TRANSACTIONS
OF THE
EDINBURGH GEOLOGICAL SOCIETY
VOLUME 17, PART 3

A Revised Geological Time-Scale

ARTHUR HOLMES

(MS received 14th December 1959)

ABSTRACT

The time-scale constructed in 1947 was based on certain assumptions that have recently been shown to be wrong. Appalachian pegmatites dated at 350 million years (m.y.) and thought to be *Taconic* (Ordovician) are now found to be *Acadian* (late Devonian), while others, dated at 255 m.y. and thought to be *Acadian* can now be referred to the Permian. Other recent evidence consistently leads to an extension of the 1947 scale that carries the beginning of the Cambrian back to about 600 m.y. ago. The scale now constructed from the data available up to October, 1959, is as follows (in m.y.):

Tertiary	70	
		70 ± 2
Cretaceous	65	
		135 ± 5
Jurassic	45	
		180 ± 5
Triassic	45	
		225 ± 5
Permian	45	
		270 ± 5
Carboniferous	80	
		350 ± 10
Devonian	50	
		400 ± 10
Silurian	40	
		440 ± 10
Ordovician	60	
		500 ± 15
Cambrian	100	
		600 ± 20

One of the more significant consequences of this revision is that many dated rocks from Africa and the other "Gondwanaland" continents which were formerly ascribed to the late Precambrian now become Cambrian. Important orogenic and plutonic phases of a major geological cycle, implying by analogy an extensive system of geosynclines, occurred at about the close of the Precambrian and early in the Ordovician.

CONTENTS

I. The Need for Revision

My 1947 attempt to construct a time-scale for the geological periods since the end of the Precambrian has now outlived its usefulness. Of the two alternatives then proposed, the " B scale " in particular enjoyed an unexpected success for ten years in a wide variety of scientific fields. But now I come to bury the B scale, not to praise it. As a result of the developments in geochronology during the last two or three years it has become doubly out of date, and henceforth it should be regarded as of no more than historical interest. The revised time-scale presented in this paper, while appropriate to the information available in 1959, will also require revision in its turn, since each year the dated control points become more numerous, more precisely fixed, and less unevenly distributed through the geological column. Meanwhile, however, it is not unreasonable to hope that subsequent modifications will be far less drastic than those now called for.

" B scale " correlations		Dates in m.y. available in 1947	1959 interpretations	
End Cretaceous	*Laramide*	58	*Laramide*	End Paleocene phase
Late Carboniferous	*Asturian*	214	(now *ca* 250) *Saalian* and *Appalachian*	Late Upper or Early Middle Permian
End Devonian	*Acadian*	255	(*Asturian*, now *ca* 280)	
End Ordovician	*Taconic*	350	*Acadian*	End Devonian
			(*Taconic*, now *ca* 470)	Mid Ordovician
Upper Cambrian, *Peltura* zone		440	(now 500 +)	

The 1947 scale was tied to the five dates listed in the middle column of the adjoining table. These were calculated from the results of Nier's classic work (1939 and 1941) on the lead isotopes of chemically analysed radioactive minerals of which the geological age was known, or thought to be known, at least approximately. In order to estimate dates for the beginning and end of each period by interpolation, I adopted a modification of Samuel Haughton's celebrated principle of 1878 that "the proper relative measure of geological periods is the maximum thickness of the strata formed during those periods", and plotted the five dates against the cumulative sums of the maximum thicknesses in what were thought to be their most probable positions (*cf.* Fig. 2). I am fully aware that this method of interpolation has obvious weaknesses, but at least it provides an objective standard and, so far as I know, no one has suggested a better one. The only practicable alternatives introduce a subjective element, as, for example, the preference for Welsh thicknesses expressed by O. T. Jones (1956, p. 331) with their implication that the Lower Palaeozoic periods were all of about equal duration.

Looking back, it is easy to see how the errors in the B scale arose, and also how it came to be so long before the errors were detected. 440 m.y. continued to be accepted as the probable age of the Swedish Kolm (*Peltura* zone) until 1958, when Kulp and his colleagues at the Lamont Geological Observatory investigated more than a score of samples (Cobb and Kulp, 1958; *in press* 1959). They found considerable variation from sample to sample, the pattern of the results pointing to just over 500 m.y. as more likely to be the correct age (Kulp, Cobb *et al.*, 1959). About the same time the dating of the Acadian granitic rocks of Acadia itself (Nova Scotia and adjoining parts of New England) made it necessary to extend the Palaeozoic part of the time-scale by 70 to 90 m.y. Before this, however, several other sets of results had tended to support the B scale. With the development of the K/A method of dating potassic minerals and rocks it was hopefully expected that lavas and glauconite-bearing strata of known geological age would soon be precisely dated. Unfortunately, many of the " glauconite ages " so determined have turned out to be too low to fit the revision indicated above. They did, however, cluster along the B scale remarkably well (Fig. 1). Finally, an upper limit to the base of the Cambrian appeared to be set by a date of about 580 m.y. assigned to a late Precambrian granite in South Australia (Campana, 1954). This is also now known to have been too low. These considerations are dealt with in the appropriate sections of the paper.

II. Dating the Plutonic Events of the Appalachians

Having adopted 440 m.y. for the *Peltura* zone of the Upper Cambrian, and 214 m.y. for the late Carboniferous (Holmes, 1947, p. 142), it would have been inconsistent not to correlate the intervening dates, which were for Appalachian pegmatite minerals, with the plutonic events accompanying the Acadian and Taconic orogenic phases, especially as these correlations were not at variance with the supposed geological relationships of the two suites of pegmatites. Indeed, in two recent contributions to Appalachian geochronology Eckelmann and Kulp (1957, pp. 1125-1127) and Long and Kulp (1958) found no reason to dissent from them, although they have since done so (Long, Kulp and Eckelmann, 1959).

However, during 1958 the M.I.T. team (Hurley *et al.*, 1958, pp. 28-47 and 107) were applying the K/A and Rb/Sr dating methods to micas from a large number of the post-Lower Devonian granitic rocks of Acadia. The ages found lie mainly within the range 350 to 370 m.y. So for the first time it was demonstrated that rocks of this age, previously dated by pegmatite minerals from New York, Connecticut and North Carolina, were amongst the products of Acadian plutonic events—not Taconic, as had been conjectured. Long, Kulp and Eckelmann (1959) have more recently published further data, together with a comprehensive review of Appalachian geochronology. They now agree that the Taconic orogeny cannot be placed at 350 m.y., which they recognise as the focal date of the major Palaeozoic metamorphic event in the southern Appalachians. They add, however: ' It cannot yet be decided whether the 350 m.y. metamorphism . . . is to be correlated with the Acadian or younger Mississippian activity."

This uncertainty is partly a matter of definition. Here and in much other current work, the measured range in time of the rocks associated with a particular orogenic phase is considerably greater than the probable error of single determinations. For the granitic rocks of Acadia the actual range is from 330 to 390 m.y. This suggests that there are probably real differences in the ages of the rocks concerned, *i.e.* in the times of their final crystallisations. Such differences are to be expected and, moreover, they would be in harmony with the growing recognition that tectonic activity is locally episodic and varies greatly in intensity from place to place over a considerable span of time, instead of being contemporaneous in different parts of the globe during relatively short spasms or "phases" (King, 1955). Stille's persuasive influence in favour of the latter interpretation is waning, but his pioneer spectrum of the main orogenic crises, though incomplete, continues to serve as a basis for further discovery. One such development, arising from both field work and geochronology, is that terms like *Taconic* and *Acadian* are no longer expected to connote events limited by sharply defined dates. More probably the movements and plutonic events to which they refer were continued intermittently during many millions of years. An orogeny appears to be like a fugue, with overlapping repetitions which are themselves variations of the basic theme. Further work, now in progress, will show whether the Acadian "movement" was a long fugue that locally continued into the early Carboniferous, or whether, during the Upper Devonian, it faded away during a time of comparative rest sufficiently long to justify calling the next "movement" by a new name.

The younger pegmatites of Connecticut, with ages around 250 m.y., now fall into the Permian and are presumably products of the so-called Appalachian "revolution", which was formerly supposed—quite unaccountably—not to have been accompanied by metamorphism and igneous activity (Hess, 1955).

So far there are only a few dated rocks—and those only provisionally—that might be referable to the Taconic orogenic phase. In Maine, a large body of biotite-bearing gabbro that is older than the Taconic unconformity has been dated by Faul (*in* *press*, 1959) at 459 and 469 m.y. by the K/A method on biotite. Long, Kulp and Eckelmann (1959) have dated biotite from metamorphosed diabase dykes in North Carolina at 455 m.y. This figure is necessarily a minimum, since the area could not have remained unaffected by the 350 m.y. metamorphism. Woodward (1957) has recorded evidence that relatively little deformation can be assigned to the "closing days of the Ordovician". Much of the Taconic activity seems to have occurred about Middle Ordovician time, with which the above minimum datings would be consistent (see also p. 196).

Now that it is realised that most of the plutonic events of the Appalachians have hitherto been attached to the wrong orogenic phases, the necessary data for re-writing the history of this classic orogenic belt will soon be forthcoming. Several enthusiastic teams are currently engaged in furnishing dates with steadily increasing precision: *e.g.* Carnegie Institution and U.S. Geological Survey (Washington); Department of Geology and Geophysics, M.I.T. (Cambridge, Mass.); Lamont Geological Observatory (Palisades, New York).

III. The K^{40}/A^{40} and Rb^{87}/Sr^{87} Methods of Dating

In recent years the methods of age measurement based on the accumulation of lead isotopes in radioactive minerals containing uranium (U^{238} and U^{235}) and/or thorium (see Kulp *et al.*, 1954; and Stieff *et al.*, 1959) have been greatly reinforced by the successful development of new methods based on the radioactive isotopes of potassium, K^{40}, and rubidium, Rb^{87}. Since potassium minerals such as feldspars, micas and glauconite usually contain rubidium, they can, in principle, be dated by two independent methods. Glauconitic sediments and potassic lavas of which the geological age is known should eventually provide data for an increasingly accurate time-scale. In pegmatites that contain uranium and thorium minerals as well as feldspars and micas five independent age measurements are now practicable (see Aldrich and Wetherill, 1958, for a general review).

The radioactivity of Rb^{87} is of the simplest kind. On disintegration an atom of this isotope loses a β-particle (*i.e.* an electron) from its nucleus, which means that a neutron has become a proton, thereby transforming the atom into an isotope of strontium, Sr^{87}. The half-life of Rb^{87} is 50,000 m.y. to within a few per cent (Aldrich *et al*., 1956).

The radioactivity of K^{40} is more complex. Of the atoms that disintegrate about 89 per cent behave like Rb^{87}, each losing a β-particle from its nucleus and so changing to Ca^{40}. Since ordinary calcium is almost ubiquitous and is itself mostly Ca^{40}, the production of this isotope in potassic minerals is of no value for dating purposes except in a few late evaporite minerals, such as sylvite, which may have been initially free from ordinary calcium (see p. 200 for an example). The remaining 11 per cent of the K^{40} atoms are transformed by an opposite process, so to speak. Each nucleus captures an orbital electron, so that a proton becomes a neutron, and the atom is changed into an isotope of argon, A^{40} (Wetherill, 1957; Carr and Kulp, 1957; Aldrich and Wetherill, 1958).

The ages reported in this paper are all based on the following data; where necessary, the ages have been recalculated.

Radioactive parent isotope	End product	Disintegration constant, λ, per year	Half-life in millions of years
U^{238}	Pb^{206}	$1{\cdot}541 \times 10^{-10}$	4,498
U^{235}	Pb^{207}	$9{\cdot}722 \times 10^{-10}$	713
Th^{232}	Pb^{208}	$0{\cdot}4987 \times 10^{-10}$	13,900
Rb^{87}	Sr^{87}	$0{\cdot}139 \times 10^{-10}$	50,000
K^{40}	Ca^{40}	$4{\cdot}715 \times 10^{-10}$	1,470
	A^{40}	$0{\cdot}585 \times 10^{-10}$	11,850

Argon, being a gas, tends to escape by outward diffusion from minerals in which it has accumulated, such leakage being facilitated by heating, shearing, weathering, etc. By comparison with the lead and Rb/Sr ages of minerals from the same pegmatite, it was soon found that leakage was generally considerably greater from feldspars, where it might be up to 30 per cent or more, than from micas, where the deficiency is usually confined to within five per cent. The first attempt to date the Lewisian pegmatites of Harris and the North-West Highlands of Scotland provides a striking example of how misleading the K/A method may be (Holmes, Shillibeer and Wilson, 1955). Calculated with constants that were considered to allow for argon leakage, the K/A ages for the younger, Laxfordian, suite of pegmatites ranged from 930 to 1,140 m.y. Samples from the same specimens, sent to Harwell for check determinations and there dated by the Rb/Sr method, gaves ages ranging up to $1{,}900 \pm 350$ m.y. (Smales *et al.*, 1958). Attempts to date the older, Scourian, suite of pegmatites were even less successful, two samples giving K/A ages of only 800 and 880 m.y. The Rb/Sr method, however, shows that the Scourian pegmatites are about 2,700 m.y. old (Giletti, 1959). The division of the Lewisian into Laxfordian and Scourian by Sutton and Watson (1950) is far more dramatic in terms of time than could have been suspected a few years ago.

These remarkable discrepancies indicate that the pegmatite-feldspars, despite their beautifully fresh appearance, had at some stage or stages in their history lost very much more argon than could be accounted for by normal leakage. Laxfordian activity would be expected to drive off most of the argon accumulated in the Scourian pegmatites up to that time, and subsequent invasion of the region by pre-Torridonian dykes would reduce the argon contents of both suites of pegmatites to proportions that would vary locally with the rise of temperature. The resulting K/A ages, being far too low, originally suggested a correlation of the Lewisian pegmatites with those of the Grenville orogenic belt of Ontario and Quebec. Now, however, it appears that the Laxfordian suite is comparable in age with the Svecofennian pegmatites of Finland (Kuovo, 1958) and Sweden; while the Scourian suite corresponds in age to the Keewatin suite of the Canadian Shield and to the oldest known pegmatites (Kola Peninsula) of the Baltic Shield (Polkanov and Gerling, 1958).

Returning to the K/A method: it is only fair to point out that the Lewisian discrepancies cannot be referred to experimental error. In the course of the same investigation (Holmes, Shillibeer and Wilson, 1955) the same K/A method was applied by Shillibeer to a series of feldspars from Svecofennian pegmatites. The resulting ages averaged 1,810 m.y. and this has since been amply confirmed by the recent work of Finnish and Russian teams, whose results, based on the lead method, range between 1,800 and 1,850 m.y.

Two morals may be drawn from this Lewisian story. First, it must not be thought that low K/A ages are useless. In this particular case they show that the Torridonian, already known to be Precambrian, is also younger than about 800 m.y. and therefore of very late Precambrian age. The second point is that, taken by themselves, the K/A ages of feldspars and micas from pegmatites are of dubious value in constructing a time-scale. Given a geological history favourable to their having remained a closed system, these minerals may retain most of their radiogenic argon, but whether or not this has been so cannot be known unless the K/A ages have been confirmed, or otherwise, by one or more of the other methods available. Phenocrysts from close-grained lavas or from tuff-flows, such as ignimbrite, appear to be much more reliable (Evernden, 1959).

Where Rb/Sr and K/A ages have both been measured on micas from the same igneous rocks, the K/A age is almost invariably the lower (Aldrich *et al.*, 1958, p. 115). This difference is, of course, to be expected, but a remarkable anomaly in the other direction is that in some metamorphic rocks the K/A age of biotite turns out to be conspicuously higher than the Rb/Sr age (*loc. cit.*). The implication is that during the metamorphism not all the pre-existing radiogenic argon escaped, so that the recrystallised biotite began its life with a certain amount of inherited argon enclosed within it, possibly occupying some of the "hexagonal" spaces of its crystal lattice. The interest of this discovery is essentially geochemical and petrogenetic. At least in part, it may indicate the significance of the high and varied K/A ages recorded by Mayne *et al.* (1959) for biotite from Shap granite (475 to 510 m.y.). However, these preliminary results by the Oxford team would require confirmation before such weighty inferences could be drawn from them. Kulp (1959, a) records 400 m.y. for Shap biotite, and there is other evidence that the Oxford results are too high for use in constructing a time-scale. The paper by Mayne *et al.* (1959) has already been fully discussed by Davidson (1959, a) and Kulp, Cobb *et al.* (1959).

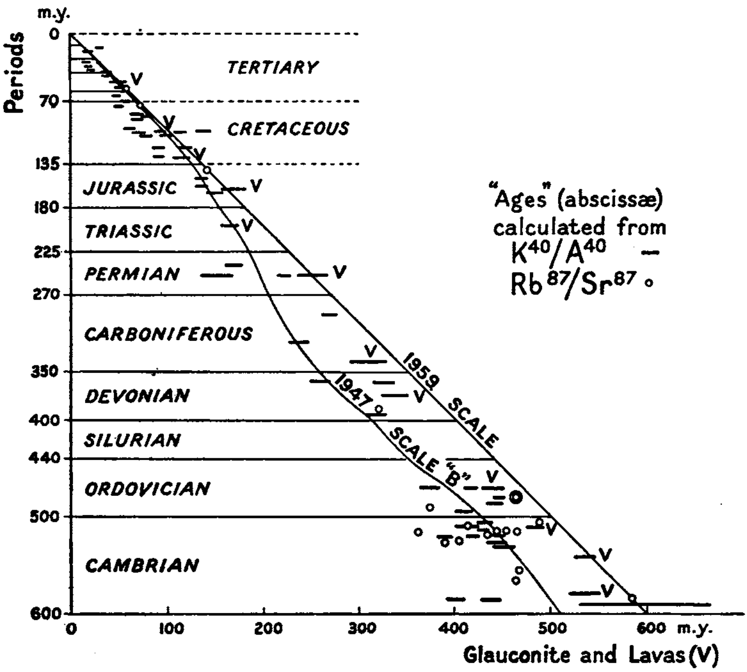

FIG. 1. The 1947 "B scale" and the 1959 scale are plotted against the latter (shown vertically on the right), together with the K/A and Rb/Sr ages of glauconites and lavas of known stratigraphical horizons.

The advantages and limitations of glauconite as a timekeeper for dating sedimentary rocks of known stratigraphical horizons have been reviewed by several workers, *e.g*, Lipson (1958); Curtis and Reynolds (1958); Cormier (1957). Obviously the greatest care must be taken to ensure that all traces of older detrital materials are removed; otherwise the measured age will be too high. On the other hand, glauconite is sensitive to slight chemical changes in its environment, such as might be due to ground-waters or incipient, though imperceptible, weathering. Not only may outward diffusion of argon occur, but in the course of processes like base exchange radiogenic strontium, Sr^{87}, may also be lost. Consequently glauconite ages are commonly more or less low. Kazakov and Polevaya (1958) and Evernden (1959) find that glauconites obtained from the cores of deep bore-holes give higher and presumably more reliable ages than those that have been exposed to near-surface conditions. It is therefore possible that with more selective sampling some of the initial hopes based on glauconite may yet be fulfilled.

Meanwhile Fig. 1 clearly demonstrates why the B scale of 1947 remained so long uncorrected. The glauconite ages, though scattered, decisively favour the older scale. But the ages of the volcanic rocks or their phenocrysts (marked "V" on Fig. 1), for the most part more recently determined, are not inconsistent with the 1959 scale, if allowance be made here and there for slight leakage of argon.

IV. Limiting Dates for the Base of the Cambrian

A fairly well defined limit to the age of the base of the Cambrian is set by the dating of the pre-Sturtian uraniferous granite of the Adelaide System in South Australia. The relevant sequence (Glaessner, 1958) may be summarised as follows:

Lowest Cambrian limestones

Adelaide System

Marinoan Series with the Pound Quartzite at the top, containing an assemblage of fossils entirely unlike any known Cambrian fauna (Glaessner, 1959)	Max. thickness 24,000 feet
Sturtian Series with Tillites containing pebbles of the underlying U-granite and pegmatites	

Emplacement of U-granite and pegmatites and their subsequent exposure by erosion

Torrensian Series

The U-granite and pegmatites contain a thorian variety of brannerite known as "absite", two specimens of which from Crocker's Well have been dated by the complete lead method, with the following results (in millions of years):

	Pb^{206}/U^{238}	Pb^{207}/U^{235}	Pb^{207}/Pb^{206}	Pb^{208}/Th^{232}
J. L. Kulp *in* Campana, 1954	520	600	(915)	585
Greenhalgh and Jeffery, 1959	610	674	895	675

In Campana (1954), and Campana and King (1958), the bracketed age corresponding to 207/206[1] is not given, and Kulp is quoted as suggesting 580 ± 30 m.y. as the "best" age. This led Glaessner to write in 1958, "Recent datings of pre-Sturtian uraniferous granites in South Australia show that the middle portion of the Adelaide System is well within the Late Proterozoic." The latter term was adopted by Glaessner to cover the 80 m.y. preceding the beginning of the Cambrian, which he placed at 520 m.y.

The bracketed 207/206 age was not published until 1959, when Kulp's results were given in full by Greenhalgh and Jeffery, together with their own. The pattern of Kulp's results implies loss of both radon and lead and cannot be uniquely interpreted. It is most likely to mean, however, that the real age is higher than 585 and 600 m.y., with 915 m.y. as an improbably high upper limit. The new set of results by Greenhalgh and Jeffery makes a typical loss-of-radon pattern, with 674 m.y. as the probable age. This is strongly supported by the 208/232 age of 675 m.y. But in view of the evidence that Kulp's specimen had lost lead as well as radon, the possibility that the other might also have lost a little lead needs to be allowed for. Here again no unique solution is possible, but a few trial calculations show that a maximum age of about 700 m.y. is all that can be accommodated consistently with the analyses.

The age limits adopted for the pre-Sturtian granite are 675 and 700 m.y., and these are the values plotted at the bottom right-hand corner of Fig. 2. Combined with the maximum thickness (24,000 feet) of the post-granitic Precambrian formations of the Adelaide System (Campana and Wilson, 1955) they point to 600 ± 20 m.y. as a reasonable estimate for the beginning of the Cambrian.

It is here accepted that the base of the Cambrian System is the stratigraphically lowest formation in which the biozone of *Olenellus* or its equivalent is represented; and, moreover, that it is also the base of the Palaeozoic. Ill-defined terms like "Eo-Cambrian" confuse the issue in two ways. They appear to extend the Palaeozoic downwards, and they suggest a possibility of world-wide correlation in time that cannot as yet be justified. Concrete terms for well-defined successions of strata in particular regions or provinces, like the "Adelaide System" or the "Kundelungu System" or the "Katanga Group", are at present far more satisfactory. Correlations from one province to another can be safely left to the development of geochronology; some tentative beginnings are illustrated in this discussion.

The Katanga evidence for setting a limit to the base of the Cambrian, suggested by Davidson (1959, a), is not as sharply

[1] The above lead isotope ratios are now commonly expressed by the isotope numbers only, when there is no ambiguity.

focussed as we could wish, but is nevertheless of very weighty significance. The age determinations of the uraninites are more numerous and concordant than elsewhere in this critical part of the geological column, and although their exact relationship to the Cambrian remains inferential, the inference is one of high probability.

Dr. L. Cahen has kindly communicated the most recent information bearing on this important question; for present purposes he has provided the following "simplified picture", which summarises the relevant events leading up to the uranium mineralisations of Katanga:

11.	*Uranium phase 3* (SE Katanga—N Rhodesia)	520 m.y.
10.	*Tectonisation in continuation of 7*	
9[1].	*Uranium phase 2b* (Kalongwe—Luishya)	610 m.y.
8[1].	*Uranium phase 2a* (Shinkolobwe—?Swambo)	625 m.y.
7.	*Post-Upper Kundelungu thrust-faults, probably continuing, perhaps intermittently, to 10 (fault planes are slightly folded)*	
6.	*Uranium phase 1* (Musonoi)	undated
5.	*Folding*	
4[2].	*Upper Kundelungu*, including cherts with a typical late Precambrian fauna of algae and protozoans	
3.	*Middle Kundelungu*, including limestones with stromatoliths; Tillite of the Petit Conglomérat at base	
2.	*Important movements of the same kind and direction as 5, but less intense.*	
1.	*Lower Kundelungu*, including dolomites with stromatoliths. The Kundelungu System rests discordantly on the Grand Conglomérat Series, which includes a thick and widespread Tillite.	

The main Katanga uranium mineralisations of 610 to 625 m.y. were clearly contemporaneous—or at least coeval—with the later phases of the Kundelungu orogeny. Cahen concludes, "I therefore think we can dismiss the idea that the Kundelungu sediments are much older than the uraninites." Now, as noted above, some of the Kundelungu strata contain late Precambrian fossils. Apart from the cherts and limestones, there are beds of grey and greenish shales which should, if Cambrian, have proved to be fossiliferous. But no trace of a Cambrian fauna has been detected. It can therefore be inferred that while the close of the Precambrian may well have been later than 625 m.y., it is hardly likely to have been much earlier. "In other words", as

[1] These two phases may in reality merge into one, but Derricks and Oosterbosch (1958) have reason to believe them to be distinct.

[2] The uppermost Kundelungu is known only in regions where no folding (5, 7 and 10) has occurred; it may be in part later than 4.

Davidson (1959, a) pertinently remarks, "at round about 650 m.y. ago a Cambrian fauna had not yet developed."

We now turn to the Wichita Mountains of Oklahoma, where there is a complex of crystalline rocks, commonly regarded as being of Precambrian age, which is unconformably overlain by Palaeozoic strata, including Upper Cambrian. The geochronology team of the Carnegie Institution of Washington have dated biotite from one of the granite masses of this complex, and zircon from a pegmatite cutting the same granite (Davis *et al.*, 1957, p. 170), with the following results (in millions of years):

	206/238	207/235	207/206	208/232	Rb/Sr	K/A
Biotite from Lugert Granite, Wichita Mts.	—	—	—	—	500	480
Zircon from pegmatite	520	527	550	506	—	—
in same granite	514	522	550	493	—	—

The two sets of results for zircon refer to two separate zones of a single large crystal, the first being about six times as radioactive as the other. The age patterns correspond perfectly to recent loss of lead and, accordingly, both samples have the same 207/206 age (550 m.y.), despite the fact that the second has lost a little more lead than the first. The biotite "ages" are on the low side, as so often is the case. Davis and his colleagues write: "If the granite is in fact Precambrian, it would be the youngest Precambrian rock known and would thus be of considerable importance to the fossil time scale." Strictly speaking, however, all that can be said is that the granite is pre-Upper Cambrian. In other words, the Upper Cambrian is younger than 550 m.y.

V. Data for constructing a "Post-Precambrian" Time-Scale

Cambrian (600 ± 20 m.y. to 500 ± 15 m.y.). With the above limit for the Upper Cambrian, another limit, set by the (?early Taconic) granitic rocks near Boisdale Hills on Cape Breton Island, can be combined. The average of three age determinations on a fresh sample of granite, one by K/A and two by Rb/Sr, is 490 m.y. (Hurley *et al.*, 1958, p. 108). Less than a mile away the same or similar granite is emplaced in a sequence of strata extending from the Middle Cambrian, through the Upper, to what is either the uppermost Cambrian or the lowermost Ordovician. It seems safe to say that the Upper Cambrian is older than 490 m.y. as well as younger than 550 m.y.

Consistent with this pair of guiding points is the re-assessment of the age of the uranium-rich lenses of Kolm in the *Peltura* shales of southern Sweden (Cobb and Kulp, 1958; *in press*, 1959). Their results (in m.y.) are summarised below, for comparison with those I used in 1947.

	206/238	207/235	207/206
Holmes (1947) from Nier's isotopic analysis of lead from one sample	377	440	800
Cobb and Kulp (1958) from over 20 samples . . .	355-455	420-480	650-945

Following Wickman (1942) I interpreted this pattern of discordant ages as one corresponding to loss of Pb-206 by outward migration of radon; accordingly, 440 m.y. was adopted as the most probable age. Cobb and Kulp confirm the migration of radon, but find evidence that there was also loss of lead as a whole, to a varied extent from sample to sample. On this interpretation the most probable age falls between 480 and 650 m.y. Kulp (1959, a) concludes that "analysis of the data indicates a minimum age for this formation of about 500 m.y. . . . The evidence points to the minimum age being nearly correct, but there is no unique solution."

A number of Rb/Sr ages of Cambrian glauconites have been determined by the M.I.T. team (Cormier, 1957; and reported in Hurley *et al.*, 1958, pp. 59-60). These range from 412 ± 60 m.y. for the late Upper Cambrian to 584 ± 30 for the Lower Cambrian. The last of these refers to glauconite from a finely laminated sandstone in the Murray Shale formation of Tennessee. The first diagnostic Lower Cambrian fossils appear in shales 500 feet higher up in the section.

Several late Precambrian and Lower Cambrian glauconites have been dated by Russian workers, using the K/A method, and a report is now available in English (Kazakov and Polevaya, 1958). One typical set of results refers to drill-cores of glauconitic sandstones from the deep Serdobskaya Borehole R-2: Lower Cambrian from a depth of 1,380 metres is dated at 585 m.y., Upper Sinian (late Precambrian) from 1,758 metres at 715 m.y., and two samples from 1,787 metres at 710 and 720 m.y. Other Russian results for the Lower Cambrian are 560 and 615 m.y. The K/A ages are all $\pm$ about ten per cent; they have been recalculated and are 20 to 30 m.y. higher than those published by Kazakov and Polevaya (1958, p. 379).

Ordovician (500 ± 15 m.y. to 440 ± 10 m.y.). A joint Rice Institute and Shell Development Company team have provided the best guide so far available for the Middle Ordovician by dating biotites (Adams *et al.*, 1958) and zircons (Edwards *et al.*, 1959) from bands of volcanic tuff, occurring in Tennessee, of which the stratigraphical horizons are well defined. These tuffs, originally mainly vitric, like ignimbrite, and containing euhedral crystals of sanidine, biotite and zircon, weather to bentonite where exposed at the surface, but fresh materials suitable for age work have been obtained from boreholes and mines.

Bands of volcanic tuff occurring in	Biotites Rb/Sr (± 50)	Zircons 206/238 (± 10)
Carters limestone	496 m.y.	452 m.y.
	—	446
	—	438
Egglestone limestone	451	—
	479	—
Bays formation	—	453

So far these results have been reported only in abstracts, and the other lead ratios for the zircons are not published at the time of writing; but the 206/238 ages are known to be minima. Meanwhile, the average for the biotites, 475 m.y., is plotted in Fig. 2 in the appropriate place.

Three K/A ages, 445, 450 and 455 m.y., for glauconite from Middle Ordovician sandstones in the Maardu Mine, Estonian S.S.R. (Kazakov and Polevaya, 1958), are also likely to be minima. Keeping this proviso in mind, they are not inconsistent with the above results.

Silurian (440 ± 10 m.y. to 400 ± 10 m.y.). The only direct dating is a K/A glauconite age, 400 m.y., quoted by Kazakov and Polevaya (1958, p. 384) from a paper (in Russian only) by Amirkhanov *et al.*, 1957. Recalculated, this becomes 415 m.y. Indirect guidance is afforded by the dating of several Caledonian granites, which in Britain are generally regarded as of very late Silurian or early Devonian age. Biotite from the Shap granite, for example, gives a K/A age of 400 ± 15 m.y. (Kulp, 1959, a). From this result it can be inferred that all the Silurian, or nearly all, is older than about 400 m.y. A related result is the Rb/Sr dating of the Hill of Fare granite (one of the "Newer Granites" of Aberdeenshire) at 390 ± 50 m.y. by Smales *et al.* (1958). Petrographically this granite is like those that supplied pebbles to the conglomerates of the Lower Old Red Sandstone, and possibly to the Downtonian. Dating of some of these pebbles might add precision to a part of the time-scale that at present remains uncertain.

Devonian (400 ± 10 m.y. to 350 ± 10 m.y.). As already noted on p. 185, the Lower Devonian strata of Maine and Nova Scotia (Acadia) have been invaded by numerous bodies of granitic and related rocks. Biotite concentrates from many of these give K/A and Rb/Sr ages averaging about 370 m.y. (Hurley *et al.*, 1958, pp. 28 and 107, and map on p. 47). In a later and more accessible publication Hurley, Boucot *et al.* (1959) record K/A ages of 360 to 370 $\pm$ 17 m.y. and a Rb/Sr age of 360 $\pm$ 28 m.y. for biotite from a quartz-monzonite in N.W. Maine. The adjoining contact-metamorphosed rocks, representing Upper Silurian and Lower Devonian sediments, yielded K/A ages ranging from 350 $\pm$ 10 to 377 $\pm$ 18 m.y. It is concluded that the age of the quartz-monzonite and the accompanying metamorphism is at least 360 m.y. The Lower Devonian may therefore be regarded as older than, say, 370 m.y.

From the lead isotope ratios, as in the case of Swedish Kolm, Cobb and Kulp (*in press*, 1959) find that a band of uranium-rich black shale of uppermost Devonian age (in the Chattanooga shale, Tennessee) has a minimum age of 340 $\pm$ 10 m.y. For biotites from a thin layer of volcanic tuff high up in the same formation Faul and Thomas (1959) also record a K/A age of 340 m.y. which is regarded as a minimum. In round figures 350 $\pm$ 10 m.y. should be about right for the top of the Devonian.

Carboniferous (350 $\pm$ 10 m.y. to 270 $\pm$ 10 m.y.). While the Devonian part of the time-scale was being extended by the M.I.T. discoveries in Acadia, a similar extension to the Carboniferous was being found necessary by Faul (1957; and *in* Davis *et al.*, 1957, p. 168). Micas separated from seven specimens of post-Tournaisian and pre-Visean granites collected by Faul in the Vosges and Black Forest gave Rb/Sr ages ranging from 330 to 345 m.y. and K/A ages which are lower and show more scatter.

Zircons from these same granites from the Vosges and Black Forest have been dated by the complete lead method (Davis *et al.*, 1957) but the results are discordant and point to ages that would be pre-Carboniferous. The investigators correlate these discrepancies with the presence of an unusual amount of inherited lead in the zircons, but without offering any explanation. It may be suggested that the zircons were not entirely the products of the new crystallisation that accompanied the transformation of pre-existing rocks into Hercynian granite. Retention of traces of either older zircons (*e.g.* detrital grains in antecedent sediments, or accessories in antecedent metamorphic or granitic rocks), or of radiogenic lead that had already accumulated in the ancestral zircons, would amply account for these apparently incongruent results. Indeed, the same team (Tilton *et al.*, 1958, p. 1469; Aldrich *et al.*, 1958, p. 114) have recorded more striking discrepancies of this kind. Zircons from two of the migmatite domes of the Baltimore gneiss-complex give ages of 1,120 m.y. by the complete lead method; microcline from one of the domes gives nearly the same age by the Rb/Sr method; whereas microcline from the other dome and biotites from both (and also from a third dome) have ages ranging between 300 and 350 m.y. Evidently a Precambrian rock that once formed part of the floor of the Appalachian geosyncline was mobilised and rejuvenated, but not completely reconstituted, during the Acadian or some later phase of orogenesis and metamorphism. Examples of other cases of the same kind are recorded from New York and Virginia.

Little doubt now attaches to Faul's age of about 330-345 m.y. for a point well down in the Carboniferous, since it links on smoothly with the Devonian data, and also with some well determined ages for the Upper Carboniferous.

In 1947 the pitchblende of St. Joachimsthal (now Jachymov), Czechoslovakia, was used to date the Upper Carboniferous or, alternatively, the Lower Permian. It has since been shown that the mineralisation followed Lower Permian quartz-porphyries and lamprophyres (Frohberg, 1950). The age originally calculated from the isotopic constitution of the lead extracted from the pitchblende (Nier, 1939) was 214 m.y. Unfortunately, no satisfactory correction for inherited lead can be made and ages of 240 to 250 m.y. can equally well be justified (*cf.* Kulp *et al.*, 1954). Later attempts to date this mineral have proved to be even more unsatisfactory. Cornish pitchblende was no more rewarding. However, uraninite from Geevor Tin Mine, near Land's End, Cornwall, has at last yielded thoroughly convincing results (Darnley, 1959). Without correction for inherited lead, the "chemical age" is 290 m.y. Isotopic analysis of the lead shows that the inherited lead was less than 0·2 per cent. The four isotopic ages, in m.y., after this minor correction, are:

206/238	207/235	207/206	208/232
288 ± 6	288 ± 8	(307 ± 25)	300 ± 15

For ages of this order, the 207/206 "age" is of little value, since it is extremely sensitive to small errors and becomes increasingly so for younger ages. Darnley adopts 288 m.y. as the most probable age, and adds: " it is interesting to note the agreement between the present determination and one of alluvial monazite derived from Bodmin Moor granite (Holmes, 1948). Careful analysis of uranium, thorium and lead (Smales, 1948) resulted in a chemical age of 290 m.y. At the time the discrepancy between the result and the 'B' time-scale suggested that monazite was an untrustworthy timekeeper and no isotopic analysis was carried out. In view of the uraninite age now reported, however, it seems likely that the monazite may have been reliably dated after all." It should be explained that, as I wrote in the paper referred to (1948, p. 123), "the sample of monazite from Bodmin Moor was too small to yield sufficient lead for isotopic analysis." With present techniques this is no longer the case and, thanks to the Lamont Observatory team, under the direction of Professor J. L. Kulp, an isotopic analysis should soon be available. Meanwhile, Kulp (1959, a) has recorded a K/A age of 275 ± 10 m.y. for biotite from Dartmoor granite; and Faul (*in press*, 1959), applying the same method, gets 290 m.y.

A brief reference may be allowed to the helium age of 196 m.y. found for the Whin Sill by Dubey thirty years ago (Dubey and Holmes, 1929). This result had always seemed to constitute an exception to the rule that basaltic rocks in general rarely retain as much as 70 per cent of the helium generated within them. However, if 196 m.y. represents only 70 per cent of the real age, the latter becomes 280 m.y., which is now of the right order for a late Carboniferous event.

It remains to consider the geological age of the granites of Cornwall and Dartmoor. Stratigraphically, all one can say is that they are post-Lower Westphalian. A significant sentence in the summary of a lecture by T. R. Owen (1958, p. 46) to the Seventh Inter-University Geological Congress at Swansea impressed me as having a definite bearing on this problem. Discussing the northward migration in time of the Armorican earth-movements, Owen remarked: "The Pennant Sandstone may be the product of the rapid erosion of the rising Cornubian chains." One would expect the Cornubian chains to have been rising during and immediately after the last stages of granite emplacement and mineralisation. Research on the Pennant Sandstone with special reference to its origin, mode of deposition and source-area is now in progress at Swansea. Meanwhile, I am indebted to Mr. Owen for the suggestion, based on a variety of relevant considerations, that the granite emplacement and mineralisation may have extended through mid-Morganian time, perhaps beginning a little earlier in some places and continuing a little longer in others. Since then, Scott Simpson (1959) has published evidence supporting essentially similar conclusions. In Fig. 2 the adopted age of 290 m.y. is plotted in the appropriate position. For other Carboniferous ages that are consistent with this dating see Davidson (*in press*, 1959).

Permian (270 ± 5 m.y. to 225 ± 5 m.y.). As already mentioned, the Jachymov pitchblende might now be used to date the Lower Permian at between 240 and 250 m.y., were it not for the ambiguity of the correction for inherited lead. The well-known thorite from the pegmatites of the Oslo province is a severely altered metamict mineral; it also yields data (Nier, 1939) that are difficult to interpret. Its calculated age could be between 245 and 255 m.y.

The Oslo intrusive rocks are a little younger than the Lower Permian lavas and associated sediments of the region. From the results of a recent investigation, by the complete lead method, of zircon from nordmarkite freshly exposed in a road cutting along Trondheimsveien, Oslo, the following calculated ages have been recorded (Faul *et al.*, 1959):

206/238	207/235	207/206	208/232
267	282	(395)	225 m.y.

The high apparent age indicated by this loss-of-lead pattern is a result of the correction for inherited lead having been made with a lead of isotopic constitution corresponding to a Cretaceous age. On recalculation after correction for inherited lead corresponding to an age of 250 m.y. the "ages" become

255	260	(365)	210 m.y.

suggesting an age not far from 260 m.y. for the zircon. Faul *et al.* (1959) have also obtained ages of 257 and 260 m.y. for biotite from the Drammen granite. They adopt an age of about 260 m.y. for the Oslo intrusions.

These results, so much higher than could have been anticipated a few years ago, led me to look back at the long-forgotten analyses of three zircons from the Oslo province made by my old friend Dr. R. W. Lawson (Th) and myself (U and Pb) early in 1914, at a time when the Oslo igneous rocks were thought to be of Lower Devonian age, and it had not yet been recognised that the end product of the thorium series was an isotope of lead (Holmes and Lawson, 1914). The chemical ages, necessarily uncorrected for inherited lead, can now be calculated; they are found to be 290, 235 and 270 m.y. In 1914, however, the average age calculated from Pb/U for these zircons and other associated Oslo minerals was 380 m.y., which can now be seen to have been about right for the Lower Devonian—but only unwittingly "right", because ignorance of the existence of Pb^{208} had compensated for the mistaken geological age; two fundamental errors had cancelled out. It was partly because of this double mistake, unsuspected by anyone at the time, that Barrell (1917, pp. 884-885) presented a time-scale very like that of Fig. 2, but with maximum and minimum estimates somewhat further apart.

By courtesy of a personal communication from N. I. Polevaya, Kulp (1959, a) records K/A ages of 234 to 261 m.y. (regarded as minima) for Permian lavas in the U.S.S.R. Kulp also records two very interesting results, already published in Russian by Polevaya and her colleagues, for sylvite of early Middle Permian age from Solikamsk. The age found by the K/Ca method was 241 ± 7 m.y. for both primary and recrystallised varieties of sylvite. By the K/A method the primary sylvite gave 222 ± 5 m.y., indicating some loss of argon, while the recrystallised sylvite gave only 154 ± 5 m.y., pointing to a much greater loss as a result of the process responsible for the recrystallisation.

Triassic (225 ± 5 m.y. to 180 ± 5 m.y.) and *Jurassic* (180 ± 5 m.y. to 135 ± 5 m.y.). Very little precise information is available for the geochronology of these two periods. Hurley *et al.* (1958, p. 96) have dated biotite from the "tin granite" of the Island of Billiton, Indonesia, their result being 180 ± 5 m.y. by the K/A method. The geological age of this granite is probably late Triassic or early Jurassic (Schürmann *et al.*, 1957), Triassic fossils having been metasomatically replaced by cassiterite, and similar granites having contributed to Jurassic sediments. A parallel situation is recorded by Baadsgaard *et al.* (1959) from central British Columbia, where biotite from "the Upper Triassic or Lower Jurassic Guichon batholith" also yields a K/A age of 180 m.y. In the absence of further information one can hardly do better at this stage than adopt 180 ± 5 m.y. as a provisional estimate for the boundary between the two periods.

The recent Russian results communicated to Kulp by Polevaya include minima K/A ages for Jurassic lavas ranging from 164 to 177 m.y. For the Upper Jurassic there are two useful guides. Curtis and Reynolds (1958) have dated biotite from the Upper Kimmeridgian Sierra Nevada granite (Arkell, 1956, pp. 551 and 633) at 139 ± 4 m.y. Cormier (1957) has applied the Rb/Sr method to glauconite from the Oxfordian Sundance formation of Wyoming and finds ages of 137 and 140 ± 40 m.y.

Cretaceous (135 ± 5 m.y. to 70 ± 2 m.y.). Other Russian results communicated by Polevaya include the following minima K/A ages:

Upper Cretaceous lavas	67 to 77 m.y.
Middle Cretaceous lavas	70 to 93 m.y.
Lower Cretaceous lavas	105 to 121 m.y.

Comparable, but mostly lower results have already been published by Kazakov and Polevaya (1958) in their paper on the K/A ages of glauconites. These range between 72-114 m.y. for the Cenomanian to 118 m.y. for the Albian.

Sanidine from the Crowsnest Volcanics of Blairmore, Alberta (between late Albian and Cenomanian) gives a K/A age of 98 ± 5 m.y. (Folinsbee and Baadsgaard, 1958). Lepidolite from the well-known lithium-rich pegmatite at Pala, California, of Middle or early Upper Cretaceous age, gives Rb/Sr ages of 96 m.y. (Webster *et al.*, 1957) and 100 m.y. (Aldrich *et al.*, 1958). Glauconite from the Upper Cretaceous Navesink Formation at Clayton, New Jersey, gives a Rb/Sr age of 71 ± 11 m.y. (Cormier, 1957).

Tertiary (70 ± 2 m.y. to about 1 m.y.; dates in brackets are by interpolation only).

	Evernden (1959)	Kulp (1959, a)	Here adopted (to nearest '5' beyond the Pliocene)
Pleistocene			
	ca 1	*ca* 1	*ca* 1
Pliocene			
	12-13	(12)	(11)
Miocene			
	25-26	(28)	(25)
Oligocene			
	34-35	40	40
Eocene			
	48-50	60	60
Paleocene			
	57-59	70	70 m.y.
Cretaceous			

Evernden's time-scale for the Tertiary sub-systems is based on K/A ages, but no details are yet available. Kulp's scale and mine are necessarily alike, since they are based on the same data. My interpolations above the Oligocene, read from the original of Fig. 2, differ only slightly from the other estimates.

Evernden's estimate for the base of the Eocene is low compared with other results now available. Cormier (1957), using the Rb/Sr method, finds 59 ± 6 m.y. for glauconite from the Lower Eocene Hornerstown Formation at Clayton, New Jersey. Kalevaya (in Kulp, 1959, a) reports 43 to 64 m.y. for Eocene glauconites and 50 to 55 m.y. for Eocene lavas. Nine Laramide pitchblendes from the Front Range, Colorado, have now been dated by the complete lead method (Eckelmann and Kulp, 1957), the average age being 59 ± 5 m.y. In 1947 two sets of results averaged 58 m.y. and this I ascribed to the end of the Cretaceous. Since then, however, Knopf (1957) has shown that the veins are younger than the Fort Union Formation, which is of Paleocene age. He regards the veins in which the pitchblende occurs as having been formed at or near the end of Paleocene time. From these data, combined with Cormier's age of 71 ± 11 m.y. for the late Cretaceous, it now seems reasonable to adopt a span of 10 m.y. in round figures (from 70 to 60 m.y.) for the duration of the Paleocene.

Faul (*in press*, 1959) reports a K/A age of 52 ± 2 m.y. for biotite from a carbonatite occurring in the Bearpaw Mts., Montana. The geological age of the complex of which the carbonatite is a member is post-early Eocene and probably (*i.e.* by analogy with similar occurrences in the same region) pre-Upper Eocene. From the report of the Annual Meeting of the U.S.S.R. Commission on Absolute Age Determination held in

Moscow in May, 1959, Kulp (1959, a) cites a K/A age of 40 ± 5 m.y. for biotite from an intrusive rock occurring in the Caucasus, where it cuts Upper Eocene strata and is unconformably overlain by Lower Oligocene. This very valuable result may be provisionally adopted for the Eocene/Oligocene boundary. A variety of results are more or less consistent with this reading and have been summarised by Davidson (1959, c) and Kulp (1959, a), together with others relating to the Miocene and Pliocene. These are all K/A or Pb/α ages with no well-established dates—except the present—to judge them by. They serve, therefore, only as rough guides. However, in view of the special importance of Pleistocene chronology, two K/A results by Evernden (1959) and his colleagues (Curtis *et al.*, 1956) may be singled out for mention. Biotites from a rhyolite volcanic plug (one of the Sutter Buttes of California) which cuts through strata of very late Pliocene age, and from one of the andesite lavas, have been dated at 1·6 and 1·9 m.y. respectively, each determination being ± 0·5 m.y. The Bishop Tuff of the Sierra Nevada of California has been similarly dated at 1·0 m.y. This tuff lies beneath the oldest of the more widely distributed moraines of the Sierra and rests upon a still older moraine of which little is known. Thus there is some justification for continuing to adopt the round figure of one million years as an approximate estimate for the duration of the Pleistocene.

VI. A Revised Time-Scale (1959)

To meet the requirements of a reasonably accurate time-scale measured ages need to be far more reliable, closely correlated, and evenly distributed through the periods than has yet proved to be practicable. It is clear from the preceding review that the geochronological evidence currently avaliable, though rapidly becoming abundant, is still patchy in distribution, widely varied in quality, and in part subject to systematic errors that cannot yet be evaluated. For these reasons the data are not yet suitable for statistical treatment, as a list prepared by Davidson (1959, b) for the calculated mid-points of the periods clearly shows. According to the figures there given, some of the periods are obviously too short: in one case, the Triassic, even becoming negative. Consequently it is still desirable to have some independent geological standard, however rough and variable, which will serve as a general check on the coherence of the geochronological data to be admitted, and also as a means of interpolating from one fairly well dated part of the column to another. The geological "standard" here adopted, as before, is based on the maximum known thicknesses of the strata of each system. The actual figures and the sources of the information (mainly from Kay, 1955) are listed in the following table.

Maximum Thicknesses and Revised Time-Scale

Locality and Reference	World Maxima (thousands of feet)	Cumulative Maxima (thousands of feet)	PERIODS		Since beginning of period (millions of years)	Duration of period (millions of years)
Ventura California	6		PLEISTOCENE			*ca* 1
		6			*ca* 1	
Caucasus (Kay, No. 81)	15		PLIOCENE			10
		21			11	
California (Wilmarth, p. 6)	21		MIOCENE			14
		42			25	
Switzerland (Kay, No. 80)	26		OLIGOCENE			15
		68			40	
Washington (Kay, No. 79)	30		EOCENE			20
		98			60	
Wyoming (Wilmarth)	12		PALEOCENE			10
		110			70± 2	
Pacific coast (Anderson, 1958, pp. 7-8)	23			Upper		
	51		CRETACEOUS			65
Lr. California (Kay, No. 52)	28			Lower		
		161			135± 5	
California (Kay, No. 47)	24			Upper		
	44		JURASSIC			45
California (Arkell, 1956)	20			Mid. & Lower		
		205			180± 5	
Japan and Pennsylvania (Kay, Nos. 39, 40, 41)	30		TRIASSIC			45
		235			225± 5	
Queensland (Kay, No. 32)	19		PERMIAN			45
		254			270± 5	
Germany (Kay, No. 23)	20			Upper		
	46		CARBONIFEROUS			80
New Brunswick (Kay, No. 26)	26			Lower		
		300			350±10	
New South Wales (Kay, No. 18)	13			Upper		
	38		DEVONIAN			50
New Hampshire (Kay, No. 19)	25			Lower		
		338			400±10	
New Brunswick (Kay, No. 9)	34		SILURIAN			40
		372			440±10	
New South Wales (Kay, No. 5)	40		ORDOVICIAN			60
		412			500±15	
British Columbia (Dawson, 1891)	40		CAMBRIAN			100
		452			600±20	

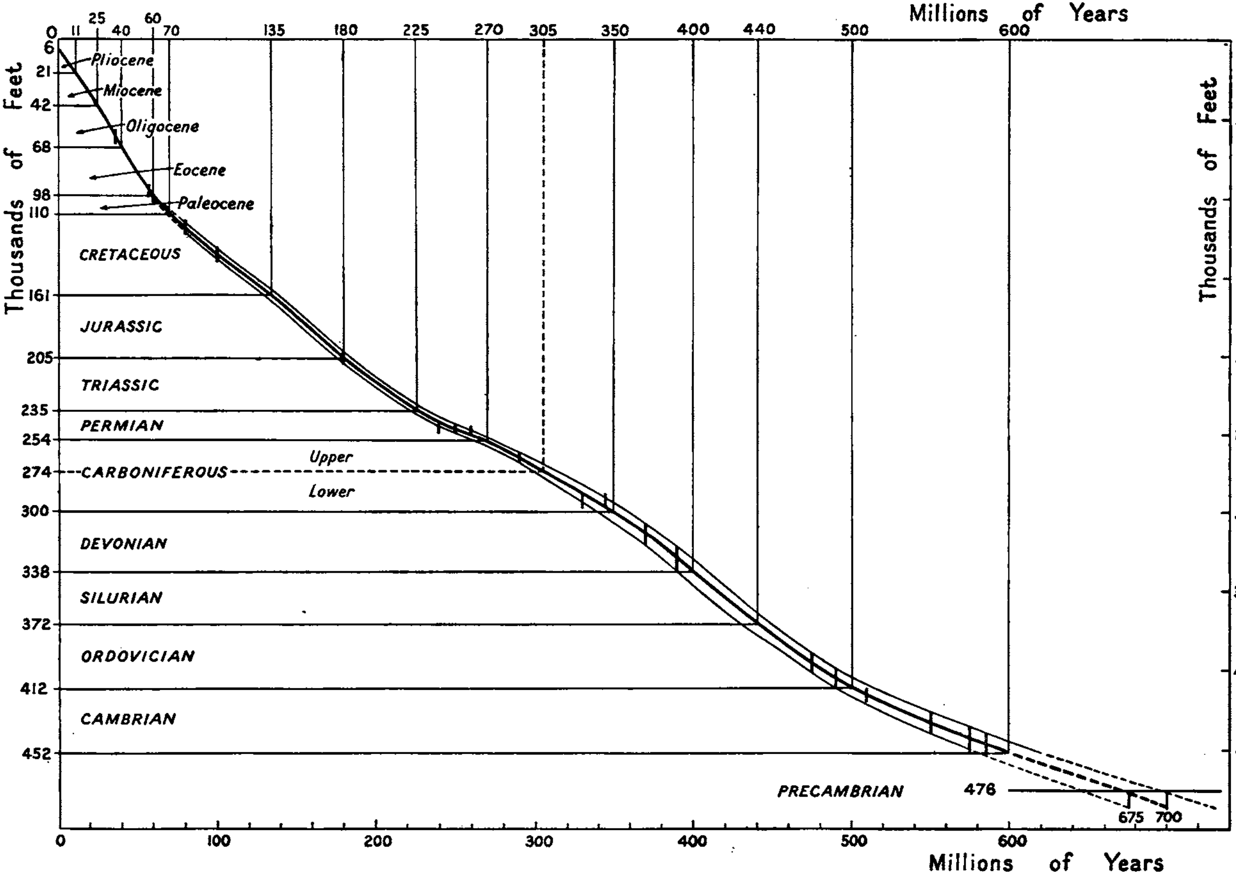
Millions of Years
Thousands of Feet
Pliocene
Miocene
Oligocene
Eocene
Paleocene
CRETACEOUS
JURASSIC
TRIASSIC
PERMIAN
Upper
CARBONIFEROUS
Lower
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN
PRECAMBRIAN
476
675
700
0 11 25 40 60 70 135 180 225 270 305 350 400 440 500 600
6 21 42 68 98 110 161 205 235 254 274 300 338 372 412 452
0 50 100 150 200 250 300 350 400 450
0 100 200 300 400 500 600

FIG. 2

By plotting ages against cumulative thicknesses, we can achieve a step-by-step approximation towards the "true" time-scale by means of successive stages of trial and error; Fig. 2 represents one such stage. Ideally, the points plotted would be so closely spaced as to determine a time-scale line, probably more or less undulating, but internally coherent throughout in the sense that increase of age would in all cases be accompanied by increase in the cumulative thickness. In the present state of geochronology the "points" are either horizontal lines (as in Fig. 1) or rectangles (when both geological age and measured age are known only between limits). The "coherence" criterion enables one to dispose of much of the doubt that is graphically expressed by such lines and rectangles, since the time-scale line cannot become vertical or turn back on itself. For example, if it be accepted that the top of the Lower Permian can be correlated with, say, about 250 m.y., then the Geevor uraninite, with an age of about 290 m.y., falls comfortably into the Upper Carboniferous. In this case the geological evidence, though indirect, is not inconsistent and, indeed, favours this placing. However, if there were some fatal objection, *i.e.* if the measured age and the geological age could obviously not be coherently paired, then one age or the other, or possibly both, would be wrong, and the data in question would be inadmissible for time-scale purposes.

Special attention has been directed to a most interesting example of this kind of incoherence by the M.I.T. team (Hurley *et al.*, 1958, p. 107). They write:

> "The unroofing of the Quincy Batholith near Boston took place in Pennsylvanian times, as indicated by well dated fossils in the basal conglomerate horizon unconformably overlying it, which contains boulders of the Quincy granite. The Quincy granite is therefore pre-Pennsylvanian, so that the Pennsylvanian is younger than 250 m.y. This means that the Devonian lasted for over 100 million years, as long as three ordinary periods. . . . Evidence based on evolutionary changes during the Devonian does not support this three-fold increase in the length of the Period."

A more cogent argument is now available. According to its measured age the Quincy granite should be geologically of Permian age, whereas in fact it is pre-Pennsylvanian. The measured "age" is therefore misleading. The discrepancy may be of considerable petrogenetic interest, but until the reason for the lack of coherence is cleared up, the Quincy data cannot be utilised for time-scale purposes.

On the other hand, it is by no means always the geochronological data that are at fault. Some of the Connecticut pegmatites are amongst the most accurately dated of rocks, but unfortunately there are so many geological possibilities that the measured age would appear on Fig. 2 as a long vertical line. Actually, of course, the measured age in this case serves to fix the geological age within the limits of reliability of the time-scale adopted, but it cannot also be used in the construction of that time-scale.

After rejecting many results that are inadmissible for one reason or another, the data that remain serve as rough guides in outlining what may be called a "channel of uncertainty". If all the guides were fully reliable the channel would enclose the real time-scale line within its boundaries. But since this is too much to expect at present, it must be frankly stated that the degree of reliance to be placed on some of the guides (*e.g.* those in the time-neighbourhood of the Triassic/Jurassic boundary) still unavoidably involves some personal choice and judgment. To some extent I have limited the effect of these (a) by working only to the nearest 5 m.y. beyond the influence of the conventional 1 m.y. ascribed to the Pleistocene; and (b) by gradually widening the channel of uncertainty from zero at the present day to 4 m.y. at the beginning of the Tertiary and eventually to 40 m.y. at the beginning of the Cambrian.

The results are displayed both graphically and numerically on Fig. 2 and are summarised in the accompanying table. The main differences between the 1959 and 1947 scales are that the Jurassic and Permian are more or less doubled in duration; the Trias and Carboniferous are extended by about 50 per cent; the Cambrian gains 20 m.y. at the expense of the Ordovician; and the Cambrian begins about 600 m.y. ago instead of about 500. No evidence has been found that would justify carrying back the beginning of the Cambrian to 750 m.y. as indicated in a diagram published by Mayne *et al.* (1959).

VII. Some Geological Inferences and Implications

Barrell (1917, p. 892) was the first to draw attention to the evidence suggesting that since the beginning of the Cambrian the maximum rate of accumulation of geosynclinal sediments (averaged over a whole period) has speeded up. This inference does not necessarily imply that rates of sedimentation have increased; but since "maximum thicknesses are in reality a measure of crustal depression", it does imply that the average maximum rate of crustal depression per period has increased. The 1947 data pointed to a progressive rate of increase that was almost mathematically regular. A glance at Fig. 2 shows that the supposed regularity of acceleration is no longer confirmed. An overall increase is still indicated by the fact that the time-scale curve or channel, taken as a whole, is concave upwards. But equally obviously it is interrupted by a marked convexity during the Upper Palaeozoic. By Permian times the rate (1 foot in 2,370 years) had become almost as slow as during the Cambrian (1 foot in 2,500 years). The variations can now be interpreted as due to the interplay of large-scale rhythmic or cyclic processes superimposed on a progressive increase.

It should, however, be pointed out that there are other reasons for inferring that the earth's activities have become increasingly vigorous during the later part of geological time. A striking example is provided by the increase in rate of right-lateral displacement along the San Andreas "Rift" or "megashear" in the stretch N.W. of the Garlock Fault. Since the late Jurassic the average rate of displacement has been about 2·5 miles per million years. Today, systematically repeated surveys show that the present rate is about two inches a year, or 2·5 miles in about 80,000 years. Some of the details for this part of the Rift are as follows:

Cumulative displacement in miles, of		Approx. age in m.y.	Average rate in miles per m.y.	Average rate during interval
Jurassic	350*	140	2·5	
				0·75
Cretaceous	320	100	3·2	
				1·9
Eocene	225	50	4·5	
				4·2
Late Miocene	65	12	5·4	
				4·8
Mid. Pleistocene	10	0·5	20	
				20
Present	(two inches per year)		30	

* According to Evernden *et al.* (1958, b) this movement of 350 miles may have taken place during the last 80 m.y. If so, the average rate over that period would be 4·4 miles per m.y.

S.E. of the Garlock Fault the cumulative displacements are shorter, mainly because the movements have been distributed along several faults, of which only one is regarded as the continuation of the San Andreas.

Movement along the Alpine Fault of New Zealand has similarly accelerated, the cumulative displacement (also including Jurassic rocks) being about 300 miles, while the Pleistocene and recent displacements imply rates of movement that are far above the average. The main Alpine Fault zone fans out into a series of faults at the N.E. end.

The space problems presented by great "megashears"—of which these are only two of the better known examples—almost baffle the imagination. So far as I know, the only attempt to face the challenge is by Carey (1958, p. 336 and Fig. 56) and the reader need not be surprised that he should find it necessary to resort to an expanding earth, accompanied by the additional complications of both crustal and continental migrations. These topics are outside the scope of this paper, but those to whom the idea that we live on an expanding globe may be unfamiliar should read an admirable and lucid introduction—in English—by Egyed (1957). Professor Egyed is Director of the Geophysical Institute at Budapest.

In an earlier contribution, which depends in part on a geological time-scale, Egyed (1956) plots against time the continental areas covered by sea water, after estimating the latter from the latest French and Russian palaeogeographical maps. The smoothed-out curves descend increasingly rapidly from the Cambrian to the present, but on this there are superimposed oscillations corresponding to the major geosynclines, orogenies and epeirogenic uplifts. The inevitable inference is that, despite denudation, the continents have continued to emerge as land largely because of a progressive fall in sea level, the latter being ascribed to the increasing area of the ocean floors that results from global expansion (*cf.* Heezen, 1959). The only quantitative effect of the revised time-scale is to spread this part of the expansion over 600 m.y. instead of 500. It should be added, however, as a matter of widespread interest, that the expansion hypothesis provides a simple explanation, hitherto unrecognised, for the progressive fall of sea level that was superimposed on the falls and rises accompanying the growth and shrinkage of the Pleistocene ice-sheets. The evidence is clearly marshalled by Zeuner (1958, p. 144; 1959, p. 305). The essential feature that has mystified so many investigators of the Pleistocene fluctuations of sea level is that the rise of sea level after the ice-sheets had melted away systematically failed each time to reach the height at which it stood before the glaciation concerned.

In another respect, the revised time-scale has revolutionary consequences for Cambrian and Lower Ordovician palaeogeography; and these, incidentally, add support to the Cambrian end of Egyed's curve. Minerals, mainly from pegmatites, representing the later plutonic phases of the Mozambiquian orogenic belt of eastern Africa have been dated (Holmes and Cahen, 1957) at 650-600 m.y. (Kenya, Tanganyika and Mozambique) and at 500-480 m.y. (Kenya and Mozambique). Similar activity in Madagascar is dated at 620 and 480 m.y. What we called the "cycle cambrien inférieur" (Holmes and Cahen, 1957, pp. 31 and 101) now becomes an important Lower Ordovician phase—probably in many places the closing plutonic phase—of a major geological cycle that began in the later part of the Precambrian. The earlier plutonic crisis of which we have clear evidence occurred towards the close of the Precambrian or the beginning of the Cambrian. Less well defined, but mostly intermediate ages characterise the granites or pegmatites of the Cape, South West Africa and the Bas Congo. By analogy with the better known histories of later orogenic belts we may reasonably infer that the whole of what we now know as Africa south of the Equator was roughly outlined by a major geosyncline, which was renewed and possibly extended during the Cambrian. A branch that at a much earlier time extended through the Copper Belt and Katanga ended its activity before the Cambrian, apart from a late phase of mineralisation (p. 193); but another branch, now represented by the Darwin and Miami gneisses of Southern Rhodesia, suffered intense metamorphism as late as 440 m.y. ago, about the close of the Ordovician.

The early Ordovician plutonic phase, formerly ascribed to the Lower Cambrian, is well represented by the thorianites of Ceylon, and by the monazites of Travancore, where there is also some evidence of an earlier phase, dated at 625 m.y. and thus adding a further link with Madagascar (Holmes, 1955). Lower Ordovician pegmatites, with ages of 450-500 m.y., are also known from Western Australia and, more abundantly, from Brazil; while the first mineral to be dated from Antarctica is a biotite (520 m.y. by the K/A method) from gneiss that occurs at McMurdo Sound. Few unmetamorphosed remains of marine geosynclinal sediments from these areas have been discovered, but it is notable that Cambrian sediments have been recorded from N.W. Australia (Teichert, 1958). Cambrian seaways appear to have been present along many of the coastal regions now bordering the Indian and South Atlantic Oceans. Since the rocks concerned in these regions have previously been regarded as Precambrian, they would not be included in Egyed's estimates of the continental area covered by water during the Cambrian; these estimates therefore need to be considerably increased.

Whether the Cambrian geosynclines of the southern hemisphere were like Mediterraneans separating the parts of an early "Gondwanaland" that were destined to become united by Ordovician mountain ranges, or were marginal to ancestral oceans that foreshadowed the Indian and Atlantic Oceans of today, raises problems of a kind that can hardly be approached without organised team work. A combined attack by palaeomagnetism, palaeoclimatology and geochronology, with geology at the controls, is essential to success. So far our relevant knowledge is slight, but before concluding, I should like to indicate the probability that late Precambrian palaeogeography must have been very different from anything resembling Wegener's *Pangaea*.

It has long been recognised that in many parts of the globe tillites occur not far below the base of the Cambrian and it is tempting to correlate these in a very broad way and to follow up the implications. Beginning with the Sturtian tillites, younger than about 675 m.y., and the Kundelungu tillites, older than 625 m.y., we have some justification for regarding the late Precambrian (at, say, a time of around 650 ± 20 m.y. ago) as having been comparable with the Permo-Carboniferous and the Pleistocene in the number and intensity of its ice ages. In Africa the main area of dispersal appears to have been well to the north and north-west of Katanga, since tillites of about the same age appear near the mouth of the Congo and even as far afield as Senegal and the neighbouring Soudan.

In striking contrast to the climatic conditions of the Permo-Carboniferous, which produced no major glaciation in Laurasia, late Precambrian glaciation is attested by widespread evidence from Greenland to Korea. Tillites of this generalised age are well known to occur in E. and N.E. Greenland, Spitzbergen and Norway. Corresponding marginal evidence—at least of floating ice—is found in the British Dalradian from Donegal to Schiehallion. Similar "boulder beds" of late Sinian age occur east of the Volga, where they appear to be marginal to the late Sinian tillites of the Tien Shan, Yenesei and Yangtse areas and Korea. From the K/A ages of Upper Sinian glauconites it is probable that at least some of these tillites are younger than 700 m.y. They are unlikely to be very different in age from the Sturtian tillites.

This distribution is obviously of great significance. It seems to imply that regions now less than 90° apart (*e.g.* Central Africa—Norway and Spitzbergen; South Australia—China and Siberia) were widely separated in the late Precambrian times by anything from 120° to 180°. Whether or not the correlations are exact, we catch a glimpse of a world with features that are not only unlike those of the present day but are also—though in a quite different way—unlike those of the world of the Permo-Carboniferous ice ages. To bring this shadowy picture into better focus it is essential to determine the time relationships of the various parts as accurately as possible. Where there are glauconitic sediments associated with the tillites, this can best be done by dating the glauconites, preferably by the Rb/Sr method, if practicable. The importance of such work, especially if combined with palaeomagnetic surveys, also of carefully dated materials, cannot be over-emphasised, now that "polar wandering", continental drift and global expansion have at last become respectable subjects for serious research.

VIII. Acknowledgments

Professor C. F. Davidson, Dr. H. Faul and Professor J. L. Kulp have generously assisted towards the preparation of this paper by sending me pre-publication copies of their own most recent papers bearing on the same subject. As noted in the text, I have also profited greatly from discussions with Dr. L. Cahen and Mr. T. R. Owen and from the information they have willingly placed at my disposal. To these good friends I extend my warmest thanks for their constructive interest and co-operation.

IX. References

ADAMS, J. A. S., EDWARDS, G., HENLE, W., and OSMOND, K., 1958. Absolute dating of bentonites by strontium-rubidium isotopes. *Bull. Geol. Soc. Am.*, **69**, 1527.

ALDRICH, L. T., and WETHERILL, G. W., 1958. Geochronology by radioactive decay. *Ann. Rev. Nuclear Sci.*, **8**, 257-298.

ALDRICH, L. T., WETHERILL, G. W., DAVIS, G. L., and TILTON, G. R., 1958. Radioactive ages of micas from granitic rocks by Rb-Sr and K-A methods. *Trans. Am. Geophys. Union*, **39**, 1124-1134.

ALDRICH, L. T., WETHERILL, G. W., TILTON, G. R., and DAVIS, G. L., 1956. Half-life of Rb^{87}. *Phys. Rev.*, **103**, 1045-1047.

——, 1958. *Rept. Dept. Terrestrial Magnetism, Carnegie Inst. Washington, Year Book* 57 (1957-1958), 111-117.

ANDERSON, F. M., 1958. Upper Cretaceous of the Pacific Coast. *Geol. Soc. Am. Mem.*, **71**, 7-8.

ARKELL, W. J., 1956. *Jurassic Geology of the World.* Oliver and Boyd, Edinburgh.

BAADSGAARD, H., FOLINSBEE, R. E., and LIPSON, J., 1959. Potassium-argon ages of biotites from Cordilleran granites of central British Columbia. *Bull. Geol. Soc. Am.*, **70**, 1564.

BARRELL, J., 1917. Rhythms and the measurements of geologic time. *Bull. Geol. Soc. Am.*, **28**, 745-904.

CAMPANA, B., 1954. Absolute age of the uraniferous granite and Precambrian tillite in the Crocker's Well area (Olary District). *Aust. Journ. Sci.*, **16**, 240-241.

CAMPANA, B., and KING, D., 1958. Regional geology and mineral resources of the Olary Province. *Geol. Surv. S. Aust. Bull.* **34**, 28 (age of absite); 54 (chemical analysis).

CAMPANA, B., and WILSON, R. B., 1955. Tillites and related glacial topography of South Australia. *Eclog. Geol Helvetiae*, **48**, 1-30.

CAREY, S. W., 1958. The tectonic approach to continental drift. *In* Continental Drift: A Symposium. University of Tasmania, 177-355 (mimeographed).

CARR, D. R., and KULP, J. L., 1957. Potassium-argon-method of geochronology. *Bull. Geol. Soc. Am.*, **68**, 763-784.

COBB, J. C., and KULP, J. L., 1958. Uranium-lead dating of black shales. *Bull. Geol. Soc. Am.*, **69**, 1547.

—— (*In press*, 1959). Isotopic geochemistry and age of the Swedish Kolm. *Geochim. et Cosmochim. Acta.*

CORMIER, R. F., 1957. Rb-Sr ages of the mineral glauconite and their application to the construction of a post-Precambrian time scale. *Ph.D. Thesis*, M.I.T., Cambridge, Mass.

CURTIS, G. H., LIPSON, J., and EVERNDEN, J. F., 1956. Potassium-argon dating of Plio-Pleistocene intrusive rocks. *Nature*, **178**, 1360.

CURTIS, G. H., and REYNOLDS, J. H., 1958. Notes on the potassium-argon dating of sedimentary rocks. *Bull. Geol. Soc. Am.*, **69**, 151-160.

DARNLEY, A. G., 1959. Uraninite from Geevor Mine, Cornwall. *Geol. Surv. Gt. Britain, Age Determination Report*, No. 6.

DAVIDSON, C. F., 1959, a. How old is the Cambrian System? *Nature*, **183**, 768.

DAVIDSON, C. F., 1959, b. The geological time-scale. *Nature*, **184,** 1310.

——, 1959, c. Some aspects of radiogeology. *Liverpool and Manchester Geol. Journ., Centenary volume.*

—— (*In press*, 1959). Rejuvenation of pitchblendes in Hercynian ore deposits. *Econ. Geol.*

DAVIS, G. L., TILTON, G. R., ALDRICH, L. T., WETHERILL, G. W., and FAUL, H., 1957. *Rept. Geophys. Lab., Carnegie Inst. Washington, Year Book* 56 (1956-1957), 164-171.

DAWSON, G. M., 1891. Note on the geological structure of the Selkirk Range. *Bull. Geol. Soc. Am.*, **2,** 165-176; see also *ibid.*, **12,** 64-68.

DERRICKS, J. J., and OOSTERBOSCH, R., 1958. The Swambo and Kalongwe deposits compared to Shinkolobwe; contribution to the study of Katanga uranium. *Proc. Second U.N. Internat. Conf. on Peaceful Uses of Atomic Energy*, Geneva, **2,** 663-695.

DUBEY, V. S., and HOLMES, A., 1929. Estimates of the ages of the Whin Sill and the Cleveland Dyke by the helium method. *Nature*, **123,** 794.

ECKELMANN, W. R., and KULP, J. L., 1957. Uranium-lead method of age determination; Part II, North American localities. *Bull. Geol. Soc. Am.*, **68,** 1117-1140.

EDWARDS, G., HENLE, W. K., OSMOND, J. K., and ADAMS, J. A. S., 1959. Further progress in absolute dating of the Middle Ordovician. *Bull. Geol. Soc. Am.*, **70,** 1596.

EGYED, L., 1956. Determination of changes in the dimensions of the Earth from palaeogeographical data. *Nature*, **178,** 534.

——, 1957. A new dynamic conception of the internal constitution of the Earth. *Geol. Rundschau*, **46,** 101-121.

EVERNDEN, J. F., 1959. First results of research on the dating of Tertiary and Pleistocene rocks by the potassium/argon method. *Proc. Geol. Soc. London*, No. **1565,** 17-19.

EVERNDEN, J. F., CURTIS, G. H., and LIPSON, J., 1958, a. Potassium-argon dates for the intrusives of northern and central California; and for Tertiary Rocks of California, Nevada, and the Gulf Coast. *Bull. Geol. Soc. Am.*, **69,** 1684.

——, 1958, b. Potassium-argon dates for Tertiary rocks of California, Nevada and the Gulf Coast. *Ibid.*, **69,** 1684.

FAUL, H., 1957. Study of a point in the fossil time scale. *Report Dept., Terr. Mag. Carnegie Inst. Washington, Year Book* 56 (1956-1957), 168-170.

—— (*In press*, 1959). The geological time scale; a critical review. *Bull. Geol. Soc. Am.*

FAUL, H., ELMORE, P. L. D., and BRANNOCK, W. W., 1959. Age of the Fen carbonatite (Norway) and its relation to the intrusives of the Oslo region. *Geochim. et Cosmochim. Acta*, **17,** 153-156.

FAUL, H., and THOMAS, H. H., 1959. Argon ages of the great ash bed from the Ordovician of Alabama and of the bentonite marker in the Chattanooga shale from Tennessee. *Bull. Geol. Soc. Am.*, **70,** 1600-1601.

FOLINSBEE, R. E., and BAADSGAARD, H., 1958. An absolute age for the Exshaw Shale. *Guide Book, Eighth Annual Field Conference, Alberta Soc. Pet. Geol.*, 69-73.

FROHBERG, M. H., 1950. Uranium in Russian Occupied Saxony. *Proc. Geol. Assoc. Canada*, **2,** 43-49.

GILETTI, B. J., 1959. Rubidium-strontium ages of Lewisian rocks from North-West Scotland. *Nature*, **184,** 1793-1794.

GLAESSNER, K. F., 1958. The oldest fossil fauna of South Australia. *Geol. Rund.*, **47,** 522-531.

GLAESSNER, K. F., 1959. Precambrian Coelenterata from Australia, Africa and England. *Nature*, **183**, 1472-1473.

GREENHALGH, D., and JEFFERY, P. M., 1959. A contribution to the pre-Cambrian chronology of Australia. *Geochim. Cosmochim. Acta*, **16**, 39-57.

HEEZEN, B. C., 1959. La topographie et la géologie des profondeurs océaniques. *Colloques Internat. du Centre National de la Recherche Scientifique* (May, 1958) **83**, 295-304.

HESS, H. H., 1955. Serpentines, Orogeny and Epeirogeny. *In* Crust of the Earth (A Symposium). *Geol. Soc. Am. Spec. Pap.* **62**, 395.

HOLMES, A., 1947. The construction of a geological time-scale. *Trans. Geol. Soc. Glasgow*, **21**, 117-152.

——, 1948. Monazite from Bodmin Moor, Cornwall: a study in geochronology: Part I. Monazite as a geological timekeeper. *Proc. Roy. Soc. Edinburgh*, **63B**, 115-124. (See SMALES.)

——, 1955. Dating the Precambrian of Peninsular India and Ceylon. *Proc. Geol. Assoc. Canada* **7**, 81-106.

HOLMES, A. and CAHEN, L., 1957. Géochronologie africaine 1956. *Mém. Acad. roy. des Sciences colonials* (*Classe Sci. Nat. et Med.*) n.s. **5** (1), 1-169.

HOLMES, A., and LAWSON, R. W., 1914. Lead and the end product of thorium. *Phil. Mag.*, **28**, 823-840.

HOLMES, A., SHILLIBEER, H. A., and WILSON, J. T., 1955. Potassium-argon ages of some Lewisian and Svecofennian pegmatites. *Nature*, **176**, 390-392.

HURLEY, P. M., *et al.*, 1958. Variations in isotopic abundances of strontium, calcium and argon and related topics. *Dept. Geol. and Geophys., M.I.T., Sixth Annual Progress Rept. for 1958. NYO-3939. U.S. Atomic Energy Commission Contract AT(30-1)-1381.* 1-193.

HURLEY, P. M., BOUCOT, A. J., ALBEE, A. L., FAUL, H., PINSON, W. H., and FAIRBAIRN, H. W., 1959. Minimum age of the Lower Devonian Slate near Jackman, Maine. *Bull. Geol. Soc. Am.*, **70**, 947-950.

HURLEY, P. M., PINSON, W. H., CORMIER, R. F., and FAIRBAIRN, H W., 1959. Age study of Lower Palaeozoic glauconites. *Journ. Geophys. Research*, **64**, 1109.

JONES, O. T., 1956. The geological evolution of Wales and the adjacent regions. *Quart. Journ. Geol. Soc. London*, **111**, 323-351.

KAY, M., 1955. Sediments and subsidence through time. *In* Crust of the Earth (A Symposium). *Geol. Soc. Am. Spec. Pap.* No. **62**, 665-684.

KAZAKOV, G. A., and POLEVAYA, N. I., 1958. Some preliminary data on elaboration of the post-Precambrian scale of absolute geochronology based on glauconites. *Geochemistry*, No. **4** for **1958**, 374-387.

KING, P. B., 1955. Orogeny and epeirogeny through time. *In* Crust of the Earth (A Symposium). *Geol. Soc. Am. Spec. Pap.* **62**, 723-740.

KNOPF, A., 1957. Measuring geologic time. *The Scientific Monthly*, **85**, 225-236.

KOUVO, O., 1958. Radioactive ages of some Finnish Pre-Cambrian minerals. *Bull. Comm. Geol. Finlande*, **182**, 1-70.

KULP, J. L. (*In press*, 1959, a). Absolute age determination of sedimentary rocks. (Presented at the *Fifth World Petroleum Congress*. New York City, June 1959.)

——, 1959, b. Geological time scale. *Bull. Geol. Soc. Am.*, **70**, 1634.

KULP, J. L., BATE, G. L., and BROECKER, W. S., 1954. Present status of the lead method of age determination. *Am. Journ. Sci.*, **252,** 345-365.

KULP, J. L., COBB, J. C., LONG, L. E., and MILLER, D. S., 1959. The geological time-scale. *Nature*, **184,** B.A. 62-63.

LIPSON, J., 1958. Potassium-argon dating of sedimentary rocks. *Bull. Geol. Soc. Am.*, **69,** 137-150.

LONG, L. E., COBB, J. C., and KULP, J. L. *In press*, 1959. Isotopic ages of some metamorphic rocks in the vicinity of New York City. *Trans. New York Acad. Sci.*

LONG, L. E., and KULP, J. L., 1958. Age of the metamorphism of the rocks of the Manhattan Prong. *Bull. Geol. Soc. Am.*, **69,** 603-630.

LONG, L. E., KULP, J. L., and ECKELMANN, F. D., 1959. Chronology of major metamorphic events in the southeastern United States. *Am. Journ. Sci.*, **257,** 585-603.

MAYNE, K. I., LAMBERT, R. St. J., and YORK, D., 1959. The geological time-scale. *Nature*, **183,** 212-214 and 769.

NIER, A. O., 1939. The isotopic constitution of radiogenic leads and the measurement of geological time. *Phys. Rev.*, **55,** 150-163.

NIER, A. O., THOMPSON, R. W., and MURPHY, B. F., 1941. The isotopic constitution of lead and the measurement of geological time. *Phys. Rev.*, **60,** 112-116.

OWEN, T. R., 1958. The Armorican Earth-movements. *Seventh Inter-University Geological Congress, Swansea*, 46-50.

POLKANOV, A. A., and GERLING, E. K., 1958. K-A and Rb-Sr methods and ages of Precambrian of U.S.S.R. *Trans. Am. Geophys. Union*, **39,** 713-715.

SCHÜRMANN, H. M., *et al.*, 1957. Third preliminary note on age determination of magmatic rocks by means of radioactivity. *Geol. en Mijnbouw*, **19,** 398-413.

SIMPSON, S., 1959. Culm stratigraphy and the age of the main orogenic phase in Devon and Cornwall. *Geol. Mag.*, **96,** 201-208.

SMALES, A. A., 1948. Monazite from Bodmin Moor, Cornwall: a study in geochronology: Part II. Analysis of Bodmin Moor monazite for lead, thorium and uranium. *Proc. Roy. Soc. Edinburgh*, **63B,** 125-129.

SMALES, A. A., MAPPER, D., MORGAN, J. W., WEBSTER, R. K., and WOOD, A. J., 1958. Some geochemical determinations using radioactive and stable isotopes. *Proc. Second U.N. Internat. Conf. on Peaceful Uses of Atomic Energy, Geneva*, **2,** 242-248.

STIEFF, L. R., STERN, T. W., OSHIDO, S., and SENFTLE, F. E., 1959 Tables for the calculation of lead isotope ages. *U.S.G.S. Prof. Pap.* **334-A,** 1-40.

SUTTON, J., and WATSON, J., 1950. The pre-Torridonian metamorphic history of the Loch Torridon and Scourie areas in the North-West Highlands, and its bearing on the chronological classification of the Lewisian. *Quart. Journ. Geol. Soc. London,* **106,** 241-308.

TEICHERT, C., 1958. Australia and Gondwanaland. *Geol. Rundschau*, **47,** 562-590.

TILTON, G. R., WETHERILL, G. W., DAVIS, G. L., and HOPSON, C. A., 1958. Ages of minerals from the Baltimore Gneiss near Baltimore, Maryland. *Bull. Geol. Soc. Am.*, **69,** 1469-1474.

WEBSTER, R. K., MORGAN, J. W., and SMALES, A. A., 1957. Some recent Harwell analytical work on geochronology. *Trans. Am. Geophys. Union*, **38,** 543-546.

WETHERILL, G. W., 1957. Radioactivity of potassium and geologic time. *Science*, **126**, 545-549.

WICKMAN, F. E., 1942. On the emanating power and the measurement of geological time. *Geol. Fören Förh. Stockholm*, **44**, 465-476.

WILMARTH, M. G., 1925. The geological time classification of the United States Geological Survey compared with other classifications. *U.S.G.S. Bull.*, **769**, 1-138.

WOODWARD, H. P., 1957. Chronology of Appalachian folding. *Bull. Am. Assoc. Petrol. Geol.*, **41**, 2312-2327. See also *Bull. Geol. Soc. Am.* (1958), **69**, 1666.

ZEUNER, F. E., 1958. *Dating the Past*, 4th ed. Methuen, London. 1-516.

——, 1959. *The Pleistocene Period*. Hutchinson, London. 1-447.

Grant Institute of Geology,
University of Edinburgh.