PROBLEMS OF STRATIGRAPHY AND CORRELATION OF PRECAMBRIAN ROCKS WITH PARTICULAR REFERENCE TO THE LAKE SUPERIOR REGION*

HAROOL L. JAMES

U. S. Geological Survey, Menlo Park, California

ABSTRACT. Two great advances in geologic knowledge—the gradually accruing evidence of the immense duration of Precambrian time, which is now believed to represent about 8 times that of the Paleozoic, Mesozoic, and Cenozoic combined, and development of the facies concept, with concomitant destruction of "layer cake" stratigraphy—have forced thorough reappraisal of stratigraphic correlations of Precambrian rocks. This reappraisal, which is being made by many students of the Precambrian, has thrown doubt on heretofore accepted correlations and has led to greater caution in regional syntheses. Most of the familiar time and time-stratigraphic terms have been virtually abandoned except in type areas, but despite this apparent retrogression, Precambrian stratigraphy probably is on a sounder basis than ever before.

Within individual areas, even areas of highly deformed and metamorphosed rocks, problems of stratigraphy and of correlation are being solved by detailed mapping and application of the physical criteria of correlation. In the Lake Superior region, for example, about 100 formations, plus named stratigraphic equivalents, can be placed in sequential position; these formations represent a probable time span of more than two billion years. District-to-district correlations are made on the basis of structural position, highly distinctive sequences and "carry-over" units, and bracketing by isotope age determinations on older and younger crystalline rocks. The resultant stratigraphic classifications and correlations cannot attain the refinement possible in fossiliferous strata, but they provide useful approximations for reconstruction of regional geologic history.

INTRODUCTION

The history of attempts at correlation (of Precambrian rocks) has been one of early simple generalization, followed by the recognition of many qualifications and increasing complexity to a point where the initial simple assumptions become almost unrecognizable or are abandoned entirely. Looking back on most of the sweeping generalizations which were made in the past, it is easy to recognize the influence of the Wernherian hypothesis of sedimentation, the assumption of uniform marine conditions, the assumption of uniform orogenic and epeirogenic disturbances over wide areas, belief in the wide extent and uniformity of unconformities and metamorphic conditions, and, finally, a lingering faith in the existence of an igneous basement complex, possibly a remnant of the primordial shell, affording a world-wide base for beginning pre-Cambrian sedimentation. (Leith, 1934, p. 167).

This statement, made by Leith in his presidential address to the Geological Society of America a quarter century ago, is as pertinent today as it was then. The retreat from the broad generalizations and correlations of the past still continues. By now, most of our familiar time and time-stratigraphic terms—such as Archean, Proterozoic, Algonkian, Laurentian, Keewatin, Algoman, and Huronian—have been abandoned or are under attack except in their type areas: in their place we see a chaotic proliferation of local names that do not lend themselves to regional synthesis. In view of the unquestioned need, both economic and scientific, for syntheses broader than those of small districts, it is worthwhile to look into the basic causes of the apparent degeneration of stratigraphic concepts for the Precambrian, then to consider what can be done and, for one small region, what is being done.

DURATION OF PRECAMBRIAN TIME

The first great factor affecting the status of Precambrian stratigraphy is the immense change that has taken place in the concept of duration of Pre-
Cambrian time, Walcott (1893, p. 675), using rate and volume of sedimentation as a guide, held that the span of Earth's history was about 55 million years, and Sollas (1909, p. cxii), following Joly, recomputed the salt content of the oceans to arrive at an estimate of "between 80 and 150 millions of years". In 1917, the classic paper by Barrell was published in which full account was taken of radiometric age determinations (Barrell, 1917), but even as late as 1924, Clarke, author of the authoritative Data of Geochemistry, doubted the validity of the radiometric method and stated (Clarke, 1924, p. 323):

From chemical denudation, from paleontological evidence, and from astronomical data the age has been fixed with a noteworthy degree of concordance at something between 50 and 150 millions of years. The high values found by radioactive measurements are therefore to be suspected until the discrepancies shall have been explained.

Barrell's assignments of time for the Paleozoic, Mesozoic and Cenozoic are not greatly different from those now accepted, but Precambrian time was assumed to be "perhaps a billion years" (Barrell, 1917, p. 895). In 1947, Holmes published his "A" and "B" scales, the latter of which has received wide acceptance. Holmes' estimate (p. 147) at that time for the age of the earth was "about 3,000 m.y."

Recent work has suggested some appreciable modification of the "B" scale for Paleozoic and younger time units, and most present estimates for the age of the earth are 4,500 m.y. or greater (Patterson, Tilton, and Inghram, 1955). These changes in age concepts are shown graphically in figure I. The oldest rocks dated by radiometric methods are older than 3,000 m.y. (see

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Fig. 1. Graphic illustration of changes in concepts of geologic time.
Aldrich and Wetherill, 1958, for a recent comprehensive review of radiometric dating).

Of more critical importance to the problems of Precambrian correlations than absolute age assignments, however, are the early underestimates of the relative length of Precambrian time as compared to that of younger eras. When much of the major nomenclature of the Precambrian was set up 50 or 60 years ago, the duration of Precambrian time was assumed to be roughly equal to or less than that of the Paleozoic, Mesozoic, and Cenozoic combined. Correlations, under this concept, had a far greater a priori chance of being correct than in the light of present knowledge—if separated areas, for example, each contained three well-defined rock sequences separated by profound unconformities, it would not seem unreasonable to conclude that they were correlative. But now that it is known that at least 2,500 m.y. of Precambrian history is represented by rocks—a period at least five times as long as all succeeding time—it is quite evident that the probability of any correlation being correct is greatly reduced. To put this in another way: if a Precambrian system equivalent in time duration to the Cretaceous is given a length of 3 inches, 50 years ago it had to be placed in a scale 20 inches long; now this 3 inches has to be given a position in a scale with a minimum length of 9 feet and a possible length of 15 feet.

The significance of the great expansion of the time scale for the Precambrian is still not fully appreciated—probably not even by those of us working actively in the field—and the impact is not restricted to stratigraphy alone. Gilluly (1949, 1950) has effectively pointed out that if correlated sequences in separated areas are not truly equivalent in age, if doubt is placed on equivalence of their bounding unconformities (which represent orogenic intervals), and if proper account is taken of greater opportunity for observation for younger rocks, then some common generalizations, such as those dealing with "increasing tempo of orogenies with time" and progressively greater rate of sedimentation with time, rest on very shaky foundations. In the Precambrian, as for younger rocks, each rejected correlation may add significantly to the cumulative total of stratigraphic thicknesses (and therefore increase the apparent rate—though not necessarily the volume—of sedimentation per unit of time), and it may add one or more orogenies to the record. The ultimate dependence of concepts of this sort upon correlation is perhaps more evident for younger rocks, but it is no less true for the Precambrian. And it is within the Precambrian that correlations are most uncertain and for which unrealistic correlations are clung to most tenaciously. Stille (1955, p. 188-189), for example, writes:

Between Huronian and Algonkian¹ occurred one of the mightiest folding deformations of the earth, known as the Algoma revolution in American usage or the Karelian revolution elsewhere. One can say that this event produced an essentially complete consolidation of the earth's crust in the sense that there were no regions of appreciable size capable of sustaining Alpine-type folding. This is borne out by the fact that not a single instance of unquestionable orthogeousinal continuity between the Huronian and the Algonkian has been discovered. (My italics.)

¹ Stille's use of Huronian, Algonkian, and Algoman is, of course, completely at variance with "classic" terminology in the type areas from which these names are derived. As that terminology is summarized by Leith (1935, table opp. p. 10), Huronian is a subdivision of Algonkian and rocks assigned to it rest unconformably on Algoman granite. Similarly, Bucher (1933, p. 418) states:
Problems of Stratigraphy and Correlation of Precambrian Rocks

So far as the writer knows, the Archeozoic rocks were strongly deformed everywhere on the face of the earth before the Proterozoic era began. But the argument is completely circular: it is precisely because of great structural discordance that rocks in individual regions have been designated Archeozoic and Proterozoic (or "Huronian and Algonkian"). Until the advent of radiometric dating, there was no independent evidence to show, for example, that the Proterozoic of one area is equivalent to that of another, or that their bounding unconformities are the same. Gilluly's trenchant analysis (Gilluly, 1949) shows that even for thoroughly studied fossiliferous strata, the minimum unit of time that can be distinguished is rarely less than several million years, and that events that take place intermittently or continuously during this period are commonly grouped to give an erroneous impression of widespread simultaneity. For the Precambrian, the minimum unit of time that can be discriminated by radiometric methods surely is at least tens of millions of years; as a result, for rocks in excess of a billion years old it is quite unlikely that successive deformations comparable to the Nevadan and Laramide orogenies could be separately defined. It is small wonder that the classic Precambrian deformations appear to have been events of vast significance; each named orogeny, such as Algoman and Laurentian, probably is a composite of many diastrophisms that took place in different places at different times.

The great increase in time assigned to the Precambrian has impact on other facies of the analysis of earth history. The limitation of the cherty iron- formations to the Precambrian, for example, often has been cited as potent evidence in favor of the view that the Precambrian atmosphere and environment must have been substantially different from those of younger eras. Differences may have in fact existed, but the lack of iron-formation in post-Precambrian rocks is now far from a compelling argument. Iron-formation of many different ages occur in the Lake Superior region. Radiometric dating of rocks in Minnesota (Goldich, Baadsgaard, and Nier, 1957b) indicates that the Biwabik iron-formation of the Mesabi district is 700 m.y. or more younger than the Soudan iron-formation of the Vermilion district. Unless it can be shown that iron formations of intermediate age exist, this could mean that there were intervals within the Precambrian as long as or longer than all of post-Precambrian time during which the specific combination of environmental factors necessary for deposition of iron-formation did not exist.

NEWER CONCEPTS OF SEDIMENTATION AND OROGENESIS

The second great factor in the apparent degeneration of stratigraphic generalizations for Precambrian rocks is the advance in knowledge of spatial and temporal aspects of sedimentation and of orogenesis.

Some part of older views on deposition of sediments is expressed in the term "layer-cake stratigraphy"—the assumption that similar or identical conditions existed over great areas and that the interruptions or changes in conditions of sedimentation were similarly widespread. As a result correlations were accepted because, and often only because, of similarities in lithology; correlations were rejected because of dissimilarities. In the absence of any means of establishing age equivalence or the lack of it, both acceptances and rejections
must be reviewed critically. It is more difficult to establish the existence and nature of lateral changes in unfossiliferous rocks than in fossiliferous rocks, but that these changes must exist is not open to question. The fine study by White of the iron-formation of the Mesabi district (White, 1954) demonstrates that facies analysis of Precambrian stratigraphic units is possible if sufficient data can be acquired.

The development of major terminology for Precambrian strata was also greatly influenced by a concept, largely abandoned by 1900 but still exerting subtle influence, that Precambrian rocks are the products of truly world-wide processes that took place during the transition from a primordial crust to what would be considered normal geologic conditions (for review and criticism, see Irving, 1888). These processes were conceived to be essentially chemical, and they demanded a universal and certain succession; gaps in the record might exist, but the order is invariable. Names such as Laurentian and Huronian were applied to subdivisions and doubtless this accounts in part for the use of these terms in many parts of the world. A curious sidelight of this classification is afforded by the evolution of the word “taconite”, now a well-known term for low-grade iron ores of the Lake Superior region. The term stems from “Taconic”, one of the major subdivisions of this older classification of the Precambrian, which in turn is derived from the Taconic Mountains of New York, the strata of which are now known to be Paleozoic in age; “taconite” is the only relic of this nomenclature remaining in the Lake Superior region.

Many other correlations were made and names assigned on the basis of similarity in degree of deformation and metamorphism—in fact, the early definitions of “Archean” were in terms of such criteria—and on the assumption that orogenic revolutions were of great extent, perhaps even world wide. The temporal aspects of orogeny are discussed earlier in this essay; the spatial aspects also have significance to the problems of correlation. The concept of orogeny affecting broad areas has long since given way to that of deformations confined to narrow belts, with rapid cross-strike transition from orogenic to non-orogenic environments. Age equivalence between rocks strikingly different in structural and metamorphic characters must not only be accepted, it must be expected. The attempts to define Precambrian orogenic belts for the Canadian Shield (Wilson, 1949) is recognition of the predominantly linear aspect of zones of orogenic deformation. If such belts could be located accurately by geologic mapping, perhaps some headway could be made toward proper correlation of dissimilar rocks.

**METHODS OF ATTACK ON CORRELATION PROBLEMS OF THE PRECAMBRIAN**

Abundant reasons have been given in the preceding pages for viewing with great skepticism most of the classic generalizations regarding Precambrian stratigraphy and history. How then do we cope with the problems of analyzing and synthesizing the more than three-fourths of all geologic history represented by the non-fossiliferous Precambrian rocks? And cope we must, because no matter what the difficulties, the questions are far too important, for both scientific and economic reasons, to be ignored. Even though we must acknowledge that in some places intense deformation and metamorphism have virtually de-
Problems of Stratigraphy and Correlation of Precambrian Rocks

strored original characteristics of the rocks, in many areas and probably in parts of all areas, stratigraphic geology is possible. It is my purpose now to show that in the attack on such areas we are not wholly without weapons, nor are we wholly without success in using them.

The weapons are the physical criteria of correlation and radiometric age determinations.

The most basic geologic law is that of superposition. Though the principle itself can be called obvious, its application to highly deformed rocks is rarely easy. In many Precambrian terranes, the dip of a bed is without significance as to which rocks are younger or older. Determination of the original "top direction" of a bed may not be possible from internal evidence, as it depends first upon whether diagnostic features ever existed and second upon whether they have been preserved. Even where there is preservation, recognition may be difficult, but in rocks of sedimentary origin features such as cross bedding, ripple mark, cut-and-fill, graded bedding, and algal structures commonly are retained to some degree in all but the most intensely sheared and altered terranes. The recognition does of course require knowledge both of the nature of the original feature and the effects of later processes on that feature, as in the familiar example of grain-size reversal in an original graded bed because of metamorphism. In rocks of volcanic origin, one uses relict pillow structures in greenstone and vesicular and breccia tops in subaerial flows. In igneous rocks it may be a pattern of differentiation—granophyre near the top of a gabbroic sill and ultramafic rock near the base, or their metamorphic equivalents. The determination of top direction in areas of low to moderate metamorphism may be based on secondary structural features, particularly drag folds and cleavage, by means of which a particular bed can be located with respect to synclinal or anticlinal fold axes, and by the mapping out of major folds. These procedures are time consuming, and rarely do they yield results that are beyond question, but it is by such means that the stratigraphic order within sequences, and the relationships between sequences, are established for individual districts.

In correlating from one area to another, we must rely on a combination of clues, none of which individually is above suspicion. In districts such as Lake Superior, formations cannot be "walked out" between areas because of lack of exposure or because of structural discontinuities. More often, the gross position of a sequence must be fixed by broader relations to igneous activity, deformation, and metamorphism. This must, of course, be done with full awareness of the dangers involved, but the errors are perhaps more likely to be those of failure to correlate strata that are actually time equivalent than those of incorrect correlation.

Within the shaky framework set by major unconformities, use is then made of distinctive aspects of the succession. This might be a single unit, such as a thick dolomite that might reasonably be inferred to have had wide original extent, but more reliable are distinctive combinations of clastic sediments, chemical sediments, and volcanic rocks. The point can be illustrated by reference to rocks of the Lake Superior region (fig. 2). The Animikie group of Minnesota, for example, consists of the basal Pokegama quartzite, the Biwabik
Fig. 2. Generalized stratigraphic successions in Precambrian rocks of the Lake Superior region.
iron-formation, and the overlying Virginia slate\(^2\) (Crout, Gruner, Schwartz, and Thiel, 1951). On the south shore of Lake Superior, in the Gogebic district of Wisconsin and Michigan, a sequence occupying a similar structural position consists of the basal Palms quartzite, the Ironwood iron-formation, and the Tyler slate, which like the Virginia slate is a thick formation of graywacke and argillite. In the Gogebic district, however, remnants of quartzite and dolomite locally separate this sequence from the underlying crystalline rocks. Farther east in the Marquette and Menominee district of Michigan, the quartzite and dolomite are thick formations that conformably or disconformably underlie the iron-bearing sequence, and the overlying rocks attain great thickness and complexity. The entire succession, despite the presence of minor unconformities, has unity in character in that the rocks provide a record of progressive change in depositional environment from that of a stable shelf, characterized by deposition of quartzite and dolomite, to that of a eugeosyncline characterized by deposition of graywacke and submarine volcanic rocks. It has therefore been designated as the Animikie series (James, 1958). Aside from correlated equivalents and subdivisions of individual formations, it contains about 20 established stratigraphic units that are placed in four groups; the aggregate thickness is at least 50,000 feet.\(^3\)

Below the Animikie group in Minnesota and Ontario are two more groups, the Knife Lake with between 10 and 20 formational units, and the Ely greenstone with the interbedded Soudan iron-formation. Similarly, in Michigan, the Animikie series is underlain by relics of two older groups. But correlation between these older groups is not possible, at least with the means at hand. Overlying the Animikie is the Keweenawan series, which has several major subdivisions and a total thickness of 40,000 to 50,000 feet. In all, at least 100 noncorrelative Precambrian formations, with an aggregate thickness of more than 150,000 feet, can be placed in sequential position within the Lake Superior region. Correlations within this immense pile of rock are of varying degrees of reliability, but still they are adequate for reconstruction of large chapters of geologic history—a history that spans more than 2,000 million years. I might add that there is evidence of life throughout: graphitic rocks in the Soudan iron-formation, algal forms and structures in the Kona dolomite and the Biwabik iron-formation, coal in strata of the Paint River group, and oil in the Keweenawan.

In order to place these sequences in a time scale—and to provide a basis for correlation between separated regions—it is necessary to turn to radiometric dating. While this is the shining hope for ultimate subdivision of the Precambrian, it must not be thought that it requires merely more measurements. or even that ultimate success is assured. In the first place, only in rare cases will it be possible to obtain suitable material of primary or diagenetic origin by means of which the actual age of a stratigraphic unit can be determined: in general, most of the age determinations will be made on minerals of

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\(^2\) These individual formations, and others mentioned, are indicated only by lithologic pattern or figure 2.

\(^3\) For nearly 60 years this sequence was called Huronian and correlated with the rocks of the type area 300 miles to the east. The abandonment of that designation is part of the general retreat from older and now uncertain correlations.
igneous or metamorphic origin. The values obtained for the minerals from a metamorphic rock provide only the age of recrystallization, which may be far removed from the original age of the rock unit. In the second place, metamorphic and igneous rocks alike may be remetamorphosed, with varying degrees of response by individual minerals in the rocks, so that the age values obtained may be discordant or lacking in agreement with geologically determined relationships.

The kinds of complexity that must be dealt with are illustrated by the geochronologic data now available for Dickinson County, in northern Michigan. The Felch trough in this area is a complex infold of strata of the Animikie series. These strata rest with profound unconformity on an older granite, which is later than the metasedimentary and metavolcanic rocks of the Dickinson group. Pegmatite dikes cut the granite and older metamorphic rocks, and granite dikes cut the Animikie strata. The relations are shown diagrammatically in figure 3. Age determinations from localities 1-8 were made by L. T. Aldrich of the Carnegie Institution, using the Rb/Sr and K/A methods, and the data are reproduced here with his permission. Data for localities 1a and 6a are reported by Wasserburg, Hayden, and Jensen (1956, p. 159); these were obtained by the K/A method, with an empirical factor used to correct for assumed argon loss in the microcline and whole-rock samples. The value for the muscovite from locality 1a has been recalculated from the basic data given, using the same constants used by Aldrich. The disagreement between the radiometric age determinations and the geologic history deduced from field
Problems of Stratigraphy and Correlation of Precambrian Rocks

studies is profound, and significant differences exist between ages obtained by
different methods or from different minerals in the given rock. This lack of
agreements does not necessarily mean that some of the data or geological in-
terpretation must be incorrect, though this possibility must be continually ap-
praised. In actual fact, all may be valid, and each “disagreement” may furnish
important evidence leading to a more complete geologic history.

This is not the place to attempt interpretation of the discordant data given
in figure 3. A more complete statement of the problem, together with further
data and possible solutions, will be made in a forthcoming paper by Aldrich
and his associates. But it is clear that any interpretation will call for some of
the rocks to have undergone more than one metamorphism.

Two possibilities remain for obtaining an age closer to the real value for
remetamorphosed rocks. First, by correlation, a given rock unit may be traced
into areas of negligible metamorphism. In Minnesota, for example, where much
of the Animikie is very weakly metamorphosed, ages of 2,500-2,700 m.y, have
been obtained for minerals in the pre-Animikie rocks (Goldich, Nier, and
Baadsgaard, 1957a), and although no correlations can be made with the
Michigan rocks at the present time, the possibility does exist. Second, the
work of Tilton, Wetherill, Davis, and Hopson (1958) on the Baltimore gneiss
has shown that isotopic measurements of uranium-lead in zircon may yield
an “original” age whereas K/A and Rb/Sr measurements on micas give an
age of a later metamorphism; the “primary” age for the Baltimore gneiss is
about 1,100 m.y; and the superimposed metamorphism is about 300 m.y.
These methods give hope that most major sequences can eventually be bracket-
ed so that at least crude correlation from region to region or even continent
to continent can be eventually made.

In conclusion, I want to make it clear that although the immense duration
of time and the lack of diagnostic fossils are formidable obstacles to overcome,
the problems of stratigraphy and correlation in the Precambrian can and must
be solved. Despite the difficulties, the Precambrian is not a world apart: It
contains the same kinds of rocks and reveals the same kinds of geologic
processes known from the record of younger eras; the same principles apply
and the same rules must be used. And as with rocks of the younger eras,
stratigraphy and correlation are the very essence of understanding the geologic
record.

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