1 Introduction

1.1 Objective

A geologic time scale is composed of standard stratigraphic divisions based on rock sequences and calibrated in years. It is thus the joining of two different kinds of scale. A chronometric scale is based on units of duration – the standard second – hence a year. A chronostratic scale is now conceived as a scale of rock sequence with standardised reference points selected in sections, each particularly complete at the boundary and known as a boundary stratotype. The chronostratic scale is a convention to be agreed rather than discovered, while its calibration in years is a matter for discovery rather than agreement. Whereas the chronostratic scale once agreed should generally stand unchanged, its evaluation will be subject to repeated revision. For this reason no geologic time scale can be final and our particular attempt must be qualified by 1982, its year of publication.

1.2 The traditional stratigraphic time scale

The prodigious stratigraphic labours of the nineteenth century resulted in innumerable competing stratigraphic schemes. To impose some order the first International Geological Congress (IGC) in Paris in 1878 set as its objective the production of a standard stratigraphic scale. Suggestions were made for standard colours (Anon. 1880, pp.70–82), uniformity of geologic nomenclature (pp.82–4) and the adoption of uniform subdivisions (pp.85–7). There was also a review of several regional stratigraphic problems. In the succeeding congress at Bologna in 1881 many of the above suggestions were taken substantially further, i.e. international maps were planned with standard colours for stratigraphic periods and rock types (e.g. Anon, 1882, pp.297–411) and annexes contained national contributions towards standardisation of stratigraphic classification etc. (pp.429–658).

In spite of this promising start the IGCs did not have the continuing organisation to carry these proposals through, except for the commissions set up to produce international maps. It was not until the establishment of the International Union of Geological Sciences (IUGS) around 1960 that the promise had a means of fulfilment, through the IUGS's Commission on Stratigraphy and its many subcommissions.

By 1878 the early belief that the stratigraphic systems and other divisions being described in any one place were natural chapters of Earth history was fading and the need to agree some convention was widely recognised. Even so, the practice continued of describing stratal divisions largely as biostratigraphic units, and even today it is an article of faith for many that divisions of the developing international stratigraphic scale are defined by the fossil content of the rocks. To follow this through, however, leads to difficulties: boundaries may change with new fossil discoveries; boundaries defined by particular fossils will tend to be diachronous; there will be disagreement as to which taxa shall be definitive. So the traditional stratigraphic scale is of necessity evolving into a new kind of standard stratigraphic scale.

1.3 Development of the standard stratigraphic scale

At the 1948 IGC one of the first attempts to standardise artificially a stratigraphic boundary (Pliocene–Pleistocene boundary at the Calabrian base in Italy) was made on the basis that such a decision had to be an agreed convention and that it was necessary to standardise divisions at their boundaries only, and in only one locality. The international procedure to standardise such a boundary at a single point in a reference section was worked out by the Silurian–Devonian Boundary Working Group. Their procedure was first to agree the approximate position in the biostratigraphic sequence that would do least violence to existing usage and then to find a succession anywhere in the world where the Silurian–Devonian boundary was represented in fossiliferous rock with the best characters for correlation.

If we take this procedure as a guide, the requirements for the standard global stratigraphic scale may be summarised as follows.

(1) A sequence of agreed reference points in continuous sections of uniform (marine) sedimentary facies selected with suitable characters for international correlation, preservation and access. The point in the boundary stratotype section is then conceived as representing the point in time when that part of the rock was formed. Pairs of such points then define the intervening time span.

(2) The procedure has a significant consequence in the conception of chronostratic divisions. Before the standardisation just described, the intervals were conceived as being the time equivalent of rocks already defined. Thus systems (series, stages or chronozones) were first described and the geologic periods (epochs, ages, chrons) were derived as the corresponding time intervals. The new procedure of defining boundary points effectively reverses the derivation. The time division (period etc.) is defined by its initial and terminal points while the corresponding rock (system etc.) can only be estimated by correlation. This generally yields a well-dated main body of the rock division, but with uncertain and often unidentifiable boundaries. Because of the primacy of time in a time scale we use Early, Middle and Late rather than Lower, Middle and Upper. To avoid usage such as 'early Early' for subdivisions it is well also to seek names for all

epochs (i.e. rank below period and above age).

(3) Various names have been proposed for this newly standardised scale. The Geological Society of London (GSL) used Standard Stratigraphic Scale (SSS) in relation to the traditional stratigraphic scale (TSS) and regional stratigraphic scales (RSS) out of which it was evolving (George *et al.* 1967). The International Subcommission of Stratigraphic Classification (ISSC) referred to it as the Standard Global Chronostratigraphic Scale (SGCS) in the *International stratigraphic guide* (Hedberg 1976). Unfortunately both the American stratigraphic code and the ISSC *Guide* into which it grew confuse the matter somewhat. They divided the standard scale of periods and systems as described here into two parts. *Geochronologic units* refer to periods etc. and *Chronostratigraphic units* to systems etc. It is obvious that time and rock are different (e.g. as indicated by the words period and system), but when defined they both derive from the same standard reference points. It is really one time scale of such points and everything that happened in the time intervals so defined has to be correlated and described as well as may be. The two apparently distinct disciplines (geochronology and chronostratigraphy in Hedberg's terminology), are likewise different aspects of the single discipline of time-correlation.

(4) It is both traditional and convenient to use a hierarchy of names for these intervals (era, period, epoch, age, chron) in such a way that the boundaries of the successively larger divisions are coterminous, i.e. they coincide. There is no difference in procedure for defining boundaries of larger or smaller divisions. Era boundaries are defined the same way as chrons and indeed the same boundary definition may serve several coterminous divisions. The use of the hierarchy is largely a matter of habit but it has its uses in both economy of description and in describing events of different duration or uncertainty of correlation.

(5) The names for the spans are generally those favoured from classic sections. Once selected for the SGCS, however, they cease to have local reference and must be used internationally for the time span defined by the limiting points. It is convenient to retain familiar names but when redefined at some distance from the eponymous locality the local geologists must accept that their name has acquired a new meaning and be careful only to use other lithostratigraphic unit names for the rocks they describe.

(6) The above principles developed for the global scale can be applied to standard regional scales as a step in the process of correlation, but the multiplication of scales is not generally helpful. The work of standardisation is considerable and need not be multiplied. Until such a global time span is standardised all regional scales may be regarded as competing for acceptance as global boundary points.

1.4 The geochronometric scale

The proposal of a chronometric scale is quite different. The scale is periodic and is compounded of units of equal duration. Therefore all that is necessary is to define a standard unit (a second based on cesium, and so derive one year, or on the alternative International Astronomers' year). In the same way that a linear scale is constructed from unit lengths and is so defined, the chronometric scale exists by virtue of the definition of a unit of duration.

There is a further matter of convention, namely, to compound the units into longer named intervals. Such a scheme of millennia (10^6 a), gigennia (10^9 a), etc. is by no means essential but, as with the higher ranks of the chronostratic hierarchy, they may be convenient in general expressions of age. Unlike the chronostratic divisions they will be defined not by reference points in rock but by initial and terminal points, each defined by a finite number of units of duration BP (Before Present – conventionally before 1950). These matters are taken further in Appendix 4.

There are those who think that there is some advantage in treating Precambrian history as sufficiently different from Phanerozoic history as to require the use of named chronometric divisions only for Precambrian time. The Subcommission on Precambrian Stratigraphy of the IUGS agreed in 1976 that the boundary between Archean and Proterozoic should be defined at 2500 Ma (exactly); moreover other subdivisions of Precambrian time are also being proposed along the same lines, as will be seen in the discussion in Chapter 2. An alternative is to extend named chronostratic divisions backwards into Precambrian time. Moreover, a parallel forward development of named chronometric divisions through Phanerozoic time cannot be discounted. The chronostratic scale is extended here (Chapter 2) as seemingly an inevitable development already in progress. Chronometric divisions for all geologic time in 500 Ma intervals have also been proposed (e.g. Harland 1975, 1978) and named from Latin rather than Greek roots thus: Priscotime (to 4000 Ma); Antiquotime (4000 to 2500 Ma); Mediotime (2500 to 1500 Ma); Novotime (1500 Ma onwards). This has not found favour, but, in the absence of other recommendations on the initial Archean (=Antiquo) boundary, Priscoan is applied in Chapter 2 for pre-4000 Ma time, i.e. defined chronometrically.

1.5 Statement of age

The two artificially devised scales outlined above (chronostratic and chronometric) do not in themselves enable us to date or to time-correlate rocks one with another. Their function is to provide common bases for comparison of ages. They reduce the number of ways in which geologic ages are generally stated (i.e. to two conventions; one verbal and one numerical as it happens). The two do not define each other and so they are both needed. According to circumstances some rocks can be dated chronometrically more precisely than chronostratically and for others more precise ages can be given chronostratically. Only if the conversion of one scale to the other were altogether more precise than it now is could all ages be usefully given in years.

So on the one hand it is not sensible to abandon either of the time scales because of the uncertainty and loss of information that would result; on the other hand it is unnecessary to use more than two scales because the ages of rocks can be usefully stated in terms of one or the other.

1.6 Natural chronologies

There are unlimited scales or chronologies that could be, and indeed have been, derived from natural phenomena.

There is the simplest binary scale of magnetic reversals in which only two alternate states are recorded; this is the subject of Chapter 4. There are scales with degrees between two extreme states such as climatic curves – e.g. between glacial and inter-glacial or cold and warm, or between high and low sea level, or between greater and lesser tectonic activity (as outlined in Chapter 5). Then there are decay scales such as in radioactive series, or cooling curves, and finally because of the multiplicity of biological evolutions there are as many biostratigraphic scales as there are useful groups of taxa within any time span; some are listed in Chapter 2. Each of these kinds of natural sequence has its own distinctive properties and value for correlation. All depend on interpretation of rock whose age is best expressed in one or other of the two time scales. While it is necessary to define the SGCS it is impossible so to agree any natural chronology except its terminology.

It is, however, the interest in natural phenomena that motivates science. The geologic time scale is only a tool or language in the interpretation of Earth history; moreover the time scale has no application without time-correlation which is entirely dependent on the interpretation of natural phenomena.

1.7 Local rock units

Rock is the ultimate objective reference for both the study of the natural phenomena of geologic history and for the evidence of age. There is a well-established geologic convention for describing and classifying rock in named units, i.e. formations combined into groups, supergroups and complexes or divided into members and beds (e.g. Hedberg 1976).

All stratigraphic units as originally described were in effect local rock units even if they were intended to have regional or global significance. There is therefore most confusion in the eponymous areas of the SGCS. The original systems, series and stages were initially described as bodies of rock and in many cases this usage persists explicitly, as for example in the hierarchy of South African stratigraphy (e.g. Kent & Hugo 1978).

1.8 Geologic time scales

To return to the point at which we began. A geologic time scale is really a dual scale: two scales – chronostratic and chronometric – side by side, fitted to each other more or less successfully. Table 1.1 shows one of the earliest attempts at a geologic time scale constructed in 1893 before radiometric methods were conceived. H. S. Williams was one of many who attempted this. He used geochrones as his unit; his geochrone being the duration of a well-known period: the Eocene geochrone. Charts 1.1 and 1.2 show the chronostratic divisions and classification adopted here with a sequence of ages (in Ma BP) from a number of earlier scales for comparison with our own. These are from Holmes 1937; Holmes (B scale) 1947; Holmes 1959; Kulp 1961; the GSL *Phanerozoic time-scale* (Harland, Smith & Wilcock 1964); Lambert in *The Phanerozoic time-scale – a supplement* (Harland *et al.* 1971); Van Eysinga 1975; Armstrong in *The geologic time-scale* 1978 from the IGC Sydney Symposium; the BP internal report by R. Walters 1980 (after a BP Alaska internal report by P. G. Llewellyn 1975); the CASP internal report by C. A. G. Pickton 1980, the table from which was published in Hambrey & Harland (1981, pp.12 and 13); and this work.

These time scales are made by interpolation between, and extrapolation from, tie-points that relate to particular rock samples in which a fortunate combination of characters allows, for example, radiometric determinations on rocks closely related to those with fossils that can be used to correlate with the stratotype. Methods other than radiometric of obtaining comparative durations are relative thicknesses, rhythmites, numbers of similar biozones and rates of ocean spreading. Other methods of making correlation feasible (besides biostratigraphic) are lithostratigraphic, paleomagnetic and paleoclimatic. Indeed the best points are those in rocks with the most characters and determinations. But it is a matter of chance where in the geologic column such useful rocks are found, and this leads to some parts of the combined scale being far more effective than others.

Some statement of qualification of uncertainty of each calibration is useful. There are several elements to be considered. Experimental error, usually expressed as standard error, informs only that the same rock unit gave such a scatter of determinations. The environmental history of the mineral in the rock and of the rock itself modify the closed system on which the determinations are based. Therefore it is well not to refer to radiometric ages as absolute ages but rather as *apparent*, i.e. distinct from *true* age. There are uncertainties introduced by interpolation between determined points. There are uncertainties due to correlation precision by paleontological methods, or whatever other methods are used; one

Table 1.1 *Standard time scale of geochronology, on the basis of the Eocene Period for a time unit or geochrone (H. S. Williams 1893, p.295)*

Recent Quaternary	1	
Pliocene Miocene	1	3
Eocene	1	
Cretaceous	4	
Jurassic	3	9
Triassic	2	
Carboniferous	6	
Devonian	5	
Upper Silurian	4	45
Lower Silurian or Ordovician	15	
Cambrian	15	

Charts 1.1 and 1.2. Chronostratic scale with successive chronometric calibrations including our own summarised from Chapters 2 and 3. Values based on old constants are printed in italics.

Chart 1.1. Holocene to Permian.

Eon	Era	Sub-era Period		Epoch		Age	Abbrev.	*Holmes1937*	*Holmes1947B*	*Holmes1959*	*Kulp 1961*	Geol. Soc. London 1964 constants *old*	Geol. Soc. London 1964 constants new	GSL 1971	Van Eysinga 1975	Armstrong 1978	BP1980 (internal)	Pickton in Hambrey & Harland 1981		This work 1982 Ma	Age	Duration	
Phanerozoic (Ph)	Cenozoic (Cz)	Quaternary (Q) or Pleistogene		Holocene			Hol								*0·01*			0·01		**0·01**	Hol	·01	2·0
				Pleistocene			Ple		*1*	*1*	*1*	*1·5/2*	1·5/2		*1·8*			2·0		**2·0**	Ple	1·99	
		Tertiary (TT)	Neogene (Ng)	Pliocene (Pli)		2 Piacenzian	Pia														Pia	3·1	22·6
						1 Zanclian	Zan	*16*	*12*	*11*	*13*	*7*	7		*5*		5	5	Labrecque et al 1978	**5·1**	Zan		
				Miocene	3	Messinian	Mes														Mes	6·2	
						Tortonian	Tor													**11·3**	Tor		
					2	Serravallian	Srv														Srv	3·1	
						Langhian - Late	Lan_2													**14·4**	Lan_2		
					1	Langhian - Early	Lan_1														Lan_1	10·2	
						Burdigalian	Bur														Bur		
						Aquitanian	Aqt	*32*	*26*	*25*	*25*	*26*	27		*22·5*		22·5	22·5		**24·6**	Aqt		
			Paleogene (Pg)	Oligocene	2	Chattian	Cht										32		Hardenbol + Berggren 1978	**32·8**	Cht	8·2	40·4
					1	Rupelian	Rup	*48*	*38*	*40*	*36*	*37/38*	38/39		*38*			37		**38·0**	Rup	5·2	
				Eocene	3	Priabonian	Prb				*45*						40			**42·0**	Prb	4	
					2	Bartonian	Brt										44				Brt	8·5	
						Lutetian	Lut				*52*						49			**50·5**	Lut		
					1	Ypresian	Ypr	*68*	*58*	*60*	*58*	*53/4*	54/5		*55*		53·5	53·5		**54·9**	Ypr	4·4	
				Paleocene (Pal)	2	Thanetian	Tha										60			**60·2**	Tha	5·3	
					1	Danian	Dan			*70*	*63*	*65*	67		*65*	65	65	65		**65**	Dan	4·8	
	Mesozoic (Mz)	Cretaceous (K)		K_2	Senonian	Maastrichtian	Maa				*72*	*70*	72			72	70	73	Odin 1978	**73**	Maa	8	79
						Campanian	Cmp					*76*	78			84	78	84		**83**	Cmp	10	
						Santonian	San				*84*	*82*	84			88	82	86		**87·5**	San	4·5	
						Coniacian	Con					*88*	90		*80*	90	86	88		**88·5**	Con	1	
						Turonian	Tur				*90*	*94*	96			92	92	90		**91**	Tur	2·5	
						Cenomanian	Cen				*110*	*100*	102	*95*	*100*	106	100	95		**97·5**	Cen	6·5	
				K_1		Albian	Alb				*120*	*106*	109			116	108	107	Van Hinte 1978 a	**113**	Alb	15·5	
						Aptian	Apt					*112*	115			123	115	115		**119**	Apt	6	
						Barremian	Brm					*118*	121		*118*	127	121	121		**125**	Brm	6	
					Neocomian	Hauterivian	Hau					*124*	127			130	126	126		**131**	Hau	6	
						Valanginian	Vlg					*130*	133			136	131	131		**138**	Vlg	7	
						Berriasian	Ber	*108*	*127*	*135*	*135*	*(136)*	(139)	*(125)*	*141*	143	135	135		**144**	Ber	6	
		Jurassic (J)		J_3	Malm	Tithonian	Tth					*(146)*	(150)	*(145)*		149	138	141	Van Hinte 1978 b	**150**	Tth	6	69
						Kimmeridgian	Kim					*151*	155			157	143	143		**156**	Kim	6	
						Oxfordian	Oxf					*157*	161		*160*	162	149	149		**163**	Oxf	7	
				J_2	Dogger	Callovian	Clv					*162*	166			166	156	156		**169**	Clv	6	
						Bathonian	Bth				*166*	*167*	171				165	165		**175**	Bth	6	
						Bajocian	Baj								*176*	177	171	171		**181**	Baj	6	
						Aalenian	Aal					*172*	176				174	174		**188**	Aal	7	
				J_1	Lias	Toarcian	Toa					*178*	182			188	178	178		**194**	Toa	6	
						Pliensbachian	Plb					*183*	187			198	183	183		**200**	Plb	6	
						Sinemurian	Sin					*188*	192				189	189		**206**	Sin	6	
						Hettangian	Het	*145*	*152*	*180*	*181*	*192*	196		*195*	211	192	192		**213**	Het	7	
		Triassic (Tr)		Tr_3		Rhaetian	Rht									220		(197)	Banks 1973	**219**	Rht	6	35
						Norian	Nor									228		(202)		**225**	Nor	6	
						Carnian	Crn				*200*	*205*	210			234		(207)		**231**	Crn	6	
				Tr_2		Ladinian	Lad									238		(214)		**238**	Lad	7	
						Anisian	Ans					*215*	220			242		(221)		**243**	Ans	5	
				Scythian Tr_1 (Scy)	Olenekian	Spathian	Spa											(224)			Spa	1¼	
						Smithian	Smi											(228)			Smi	1¼	
					Induan	Dienerian	Die											(231)			Die	1¼	
						Griesbachian	Gri	*193*	*182*	*225*	*230*	*225*	230	*235*	*230*	247	225	235		**248**	Gri	1¼	
	Paleozoic	Permian (P)		P_2		Tatarian	Tat					*230*	235			252		(239)		**253**	Tat	5	38
						Kazanian	Kaz					*240*	245			259		(242)			Kaz	2½	
						Ufimian	Ufi								*251*		240	(255)		**258**	Ufi	2½	
				P_1		Kungurian	Kun					*256½*	262½			269		(266)		**263**	Kun	5	
						Artinskian	Art					*266½*	272½			278		277		**268**	Art	5	
						Sakmarian	Sak											(248)			Sak	9	
						Asselian	Ass	*227*	*203*	*270*	*280*	*280*	286	*>276*	*280*	288	290	290		**286**	Ass	9	

Chart 1.2. Pre-Permian.

Eon	Era	Period	Sub-period	Epoch	Age		Abbrev.	Holmes 1937	Holmes 1947B	Holmes 1959	Kulp 1961	Geol. Soc. London 1964 constants old	new	G.S.L. 1971	Van Eysinga 1975	Armstrong 1978	BP 1980 (internal)		Pickton in Hambrey & Harland 1981	This work 1982 Ma	Age	Duration	
Phanerozoic	Palaeozoic	Permian P_1			Asselian C	Stephanian	Ass	227	203	270	280	280-	286	>276	280	288	290		290	286	Ass	9	
		Carboniferous	Pennsylvanian	Gzelian	Noginskian		Gze														Gze	?	
				Kasimovian	B; Krevyakinsk. A		Kas														Kas	?	
				Moscovian	Myachkov. Ctb; D; C; B	Westphal.	Mos					292½	296·5			307	300	Gordon+Manet 1978	300 308	296	Mos	?	34
			(Pen)	Bashkirian	A; Yeadonian C; B		Bsh					312½	319·5			330	315		(320) (328)	315 320?	Bsh	?	
			Mississippian	Serpukhovian	A	Namurian	Spk					325	332		325	341	325	Bouroz 1978,	(335)	333	Spk	13	?
				Visean	Holkerian		Vis				320	337½	344·5			356	335		(350)	352	Vis	19	40
		(C)	(Mis)	Tournaisian	Ivorian; Hastarian		Tou	275	255	350	345	345	352	360	345	368	345		365	360	Tou	8	
		Devonian		D_3	Famennian		Fam					353	360			379			373	367	Fam	7	
					Frasnian		Frs				365	359	366			385	358		381	374	Frs	7	
				D_2	Givetian		Giv									391			388	380	Giv	6	
					Eifelian		Eif				390	370	377		370	396	370		395	387	Eif	7	48
				D_1	Emsian		Ems					374	381			401			401	394	Ems	7	
					Siegenian		Sig					390	398			406			406	401	Sig	7	
		(D)			Gedinnian		Ged	313	313	400	405	395	403	405	395	417 425	405		411	408	Ged	7	
		Silurian		Pridoli			Prd												415	414	Prd	6	
				Ludlow			Lud									432			422	421	Lud	7	
				Wenlock	Sheinwoodian		Wen								423	440		McKerrow 1978	428	428	Wen	7	30
		(S)		Llandovery			Lly	341	350	440	425	435	443		435	446	435		440	438	Lly	10	
		Ordovician		Ashgill			Ash									445			447	448	Ash	10	
				Caradoc	Costonian		Crd				445	445	453		450	465			469	458	Crd	10	67
				Llandeilo			Llo									477			477	468	Llo	10	
				Llanvirn			Lln									492		Ross *et al* 1978	485	478	Lln	10	
				Arenig			Arg	392	430	500	500	500	509		500	500	500		495	488	Arg	10	
		(O)		Tremadoc			Tre									510			505	505	Tre	17	
		Cambrian		Merioneth	Dolgellian		Dol														Dol	9	
				(Mer)	Maentwrogian		Mnt				530	515	524		515	524	515		520	523	Mnt	9	
				St. David's	Menevian		Men														Men	9	
				(St D)	Solvan		Sol					540	549		540	545	540		540	540	Sol	8	85
				Caerfai	Lenian		Len											Cowie+Cribb 1978			Len	15	
					Atdabanian		Atb												570	570	Atb	15	
(Ph)	(Pz)	(Є)		(Crf)	Tommotian		Tom	470	510	600		570	579	574	570	574	570		590	590	Tom	20	
Proterozoic	Sinian	Vendian		Ediacaran			Edi												640		Edi	40	
				Varangian			Mortensnes												700	650	Mor	20	80
		(V)		(Var)			Smalfjord													670	Sma	20	
	(Z)	Sturtian (U)					U													800	U	130	
	Riphean (Rip)	?																		~1050			
		Yurmatin (Y)					Y													~1350	Y	~300	
		Burzyan (B)					B													~1650	B	~300	
																				~2100			
(Pt)		Huronian (H)					H													~2400	H	~300	
2500																				~2630			
		Randian (Ran)					Ran													~2800	Ran	170	
Swazian																				~3750	Sw	950	
		Isuan (I)					I														I	~150	
Hadean		lunar sequence (Hde)					Hde														Hde		

N.B. These divisions are not established internationally. They are selected from works as discussed in chapter 2 so as to illustrate how the Precambrian chronostratic scale may develop around good successions anywhere.

Chronometric definitions (Ga)

Proterozoic (Pt): Pt_3 — Hadrynian — Z; 0·8; 1·0; Pt_2 — Helikian — Y; 1·8; Pt_1 — Aphebian — X

— 2·5 —

Archean (Ar): Ar_3; 2·9?; Ar_2; 3·5?; Ar_1 — W

— 4·0 —

Priscoan (Pr)

might by analogy refer here also to apparent rather than (indeterminable) true age by time-correlation. There are structural uncertainties as to whether the relationships between rocks determined are assumed. No way has yet been devised of expressing these uncertainties concisely. The expression $\pm x$ is misleading if given without qualification. One major cause of discrepancy between numerical values for the same rock has been resolved by international co-operation, namely, the agreement to use the same decay constants. Appendix 1 provides the means to convert older values to those based on constants agreed in 1976.

It is the main purpose of this work to show not so much our conclusions for a preferred time scale for 1982 – which it will be seen does not differ greatly from previous efforts – but rather to show as clearly as we can how such a scale has been constructed. Believing, as we do, that a scale is in need of frequent revision to take account of new results from many disciplines, we hope this work will encourage improvement of it by displaying its limitations. One unintended example of this is worth noting. Ideally the chapters would have been written in the order in which they appear, so that after defining the chronostratic scheme our best efforts at calibrating it in years would be made and this calibration would then be applied to the magnetostratigraphic scale. As it happened the authors were unable to work in that sequence and the values used in Chapter 3 were arrived at and the drawings were completed before a final draft of Chapter 2 was available.

The final draft of Chapter 2 differed from the earlier one in many minor but in some major respects. Significant changes in Carboniferous classification had been made. It will be seen from Chart 1.2 that radiometric ages had been related to European divisions of largely continental facies but it is a simple matter to convert to an alternative scale. A different problem emerged for the Triassic Period. The Scythian Epoch had been treated as a single age unit but was then divided into four ages. On this basis its duration has therefore probably been underestimated. Conversely the Rhaetian Age appears to be characterised by only one biozone of the kind of which six are listed for the Norian Age. So the duration of Rhaetian has probably been overestimated. But, because a tie-point occurs between Scythian and Rhaetian ages we cannot simply increase one at the expense of the other.

The number of subdivisions or their duration is unimportant when all their boundaries are well defined if they can be correlated or calibrated in time. Even if Rhaetian spanned only one-sixth of Norian time we see no reason, as some do, to suppress it or reduce its rank on these grounds provided it fulfils a distinctive correlation function. Moreover, there is no principle that can be adduced to argue that effective biozones have or should have equal duration. Nevertheless, in constructing a geologic time scale the fact is that very few boundaries are well calibrated at tie-points. Such tie-points are discussed in detail in Chapter 3 and are indicated by thicker lines in the right-hand column of Charts 1.1 and 1.2. For longer intervals between tie-points we have used a rough and ready method treating ages as being of approximately equal duration and so interpolating them between tie-points. An obvious next refinement is to consider a number of different aspects of the history encompassed by each age to assess more likely comparative durations. This we had no time to do.

So already before publication it is clear that the dual scale offered here is in need of revision. Indeed this underlines our initial statement that this kind of dual time scale is expected to improve but can never be final.

2

The chronostratigraphic scale

2.1 Introduction

In this chapter we attempt to set out a chronostratigraphic (chronostratic) scale. Some parts of it are already well established by international decision and/or conventional usage; other parts are not. Where no standard has been agreed we have taken the liberty to suggest one. This will irritate some readers; but it may be useful to have an interim scheme for the whole scale and it may hasten the day when such a scale is established. Although the first steps towards such an international convention were taken at the International Geological Congress (IGC) in Bologna in 1881 (Anon. 1882) it was only by slow degrees that the nature of the task was understood to require the precise definition of boundaries. An attempt to agree a Pliocene–Pleistocene boundary in 1948 at the IGC in London was an important first step. A thorough application of the principle awaited the decision of the International Union of Geological Sciences (IUGS) to establish the Silurian–Devonian boundary at Klonk in Bohemia – finally decided in 1972 at the IGC in Montreal (McLaren 1977). Under the same authority there are now active groups working on nearly every remaining boundary, so that within five or ten years we may expect the main points of the scale to be established.

The essential requirement of such a scale is a sequence of reference points defined in (boundary) stratotype sections which have a good correlation potential. A sufficient spread of these, named (e.g. Klonk for Silurian–Devonian boundary) or otherwise labelled, would alone define a chronostratic scale (Hughes *et al.* 1967). Of course, when such a scale is established it does no more than provide a single agreed standard for calibration or against which to correlate.

In order to convert the traditional stratigraphic names and classifications to a single standard stratigraphic scale for general use, three kinds of decision or agreement need to be made, and made by a single authority (i.e. IUGS): (1) a scheme of divisions with appropriate classification together with (2) agreed names for each division that shall correspond to the time spans between the boundaries and (3) agreed standardisation of the boundaries. We consider these three elements of a chronostratic scale.

(1) The classification has developed traditionally on a hierarchical basis with eons (e.g. Phanerozoic), eras (e.g. Mesozoic), periods (e.g. Jurassic), epochs (e.g. Late Jurassic), ages (e.g. Oxfordian) and chrons (e.g. Mariae). The number of ranks is not a matter of principle but an accident of history. There have been attempts to standardise, but sub-eras, sub-periods or sub-epochs have intervened. The rock formed anywhere in such intervals constitutes respectively the eonothem, erathem, system, series, stage and chronozone. A convenient feature of the hierarchical classification is that boundaries of divisions of higher rank shall coincide with those of lower rank; this is the convention of coterminosity. A hierarchy is not essential, and if one is used it matters little whether the distinct ranks in the hierarchy are strictly maintained. Provided each span is properly defined, then usage will consolidate a suitable number of names. Higher ranks have descriptive advantages for slower or uncertain timing and they avoid the need to remember names of lower ranks.

(2) The names for the ages mostly began as formational names of which some were used more widely as regional stages. They mostly have original body-stratotype localities and sections. In constructing the standard scale for a particular span of time of a given rank one name (and no more) is needed. This may be one most familiar for that interval or it may be newly coined. If it be a familiar name – as most are – then boundaries will be defined, possibly elsewhere, and then it may cease to name exactly the original interval. So in pressing the claims of a favourite name for international use, its supporters must accept that its boundaries, which really define the named time span, could well be fixed in better localities elsewhere.

(3) Definition and standardisation is a two-fold process. Agreement is first necessary as to the approximate time in Earth history that would make a boundary convenient and acceptable. This may well be decided on a biostratigraphic basis before the locality for the reference point in the boundary stratotype is decided.

In this chapter we divide geologic time, as is traditional, into periods (after Precambrian time); each is introduced historically and there is a commentary on a corresponding chart. In each case the charts distinguish the chronostratic time scale on the left by lower-case lettering, while the rock units or regional stages are printed to the right in capital letters.

An attempt is made to present a single standard scale with its hierarchy of time divisions and, if one is not yet agreed, a tentative scheme is suggested. On the right-hand side of the chart a selection of local successions or regional stages is selected from amongst the multitude available. These are included to give an indication of distant equivalents and exact correlation is not intended.

For epochs we prefer stratigraphic names to the formal qualifications Early, Middle and Late but generally these are not available. The advantage of such a name is that it can be defined unambiguously, whereas the terms Early, Middle and Late have often been used in different senses and are also liable to confusion with the informal usage (early, middle and late), which is perhaps more generally useful. We have not attempted to standardise the ending of epoch names. For ages on the other hand the suffix '-ian' is generally applied.

For time scale divisions we have used a system of abbreviations which has been tested for uniqueness and may have wider use (see Appendix 3). Abbreviations for eon, era and period names have largely been determined internationally and we have taken into ac-

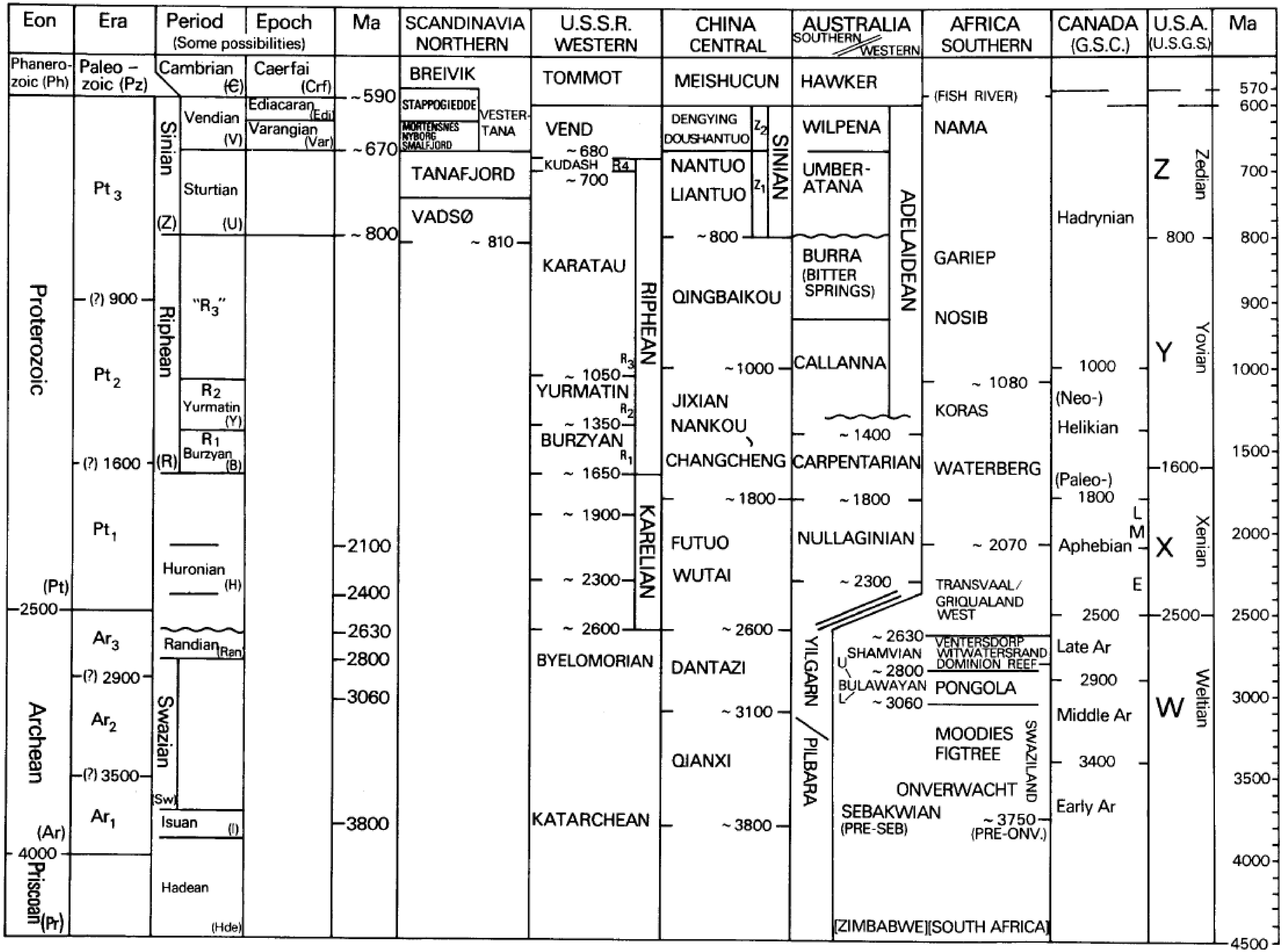

Chart 2.1. Precambrian time scales.

count the symbols used on the Unesco *Geological world atlas* (Choubert & Faure-Muret 1976). For the rest we have introduced a three-letter system after finding that two letters gave insufficient scope for recognition and uniqueness. We prefer the numerical subscript to indicate early, middle and late. Two, three or more divisions can so be noted, and it avoids the unfortunate ambiguity of the abbreviation 'L' for Late or Lower. We recommend generally to write such words in full, also to show by the initial if it is formal (with capital) or informal (with lower-case initial).

The chronometric column headed Ma (SI for millions of years) is added for convenience. The figures are transferred from Chapter 3 and are not part of the argument of this chapter. As it happens the work on Chapters 3 and 4 preceded that on Chapter 2 and the numerical calibration (and the drawing of figures in Chapters 3 and 4) were completed on an earlier chronostratic scale. If there had been time to consider the whole work together we should have applied the knowledge potentially available from Chapter 2 to give better relative durations for the different ages.

Where necessary transliteration of names has been revised: Chinese in the contemporary Pinyin, and Russian according to the standard PCGN/BGN system (Permanent Committee on Geographic Names, US Board on Geographic Names as used, e.g. in *The Times Atlas*). As already observed we have accepted American spelling to avoid diphthongs in names such as Paleozoic. This will not find favour with some British colleagues but we make this choice deliberately, believing that we are setting out a time scale for international use, the names of which should not need transliterating within the English language. It is the privilege of those whose ancestry and mother tongue is English to contribute to the evolving international language of science.

2.2 Precambrian time scales

The confusing historical sequence of names and classifications for Precambrian rocks and divisions has been recounted many times (e.g. Wilmarth 1925, Harland 1974). In the end, of the many early names proposed, only *Proterozoic* and *Archean* achieved the approval of the IUGS. The consolidated name Precambrian was also agreed in 1972 by the IUGS against the alternative pre-Cambrian (cf. pre-Vendian or pre-Pleistocene). It was thought by some to be an advance that recognised a supposed unity of Precambrian rocks and studies in contrast to Phanerozoic stratigraphy. But identical principles and procedures apply to all rocks even though the evolution of the Earth resulted in widely different rocks forming at different times and at any one time.

2.2.1 Chronometric divisions

Many students of Precambrian rocks think of dividing Precambrian time at boundaries defined only by numbered multiples of duration of a standard year. It was first attempted to discover natural divisions of Earth or regional history and to define the age of the event in years; for example the Geological Survey of Canada (GSC) introduced the names Hadrynian, Helikian and Aphebian for tectonic divisions of the Canadian shield with boundaries at 880, 1640 and 2390 Ma (Stockwell 1964) and successively rounded off to 1000, 1800 and 2500 Ma (Douglas 1980). At the same time the United States Geological Survey (USGS) accepted the principle of artificial boundaries in round numbers for Precambrian W, X, Y and Z (James 1972), even though the figures chosen also approximated to convenient American map divisions, so making it more likely that the scheme would remain a regional one.

The Subcommission on Precambrian Stratigraphy of the IUGS agreed by a majority at its Fifth Meeting in Duluth, Minnesota, 15–19 September 1979 to recommend provisionally to divide the Proterozoic Eon into three eras divided at 900 and 1600 Ma. Competing opinions favoured a boundary at 1500 Ma and/or use of four divisions. The Proterozoic–Archean boundary at 2500 Ma had already been decided. It was also suggested to divide Archean time at 2900 Ma and 3500 Ma (a three-fold division) 'to fit the Archean geologic record as now known in most parts of the world'. These recommendations and suggestions were to be reviewed at the next meeting in 1982 (Sims 1980).

Precambrian time may be conceived as extending indefinitely backwards before 4600 Ma and for that matter in so far as it has meaning before 10 000 Ma. The oldest commonly used division of Precambrian time is Archean. It originally referred to the oldest known rocks. According to the 1980 *AGI Glossary of Geology* (Bates & Jackson 1980) Archeozoic is 'the earlier part of Precambrian time corresponding to Archean rocks'. Archeozoic was indeed introduced earlier than Archean (Harland 1974). In 1976 the Subcommission on Precambrian Stratigraphy treated Archean as a standard time division terminating at 2500 Ma, no initial boundary was established. However, its relation to known terrestrial rocks persists in the minds of most geoscientists because in nearly every case attempts to divide Archean time into Early, Middle and Late; 1, 2 and 3 etc. result in divisions such that Middle and Late Archean generally refer to rocks approximately in the intervals 3500 to 3000 Ma and 3000 to 2500 Ma. Moreover the oldest rocks so far recorded from southern West Greenland and from southern Africa are commonly referred to as 'earliest Archean'.

With this in mind and with an increasing need to refer to the still earlier history of the Earth and Solar System, a solution that some of us have suggested is to define the initial Archean boundary at (say) 4000 Ma. The Eon would then span exactly 4000 to 2500 Ma. This would do no violence to majority usage of the name. On this basis we name pre-Archean time Priscoan from Prisco time (Latin priscus = former, previous, olden of times) which was suggested for this purpose in 1975 (Harland). Others of us, however, would prefer to extend Archean time back to 5000 Ma and redefine its divisions. The consequence of this alternative procedure is that all rocks in the Solar System, including meteorites are likely to be Archean in age and no new names are required. Archean time could be subdivided into five 500 Ma units, provisionally named Archean 1–5. In any case no international convention can be adopted until settled by the IUGS Committee on Stratigraphy. Until that time we make these suggestions to test opinion; for it seems that, because of prevailing preoccupation with terrestrial Archean rocks, little thought has been given to earlier history as an extension of the same fundamental stratigraphic discipline. The widespread colloquial use of adjectives as nouns (e.g. 'the Precambrian', 'the Archean') may suggest that the record in rock is in mind and some extension is needed.

2.2.2 Chronostratic divisions

The alternative and equally valid approach to a Precambrian time scale is to follow the principles being applied successfully to define Phanerozoic divisions by reference to supracrustal rocks. On the coterminosity principle the terminal Proterozoic boundary coincides with the initial Phanerozoic, Paleozoic and Cambrian boundary. This is expected (in 1983 or 1984) to be defined in a stratotype. It will have the effect of making the Proterozoic division a hybrid – beginning with a chronometric boundary and ending with a chronostratic one.

Similar boundaries will be defined to limit divisions where there are good stratal characteristics for correlation. The five columns listed on Chart 2.1 represent successions in Scandinavia, USSR, China, Australia and Africa; each indicates a possible chronostratic standard for some part of Precambrian time. These columns were selected and simplified as follows. The Scandinavian column is based on that in Finnmark by Edwards & Føyn (1981). The USSR column is from Keller (1979, p.421). The China column is composite and based on Wang & Liu (1980). In it the Sinian units are from the Yangtze Gorge and south China region and the older units are from north China. The southern Australia column is based on Coats (1981) and Rutland *et al.* (1981) and the units from western Australia are plotted approximately according to Hallberg & Glikson (1981). The southern Africa column is composite, some names being selected from those proposed by Kent & Hugo (1978) for international chronostratic use: Swazian, Randian, Vaalian, Mogolian (from River Mogol in Griquatown West) and Namibian. The rock sequences are also adapted from Anhaeusser & Wilson (1981) for Swazian rocks, and Button *et al.* (1981) for Randian through Mogolian. Button *et al.* included the Dominion Reef as well as the West Rand and Central Rand Groups in the Witwatersrand Supergroup but we identify it as one of the familiar 'Witwatersrand Triad'. The Zimbabwe sequence is from Nisbet, Wilson & Bickle (1981).

No international decisions have yet been made, so it might be premature to select from the above successions those that may provide international standards. Nevertheless in the period and epoch columns of our chart the suggestions made are indicative of the approach which will develop by degrees as the chronostratic scale extends backwards in time.

The Sinian Era. With the impending definition of the initial Cambrian boundary the question arises as to what scheme of classification and nomenclature shall be applied to the preceding chronostratic time divisions. The ambiguity of the name Eo-Cambrian, both in definition and classification, has effectively ruled it out for international use. It may, however, still have a value in informal use to indicate an uncertain age at about the Phanerozoic threshold. Sinian and Vendian are two contenders for the formal division to precede Cambrian. Sinian has priority and was extensively used in the USSR as well as China for many years. Then when Precambrian studies in the USSR advanced beyond those in China the name Vendian was introduced and has been widely used. It seems almost to have been adopted internationally. There are however some difficulties, not least that good type sequences with reference points have not been established, nor has the classification scheme achieved agreement even in the USSR. In the meantime research in China has surged and the claims of Sinian are being pressed again. Sinian had two widely differing meanings – including or excluding the thick northern succession of Jixian altogether older than about 800 Ma. Now that sequence has been excluded, Sinian is again restricted to rocks younger than about 800 Ma as originally so named from the widespread platform succession typified in the Yangtze Gorge (as on Chart 2.1). A more complete geosynclinal succession in Xinjiang may well provide a better standard with four distinct tillite horizons that facilitate international correlation elsewhere. These are the Bayishi, Altungol, Tereeken and Hangeerqiaoke of Wang *et al.* (1981). The suggestion tabulated in Chart 2.1 is to establish a Sinian Era or Sub-era (Bayishi to Hangeerqiaoke) divided into two periods, Sturtian and Vendian. So Vendian is retained in the restricted sense commonly used so as to include two epochs (e.g. Harland & Herod 1975), i.e. Varangian (Kulling 1951) and Ediacaran (Cloud 1972). This would be appropriate if a Xinjiang section for Sinian correlation were used and might avoid some difficult problems of correlation between Vendian and latest Riphean (e.g. Vidal 1979). Within this span there are relatively good palynological and climatological bases for correlation. Vidal suggested a three-fold division of Vendian namely Valdaian, Varangerian and an early division (Vidal 1981). Certainly northern Europe has good successions for correlation in this interval but Valdaian is not used here (it is already established in Quaternary nomenclature). Varangian has priority over Varangerian. Vetternian was suggested by Vidal for the early division (personal communication 1981); it is related to a small and isolated outcrop area in Sweden.

The classification favoured here is designed to satisfy the aspirations of the Australian, Chinese, Russian and Scandinavian communities who have each contributed significantly to this latest Precambrian scale in describing key successions. The Ediacaran division has been proposed for some time e.g. Cloud (1972), Glaessner (1977) and most recently Jenkins (in press) who renewed the case for an 'Ediacaran Period'. On this basis at least two ages are proposed within it, namely (later) Poundian and (earlier) Wonokan. Varangian is also divided into at least two ages, (later) Mortensnes and (earlier) Smalfjord from the two tillite horizons in the Varanger Fjord area. Sturtian is similarly capable of divisions that have a correlation potential combining biostratigraphic and climatic characters.

Pre-Sinian eras. If Riphean is to be used for the next earlier era (as shown on Chart 2.1) then a radical restriction of R_3 would be needed as Karatavian (based on Karatau) overlaps Sturtian. Confusion has long existed in the later Riphean classification and on the basis suggested here, if (and only if) a Russian-based international chronostratic division were wished by Soviet colleagues would a new definition be necessary.

Still earlier chronostratic divisions are merely suggested here to indicate the way in which the classification will develop. The Huronian sequence with its four potential epochs (three of them being glacial cycles) has a distinct correlation potential and would provide a good standard for this part of Earth history.

Earlier names in the column are culled from Kent & Hugo (1978) who with good reason have argued that African Precambrian successions provide good standards for international use. Of these we adopt the Archean sequences: Randian (including the Witwatersrand) and Swazian to include the rich sequences of Swaziland and Zimbabwe. Isuan (from West Greenland) is suggested for the earlier terrestrial record. Hadean is adopted from Cloud (1976) for the pre-Isuan sequence whose record may not be preserved on Earth but is perhaps best known from the Moon.

2.3 The Phanerozoic Eon

The *Palaeozoic Series* was first proposed by Sedgwick in 1838 for the rocks overlying the *Primary Stratified Groups*; J. Phillips in 1840 applied Paleozoic to those 'transitional' rocks up to and including the Old Red Sandstone, and in 1841 he extended it to include all rocks from Cambrian to Permian, when he also introduced the names *Mesozoic* and *Cainozoic* in the modern sense.

'Post-Pre-Cambrian' time was the alternative to expressing Cambrian through Holocene time until Chadwick in 1930 proposed *Phanerozoic* for this span (Paleozoic + Mesozoic + Cenozoic) and *Cryptozoic* was his Proterozoic + Archeozoic (e.g. Harland 1974).

All the above names carry a descriptive meaning related to the evolution of animal life; but they have also become conventional names in a stratigraphic hierarchy and that is how we use them. In other words these boundaries are coterminous with successively lower ranks at the defined point. Thus the initial Phanerozoic boundary will be defined at the point that will define the initial Cambrian boundary and it is not to begin according to successive discoveries or opinions about animal evolution.

2.4 The Cambrian Period

The history of the definition and classification of Cambrian rocks in the British Isles, especially in North Wales, from the initial publication of the name in 1835 by Adam Sedgwick to the ultimate resolution of the conflict about the Cambrian-Silurian boundary, through establishment of the Ordovician System by Lapworth in 1879, has been outlined by Stubblefield (1956) and Cowie, Rushton & Stubblefield (1972). Cambria is a variant of Cumbria (ancient British kingdom, in present day north-west England) latinised from the Welsh *Cymry* (= fellow country-man, compatriot against invading Anglo-Saxons). The Celtic *Cymru* survives only in Wales and Cambrian already pertained to Wales when Sedgwick adopted it. Detailed stratigraphic information on the various divisions and units proposed appear in the *Lexique stratigraphique international,* not only for Cambrian rocks of the British Isles, but for rocks of all ages and many regions. These volumes will not generally be referred to here and are now mainly useful for the history of stratigraphic names. However, Vol. 1, Europe Fasc. 3aIII by Stubblefield in 1959 gives much definitive information on the Cambrian strata of the British Isles.

Sedgwick had first used the group names Lower and Upper. His Lower Cambrian was divided into the Bangor Group (with Llanberis Slates and Harlech Grits) below and the Ffestiniog Group (with Lingula Flags, Tremadoc Slates and Arenig Slates) above; his Upper Cambrian included Bala strata and extended up to the base of the Woolhope Limestone. Since 1879 the Cambrian System has comprised only Sedgwick's Lower Cambrian and not all of that. Arenig was the lowest series of the new Ordovician System and Tremadoc has long properly been a part of the Cambrian System, as argued by Whittington & Williams (1964) for example. However, we accept the prevailing international practice, whether or not based on a misunderstanding, to make Tremadoc the first Ordovician epoch.

The difficulties of Cambrian classification and correlation arise partly from the paucity of appropriate fossils. A consequence of this led in North America to the early placing of *Olenellus*-bearing rocks above, rather than below, those with the more abundant *Paradoxides.* These relationships were hardly cleared up until about 1890 (Cowie *et al.* 1972).

In central Europe Barrande (in 1859) listed the old primordial fauna with *Paradoxides* and Brøgger showed the Olenellid *Holmia* to be older than *Paradoxides* in central Norway (e.g. Harland 1974).

In North America in the meantime the name Acadian, introduced by J. W. Dawson in 1868, was proposed for strata characterised by *Paradoxides* etc. as 'the oldest member of the Paleozoic of America' by Walcott in 1891 when he also introduced the name Potsdam for Upper Cambrian. The order was sorted out but not the nomenclature. In 1903 Walcott replaced Potsdam by Saratogan and then in 1912 by St Croixian. He had used Georgian originally from 1882 (Hitchcock in 1861) for Lower Cambrian and in 1912 Walcott recommended Waucoban as a provincial rock series and applied the name Taconian for general use for the Early Cambrian Epoch. The Taconic System had been proposed as early as 1842 by Emmons for the earliest system beneath the New York System (Wilmarth 1925).

In due course in North America these and other names have had regional significance often contrasted between Appalachian and Cordilleran usage, i.e. Georgian, Acadian and Potsdam (or Saratogan) in the east (e.g. Blackwelder 1912) and somewhat later, in the west, Waucoban, Albertan and Croixian. Usage now tends to favour the western nomenclature in North America.

This leaves us today with a general acceptance of three Cambrian epochs, but no internationally accepted names for them. Because of the widely different usages of the names Early, Middle and Late Cambrian, and also because of the need to refer informally to parts of epochs (e.g. early Early Cambrian or worse) a nomenclature defined by a stable classification and standardised in type areas, not necessarily near the eponymous localities, is to be preferred. The choice made here is for names long used unambiguously for British Cambrian rocks and/or recently proposed by the Geological Society of London (GSL) Working Group (Cowie *et al.* 1972).

2.4.1 The Caerfai Epoch

Caerfai is used here in preference to Comley for the Early Cambrian Epoch because Comley, however well defined (Cowie *et al.* 1972), could mislead so long as the Upper Comley Group of Middle Cambrian age be so named. There is not a definitive sequence in South Wales to justify

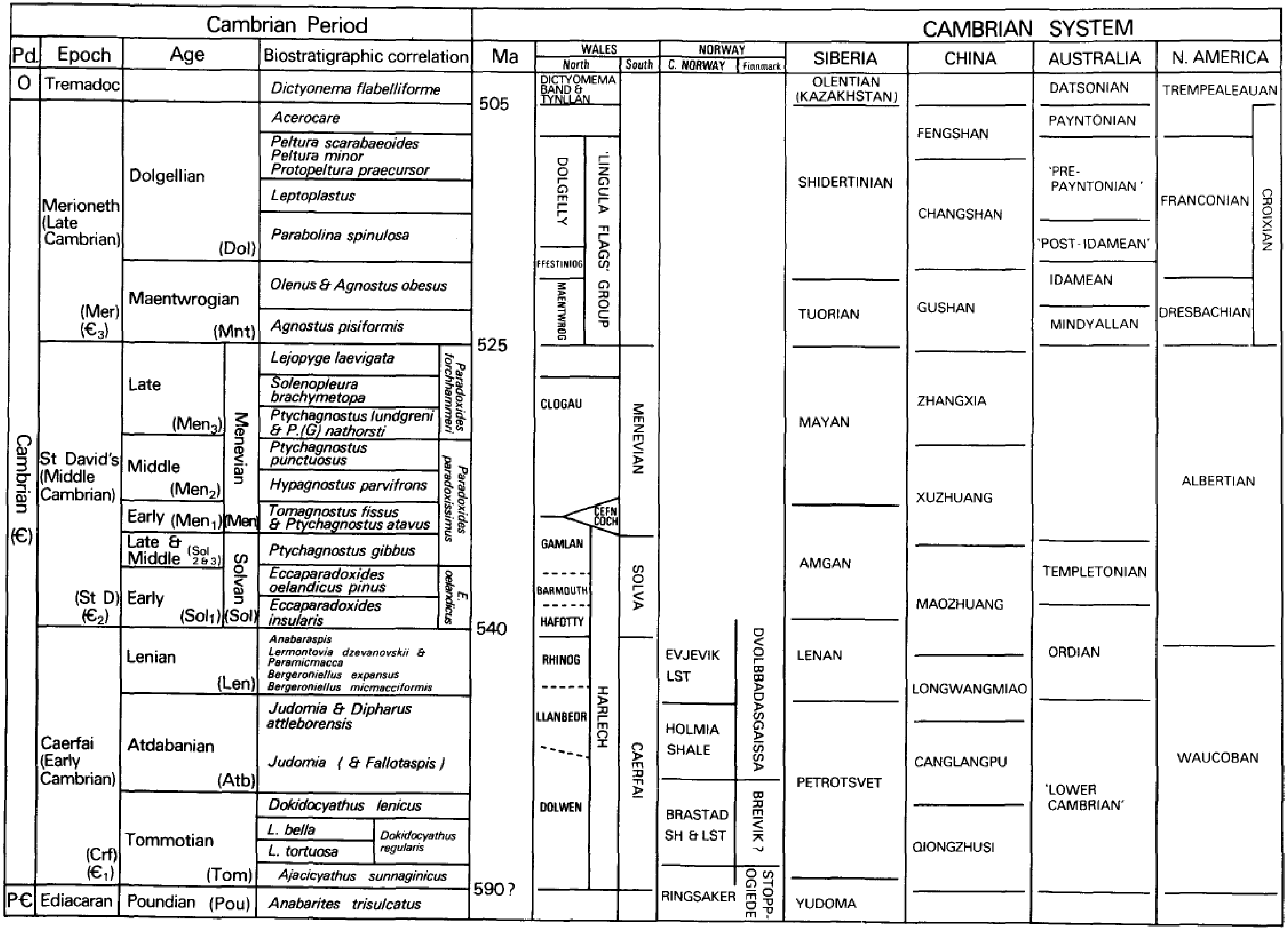

Chart 2.2. Cambrian chronostratic scale and correlation.

using the name Caerfai; that could well be a composite one from extra British regions. But Caerfai has, for example, been selected by the USGS (Cohee 1970) as the European standard name and appears also on Van Eysinga's (1975) chart. So it is already familiar internationally.

2.4.2 The St David's Epoch

St David's (?Davidian by analogy with Croixian) is the name suggested for the Middle Cambrian Epoch (Cowie *et al.* 1972). This seems to be entirely appropriate. Rocks with *Paradoxides* were first identified in the St David's area; and the divisions Menevian and Solvan from the same area in South Wales have a long history in Middle Cambrian stratigraphy.

2.4.3 The Merioneth Epoch

Merioneth (a former county in North Wales, now included in Gwynedd) is the name for the restricted Late Cambrian Epoch and such a name is necessary to make it clear that Tremadoc is excluded. The form of these names is left as proposed without adding the familiar '-ian' suffix and is also in conformity with some British practice for Ordovician and Silurian epochs. This practice also serves to distinguish epochs from age divisions which are generally preferred to end with an '-ian'.

The sequence of ages listed here are taken from Cowie (in press) and we have not the information to attempt to justify them. Their identity is clear to some extent from the column of correlative fossils listed also in that work.

The initial Cambrian boundary has been discussed many times and one such paper (Harland 1974) contributed to the formation of the Precambrian-Cambrian Boundary Working Group Project No.29 of the International Geological Correlation Programme (IGCP) (Leader: J. W. Cowie), which is expected to establish an internationally agreed initial Cambrian boundary in 1983/4. It is premature to discuss where the reference boundary stratotype will be; however, the Siberian successions are amongst the most serious contenders and it is not surprising that the three ages proposed by Cowie (in press) for the Early Cambrian (Caerfai) Epoch are Siberian (Tommotian, Atdabanian and Lenian).

For Middle Cambrian (St David's) ages, Cowie (in press) uses three *Paradoxides* zones as ages. In Chart 2.2 we have included these and retained Solvan and Menevian which have a long tradition, and all are South Welsh names like St David's.

In the Late Cambrian (Merioneth) Epoch Maentwrogian and Dolgellian units are retained but the Ffestiniog stage that once separated them (in a three-fold division – e.g. Cohee *et al.* 1967) has been dropped. All are North Welsh names.

The columns in Chart 2.2 are modified as explained above from Cowie (in press) for the left-hand side of the chart. On the right the Norway column is from Martinsson (1974) and gives only Early Cambrian divisions because thereafter all the Scandinavian sequences are described in terms of a complex of biostratigraphic names. The China column is from Wang & Liu (1980). The other columns are from Cowie *et al.* (1972).

2.5 The Ordovician Period

The Ordovician System was founded by Lapworth in 1879 and solved the Murchison-Sedgwick conflict with overlapping claims for their Silurian and Cambrian systems respectively. It was therefore instrumental in defining the three periods of the Early Paleozoic Era. The history was outlined by Whittington & Williams (1964) and detailed British sequences were charted by Williams *et al.* (1972).

Lapworth cited 3600 m of volcanic ash and sedimentary rocks in the Arenig-Bala district and the boundaries of the original system were clearly defined there – above the Tremadoc (Amnodd Shales), i.e. beginning with the Basal Grit of Sedgwick's Arenig Group and ending below the Llandovery (Cwm yr Aethnen Mudstones) at the top of the Foel y Ddinas Mudstone which was the youngest formation of Sedgwick's Bala Group.

Whittington & Williams (1964) recounted the complex history of error and confusion that led to various departures from the above simple definitions and so gave some support for including Tremadoc rocks in the Ordovician System. In short, while priority and the logic of the initial definition would exclude Tremadoc rocks, the fact is that a majority of geologists throughout the world have allowed these mistakes to pass unchecked into general use and so established the convention that we now follow by beginning the Ordovician Period at the point that would make the Tremadoc Group also Ordovician. There is, after all, no truth to be established – only a convention to be agreed. In fact, *Dictyonema flabelliforme* has commonly been taken as the index fossil in correlation of earliest Ordovician rocks, though a point in a reference section somewhere will be needed to standardise the initial point of the Ordovician Period.

The divisions of the Ordovician Period are therefore based on names and successions of rocks in Britain. These successions are, however, scattered and do not comprise a single or even two or three standard sequences so that no column of British rock units has been attempted in Chart 2.3. They are clearly depicted in the correlation charts in Williams *et al.* (1972).

Lapworth used two rather than three Ordovician divisions which corresponded to Sedgwick's original Arenig and Bala. This two-fold division was reaffirmed by Whittington & Williams (1964). We adopt the same Late Ordovician Subperiod bringing back the name Bala for it. Bala happens to coincide with Upper Cambrian as defined by Sedgwick in 1852 and 1873. For the earlier part of Ordovician time there is some difficulty. Sedgwick's Arenig has since been divided into Arenig, Llanvirn and Llandeilo so cannot now be used in a different sense. A three-fold division of the Period is also commonly employed, especially in America, and although Whittington & Williams argued against it, now that we have added the Tremadoc Epoch this makes the three-fold division seem more reasonable to us. The name Canadian if defined as coterminous with Tremadoc plus Arenig, would be an unambiguous name for our Early Ordovician Subperiod in spite of Canadian facies being totally foreign to the type successions. We are after all seeking names for time

Chart 2.3. Ordovician chronostratic scale and correlation.

Ordovician Period

Period		Epoch	Age	Biostratigraphic correlation	Ma
S		Llandovery	Rhuddanian		
					438
Ordovician (O)	Bala O_3 (Bal)	Ashgill (Ash)	Hirnantian (Hir)	*Dicellograptus anceps*	
			Rawtheyan (Raw)		
			Cautleyan (Cau)		
			Pusgillian (Pus)	*Dicellograptus complanatus*	
					448
		Caradoc (Crd)	Onnian (Onn)	*Pleurograptus linearis*	
			Actonian (Act)	*Dicranograptus clingani*	
			Marshbrookian (Mrb)		
			Longvillian (Lon)		
			Soudleyan (Sou)	*Climacograptus wilsoni* / *Diplograptus multidens*	
			Harnagian (Har)	*Climacograptus peltifer*	
			Costonian (Cos)	*Nemagraptus gracilis*	
					458
	O_2	Llandeilo (Llo)	Late (Llo_3)		
			Middle (Llo_2)		
			Early (Llo_1)	*Glyptograptus teretiusculus*	
					468
		Llanvirn (Lln)	Late (Lln_2)	*Didymograptus murchisoni*	
			Early (Lln_1)	*Didymograptus bifidus*	
					478
	O_1	Arenig (Arg)	Late (Arg_2)	*Didymograptus hirundo*	
			Early (Arg_1)	*Isograptus gibberulus* / *Didymograptus extensus*	
				Didymograptus nitidus	
				Didymograptus deflexus	
				Tetragraptus approximatus	
					488
		Tremadoc (Tre)	(Tre)	*Apatokephalus serratus*	
				Clonograptus heres & Shumardia pusilla	
				Symphysurus incipiens	
				Dictyonema flabelliforme	
					505
€		$€_3$	Dolgellian		

ORDOVICIAN SYSTEM

EUROPE: BOHEMIA		EUROPE: ESTONIA		KAZAKHSTAN	CHINA		AUSTRALIA	NORTH AMERICA	
KOSOV		PORKUNI	HARJU	TOLEN	WUFENG	JIANGTANGJIANG (CHIENTANGKIANG)	BOLINDIAN	RICHMOND	CINCINNATIAN
KRÁLŮV DVŮR		PIRGU							
BOHDALEC	BOHDALEC	VORMSI	VIRU	ZHARYK				MAYSVILLE	
		NABALA		DULANKARA	LINXIANG (LINHSIANG)			EDEN	
		RAKVERE		ANDERKEN					
	LODĚNICE	OANDU			BAOTA (PAGODA)		EASTONIAN	SHERMAN	CHAMPLAINIAN
ZAHOŘANY		KEILA							
VINICE		JÕHVI		YERKEBIDAIK				KIRKFIELD	
LETNÁ		IDAVERE						ROCKLAND	
								BLACK RIVER	
LIBEŇ	CHRUSTENICE	KUKRUSE		TSELIN - OGRAD	HULE	AIJIASHAN (NEICHIASHAN)	GISBORNIAN	?	
								CHAZY	
DOBROTIVÁ		UHAKU							
ŠÁRKA		LASNAMAGI		KARAKAN	NIUSHANG		DARRIWILIAN	WHITEROCK	
		ASERI							
		KUNDA		KOPALY					
KLABAVA		VOLKHOV	OELAND	KOGASHYK	CHONGYI		YAPEENIAN	BEEKMAN - TOWN	CANADIAN
							CASTLE - MAINIAN		
		LATORP		RAKHMET	NINGGUO (NINGKUO)	YICHANG (ICHANG)	CHEWTONIAN		
							BENDIGONIAN		
							LANCEFIELDIAN		
		OLENTIAN			XINCHANG		WARENDIAN	GASCONADA	
							DATSONIAN		
							PAYNTONIAN		

divisions only. But we are at a loss for a name (short of inventing one) for Llanvirn and Llandeilo. This is not so serious because if Middle Ordovician be used then that is what we intend.

Referring now to the finer division of Ordovician time into epochs and ages we first note that pre-Bala epochs are not yet formally divided into named ages whereas eleven Bala ages have been established for some time. The ***Tremadoc*** Epoch is unambiguously related to the Tremadoc Group in North Wales with *Dictyonema;* on historical grounds it is Cambrian as explained above but by popular preference we take it as Ordovician. ***Arenig*** was reduced to its present span by separation of Murchison's ***Llandeilo*** (e.g. by Ramsay and Salter in 1866) and from this in due course Hicks in 1881 introduced the ***Llanvirn*** together with Llandeilo between Arenig and Bala. ***Caradoc*** was Murchison's name first used for Bala by Ramsay and Salter in 1866 from which in due course Marr (in 1905) separated ***Ashgill.*** All these epochs are now defined approximately in terms of graptolite zones as shown in Chart 2.3. The Ashgill–Llandovery boundary referred to below in Scotland may be related to the Welsh section where Hirnantian age is related to the Hirnantian fauna of the Foel y Ddinas Mudstone but the Dobb's Linn (south Scotland) sequence may be better as a standard for correlation.

The chart shows the major British graptolite zones used for correlation as in Williams *et al.* (1972). The consolidation of two biozones to *Diplograptus multidens* is based on common usage. The biozones are generally of longer duration than the ages, whose finer division is possible using fossil assemblages. The Tremadoc biostratigraphic correlation is based on Scandinavian biozones taken from Cowie *et al.* (1972). The post-Tremadoc divisions are from Williams *et al.* (1972) as are the columns for Bohemia, Estonia and Kazakhstan. The China section is from Sheng Shen-Fu (1980). The Australian stages are from Webby *et al.* (1981). The post-Canadian North American sequence is from Sweet & Bergstrom (1976, p.134), and the earlier part of the sequence is based on Sweet & Bergström's 1975 column, as given in Sheng Shen-Fu (1980).

2.6 The Silurian Period

The Silurian System was named by Murchison in 1839 for the Welsh Borderland tribe the Silures, and first included rocks that were claimed as Cambrian by Sedgwick. Silurian was subsequently used in two senses – to include or exclude what are now recognised as Ordovician strata, so the less ambiguous name Gotlandian was proposed in 1893 for the post-Ordovician period and competed with the name Silurian until in 1960 at the IGC in Copenhagen, Silurian was officially adopted in its restricted sense, i.e. Murchison's Upper Silurian.

Murchison included Llandovery, Wenlock and Ludlow in his Upper Silurian in 1859. These names are unambiguous and are preferred to Early, Middle and Late Silurian epochs for that reason. Lapworth in 1879 and 1880 used Valentian (approximately = Llandovery) and Salopian (approximately = Wenlock + Ludlow) but this usage was discontinued (e.g. by O. T. Jones in 1929) when a fourth division (the Downton) came into use (including part of Murchison's Tilestones that he had included with what later became the Old Red Sandstone). Whittard (1961) and Cocks *et al.* (1971) summarised the confused nomenclatural history of the Period.

The four epochs (S_1 – S_4) have more recently been recombined informally into two sub-periods (Early Silurian = $S_1 + S_2$ and Late Silurian = $S_3 + S_4$) when the divisions of the Wenlock (S_2) and Ludlow (S_3) epochs were recommended (as here) by the IUGS Subcommission on Silurian Stratigraphy (Holland 1980).

2.6.1 The Llandovery Epoch

The initial Llandovery (Ordovician–Silurian) boundary is not well standardised in the Llandovery district itself and so is referred to the Dobb's Linn section near Moffat, Scotland where Lapworth conceived the Ordovician System. It is taken at the base of beds bearing a *Glyptograptus persculptus* zone assemblage.

The ages plotted in our chart were named by Cocks, Toghill & Ziegler (1970) in the type area in Wales. These four ages may informally constitute in pairs early and late Llandovery. The equivalence of graptolitic and shelly facies has long been a question in these rocks, with problems of correlation between Scotland and Wales. The lettered symbols in the biostratigraphic correlation column refer to a sequence A, B and C for a superseded usage of Early, Middle and Late Llandovery and are based upon a sequence of Welsh shelly (largely brachiopod) faunas (Cocks *et al.* 1970).

2.6.2 The Wenlock Epoch

The name Wenlock was first used by Murchison in 1839 from the type area of Wenlock Edge in the Welsh Borderlands. A scheme of formations and members was developed over the years. However, a GSL initiative led to a reinvestigation of these rocks and proposals for an international scale that could be correlated by the graptolite sequence (Bassett *et al.* 1975). This is adopted in the accompanying classification (without detailing the sequence of evolving classifications) and the definitions are abstracted below.

The initial ***Sheinwoodian*** (Llandovery–Wenlock) boundary is seen in the standard section (National Grid SO 5688 9839) in Hughley Brook which lies 200 m SE of Leasowes Farm and 500 m NE of Hughley Church. The marker point for the boundary is taken in the left (N) bank of the stream at the base of unit G which is the base of the Buildwas Formation and immediately above the Purple Shales in a measured section (Bassett *et al.* 1975, p.13).

The ***Homerian*** Age was divided into the two chrons – Whitwell and Gleedon – because of the possibility of international correlation by the graptolite zones and the likely ease of recognition of their bases elsewhere by correlation with the standard section. The spacing of these graptolite zones in the chart follows that of Bassett *et al.* (1975, p.2) presumably being the best time scale interpolated by thicknesses in the 'Wenlock Shales' – mainly Coalbrookdale Formation.

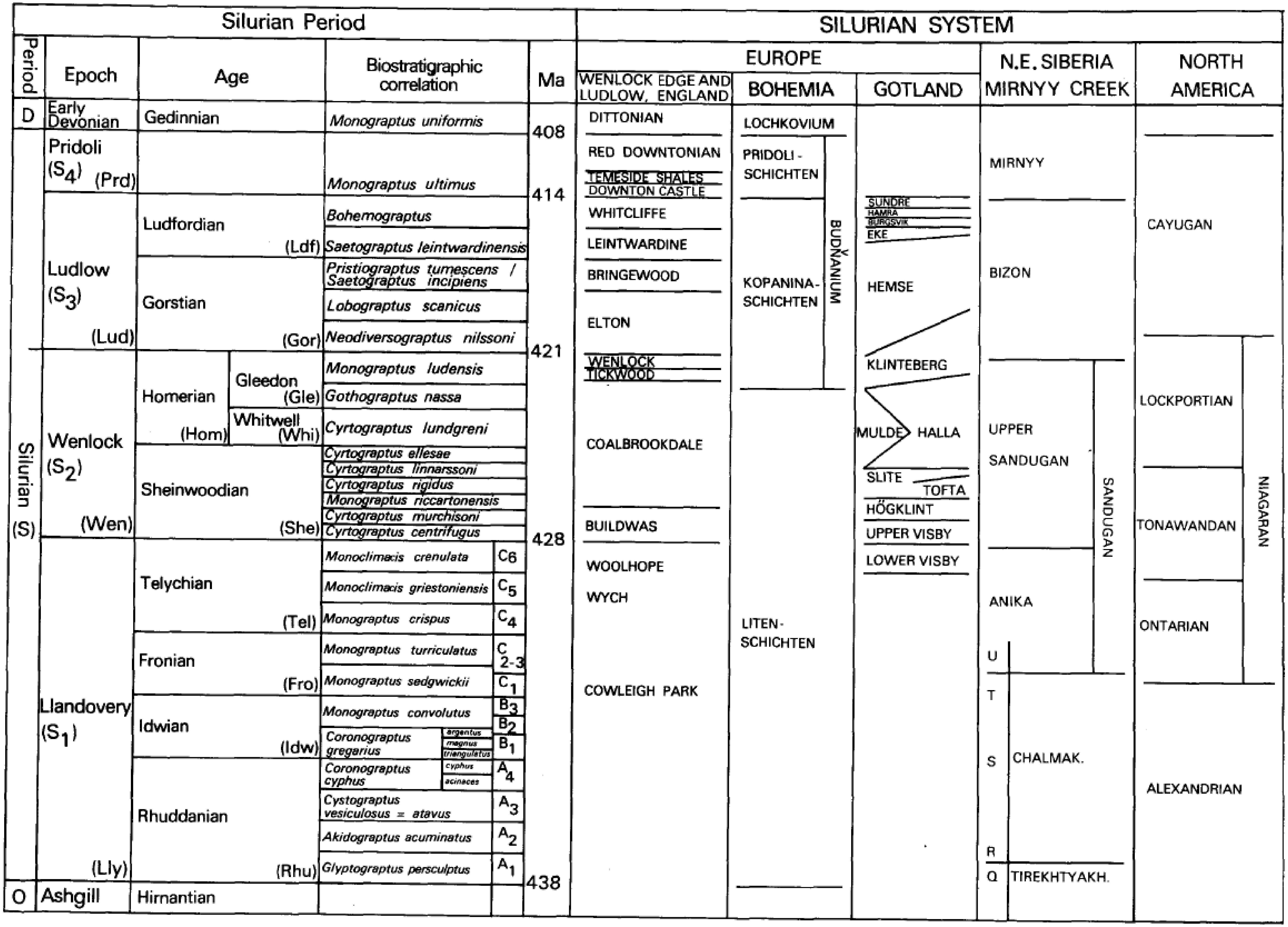

Chart 2.4. Silurian chronostratic scale and correlation.

The initial ***Whitwell*** boundary is located in the 'small side-stream (National Grid SO 6194 0204) to the tributary of Sheinton Brook which flows through Whitwell Coppice, 500 m north of Homer. The marker point . . . is within a more or less continuous section of olive to grey-green mudstones, blocky-fractured and thin-bedded, its exact position coinciding with the point at which the *ellesae/ lundgreni* biozone boundary cuts the right (north) bank of the stream.' More biostratigraphic details were given for international correlation by Bassett *et al.* (1975).

The initial ***Gleedon*** boundary is defined (at National Grid SO 5016 8999) on the SE side of the track 182 m E of Eaton Church and coincides with the point where the *lundgreni/nassa* biozone boundary cuts the track.

2.6.3 The Ludlow Epoch

The Ludlow Epoch has been redivided (Holland 1980) by combining four ages used earlier (e.g. Cocks *et al.* 1971) into two that are now better established as follows:

Holland (1980)	Cocks *et al.* (1971)
Ludfordian	Whitcliffian Leintwardinian
Gorstian	Bringewoodian Eltonian

The initial ***Gorstian*** (Wenlock–Ludlow) boundary was defined by Holland, Lawson & Walmsley (1963) at Pitch Coppice in the Ludlow anticline in the standard section in the Old Quarry (National Grid SO 4726 7301) on the S side of the Ludlow/Wigmore road, about 2 km NE of Aston Church. This definition is in younger strata than was sometimes earlier supposed.

The initial ***Ludfordian*** boundary was taken at the base of the beds with *Saetograptus leintwardinensis* (Holland 1980) but was defined precisely by Holland *et al.* (1963) in the section on the NW face of Sunnyhill Quarry in Mary Knoll Valley 2.8 km SSW of Ludlow (National Grid SO 4953 7255).

2.6.4 The Pridoli Epoch

This epoch approximates to post-Ludlow, pre-Gedinnian time but its name is not yet internationally established. Downton is the name used in the Welsh Borderland sequence and would rationally follow on the sequence Llandovery, Wenlock and Ludlow. Graptolites have not been found in this facies. The alternative preferred in this work is Pridoli from Pridoli-Schichten (labelled E332 20–80 m in Barrande's section in Bohemia). It is preferred partly because the classic Silurian–Devonian boundary is established there, as is also the Pridoli–Lochkovian boundary. The Ludlow–Pridoli boundary has not been defined in any locality, but it approximates to the base of the *Monograptus ultimus* biozone.

The epochs, ages and biostratigraphic correlation columns on Chart 2.4 are based on Cocks *et al.* (1971) with modifications from Bassett *et al.* (1975) and Holland (1980) as detailed above. R. B. Rickards kindly provided details of the zone fossils. The Wenlock Edge and Ludlow, Bohemia and Gotland columns are also from Cocks *et al.* (1971); the north-east Siberia column is based on Oradovskaya & Sobolevskaya (1979) and the North American column is from Norford *et al.* (1970, p.604).

2.7 The Devonian Period

The Devonian System was established in Devon, England by Sedgwick and Murchison in 1839, after a controversy from 1834 to 1840 as to whether the rocks were Silurian or Carboniferous (Rudwick 1979) They were shown to be coeval with the Old Red Sandstone. The division of the System on the basis of marine faunas, however, came to be established through the work of Dumont, Beyrich, Roemer and many others in the Ardenne–Rhenish area where more recent attempts to standardise the time divisions of the period have been based (Ziegler 1979). For a time the name Rhenian was preferred by some to Devonian.

2.7.1 The Early Devonian Epoch

Gedinnian was first defined by Dumont in 1848 from Gedinne in Belgium as the initial Lower Devonian stage. Its initial boundary is also the Silurian–Devonian boundary which was the first to be fully agreed by the Commission on Stratigraphy of the IUGS (at Montreal 1972). They defined the boundary stratotype section at Klonk near Prague in the Barrandian area of Bohemia, Czechoslovakia. The reference point selected is just below a bed with the first and abundant occurrence of *Monograptus uniformis* and *M. uniformis angustidens*, i.e. in bed No. 20 (7–10 cm thick), described by Chlupáč, Jaeger & Zikmundova (1972). This horizon was approximately the base of the Gedinnian stage so that the initial point of the Gedinnian Age is now thereby standardised (McLaren 1977). The boundary being established in Bohemia (Pridolian–Lochkovian boundary) gives some claim to Lochkovian as a stage name approximating to Gedinnian but Gedinnian is internationally established.

Siegenian (named by Kayser in 1881, from Siegen in Germany) was originally the Coblentzian (Coblenzian) of Dumont 1848 and the lower Coblenzian of Gosselet 1880–88. The Gedinnian–Siegenian boundary would correspona to the base of the type Siegenian. However, that is poorly fossiliferous and a better standard for the age boundary might be established in Bohemia.

Emsian was introduced by Dorlodot in 1900 to clarify confusion on nomenclature (discussed in detail by Ziegler (1979)). The initial boundary of the Emsian Age might be taken, for example, at the base of Grès de Vireaux (Ziegler 1979).

2.7.2 The Middle Devonian Epoch

Eifelian, named from Eifel in Germany, was first applied by Dumont in 1848 to older and younger rocks. The standard stage as now understood was restricted to the present meaning in 1937 (see Richter 1942, Ziegler 1979). The name Couvinian (from Couvin in Belgium named by Dupont in 1885) has been widely used by French-speaking geologists; it corresponds to all present Eifelian and part of the upper Emsian strata and so it is not recommended here for the standard scale. The initial Eifelian boundary might be taken at the base of the Eifel Stufe in the Welleldorf standard Eifel section at the boundary between Heisdorf and Lauch beds.

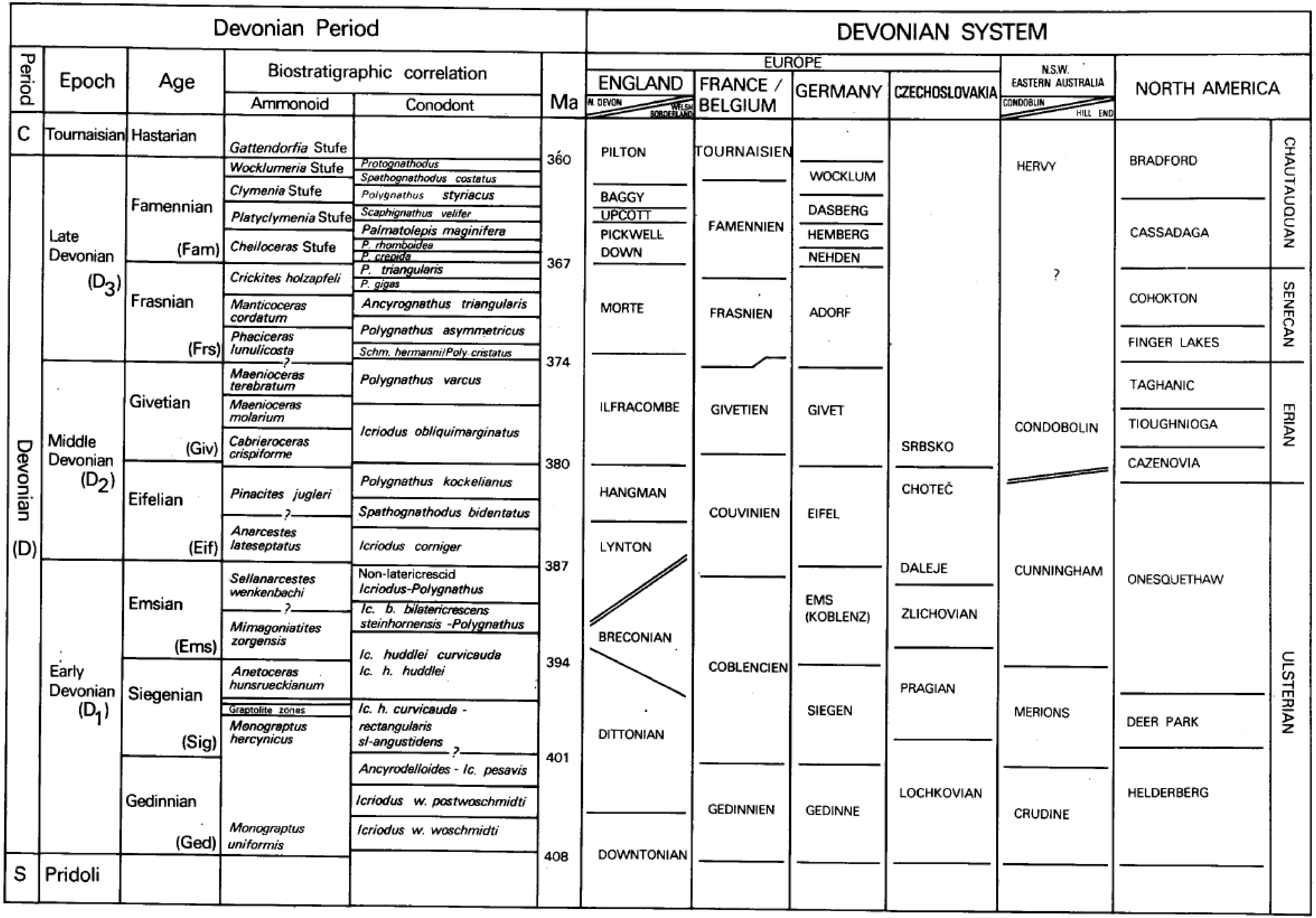

Chart 2.5. Devonian chronostratic scale and correlation.

Givetian (named from Calcaire de Givet, France, by Gosselet in 1879) has been used in approximately the present sense from its inception. The initial boundary of the age is taken by modern German authors at or near the lower range of *Stringocephalus burtini* (Ziegler 1979).

2.7.3 The Late Devonian Epoch

Frasnian from Frasnes, Belgium (Gosselet in 1880) is used approximately in its original sense: Adorfian, Manticoceras Stufe, as well as the North American Senecan have also been proposed. The initial boundary would be placed at approximately the base of the Assise de Fromelennes or alternatively at the base of the Assise de Frasnes. In House *et al.* (1977, p.8) the boundary is taken 'at the base of the goniatite *Phaciceras lunulicosta* zone of the Manticoceras Stufe'. This is the boundary of the German orthochronologic scale which ammonoid workers have used throughout this century and which conodont workers have also sought to use.

Famennian from Famenne in Belgium was first used by Dumont in 1885 for his earlier (1848) Système de Condroz. Gosselet in 1879 used it in the present sense. The initial boundary of the age would be near the base of the Schistes de Senzeilles but, as with all the other boundaries within the Devonian Period, has yet to be defined. The terminal boundary is related to the top of the Wocklumeria Stufe (with *Wocklumeria sphaeroides)* and below the Gattendorfia Stufe (see discussion under Tournaisian (Section 2.8.1)).

The time divisions and the two biostratigraphic correlation columns of Chart 2.5 are from House *et al.* (1977) upon which the four European columns have also been based. Details of eastern Australian rocks are taken from Hill (1967) and those of North America (Appalachian Basin) from Oliver *et al.* (1967).

2.8 The Carboniferous Period

Because of their economic value and good outcrops in Britain, Carboniferous rocks were amongst the first to be classified. The name Coal Measures was proposed by Farey in 1807 and 1811, Millstone Grit by Whitehurst in 1778 and with the Mountain or Carboniferous Limestone these three major divisions (listed by William Phillips in 1818) constituted the Medial or Carboniferous Order (the latter including the Old Red Sandstone) as set out by Conybeare & Phillips (1822). In a detailed historical discussion Ramsbottom showed that Carboniferous was Conybeare's creation in that work (140 pages of detailed description in England and Wales). It was the first system to be established though it was referred to variously as an order, formation, group or series before system was applied by John Phillips in 1835 (Ramsbottom 1981). The three British units correspond to the three north European divisions. Green and others in 1878 grouped the upper two units as Upper Carboniferous and a two-fold division was again used in Belgium by d'Omalius d'Halloy in 1808, the upper one being the Terrain Houiller (Zittel 1901, Ramsbottom *et al.* 1978).

The three divisions, Namurian (proposed by Purves in 1883), Westphalian and Stephanian (both by de Lapparent in 1893), were systematised by Jongmans in 1928 when Westphalian was divided into A, B and C based on goniatite biozones and Westphalian D based on floras. Westphalian E was later referred to Stephanian.

The two-fold division of the Period was recognised by the Heerlen Conference in 1935 when Dinantian was introduced for Lower Carboniferous and the IUGS Subcommission on Carboniferous Stratigraphy proposed Silesian for the upper part in 1960. The same Subcommission in 1972 (George & Wagner) regarded Dinantian and Silesian as sub-systems, Namurian, Westphalian and Stephanian being ranked as series.

The definition of the initial Silesian Sub-period markerpoint corresponds to the earliest occurrence of *Cravenoceras leion* (Heerlen Conference 1958) and the section at Little Mearley Clough, Pendle Hill, Lancashire, England was suggested as a boundary stratotype for deciding a reference point to mark also the initial Pendleian Age.

The division of the 'Carboniferous or Pennine' System into Coal Measures or Pennsylvanian (above) and Lower Carboniferous or Mississippian is attributed to H. S. Williams in 1891 (Wilmarth 1925). Williams also included in the Pennsylvanian the 'Coal Measure Conglomerate' or Millstone Grit (Pottsville Formation). Mississippian had already been in use since Winchell proposed it in 1869 as the designation of the Carboniferous or Mountain Limestone of the United States. By 1891 it already encompassed three groups of several formations. Ulrich in 1911 divided the Mississippian into Waverleyan and Tennesseean 'systems'. Anthracolithic was also used for Carboniferous by the USGS (Wilmarth 1925).

The Russian sequences have more to offer in the way of marine facies which are richly fossiliferous through to Permian rocks. Unlike those of western Europe and North America, Soviet Carboniferous rocks were classified into Lower, Middle and Upper which led to much ambiguity because Lower Carboniferous and Upper Carboniferous each span quite different times in each region.

Uralian (Ouralien) was proposed by de Lapparent in 1893 as the latest Carboniferous division intended as a marine equivalent of Stephanian but discontinued when many supposedly Uralian rocks proved to be Permian. Orenburgian was also proposed as the latest Carboniferous division in the southern Urals, and even recently this was shown as a Carboniferous stage above the Gzelian, but it was later abandoned as being part Permian (Sherlock 1948, p.14).

The conclusion of a long story in which three areas (western Europe, Russia and North America) seemed to be competing equally for the role of providing names and possibly stratotypes for a global Carboniferous scale seems now to be approaching and the proposal made here anticipates it. Chart 2.6 combines the recent thinking of some authorities and we are reinforced in this step by an impression

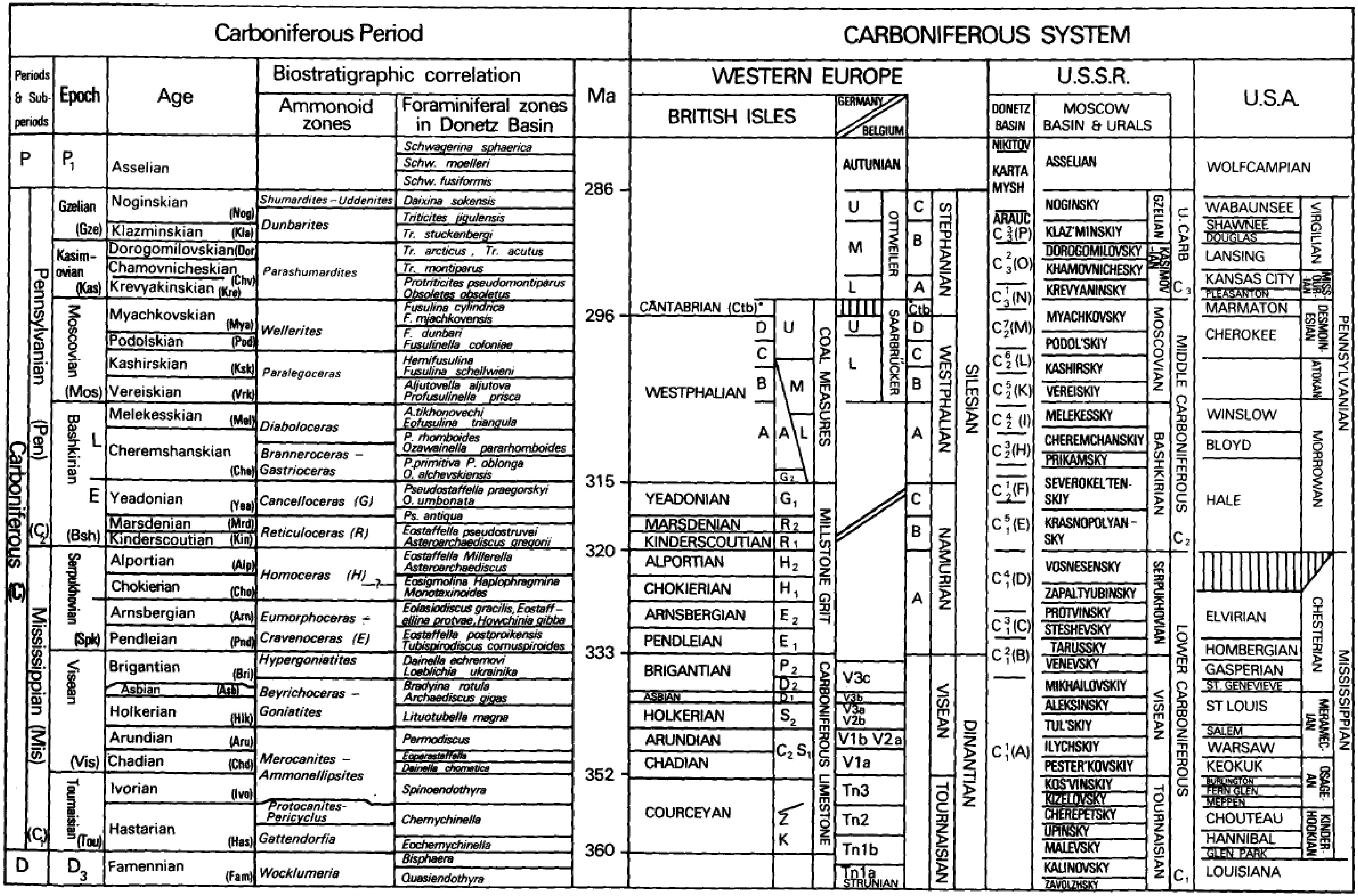

Chart 2.6. Carboniferous chronostratic scale and correlation.

that the Carboniferous Subcommission of IUGS may be formalising some such scheme (e.g. Ramsbottom 1981). We follow Bouroz and others in 1977 (Rotai 1979) in adopting Mississippian and Pennsylvanian as sub-systems for the international scale partly because of priority over Silesian but mainly because their mutual boundary coincides approximately with that of the Lower–Middle Carboniferous boundary in Russia. We propose then to use a largely European scheme for Mississippian divisions and a largely Russian scheme for the major part of Pennsylvanian. Apart from acknowledging by name the three regional communities that have contributed, this scheme also makes use of the detailed preparatory work in defining ages as well as epochs in the two Special Reports of the Geological Society of London (George *et al.* 1976, and Ramsbottom *et al.* 1978) and in the symposium: *The Carboniferous of the USSR* (Wagner, Higgins & Meyen 1979). We outline its epochs and ages in order.

2.8.1 The Mississippian Sub-period

The initial ***Tournaisian*** boundary is likely to be defined at a horizon approximating to the top of the Etroeungt Limestones and the base of the Hangenberg Kalk in Germany with the appearance of *Gattendorfia subinvoluta.*

'The level chosen represents an attempt at closest possible conformity with the current definition of the boundary, namely at the base of the *Gattendorfia* zone as recommended by the 1935 Heerlen Congress. It is at the first appearance of the conodont *Siphonodella sulcata* within the evolutionary lineage from *S. praesulcata* to *S. sulcata.* This is immediately below the lowermost record of *Gattendorfia* in Hönnetal. It is now essential to begin the search for the section best suitable as the boundary stratotype . . .' (from the recommendation and invitation of the Working Group on the Devonian–Carboniferous Boundary, Paproth 1980).

However, an initial reference point for the Devonian–Carboniferous boundary, while awaiting international definition, has been provisionally described in Ireland at a coastal section at the base of the Castle Slate Member of the Kinsale Formation (Irish National Grid 16242 04069; George *et al.* 1976, pp.6 and 7). George *et al.* accordingly used the Irish name *Courceyan* for the earliest Carboniferous division. It corresponds rather closely to Tournaisian and as the name Tournaisian has priority and is very widely used it would seem that Courceyan could only have regional value.

The Tournaisian Epoch is divided into two ages based in Belgium, namely ***Hastarian*** and ***Ivorian.*** These correspond indeed to the British zonal scheme K + Z and γ respectively and will be used by the British Institute of Geological Sciences as well as internationally by the IUGS Subcommission on Carboniferous Stratigraphy (Ramsbottom 1981). So it seems the Belgian names for these divisions are likely to be used. It does not, of course, follow that the ages will be defined at boundary stratotypes in the eponymous localities. There can only be one such reference point for each boundary and we are not clear whether that will be in Ireland, Belgium or elsewhere. The initial Hastarian boundary has been described at the stratotype at Hastière.

The ***Visean*** Epoch is approximately defined according to the Belgian biostratigraphic sequence (see chart). Attempts at precise definitions of the constituent ages made by George *et al.* (1976) are only briefly indicated here as follows.

The initial ***Chadian*** boundary (after St Chad) lies within the Chatburn Limestone Group at the base of the Bankfield East Beds near Clitheroe, Lancashire, England (National Grid SD 7743 4442). The initial ***Arundian*** boundary lies at the base of the Pen y holt Limestone on the east side of Hobbyhorse Bay in south Pembrokeshire, Wales (*arundo,* Latin for hobby-horse, National Grid SR 8800 9563). The initial ***Holkerian*** boundary lies at the base of the Park Limestone, in sea cliffs near Holker Hall, Cumbria, England (National Grid SD 3330 7827). The initial ***Asbian*** boundary lies at the base of the Potts Beck Limestone at Little Asby Scar, Cumbria, England (National Grid NY 6988 0827). The initial ***Brigantian*** (named for the Celtic tribe of Brigantes) boundary lies at the base of the Peghorn Limestone (lowest unit of Yoredale facies), in the east branch of River Eden, 5 km SSE of Kirkby Stephen, Cumbria, England (National Grid NY 7832 0375). The terminal Brigantian boundary would end the Dinantian regional sub-period.

Serpukhovian is perhaps an unsatisfactory name for the late Mississippian epoch; it approximates to Namurian A (?Namuralian a possible alternative).

The Serpukhovian ages are standardised in the British Isles (Ramsbottom *et al.* 1978, Ramsbottom 1981). The initial ***Pendleian*** boundary (as well as Serpukhovian, Namurian A, or Silesian boundaries) was proposed by the Heerlen Conference in 1958 to be at the base of strata containing the 'earliest occurrence' of *Cravenoceras leion* Bisat. A stratotype marker-point has been suggested at Little Mearley Clough, Pendle Hill, Lancashire, England or alternatively at Slieve Anierin, Co. Leitrim, Ireland. Pendleian, ***Arnsbergian, Chokierian, Alportian*** (i.e. to end of Namurian A and to the initial Pennsylvanian boundary) are each approximately equivalent to the goniatite zones used in Britain for many years, respectively E1, E2, H1 and H2, initiated by Bisat in 1928 (Ramsbottom 1981). We do not know of more precise definitions.

2.8.2 The Pennsylvanian Sub-period

The ***Bashkirian*** Epoch as defined here begins with the initial Kinderscoutian boundary which should also perhaps now define the initial Pennsylvanian boundary. The whole Epoch is usefully described with evidence for international correlation by Semichatova and others in Wagner *et al.* (1979).

The three ages ***Kinderscoutian, Marsdenian*** and ***Yeadonian*** were similarly defined in the British Isles, i.e. based on goniatite zones of Namurian B and C (Ramsbottom *et al.* 1978). These may be referred to collectively as early Bashkirian. The ages ***Cheremshanskian*** and ***Melekesskian*** are part of the standard Russian sequence and with all the later ages to the end of the Carboniferous Period are based on successions in the Moscow Basin and the Urals and are adopted for the standard scale but, as yet we think, without definition of boundary stratotype points.

The ***Moscovian*** Epoch is divided into four ages which are described in detail with biostratigraphic evidence for international correlation by Ivanova and others in Wagner *et al.* (1979). So far as we know the ages have been defined in biostratigraphic terms but not standardised at reference points in stratotypes.

The initial boundary of the ***Kasimovian*** Epoch (also the base of the Russian Upper Carboniferous) is suggested by Rotai (1979) to correspond to the incoming of *Protriticites pseudomontiparus – Obsoletes obsoletus,* i.e. at the base of Limestone N_2 of the Donetz succession. The three Kasi-

Permian Period							PERMIAN SYSTEM							
Period	Epoch	Age	Chron	Biostratigraphic correlation: Fusulinid zones	Biostratigraphic correlation: Brachiopods	Ma	N.W. EUROPE (GERMANY)	U.S.S.R.: EASTERN RUSSIAN PLATFORM	U.S.S.R.: TIMAN	JAPAN	AUSTRALIA (QUEENSLAND)	U.S.A. (DELAWARE BASIN)		
Tr	Tr_1	Griesbachian												
Permian (P)	Late (P_2)	Tatarian (Tat)		*Yabeina yasubaensis* and *Lepidolina toriyamai*		248	BUNTSANDSTEIN	VYATSKIY SEVERODVINSKIY URZHUMSKIY	RED CLAYS AND MARLS PYTYR'YUSKIY	KUMAN	? REWAN BARALABA TAMAREE	DEWEY LAKE	OCHOAN	UPPER PERMIAN
		Kazanian (Kaz)				253	OHRE 5 ALLER 4 LEINE 3	UPPER KAZANSKIY	VESLYANSKIY		U CURRA LST ? PELICAN CREEK	RUSTLER		
				Verbeekina verbeeki	*Cancrinelloides*		STASSFURT EVAPORITES 2 (ZECHSTEIN)				SCOTTVILLE	SALADO CASTILE		
							HAUPTDOLOMIT-STINKSCHIEFER	LOWER KAZANSKIY	CHEV'YNSKIY	AKASAKAN		CAPITAN	GUADALUPIAN	
		Ufimian (Ufi)		*Neoschwagerina craticulifera*	? *Lissochonetes*		WERRA ZECHSTEINKALK 1 KUPFERSCHIEFER	SHEMSHINSKIY SOLIKAMSKIY	UST'KULOMSKIY VYCHEGODSKIY		EXMOOR	WORD		
	Early (P_1)	Kungurian (Kun)	Irenian	*Neoschwagerina simplex*	*Pseudosyrinx*	258		IREN'SKIY	IREN' SKIY					
			Filippovian				WEISSLIEGENDES	FILIPPOVSKIY	VYL' SKIY					
		Artinskian (Art)	Baigendzinian	*Parafusulina kaerimizensis*	*Sowerbina* *Antiquatonia*	263	ROTLIEGENDES	IKSKIY	KOMICHANSKIY	NABEYAMAN	GEBBIE		LEONARDIAN	LOWER PERMIAN
			Aktastinian		*Jakutoproductus*				NERMINSKIY		SIRIUS SHALE			
		Sakmarian (Sak)	Sterlitamakian	*Pseudofusulina vulgaris*	*Tornquistia* *Attenuatella*	268		STERLITAMAK-SKIY	PEL' SKIY	SAKAMOTOZAWAN	TIVERTON			
			Tastubian		*Yakovlevia*			TASTUBSKIY	ILIBEYSKIY		LIZZIE CREEK		WOLFCAMPIAN	
		Asselian (Ass)	Krumaian	*Pseudoschwagerina morikawai*	*Tomiopsis*			KOKHANSKIY	NENETSKIY					
			Uskalikian		*Orthotichia*						BURNETT			
			Surenan		*Kochiproductus*	286		SOKOL'YEGORSKIY	INDIGSKIY		JOE JOE			
C	Gze	Noginskian		*Triticites*						HIKAWAN				

Chart 2.7. Permian chronostratic scale and correlation.

movian ages originated by reference to three foraminiferal zones.

The *Gzelian* Epoch as defined by Rotai (1979) corresponds to three fusulinid zones and is divided into two ages. It terminates with the initial Asselian (Permian) boundary. As already indicated, the latest Carboniferous and earliest Permian stratigraphy has been confused, in part by difficulties arising from previous correlations. Until recently the Upper Carboniferous in Soviet usage comprised an upper Orenburgian and a lower Gzelian stage, so it may seem odd that Chart 2.6 shows an earlier Kasimovian and a later Gzelian age to terminate the Carboniferous Period. But this seems now to be well established.

Chart 2.6 is constructed from the papers cited above. The biostratigraphic scheme has been taken from Rotai (1979, p.245), except that the biostratigraphic correlation of the Hastarian, Ivorian and Chadian ages has been modified according to a scheme proposed by the Carboniferous Subcommission in 1979, and kindly made available to us while in press by W. H. C. Ramsbottom, currently President of the Subcommission. The principal change was to show *Gattendorfia* rather than *Wocklumeria* as the initial Carboniferous zone.

2.9 The Permian Period

In 1841, after a tour of Imperial Russia, R. I. Murchison named the Permian System to take in the 'vast series of beds of marls, schists, limestones, sandstones and conglomerates' that surmounted the Carboniferous System throughout a great arc stretching from the Volga eastwards to the Urals and from the Sea of Archangel to the southern steppes of Orenburg. He named it from the ancient kingdom of Permia in the centre of that territory, and the city of Perm which lies in the flanks of the Urals. In 1845 he included rocks now known as Kungurian to Tatarian in age and for a time the underlying strata (Artinskian etc.) were known as Permo-Carboniferous (i.e. intermediate between Carboniferous and Permian).

Already by 1822 (e.g. Conybeare & Phillips) the Magnesian Limestone and New Red Sandstone of England were well known as were the equivalent German Rotliegendes and Zechstein (a traditional miner's name), with its valuable Kupferschiefer. However, they lacked richly fossiliferous strata, were difficult to correlate and inadequate to justify the erection of a new system in western Europe. The lack of fossils had been noted by d'Omalius d'Halloy in 1808 who referred to the Kupferschiefer as Terrain Penéen including at first a part of the Triassic Bunter. Permian in due course displaced Penéen in general use.

J. Mancou in 1853 recognised Permian rocks in a large area from the Mississippi to the Rio Colorado and noted two divisions analogous to those in western Europe. He accordingly suggested the name Dyassic as more suitable than Permian and proposed a combined Dyas and Trias as a major period (Zittel 1901). It is thus appropriate to preserve the division of the Permian Period in two epochs (or subperiods) – Early and Late – and the names for these, Rotliegendes and Zechstein, may be appropriate as recognising the earliest detailed stratigraphic researches in these rocks.

Karpinskiy in 1874 extended the Permian System in Russia downwards to include Artinskian and Sakmarian sediments.

The name Thuringian was introduced in 1874 as equivalent to Zechstein and in 1893 de Lapparent used a three-fold division with Thuringian as Upper Permian, Saxonian (= Upper Rotliegendes) as Middle and Autunian (from Autun, in France) for Lower Permian. As recently as 1978 a three-fold division has been suggested by Waterhouse, his middle epoch spanning Kungurian (Filipovian) to Djulfian or Dzhulfian (named after Dzhul'fa on the River Araks, Caucasus and ?part Tatarian, ?part Early Triassic) times; his Late Permian included our (Tozer's 1967) Early Triassic Griesbachian. After much debate the scheme of stages (or ages used here) was proposed by Likharev and others in 1966 and accepted by the GSL Working Group (Smith *et al.* 1974). However there appear to be many gaps in the Soviet successions, so that while our scheme of ages represents a likely standard for nomenclature and classification, little progress appears yet to have been made with regard to standardisation in stratotypes (Smith *et al.* 1974). To attempt in the space available to characterise the standard divisions by fossil zones for the Russian sequence would lead to excessive simplification, but indications of the origins of the names and classifications of the proposed standard ages are listed below from Kotlyar (1977).

2.9.1 The Early Permian Epoch

The earliest ***Asselian*** rocks in the Urals correlate with the earliest formed rocks containing *Triticites californicus* in North America, at the base of the Wolfcampian; the initial Permian boundary would therefore be defined between the zones of latest Pennsylvanian *Triticites coronadoensis* and the earliest *T. californicus.* It will be noted that the long uncertainty in both classification and correlation may well account for some rocks traditionally regarded as Carboniferous (e.g. later Stephanian C) being indeed Asselian. The boundary problem with respect to the USSR is reviewed by Rauser-Chernousova & Shchgolev (1979).

Rocks of ***Sakmarian*** age (from Sakmara, a tributary of the River Ural, in the southern Urals) originally included all deposits from the top of the Upper Carboniferous to the base of the Artinskian. In 1950 Ruzhentsev distinguished two sub-stages – Asselian (lower) and Sakmarian (upper) and the latter was then raised in rank.

Rocks of ***Artinskian*** age (named after Arti in the central Urals by Karpinskiy in 1874) are widespread in east European USSR and in central Asia and contain *Pseudofusulina* and primitive *Parafusulina.* The name has been used for the upper division of Lower Permian rocks and it has been divided into two sub-stages.

Rocks of ***Kungurian*** age (named after the town Kungur near Perm in the Urals, in 1890) have been included in the Artinskian stage and/or combined with Ufimian.

2.9.2 The Late Permian Epoch

Rocks of ***Ufimian*** age (from Ufa, Russia, in 1915, and also referred to as Ufian) were previously known as the 'lower red unit' or the 'lower division of the Permian System (P_1)' and 'lower

Triassic Period					TRIASSIC SYSTEM											
Per-iod	Epoch	Age	Biostratigraphic correlation	Ma	ALPS		GERMANY		SIBERIA		CHINA	NEW ZEALAND		NORTH AMERICA: CANADIAN ARCTIC ISLANDS	NORTH AMERICA: N.E. BRITISH COLUMBIA	NORTH AMERICA: S.W. NEVADA
J	Lias	Hettangian														
Triassic (Tr)	Late Triassic	Rhaetian (Rht)	*Choristoceras marshi*	213			RHÄTKEUPER		IUOSUCHANSKAYA		ERCHIAO	OTAPIRIAN			?	
		Norian L	*Rhabdoceras suessi*	219	DACHSTEIN-KALK OR											
			Himavatites columbianus													GABBS
		M	*Drepanites rutherfordi*		HAUPT-		STEIN-MERGEL				HUOBACHONG	WAREPAN		HEIBERG	PARDONET	
			Juvavites magnus		DOLOMIT								BALFOUR			
		E	*Malayites dawsoni*						KHEDALICHENSKAYA							
		(Nor)	*Mojsisovicsites kerri*													
		Carnian L	*Klamathites macrolobatus*	225			ROTE-WAND	KEUPER								
			Tropites welleri									OTAMITAN				
			Tropites dilleri		RAIBLER [SCHICHTEN]		SCHILF-SANDSTEIN				BANAN				GREY BEDS	LUNING
		E	*Sirenites nanseni*									ORETIAN				
	Tr_3	(Crn)	*Trachyceras obesum*				GIPSKEUPER							SCHEI POINT		
	Middle Triassic	Ladinian L	*Paratrachyceras sutherlandi*	231	CASSIAN	WETTERSTEINKALK	LETTEN-KEUPER									GRANTSVILLE
			Maclearnoceras maclearni											BLAA MOUNTAIN	LIARD	
			Meginoceras meginae		WENGEN				TOLBONSKAYA		FA LANG	KAIHIKUAN				
		E	*Progonoceratites poseidon*					MUSCHELKALK								
		(Lad)	*Protrachyceras subasperum*		REITZI											
		Anisian L	*Gymnotoceras chischa*	238												
			Gymnotoceras deleeni		RAMSAU-DOLOMIT						GUAN LING	ETALIAN	GORE			
		M	*Anagymnotoceras varium*													
	Tr_2	(Ans) E	*Lenotropites caurus*												TOAD	EXCELSIOR
	Early Triassic = Scythian (Scy); Olenekian (Olk)	Spathian	*Keyserlingites subrobustus*	243			RÖT; SOLLING FOLGE		SYGYNKANSKAYA	OLENEKIAN						
		(Spa)	*Olenikites pilaticus*				HARDEGSEN				YONGNINGZHEN	MALAKOVIAN				CANDELARIA
		Smithian	*Wasatchites tardus*				DETFURTH		MONOMSKAYA							
		(Smi)	*Euflemingites romunderi*		WERFEN		VOLPRIEHAUSEN									
	Induan	Dienerian	*Vavilovites sverdrupi*					BUNTER		INDUAN						
		(Die)	*Proptychites candidus*				OBERE-FOLGE							BJORNE/BLIND FIORD		
		Griesbachian L	*Pachyproptychites strigatus*				UNTERE FOLGE		UST'KEL'TERSKAYA							
			Ophiceras commune								FEIXIANGUAN	?			GRAY-LING	
		E	*Otoceras boreale*				BRÖCKEL-SCHIEFER									
	Tr_1 (Ind)	(Gri)	*Otoceras concavum*	248											?	
P	P_2	Tatarian														

Chart 2.8. Triassic chronostratic scale and correlation.

Permian Red Group'. Ufimian was adopted as the initial age of the upper epoch in 1960.

The ***Kazanian*** age (after the town of Kazan on the Middle Volga) was recently divided into seven (chrons). Some authors have combined it with Ufimian as the Kama age. Indeed Ufimian and Kazanian ages together comprise the earlier of the two divisions of the Late Permian Epoch.

Rocks of ***Tatarian*** age (named in 1887 after the Tartar people) were known as 'upper mottled units' or 'mottled marl stage' and were originally included within the Triassic System. Their exact equivalence is not easy to establish on a global scale; this difficulty reflects the regressive or other distinctive environments towards the end of the Paleozoic Era.

Stevens, Wagner & Sumsion (1979) described and listed twelve fusuline zones for the Early Permian succession in central Cordilleran America. Because they are not correlated with the Russian ages we have not attempted to fit them into Chart 2.7, but list them below, in order to give some indication of the sequence of fusuline faunas.

Leonardian
Parafusulina spiculata
Parafusulina communis
Parafusulina allisonensis
Parafusulina leonardensis

Wolfcampian
Schwagerina aculeata
Pseudoschwagerina convexa
Schwagerina cf. *S. crebrisepta*
Eoparafusulina linearis
Pseudofusulina hueconensis
Schwagerina bellula
Pseudofusulina attenuata
Triticites californicus

The fusulinid zones on Chart 2.7 are taken from a list from Japan, which is rich in fossils of the period (Takai, Matsumoto & Toriyama 1963). Brachiopods in the adjacent column are from the Canadian Arctic, which is not so remote from the USSR; the list and correlation are from Smith *et al.* (1974).

The other columns on Chart 2.7 are derived as follows: NW Europe and USA from Smith *et al.* (1974); Japan from Takai *et al.* (1963); Australia from Waterhouse (1978); the USSR columns from the unnumbered table that plots a comparative scheme of Permian sections abstracted from the whole work by Likharev (1966). Details of these two USSR columns are summarised in that work in Tables 1 and 2 and 4 and 5 respectively.

2.10 The Triassic Period

The Triassic System was established in Germany from the three-fold division into Bunter, Muschelkalk and Keuper by Alberti in 1834. The traditional stages (Scythian, Anisian, Ladinian, Carnian, Norian) were established in the marine Northern Calcareous Alps of Austria where, however, the ammonite zones first used have proved to be incomplete or not always in chronological sequence. For this reason, and because of the excellent Arctic successions and those from the Western Cordillera of North America, Tozer (1967) proposed 'a standard for Triassic time' in which ammonite zones were used to characterise the standard stages more precisely. New stages were proposed to divide Scythian or Early Triassic, for which epoch the name is useful and is retained. In that work Tozer went so far as to define boundary reference points in type sections; and because this is the essential method for defining the chronostratic scale we adopt it here almost in its entirety. Silberling & Tozer (1968) elaborated this scheme for North America as a whole. Therefore the chronostratic scale of the Triassic Period is largely from Table II of Tozer (1967) and the definitions are selected from that work as follows.

2.10.1 The Early Triassic (Scythian) Epoch

The Permian–Triassic transition is nowhere known to be fully represented by fossiliferous strata. A hiatus is generally evident and this is usually regarded as belonging to Permian time followed by the initial Triassic (Griesbachian) age that corresponds in Arctic Canada with the *Otoceras woodwardi* zone of the Himalayas. This is a controversial question involving as it does the difficult and classic problem of the Paleozoic–Mesozoic boundary so that other points of view abound. The boundary is thus proposed (perhaps unsatisfactorily) at the base of the Blind Fjord Formation of north-west Axel Heiberg Island.

Some scientists may doubt the value of dividing the Scythian Epoch into ages, it having been regarded as an age itself (e.g. Kummel in 1957). However, Spath in 1935 divided Early Triassic into Early and Late 'Eo-Trias' each with three subdivisions. His Early and Late divisions corresponded to the Induan and Olenekian ages of northern Siberia introduced by Kiparisova and Popov in 1956 (but changed in 1964). Tozer's four ages (1967) are accepted here. His Dienerian–Smithian boundary divides Scythian as above.

The ***Griesbachian*** Age (from Griesbach Creek, Axel Heiberg Island) was proposed by Tozer in 1965 (1967) and divided into two sub-ages each with two ammonite zones.

The initial ***Dienerian*** (from Diener Creek, Ellesmere Island) boundary is in the Blind Fjord Formation of north-western Ellesmere Island (Tozer 1967, note 16) and is generally recognised by the appearance of Gyronitidae. It is correlated in the Himalayas at the boundary between *Otoceras* and *Meekoceras* beds (Diener in 1912, see Tozer (1967)), and in the Salt Range between the *Ophiceras connectens* bed and the Lower Ceratite Limestone (Kummel & Teichert 1966).

The initial ***Smithian*** (from Smith Creek, Ellesmere Island) is also in the Blind Fjord Formation of north-western Ellesmere Island, corresponding to the boundary between the Induan and Olenekian stages of Kiparisova & Popov (1956, 1964).

The initial ***Spathian*** boundary (from Spath Creek, Ellesmere Island) is in the lower shale member of the Blaa Mountain Formation, the type locality being at Spath Creek, Ellesmere Island (see Tozer 1967; note 11) with a useful additional sequence in Axel Heiberg Island.

2.10.2 The Middle Triassic Epoch

The type locality for the ***Anisian*** Age is in Austria but it lacks ammonoids near its base. Tozer (1967) defined its initial boundary by the Caurus zone in the type locality (east limb of anticline west of Mile Post 375, Alaska Highway, north-east British Columbia, note 28).

The initial ***Ladinian*** (from Ladini, people of Tyrol) boundary is (for the same reason) not defined in the original Ladinian rocks of Italy but in the Humboldt Range, Nevada, USA (Tozer 1967).

2.10.3 The Late Triassic Epoch

Carnian is from the Carnic Alps (the alternative spelling Karnian as used by Tozer (1967) is from German rather than from the Latin form). The stage was introduced by Mojsisovics in 1869. The initial boundary of this age is based in the type locality at Ewe Mountain, 4 miles ENE of Triangulation Station 6536, Toad River area, north-east British Columbia (Tozer 1967, note 23).

The ***Norian*** (or Juvavic) stage of the Eastern Alps (Mojsisovics in 1895, and Diener in 1926) was divided into three parts but doubt has been thrown on their sequential arrangement.

Rocks of ***Rhaetian*** (from the Rhaetic Alps) age are not rich in pelagic fossils. They have been included within the Jurassic System (e.g. Arkell 1933) and there remains some question of correlation of the younger rocks with *Rhaetavicula contorta.*

The type locality of the initial Rhaetian boundary is at Brown Hill, Peace River, north-east British Columbia (Tozer 1967, note 20). The type locality for the original stage is at Kendelbachgraben, St Wolfgang, Austria, and the Rhaetian division (older than Hettangian with *Psiloceras planorbis*) is now unambiguously Triassic. However, according to our chart it spans only one ammonite zone in contrast to the six zones of Norian Age. Tozer (1979) suggested abandoning the Rhaetian division as an age and incorporating it in the Late Norian Sevatian sub-stage so as to replace the *Rhabdoceras suessi* and *Choristoceras marshi* zones by three zones of a revised Sevatian sub-stage – namely Cordilleranus zone, Amoenum zone (both approximately equivalent to the original Suessi zone), and a third Crickmayi zone to replace the Marshi zone. For the present we retain Rhaetian as a useful age.

A further point concerns the time interval immediately preceding the Jurassic Period as defined approximately by the arrival of *Psiloceras planorbis.* The Blue Lias begins with pre-Planorbis beds which are therefore Triassic. Hallam (1981) has suggested that such a conclusion would amount to stratigraphic pedantry because 'common sense dictates that the horizon of most notable facies change over a wide area, coinciding as it does almost exactly with the appearance of the first Jurassic ammonites, should be taken as marking the system boundary'. In spite of these strictures we adhere to the recommendation of the Stratigraphy Committee of the GSL (George *et al.* 1969, p.53) and reaffirmed in Section 2.11.1 of this chapter (following Cope *et al.* 1980b) for the definition of the initial Hettangian (Jurassic) boundary. Lithostratigraphic boundaries are defined at facies changes but chronostratigraphic boundaries should be standardised within a sequence of uniform facies so the Blue Lias would appear to serve this purpose well and its basal pre-Planorbis beds are therefore Triassic.

2.10.4 Triassic Time Scale

As explained in Chapter 1, Chapters 3 and 4 were completed before Chapter 2 and its charts. The time scale adopted the principle of distributing ages equally between tie-points. It will be seen that the calculations were made on the basis that Scythian was one age unit and Rhaetian another. We now argue that on a quantitative basis Scythian corresponds to more than a division of unit duration and, from what appears above, Rhaetian would appear to represent about a sixth or so of Norian time. Unfortunately we cannot just apply the Rhaetian surplus of time to augment our Scythian interval because a tie-point falls between them. To re-adjust the ages through a much longer time span is of course necessary to make the best time scale, and we leave it to the next attempt at a time scale to do this. We merely point the way to a needed revision, partially satisfied that our main contribution may be to display the reasoning behind the construction of a time scale.

The columns to the right of Chart 2.8 have been based as follows: Alps on Sherlock (1948); Germany on Warrington *et al.* (1980); Siberia on Kiparisova, Radchenko & Gorskiy (1973); China on Chen (1974); New Zealand on Suggate, Stevens & Te Punga (1978); Canadian Arctic Islands and NE British Columbia on Tozer (1967); and SW Nevada of Kummel (1961, p.574).

2.11 The Jurassic Period

Between 1797 and 1815 William Smith published successions and geologic maps of England and Wales in which detailed stratigraphy of successive strata of Jurassic age played a key part, the sequence in England being especially well displayed. Many of these were grouped as the Oolite Formation by Buckland in 1818 or Oolitic Series (divided into Lower, Middle and Upper Oolites) overlying the Lias by Conybeare & Phillips (1822). They were equated with the Jura-Kalkstein of Alexander von Humboldt who in 1795 so referred to the Calcaire de Jura (thinking they were older than the Muschelkalk). From this Alexander Brongniart in 1829 first used the name Terrains Jurassiques but only for the Lower Oolitic Series of Conybeare and Phillips. In Britain until recently the name Jurassic coexisted with the earlier named constituent parts: Lias and Oolites. The above history is surveyed by Zittel (1901), Wilmarth (1925), Arkell (1933, 1956) and Torrens in Cope *et al.* (1980a, b).

Because of the immense wealth of fossils, particularly ammonites, in the Jurassic rocks of Britain, biostratigraphic zonation was generally further advanced than for rocks of all other periods and many distinguished scientists (e.g. Buckman and Oppel) contributed to this. By 1933 Arkell was able to review the Jurassic rocks of Britain, and in 1956 of the world. The scheme here is the same as that developed by Arkell as a European standard from 1946 to 1956 except dividing the Bajocian and we have used Tithonian in place of Arkell's Portlandian and Purbeckian; the latter with freshwater facies had no ammonite zones to characterise it and is in any case partly Cretaceous in age.

For the three standard Jurassic epochs it may be objected that we have used the old rock names Lias, Dogger and Malm in preference to Early, Middle and Late. We think they are of more use in this rôle than as their diverse rock terms but time will tell. Their context will distinguish their intended use.

Perhaps because of the success and relative precision of ammonite zonation, which may approximate more closely to isochronous horizons than biostratigraphic criteria can attain for other periods, the difference between biozones and chronozones has been confused by many writers. But the principle is simple and is the same for all strata. Time divisions of the chronostratic scale are for general use; they must be *defined* by reference points in boundary stratotypes and *correlation* with these reference sections will be correspondingly good because of the advantages that Jurassic ammonites confer. Biostratigraphic units on the other hand are defined only by the presence of their stated fossil content. Chart 2.10 illustrates biostratigraphic correlation with the reference scale.

In the following list of ages the definition of the initial boundaries follows the UK recommendations to the Colloque Jurassique in Luxembourg (July 1967) and the UK Contribution to the International Geological Correlation Programme submitted in Prague in 1968 to the IUGS by the Royal Society (later reprinted in George *et al.* 1969). The boundary definitions will only be indicated here and in any case generally await a firm decision. These ages are summarised and approximately equivalent rock sequences in some other parts of the world are given in Chart 2.9. The classic 74 or so zones are listed in Chart 2.10 (Cope *et al.* 1980a, b). It may be noted that each age on average spans about 5 biozones and 10–15 subzones and these are potential chrons for standardisation in the future. However, as now used they are conceived as standard time divisions or chrons. To make this clear chrons and subchrons, although named from the original zonal name, will in due course be defined by reference points in boundary stratotypes and they should be printed in roman rather than in italic type.

2.11.1 The Early Jurassic (Lias) Epoch

The ***Hettangian*** initial boundary (name from Hettange, France) is recognised by the first appearance of the genus *Psiloceras*. The initial boundaries of the Planorbis Chron and of the Jurassic Period coincide with it. Oppel (in 1856, pp.24–8) described sections at Lyme Regis and in quarries near Uplyme, Dorset, England, as being characteristic of the Planorbis Zone; he also referred to the coastal section at Watchet, Somerset, England. Morton (1971, p.84) recommended that the coastal section between Blue Anchor and Quantock's Head, in the Watchet area, be regarded as the type area of the Planorbis Zone. Cope *et al.* (1980b) regard the Planorbis Subzone as being 'clearly and unequivocally acceptable as the basal subzone of the basal Jurassic Planorbis Zone' (p.22). The portion of the Blue Lias Formation below the base of the Planorbis Subzone, together with the 'Watchet Beds' and the Penarth Group, are thus of Triassic age.

The ***Sinemurian*** initial boundary (name from Sémur, France) is also that of the Bucklandi Chron and the Conybeari Subchron. No type area for the Bucklandi Zone was given by Oppel in 1856. The Conybeari Subzone was founded in the Keynsham area, Somerset, England, but lack of permanent sections renders it unsuitable as a type area. Morton (1971, p.85) recommended that the type area be designated 50 miles SSW of Keynsham, on the Dorset coast, SW of Lyme Regis. Here the base of the Conybeari Subzone is placed at the base of Lang's bed 21, which outcrops at Seven Rock Point and at Devonshire Head. An exactly designated type locality remains to be decided.

The ***Pliensbachian*** initial boundary is also that of the Taylori Subchron and the Jamesoni Chron. According to Morton (1971, p.85) 'there is no explicit type section for the Taylori Subzone, but it was first used with reference to the Dorset coast section' (south England). There it is seen in Lang's (1928) bed 105, the base of the Belemnite Marls, separated from the underlying bed 104 by a nonsequence (Spath 1956, p.148). Bed 105 outcrops near Charmouth. At Pliensbach in south-west Germany, the upper two subzones of the Sinemurian Raricostatum Zone are absent (Geyer, 1964, p.165). Morton (1971, p.85) regarded the Pliensbach section as being 'acceptable for defining the Pliensbachian Stage in terms of its basal subzone... Here, the Taylori subzone rests nonsequentially on the lower part of the Raricostatum Zone.'

The ***Toarcian*** initial boundary (name from Thouars, France) is also that of the Tenuicostatum Chron. Morton (1971, p.85) designated the outcrop west of Kettleness, on the north Yorkshire coast, England, as the type section of the Tenuicostatum Zone, and therefore for the basal Toarcian. The marker-point for the base of the Zone is between beds 28 and 29 of Howarth (1955).

2.11.2 The Middle Jurassic (Dogger) Epoch

The name ***Aalenian*** was proposed by Mayer-Eymar in 1864 for the lowest part of the 'Braunjura' in the vicinity of Aalen, Germany at the northern edge of the Swabian Alps. The initial Aalenian (and so Middle Jurassic) boundary is recognised at the base of the Opalinum Zone. However only later Aalenian is represented near the present-day village of Aalen-Attenhofer so an initial boundary stratotype elsewhere is needed. Some workers have regarded Aalenian as Early Bajocian in a three-fold division (e.g. Morton and others at the Colloque Jurassique at Luxembourg, 1967). We have accepted Aalenian as a distinct age and so divide Bajocian into Early and Late only. Arkell's Scissum Zone inserted between Opalinum and Murchisonae zones is not so useful in Europe where the index fossil is found in earlier and later beds.

The ***Bajocian*** was introduced by d'Orbigny in 1852 for strata outcropping near Bayeux, France (hence the name). Its initial boundary would be taken at the base of the Discites Zone (since the Aalenian is being treated here as a separate age). On the northwestern periphery of the Anglo-Paris Basin, the Bajocian is represented by the Middle and Upper Inferior Oolites (and the Aalenian by the Lower Inferior Oolite).

The ***Bathonian*** initial boundary (name from Bath, England) is that of the Zigzag Chron (and the Convergens Subchron) at the base of bed 23 of Sturani (1967) at the Bas Auran section, 4 km W of Barrême, Basses-Alpes, south-east France.

The initial boundary of the ***Callovian*** (name from Kellaway, England; Kellaways Rock) and that of the initial Macrocephalus Subchron was proposed with the Chippenham–Trowbridge area, Wiltshire, England as the type area (of the Macrocephalus Subzone). No exact type section has yet been designated.

2.11.3 The Late Jurassic (Malm) Epoch

The initial boundary of the ***Oxfordian*** (name from Oxford, England; Oxford Clay Formation) is that of the Mariae Chron and Scarburgense Subchron, and seems to be better defined in the cliff of Cornelian Bay, 3 km SE of Scarborough, Yorkshire, England, than in the earlier standard on the shore at Auberville, Normandy, France. Fortunately, conflict is avoided, since 'the Oxford Clay of the