve without unique explanation, but with some application.

Finally the chapter on paleomagnetic correlation methods is by J. E. T. Channel (Ch. 5), who, as is common amongst paleomagnetists, assumes no knowledge at all of the reader and by introducing elementary paleomagnetism leaves little space to discuss its correlation potential critically. This and so many other principles explained *ab initio* may give a sense of completeness to the work but they dilute the significant points and add to its cost. The work is not comprehensive and was probably not so planned.

Section 2 under methodology treats isotopic dating. Its first chapter (6), by N. H. Gale, reviews the reasoning that led to international agreement on some constants at Sidney in 1976 (Steiger & Jäger in Cohee *et al.* 1978, and abbreviated in the book to ICC), and these together with the recommended value for ^{147}Sm are usefully tabulated. This is partially abstracted in Table 1 with addition of ^{14}C and half life T to relate it to geologic time. When these are used one widespread source of age differences is eliminated. In Chapter 7, Odin and 35 collaborators examine the state of interlaboratory standards and in particular describe the production of a large supply of 'GL–O' (Glauconite collected by Odin) and various determinations done on it. Chapters 8–10 then treat three methods in use based on K-Ar. These are standard and are discussed fairly thoroughly. Finally in Chapter 11 some needed cautions in fission track dating are given. This section provides a convenient state of the art survey but does not compare or discuss other methods (see also Gale & Beckinsale, 1983, or Ross *et al.* 1982).

Section 3 – the utilization of sediments as chronometers is the heart of the matter for Odin as it refers to *glaucony* (pl. *glauconies*). These terms are used throughout the volumes to refer to glauconitic facies and to avoid the more precise or misleading mineralogical significance attached to 'glauconite'. Glaucony ages have a bad reputation generally, having been commonly thought to be too low from escape of Ar. But it is argued in much detail (through Chapters 12–20) that the whole glaucony system, while exceedingly complex, is capable of being mastered. When suitably interpreted it will yield good ages – moreover if they are good it opens the door to large numbers of direct sedimentary determinations. Often glauconies have been reworked so the ages may indeed be older than the sediment age and some critical contaminants may be got rid of if possible. Glauconies evolve, mature and are subject to many influences so their selection and treatment is critical.

Clay is analogous to glaucony, having a complex range of mineral constituents whose genesis needs to be understood in much the same way as glaucony. Hence problems arise with whole rock determinations of shales. The genesis of both clays and glauconites is complex, chemical changes continue after deposition so long as sea water is avialable so that the interpretation of the time of closure of the system (e.g. a faecal pellet) requires rather a precise knowledge of these changes; moreover the theory of these changes is not yet complete – so it is not surprising if the use of glauconies is fraught with difficulties that can be overcome only in good samples by an expert. It leaves one wondering how useful may be any glaucony data that have not been fully investigated by Odin himself. The test of this will eventually be found in comparisons between a glaucony time scale and others based on different minerals and methods.

Section 4 treats the commonly used high temperature minerals – but here again the emphasis is on the use of bentonites for radiometric age determinations and hence of the stratigraphic record. Only one chapter (by N. H. Gale) concerns the traditional use of plutonic rocks and even that contains lingering references to volcanic rocks. Belonging to the methodological part of the book is a displaced Chapter 36 coming between the abstracts and the final time scale. It is a table for calculating the K-Ar age using, naturally enough, contemporary constants for the ratio of ^{40}Ar and % K. There are also some conversion factors for converting K-Ar ages from old to new constants.

2. Abstracts

In relation to the methodology or state of the art outlined above we may next consider the abstracts. They are the core of the work and will long survive in value the rest of the publication. As indicated, they follow in principle the Geological Society of London's Phanerozoic time scale (1964 and 1971) 404 numbered items (PTS) in which data concerning radiometric determinations were abstracted and discussed in relation to stratigraphic relations, petrogenetic and analytical data. This does the same job on new determinations only much more thoroughly and 251 (NDS) abstracts of new determinations appear. Thus by combining the NDS and PTS data and abandoning the less satisfactory determinations a new data base is available.

A similar updating of PTS with additions was published in tabular form in 1978 by Armstrong. Odin does not state on what principles his abstracts were included, certainly many are said to be of no great value; but it may be surmised that essentially relatively new data have been abstracted in NDS 1–251 without necessarily including some better earlier data listed by Armstrong. No doubt Armstrong will already have in hand the updating of his own comprehensive computer file. The new abstracts are inevitably of variable quality but many critical determinations or whole groups of determinations have been so fully repeated that there is in many cases no real need to go back to the original publication. This is a valuable service.

But in many abstracts it is not made clear to the uninitiated how much of the abstract is from a previously published paper and if so what it was. First references in the form '(see Odin *et al.* 1978)' are often ambiguous in this respect and it is not made easier by the fact that the one bibliography, pp. 961–1003, to which all citations must be referred, completely lacks titles of papers. In a scholarly reference work of this magnitude that was an appalling economy. One is often left guessing. It would have been better to give the full reference within the abstract at least for the original paper abstracted.

Nevertheless it is clear that the glaucony ages assembled here make a substantial contribution to the later part of the Phanerozoic time scale. Lack of tabulation or other easy access to the abstracts makes the business of searching them quite formidable.

3. Time scale

If we now turn to the third aspect of the work – namely the calibration of stratigraphic divisions by numerical dates – we find the conclusions regarding the time scale distributed in three places.

In Part I calibrating the time scale is attempted in Chapters 24–34 each with different authors treating either a span of time from their own regional viewpoint or with respect to specific boundaries (e.g. Chapter 31 'dating the Albian–Cenomanian boundary').

Then in Part II, inserted without explanation in Chapter 35 between Odin's introduction to the abstracts and the abstracts themselves, is a discussion by different authors on the definition of (most) period boundaries. In each case the current state of international agreement on the boundary is discussed but generally in purely biostratigraphic terms and sometimes mistakenly as though the boundaries are to be defined palaeontologically rather than by reference points in stratotype sections. This is a rather important principle because if radiometric determinations improve in precision, as seems possible, the characterization radiometrically and palaeomagnetically of such a boundary stratotype will be no less critical than biostratigraphically. It is, of course, necessary first to decide the approximate biostratigraphic range in which to select the boundary stratotype. These pages which are potentially so useful are strangely lacking in that particular understanding.

Finally in Part III, Chapter 37, Odin, Curry, Gale and Kennedy give a summary time scale for the volume and the main points from this are abstracted in Table 2 here. Three component parts of this scale had already appeared in separate publications (Odin & Gale, 1982; Odin & Kennedy, 1982; and Odin & Curry, 1982) and the whole scale was again published solo by Odin (1982).

Before reviewing the main results of this study, namely the Odin *et al.* time scale, it will be useful to introduce briefly some other time scales recently available. We follow Odin's scheme by referring to his own 1982 work as NDS (Numerical Dating in Stratigraphy) and in the same way to the Geological Society 1964 and 1971 as PTS (Phanerozoic Time Scale). In addition he referred to that valuable contribution to time scales by R. L. Armstrong in 1978 referred to as RLA. To these we may add the recent Geological Society Symposium, part of whose object was to resurvey the time scale in several papers presented in London in May 1982 (Snelling, 1982) the results of which will be referred to here as GSL. Almost in parallel with NDS, and in ignorance of it, was a project by others of us to produce A Geologic Time Scale (Harland *et al.* 1982) which is referred to here as GTS. That was completed in 1981 but not published until late 1982. Proofs of the book were made available to the Geological Society so that when that symposium is published it will be able to take into account at least all the other work mentioned here. For convenience of comparison some of the figures from these scales are tabulated in Table 2. Namely (1) PTS (altered somewhat from the original values to acknowledge the changes that the 1976 constants – ICC – could make). It is safe to assume that all values now are based on these constants. The others are (2) RLA (3) NDS (4) GTS (5) GSL. It is not the purpose of this review to comment on other scales except by way of noting differences which will inevitably attract attention.

The NDS scale clearly sets out to be the current standard. For example: (p. xxvii) 'Finally, it is hoped that the time scale proposed in this book, being more precise and better founded than the preceding ones, will serve as a good *instrument* to geologists...,' and on page 960: 'We are, however, convinced that previous estimates, when obviously different from the present ones, must be abandoned....' It could be argued that all except the GSL 1982 and 1983 are earlier than NDS 1982 or based on earlier data bases and so are obsolete. But let us review the Phanerozoic scale of NDS from the beginning where undoubtedly the most conspicuous of the previous estimates to be abandoned apply to the initial Cambrian boundary.

The Precambrian–Cambrian boundary is given as 530 ± 10 Ma. This compares with about 579 (PTS), 574 (RLA), 590 (GTS), and with these and others before them 520–610 Ma (GSL). Now the issue here is very considerable because if Gale and those who go with him are correct (Chapter 25) a radical change is called for and it is the most dramatic in the whole volume. Moreover, to emphasize this challenge made in the volume and independently in the earlier paper (a value of 530 Ma for the initial Cambrian boundary) in still another and fuller paper Odin *et al.* (1983) argue strongly for calibration of the initial Cambrian boundary at between 520 and 540 Ma. As a consequence they

Table 2. Some Phanerozoic and latest Proterozoic time scales (see text for abbreviations)

Era	Period	Epoch	initial age only	PTS ICC	RLA 1978	NDS 1982	GTS 1982	GSL 1982	Period	Epoch
Cz	Pleistogene		Ple	1.5–2.0		1.8–2.0	2.0	1.8–2.0	Q	
	Neogene	Pliocene	Zan	7		5.0–5.5	5.1	5.3	Ng	Pli
		Miocene	Aqt	27		23	24.6	23–24		Mio
	Paleogene	Oligocene	Rup			34	38.0	36.5	Pg	Oli
		Eocene	Ypr	54–55		53	54.9	58		Eoc
		Paleocene	Dan	67	65	65	65	66.5		Pal
Mz	Cretaceous	K_2 Senonian	Con						K	K_2
			Cen							
			Brm	90	106	95	97.5	95.5		
		K_1 Neocomian	Ber	139–150	143	130	144	135		K_1
	Jurassic	J_3	Oxf	161	162	150	163	154	J	J_3
		J_2	Baj	176		178	188	175		J_2
		J_1	Her	196	211	204	213	205		J_1
	Triassic	Tr_3	Crn	210	234	229	231	230	Tr	Tr_3
		Tr_2	Ans	220	242	239	243	245		Tr_2
		Tr_1	Gri	230	247	245	248	250		Tr_1
Pz	Permian	P_2	Ufi				258		P	P_2
		P_1	Ass	286	288	290	286	290		P_1
	Carboniferous: Pennsylvanian	Gzelian	Kra						C	
		Kasimovian	Kre							
		Moscovian	Vrk							Pen
		Bashkirian	Kin							
	Carboniferous: Mississippian	Serpukhovian	Cho	332	341	320	320	325		Ser
		Visean	Chd	344.5	356		352			Vis
		Tournaisian	Has	352	368	360	360	365		Tou
	Devonian	D_3	Frs	366	385	375	374		D	D_3
		D_2	Eif	377	396	385	387			D_2
		D_1	Ged	403	417–425	400	408	409		D_1
	Silurian	Pridoli							S	Pri
		Ludlow	Gor		432					Lud
		Wenlock	She		440					Wen
		Llandovery	Rhu	443	446	418	438	439		Lly
	Ordovician	O_3 Ashgill	Pus		445					Ash
		O_3 Caradoc	Cos	453	465		458	464	O	Car
		O_2 Llandeilo			477		468			Llo
		O_2 Llanvirn			492		478	481		Lln
		O_1 Arenig		509	500			499		Arg
		O_1 Tremadoc			510	495	505	520		Tre
	Cambrian	Merioneth	Mnt	524	524		523		Є	Mer
		St. Davids	Sol	549	545		540			StD
		Caerfai	Tom	579	574	530	590	520–610		Cae
Z Sinian	Vendian	Ediacaran	Won				630		V	Edi
		Varangian	Sma				670			Var
	Sturtian						800		U	

comment that the initial Ordovician boundary taken by some at 519 Ma would need to give place to the NDS age of 495 Ma.

The early part of the NDS Phanerozoic scale has been largely constructed by N. H. Gale in collaboration with Odin and others. At the outset Gale criticized the others, e.g. Cowie in PTS and RLA for depending indiscriminately on bad as well as good determinations. There is clear logic in this and no doubt a consensus will increasingly be possible as to what constitutes determinations good in all respects. Nevertheless there is difficulty in that experimentalists, while confident that they themselves can identify the good ones, are by no means all agreed. The argument of Odin *et al.* is

Table 3. Comparison of recent calibrations of Cambrian–Precambrian boundary

GTS 1982			RLA 1978	NDS 1982	GTS 1982	GSL 1982	CHINA in press	USSR in press	GTS 1982
S									S
			446	418	438	430–39			O_2+O_3
O			492		478				
	Arg		500		488				Arg
	Tre		510	495	505	507–20			Tre
	Mer		524		523				Mer
-C-	StD		545		540				StD
Cre									Cre
		Tom	574	530	590	520–610	610	590	
		Pen							
V	Edi	Won			630			614–20	Edi
	Var	Mor			650				Var
		Sma			670			650–65	
U					800		760	690–700	U

based on five main groups of determinations from Sinai, Normandy, North Brittany, Morocco and England. All are young ages constrained by intrusions supposedly Precambrian. Others will no doubt point out the less-than-perfect evidence in each case from which to force such a radical new value. But then almost no determinations are good in all respects and NDS have already abandoned almost all the others. So we have the remarkable situation in which the Precambrian–Cambrian boundary has been variously and strongly claimed to lie between 520 and 620 Ma, an uncertainty of its boundary larger than most estimates for the duration of the Cambrian Period itself.

Two observations may be made on this dilemma. (1) New data from China (Ma *et al.* 1980; Ma *et al.* 1982; Gao *et al.* 1982) and USSR (Keller & Krasnobaev, in press) give respectively estimates around 610 and 590 Ma but the full details are not yet published and the work is not referred to in NDS. These are indicated here in Table 3. Now some of these are on glauconitic facies, but mostly on clays (illites) by more than one method and are said to be rigorously tested (e.g. the Chinese Yichang Laboratory, e.g. by Ma *et al.* being confirmed by the ANU in Australia, e.g. by Compston). If the younger figure is correct then we may explain the older ages as a result of a previously unsuspected component of older detrital material (memorized in the chronometer). In other words there may be a systematic error throughout the eliminated determinations on sedimentary rocks which Odin and his co-workers alone have identified. Alternatively it can be argued that each of the five groups of younger determinations by which the boundary is constrained lack some rigour in the structural stratigraphical claims made for them. Compston & Zhang (in press) concluded their abstract as follows '602 ± 15 Ma would be regarded as a *minimum* age estimate for the deposition of the Tientzushan Member and, subject to agreement over biostratigraphic definitions, for the Cambrian–Precambrian boundary also. The recent suggestion by Odin & Gale (1982) of 530 Ma as the best estimate for the base of the Cambrian cannot be correct in view of the present results. Close examination of some of the evidence used by Odin and Gale as well as earlier work which they chose to ignore, is also strongly against the 530 Ma figure.' (2) The other and related comment is that Odin *et al.* treated the time scale as though it began with Cambrian time. Others see this as only a notable point in a longer and lengthening scale. If the Cambrian scale is compressed from the longer one commonly accepted earlier the late Precambrian scale (especially Ediacaran and Varangian Epochs) would be correspondingly stretched unless all late Precambrian data have suffered a systematic exaggeration of age through detrital memory. In that case the stretching would need to move back to an age where it would not be noticed. The very large discrepancy between differing calibrations adds both spice for the observer and incentive for the worker.

Little information is available for divisions within Cambrian time so it is still quite uncertain what the proportion of Early Cambrian would Tommotian time be. Table 2 shows that the NDS scale for Early Palaeozoic time is considerably younger than others with a relatively short Silurian Period (18 Ma). On the other hand Devonian and Carboniferous ages are not markedly different between any of the scales. Indeed, as expected, discrepancies between the scales reduce with decreasing age. The Triassic scale has long been one of the weakest parts of the Phanerozoic time scale. Recently however, a number of new determinations has become available in three areas: Indonesia, British Columbia, and eastern Australia. Although the NDS calibration is not revolutionary in its effect it is manifestly better based than was possible without the new data. The same must be true for the remainder of the Phanerozoic scale because of the great effort put into determinations of authigenic sedimentary chronometers from strata well correlated biostratigraphically. The most notable Mesozoic difference appears to be at the Jurassic–Cretaceous boundary, NDS list it with fewer years. The Albian time span has been something of a rogue value ranging widely and has probably been tamed now with a span 107 to 95 Ma. Many new Cenozoic determinations are based on precise sampling of fossiliferous strata in classical European sections by D. Curry and give confidence in a scale still further refined. The emphasis has thus changed from the predominant tie points that in PTS depended largely on volcanic horizons in North America.

The above scant survey does not do justice to the immensely careful work that has gone into improving the Phanerozoic scale and it will need more than a cursory scanning of the work to focus on critical determinations. In conclusion then, whatever the merits of the scale proposed, and it must be presumed to be an improved one, the publication NDS is a major work in this field that cannot be ignored, and specialists and librarians alike should get it. A. G. Smith suggested useful improvements to this review and T. A. Brewer typed both text and tables.

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