Early Proterozoic climates and plate motions inferred from major element chemistry of lutites

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The early Proterozoic Huronian Supergroup of the north shore of Lake Huron (Fig. 1) is a thick (up to 12,000 m) succession of sedimentary and volcanic rocks deposited between about 2,500 and 2,100 Myr ago[1]. Here we present a palaeoclimatic interpretation of the Huronian based on approximately 200 major elements analyses of lutites. Most of these are new analyses from the Gowganda and Serpent Formations (Fig. 2). The remainder are from published sources cited in Fig. 4. The composition of lutites from the Huronian Supergroup records an early period of intense, probably tropical, weathering followed by climatic deterioration that culminated in widespread deposition of glaciogenic sediments of the Gowganda Formation. Climatic amelioration followed during deposition of the succeeding Huronian formations. The Huronian succession can be interpreted using a uniformitarian approach in that present day seafloor spreading rates and latitude-related climatic variations are compatible with available geochronological and palaeomagnetic data.

Earlier studies of the palaeoclimatology of Huronian rocks have largely revolved around the Gowganda Formation which has been interpreted both as glacial or glaciomarine and/or as fault-related submarine debris flows[2–4]. Diamictites of the Bruce and Ramsay Lake Formations (Fig. 2) have also been considered to be glaciogenic[5]. It has been suggested that pre-Huronian palaeosols and pyritic uraniferous conglomerates at the base of the Huronian formed in a cold climatic regime[6,7]. Gay and Grandstaff[8] noted that palaeosols developed beneath the Huronian appear to represent intense weathering and suggested a temperate humid regime.

The 'aluminous' nature of the Pecors Formation led Roscoe[6] to conclude that a regolithic cover was restored on the landmass following deposition of the possibly glaciogenic Ramsay Lake Formation. Dolomite in the Espanola Formation has been interpreted as indicating an amelioration of climate after deposition of the glaciogenic(?) Bruce Formation.

Following the major glacial period of Gowganda deposition, tropical-type weathering conditions have been inferred from the presence of diaspore, kaolinite, pyrophyllite, andalusite and kyanite in the overlying Lorrain Formation[9-11]. Temperate conditions have been suggested[12] during deposition of the Gordon Lake Formation and the presence of gypsum and anhydrite[12] may indicate a somewhat warm and dry climate. Quartzites of the Bar River Formation contain kaolinite and pyrophyllite which were interpreted[12] as indicating tropical weathering conditions. Card[13] stated that rocks of the lower part of the Huronian are immature and indicate negligible weathering of the source rocks. He contrasted this with the upper Huronian which contains evidence of extreme chemical alteration of feldspars.

There is, therefore, no concensus on palaeoclimatic interpretation of Huronian rocks although most authors accept a glaciogenic origin for the Gowganda Formation and possibly also for other diamictites lower in the Huronian succession. We use a geochemical approach in an attempt to resolve some of these problems. Mineralogical evidence from the upper Huronian formations, above the Gowganda Formation, is consistent with a high degree of chemical weathering. Apart from the glaciogenic(?) diamictites, the rocks of the lower part of the Huronian Supergroup have been variously interpreted as having formed in a frigid climate or in temperate humid conditions.

Wedepohl[14] estimated that the upper crust consists of approximately 21% by volume of quartz, 41% plagioclase and 21% potassium feldspar. Feldspars are by far the most abundant of the reactive (labile) minerals; consequently the dominant process during chemical weathering of the upper crust is the degradation of feldspars and concomitant formation of clay minerals. Calcium, sodium and potassium generally are removed from the feldspars by aggressive soil solutions so that the proportion of alumina to alkalis typically increases in the weathered product. A good measure of the degree of weathering can be obtained by calculation of the chemical index of alteration (CIA) using molecular proportions:

$$CIA = [Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O] \times 100$$

where CaO^* is the amount of CaO incorporated in the silicate fraction of the rock. A correction is made for carbonate and apatite content. The resultant value is a measure of the proportion of Al_2O_3 versus the labile oxides in the analysed sample. Values of the index are 50 for unaltered albite, anorthite and potassic feldspars, whereas the value for diopside is 0; consequently fresh basalts have values between about 30 and 45 and granites and granodiorites have higher values, ranging between 45 and 55. Idealized muscovite gives a value of 75 and illite ranges between 75 and 85 as do montmorillonites and beidellites. Kaolinite and chlorite yield the highest values, very close to 100. Thus values for average shales range from about 70 to 75 (Fig. 4) because of the large proportion of clay minerals.

Figure 3 is a plot of CIA values against depth in two fairly mature Recent weathering profiles developed on a basalt in southeastern Australia[15] and a granite from Guyana[16]. There is an obvious trend from low values in fresh rock to progressively higher values in more intensely altered materials. The changes in CIA reflect changes in the proportion of feldspar and the various clay minerals in the profiles. Such profiles ultimately are subject to mass wasting, the materials being transported and deposited in sedimentary basins as sands and muds. Size sorting during transportation and deposition generally results in some degree of mineralogical differentiation[17] which may modify the CIA. We have therefore restricted this study to rocks of mud grade (lutites). The mineralogical and chemical composition of the muds will reflect the intensity of weathering

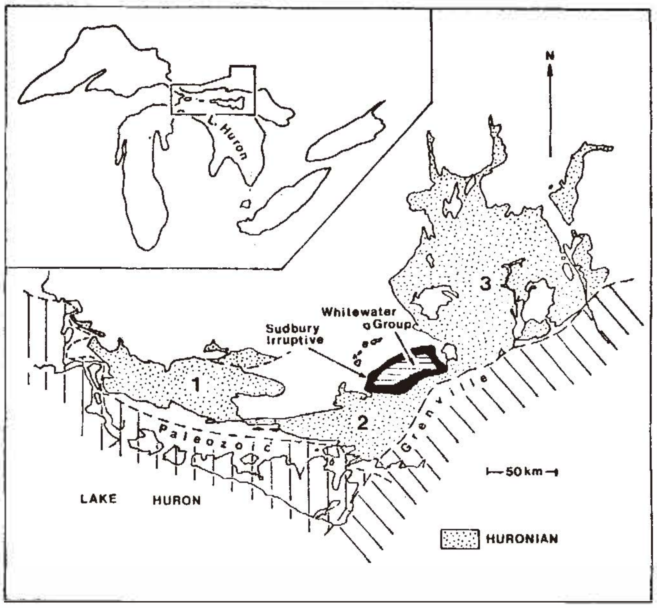

Fig. 1 The distribution of the early Proterozoic Huronian Supergroup. Rocks of area 1 and area 3 are generally less deformed and metamorphosed than those of area 2.

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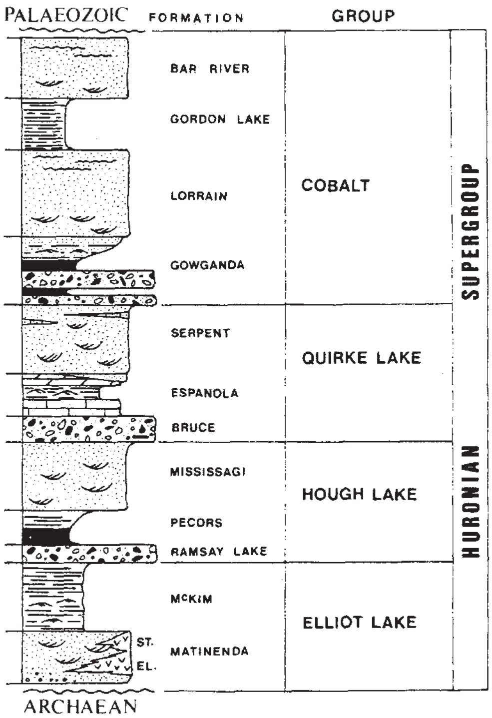

Fig. 2 Generalized stratigraphical column of the Huronian Supergroup. Note the presence of three major diamictite horizons (Ramsay Lake, Bruce and Gowganda Formations). Letters EL and ST near the base of the column represent the dominantly volcanic Elsie Mountain and Stobie Formations respectively. Maximum thickness of the succession is ~12,000 m.

because highly aluminous minerals such as kaolinites and beidellites are produced in quantity during intensive weathering and such sediments will have correspondingly high CIA values. Mass wasting of profiles in which chemical weathering is minimal, such as those produced in glacial conditions, may result in fine grained detrital sediment containing less aluminous clay minerals (montmorillonites and illites) and a high proportion of unaltered comminuted feldspar.

All of the analysed rocks have undergone some degree of metamorphism, ranging from 'sub-greenschist' facies in the north (areas 1 and 3, Fig. 1) to upper greenschist-amphibolite facies in the south[18]. The CIA values are not considered to have been significantly changed during metamorphism because similar values have been obtained from diamictite matrix materials of the Gowganda Formation from northerly areas of lower metamorphic grade and more highly metamorphosed rocks to the south (area 2, Fig. 1).

To facilitate interpretation of CIA values obtained from Huronian lutites, values were also calculated from a variety of other rocks and sediments. The average chemical composition of the Archaean Shield of north-west Ontario[19] with a value of 49.5 is included in Fig. 4 to give an idea of the Huronian source rocks[20,21]. Chemical analyses of the fine grained portion of the matrix of nine Pleistocene till samples collected by R.W. Stewart in the southern part of the Archaean Superior Province of the Canadian Shield yielded CIA values of about 52, close to the value obtained from the average shield composition. Data from Pleistocene glacial clays[17,22] gave values in the 60–65 range. These are considerably lower than average shale values which plot in the 70–75 range (Fig. 4). The highest values shown in Fig. 4 were obtained from residual clays listed by Pettijohn[17] and from sediments of the Amazon cone[23].

Fossil soils or palaeosols have been noted in several places beneath the Huronian succession[6,7,8,24]. Near-complete removal of Ca and Mg, and the development of deep (>10 m) weathering profiles suggest fairly intense weathering under a wet or humid climate. The abundance of sericitic matrix material in sandstones of the Matinenda and Mississagi Formations indicates that chemical weathering was both deep and intensive before the onset of Huronian deposition.

The names Elsie Mountain and Stobie Formation and other local formation names have been applied to thick dominantly volcanic units at the base of the Huronian succession[13]. These are probably equivalent in part to the Matinenda Formation as suggested in Fig. 2. Metamorphosed sedimentary rocks comprise about 10% of the Elsie Mountain Formation[13]. They are mostly thin intercalations in metamorphosed basalt flows. The Elsie Mountain Formation has yielded the highest CIA values of all the Huronian lutites examined (Fig. 4) suggesting a high degree of alteration by weathering processes.

The Stobie Formation also consists of interbedded metamorphosed volcanic and sedimentary rocks. CIA values obtained from lutites of the Stobie Formation yielded an average just greater than 70, comparable to the average shale.

The McKim Formation includes sandstones, siltstones and argillites. It varies greatly in thickness (up to 2,000 m in the east[4]) and appears to be largely resedimented. CIA values from fine grained rocks of the McKim Formation show a wide variety of values ranging from 67 to 86, with an average of about 75. The high values indicate the weathered nature of some of the materials incorporated in turbiditic mudstones of the McKim Formation. Lutites of the Elsie Mountain and McKim Formations include high CIA values comparable to residual clays cited by Pettijohn[17] and sediments of the Amazon cone[23] (Fig. 4).

Lower CIA values from the Pecors and Serpent Formations suggest that, following deposition of the McKim Formation, there was a cooling climatic trend. Values for the Pecors Formation (average 71.5) are lower than those obtained from average shales. Mudstones from the upper part of the Serpent Formation in the southern part of the Huronian outcrop belt give still lower values.

Diamictites of the Ramsay Lake and Bruce Formations (Fig. 2) have been considered to be glaciogenic and may provide independent evidence of a cooling climatic trend beginning after deposition of the McKim Formation.

Most of the geochemical data reported in this study are from the Gowganda Formation. They have been separated on Fig. 4 according to whether they represent diamictite matrix material or laminated argillites. All the data from Gowganda diamictites have been grouped together on a single histogram and plotted below the argillites but these two rock types are in fact interbedded in the formation[2].

Results from the three areas of Gowganda outcrop (Fig. 1) are differentiated on the histogram of CIA values shown on Fig. 4 but are not significantly different. The average value for the diamictite matrix material (56) is the lowest obtained from Huronian mudstones and supports the glacial interpretation of the Gowganda Formation. CIA values from the Gowganda

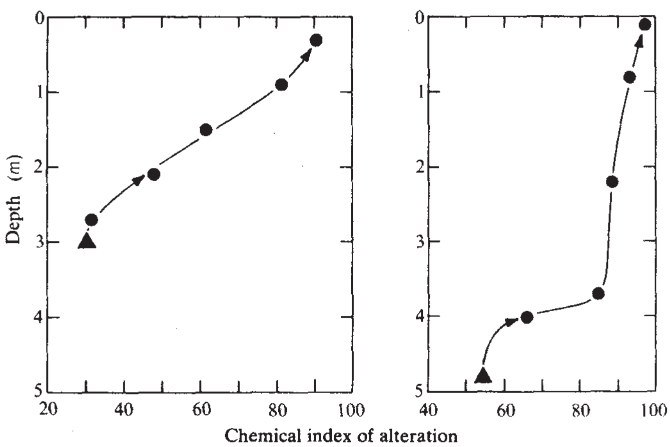

Fig. 3 Relationship between depth and chemical index of alteration in Recent weathering profiles developed on a basalt[15] (*a*) and a granite[16] (*b*) in Guyana. In each case the triangle represents fresh rock with successively higher CIA values upward in the weathering profile.

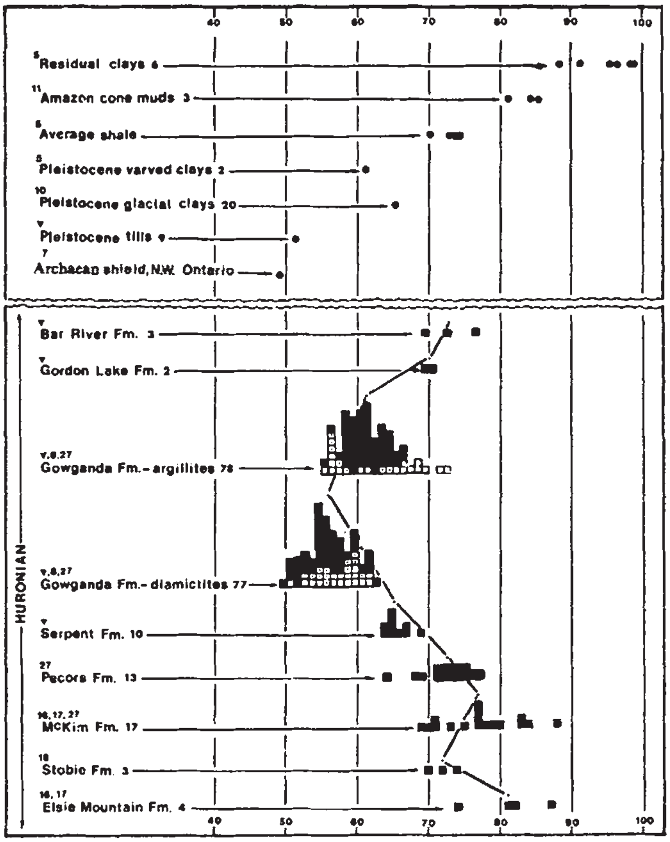

Fig. 4 Values of chemical index of alteration (CIA) for Huronian formations and various other rocks and sediments (upper part of diagram). Each square in the lower part of the diagram represents a single chemical analysis. Black dots in the upper part of the diagram are either individual analyses or averages. Numbers following formation names and so on indicate the number of chemical analyses involved. Numbers above formation names at left side are sources of data obtained for this study. ▲ (at left) indicate new data. For the Gowganda Formation □ are data from the Cobalt area (area 3); ⊡ are from the Bruce Mines area (area 1); ■ are from the Whitefish Falls area (area 2).

diamictites are comparable with those derived from Pleistocene tills on the Archaean shield (Matachewan tills of Fig. 4).

Argillites of the Gowganda Formation yield CIA values higher than those of associated diamictites, reflecting incorporation of slightly more weathered materials. These argillites, however, contain less weathered materials than the average shale (Fig. 4) due to incorporation of glacial flour. Some samples from the northeastern part of the Huronian outcrop belt (area 3, Fig. 1) have relatively high CIA values, suggesting incorporation of more highly weathered material.

In general CIA values from the Gowganda argillites indicate that they were derived from muds of unusual composition, containing a relatively low proportion of alumina. Pleistocene varved and other glacial clays give similar low CIA values (Fig. 4) supporting the glacial origin of the Gowganda argillites and suggest that these form a chemically distinctive category of relatively unweathered muds and mudstones.

Data from lutites in Huronian formations above the Gowganda are few. Samples from the Gordon Lake and Bar River Formations (Fig. 4) have values similar to those of average shales and support the idea of climatic amelioration[9,12] following deposition of the Gowganda Formation.

The geochemical evidence presented above suggests that the lowest Huronian formations, and in particular the Elsie Mountain and McKim Formations, contain significant amounts of highly weathered detritus. It is not known whether this material was derived by erosion of older palaeosols or by weathering contemporaneous with deposition. In the former case remarkably thick palaeosol development would be indicated, for the McKim Formation is up to 2,000 m thick and is extensive. In either case such a high degree of chemical alteration is suggestive of weathering in humid, possibly tropical conditions. Geochemical results from the Gowganda Formation confirm the widely held belief that it was deposited in a glacial environment. High CIA values for the overlying formations suggest an amelioration of climate.

The general interpretation based on CIA values suggests deposition in low latitude, possibly tropical conditions followed by climatic deterioration and subsequent amelioration. If the changes recorded in the Huronian Supergroup were related simply to global climatic variations then similar changes should be recorded in many other early Proterozoic sequences. Glacial deposits of comparable age to the Huronian are, however, relatively scarce[9]. An alternative interpretation of these results, based on uniformitarian principles, is that the Huronian succession records migration of the depositional site through various climatic zones. In present conditions, climatic variations as dramatic as those proposed for the Huronian succession would require a minimum change in latitude of about 30°. As the Huronian succession is thought to record a warm humid climate with subsequent deterioration and amelioration, migration of the depositional basin through a total distance equivalent to about 60° latitude is required on a uniformitarian basis. Current rates of seafloor spreading are typically in the range from 2 to 8 cm yr^{-1} (ref. 25). These rates of spreading would require 350 and 100 Myr respectively to allow a 60° latitudinal spread. These estimates are calculated on the assumption that spreading took place in a direction normal to the palaeoequator and are therefore minimum values. They fall within the limitations suggested by available radiometric dates for deposition of the Huronian Supergroup (~2,500–2,100 Myr). The above estimates of variation in palaeolatitude during Huronian deposition are also in agreement with recent palaeomagnetic studies[26] suggesting that volcanic rocks in the lower part of the Huronian were extruded at a palaeolatitude of about 32° and that the Gowganda Formation was deposited at about 60° of latitude. Recent studies of early Proterozoic successions in the northern Great Lakes region[27,28] and elsewhere in the Canadian Shield[29] support the existence of plate tectonics at that time. Although the solutions presented above is not unique, a uniformitarian approach, involving plate tectonic processes and latitude-related climatic variations, can be used to interpret the ancient rocks of the Huronian Supergroup.

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