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PROPOSALS FOR TIME CLASSIFICATION AND CORRELATION OF PRECAMBRIAN ROCKS AND EVENTS IN CANADA AND ADJACENT AREAS OF THE CANADIAN SHIELD

PART 3: A PRECAMBRIAN TIME CHART FOR THE GEOLOGICAL ATLAS OF CANADA

A. V. OKULITCH

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"I measure time and know not what it is that I am measuring."
St. Augustine, Confessions (ca. 600 AD).

PROPOSALS FOR TIME CLASSIFICATION AND CORRELATION OF PRECAMBRIAN ROCKS AND EVENTS IN CANADA AND ADJACENT AREAS OF THE CANADIAN SHIELD

PART 3: A PRECAMBRIAN TIME CHART FOR THE GEOLOGICAL ATLAS OF CANADA

Abstract

The third part of the debate about time classification and correlation of Precambrian rocks and events in Canada continues with discussion of the fundamental philosophies of geological time scales, assessment of previous proposals and the description of a chart with three scales. This chart is intended for use in the Geological Atlas of Canada. The chart includes a chronometric scale for international correlation and reference to isotopic ages, the chronometric/chronolithic hybrid scale proposed for the Decade of North American Geology publications, and a modified (primarily chronolithic) version of Stockwell's chrono-orogenic scale which appeared in the first part of this debate. Participants in the Geological Atlas program may utilize whichever scale they prefer, however at present, use of the third scale is encouraged to provide a uniform format for Atlas maps and charts.

In making the third scale, the modifications proposed to Stockwell's scale are the addition of uncertainties to boundary positions derived from assessment of defining data, a change in emphasis from chrono-orogenic to chronolithic definitions while retaining, in most instances, both boundary positions and original defining data, and minor changes in nomenclature.

Résumé

La troisième partie de la discussion sur la classification et la corrélation chronologiques des roches et des événements du Précambrien au Canada se poursuit en examinant les philosophies fondamentales des échelles géochronologiques, en évaluant les propositions antérieures et en décrivant une carte a trois échelles qui sera utilisée dans l'Atlas géologique du Canada. La carte comprend une échelle chronométrique des âges absolus qui peut servir aux fins de corrélation internationale, une échelle chronométrique-chronolithologique de nature hybride proposée pour les documents publiés dans le cadre de la Décennie de géologie en Amérique du Nord, ainsi qu'une version modifiée, principalement chronolithologique, de l'échelle chrono-orogénique de Stockwell présentée dans la première parties de la présente discussion. Les participants au programme de l'Atlas géologique sont libres de choisir l'une ou l'autre de ces trois échelles, bien que l'on encourage l'utilisation de la troisième afin d'uniformiser la présentation des cartes de l'Atlas.

Dans le cas de la troisième échelle, les modifications proposées a l'échelle de Stockwell sont les suivantes: l'addition d'incertitudes aux limites déduites par évaluation des données définitoires; une plus grande importance accordée aux définitions chronolithologiques par rapport aux définitions chronoorogéniques, bien que dans la plupart des cas la position des limites et les données définitoires d'origine aient été conservées; et des changements mineurs apportés a la nomenclature.

INTRODUCTION

This report is the third part of "Proposals for time classification and correlation of Precambrian rocks and events in Canada and adjacent areas of the Canadian Shield". Part 1, "A time classification of Precambrian rocks and events" (Stockwell, 1982a) summarized a chrono-orogenic division of time evolved over 20 years (Stockwell, 1964, 1973, 1982a) and listed most isotopic ages from the Canadian Shield available up to about 1976. Part 2, "A provisional standard for correlating Precambrian rocks" (Douglas, 1980) used orogenic, intrusive, paleomagnetic and stratigraphic criteria to establish time scale boundary definitions. Part 3, "A Precambrian time chart for the Geological Atlas of Canada", owes much to parts 1 and 2, and specifically addresses the need for a practical standard for the atlas.

The Precambrian time chart discussed here is the result of investigations of time, geological time and geological time scales in general, Precambrian time scales specifically and numerous consultations with Precambrian geologists, primarily those of the Lithosphere and Canadian Shield Division of the Geological Survey of Canada. The chart is a necessary part of the Geological Atlas of Canada which will be a set of 100 maps of the bedrock geology of Canada and adjacent areas at 1:1 million scale. About 1/3 of the atlas is published, in press or being compiled. The chart is designed with the needs of the atlas in mind; whether it may or may not be of use elsewhere is a secondary consideration. Further discussion of time scales and the atlas has appeared in Part 2 (Douglas 1980, Introduction).

This paper begins with a brief overview of the philosophy and principles underlying geological time scales and the selection of those considered valid and practical for present purposes. This is followed by comparison of some past proposals, primarily those made for the Precambrian of North America. The paper concludes with presentation of the proposed time chart. The specific decisions made during its assembly are in Appendix A. Proposals for additional refinements of the chart are made in Appendix B.

The chart (Fig. 1) is not substantially different from its predecessors. This is intentional; there are not enough new data on which to base a totally new chart. Even if there were, no consensus exists with regard to fundamental philosophies and principles or their practical application; the approach adopted here is thereby multifaceted, with emphasis on the author's preferences. These are dictated to a considerable extent by specific needs of the atlas program: regional compilation maps of bedrock geology must clearly show map unit ages by symbols and colours that provide mnemonic cues to readers. Also, such maps draw upon data published over many years, using various terminologies, therefore some reference to previous data and literature would have to be provided. The scale proposed by the North American Commission on Stratigraphic Nomenclature (Harrison and Peterman, 1980) is included because the atlas extends into the United States. Moreover, that scale will appear in the Geological Society of America's Decade of North American Geology publications, (Palmer, 1983), of which 9 volumes, by the Geological Survey of Canada, form the "Geology of Canada" series, and is likely to be widely used. It will be referred to as the DNAG scale hereafter. The time scale proposed by the Subcommission on Precambrian Stratigraphy (Plumb and James, 1986) is essentially a minor modification of the DNAG scale, has not yet been formally recommended, and is therefore not shown seperately. In the following discussion it will be referred to as the Subcommission scale. Stockwell's (1982a) scale is used with some modification because the nomenclature, if not the exact boundaries, are well known and still used by some Precambrian geologists in Canada. The nomenclature and boundaries of this scale will form the basis for map unit symbols and correlation charts of the Geological Atlas at present. New data, changing concepts and shifts in common usage of terms will dictate reassessment and revision of the chart in the future.

During the formation of the Stockwell, DNAG and Subcommission scales, entirely consistent application of scientific and philosophical principles, and the North American Stratigraphic Code (1983), was not achieved. Some of the experience gained from the evolution of the Phanerozoic time scale does not appear to have been utilized (cf. Kitts, 1966). These scales possess a practical utility nonetheless. The chronometric scale, although based on unverifiable assumptions about the nature of time, provides universally accepted units against which divisions of geological time, events and rock units can be ordered.

Philosophical preamble

Whatever time may be, whatever analogues we employ to try to understand it, it remains intangible. Our senses and scientific instruments record only sequences of physical changes (Whitrow, 1961). Neither theories of an abstract time continuum (Newton, 1687; Jeletzky, 1956, p. 701, para. 4), quantized time (the movie-film frame analogy), nor time as a fourth (or higher) dimension can be demonstrated to be correct (Kitts, 1966).

Time is defined by counting regularly repeated events and is represented by this count. Time itself has neither been observed nor measured. Geological events are related to this representation of time by comparing the number of atoms of an isotope that disintegrate during a number of vibrations of an atomic clock. The clock can also measure planetary motions and the age of an event or rock can thereby be expressed in years. The attempt to define geochronometric units in Articles 96 and 97 of the North American Stratigraphic Code (1983) is thereby a scientifically unverifiable extrapolation of regularly occurring present events (atomic vibrations and planetary motions) into the distant past.

The record of events preserved within that portion of the earth's crust accessible to us therefore remains the only basis for a geological time scale. Moreover, it is directly applicable to the objects being studied. This record includes those numbers called 'ages' acquired by chemical and isotopic analyses. These have no absolute reality outside the

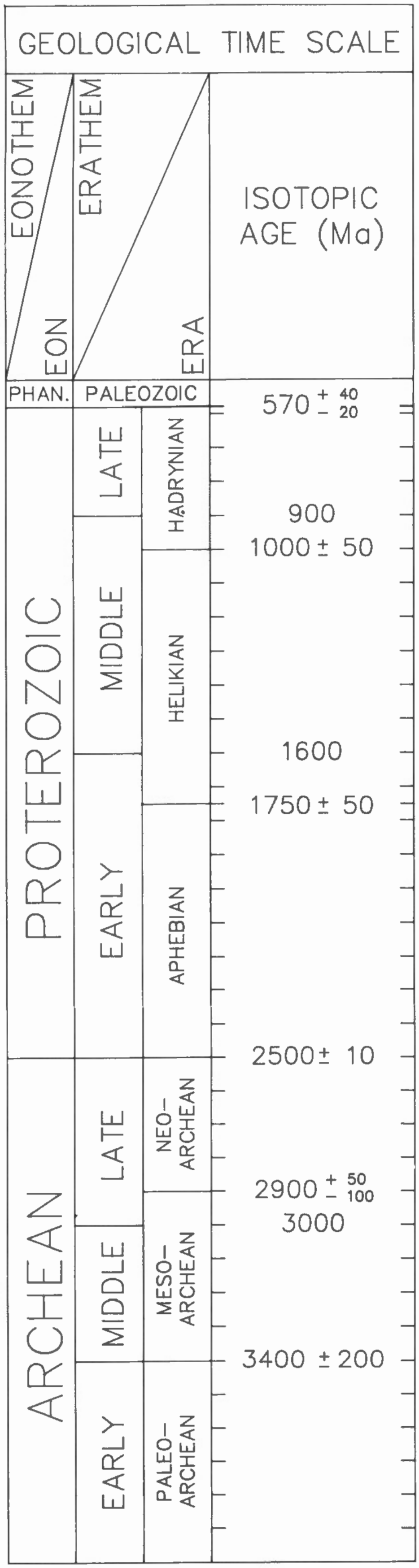

Figure 1. The Precambrian time chart proposed for use with the Geological Atlas of Canada.

rocks from which they were obtained but they can be positioned relative to one another using the extrapolated chronometric scale.

Practical principles

The construction of a geological time scale should be governed not only by valid philosophical and scientific principles but by practical factors as well. All scales result from arbitrary decisions; their primary aim is to foster effective communication about crustal history. Two schools (formed in the past 20 years during the growing use of isotopic analytical methods) are the traditional (chronostratigraphic or "chronolithic") school which extends the use of the rock record from the Phanerozoic into the Precambrian, and the chronometric school which uses a numbered scale on which isotopic ages and the events they date can be located. The term "chronolithic" is used in this paper in a general, 'root' sense, not equivalent to chronostratigraphic, to mean a time unit defined by any rock unit, not necessarily stratified. For example, a plutonic complex, intruded over a known interval of time could be the defining body of rock for that interval. This use of the term chronolithic expands that of Article 66 of the North American Stratigraphic Code (1983), and in the terminology of the code, includes both chronostratigraphic and "chronolithodemic" units. It may be of considerable use for a Precambrian time scale.

A variety of characteristics of the rock record have been used by the traditional school: major breaks in the stratigraphic column, tectonic, magmatic and metamorphic events, substantial changes in sedimentation and rapid episodes of extinction and evolution. The last two commonly produce distinctive new fossil assemblages. All of these were used to define upper and lower boundaries of Phanerozoic time scale units and many coincide with gaps in the rock record. However, gaps are poor datum points and definition of both upper and lower boundaries of units results in spaces and overlaps in the scale (Kitts, 1966), hence complete stratotypes are now used and the stratigraphic code has been revised to require definition of only the lower boundary of each unit, the upper boundary being set by the lower boundary of the next unit.

This approach to time scale construction has only partial application to Precambrian rocks, primarily because they are rarely fossiliferous. The need to understand paleontological relationships has been one of the motivating factors in seeking detailed stratotypes in the Phanerozoic, but the chronometric school has argued that Precambrian units, mostly barren of fossils, largely unstratified plutonic and metamorphic rocks, are best described in 'pure' time terms only. Although the search for complete sequences of closely spaced events in type localities to serve as precise boundary definitions is philosophically correct, it is also time consuming and sometimes leads to acrimonious debate. A chronometric scale, although without rigorous philosophical or scientific support, is simple and non-controversial (in its form, if not its use).

As usual in such debates, the extreme views of each school appear irreconcilable but a broad middle ground exists. Harland (1975) recommended the use of both chronostratigraphic and chronometric scales. Proponents of purely chronometric scales have stated that nomenclatures with local and natural significance combined with a time scale of years provide the only possibility of international coordination of Precambrian research (Trendall, 1966, p. 522) and that subdivision of time should reflect major events (James, 1978, p. 200, criterion 2). The Subcommission on Precambrian Stratigraphy at one time had as an objective the definition of rock references for specific periods of time but independent of the time scale (James, 1978, p. 202). Recent recommendations of the Subcommission (Plumb and James, 1986) acknowledge the utility of orogenic, magmatic, sedimentological, biological and climatic events in defining time boundaries. The growing use of isotopic ages in the Phanerozoic and the extension of chronostratigraphic and biostratigraphic techniques into the Proterozoic illustrate the need for two complementary scales. For example, rock sequences and the spans of time they represent that are not amenable to isotopic dating, can be situated on a time scale only by the usual geological relationships of lithological correlation, superposition and intrusive relationships. Such sequences have no direct link to a chronometric scale. The opposite case, an isolated rock unit with no known relationship to any others, but which can be isotopically dated, can only be related to chronometric units and only indirectly be related to chronolithic units.

If the use of complementary scales is accepted, then the principles by which they are made must be defined. The chronometric scale is the straight-forward extrapolation of present time units into the past. The chronolithic scale is less simply made, and its definition should be a balance between allowing maximum applicability of a variety of geological relationships and an inconsistent hodge-podge of numerous criteria.

Recent revision of the North American Stratigraphic Code (1983) addressed problems often associated with Precambrian rocks and may provide such a balance. Broadening the code to embrace chronolithic units as redefined above may further enhance its utility. The following articles are pertinent:

Article 66: "A chronostratigraphic unit is a body of rock established to serve as the material reference for all rocks formed during the same span of time ... its [lower] boundar[y] is synchronous".

Article 66(c): "A chronostratigraphic unit may be ... any arbitrary but specified sequence of rocks ... allowing chronocorrelation with rock sequences elsewhere".

Article 67, Remark (a): "... a chronostratigraphic unit with its base defined at one locality, will have its top defined by the base of an overlying unit at the same, but more commonly another locality".

Article 78: "An ideal stratotype for a chronostratigraphic unit is a completely exposed unbroken and continuous sequence of fossiliferous stratified rocks extending from a well-defined lower boundary to the base of the next higher unit". This article is sometimes used to support the contention that principles of the stratigraphic code have no practical application to Precambrian time scales. Without qualification, this article would preclude using the code for Phanerozoic time as well. However, the code recognizes the necessity of defining boundaries with stratotypes that do not extend to represent entire chronostratigraphic units [Article 8(b)], composite stratotypes [Article 8(d)] and reference localities for nonstratiform (and non-fossiliferous) rock bodies [Article 8(c)]. Implicit in these recommendations is the fact that nonrepresented and hence undefinable gaps will initially exist and may remain in the chronostratigraphic and thereby, the geochronological continuum (but not in the temporal continuum, which may or may not exist).

It is (and was) possible to construct traditional time scales without isotopic ages or paleontological data. However, it is not possible to use such scales anywhere except where they were established without some means of correlation, the best of which are provided by these two methods. A time scale is defined by events in the rock record observed in particular areas. To be useful outside those areas the definition must include properties of that record which exist in other areas. Such properties can include lithology, relationships between rock units, etc. but the most useful, because they vary least from area to area, are isotopic and paleontological data. The reliability of even these is limited by such factors as rates of species radiation, redeposition of fossils, local pertubations of isotopic systems, propagation of deformational and metamorphic fronts, and migration of crustal plate interactions.

Next, the defining events are positioned on the scale by isotopic or paleontological data, preferably both. Finally, the resulting scale serves as a standard in other areas where the rock record is analyzed for properties present in the type area, correlations are proposed and ages are assigned to rock units and events.

Controversy then focuses on selection of type areas and which of their properties are most helpful in both local and regional definition of time boundaries based on chronolithic units. There is an 'uncertainty principle' at work here, particularly in the unfossiliferous Precambrian although it applies in lesser degree to the Phanerozoic. Events affecting large portions of the earth's crust are potentially the most useful for an international time scale. Such events (except very large meteorite impacts) are also complex and diachronous. Any boundary definitions based on them are thereby imprecise and vague. For example, the arbitrary positioning of the Archean/Proterozoic boundary (Sims, 1980) is merely an artificial numerical constraint on events that occurred from about 2700 to 2400 Ma. Even proposals utilizing worldwide aspects of the rock record more directly, such as Snelling's (1985) division of the Proterozoic at ca. 2000 Ma (the beginning of most redbeds and the Gunflint microbiota and the end of most banded iron-formations) are subject to uncertainty because of diachronism. The possibility that local conditions allowed such facies to persist beyond or to begin before the age of his boundary introduces additional uncertainty.

Events of more local effect, such as orogenies, can be useful criteria within a single structural province, but even within a province are neither simple nor short-lived. Definitions based on them are imprecise and may be difficult to correlate with events in other structural provinces. Geological relationships within small areas (stratotypes, well dated igneous rocks, etc.) can sometimes be positioned very accurately on a time scale but correlation away from the area becomes increasingly uncertain as the same relationships rarely have substantial expression outside it.

The major divisions of the Precambrian time scale used in Canada have been imprecisely positioned by complex, diachronous events spanning the craton, or at least large parts of structural provinces. Refinement of this scale will require detailed descriptions of the rock record in selected areas followed by definition of a standard that must, by necessity, be arbitrarily applied to all other Precambrian rocks. Compilation of the Geological Atlas will play a key role in such a process. Data portrayed on correlation charts may permit subdivision of the scale and evaluation of potential type localities. A similar process, the results of which are being published in United States Geological Survey Professional Paper 1241 (Rankin *et al.*, 1983; Harrison and Peterman, 1984; Denison *et al.*, 1984; and others in press), but one not taken beyond major divisions, was used to produce the DNAG scale. Definition of the Subcommission scale was guided by the ages of major events recorded in cratons from all continents (Plumb and James, 1986, Fig. 1).

Past proposals

The numerous (James, 1978, noted over 50) scales for Precambrian time that have been advanced previously will not all be discussed as most are not applicable to Precambrian rocks of the Canadian Shield and exposed in bordering orogens. Five scales represent, in their fundamental philosophies, most of the concepts found in earlier suggestions (Fig, 2),

The first scale (Fig. 2, column A), a linear chronometric one with no named units, is favoured by those requiring the security of an absolute, fixed, external reality. The intangible nature of such comforting concepts has been noted before. This scale can also be thought of as merely a sequential list of numbers, a ruler, which allows the easy location of isotopically dated rock units and events relative to one another. The absence of any demonstrable relationship between such dates and a hypothetical absolute time scale should not be forgotten but can be set aside for practical reasons.

The DNAG scale (Fig. 2, column B), intended as an interim solution, was made by examining the scattered rock record of the United States and Mexico as well as portions of the extensive record from the Canadian Shield (Harrison and Peterman, 1984, p. A1, Acknowledgments) and by choosing boundaries that passed through gaps in the record or periods containing minimal data. It was described as a chronometric scale despite the influence of the rock record, but as such would be a definition of the unknowable by the non-existent. In fact, it is a hybrid composed of a fragmentary chronolithic scale tied together across its gaps by a chronometric scale. The boundaries of this hybrid scale, placed in the gaps, are presently defined chronometrically but could have been defined chronolithically if placed within the preserved rock record. No consensus was obtained for the latter approach but the future intent (J. E. Harrison, pers. comm., 1984) is to insert a chronolithic scale into the chronometric framework.

The Subcommission scale (Plumb and James, 1986) is not illustrated as it was constructed on principles similar to those used for the DNAG scale. Despite consideration of data from all other continents, no modifications to the DNAG scale were proposed except that divisions of the Archean were dropped, Proterozoic era nomenclature was altered slightly, and divisions of those eras (periods) were proposed. It also is stated to be a chronometric scale but boundaries were selected by considering the total geological record, i.e. it is derived chronolithically but simplified, seemingly to avoid too close a philosophical link to the rocks themselves and the interminable controversy that attends selection of type localities, nomenclature and the like.

The third scale (Fig. 2, column C) was proposed by Stockwell (1964) and subsequently refined (Stockwell, 1973, 1982a) and modified (Fig. 2, column D; Douglas, 1980). Frarey (1981) proposed additional minor changes (Fig. 2, column E). The 'Stockwell' scale is the result of much meticulous study of the rock record and geochronological data, and thereby deserves both serious consideration and careful critical analysis. One such appraisal appeared in Harland (1983).

Stockwell (1982a, p. 1) stated that:

> ''The framework of the time classification is based on orogenies whose terminations define boundaries between time units ... . Orogenies are defined by rock at type localities and not by isotopic age which varies with the method used and has a margin of error; the rock serves as a standard, and any future revision of its isotopic age will not alter the nomenclature of the orogenies nor of the derived time units.''

Such traditional chronolithic principles were not consistently applied, however. The rock record (including isotopic ages) was used to define orogenies, syn- and epiorogenic events were selected from the record to delimit dates of the terminations of orogenies, then those dates were used to position time boundaries. Terminations of orogenies were favoured because final setting of isotopic systems is more easily measured than the initiation of thermal events. Orogenies were said to be good boundary-defining events because they are datable by isotopic means, mark drastic changes in earth history, are episodic and cyclic and bracket periods of sedimentation and volcanism with mappable boundaries. All these reasons are inaccurate generalizations. Orogenies, unless narrowly defined in restricted areas, are complex, di-

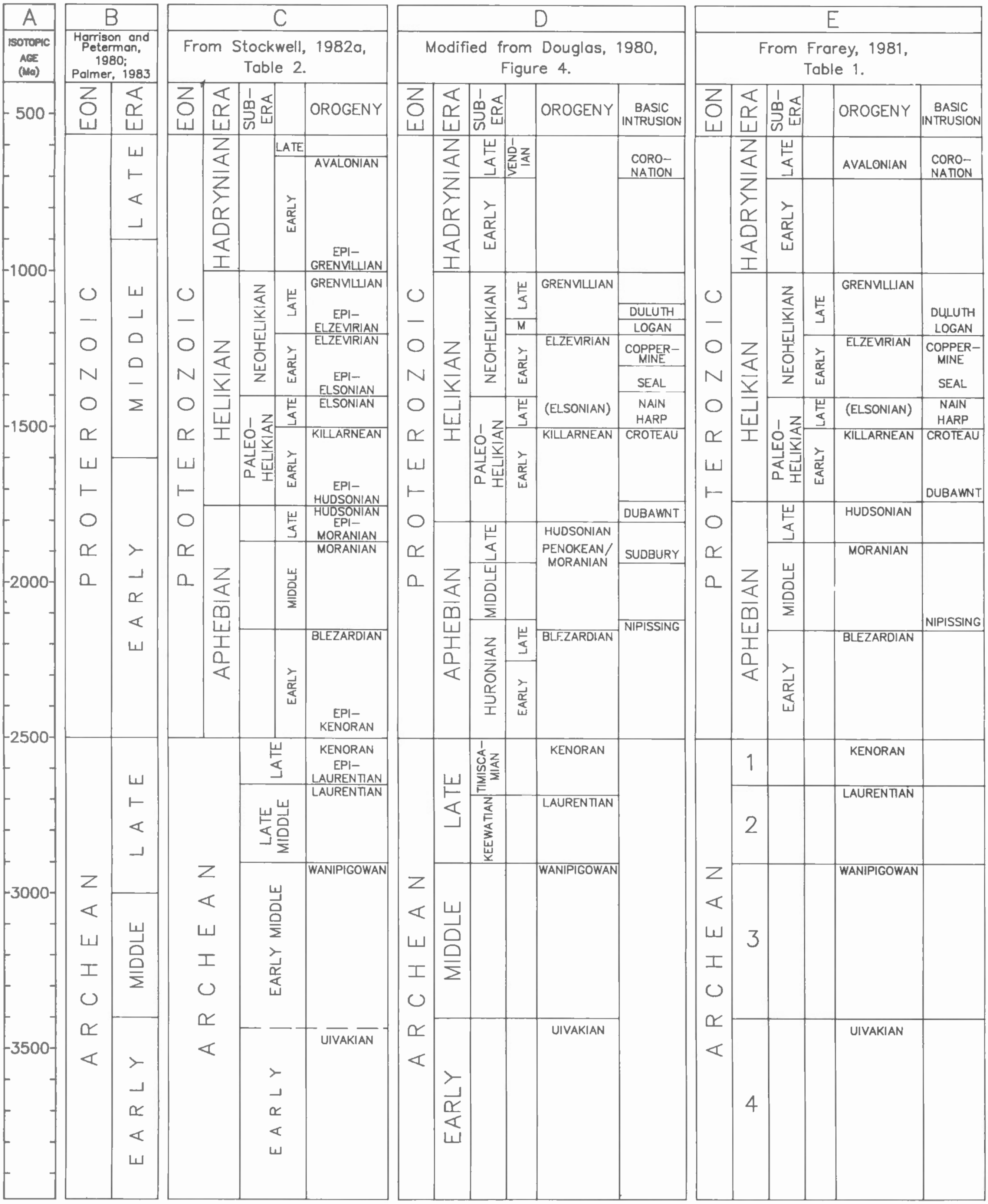

Figure 2. Time scales proposed for Precambrian rocks of the Canadian Shield.

achronous events composed of multiple magmatic, tectonic and metamorphic episodes, followed or accompanied by uplift, cooling, erosion and, beside the orogen, redeposition of its constituents. Orogenies do not necessarily mark drastic changes in earth history, as they can be, depending on their definition, restricted to limited areas. They are neither episodic nor cyclic; each is unique depending upon crustal plate configurations and motions which derive from earlier crustal evolution. They do bracket periods of deposition locally, but synorogenic deposition continues elsewhere.

The terminations of orogenies within a structural province are also diachronous. An example of this diachroneity appears in the discussion of the early/late Neoarchean boundary (Appendix B). Terminations are represented by a variety of events such as post-tectonic magmatism, waning metamorphism, late gentle folding, uplift and cooling. The last two processes were considered by Stockwell (1982a) to provide an upper limit to terminations of orogenies and to be dated by averages of cooling ages (primarily Rb-Sr and K-Ar isotopic mineral ages). As such, these isotopic systems were integral parts of several boundary definitions and the averages of ages produced numerical estimates of boundary positions. Although he (*op cit.*, p. 5,6) maintained that such averaging:

"... tends to cancel out the errors and unknown factors and is a reasonably good estimate of the age of the great majority of the determinations. [and that] The average ... is therefore thought to be more meaningful and generally to be more accurate than the ages considered individually.",

such an approach is in fact statistically invalid. Every date, whose laboratory errors are small, has its own geological significance, whether that is understood or not. It is not a randomly generated figure amenable to statistical reduction. Any average so derived is no more meaningful than an individual date. Moreover, such averaging obscures a rich and diverse set of events of potential significance, much in the way that averaging the chemical compositions of a rock unit obscures important variations of possible genetic significance. What must be sought and selected are the best individual determinations.

When orogenies are made the fundamental criteria of time scale boundaries, and when by definition and description they include events that spanned considerable intervals of time and occurred throughout large geological provinces, then they are not sufficiently well focused criteria for precise boundary location. This is true for terminations of orogenies also, albeit to a lesser degree. This does not mean that Stockwell's scale should be abandoned. Orogenies form an important part of the rock record and the relationships produced by magmatism, tectonism, metamorphism, uplift and erosion, if selected carefully remain useful criteria with which boundaries may be defined and positioned. Orogenies are the "major events" required by James (1978, p. 200) for initial subdivision of time, and "... are generally accepted as the key markers in Precambrian history [which] influence strongly the selection of time boundaries, ..." (Plumb and James, 1986, p. 69, 70). The elegant nomenclature and basic principles underlying Stockwell's scale remain relevant but refinement of his application of those principles likely demands replacing terminations of orogenies by selected (type) areas. In a gradual shift away from broad use of orogenies, type areas initially could be selected to contain an orogen unconformably overlain by post-orogenic strata, or cut by post-orogenic intrusions. The span of time represented by the unconformity should be short and well constrained by isotopic ages. In subsequent evolution of methodology, if datable stratotypes of syn- to post-orogenic successions become available, they could supplement or supplant relationships in orogenic type areas. For some boundaries, such areas have already been described by Stockwell (1982a), e.g. the Wanipigowan Orogeny (*op cit.*, p. 19, 20) and the Laurentian Orogeny (*op cit.*, p. 20, 21).

It might be noted at this point that the differences between Stockwell's approach and that of the 'gap' method of Harrison and Peterman (1980) and Plumb and James (1986) are actually far less than either proponents may realize. In both, the rock record is examined and arbitrary decisions are made about how to position boundaries. In both, only relatively broad constraints (± 50 to 100 Ma) can be placed on these positions unless further arbitrary selections are made from the rock record or the positions arbitrarily fixed on a chronometric scale. In both, the accompanying chronometric scale serves as a reference for correlation between separate parts of the rock record.

The desire not to split rock sequences, assemblages or orogenies seems to pervade the minds of both sides. This feeling is perhaps a remnant of the traditional method used to make first-order divisions of the Phanerozoic. If we were blessed with a complete record of Precambrian time, all time boundaries would split some sequences of depositional or orogenic events somewhere. Yet, because gaps exists, whether they be undefined, missing or unobserved parts of the record, as in the DNAG scale, or those bounded below by terminations of orogenic events and above by basal unconformities or post-orogenic intrusions as in the Stockwell scale, they are accorded importance out of all proportion to their use for precise boundary definitions.

The fourth scale (Fig. 2, column D) resulted from Douglas' (1980) modification of Stockwell's scale. Minor changes of era and subera boundaries occurred because of his use of smaller type areas and additional criteria such as basic intrusions and magnetochronological units. He also proposed or resurrected several time unit names derived from lithostratigraphic units (Keewatian, Timiscamian and Huronian). Positive aspects of Douglas' approach were the use of more precisely defined events in small type areas (although the choice of events and areas has been questioned), and the use of basic intrusions, which may not coincide with breaks in stratigraphic successions but which are widespread events displaying unambiguous relations with other rock units and having potential for accurate dating by Nd-Sm isotopes. Less desirable aspects of his approach were the new names and introduction of magnetochronological units. The new time unit names were rightly criticized

(Frarey, 1981; Stockwell, 1982b) as their use contravened the North American Stratigraphic Code (1983), (Article 77: "... naming of a new chronostratigraphic unit ... by adding "-an" or "-ian" to the name of a lithostratigraphic unit is improper."), but mainly because their new definitions as chronostratigraphic units altered and expanded their original definitions as lithostratigraphic units.

With regard to magnetochronological units, Roy (1983, p. 319, Abstract) concluded that:

"It is shown that this limited data base with all its deficiencies and uncertainties cannot be used to support certain hypotheses, or for the drawing of a meaningful apparent polar path for the whole of the Precambrian."

Condensation of the scale determined for the past 150 Ma (Fig. 3) onto a small part of the Proterozoic scale illustrates the problem. Only superchron units (*cf.* Harland *et al.*, 1982, p. 83) spanning 30 to 100 Ma which lie close to the limits of resolution of present paleomagnetic and many radiometric techniques might be of use. Given the possibility of greater heat flow and presumably more rapid plate motions in the Precambrian than at present, determination of a complete, accurate apparent polar wander path or magnetic reversal time scale seems unattainable at present. This does not invalidate the use of certain parts of the paleomagnetic record in which reversals were infrequent and good ages are available. Nonetheless, magnetochronological units cannot be considered helpful in precise definition of time divisions or correlation of widespread rock units in the immediate future.

The fifth scale (Fig. 2, column E; Frarey, 1981) retained the boundaries and nomenclature of the Stockwell scale but added the basic intrusive events proposed by Douglas (1980).

Present plans

The time chart proposed for the Geological Atlas (Fig. 1) includes three scales to allow comparison and reference to terms in the literature, to provide useful map unit symbols and to permit application of a variety of treatments of time and rock units. In the detailed discussion in the appendices, and in all figures, no distinction is made between formal and informal time unit names. The only terms formally defined internationally are Archean and Proterozoic. Divisions of these eons (early, middle and late) in the DNAG scale (and Proterozoic I, II, III in the Subcommission scale) have achieved preliminary acceptance. Stockwell (1982a) considered his three divisions of the Proterozoic as being formally defined and established but neither national consensus nor international recognition exists for their

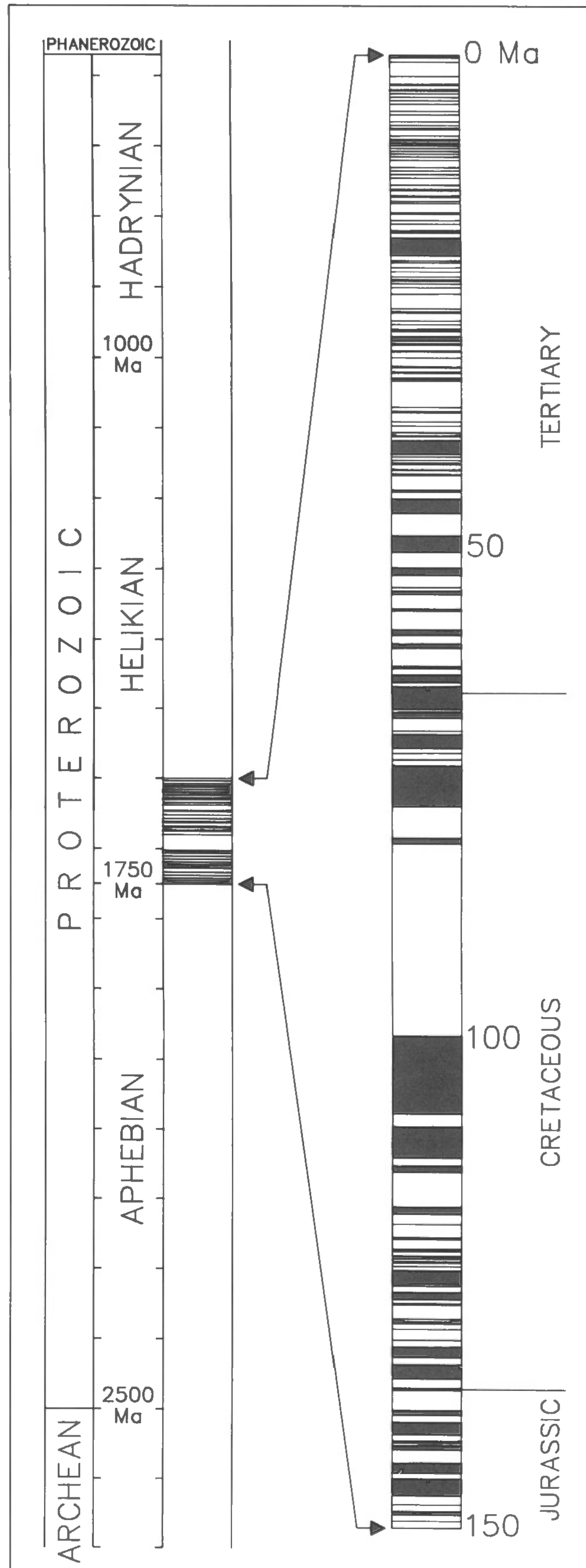

Figure 3. Part of the Phanerozoic magnetostratigraphic scale superimposed upon part of the Precambrian time scale to illustrate the possible undetectable fine structure of reversals. Data from Harland et al. (1982).

definition or use. All other subdivisions of Stockwell's, the DNAG, and the Subcommission scales must be considered informal at this time. Formal proposals for the Ediacaran System and Period also await resolution of boundary criteria and positions before international acceptance is achieved.

On the tripartite chart discussed here, the linear numbered 'time' scale, as noted before, is a representation of time by extrapolation of present events into the past, and provides a noncontroversial method of ordering events and rock units. The DNAG scale is included primarily for cross-reference, however, if it or the Subcommission scale gains wide acceptance, it may become the primary scale for the atlas. Stockwell's nomenclature (modified somewhat) is used on a scale most of whose boundaries are those defined by Stockwell (1982a). Several changes (*cf.* appendices), derived from the principles discussed previously and from some proposals made by Douglas (1980) and Frarey (1981), and some resulting from new data, have been introduced. At present, this scale is intended for use in the Geological Atlas of Canada to define map unit symbols and colours.

Such a chart should enable "chronometricians" to locate dated rock units and events relative to one another on the correlation charts accompanying atlas maps. Names of time divisions and their boundaries, should they choose to use them, can be accepted as fixed at their selected values and no regard taken of any uncertainties. Those preferring the orogenic system of Stockwell will find that most boundary definitions incorporate some significant facets of those made by him. Those wishing to pursue a traditional chronostratigraphic or chronolithic approach will find that suggestions for refinement of most boundaries are made on a general chronolithic basis but that they are rarely defined by rigorous application of chronostratigraphic principles because few suitable units have been studied with this aim in mind. Boundary definitions and positions, and suggestions for future refinements must be treated as provisional and subject to change as new data become available through the efforts of active field geologists.

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APPENDIX A

The boundary definitions are discussed in order from eon to era to period, so the reader may progress from major, well established time divisions to smaller ones not yet in common use. The latter appear in Appendix B. The primary aim is to produce a working version of a time chart for the Geological Atlas and to mark out principles and processes for its future refinement. Details of isotopic ages used in positioning boundaries are not included; the most precise ages available (usually derived from analyses of U-Pb isotopes) have been used and uncertainties in these ages are given graphically in figures 4 to 16 (in pocket). Although much valuable material was received in the course of critical review of this paper, the chronolithic data utilized for boundary definitions are not necessarily the best available and are subject to change. Detailed and well documented chronolithic data that would replace or augment those discussed would be welcomed by the author.

Eon boundaries

A beginning to the Archean Eon has been suggested in the DNAG scale (Harrison and Peterman, 1980, p. 378) at about 3800-3900 Ma. Although this may have been a time of major change in earth history (perhaps when crust-forming processes began to dominate over destructive accretionary ones), so little record remains of this stage of crustal evolution that definition of this time boundary would seem to have little practical use at present.

The boundary between the Archean and Proterozoic eons is set at 2500 Ma following the decision of the International Subcommission on Precambrian Stratigraphy (Sims, 1980; Plumb and James, 1986). It falls, within the resolution of analytical techniques and available data, close to that established by Stockwell (1982a, p. 14, 23-25) as lying between the late phase of the Kenoran Orogeny (*ca.* 2650-2500 Ma) and the late phase of the epi-Kenoran cooling period (*ca.* 2600-2300 Ma). Relationships that might refine this definition have been known for many years (Alcock, 1934; Robertson *et al.*, 1969) but until recently were not well dated. Data portrayed in Figure 4 confine a boundary on a chronolithic basis to 2500 $^{+150}_{-10}$ Ma (Stockwell, 1982a; Frarey et *al.*, 1982; Krogh *et al.*, 1984b). Initiation of Huron Supergroup mafic volcanism and comagmatic anorthositic intrusion (Card *et al.*, 1977) might be a reasonable chronostratigraphic definition for the beginning of the Proterozoic, thus returning to a definition (Alcock, 1934; Church and Young, 1970), abandoned because of a lack of age information. The boundary could be fixed at 2500 $\pm$ 10 Ma. Nowhere in the Canadian Shield do strata closely follow the Kenoran Orogeny and lie on latest Archean basement, and correlation with this boundary can only be made using Stockwell's (1982a) criteria.

The end of the Proterozoic Eon was set at 570 ± 20 Ma for the DNAG scale (Palmer, 1983). Harland *et al.*, (1982) suggested 590 Ma with unstated but considerable uncertainty, perhaps ±30 Ma. Chronostratigraphic definition awaits final decisions by the Precambrian-Cambrian Working Group which recently examined a stratotype in China with a boundary at 610 + 10 Ma (Xing Yuseng *et al.*, 1984). Such an age may be too old, as Lower Cambrian strata unconformable on plutons as young as 607 + 11 Ma are known from the Avalon Zone of Newfoundland (*cf.* Fig. 13, column A) and Cambrian deposition likely followed the Avalonian Orogeny which includes tectonism and plutonism at about 610 to 580 Ma and uplift and cooling up to about 565 to 560 Ma. Jenkins (1984) has suggested that underlying Ediacaran strata may be as young as *ca.* 550 Ma. Cowie and Johnson (1985) concluded that calibration of the boundary remains uncertain with a range from 530 to 600 Ma and may be diachronous. Odin et al., (1985) favoured the younger age. Cope and Gibbons (1987) described Lower Cambrian (lower Atdabanian, possibly upper Tommotian) strata unconformable on the Ercall Granophyre in southern Britain. Isotopic dates (Cowie and Johnson, 1985) from the granophyre are 564±7 Ma (Pb-Pb zircon), 531±5 Ma (U-Pb zircon) and 533±13 Ma Rb-Sr whole-rock). The oldest date is interpreted as inherited but, conversely, the younger dates could be reset. At present, the boundary is set at 570^{+40}_{-20} Ma, a position with an uncertainty that includes most current estimates.

Era boundaries

Archean Eon

The Archean Eon is divided into three eras. Names that might be derived from Stockwell's Greek-based nomenclature system (e.g. Aphelikian, Geratian, Presbistian) are not proposed since any attempt to reach consensus on their adoption is time consuming and diverts debate from more essential matters. The neutral terms Paleo-, Meso- and Neoarchean are suggested. These allow subdivision if necessary using early, middle and late modifiers. They also distinguish these eras from the early, middle and late Archean eras of the accompanying DNAG scale, whose boundaries are neither coincident nor defined in the same way.

The relative importance of boundary-defining events, suggested by Frarey (1981) to require division of the Archean into four parts, is a difficult criterion to apply consistently and the nomenclature of four-fold divisions can be contentious. The importance of a boundary-defining event (orogeny) is partly subjective, depending on depth of erosion, degree of overprinting by later orogenic events and available data. Of the three Archean orogenies used by Stockwell (1982a; Fig. 2, column C, this paper), the Uivakian and Wanipigowan appear to be of less significance than the Laurentian. However, the last will be herein used as a subera boundary (Appendix B). In this case, presently perceived geological reality has been subordinated to convenience of subdivision and nomenclature, and the apparent orogenic hierarchy does not correspond to that of time scale boundaries.

The base of the Paleoarchean is not defined, as discussed above. The Paleo-/Mesoarchean boundary was defined by Stockwell (1982a, p. 60) as the approximate time of termination of the Uivakian Orogeny, a gneiss-forming event at about 3650-3400 Ma in the Nain Province (*cf.* Stockwell's map [1982a, Fig. 20] of structural provinces and subprovinces of the Canadian Shield and bordering areas.) Recent studies revealed two poorly constrained episodes of deformation and metamorphism at *ca.* 3800-3400 and 3400-3200 Ma (Fig. 5, column A; Stockwell, 1982a; Ryan *et al.*, 1984; Collerson *et al.*, 1985; Finn, 1985). In northern Michigan and Minnesota, gneissic units formed at about 3600-3400 Ma (Fig. 5, column B) and are overlain by metasediments about 2650 Ma old (Stockwell, 1982a; Morey and Hanson, 1980; Sims and Peterman, 1983). The boundary cannot be well positioned and is tentatively set at 3400 ± 200 Ma. Chronolithic definition of the boundary may eventually be possible if better isotopic data become available from the Nain Province.

The Meso-/Neoarchean boundary is placed at about 2900 Ma following Douglas (1980) rather than at 2660 Ma (Stockwell, 1982a). The new boundary coincides with Stockwell's boundary between the early middle and late middle Archean, which was defined (Stockwell 1982a, p. 19, 20) by the termination of the Wanipigowan Orogeny in the western Uchi Subprovince (*cf.* Card and Ciesielski [1986, Fig. 6] for current proposals for nomenclature and delineation of subprovinces of the Superior Province).

Figure 6, column A (Stockwell, 1982a; Ermanovics, 1981) illustrates chronolithic data from the type area of products of the Wanipigowan Orogeny. If the assumed correlation of Hole River, San Antonio and Manigotagan metasediments is correct (Ermanovics 1981, p. 13) and if pervasive cataclasis and metamorphism have not substantially perturbed the isotopic age of the metatonalite, the boundary can be positioned at 2900^{+100}_{-150} Ma. Eventual chronostratigraphic definition of this boundary might be based on meticulous mapping in this region by Brown (1981) and future radiometric studies. Relationships between cycles of volcanism in the central Uchi and Sachigo subprovinces (Fig. 6: column B, Nunes and Thurston, 1980; column C, Nunes and Wood, 1980) may be used to reduce the uncertainty to 2900^{+50}_{-100} Ma.

Proterozoic Eon

The Proterozoic Eon is divided into three eras using Stockwell's nomenclature: Aphebian, Helikian and Hadrynian. The boundary between the Aphebian and Helikian eras was placed by Stockwell (1982a, p. 14, 39, 40) at the close of the Hudsonian Orogeny (1750 Ma). This orogeny was defined in a general way ("... the last period of important folding which may or may not be accompanied by closely related regional metamorphism and granitic intrusions in the Churchill province ..."; *op. cit.*, p. 39) but the definition is very broad, the event is certainly complex (likely consisting of several orogenies in different parts of the province) and diachronous. Moreover, timing of the key event (folding) cannot be readily determined except in a few cases and neither it nor accompanying metamorphic and plutonic events have been well dated. Unconformably overlying, postorogenic strata, which would be very helpful in establishing upper limits to both the orogeny and the Aphebian /Helikian boundary form no part of the original definition, although such relationships were considered by Stockwell (1982a, p. 12, para. 7, 8) to form common brackets to orogenies. Further problems arise when the last period of folding in some parts of the province (e.g. Ennadai Fold Belt) is somewhat older and conflict arises in assignment of the event to either the Hudsonian (Douglas, 1980, p. 12, 13, Fig. 7) or Moranian (Stockwell, 1982a, p. 37-40) orogenies. No distinction is made between the two by many workers (e.g. Green *et al.*, 1985), and recent U-Pb ages from zircons suggest that the primary orogenesis was of "Moranian" or early Hudsonian age (P. F. Hoffman, pers. comm., 1986).

As the data in Figure 7 (this paper; Stockwell, 1982a; Ray and Wanless, 1980; Lecheminant *et al.*, 1983; A. N. Lecheminant pers. comm., 1984) illustrate, neither orogeny is well constrained by the rock record. Some overlap in ages of events ascribed to both in the Churchill Province is evident. Data from four areas within the province selected by Stockwell (1982a; Fig. 7, columns A-D, this paper) constrain the time of a few Hudsonian events somewhat better and indicate that a boundary limiting them and pre-dating post-orogenic rock units could be set at 1750 ± 50 Ma, as suggested by Frarey (1981). A boundary at 1800 Ma suggested by Douglas (1980, Fig. 7, p. 12, 13) is invalidated by new data (Fig. 7, column E, this paper). Closer limits might eventually be placed on a boundary definition based on chronostratigraphic data by better dating of the Thelon and Pitz formations of the Dubawnt Group (Fig. 7, column E). A preliminary isotopic age of *ca.* 1730 Ma has been obtained from diagenetic minerals from the Thelon Formation (A. N. Lecheminant, pers. comm., 1985).

Such a process of refinement of the time scale can be taken as an example of its evolution from one based on initial definitions using chronometry of defined orogenic events (Stockwell, 1982a); similar in a general way to the selection (without definition) of gaps and boundaries for the DNAG and Subcommision scales (Harrison and Peterman, 1980; Plumb and James, 1986); to one with boundaries more closely positioned by chronolithic relationships in one or more specific areas and to a scale still more precisely defined by chronostratigraphic data. This evolution also results in a shift in type areas from those containing products of orogenic events (Fig. 7, columns A-D) to those where orogenic effects were minimal and more complete stratigraphic successions are preserved (Fig. 7, column E). Throughout this evolution of what is essentially a "local" scale, the chronometric scale provides a framework for international correlation and communication.

The boundary between the Helikian and Hadrynian eras was placed by Stockwell (1982a, p. 70, 71) at 1000 Ma. This marked the end of the Grenvillian Orogeny, defined as: " ... the last period of important widespread folding and closely related regional metamorphism and granitic and pegmatite intrusions in the Grenville Province.". Few structural field relationships were available, however, and the position of the boundary was influenced primarily by dates obtained from histograms of granite and pegmatite U-Pb and Rb-Sr isotopic ages, and histograms of epi-orogenic K-Ar isotopic ages (Fig. 8, column A; Stockwell, 1982a; Easton, 1986b). As noted before with regard to the Hudsonian Orogeny, the application of defining criteria (" ... important folding ... intrusions ... metamorphism ... ") can be difficult. Several spatially overlapping orogenic events occurred in close succession in the interval 1250 to 900 Ma (compare Fig. 8, columns B and C; Baer, 1981; Brock and Moore, 1983; Easton, 1986b; with Fig. 16, column A; Stockwell, 1982a; Moore and Thompson, 1980; Connare and McNutt, 1985; van Breemen *et al.*, 1984). Their resolution is difficult and reliable assignment of isotopic ages to either orogenic or epi-orogenic periods may commonly be impossible.

Baer (1981; Fig. 8, column B) suggested that two Grenvillian pulses may have occurred. The first (main) pulse intensely affected the Central Metasedimentary Belt of the province at 1150 to 1000 Ma; the second included intrusions syn-kinematic with late folding and widespread pertubation of Rb-Sr and K-Ar isotopic systems that occurred at about 950-900 Ma. If two such pulses did occur, their variable imposition on a complex array of chronological terranes, suggested by Easton (1985; 1986b) to constitute the Grenville Province, likely gave rise to a spectrum of Rb-Sr and K-Ar isotopic ages in the Grenville Province in the range 1300 to 800 Ma (Fig. 8: columns B and D, Wiener *et al.*, 1984; column E, Barton and Doig, 1972; and column I, Dallmeyer, 1978; Dallmeyer and Sutter, 1980). Times of so-called epiorogenic cooling cannot be determined from this spectrum and cannot be relied upon to establish an upper limit to the boundary.

Despite such uncertainties, comprehensive compilation of geochronological data from the Grenville Province (Easton, 1986b) and examination of data from selected areas where detailed structural and radiometric studies have been integrated (Fig. 8: columns D and E; column F, Barton and Doig, 1974; column G, Easton, 1986b, Tables Xb and XII; column H, Helenek and Mose, 1984) support Stockwell's boundary position on a chronolithic basis, with the qualification that products of the second orogenic pulse described by Baer (1981) constitute upper limits to the boundary, herein placed at 1000 ± 50 Ma. Recent work in the Central Metasedimentary Belt (van Breemen and Hanmer, 1986) that revealed syntectonic plutonism from 1060 ± 6 to 1029^{+14}_{-4} Ma and late-tectonic pegmatite emplaced at about 990 ± 21 Ma, is consistent with such a boundary position. The oldest sediments lying unconformably on the Grenville Orogen are lowermost Cambrian, possibly uppermost Proterozoic and cannot provide close chronostratigraphic constraints to this boundary.

APPENDIX B

Application of the chronolithic principles used to make the proposed time chart (Fig. 1) can be extended to provide further divisions of Precambrian time. As these are not in common use, they are set apart in this second appendix. Their use is the prerogative of individual compilers of Geological Atlas maps and they will be subject to refinement, redefinition and abandonment as new data and time scale philosophies arise. A time chart incorporating all proposed time units appears in Figure 17.

Subera boundaries

Suberas are not recognized as units by the North American Stratigraphic Code (1983) but are the temporal equivalents to supersystems (*op. cit.*, Article 72, Remark [a]). However, they are defined in the Glossary of Geology (Bates and Jackson, 1980), and being divisions of eras rather than agglomerations of systems, are considered the appropriate units. In contrast, the Subcommission scale (Plumb and James, 1986) contains divisions of Proterozoic eras called periods, of up to 400 Ma duration.

Archean Eon

No subdivisions of the Paleo- and Mesoarchean eras are proposed at this time.

Neoarchean Era

The Neoarchean is divided into late and early suberas following Douglas (1980) who placed their boundary at 2700 Ma. This was near Stockwell's (1982a) boundary between the late middle and late Archean suberas at 2660 Ma. In both cases, the boundary was defined as lying between the end of the Laurentian Orogeny and epi-Laurentian uplift and cooling (Stockwell, 1982a, p. 20-22). Data from the area (western Wabigoon and Wawa subprovinces; *cf.* Card and Ciesielski, 1986, Fig.6) where the orogeny was defined (Fig. 9, column A; Stockwell, 1982a) indicate Laurentian tectonomagmatism occurred from 2750 to 2650 ± 60 Ma. It was followed by epi-Laurentian cooling sometime between 2750 and 2550 Ma, unconformable deposition of metasediments and metavolcanics (Knife Lake Group) between 2750 and 2560 Ma and intrusion of post-tectonic plutons (and those presumably syntectonic with early phases of the next orogeny — the Kenoran) sometime between 2750 and 2550 Ma. Individually, the ranges of isotopic ages likely greatly exceed the true durations of these events, but as cited, the ranges provide poor constraints to timing of the Laurentian Orogeny or any boundary based on it. Taken together, however, they form a consistent series restricting Laurentian events to 2700 ± 50 Ma and post-Laurentian deposition and intrusion to 2650 ± 50 Ma. Chronolithic positioning of the boundary could therefore be made at 2675 ± 75 Ma.

Boundary restriction on the basis of K-Ar isotopic ages, interpreted to represent epi-Laurentian cooling, can be seen

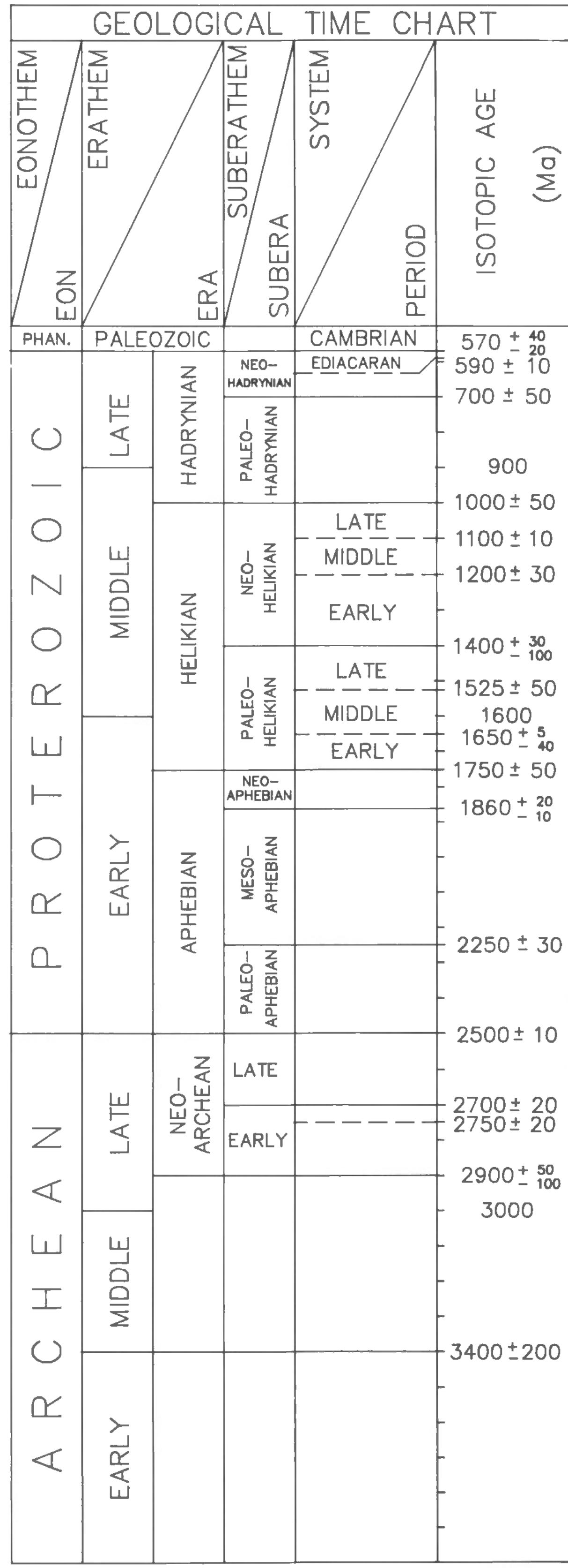

Figure 17. A Precambrian time chart incorporating proposed time units down to period level.

to be inadvisable by noting, for example, the wide range in ages obtained from one pluton (Fig. 9, column B; Stockwell, 1982a). These can be variously interpreted as perturbed by excess argon, set at the time of intrusion, Laurentian metamorphic ages, epiLaurentian cooling, metamorphism by post-Laurentian plutons, early metamorphism during the Kenoran Orogeny or any combination of these. Regionally, such uncertainties have cast doubt on the existance of two orogenies (Laurentian and Kenoran) and the latter term is used for the earlier, possibly single, event at 2700 $\pm$ 50 Ma by some workers.

High resolution isotopic techniques have provided excellent data from the Superior Province (Easton, 1986a) that permits refinement of the position of the late/early Neoarchean boundary. Precisely dated volcanism and cogenetic plutonism, followed by orogenesis and subsequently by further plutonism occurred throughout much of the Superior Province from about 2750 to 2650 Ma. Krogh *et al.* (1984a) suggested that orogenically related magmatism progressed from north to south across the province and that major deformation followed the youngest magmatism. Three localities illustrate this diachroneity. In the Red Lake Belt (Uchi Subprovince) volcanism (2760 — 2730 Ma) and plutonism (2719 Ma) were followed by development of major shear zones at 2703 Ma. Post-orogenic intrusions are 2700 Ma old (Corfu and Andrews, 1986). Volcanism in the Wabigoon Subprovince, Manitou Lakes area, ceased at 2703^{+15}_{-5} Ma, and was followed by deformation, metamorphism and emplacement of post-tectonic plutons at 2695 $\pm$ 4 Ma (Fig. 9, column C; Davis *et al.*, 1980, 1982; Poulsen, 1984). To the south, in the Wawa Subprovince, similar events are slightly younger (Fig. 9, column D; Corfu and Stott, 1986). Following Stockwell (1982a, p. 12, 13): " ... the last period of important wide-spread folding ... " is used. Such relationships constrain the boundary to 2700 $\pm$ 20 Ma.

Elsewhere in these and adjacent subprovinces, cessation of volcanism has been recorded at 2703 to 2696 Ma and analyses of post-orogenic plutons indicated emplacement from 2680 to 2660 Ma; a manifestation of slight diachroneity of latest Laurentian events (Krogh *et al.*, 1976, 1984a; Corfu and Grunsky, 1984; 1984a; Poulsen, 1984; Frarey and Krogh, 1986). Similar but slightly younger events seem to have occurred in the Slave Province, Yellowknife area, where volcanism occurred *ca.* 2680-2660 Ma followed by plutonism and regional metamorphism in the range 2660-2620 Ma (Frith and Loveridge, 1982; Easton, 1984).

Proterozoic Eon

The definition of Proterozoic subera boundaries is a somewhat more contentious and difficult problem than that of era boundaries. The latter can be readily, if not always precisely, related to major orogenic events that have affected substantial portions of the craton. Extension of Stockwell's (1982a) chrono-orogenic approach to subera boundaries has led to selection of intervening events whose products are sometimes less obvious, less well dated, and of lesser extent than those of major orogenies.

The original definitions are examined, their utility and precision assessed, and alternate definitions are proposed where necessary. At this level of subdivision of the time scale, it might be worth considering a shift in emphasis from orogenies to specific chronolithic relationships, much as has been suggested for other boundaries. Although this would appear to depart from Stockwell's consistent approach, it remains consistent within the process of refinement of boundary definitions and positions described previously. Any consistent approach which relies on progressively less definite criteria to establish progressively finer subdivisions is ultimately self-defeating.

Aphebian Era

The Aphebian Era was divided by Stockwell (1982a), Douglas (1980) and Frarey (1981) into three suberas (Fig. 2, columns C, D, E). The terms Paleo-, Meso- and Neoaphebian are herein substituted for early, middle and late Aphebian to allow future subdivision with slightly less cumbersome nomenclature, e.g. late Mesoaphebian rather than late middle Aphebian.

The position of the boundary between the early and middle Aphebian was set by Stockwell (1982a, p. 50, 51) at 2140 Ma using the defined end of the Blezardian Orogeny, based on available ages of syn-tectonic granites (2165 Ma) and the Nipissing Diabase (2113 Ma) which post-dates earliest folding. Douglas (1980) used a chronolithic definition (the end of Nipissing Diabase intrusion) to place the boundary at 2100 Ma. He renamed the early Aphebian the "Huronian".

The syn-tectonic granites were subsequently dated at 2333^{+33}_{-22} Ma (Frarey *et al.*, 1982) and 2388^{+20}_{-13} Ma (Krogh *et al.*, 1984b), and are now considered to be the older age (Card *et al.*, 1983; amended by K.D. Card, pers. comm., 1984). The younger phase of the Nipissing Diabase was intruded at 2219 $\pm$ 4 Ma (Andrews *et al.*, 1986). A boundary based on Stockwell's definition would have to be relocated to perhaps 2370 Ma. However, the Blezardian Orogeny, or more accurately, the poorly defined episodes of folding, metamorphism and intrusion (Card, 1979) that affected parts of the Huron Supergroup and which might have lasted from some time during Huronian deposition (tilting and[?] folding *ca.* 2400 Ma?) in one or more pulses (synplutonic folding *ca.* 2400–2380 Ma) up to emplacement of the Nipissing Diabase (2250[?]-2220 Ma), cannot be considered either a well constrained event, one clearly documented by the rock record nor one of proven regional significance (Dutch, 1979). It is therefore suggested, following Douglas (1980) in part and the usage of Card *et al.* (1983), that the boundary between the Paleo- and Mesoaphebian be set at 2250 $\pm$ 30 Ma, the beginning of Nipissing intrusion (Fig. 10; Stockwell, 1982a; Frarey *et al.*, 1982; Card *et al.*, 1983; Krogh *et al.*, 1984b; Andrews *et al.*, 1986).

The boundary between the middle and late Aphebian was established by Stockwell (1982a, p. 37, 38) as marking the close of the Moranian Orogeny of the Taltson Fold Belt, Churchill Province at about 1870-1850 Ma. As noted in the discussion of the Aphebian/Helikian boundary, manifestations of this orogeny are episodes of intrusion of pegmatite and granitoids prior to deposition of red beds and basic volcanics of the Martin Formation. The difficulties in distinguishing the Moranian and Hudsonian orogenies have been noted also (*cf.* Stockwell 1982a, p. 39, "Hudsonian Orogeny"). These have prompted many workers to call tectonomagmatic events in the range 2000 to 1600 Ma, Hudsonian, divided into early and late stages. Whichever names are used, sufficient evidence (Fig. 11) can be compiled to suggest that intrusion, as well as intense deformation and high grade metamorphism occurred in the interval 2000 to 1850 Ma and affected parts of the Churchill Province. Data portrayed in Figure 7, column D and Figure 11, column A (L. P. Tremblay, pers. comm., 1983) and column B (Langenberg and Neilsen, 1982; Langenberg, 1983), suggest a boundary between the Meso- and Neoaphebian could be placed at 1850 ± 50 Ma following Stockwell's original definition. Relationships shown in Figure 7, columns B and C are compatible with this boundary.

High resolution U-Pb isotope ages from the Lynn Lake region (Fig. 11, column C; Baldwin et al., 1985) closely constrain an episode of isoclinal folding to 1880 $^{+30}_{-10}$ Ma, within the uncertainty of the original definition and close to the suggested cessation of the Moranian Orogeny at 1870 Ma (Stockwell, 1982a, p. 37, 38). Deformation may have occurred during two or more pulses (see discussion of the Wopmay Orogen, below) or orogenesis may have been diachronous. Chronostratigraphic refinement of the boundary might be possible by placing it at the beginning of lowermost Dubawnt Group sedimentation (Fig. 7, column E), if the age of these strata could be established.

Approximately coeval orogenic events occurred in the Penokean Fold Belt, Southern Province, in Minnesota, Wisconsin and the Huronian Fold Belt in southern Ontario. As in the Churchill Province, definition and distinction of these and younger events has been imprecise; the terms Penokean and Hudsonian have not been consistently used. Following Card (1978), Van Schmus (1980) and Maass (1983), the Penokean Orogeny is considered to include tectonomagmatic events between about 1900 and 1820 Ma. Younger events up to 1700 Ma, termed by some as late Penokean (e.g. Sims and Peterman, 1983), are here considered post-Penokean and possibly related to the Hudsonian Orogeny (of Stockwell, 1982a; the late Hudsonian of others). Following Stockwell's approach for the Moranian Orogeny, a boundary based on data shown in Figure 11, column D (Van Schmus, 1980, 1984; Dott, 1983; Maass, 1983) could be positioned at 1800 ± 50 Ma. However, data in Figure 11, column E suggest that in Ontario, Penokean deformation pre-dated the Sudbury Irruptive (Card, 1978), a precisely dated unit 1850 ± 1 Ma old (Krogh *et al.*, 1984b). Younger Penokean events (post-1850 Ma) may have occurred only in Wisconsin or the orogeny was diachronous. For the present, the Sudbury Irruptive is taken as the best chronolithic limit to both the orogeny and the boundary between the Meso- and Neoaphebian which is therefore provisionally set at 1860$^{+20}_{-10}$ Ma.

Still another area with promise for precise chronolithic definition of this boundary is the Wopmay Orogen. Data (Fig. 11, column F; Bowring and Van Schmus, 1982; Hildebrand *et al.*, 1983; Hoffman and Bowring, 1984; Hildebrand and Hoffman, 1986) indicate the occurrence of three episodes of tectonism bracketed and accompanied by plutonism and closely constrained to intervals 1915-1902, 1896-1878, and 1858-1843 Ma. A boundary could be defined chronolithically by Great Bear magmatism and folding, and post-kinematic granites and set at 1860 ± 10 Ma.

Helikian Era

The Helikian Era was divided into Paleo- and Neohelikian suberas by Stockwell (1964). The boundary was positioned by him (1982a, p. 63, 64) at 1400 Ma based on relationships shown in Figure 12, Column A (Stockwell, 1982a; Emslie, 1978) in the Nain Province. These relationships were stated to have been produced by the Elsonian "Disturbance", an episode of folding, metamorphism and intrusion followed by uplift.

Emslie (1978) questioned occurrence of folding in the type region, considered intrusion of anorthosite-adamellite plutons to be anorogenic from about 1500 to 1400, or perhaps 1300 Ma, (Fig. 12, column B; Brooks *et al.*, 1981; Schärer *et al.*, in press), and suggested that Elsonian events be called a magmatic episode rather than an orogeny or even a disturbance. Other data (Fig. 12, column D; Krogh and Davis, 1969a, 1969b, 1970a, 1970b; Frith and Doig, 1973; Stockwell 1982a, p. 69; van Breemen *et al.*, 1984; Easton, 1986b) suggest intrusion and metamorphism between about 1550 and 1350 Ma. Coeval tectonism has not been documented, but at least local deformation may be presumed in the presence of high grade (contact?) metamorphism and possible forceful intrusion.

Stockwell's definition is therefore primarily a chronolithically based one and is retained with the addition of error limits at 1400$^{+30}_{-100}$ Ma. Deposition of post-Elsonian strata (Seal Lake Group and Grenville Supergroup; Fig. 12, column C; Barton and Doig, 1973, 1974; Silver and Lumbers, 1966) apparently did not follow magmatism immediately and does not place close upper limits to the boundary.

An extensive episode of anorogenic granite/rhyolite magmatism in the central United States (and perhaps as far north as Wisconsin and Lake Huron) occurred between 1485 ± 15 and 1370 ± 20 Ma (Van Schmus and Bickford, 1981), and is temporally related to Elsonian anorogenic plutons (Easton, 1986b, Table XIX).

Hadrynian Era

Stockwell (1982a, p. 86, 87) divided the Hadrynian Era into early and late suberas by defining a boundary by the termination of the Avalonian Orogeny in the Trinity Belt (Avalon Zone of Williams, 1979), Newfoundland. This was a brief period of block faulting followed by granitic intrusion and locally unconformable deposition of continental clastic units. Timing of these events was indirectly suggested by K-Ar (cooling?) isotopic ages of plutons elsewhere in the Avalon Zone from 680 to 550 Ma; the end of orogenic events was estimated at *ca*. 620 Ma. Dallmeyer *et al.*, (1981) indicated that magmatism occurred at 590 ± 30 to 580 ± 20 Ma. Plutons cooled by 566 - 560 ± 15 Ma. Using these data in the manner of Stockwell (1982a) constrains a boundary to 575 ± 35 Ma (Fig. 13, Column A; O'Brien *et al.*, 1983; Dallmeyer *et al.*, 1981).

Relationships between the Avalon Zone and the North American craton are suspect (Williams, 1979). The nature and extent of the orogen suggest it has close affinities with the late Precambrian Pan-African Orogeny (O'Brien *et al.*, 1983; Williams, 1984). No coeval events appear to have affected rocks of the Canadian Shield or the rest of the Appalachian Orogen. The timing of the Avalonian Orogeny may be such that it provides better chronolithic limits on the Hadrynian/Paleozoic boundary than on a boundary dividing the Hadrynian (Fig. 13, column A). It seems better therefore, to seek data from the rock record of the North American craton for intra-Hadrynian boundary definitions.

In keeping with Aphebian and Helikian suberas, Hadrynian suberas will be called Paleo- and Neohadrynian. Douglas' (1980) suggestion that the term Vendian be substituted for late Hadrynian is not adopted because no definitive equivalents of Vendian strata of the Soviet Union have been identified in Canada and the term does not yet have international recognition.

Following Douglas (1980, p. 7, 8) and Frarey (1981, p. 87), a boundary between the Paleo- and Neohadrynian is defined by initiation of intrusion of the Coronation sills and Franklin diabase dykes (Fig. 13, column B; Fahrig *et al.*, 1971; Palmer and Hayatsu, 1975; Baragar and Loveridge, 1982) and approximately coeval episodes of dyke intrusion and major faulting of the Boothia Uplift (Fig. 13, column C; Stevens et al., 1982b, p. 28, 29) and is provisionally set at 700 ± 50 Ma. This definition is based solely on K-Ar isotopic ages. Preliminary and inconclusive Rb-Sr dating of the presumably cogenetic Natkusiak Formation (Baragar and Loveridge, 1982) suggests that magmatic activity began earlier (*ca*. 750 Ma) or occurred in two episodes. Data from Baffin Island (Fig. 13, column D; Fahrig *et al.*, 1971, Stevens *et al.*, 1982a, p. 28) also support these possibilities. If future analyses provide a more precise age for this formation, consideration might be given to chronostratigraphic definition of this boundary, placing it at the disconformity between the Natkusiak Formation and the Shaler Group, perhaps at about 800 Ma. Such a boundary would restrict almost all basic magmatism to the Neohadrynian.

Period boundaries

The definition of periods is considered premature for much of Precambrian time, but preliminary suggestions are included. Proposals have been made for division of some suberas by Stockwell (1982a) and Jenkins (1981, 1984). Only the latter provided a formal chrono- and biostratigraphic definition. High resolution isotopic data hold promise for sufficiently precise delineation of events that may serve to position period boundaries. Discovery of orogenic events not previously recognized may also provide data that are useful for time unit subdivision. Five chronolithically positioned boundaries are therefore proposed here.

Early Neoarchean Subera

Precisely dated greenstone belt magmatism, deformation and post-tectonic plutonism has served to position the early/late Neoarchean boundary (Fig. 9, column C). Similar sequences of events occurring from 2750 to 2700 Ma have been dated in many areas of northern Ontario and eastern Manitoba and have been suggested to be part of one protracted orogeny that migrated from north to south across the Superior Province (Krogh *et al.*, 1984a). Data primarily from the Wabigoon Subprovince (Fig. 14, column A; Davis *et al.*, 1980, 1982; and columns B and C, Poulsen 1984, Fig. 2.1 and 2.2) suggest the occurrence of two discrete events. The earlier one (2750-2730 Ma) is subordinate to the culmination of the Laurentian Orogeny (Fig. 9) in parts of this subprovince but appears to be the primary event in other areas (Fig. 14: column D, Ermanovics and Wanless, 1983; column E, Turek *et al.*, 1986; column F, Nunes and Thurston, 1980). Available chronolithic data might therefore be used to position a boundary at 2750 ± 20 Ma.

Paleohelikian Subera

Stockwell (1982a) divided the Paleo- and Neohelikian suberas into early and late parts and Frarey (1981) suggested these be termed periods. Division of the Paleohelikian Subera into three parts may now be possible. A boundary between the early and middle Paleohelikian might be positioned on the basis of geochronological data that permits description and definition of the Labradorian Orogeny (Fig. 15, column A; Nunn *et al.*, 1985) and coeval events southwest of the Canadian Shield (Fig. 15, column B; Van Schmus and Bickford, 1981). The termination of early Labradorian deformation, high grade metamorphism and emplacement of the Trans-Labrador Batholith fixes the boundary at 1650^{+5}_{-40} Ma, prior to late Labradorian events. This orogeny is approximately coeval with metamorphism in the Great Lakes region at 1630 ± 20 Ma, and the 1650 ± 25 Ma Mazatzal Orogeny of the southwestern United States (Van Schmus and Bickford, 1981; Easton, 1986b, Table XIX).

The boundary between the early and late parts of the Paleohelikian (now the middle and late periods) was defined by the termination of the Killarnean Orogeny of the western Grenville Province whose primary manifestation appears to be granitic intrusion from 1700 to 1550 Ma and metamorphism at one or more times from before 1750 Ma to about 1500 Ma (Fig. 15, columns C and D; Stockwell, 1982a, p. 68, 69). No clearly described folding nor unconformably overlying, post-orogenic strata are known. Volcanism, rifting and possible folding at about 1550 Ma (Fig. 12) may be related to this "orogeny" but were considered by Stockwell (1982a, p. 69) to be part of the Elsonian Disturbance.

The Killarnean "Orogeny" does not appear to include all events typical of orogenies; its timing is vague and events attributed to it are likely restricted in extent. The earliest of these events may overlap the last of the Hudsonian Orogeny. It is not a suitable standard by Stockwell's criteria or any others. A chronolithic definition of the middle/late Paleohelikian boundary is thereby proposed based on initiation of deposition of the Belt and Purcell supergroups of the Cordillera during rifting of the cratonic margin. Youngest zircon ages of gneissic basement adjacent to the Belt-Purcell basin are 1575 ± 20 Ma. Mafic sills in the Aldridge Formation (near but not at the base of the supergroups) are 1433 ± 10 Ma old. Initiation of BeltPurcell sedimentation likely occurred ca. 1525 ± 50 Ma (Fig. 15, column E; McMechan, 1981; Evans and Fischer, 1986).

Neohelikian Subera

The boundary between the early and late parts of the Neohelikian was defined and located by Stockwell (1982a, p. 69, 70) at the close of the Elzevirian Orogeny in the western Grenville Province at 1200 Ma. Specific data (Fig. 16, column A; Stockwell, 1982a; Moore and Thompson, 1980; van Breemen *et al.*, 1984; Connare and McNutt, 1985) permit limiting the boundary to no better than 1200 ± 75 Ma following Stockwell's chronostratigraphic definition of the orogeny ("... post-Tudor, pre-Flinton period of folding ..."). Using his (1982a) chronoorogenic criteria limits it to 1200^{+25}_{-100} Ma. The younger uncertainty remains large because in the type region syntectonic plutons were emplaced during two episodes, ca. 1250 - 1200 Ma and 1150 - 1100 Ma. The two are only distinguishable geochronologically. In the westernmost Grenville Province, episodes of granulite facies metamorphism occurred at 1240 ± 10 and 1160 ± 5 Ma. In the Adirondacks, episodes of magmatism occurred at similar intervals (Silver, 1969).

Following Stockwell's criterion of selecting the youngest episode would suggest placing a boundary at 1100 ± 10 Ma, between emplacement and folding of the Addington Granite and initiation of Flinton Group deposition. This is proposed as the boundary between the middle and late Neohelikian periods.

Douglas (1980) and Frarey (1981) suggested a supplementary chronolithic definition of the early/late Neohelikian boundary based on initiation of emplacement of the Logan Sills of the Southern Province, estimated at no earlier than 1200 Ma. If the youngest precise ages of the sills (1109 ± 4 Ma) are representative of cessation of their emplacement (Fig. 16, column B; Stockwell, 1982a; Davis and Sutcliffe, 1985; Turek *et al.*, 1985), this would coincide with the proposed middle/late Neohelikian boundary. Such a boundary may separate older Logan Sills from younger Keweenawan dykes and the Duluth Gabbro.

The 100 Ma gap between the Elzevir Batholith and other coeval plutons, and younger syntectonic plutons (Easton, 1986b, Table XII), may serve as a boundary between the early and middle Neohelikian periods. It is positioned chronolithically as following emplacement of the Elzevir Batholith, lying between episodes of granulite facies metamorphism and preceding emplacement of the Logan Sills, at 1200 ± 30 Ma.

Neohadrynian Subera

Jenkins (1981) formally proposed an Ediacaran Period and System. Cloud and Glaessner (1982) made similar proposals. Both proposals used a chrono- and biostratigraphic definition based on a reference section in South Australia but placed the base of the system at different levels (Jenkins, 1984, Fig. 1). Use of this period in Canada is justified by the presence of Ediacaran fauna in Newfoundland, Yukon Territory and British Columbia (Hofmann *et al.*, 1985). Following Jenkins (1981) and Harland *et al.* (1982), the name used is Ediacaran, not Ediacarian (Cloud and Glaessner, 1982), as it is derived from the Ediacaran faunal assemblage. On the basis of affinities between Ediacaran metazoan and Paleozoic fauna, Cloud (in Cloud and Glaessner, 1982) proposed making this period part of the Phanerozoic Eon and Paleozoic Era. However, pre-Cambrian rocks are universally equated with Proterozoic ones, and therefore any period preceding the Cambrian must be placed in the Proterozoic and Neohadrynian divisions. This is supported by the likelihood that Metazoa existed prior to the Ediacaran Period (Glaessner, 1983).

Cloud and Glaessner (1982) suggested a lower boundary at about 670 Ma. Associated uncertainties were large (±80 Ma) but were limited below by pre-Ediacaran glacial episodes 770 to 660 Ma ago (Glaessner, 1984) and above by the Ediacaran/Cambrian boundary at 570^{+40}_{-20} Ma. Harland *et al.*, (1982) suggested a lower boundary at about 630 Ma but provided no supporting data or estimates of uncertainty. Glaessner (1984, Table 1) indicated a boundary at 660-650 Ma, following closely the youngest glacial episode in the region. However, still younger glacial episodes are known (Chumakov, 1981). Jenkins (1984) discussed numerous data from key sections on most continents and concluded that his (higher) position of the lower boundary lay at about 593 Ma. In the Avalon Zone of Newfoundland, Ediacaran fauna lie above a tillite which rests on a volcanic succession which includes ignimbrite units 607^{+8}_{-4} and 606^{+4}_{-3} Ma old (Fig. 13; Krogh *et al.*, 1983; O'Brien *et al.*, 1983). Present lack of consensus on the stratigraphic level of the boundary and, thereby, substantial differences as to its age, as well as the apparent overlap between some estimates of the span of the Ediacaran and the beginning of the Cambrian (compare Harland *et al.*, 1982 with Jenkins, 1984, and Cowie and Johnson, 1985 with Odin *et al.*, 1985), make placement of the Ediacaran Period difficult. Following Jenkins (1981), who takes precedence over Cloud and Glaessner (1982), and utilizing the precise isotopic data from the Avalon Zone (Krogh *et al.*, 1983), a provisional boundary is suggested at 590 ± 10 Ma.

The adoption of any additional Precambrian periods must await acquisition of defining data, but more importantly, the need to finely divide Precambrian time units to be able to discuss particular aspects of the Precambrian rock record unambiguously. It may prove practical to merely refer the record to isotopic ages on a chronometric scale, however, for those who prefer to use the record to define the scale, future study of it for that purpose will doubtless yield numerous illuminating data of broader interest and use.

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