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Résumé de l'article

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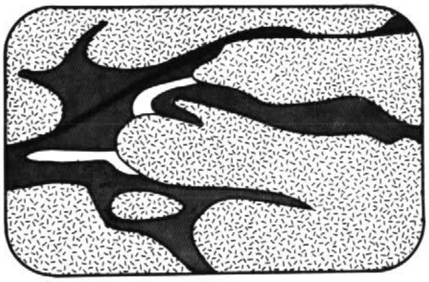

Archean Continents

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Summary
This paper is a progress report concerning some of the research being conducted at the Centre for Precambrian Studies at the University of Manitoba. The research has led to a hypothesis that stable Archean continental nucleii originated during a period of large scale melting, volcanism, and intrusion. The paper describes the work leading to the hypothesis as well as on-going field and analytical results which test the hypothesis. The hypothesis leads to the suggestion that the planetary development of the earth may have major features in common with that of the moon and other planets, but differences in development are caused by gravity differences and the early presence of abundant water on the earth.

Common Characteristics of Archean Shields

Recent mapping and research concerning the Archean shields in Canada, Australia, and southern Africa has confirmed the similarity of the three shields. The greenstone belt – granite diapir tectonic style predominates in each shield. Figure 1 (Wilson, 1971) shows this similarity of style and scale of events. An examination of the fragmentary mapping of the West African Archean shield indicates the presence of the same characteristic style.

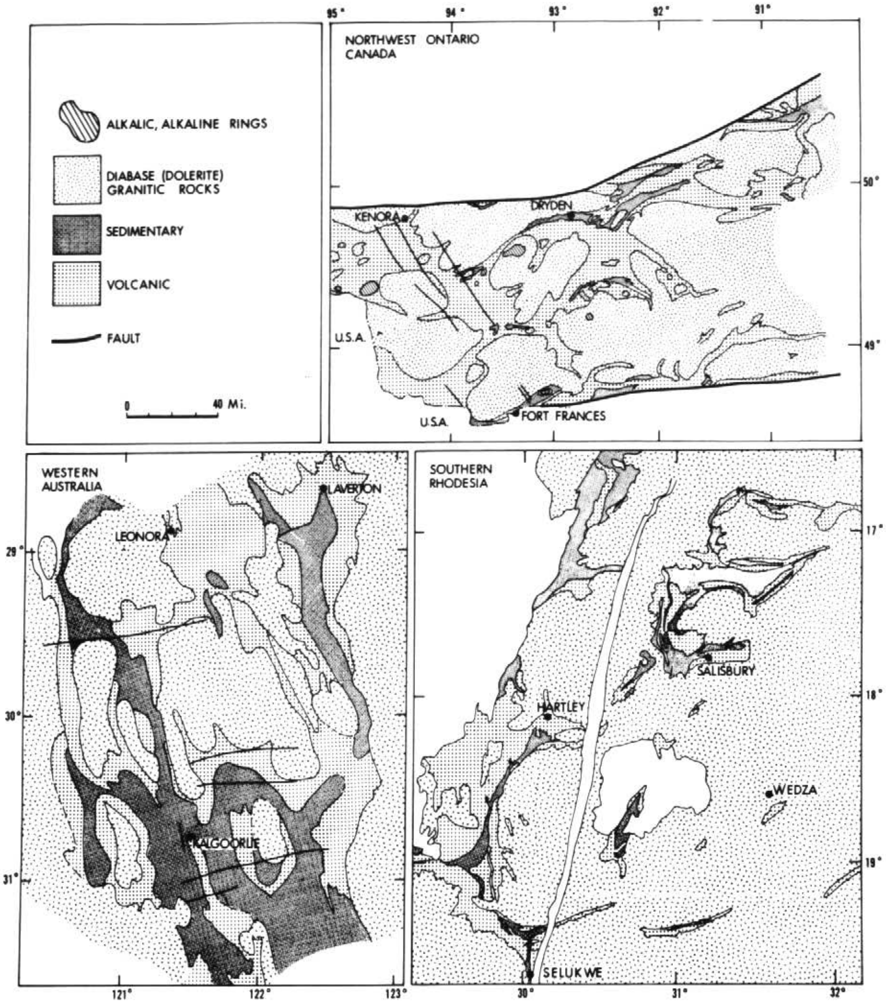

Figure 1
Similarity of Archean shields in Canada, Australia, and Rhodesia.

The volcanic belts in each shield contain similar volcanic sequences, with similar lava types containing similar quantities of major and minor elements (U. of Manitoba analyses). Sedimentary assemblages in each shield are predominantly greywacke and shale or metamorphosed equivalents.

The volcanic-sedimentary greenstone belts are intruded by oval-shaped granitic diapirs (Fig. 2) having a composition which is commonly in the quartz-diorite to granodiorite range. Recent age dating (e.g., Penner and Clark, 1971; Peterman *et al.*, 1972) is showing that the Archean volcanic belts in each shield are followed so closely by this granitic intrusion that the limits of error of age dates commonly overlap. The similarity of the sequence and timing in each Archean shield can hardly be coincidental so the direct relationship of the greenstone volcanism to the granite intrusion becomes a logical inference for testing.

In each shield, these granitic rocks mark the culmination of a great orogeny. The culmination of the orogeny in the Canadian shield is followed by the development of various types of gneissic belts (Fig. 3) such as metamorphosed aulacogens (English R. belt), metamorphosed welts of granite-greenstone terrane (Berens R. belt), and crosscutting gneissic active belts such as the Kapuskasing belt between James Bay and Lake Superior. The Archean episode is brought to a close by the

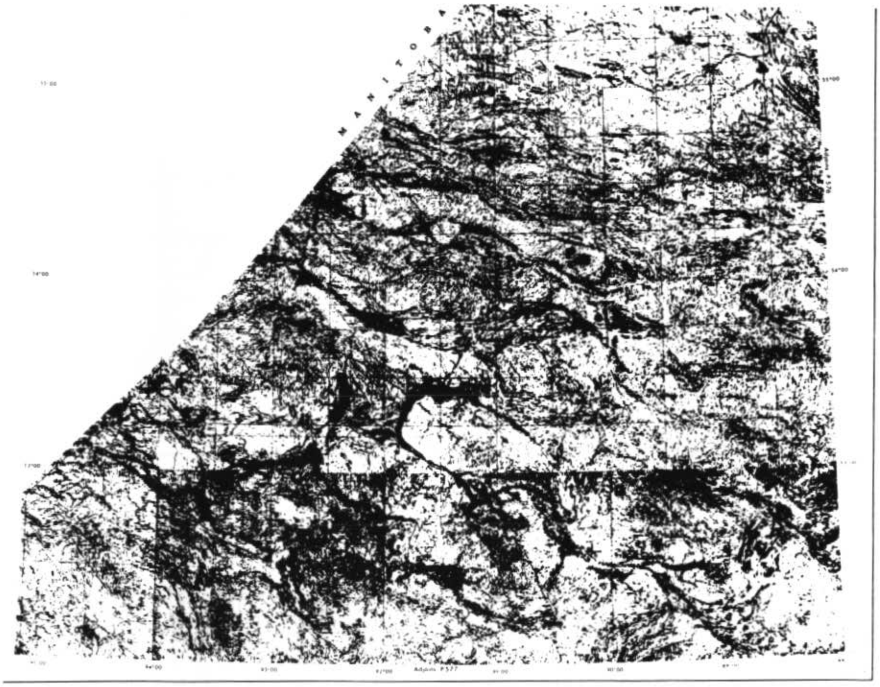

Figure 3
The fault-block structure of the Archean Shield in Manitoba and northwestern Ontario.

Figure 2
Composite aeromagnetic map of part of northwestern Ontario showing the typical oval shaped granitic diapirs in areas of poor exposure. Ontario-Federal aeromagnetic map covering 3° of latitude.

development of great systems of subparallel, and partly interlacing faults which divide the Archean into blocks (Figs. 3 and 4) and which apparently bring the Archean continents back into isostatic adjustment and permanent stability as continental masses.

Post-Archean magmatic activity is non-orogenic. Magmatism consists principally of several episodes of great floods of basalt which occur as diabase dykes cutting the shields or as sills and flows in overlying later Precambrian formations, or as great cone intrusions into the Archean platforms. The Archean shields are also penetrated by numerous ring plugs of differentiated alkalic and alkaline intrusions which added additional bulk to the Archean continents. Major magmatic activity on the Canadian and Australian Archean platforms apparently ceased a billion years ago and only broad epeirogenic movements have been recorded since.

The characteristic Archean tectonic style does not recur to any extent in post-Archean terranes so that the granitic crustal nucleii ceased to form in this manner approximately 2,600

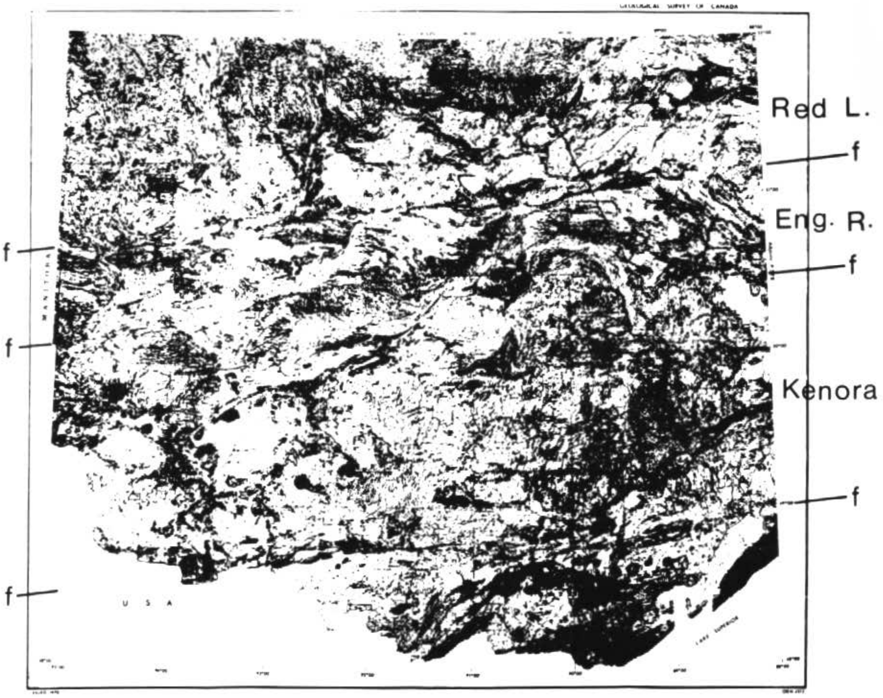

Figure 4
Composite aeromagnetic map of northwestern Ontario showing the fault-block structure and characteristic magnetic patterns of the Kenora, English River, and Red Lake blocks. Ontario-Federal Aeromagnetic map covering 4° of latitude.

m.y. ago. On the other hand, the onset of continent formation apparently began at different times on different continents because age dating shows that all major Archean shields were not formed at the same time. The southern African shield apparently predates the Australian and Canadian shield by 400 to 500 million years. It is apparent, therefore, that the formation of these continental masses spanned a period of several hundred million years.

The similarity of lithology, structure, tectonic style, and metallogeny of Archean shields results in the logical inference that these Archean continental nucleii resulted from a specific group of similar processes which occurred in each of the shields. These processes resulted in the formation of large bodies of granitic crust. A study of the processes should, therefore, lead to an understanding of the origin of the nucleii of granitic continental crust.

Primordian Crust

Age dating reveals that remnants of a variety of primordial sialic materials which predate typical Archean terrane exist in relatively small patches on almost all continents. A more ancient crust of some type existed, therefore, but the processes that produced these sialic remnants did not produce stable continental masses, or alternatively, some remnants may result from engulfment during the early portion of the Archean continent building process.

Archean Crust

Crustal seismologic research carried out in Manitoba and northwestern Ontario by Hall and his co-workers (e.g., Hall, 1971; Hall and Hajnal, 1973) have led to the interpretation that the crust of the Archean shield can be divided into two layers, an upper layer with wave velocities similar to those in granitic rocks and a lower layer with wave velocities characteristic of rocks of basaltic composition. The two layers of the crust are separated by the Riel (or Conrad) discontinuity. The Mohorovicic discontinuity lies at the bottom of the crust. Seismic wave velocities increase gradually with depth in the upper mantle, although evidence indicates some layering in the upper mantle.

Figure 5 is a diagrammatic section of the crustal layers that occur beneath some of the Archean blocks shown in Figure 3. The seismic data places a strong control on the speculation of the geologic nature of the fault blocks and this is discussed elsewhere (Wilson, 1971; Hall, 1971). One of the most important conclusions is that the low grade metamorphic greenstone belt – granitic diapir tectonic style is independent of the thickness of the granitic crust. The granitic crust in the Kenora block is only about 13 km thick, whereas in the similar appearing Red Lake block it is 23 km thick. The thinness of the granitic crust in the Kenora area leaves little room for change, or interposition of any different layer above the lower crustal layer. Gravity surveys in this area indicate that the greenstone belts reach to depths in excess of 12 km. It can therefore be inferred that the present surface in the Kenora area illustrates the nature of the whole granitic crust. There is no room, nor evidence of any other rock type or tectonic style above the lower crust. The processes that develop this type of terrane must therefore be those that produced the continental crust of the Archean.

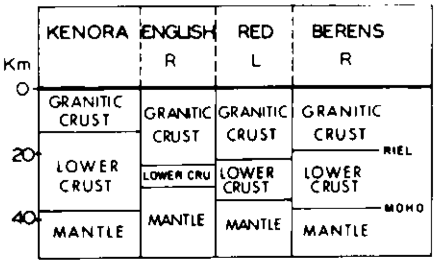

Figure 5
Diagrammatic model showing crustal thickness in Archean of Manitoba and northwestern Ontario. After Hall and Hajnal (1973).

Archean Volcanism

The examination of numerous volcanic sections in Australia, Canada, and Southern Africa has led to the observation that a generalized volcanic sequence is characteristic of Archean volcanism in all shields (Table I). Complete or nearly complete sequences are uncommon, but where they occur, criteria were established to distinguish certain parts of the sequence. The subvolcanic intrusions occurring within the volcanic rocks served as the most easily recognized criteria because of their large size and the fact that they were commonly distinguished even on reconnaissance maps. It was apparent also that ore deposits fitted into the volcanic sequence in characteristic positions.

Prior to our work during the 1973 field season, three subdivisions of the sequences were recognized. The lowermost group consisted of basalts with large ultramafic sills (or flows?). These ultramafic bodies are commonly several tens of kilometers long and as much as 300 m thick. The ultramafic rocks are not always present in this lower group, although they are common in Australia and rare in Canada. The Western Australia nickel deposits occur in this association. The Selukwe chromites in Southern Rhodesia may also occur in this association although this needs confirmation by further research.

Two characteristic types of intrusions occurred in the middle group as understood prior to 1973 as well as both basaltic and dacitic lavas which we had not separated clearly in the past. One type of intrusion consists of large, long gabbro sills which are as much as two km thick and 30 km long. The other type of intrusion consists of unhydrated layered gabbro-pyroxenite-peridotite sills, generally asociated with relatively acid fragmental volcanic rocks.

Table I
Archean Volcanism – Standard Section

Group	Lava	Intrusions
Upper Cyclic	Bas.-And.-Dac.-Rhy.	Irreg. Gab.-Anorth. (Small Ultramafic)
Middle Felsic	And.-Dacite Breccia	Layered Gab.-Pyrox.-Perid.
Middle Basic	Basalt (Andesitic)	Large Gabbro Sills
Lower Basic	Basalt	Large Ultramafic Sills

The upper group consisted of ultrabasic-basalt-andesite-dacite-rhyolite cycles, commonly with three or four complete or partial cycles. Characteristic intrusions in the upper group consist of large irregular gabbro bodies with anorthositic phases and magnetite horizons. Small ultramafic intrusions also occurred in the cyclic volcanics. Ore deposits consisted of the massive copper-zinc deposits associated with rhyolites, and small nickel-copper deposits associated with small ultramafic intrusions.

These sequences or portions of these sequences occur everywhere in greenstone belts. Most of the work in Canada, however, has concerned the upper cyclic group where massive sulphide deposits and large volcanic edifices occur.

The literature was used as a source for identifying the distribution of a lower, middle and upper group using the nature of the lava section, the associated intrusions, and the regional fold structure as criteria to define the groups (Fig. 6). This map is already obsolete but it was useful to show the wide distribution of all groups and the probable complete coverage of the surface by an extremely thick lava sequence prior to intrusion of the granitic diapirs. The map was also useful to design the 1973 field program so as to identify sections containing almost complete sequences, and to measure and sample selected sections in detail. The objectives were to clarify the stratigraphic relationships and development history of each pile, to recognize criteria which would be diagnostic of each group, and to recognize some of the differences which must undoubtedly occur between piles.

Preliminary field examination showed that two sections, Stormy Bay – Kakagi Lake, and Stormy Lake (Fig. 6) were well exposed, had few structural complications, and contained much of the whole Archean sequence. 33 members were measured in the Snake Bay – Kakagi Lake section which has a total thickness of approximately 14.5 km, with a single facing direction. Each member was composed of many beds representing flows, fragmentals, and sills. A total of 408 beds were measured in the section (Fig. 7). The Stormy Lake section is more complete but is not as well exposed.

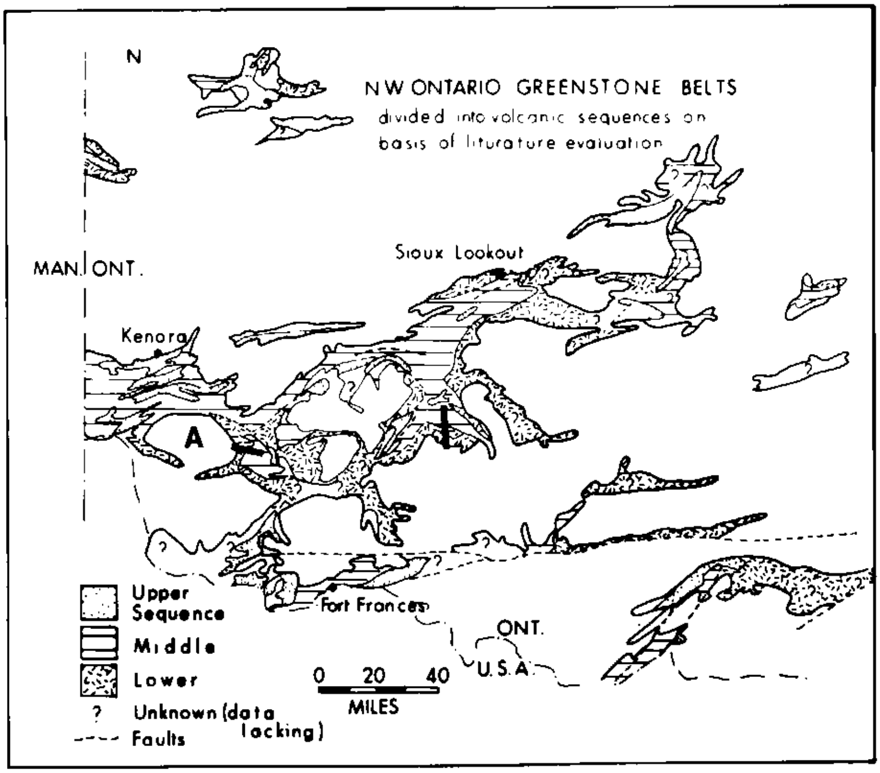

Figure 6
Tentative subdivision of the generalized Archean volcanic sequence. This map is being substantially revised. Heavy lines identify the Snake Bay – Kakagi Lake section to the west, and the Stormy Lake section to the east. A = Aulneau batholith.

The measurement of the two sections has clarified the relationship in the general volcanic sequence so that four major subdivisions or groups can now be established (Table I).

The main features of the two measured sections are as follows:

Kakagi Lake section (0 m is the bottom of the section at the Aulneau batholith)

1. Lower Basin Group (0 m - 2,773 m) This group is divided into six members. Characteristically the group is composed of monotonous flows of massive and pillowed basalt. The lavas are almost non-vesicular, and individual pillows are massive and devoid of internal structure. Individual flows appear frozen against earlier flows without any flow brecciation or brecciated flow tops. Fragmental rocks of any kind are rare. The section from 911 m to 2,724 m contains only eight fragmental basalt beds averaging 1.3 m thick. Intrusive rocks consist of sills of gabbro which tend to be relatively thin and not extensive. All sills but one are less than 20 m thick, but one sill of "Leopard Gabbro" reaches 157 m. "Leopard Gabbro" consisting of clots of

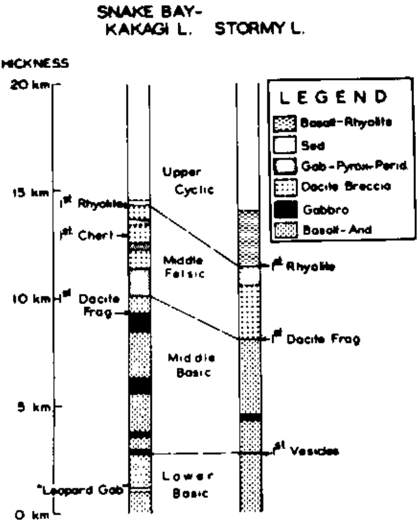

Figure 7
Columnar sections, Snake Bay – Kakagi Lake, and Stormy Lake.

plagioclase in a gabbroic matrix occurs in both sills and flows. Basic and felsite dykes are common in most members. The lowermost member (0 to 911 m) immediately adjacent to the Aulneau batholith is not typical of the rest of the Lower Basic group. It tends to be amygdaloidal and chemical analyses show variable granitization effects from the Aulneau batholith and related granitic dykes. The Lower Basic group is considered to represent basalt erupted in the abyssal part of oceans.

2. Middle Basic Group (2,773 m - 11,422 m) The Middle Basic group continues above the Lower Basic group as pillowed and massive flows. Chemical change at the boundary is gradual, but the appearance of the basalt pillows changes abruptly. The Middle group pillows are vesicular and have well developed rims and concentric structures. Large gabbro sills showing only moderate flow differentiation become prominent. The sills range from 20 m to 356 m in thickness. Fragmental basalts occur in this series but are still relatively rare as they comprise only 140 m in a section of 7,377 m. Almost all fragmental material occurs in two of the 22 members. The first flow top breccia occurs at 3,518 m and interlayered flow breccia, aquagene breccia and pillow basalt occur between 8,462 and 9,341 m. Basalt agglomerates are rare or absent in this group. The first appearance of dacite lapilli tuff occurs at approximately 9,300 m as a bed 8 m thick containing fragments as large as 5 mm in diameter. This bed is interlayered with basic beds.

3. Middle Felsic Group (11,422 m - 14,306 m) The beginning of the Middle Felsic group is marked by a relatively abrupt change to a thick, monotonous group of intermediate, grading to felsic fragmental volcanic strata. The Middle Felsic group is also characterized by the presence of unaltered, layered gabbro-pyroxenite-peridotite intrusions. These intrusions generally take the form of thick sill-like members that may be more than a kilometer thick and 25 km long. An unaltered, unhydrated mineralogy of these intrusions is characteristic although orogenesis may alter these rocks, particularly where they become squeezed between two granitic diapirs.

4. Upper Cyclic Group (14,306 m - 14,446 m) The Upper Cyclic group is not well represented in this section, but tentatively the appearance of the first thick rhyolite member is taken as the beginning of the cyclic group. The rhyolite member consists of fragmental flows interbedded with fragmental rhyolite and tuff. The remainder of the Upper Cyclic group has been removed in this section.

Stormy Lake section. The Stormy Lake section shows a similar sequence to that of the Kakagi section so that a broad group correlation can be made.

The Lower Basic group correlation is made using the nature of the basaltic flows. The pillows are non-vesicular and generally devoid of internal structures. Flows do not show brecciation and fragmental rocks are almost absent. The same abrupt change to vesicular pillows with concentric structures takes place at the beginning of the Middle Basic group. This correlation must be regarded as tentative at this stage of the investigation because chemical analyses of the lavas show gradational compositions. It is obvious also that the lower part of each section is not necessarily the bottom of the original volcanic section because the granitic diapir contacts at the bottom of the section are intrusive.

The Lower Basic group at Stormy Lake is commonly similar in composition to that at Kakagi Lake. However, some flows are much more magnesian than normal. These magnesian flows fall within the definition of komatiite as they carry as much as 13.65 per cent MgO with other elements in appropriate amounts.

The division between the Middle Basic and Middle Felsic groups in the Stormy Lake section is not well exposed because of a three km gap in exposures. However, the change from massive and pillowed basic flows to felsic fragmentals is similar to that of the Kakagi Lake section, and the felsic fragmentals section is approximately three km thick. Metasediments are interbedded with the volcanic fragmentals in the upper portion of the Middle Felsic group in this section.

The Upper Cyclic group is approximately 2.7 km thick in the Stormy Lake section. It begins with a seven meter thick fragmental rhyolite, followed by approximately 900 m of basalt, and 1,500 m of andesitic and rhyolitic flows and fragmentals. The top 300 m consists of layered andesitic tuff.

Chemistry of the volcanic sequence. 66 rock analyses are now available for the Kakagi section. The chemical trend from Lower Basic, through Middle Basic, to the top of the Middle Felsic group is clear (Figs. 8 and 10). These three lava groups represent a continuous differentiation series. Successive eruptions apparently represent the changing liquid composition of a crystallizing and differentiating magma. The analogy to the Skaergaard liquid (Fig. 9) and the sort of magma which must produce a Bushveld complex is apparent, but the physical scale involved in the Archean lava series is of much greater magnitude. The rapid chemical change of the liquid from basic through intermediate to acid begins abruptly at the 10 km mark in the Kakagi section. This apparently corresponds to the Skaergaard magma after 95 per cent of the liquid has crystallized.

The trend of the changing liquid composition is shown in the AFM diagram (Fig. 11) and the feldspar diagram (Fig. 14). The AFM diagram shows that trends cross both calk-alkaline and tholeiitic compositions. Abrupt changes in direction of the trend are probably caused by the onset of crystallization of different minerals. For example, iron enrichment in the liquid is apparently followed by magnetite crystallization producing a cumulate layer of magnetite rich material which depletes the residual liquid.

Trace element distribution (Fig. 10) shows a maximum concentration of copper in the liquid at an elevation of 6 km in the volcanic pile. The copper content of the residual liquid drops abruptly between the 8 and 9 km elevation in the pile. The direction of movement of the copper when it is

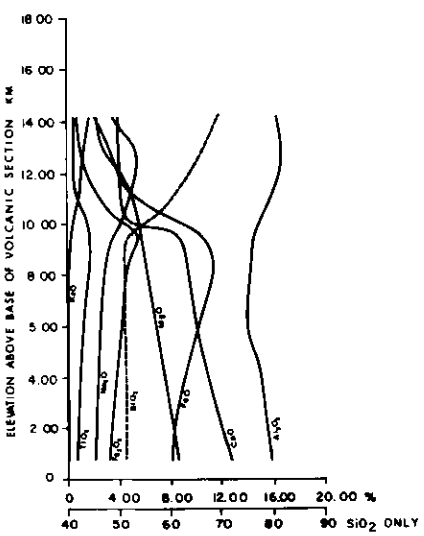

Figure 8
Chemical trends in the lavas from the Lower Basic Group to the top of the Middle Felsic Group, Snake Bay – Kakagi Lake section. The lower-most kilometer is not plotted because of granitization effects.

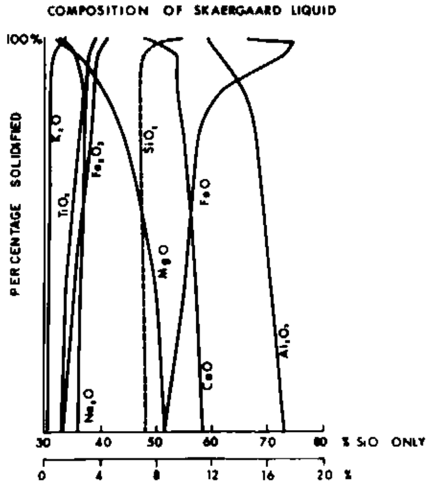

Figure 9
Chemical trend of the Skaergaard liquid. After Wager and Brown (1968, p. 169).

removed from the magma may be of considerable importance in providing a source for ore deposits. Lead is not shown on the graph as the basalts usually contain less than 5 ppm, and felsic phases average less than 10 ppm. Sulphur is not plotted because it does not show any particular trend and remains relatively constant at approximately 1000 ppm. Sulphur content is not directly related to copper and nickel in typical lava specimens or in sulphur enriched horizons (Mwanang'onze, 1974). Sulphur should be related to copper if the sulphur occurred in the magma, so it is probable that most of the sulphur is solfataric or later, and is not related to mineralization. Sulphur is related to the base metals in rare occurrences so it may be possible to distinguish areas of mineralization. Rock geochemistry used as an exploration tool must take account of stratigraphic position in the lava sequence.

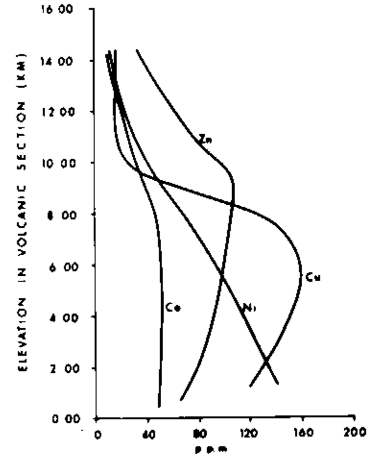

Figure 10
Trace element trends in the lavas in the Snake Bay – Kakagi Lake section.

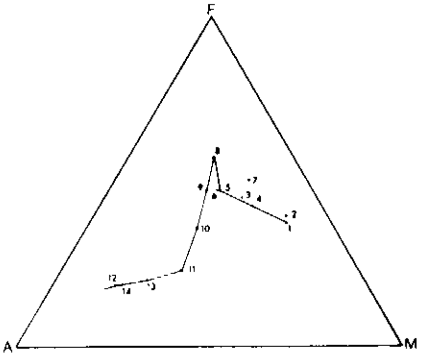

Figure 11
A.F.M. diagram showing the trend of the composition of the liquid (lavas) in the Snake Bay – Kakagi Lake section. Numbers represent plot of average analysis of samples in each km. above base section. 1 = 1 to 2 km, etc.

Inferences from the volcanic section. The logical inference from our mapping and analyses of these great volcanic piles, which are more than 14 km thick, is that the liquid series must arise from a vast magma chamber that occurred in what is now the upper mantle. Such a series cannot be formed by partial melting and extrusion from small magma chambers. It is also apparent that these Lower and Middle groups occur extensively throughout other Archean shields. We must conclude therefore that these great magma chambers were characteristic of Archean volcanism.

A second inference is that when the dacites of the middle felsic series are erupted the liquid at the top of the magma chamber has attained the composition of quartz diorite (Table II).

A third inference is that the almost monotonous section of lava flows and lack of structural complication of the first three lava groups indicates a non-orogenic process. Conversely, the Upper Cyclic volcanics show complex structural contortions, rapid alternations of flow compositions, abundant fragmentals, evidence of subaerial as well as subaqueous deposition, and abundant interlayered sediments. Conglomerates indicate the presence of positive land areas, and commonly contain granitic cobbles indicating a time overlap with granitic intrusion. The Upper Cyclic series is thus inferred to be orogenic and to have a temporal relation with granitic intrusions.

Granitic Diapirism

The elliptical Aulneau batholith (Figs. 6 and 12) was chosen for study of diapirism because of its regular shape, and because of its size which is suitable for detailed mapping, sampling, gravity, and reflection seismic studies.

Mapping indicates that the Aulneau batholith is a complex multi-phase intrusion into its present level with succeeding phases intruding earlier phases. Eleven successive phases have been mapped. Modal (Fig. 13) and chemical analyses (Fig. 14) show trondhjemite (A1) to granodiorite (A11). This differentiation trend is

Table II

	1	2	3	4	5
SiO_2	48.1	49.7	69.9	68.6	71.7
Al_2O_3	17.2	15.5	15.4	16.0	15.9
Fe_2O_3	1.3	3.1	0.8	1.2	0.8
FeO	8.4	8.2	2.1	1.9	0.9
MgO	8.6	8.8	1.8	1.3	0.7
CaO	11.4	12.2	4.8	4.2	2.5
Na_2O	2.37	1.49	3.59	4.70	5.50
K_2O	0.25	0.03	0.82	1.11	1.68
TiO_2	1.17	0.70	0.45	0.41	0.24
P_2O_5	0.10	0.12	0.22	0.14	0.10
MnO_2	0.16	0.22	0.10	0.05	0.03

Analyses are volatile free.

1. Skaergaard first liquid composition (Wager and Brown, 1968).
2. Snake Bay – Kakagi Lake, first liquid composition (average of samples 1 to 2 km).
3. Average dacite, Snake Bay – Kakagi Lake (km 14).
4. Aulneau batholith, (phase A1).
5. Aulneau batholith, (phase A9).

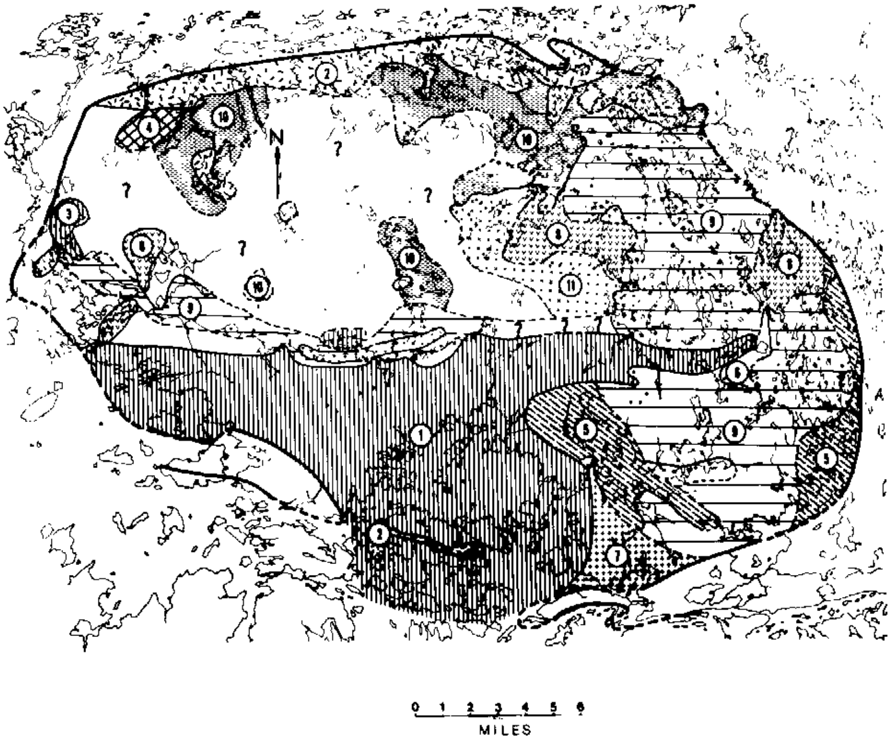

Figure 12
Geologic map of the Aulneau batholith. Numbers represent successive composition and textural phases of the batholith as determined by field mapping.

consistent with field observations of relative ages of different phases.

Table II and Figures 13 and 14 show that despite the large number of mappable phases, the chemical range of differentiation from first to final phase is very limited. Table II and Figure 14 also illustrate the similar composition of the dacite of the pre-orogenic lava series and the early trondhjemitic phases of the intrusion.

The batholith is not well lineated but foliation orientation is parallel to the contact near the margins of the batholith. Internally, the orientation of the foliation is complex. Field evidence and thin sections indicate that considerable milling and mechanical breakdown of early formed feldspars have occurred, probably during transport in a partially consolidated state. Field evidence also shows that earlier phases suffered brittle deformation in places.

The elliptical shape of the batholith, the character of its contact with the volcanic rocks, and orientation of marginal zone fabric all suggest a single emplacement event. The limited range of chemical differentiation of successive phases combined with the structural features indicate that differentiation probably took place by partial crystallization during emplacement.

The Aulneau pluton is expressed by a gravity low of 40 to 45 milligals. Theoretical Bouguer anomalies generated by a model with prisms extending to a depth of 16 km accounts for the observed gravity anomaly over the batholith. Models extending to depths of 12 km and 20 km show considerably greater degrees of under-compensation and over-compensation respectively (Brisbin, 1973).

Measurements of the relative amounts of granitic diapir and greenstone belt volcanic and sedimentary rocks show that the granitic diapirs occupy 49 per cent of the surface area in both the Kenora and Red Lake blocks in northern Ontario, despite the difference in thickness of the granitic crust in the two blocks (Brisbin, W. C., personal communication).

Inferences regarding origin of the granitic diapirs. The timing and compositional relationships between the Middle Felsic Group of pre-orogenic Archean volcanic rocks and the granitic diapirism of Archean shields indicate a genetic relationship between the two rock groups. The thick felsic volcanic section indicates that the residual liquid from the larger magma chamber had reached a quartz-diorite composition. A thick granitic layer accumulating in the upper mantle position would eventually become gravitationally unstable because of its decreasing density due to crystallization of more

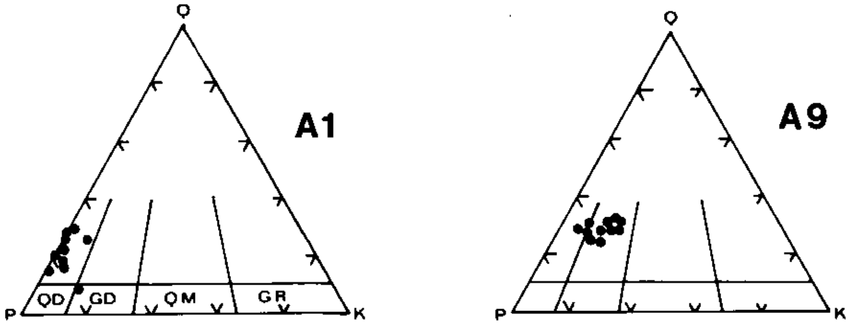

Figure 13
Modal analyses of first phase (A1) and a major late phase (A9) of the Aulneau batholith plotted on the quartz-plagioclase-potash feldspar diagram. QD = quartz diorite, GD = granodiorite, QM = quartz monzonite, GR = granite.

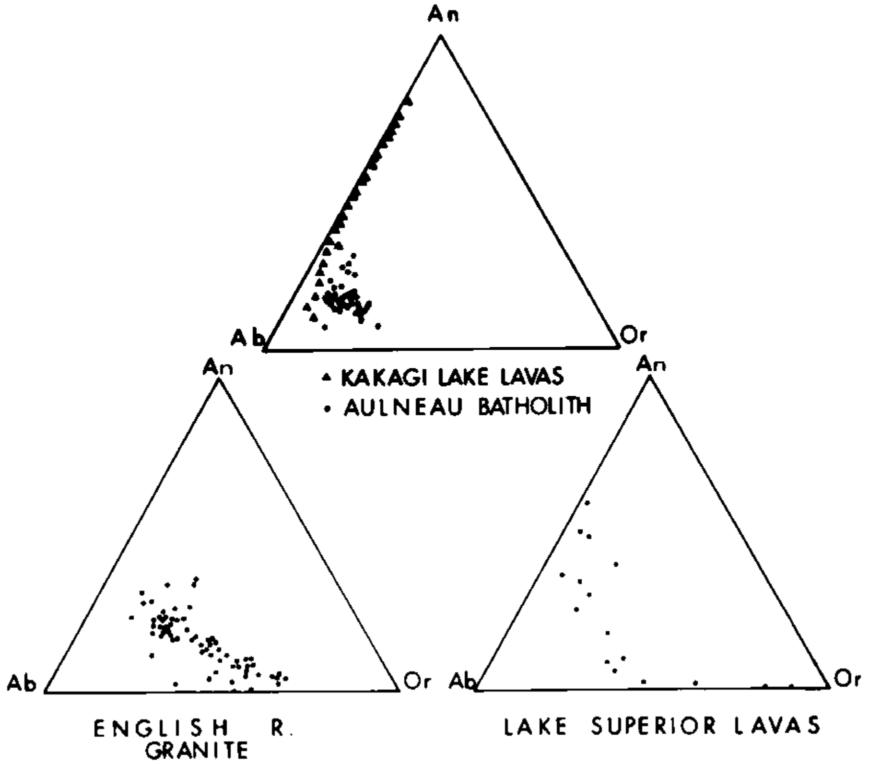

Figure 14
Normative feldspar compositions.

basic mineral phases. Diapirism eventually resulted from this instability so that the granitic liquid drained upward through the lower crust and expanded as rising diapirs through the layered Archean volcanic series. The upward orogenic movement of the granitic liquid phase would leave the heavy layered cumulates of the great magma chamber (upper mantle) in contact with the primordial crust which is represented by the lower basaltic layer of the crust. The gravity interpretation of the batholith supports the hypothesis that the lower crust was not destroyed by this event.

Late Archean Orogenic Events
Age dating, superposition of formations, and metamorphism of preexisting rock groups suggest that sedimentary basins such as the English River gneissic block and metamorphic welts such as the Berens River block were late events of the Kenoran orogeny. Ultrametamorphism of the English River block sediments produced anatectic granitic magmas with a different compositional range from those of the granitic diapirs (Fig. 14). Aeromagnetic maps show that the Berens River block retains clear vestiges of the greenstone belt – granite diapir structure and greenstone remnants show evidence of the highest grades of metamorphism.

Post Orogenic Intrusions
Age dating shows that the Archean continental nucleii reached a platform stage approximately 2400 to 2500 m.y. ago in Canada and perhaps somewhat earlier on other continents. Non-orogenic flood basalt and alkalic magmas continued to rise through the continental nucleii in episodes for a billion and a half or more years but even these appear to have ended and the nucleii remain as inactive, positive masses occasionally covered by shallow epeirogenic seas. The post orogenic basalts and other magmas are much more potassic than Archean magmas as shown by the later Precambrian lavas of Lake Superior (Fig. 14). The high potash content is usually interpreted as due to melting under extremely high pressures that occur deep within the mantle.

The Earth-Moon System
Recent research into the history of the moon can provide insight into the early history of the earth provided that the two became a planetary pair at the time of their origin. Early moon history has been partly preserved whereas that of the earth has been largely destroyed by erosion due to water and other forces on earth which may be due to the larger size of this planet.

The earliest dated moon rocks are the anorthositic rocks of the highlands which date as old as 4.5 billion years (Kamb, 1973). Similar rocks may have formed the original crust of the earth and it is possible that some of these may be preserved as the lower crust below the Archean lavas and granites of continental nucleii. These may have provided a source for melting to produce the anorthorites of the later Precambrian.

Oceans apparently existed prior to 3.5 billion years ago on earth as shown by pillow lavas in the oldest Archean shields so it is evident that the early crust underwent erosional and probably local orogenic processes. Some of the patches of very old rocks on earth may be remnants of these processes.

During the period of 3.9 to 4.0 billion years ago the moon, and presumably the earth, was blasted by huge impacts. The heat and shock waves generated by these violent impacts appear to have triggered a volcanic period on the moon that lasted from 3.9 to 3.1 billion years ago. Eruptions continued "for about 100 million years at each individual site, but shifting from place to place during the 800 million year era of lunar volcanism" (Kamb, 1973). The volcanism covered nearly one quarter of the moon's surface and magma chambers are estimated to have had a total thickness of between 100 and 300 km (*Geotimes*, Jan. 1973).

The earth must have undergone a similar period of violent impact which could trigger melting of rocks already heated by the higher concentrations of radioactivity during the early period of earth history. The magma chambers formed on earth, like those of the moon were also 200-300 km thick. However, the gravity of the earth is much greater than that of the moon, so extensive gravity differentiation of these magmas took place on earth and granitic phases resulted from crystal settling. These granitic phases eventually resulted in the continental nucleii which were not formed on the moon.

The smaller moon froze and died at the end of the volcanic period and its main later history is one of the effect of minor meteoritic impacts. The larger earth, however, remained active and a long history of activity began where continents and oceans could interact with each other. Most of the radioactive heat was removed from the melted mantle by upward transfer of the radioactive elements in the granitic liquid. This combined with the low density of the granitic crust produced stable continents.

A hypothetical comparison of earth and moon history is shown in Figure 15. This history presumes a model where a granitic crust approximately 30 km thick was formed from a lava pile 15 km thick and an additional 15 km formed from granitic intrusions. Both lavas and granitic diapirs result from a differentiating magma located in what is now the upper mantle. The lower layer of the crust is either original earth crust of probable anorthositic composition, or frozen basalt resulting from crusted chilling of the huge magma. The upper mantle is the layered basic series resulting from the heavy cumulate crystals of the magma.

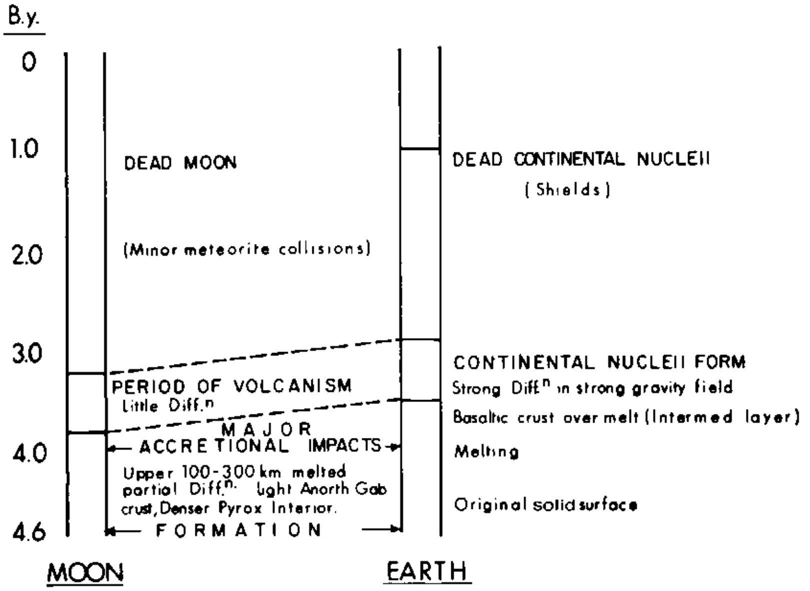

Figure 15
Comparison of moon and earth history.

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