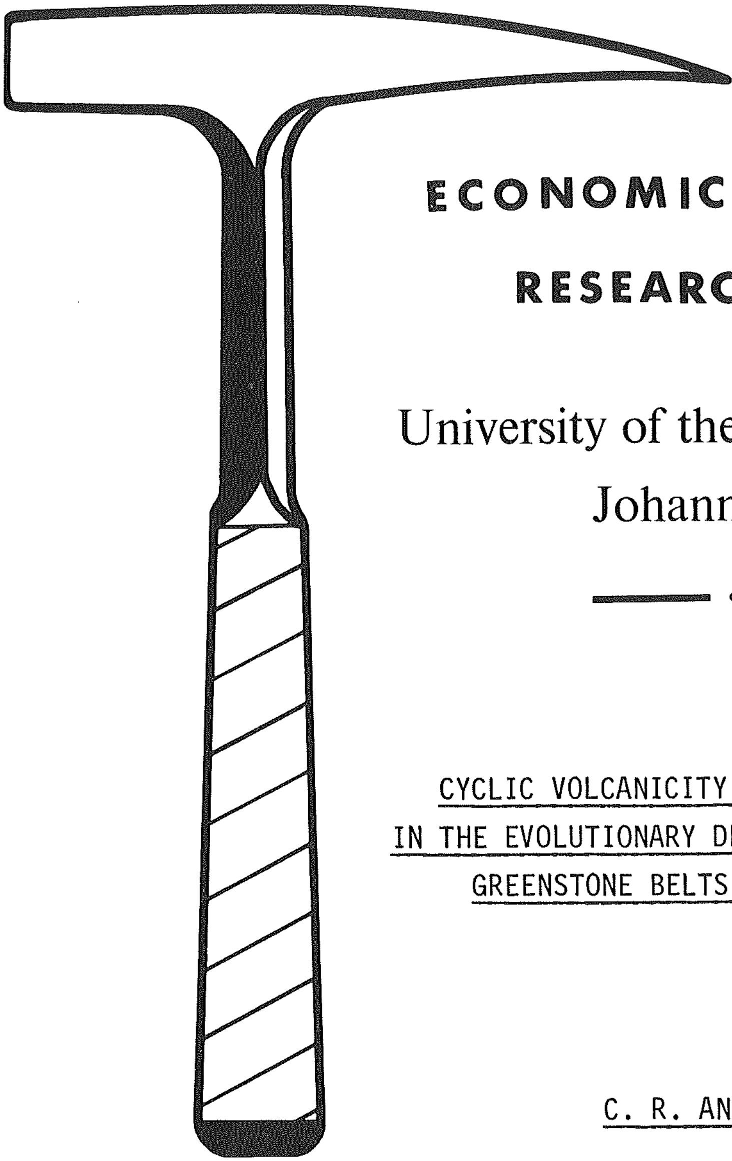

ECONOMIC GEOLOGY RESEARCH UNIT

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CYCLIC VOLCANICITY AND SEDIMENTATION IN THE EVOLUTIONARY DEVELOPMENT OF ARCHAEAN GREENSTONE BELTS OF SHIELD AREAS

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INFORMATION CIRCULAR No. 54

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by

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ABSTRACT

A great variety of volcanic and sedimentary rock-types characterize the stratigraphic successions developed in Archaean greenstone belts. Although these volcano-sedimentary piles have almost invariably been subjected to complex geological histories there nevertheless emerges from the seeming disorder, a regular and systematic pattern of greenstone belt stratigraphic evolution. For the purpose of simplification a hypothetical stratigraphic column, reflecting the main components of a fully represented, idealized greenstone belt, has been erected and is briefly discussed. Important with respect to the stratigraphic evolution of the greenstone belts is the orderly cyclicity of the volcanicity and sedimentation. The nature of Archaean volcanicity and sedimentation, as well as the nature of the cyclicity encountered in these successions, is described with the aid of examples from Canada, South Africa, and Western Australia.

The volcanic cyclicity generally reflects a progressive variation of the chemistry with height in the stratigraphic column whereas the sedimentary cyclicity reflects mainly textural and, to a lesser extent, chemical changes. The main types of chemical variation encountered corresponds to the calcic and calc-alkaline differentiation trends with rocks possessing alkaline affinities representing the latest, most highly contaminated, members of what appear to be genetically related magma suites.

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CYCLIC VOLCANICITY AND SEDIMENTATION IN THE EVOLUTIONARY DEVELOPMENT OF ARCHAEAN GREENSTONE BELTS OF SHIELD AREAS

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INTRODUCTION

The Archaean volcanic and sedimentary rocks in the Barberton greenstone belt of South Africa have recently been studied by several workers connected with the Economic Géology Research Unit of the University of the Witwatersrand, Johannesburg, and the South African Upper Mantle Project. One of the features that emerged from the studies was an awareness of a marked degree of cyclicity of both the volcanic and sedimentary members of the Swaziland Sequence stratigraphy. The importance of the cyclical nature of the volcanicity and sedimentation was, however, not fully appreciated by the writer until he had seen some sections across Archaean greenstone belts developed in the Pilbara and Yilgarn regions of the Western Australian shield. The visit to Western Australia, during the latter half of 1969, coincided favourably with an intensive mineral search underway in the State which appeared to be aimed at locating a second, or even third, Kambalda nickel deposit. The writer was thus able to avail himself of the opportunities, offered by a number of mining companies, of seeing a number of remotely situated, greenstone belts. Apart from the marked similarity of the rock-types with those of the South African and Rhodesian greenstone belts, the regular, alternating, cyclical behaviour of the volcanic and sedimentary rocks never failed to attract and demand attention. It was decided to investigate further, the nature of Archaean cyclicity, as it was considered that its development and behaviour, if better understood, might offer a useful additional approach to the establishment of order in ancient greenstone belt occurrences. It is the intention in this paper firstly, to describe briefly the typical Archaean stratigraphy and to demonstrate the nature of Archaean cyclicity. Secondly, it is hoped that this information will show how the evolutionary development of the greenstone belts is related to the volcanic and sedimentary cycles. If the paper does nothing more than to provide an awareness of the interrelationship of all the processes and products in a greenstone belt then it will have achieved its goal.

TYPES OF CYCLICITY DEVELOPED IN THE ARCHAEAN

No general agreement has yet been reached on the terminology necessary to describe rhythmic or cyclic periodicity of geological sequences (Duff and others, 1967). Restrictive definitions appear unwarranted as a certain degree of flexibility is necessary to absorb the many and varied cyclic combinations possible. For this reason the writer has suggested a number of general terms, the use of which will be clear from their context in the discussion which follows.

Cyclicity in the Archaean volcanic belts can be classified into a number of types. Firstly, there are *mini-cycles*, where repetition of units takes place on a very small scale, being particularly evident in sedimentary members of the stratigraphy. This type of cyclical repetition is frequently found in greywacke-argillite successions that show evidence of having been deposited by turbidity current action. Examples of this type, where graded-bedding and rhythmical layering of Archaean sediments is known to occur, have been given by Pettijohn (1943), Donaldson and Jackson (1965), Anhaeusser and others (1968), and Glikson (1968).

The second type of cycle, referred to here as a *minor-cycle*, is developed on a very much larger scale. Whereas mini-cycles would probably be measured in centimetres (inches), or parts thereof, minor-cycles constitute thicknesses that would be measured more in terms of metres (feet), tens of metres, or even hundreds of metres. Minor-cycles in the Archaean are particularly prominent in the volcanic sequences. Evidence of cyclicity of this type in sedimentary successions has, however, been described (Anhaeusser and others, 1968; Anhaeusser, 1969). Instances of minor-cyclicity in the volcanic assemblages are numerous and good examples of this type have been demonstrated in the well-documented accounts of the Onverwacht volcanic group in the Barberton Mountain Land (Anhaeusser and others, 1968; Viljoen and Viljoen, 1967; Viljoen and Viljoen, 1970d).

The third type of cycle, here referred to as a *major-cycle*, has been recognized in a number of volcanic belts, particularly in Canada, but also in South Africa and Western Australia. The major-cycle is of an order of magnitude larger in its dimensions than the minor-cycle, usually embraces a number of the latter cycles, and generally ranges in thickness from a few hundred metres (feet) upwards to many thousands of metres. The major-cycles commonly contain generalized mafic-to-felsic volcanic sequences (Goodwin, 1965a, b; Wilson, 1967; Viljoen and Viljoen, 1970d) but major sedimentary cycles are also known (Anhaeusser and others, 1968; Anhaeusser, 1969).

The remaining type of cycle recognized in the Archaean, and referred to as a *super-cycle*, embraces the total volcanic and sedimentary pile and may show the changes from calcic, through calc-alkaline, to alkaline volcanism, and a sedimentary terminal phase. The total thickness of the pile is generally of the order of tens of thousands of metres and usually constitutes the complete stratigraphic column of any individual greenstone belt. Examples of the super-cycle are available from all the shield areas and generally conform to the suggested breakdown of Archaean greenstone belts into an initial Ultramafic Group, a Greenstone Group, and a Sedimentary Group (Anhaeusser and others, 1969). Thus, the Onverwacht, Fig Tree, and Moodies Groups of the Swaziland Sequence constitute the super-cycle which is the Barberton Mountain Land. Similarly the Sebakwian, Bulawayan, and Shamvian Groups together, constitute super-cycles in many of the greenstone belts on the Rhodesian craton.

Cycles of varying dimensions may occur throughout the entire stratigraphic pile but there is a tendency for the earliest cycles to be larger and more complex than the later cycles. This trend appears to be controlled by the type of magma being erupted at any particular stage in the evolution of the volcanic pile. The earliest volcanics are generally mafic or ultramafic in composition and have lower viscosities than the later more felsic varieties. The changes, with time, of the viscosities of the magma-types greatly influence the degree of flowage from depth. As the lavas become more felsic, and hence more viscous, their passage to surface is gradually retarded, or even totally blocked. When this occurs, explosive activity commences and clears the way for the start of a new cycle.

The initial volcanic phases as well as the volcanogenic sedimentary phases of greenstone belts generally demonstrate the "cycle within cycle" relationship - a feature not commonly encountered in the more arenaceous, terminal phase sedimentary successions. In the case of the latter, the cyclicity, if developed at all, appears to be more characteristic of the major-cycle variety. The decrease in cyclic activity with time also corresponds to a general decline in volcanic activity during the terminal sedimentary phases of the greenstone belt evolution.

THE NATURE OF ARCHAEAN VOLCANISM

Up until fairly recently the available chemical data from Archaean volcanic successions sampled on the shield areas of Canada, Western Australia and South Africa suggested that the rocks belonged essentially to the calc-alkaline series of magma development. Evidence of alkali basalts or the alkali basalt line of descent appeared to be totally lacking. However, as more and more chemical data emerged from detailed studies of a number of individual greenstone belts it became apparent that volcanic rocks with calcic as well as alkalic affinities are also present in these environments. By far the bulk of the Archaean volcanic rocks described in Canada have a calc-alkaline or calcic character (Wilson and others, 1965). This statement appears equally valid for the volcanic rocks developed in the ancient greenstone belts developed on the Western Australian shield as well as on the Rhodesian and South African Archaean cratons.

The data from Canada is, at this stage, more comprehensive than from regions elsewhere. Wilson and others (1965) have, for example, evaluated the chemical compositions of Keewatin volcanic rocks from ten volcanic belts in the Superior Province. An unmistakeable calcic to calc-alkalic trend was noted. The same mixed tholeiitic and calc-alkali characteristics, corresponding to the iron-enrichment, and alkali-enrichment, differentiation trends respectively, are true of the Yellowknife volcanic rocks in the Slave Province (Baragar, 1966).

A further eight Archaean volcanic-rich greenstone belts distributed across the southern part of the Superior Province have been studied by Goodwin (1965a, b). With few exceptions, the volcanic assemblages in these belts also belong to the calc-alkaline magma suite. Minor alkalic volcanic components are present locally in the southernmost belts in the Superior Province where they appear to be restricted to narrow zones at the top of the normal calc-alkaline volcanic assemblages. Further evidence of Archaean volcanics with alkaline affinities is afforded by Cooke and Moorhouse (1969). These authors were able to demonstrate, in the Kirkland Lake area of Ontario, that the initial phase of Timiskaming volcanism is characterized by calc-alkaline lavas which are transitional between the later alkaline volcanics of the Timiskaming and the underlying calcic Keewatin greenstones. Flows of alkali mafic trachytes and a variety of leucitic lavas and pyroclasts are the latest differentiates represented. This occurrence of leucitic volcanics is also the first reported anywhere in the Archaean. Another variation in magma type occurs in the Noranda volcanic belt which extends through eastern Ontario into western Quebec. Here

Baragar (1968) reported the presence, not only of normal calc-alkaline volcanics, but also of distinctive high-alumina basalts.

In Western Australia the Archaean volcanic assemblages also show affinities towards the calcic and calc-alkaline magma trend. A number of chemical analyses from different greenstone belts in the Yilgarn Block, illustrating this relationship, are available in a compilation by Joplin (1963), while similar findings were made by Glikson (1968) for the volcanic rocks in the area between Coolgardie and Kurrawang, near Kalgoorlie.

In South Africa all the chemical data available on Archaean volcanic rocks relate to the Barberton greenstone belt. The Barberton rock suite, with assemblages ranging from ultramafic, mafic, and felsic volcanics, through a variety of porphyry and granitic rock-types, falls within a range representative of a calcic province (Anhaeusser, 1969). Additional chemical data relating to the volcanic successions in the area have only recently become available following studies connected with South Africa's contribution to the International Upper Mantle Project. A wide range of volcanic rock-types have been reported which approximate oceanic tholeiites in composition and which range, chemically, through continental tholeiite, to rocks having calc-alkaline affinities (Viljoen and Viljoen 1970c, d). These authors also reported a number of "primitive" ultramafic and mafic assemblages which occur towards the base of the stratigraphic column of the greenstone belt. Also in the Barberton region, in the essentially sedimentary assemblage of the Fig Tree Group, which stratigraphically overlies the Onverwacht volcanic group, mixed felspathic tuffaceous volcanics and greywackes, which show alkaline affinities, are developed. Visser and others (1956) have classified these rocks as trachyandesites on the basis of their chemical composition. Their position high in the stratigraphic column, and in association with sediments, appears to be broadly analogous to the position of the alkaline trachyte volcanic members of the Timiskaming Group of the Kirkland Lake area, described by Cooke and Moorhouse (1969).

The nature of Archaean volcanism, as determined from volcanic sequences in Canada, South Africa, and Western Australia, clearly demonstrates a marked uniformity in the trend of magma-types that developed in these early depositories. This uniformity can conceivably be expected to apply equally to other shield areas such as those of Brazil, West and Central Africa, and India, where similar ancient volcanic belts are known to exist but where chemical data is either scarce or entirely lacking. By far the bulk of the volcanic assemblages may be grouped into the calcic or calc-alkaline series - a class comparable with the volcanism typical of younger continental orogenic belts or island arc systems.

In general, the main mass of volcanic rocks in any greenstone belt is of tholeiitic composition but small volumes of alkalic lavas may also be present. The tholeiitic assemblages can be chemically similar to oceanic tholeiites and may range compositionally well into the continental tholeiite field. This trend, apparent in many volcanic greenstone belts, generally reflects a variation of chemistry with stratigraphic height. With the recognition in the Barberton region, of ultramafic and mafic lavas more primitive than the oceanic tholeiite class of volcanics, a lower limit can now be set using the newly defined peridotitic and basaltic "komatiites" as the first eruptible magma-types. These komatiitic volcanics are not confined to the Barberton belt alone, but are also present in Canada, Western Australia, and Rhodesia.

An upper limit to the trend of volcanism that may be expected in Archaean volcanic belts must now make recognition of the isolated reports, referred to earlier, of alkaline volcanic rocks. Continued work in the shield areas of the world may yield many more such examples which might nullify the tendency, possibly existing at present, not to accord these rock-types the attention they may warrant owing to their relative scarcity. As in Hawaii, where Macdonald (1968) has described the three major rock suites (tholeiitic, alkalic, and nephelinic) as being chemically gradational, so too may the varied volcanic suites of the Archaean greenstone belts also reflect, ultimately, a more pronounced genetic link than that in evidence at present.

THE ARCHAEAN STRATIGRAPHIC COLUMN

A. Introduction and Classification

The rock-types developed in the ancient greenstone belt depositories are predominantly of volcanic or pyroclastic origin. A comparison of the various lithologies found in them, however, allows the broad generalization to be made that the rock-types can be grouped into an early, essentially volcanic phase (initial magmatic phase) and a later, essentially clastic sedimentary phase. Anhaeusser and others (1969) have taken this classification a step further, the predominantly volcanic phase being subdivided into an Ultramafic Group and a Greenstone Group, while the sedimentary phase has been referred to as the Sedimentary Group.

The rock-types encountered in any individual greenstone belt may reflect one or more of the groups mentioned above, or they may reflect only parts of a group. It thus becomes essential to identify accurately the nature of the rocks in greenstone belts if any attempt is to be made to relate the successions to a particular position in a stratigraphic column, or to one of the groups mentioned above. To ascertain the precise nature of the rocks in each instance, is by no means an easy task in Archaean environments. Apart from structural and metamorphic changes that have almost invariably taken place, other complications include poor or discontinuous exposure, and a high degree of surface alteration and lateritization, such as that which affects much of the Western Australian Archaean. Due to all these problems in the oldest supracrustal rocks of the shield areas, ideas and examples have, of necessity, been developed in only a relatively few volcanic greenstone belts. In southern Africa, for example, it has been the Barberton Mountain Land that has provided most of the clues necessary to help unravel the problems of many of the Rhodesian as well as South African greenstone belts.

Metamorphic changes do pose problems but, despite this, "sheltered" areas are frequently found where detailed petrological as well as geochemical investigations have been possible. A sufficient number of these areas have been available in Canada, South Africa, and Western Australia to enable the uniformity of products typical of the Archaean greenstone belts to be recognized. A wide range of rock-types exist in greenstone belts and for the purpose of simplification a hypothetical stratigraphic column has been erected (Figure 1), the members of which will be discussed briefly from the base upwards. The column is intended to reflect the main rock-types that would be encountered in a fully represented, idealized, greenstone belt. An attempt is also made to place the rock-types in their most commonly encountered position relative to the overall stratigraphy. In reality, most greenstone belts only display parts of the total column, being aborted at varying stages due to one or other causes, the most destructive of which appears to have been the invasion of a wide variety of granitic rock-types.

B. Archaean Volcanic Rocks

Ultramafic and mafic rocks characterize the earliest volcanic members of many Archaean greenstone belts. In the Barberton belt evidence for the existence of a mobile, extrusive peridotitic magma has been presented by Viljoen and Viljoen (1970b, c). These lavas, referred to as "peridotitic komatiites", alternate with "basaltic komatiites" in the lowermost formations of the Onverwacht Group. The distinctive nature of these rocks is illustrated mainly by their chemical composition, the most definitive characteristics being :

(i) the exceptionally high Ca/Al ratios,

(ii) the exceptionally low Na_2O and K_2O contents, and

(iii) the high magnesium.

The chemical composition of an average peridotitic komatiite from the Onverwacht Group is provided in Table 1. Similar peridotitic komatiites were seen by the writer in several areas of the Eastern Goldfields of Western Australia. An analysis of a peridotitic komatiite from the Mt. Hunt area near Kalgoorlie, is listed in Table 2 for comparison.

Basaltic komatiites of three different classes have been described by Viljoen and Viljoen (1970c), examples of which are given in Table 1. Analyses of rocks with similar composition are available in Canada (P.R. Eakins, personal communication, 1969 - see Table 2). In Western Australia, basaltic lavas of the komatiite type were seen by the writer between Kalgoorlie and Norseman. Chemical data of rocks from this region confirm the komatiitic character of these rocks (Joplin, 1963; J. Hallberg, personal communication, 1969 - see Table 2).

Frequently associated with basaltic komatiites in the lower parts of the stratigraphic column (see Figure 1) are siliceous aluminous schists, analyses of which are given in Tables 1 and 2. Although aluminous minerals are usually present in these altered tuffs, varieties containing

FIGURE 1
HYPOTHETICAL ARCHAEAN STRATIGRAPHIC COLUMN

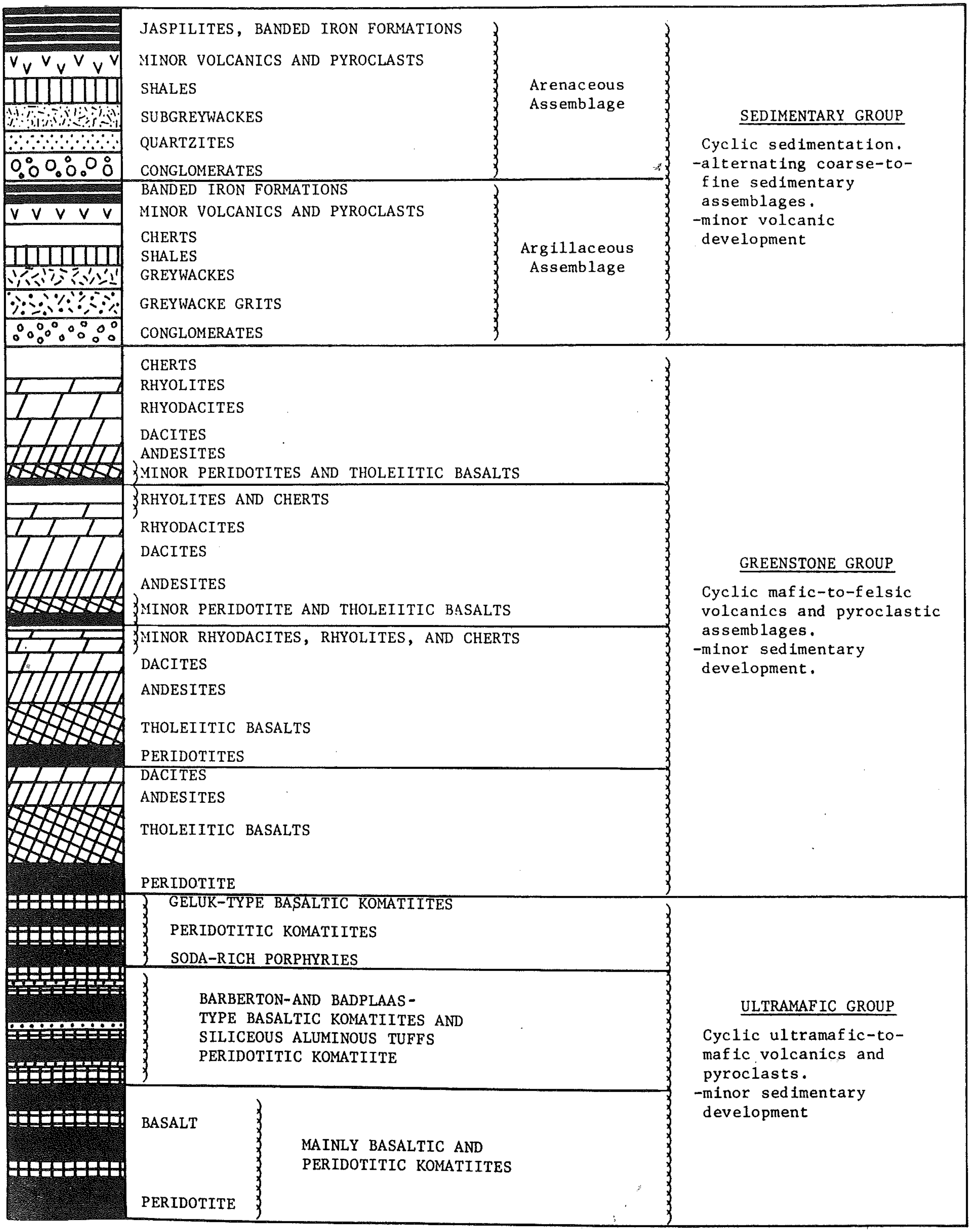


TABLE 1 : AVERAGE COMPOSITION OF ARCHAEAN LAVAS

	Peridotitic Komatiites		Basaltic Komatiites				Silica-Alumina Tuff	Basalts			Andesite	Dacite	Rhyodacite	Rhyolite	Trachytes		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO_2	44.72	41.61	47.37	49.19	52.73	52.22	78.91	49.95	49.83	49.86	51.83	61.74	67.16	74.11	50.78	55.95	50.14
TiO_2	0.52	0.31	0.46	0.43	0.85	0.56	0.54	0.69	0.94	0.70	1.11	1.22	0.46	0.14	0.84	0.47	0.63
Al_2O_3	3.25	2.70	6.76	3.76	9.83	5.42	15.14	13.48	14.64	14.25	14.53	15.17	16.73	13.59	17.11	19.43	19.63
Fe_2O_3	6.02	5.63	1.18	11.80	1.23	0.98	0.25	1.82	3.03	2.65	2.96	1.87	0.89	0.64	2.63	2.42	3.93
FeO	5.52	4.35	8.08		9.70	8.88	0.69	7.89	8.77	7.67	8.46	5.74	2.77	1.27	5.81	3.68	3.15
MnO	0.19	0.17	0.19	0.17	0.22	0.22	0.01	0.18	-	0.17	0.18	0.14	0.02	0.02	0.15	0.10	0.15
MgO	25.35	30.35	20.39	20.03	10.10	15.25	0.38	9.68	7.36	7.32	6.22	2.30	1.86	1.04	5.20	3.84	2.11
CaO	6.97	4.28	8.31	9.51	9.99	12.83	0.29	9.52	10.46	10.69	8.42	4.80	3.29	0.64	6.22	2.63	4.40
Na_2O	0.49	0.15	0.39	0.10	2.65	1.21	0.40	2.38	2.02	2.54	3.40	3.57	3.61	2.74	3.47	5.02	2.80
K_2O	0.05	0.03	0.06	0.02	0.46	0.09	2.67	0.77	0.23	0.16	0.29	0.54	1.31	3.82	4.39	2.19	7.04
H_2O	5.58	8.81	5.26		1.87	2.05	1.31	3.07	1.81	2.81	1.56	1.87	0.86	0.90	2.18	2.49	2.07
P_2O_5	n.d	0.02	n.d	n.d	n.d	n.d	0.15	0.09	-	0.05	0.22	0.32	0.12	0.12	0.48	0.29	0.25
CO_2	-	-	-	-	-	-	-	0.13	-	0.48	0.29	0.47	0.24	0.51	1.36	1.77	3.79

1. Average peridotitic komatiite, Barberton belt.
2. Average peridotitic komatiite, Barberton belt
3. Average high alumina variety basaltic komatiite of the Geluk Type, Barberton belt.
4. Average low alumina variety basaltic komatiite of the Geluk Type, Barberton belt.
5. Average basaltic komatiite of the Barberton Type, Barberton belt.
6. Average basaltic komatiite of the Badplaas Type, Barberton belt.
7. Average siliceous aluminous schist, Jamestown Schist Belt, Barberton area.
8. Average magnesian-rich basalt, Barberton belt.
9. Average tholeiitic basalt. Canadian Shield.
10. Average pillowed tholeiite, Barberton belt.
11. Average andesite (tholeiitic basalt). Canadian Shield.
12. Average dacite. Canadian Shield.
13. Average rhyodacite. Canadian Shield.
14. Average rhyolite. Canadian Shield.
15. Average mafic trachyte. Canadian Shield.
16. Average trachyte. Canadian Shield.
17. Average leucitic trachyte. Canadian Shield.

Analyses 1, 2, 3, 4, 5, 6, 8, and 10 after Viljoen and Viljoen (1970c - in press); 7 after Anhaeusser (1969); 9, 11, 12, 13, and 14 after Wilson and others (1965) and 15, 16, and 17 after Cooke and Moorhouse (1969).

TABLE 2 : ANALYSES OF ULTRAMAFIC GROUP ROCKS FROM CANADA AND WESTERN AUSTRALIA

	1	2	3	4	5	6	7
SiO_2	41.22	45.39	48.19	52.42	47.61	48.97	76.97
TiO_2	0.21	0.72	0.27	0.21	0.68	0.45	0.48
Al_2O_3	4.88	7.53	6.59	3.81	8.41	11.57	16.72
Fe_2O_3	3.44	9.28	1.09	0.81	9.97	1.08	0.58
FeO	5.54		7.55	7.49		9.65	0.99
MnO	0.14	n.d	0.17	n.d	n.d	0.26	0.11
MgO	29.67	18.94	22.42	22.42	14.59	12.29	0.51
CaO	3.78	9.12	7.58	10.06	10.28	12.85	0.11
Na_2O	0.14	0.45	0.13	0.16	1.48	1.24	0.37
K_2O	0.14	0.11	0.01	0.01	0.07	0.08	2.24
H_2O	9.15	-	4.53	2.64	n.d	0.92	1.16
P_2O_5	0.02	-	-	-	-	-	-
No. of Analyses	1	1	6	1	1	2	6

1. Peridotitic komatiite from the Mt. Hunt area - Kalgoorlie, Western Australia (unpublished analysis, C.G. Engel, U.S. Geol. Surv. La Jolla, California)
2. Basaltic komatiite of the Geluk Type - Roquemaure Township, Quebec (P.R. Eakins, written communication, 1969)
3. Average basaltic komatiite of the Geluk Type - Yilmia Hill area, between Coolgardie and Norseman, Western Australia (J. Hallberg, written communication, 1969)
4. Basaltic komatiite of the Geluk Type (low alumina variety) Yilmia Hill area, between Coolgardie and Norseman, Western Australia (J. Hallberg, written communication, 1969)
5. Basaltic komatiite of the Barberton Type - Roquemaure Township, Quebec (P.R. Eakins, written communication, 1969)
6. Average basaltic komatiite of the Barberton Type - Yilmia Hill area, between Coolgardie and Norseman, Western Australia (J. Hallberg, written communication, 1969)
7. Average siliceous aluminous schists from Mt. Leonora, Westonia, Mt. Walton, Yilgarn Goldfield, Yandanhoo Hills, and Southern Cross areas, Western Australia (Joplin, 1963)

muscovite, sericite, and fuchsite are not uncommon. Other rock-types characteristic of the base of the Archaean stratigraphic pile include tholeiitic lavas, intrusive differentiated ultramafic bodies, and soda-rich quartz and felspar porphyries.

Rocks typical of the Ultramafic Group were, until recently, only recognized in Rhodesia and South Africa (Anhaeusser and others, 1969). The new data from Canada and Western Australia demonstrates a more widespread development of these rock-types than was previously known, and now that attention has been focused on their distinctive characteristics, it may well be that further examples will be forthcoming in the future.

Unlike the Ultramafic Group, rocks of the Greenstone Group are well-known to most workers in Archaean volcanic belts and will not be dealt with here in any detail. The Greenstone Group almost invariably constitutes a mafic-to-felsic sequence of calcic to calc-alkaline volcanics. Rock-types typically include tholeiitic basalts, andesites, dacites, rhyodacites, and rhyolites, the average chemical compositions of which are given in examples listed in Table 1. Minor developments, volumetrically, of ultramafic and trachytic volcanics may also occur, together with porphyries, a wide variety of mafic-to-felsic pyroclastics, and sediments interlayered with the volcanics. A great variety of volcanogenic sediments may be represented, but chemical precipitates (cherts, banded ironstones, jaspilites) appear to predominate. There is a gradational tendency for rocks to increase in acidity with height in the column, as is demonstrated by the changes in SiO_2 content, from the basalts through to the rhyolites. If all the available silica in the system is not used up in the production of more felsic volcanic rock-types it may make itself available later for the development of chert, as is the case in the Barberton Mountain Land, where, in the upper formations of the Onverwacht Group, felsic lavas constitute only 10 per cent or less of the total volcanic assemblage (Viljoen and Viljoen, 1970c). By contrast, basaltic rocks in the Canadian greenstone sequences, according to Wilson and others (1965), constitute just under 50 per cent of the total, allowing for a greater abundance of felsic lavas and hence, it would appear, lesser developments of chert.

C. Archaean Sedimentary Rocks

Sediments characteristic of Archaean greenstone belts have been described by a number of investigators (Pettijohn, 1943; Macgregor, 1951; Visser and others, 1956; Horwitz and Sofoulis, 1964; Donaldson and Jackson, 1965; Anhaeusser and others, 1968, 1969; Glikson, 1968; Cooke and Moorhouse, 1969). In many cases a major development of the Sedimentary Group terminates the greenstone belt stratigraphy. Frequently, it is possible to distinguish one or more sedimentary assemblage in any one greenstone belt, as for example, in the Barberton Mountain Land. Here the Fig Tree Group is regarded as an essentially argillaceous assemblage, while the overlying Moodies Group constitutes an arenaceous assemblage. In Western Australia, Glikson (1968) has also been able to demonstrate a systematic change through the sedimentary succession of the Coolgardie-Kurrawang area. The Gunga and Brown Lake formations comprise essentially argillite-greywacke assemblages, while the overlying Black Flag and Kurrawang formations are composed mainly of conglomerates and greywackes.

Rock-types typical of greenstone belt argillaceous assemblages include greywackes, shales, grits, minor conglomerates, banded cherts, banded ironstones, jaspilites, and minor volcanic and pyroclastic members (Figure 1). The arenaceous assemblage is typified by major developments of conglomerate. Boulder beds, conglomerates, sandstones, subgreywackes, siltstones, and shales are commonly represented, while banded ironstones, jaspilites, and minor volcanic and pyroclastic rocks occur less frequently.

The progressive variations demonstrated by changes in sedimentary textures, structures, and composition, as well as lithology, appear to be representative of a gradual increase in the energy levels necessary for sedimentation and dispersal in the greenstone belt depositories. The fact that similar trends can be detected in Archaean sedimentation in widely separated parts of the world adds support to the uniformitarianism principle of evolutionary development of the greenstone belts - a point stressed by Anhaeusser and others (1969).

VOLCANIC CYCLICITY IN ARCHAEAN GREENSTONE BELTS

Archaean greenstone belts are characterized by tremendous accumulations of volcanic and sedimentary rock-types. In Western Australia, for example, thicknesses of approximately 100,000 feet and 60,000 feet respectively, are reported by McCall (1968), and Glikson (1968). In the Barberton belt the total thickness of the pile is in excess of 70,000 feet (Viljoen and Viljoen, 1970a) while in Canada thicknesses ranging from 25,000 to 40,000 feet have been reported by Wilson and others (1965), Baragar (1966), and Goodwin (1968). Apart from the great thicknesses there remains a further important characteristic which appears common to many greenstone belts, namely, the ordered cyclicity of the volcanicity. In the sections which follow, a number of examples from Canada, South Africa, and Western Australia, demonstrating Archaean volcanic and sedimentary cyclicity, will be outlined.

A. Canadian Volcanic Cyclicity

In a review of the chemical nature and field distribution of the Archaean volcanic rocks of Canada, Wilson (1967) demonstrated cyclic changes from calcic or calc-alkaline types of volcanism through to alkalic types. The more specific Canadian studies dealing with the cyclical behaviour of the ancient volcanic successions are, however, those of Goodwin (1965a, b) and Baragar (1966, 1968). In the Porcupine-Kirkland Lake-Noranda area Goodwin (1965b), listed, in ascending order, 10,000-20,000 feet of mafic-to-intermediate flows and pyroclastics with minor felsic flows; 5,000-10,000 feet of felsic flows and fragmentals with substantial but decreasing proportions of mafic extrusives; 2,000-6,000 feet of greywacke, shale, and conglomerate, with subordinate amounts of intercalated volcanic rocks. The average aggregate thickness of the pile ranged between 30,000 and 40,000 feet.

Chemical data in the Yellowknife volcanic belt, which is about 40,000 feet thick, define two volcanic cycles (Baragar, 1966). In each cycle, mafic lavas show a small but significant increase in sialic components with stratigraphic height, culminating abruptly in acidic layers. In the Noranda volcanic belt, a less prominent trend towards increased acidity was detected. Instead, a marked trend of increasing alumina content upward was noted, with lavas in the upper 15,000 feet of the section being distinctly of the high alumina variety (Baragar, 1968). Another mafic-to-felsic volcanic trend was demonstrated by Goodwin (1965a) in the Pashkokogan Lake-Eastern Lake, Lake St. Joseph area of Ontario. A volcanic sequence approximately 20,000 feet thick is separated into 6,000 feet of massive-to-pillowed mafic flows at the base, followed by a further 6,000 feet of mafic flows, breccia, and minor acid pyroclastic rocks above this and, finally, a 7,500 feet assemblage comprising mainly acid breccia, tuff, and minor mafic flows.

Goodwin (1968a, b) visualized the typical Canadian Archaean volcanic-sedimentary assemblage as comprising a three stage sequence of events beginning with a Platform Stage at the base. This, he considered, involved the construction of a thick, broad, platform or plateau, ascribed to the widespread effusion of predominantly tholeiitic basalt. Next followed the Edifice Stage, which featured increasingly explosive eruptions of felsic pyroclastic material of calc-alkaline chemical affinity, leading to the erection of numerous high-rising piles upon the mafic platform. Lastly followed an Erosional Stage, marked by denudation of the volcanic piles and construction of volcanogenic sedimentary blankets and prisms. He maintained, furthermore, that many Archaean volcanic assemblages of the Canadian shield comprise a single mafic-to-felsic sequence only, with some containing a mafic-to-felsic sequence with a younger mafic capping, and only rarely, two or more superimposed mafic-to-felsic sequences developed.

B. South African Volcanic Cyclicity

Good examples of Archaean volcanic cyclicity have been described from the Onverwacht volcanic sequence in the Barberton Mountain Land by Viljoen and Viljoen (1970c, d). The Onverwacht Group, which attains a thickness of over 52,000 feet, has been subdivided into six formations on the basis of distinctive rock-types and rock assemblages. The lower three formations are composed essentially of mafic and ultramafic rocks, while the upper three formations consist mainly of mafic-to-felsic associations.

The first of the three lower formations is 7,000 feet thick and consists mainly of ultramafic rocks (60-70 per cent), interlayered with minor mafic horizons (the remainder). A number of minor-cycles, each commencing with peridotitic komatiite and terminating with flows of basaltic komatiite and tholeiitic basalt, are present. Cycles nearer the base of the formation consist mainly of ultramafic rocks while those closer to the top contain greater amounts of basalt. The second of the lower three formations is approximately 6,200 feet thick and consists of a number of alternating minor-cycles of peridotitic and basaltic komatiite, tholeiitic basalt, and siliceous aluminous rocks (altered felsic tuffs). The third formation is approximately 11,500 feet thick and, like the first of the lower three formations, consists mainly of alternating cycles of peridotitic and basaltic komatiite, and tholeiitic basalt. There is a greater abundance of peridotitic rocks towards the base of the formation, with basalts more prevalent towards the top.

Some penecontemporaneous differentiated ultramafic sill-like bodies occurring in the lower formations show cyclical repetition of units containing dunite, peridotite, pyroxenite, and gabbro (Anhaeusser, 1969).

The three upper formations of the Onverwacht Group differ greatly from the lower formations in that they are characterized by normal tholeiitic lavas, with primitive peridotitic and basaltic volcanics constituting only a relatively small proportion of the successions (Viljoen and Viljoen, 1970d). The first of the upper three formations attains a thickness of approximately 16,000 feet and exhibits probably the best examples of cyclic volcanicity in the Barberton Mountain Land. Five or more cycles, each commencing with a large accumulation of basalt, pass upwards into thinner zones of dacitic to rhyodacitic lavas. The felsic volcanic zones are almost invariably capped by fairly substantial chert horizons which terminate cycles. The basaltic component of each cycle becomes thinner from the base upwards and varies from 4,500 feet in the lowermost cycle, to about 600 feet for some of the uppermost cycles. By contrast, the most prominent chert horizons are developed towards the top of the uppermost cycles and correspond to the general trend of increasing acidity with height in the stratigraphic column. Some cycles commence with interlayered ultramafic horizons, many of which show signs of magmatic segregation into a lower peridotitic zone, and an upper pyroxenitic zone. The ultramafic zones appear to be sill-like in character but their frequent position at the base of cycles suggests that they constitute part of an evolutionary magma trend.

The uppermost felsic pyroclastic zone displays a number of cycles, good examples of which occur in the 215 feet thick lower agglomeratic unit (Viljoen and Viljoen, 1970d). At least four minor-cycles are present, each comprised of coarse rhyodacite agglomerate, grading into coarse tuff and terminated by fine-grained, well-bedded tuffs. The cycles also show an evolutionary trend upwards, becoming smaller, with the felsic fragments in the agglomerate zones decreasing in size, in each successive minor-cycle.

Most of the mafic volcanic rocks consist of massive as well as pillowed tholeiitic basalts or high magnesium tholeiites which correspond closely in chemical composition to oceanic tholeiites. With increasing height in the column their composition compares more favourably with continental tholeiites. The felsic volcanic and pyroclastic rocks range in composition from dacites and rhyodacites, to rhyolites.

The second of the upper three formations has a thickness of approximately 6,700 feet and consists of essentially the same rock-types as described for the underlying formation. A mafic-to-felsic cyclic trend is again developed but is not strikingly apparent. Chert horizons, associated with carbonate and carbonaceous shale interlayers, terminate cycles. The third and uppermost formation in the Onverwacht Group consists of 3,000 feet of alternating felsic volcanic and pyroclastic rocks and substantial banded chert horizons. A number of ultramafic bands occur conformably in the layered successions.

Cycles within cycles are prominently displayed in the Onverwacht Group. Mini-cycles appear to be preferentially developed in the felsic pyroclastic zones which themselves form members of larger minor- or major-cycles. There is also a tendency for major-cycles to occur more towards the base of each formation with minor-cycles developed nearer the tops.

C. Volcanic Cyclicity in Western Australia

A number of greenstone belts in Western Australia display prominent cyclical repetition of the formations. In the Pilbara, cyclic volcanicity was seen in the areas centred about the town of Marble Bar. Rhythmic alternations of ultramafic, mafic, felsic, and siliceous rocks occur in the east-west striking Warrawoona formations south of the Eginbah Granite, where the Emu Creek joins the Talga River. Cherts terminate many of the cycles developed in this area. The spectacular red, white, and black, banded cherts near Marble Bar also terminate mafic-to-felsic volcanic cycles containing tholeiitic basalt (frequently pillowed), dacite, and rhyolite. Near Soansville, traverses across a syncline comprising a differentiated mafic igneous assemblage displayed cyclic repetition, from the base upwards, of serpentinized ultramafics, pyroxenites, gabbros, granophyres, and epidosites. At least three cycles are present, each displaying less and less peridotitic and pyroxenitic material with height in the column.

In the Murchison Goldfield of the Yilgarn Block, a traverse across the Yarraquin Syncline, 15 miles east of Cue, demonstrated at least four minor-cycles, each containing serpentinite, gabbro, and amphibolite. Minor developments of altered felsic tuff and tuff breccia, as well as felsic lavas, occur in the upper two cycles. Mafic-to-felsic volcanics and pyroclastics, with minor ultramafic horizons occur in minor-cycles near the Big Bell Mine, west of Cue. Here the compositional trend, from ultramafic to felsic volcanic rock-types, suggests that the successions are younging from west to east.

Near Menzies, in the Eastern Goldfields, sections across the Kurrajong Anticline, the Menzies Syncline, and an area near Snake Hill, south of Kurrajong, all display a number of minor-cycles consisting of serpentinized ultramafics, a variety of amphibolites and gabbroic rocks, felsic volcanics and pyroclastics, and siliceous cherty sediments. In the Kurnalpi area, north of Kalgoorlie, a number of minor-cycles of mafic-to-felsic volcanic rock-types are developed. Near Kanowna, the cycles seen west of Harper Lagoon consist of serpentinite, coarse gabbro, brecciated, pillowed, and spherulitic basalts, and acid porphyries. More siliceous volcanics constitute the cyclic volcanicity seen between Kanowna and Bulong. Here the rock-types comprise alternating felsic volcanics and tuffs (dacites, rhyodacites, rhyolites). Mini-cycles of alternating mafic-to-felsic tuffs occur in Lake Yindarlgooda, and chert horizons terminate major-cycles in the Rocky Downs area.

East of Norseman an alternating sequence of basaltic komatiites and altered siliceous tuffs (quartz-sericite-aluminous schists) are developed in a number of minor-cycles, while in the Mount Thirsty area, west of Lake Cowan, major-cycles consisting of tholeiitic basalt, andesite, dacite, rhyodacite, and chert are associated with differentiated sills containing serpentinite, pyroxenite, gabbro, and granophyre.

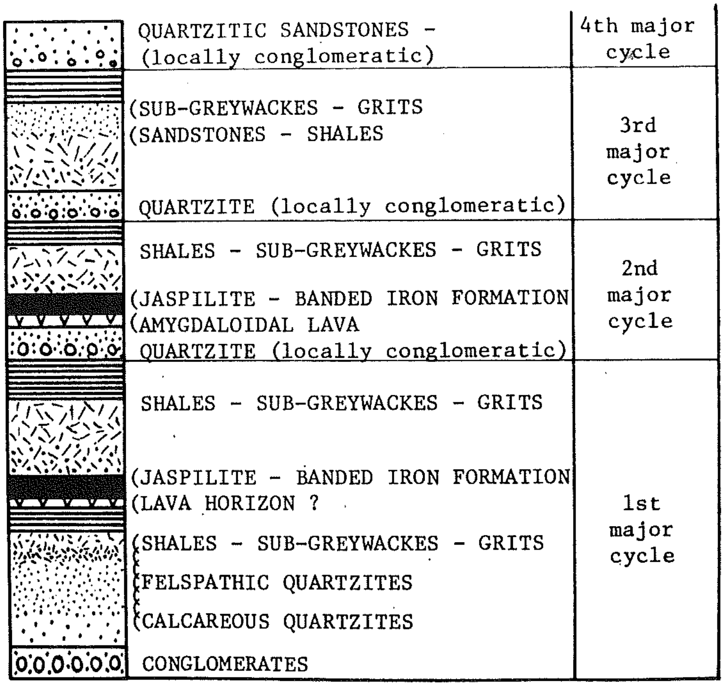
Frequently encountered in Western Australian greenstone belts are coarse- to fine-grained meta-gabbroic rocks, regarded by many as intrusive sills. Although some may represent sills their presence always in the same stratigraphic position relative to the associated members of the cyclic suite seems to indicate an extrusive origin.

SEDIMENTARY CYCLICITY IN ARCHAEAN GREENSTONE BELTS

Apart from the similarity of lithological associations and components, the Archaean sedimentary piles frequently show patterns of repetitive sedimentation. Unlike the volcanic sequences, cyclicity in the sedimentary members of the stratigraphy has not been accorded the same recognition. Sedimentation pulses have, however, been described in both the Fig Tree and Moodies successions of the Barberton Mountain Land by Anhaeusser and others (1968). Cyclicity in the Fig Tree argillaceous assemblage, has not as yet been studied in sufficient detail to define precisely the character of the cycles. There clearly exist a great many mini-cycles, contained in a number of minor-cycles. The mini-cycles consist mainly of alternating, rhythmically layered units of argillite and greywacke, as well as alternating graded-bedding units. The minor-cycles constitute an unknown number of repetitive cycles made up of grits, greywackes, and shales, with minor chert interlayers. Several major-cycles, embracing many minor-cycles, are also developed. In the first major-cycle there is a tendency for the greywackes to become texturally finer towards the top of the succession, giving way to shale, banded chert, and banded ironstone layers. The second, broadly recognizable, major-cycle again displays coarser material towards the base and terminates with a tuffaceous greywacke and greywacke conglomerate.

The cyclicity in the Moodies Group is prominently displayed in the Eureka Syncline, the lithology and structure of which has been described by Visser and others (1956), and Anhaeusser

FIGURE 2
CYCLIC SEDIMENTATION OF THE MOODIES GROUP
IN THE EUREKA SYNCLINE, BARBERTON MOUNTAIN LAND



Column represented, approximately 10,000
feet thick.

(1969). Three main pulses of sedimentation, corresponding to three major-cycles, are clearly evident while the embryonic beginnings of a fourth-major cycle is only just apparent (see Figure 2). The first major-cycle commences with a basal conglomerate, and is followed by calcareous and felspathic quartzites, and ends with shales and banded magnetic jaspilites. A lava horizon below the jaspilite is suspected, but poor exposure has prevented confirmation of this possibility. The second major-cycle begins with a locally conglomeratic quartzite and is followed by a minor volcanic member, a second banded magnetic jaspilite, and shale horizons. The third major-cycle starts with minor localized conglomerate and quartzite at the base and is followed by an alternating sequence of sub-greywackes, grits, sandstones,and shales. A small-pebble conglomerate-grit horizon above this, probably represents the initial phase of a fourth cycle. Each pulse of sedimentation, marking the start of a new cycle, began with a great influx of coarse detritus. Gradually changing conditions resulted in the deposition of fine argillites and chemically precipitated jaspilites, and banded ironstones. The depositional cycles were also interrupted by mild volcanism, during which time amygdaloidal lavas were extruded.

An example of cyclic sedimentation in the Western Australian Archaean was seen by the writer in the Tallering greenstone belt, located approximately 275 miles north of Perth. No detailed account of the area is yet available but it appears that an initial volcanic assemblage, consisting of amphibolites, mafic and felsic tuffs, and a few thin banded iron formations is overlain by a substantial sedimentary succession consisting of conglomerates, quartzites, shales, and banded iron formations. The entire structure appears to be that of a major syncline with a northeasterly-trending fold axis. Three banded iron formations are developed in the stratigraphy, those on the southeastern limb of the fold constituting potential iron ore horizons. Each banded iron formation appears to terminate a major-cycle consisting of conglomerates at the base, and grading upwards through quartzites, shales, and lava horizons. The volcanic members are poorly exposed but can be seen on the northwestern limb of the syncline. The lithological correspondence and the striking cyclical nature of the sedimentation suggests a close analogy between the Tallering sedimentary succession and that of the Moodies Group in the Eureka Syncline of the Barberton greenstone belt.

RECENT VOLCANIC CYCLICITY

The rhythmic or cyclic recurrence of many earth phenomena is a well-established and basic principle in geology. Uniformitarianism, not necessarily of products, but of processes, seems to be manifest from the earliest recorded volcanic sequences to present day active volcanoes. Eruptive cycles of a number of modern volcanoes have been methodically studied and although each volcano may have its own individual pattern of activity there nevertheless appear to be many related factors common to their development. Rittman (1962) demonstrated that it is possible to reconstruct the course of a volcanic eruption merely from the nature and stratigraphy of its products. He found a close connection generally existing between the type of eruption and the type of magma. Some of the more systematic features relating to the genesis of volcanoes that Rittman outlined are equally applicable to Archaean volcanism. Normal volcanoes, he stated, are characterized by a continuous magmatic differentiation from mafic-to-felsic, and a structure which changes from that of a lava volcano, through that of a strato-volcano, to that of a pyroclastic volcano. Rittman (1962) referred also to recurrent volcanoes, characterized by repeated returns to products, modes of activity, and structural forms corresponding to an earlier stage in the evolution of the residual magma. A recent example of this kind is provided by Krakatao which displayed a certain periodicity of volcanic activity (Van Bemmelen, 1949). Three cycles of magmatic differentiation were described, the silica content of the eruption-products increasing in each cycle. Two cataclysmic outbursts occurred at the end of the cycles. Eruption products ranged from generally andesitic, through dacitic, and rhyolitic, back to andesitic.

Cyclicity of a different kind is described by Bullard (1962). He outlined in detail, the eruptive cycles of Kilauea and Mauna Loa in the Hawaiian Islands as well as the eruptive cycles of Mount Etna and Mount Vesuvius in Italy. Although the cycles he referred to reflect times of eruptive activity in yearly cycles, there nevertheless emerged from the study a recognition of variations in the types of magma and ejectamenta accompanying each individual cycle.

CYCLICITY AND GREENSTONE BELT EVOLUTION

Modern day volcanicity is clearly associated with zones of tectonic instability on the earth's surface. These regions frequently, but not always, coincide with the most seismically active regions of the world. Rittman (1962) showed that, on closer examination, all volcanoes are situated in tectonic fault zones in which the crust is fissured as a result of tensional forces. He pointed out that even in fold mountain chains the volcanoes are always closely associated with axial and cross faults, and particularly with their intersections. By way of summary, the phases of an orogenic cycle and its magmatism were drawn together into a schematic table considered by him to be of general applicability (see Table 3).

TABLE 3

Phase of Orogenic Cycle	Corresponding Magmatism
Geosynclinal	Geosynclinal or initial volcanicity (effusive basaltic-picritic)
Tectogenesis (folding)	Tectogenetic or synorogenic plutonism (intrusive acid calc-alkaline)
Orogenesis sensu stricto (uplift)	Orogenic to late orogenic, or subsequent volcanicity (explosive calc-alkaline)

Phase of Orogenic Cycle	Corresponding Magmatism
Post-orogenesis (denudation)	Post-orogenic, or final volcanicity (effusive basaltic or ignimbritic)

An attempt has recently been made, however, to reconstruct an evolutionary model of the development of the Archaean granite-greenstone environment (Anhaeusser and others, 1969). This avoids direct comparisons with younger geological features and events, particularly the younger, Alpine-type orogenic belts with which Archaean geology has frequently been compared and equated. All available evidence including the chemistry, suggests that the greenstone belt volcanics were deposited on an early, thin, unstable, primitive crust. The initial Archaean depository is envisaged as having developed in roughly evenly spaced, strongly orientated, parallel downwarps or fault-bounded troughs on the early unstable crust. The depositories thus initiated, underwent unique geological histories, the conditions of which appear never to have been repeated in earth history.

Fundamentally, the depositories are considered to have been areas of repeated downsagging. Just as more recent volcanism is connected with tectonic disturbance, so too was this very likely the case in Archaean times when each adjustment in the developing basin appears to have been responsible for the tapping of additional subcrustal magma. In some belts primitive ultramafic and mafic magma was brought to the surface in alternating cyclic heaves. With time, gradual chemical changes, possibly related to a continually thickening sialic crust, resulted in a progressive increase in mafic-to-felsic cycles of volcanicity. These changes may also have been assisted by a number of factors including gravitative and pneumatolytic differentiation, as well as fractional crystallization in the magma chambers of the upper mantle.

The early tectonic histories of the greenstone belts are believed to have been controlled mainly by gravity deformation, the latter coinciding with the rising of granites. In this connection, the experimental work on gravity deformation by Bucher (1963), and Ramberg (1967), may offer several clues as to how fault and fold structures developed in the greenstone belts. The preponderance of synclines and longitudinal strike faults (slides) in these environments, is evidence in support of the gravity deformation hypothesis. The fact too, that cyclicity extends from the initial volcanic stage through into the later sedimentary stages adds weight to this theory. The initial cyclicity demonstrates chemical changes of the products of magmatism and volcanicity, while the later cyclicity in the sedimentary assemblages reflects essentially textural variations. Although totally unrelated, the cyclicity of both varieties has, nevertheless, a common tectonic origin.

Unconformities are often apparent in greenstone belt stratigraphy but are generally of local extent and are probably best described as disconformities. Pauses in volcanism, or in sedimentary deposition, appear frequently to have been accompanied by subsidence of the basin, with little or no erosion taking place prior to the onset of renewed deposition. Some developing basins may have remained stable for sufficiently long periods to allow the terminal sedimentary phases to develop characteristics typical of interior- or cratonic-type basins. The cyclic sedimentation displayed, for example, by the Moodies assemblages of the Barberton greenstone belt show features typical of transgressive and regressive sedimentation in an essentially shallow water environment. This particular stage in the evolution of the crust may have been the forerunner of true cratonic conditions. Before the final annealing could take place, however, further subsidence and granite emplacement caused additional deformation to the total Barberton stratigraphic sequence.

Thus, what appears to render the Archaean unique tectonically, is the fact that during the early stages of earth history subsidence of the gravity-type may have been relatively easily accomplished on a thin, unstable crust. In subsequent times, however, although downwarping did occur, the thickened nature of the crust either prevented, or limited, the degree of subsidence. On the developing cratonic areas the style of depository proceeded to that of the major interior basins. An analysis of the deformational characteristics of basins throughout time may well provide some support for this conjecture.

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