NATO CONFERENCE
ON
"THE EARLY HISTORY OF THE EARTH"

INTRODUCTION

The last decade has witnessed a great revival of interest in the study of the Precambrian in all parts of the world not only by geologists but also by physicists and chemists. Geochronology has helped in identifying older and still older episodes in Earth history. Oldest ages of 3760 m.y. have been recorded from the Godthab District of West Greenland. In India ages as old as 3200 ± 150 m.y. have been obtained for tonalite pebbles from the Dharwar conglomerates. Instrumental techniques have helped in accumulating substantial major and trace element data. Geochemists all the world over are trying to find if any significant geochemical differences exist between the oldest and relatively younger rocks. This interdisciplinary effort of geologists, geophysicists and geochemists in unravelling the early history of the Earth forms a glorious chapter in the history of development of Earth Sciences.

In September 1974 of last year a group of geologists and geochemists met at Redwood Falls, Minnesota U.S.A. to discuss the nature and problems connected with the ancient rocks. Encouraged by this meeting and perhaps make such discussions more comprehensive and broadbased, the Department of Geology of the University of Leicester U.K. had organised a six-day conference on the Early History of the Earth at Leicester between the 5th and 11th of April 1975. Over 140 delegates from Africa, Australia, Belgium, Brazil, Canada, Czechoslovakia, Denmark, France, Germany, Poland, India, Italy, Netherlands, Norway, Spain, U.K. and U.S.A. attended. I was one of those privileged to attend the conference.

The conference provided a rare opportunity of hearing at first hand details of current researches being carried out in different parts of the world in unravelling the early History of the Earth prior to 2500 m.y. ago. Each day's discussion was confined to one particular aspect. The Early Earth-Moon System, High Grade Terrains, Greenstone Belts, Archaean Tectonics, Evolution of the Archaean Crust, Archaean Atmosphere and Hydrosphere, Evolution of Archaean Life were the principal topics discussed. The conference was so structured that it provided time in the mornings for a review of major topics by specialists leaving the afternoons for consideration of research reports and for a free discussion of the papers presented earlier in the day.

A highlight of the conference was an exhibition of maps and specimens from Greenland. What the Greenland geologists have designated as the 'Amitsoq gneisses' looked exactly similar to gneisses from Peninsular India. Almost every specimen from the Malene supracrustals could be matched with our collection from the Sargur group in Karnataka. A fuchsite quartzite specimen could be easily mistaken for one collected from Belavadi; the magnetite quartzites from Isua which have given the oldest ages exactly resembles the magnetite quartzites from Kudremukh. The similarity was most striking and when the geology of the area was described with the help of many coloured slides I could not help recognising parallel episodes from the Dharwar craton.

In view of the importance the subject has for us in India, and the need for getting to know the lines on which the problem of ancient rocks is being studied in other continents, I have thought it best to give a brief account of the main contributions of the Nato conference for the information of the readers of our Journal in the hope that this will stimulate their interest in the study of the Precambrians of India.

THE EARLY EARTH-MOON SYSTEM

The discussion on the Early History of the Earth most appropriately started with a consideration of the Early Earth-Moon system.

V. RAMA MURTHY of the University of Minnesota speculating on the composition of the core and the early chemical history of the Earth argued that Fe-FeS liquids being the lowest melting liquids first formed into a core. The energy released by formation of a core of this composition raised the temperature of the earth, leading to a major geochemical differentiation reflected in the U-Pb age of the Earth. According to Rama Murthy the proto-crustal material generated during core-mantle-differentiation was of mafic composition.

D. M. SHAW of McMaster University, Canada, had a different model for the development of the early continental crust. According to him the early earth history is divisible into a Pre-Archaean and a Proto-Archaean stage. In the first stage major differentiation into core, peridotitic lower mantle and basaltic upper mantle took place. This stage terminated with the accumulation of granitophile elements near the surface resulting in a world-wide thin anorthositic crust. Mantle convection aided the rupture of the thin crust. Anatexis of the basic crust, and subcrustal granite produced light silicic magmas which underplated the upper crust. Local thickening developed continental crust nuclei and local thinning produced the ocean basin nuclei.

B. M. JAHN and L. E. NYQUIST of the Lunar Science Institute, Houston, U.S.A. presented a comparative study of the isotope and crustal evolution of the Early Earth-Moon system. Moon was shown to have passed through the following stages (1) formation about 4600 m.y. ago, (2) intensive bombardment by interplanetary debris about 4600 to 3900 m.y. ago, (3) eruption of Mare basalts 3900 to 3100 m.y. ago, (4) last episode of Mare flooding 3100 m.y. ago. The lunar Rb/Sr data showed that most lunar basalts have initial Sr^{87}/Sr^{86} ratio ($=$I) lower than 0.69960. The available Rb-Sr data on terrestrial Archaean rocks indicate that the maximum I value is 0.7004, which is approximately the maximum value for lunar basalts. The authors felt that the crustal evolution of the Earth probably involved extensive recycling to account for the value of 0.7004 of modern alkali basalt. The reason why primitive Sr isotope composition (0.69960) was preserved in lunar samples and not in the samples from the Earth was ascribed to the absence of large scale recycling processes in the moon.

R. ST J. LAMBERT from Alberta University, Canada, reported that very few characters appear to be unique to the Archaean. Low K content, generally high Ni and Cr, overall low Ti relative to younger rocks have been claimed by some as characteristic of the Archaean. Direct evidence for true secular variation, apart from the long term variation in K_2O/Na_2O appear to be confined to the granitic complexes from Kaapvaal, where K, Rb, Pb and Th abundances increase steadily from 3300 to 2500 m.y.

ARCHAEAN HIGH GRADE REGIONS

The second day started with a review by B. F. WINDLEY, of the University of Leicester of some Archaean high grade regions. He pointed to the dominance of tonalitic gneisses in all the high grade Archaean regions. As against the usual bimodal association of amphibolites and tonalites, he advocated a trimodal association of tonalite gneisses, amphibolites and layered complexes in all stages of destruction as in Labrador, Greenland, S. Africa and S. India. Windley had been to India recently and illustrated his talk with slides showing the distribution pattern of anorthosites. He felt that gneisses with anorthosite inclusions denoted stratigraphic markers. Windley was of the opinion that the Archaean tonalites and the layered igneous complexes represent the earlier fractionated residue of basaltic magma. He envisaged the intrusion of tonalites with their early fractionated complexes not as diapirs but as lateral emplacements along low angle subduction zones.

F. KALSBEEK of the Geological Survey of Greenland, speaking on the metamorphism of Archaean rocks from West Greenland, pointed out that gneisses formed 85% of the bed rock of Fiskenasset district and amphibolite, anorthosite and related rocks only 4%. The hypersthene-bearing gneisses had high K/Rb ratios compared with non hypersthene-bearing gneisses suggesting that the latter have not been in granulite facies. Differences in average chemical composition between hypersthene bearing and non-hypersthene bearing gneisses were explained by a model in which granitic (K-rich) gneisses developed by fractional anatexis of K-feldspar poor gneisses leaving hypersthene gneisses as a residue.

V. R. MCGREGOR of the Geological Survey of Greenland gave an excellent review of the geology of the Godthab Dt., West Greenland. He pointed out that the granitic gneisses which have yielded dates of 3040 to 3750 m.y. (The Amitsoq gneisses) are dominated by tonalites and trondhjemites. Isotopic and preliminary chemical data supported the hypothesis that these rocks were derived directly from the mantle.

The later gneisses (the Nuk gneisses) are a sodic suite dominated by tonalites and trondhjemites. These, according to McGregor were intruded in a period dominated by major sub-horizontal movement. This horizontal regime in the crust was supposed to have been produced by some sort of subduction. The parents of the Nuk gneisses are thought to have been produced by partial melting of basaltic crust descending into the mantle. The sheet form of the Nuk intrusions and the absence of contemporaneous basaltic magma were pointed out as important differences from present day subduction regimes. The intrusion of the Nuk gneisses resulted in a thickening of the crust. Crustal mobility lasted for several hundred million years with continued deformation and metamorphism that culminated in granulite facies conditions about 2800 m.y. ago. By about 2500 m.y. ago a thick stable crust with a foundation of refractory granulites had formed.

The description of the 3760 m.y. old supracrustal rocks of Isua presented by J. ALLART indicated that these are composed of amphibolites, biotite muscovite schists with stretched granitic fragments, biotite garnet schists containing locally staurolite and graphite, quartz-banded iron-stones, calc-silicate rocks, marbles and conglomerates with cigar shaped quartz pebbles, an association bearing a close similarity to that of Sargur and Holenarsipur schists from the Dharwar craton.

J. TARNEY of the University of Birmingham, presented a large volume of chemical data on the geochemistry of gneisses of the high grade gneissic terrains of Scotland, East and West Greenland. According to him K, Rb, U etc., were removed at granulite facies, flushing being facilitated by mantle degassing while the rocks were at deeper levels in the Archaean.

THE GREENSTONE BELTS

The problem of the Greenstone belts was the next major topic taken up for discussion on the third day. Introducing the subject Windley advocated the erection of as many models as possible for explaining the characteristic features of greenstone belts and suggested giving up the models as rapidly when tectonic and geochemical data were inconsistent with such models. He described with the help of slides the several models proposed ranging from an intra-continental rift to an oceanic accretion boundary, to an island arc to a marginal basin. He also referred to lunar maria model which involved meteorite impacts. He pointed out the defect in some of the models which did not clearly outline the relation between the greenstone belts and high grade terrains. According to Windley recent structural and isotopic evidence clearly suggest the greenstone belts to be younger and therefore could not be interpreted as remnants of the Earth's primordial crust.

A. Y. GLIKSON's thesis mainly centred round identification of what he termed 'the primary and secondary greenstone belts' in W. Australia, Transvaal, Rhodesia and India. The primary greenstones were equated with stratigraphically lower greenstones consisting of ultramafic-mafic volcanic sequences. The widespread occurrence of such ultramafic and mafic enclaves suggested that these rocks are relicts of a once extensive oceanic crust. The upper or secondary greenstones on the other hand are characterised by a bimodal mafic-sialic volcanic assemblage and/or by basalt-andesite-rhyolite cycles. This volcanicity was thought to have evolved within fault troughs developed in partly cratonized regions. The two greenstone sequences are separated in time by intrusion of tonalites. He pictured the greenstone belts as secular transformation from oceanic crust to sialic shield—a process which took place in different parts of the Archaean Earth at different times and which was terminated by a global thermal event 2600 m.y. ago.

J. G. ARTH of the Minnesota Geological Survey, presented a model for the origin of the greenstone-granite complex of northeastern Minnesota which formed 2700–2750 m.y. ago. According to him all the igneous rocks originated in the mantle or by rapid recycling of mantle-derived material and not by recycling of older continental crust.

J. J. HUBREGSTE from Winnipeg Canada, presented a picture of volcanism in the Knee Lake and Oxford Lake greenstone belts of Western Superior province in Manitoba. He too recognises two periods of volcanism—an older volcanic Hayes River Gp (HRG) which is unconformably overlain by the Oxford Lake Gp (OLG). The latter is made up of a lower volcanic subgroup and an upper sedimentary subgroup. The interval between deformation of the HRG and OLG was marked by intrusion of tonalite, trondhjemite, granodiorite and granite. Granite plutons postdated the OLG.

The models presented by Glikson and Hubregste closely resemble the sequence of events outlined for the Dharwar Greenstone belts.

K. C. CONDIE of New Mexico gave a lucid account of the trace element distribution pattern in Archaean greenstone belts. He felt that such studies can be used to infer tectonic setting, to detect undepleted upper mantle and to study magma origin and sediment provenance. He traced three major differences between the trace element contents of modern and Archaean volcanics: (1) most Archaean tholeiites are enriched in alkali and related elements, (2) most Archaean volcanics are enriched in transition trace elements, and (3) Archaean rhyolites are strongly depleted in Y and heavy REE. Trace element model studies, according to him, indicated that both progressive melting and fractional crystallisation were involved in the generation of greenstone magmas. As regards the greywackes, trace element evidence indicate that they were derived from volcanic and granitic terrains with a minor input from mafic and ultramafic sources as evidenced by the high concentration of transition metals.

The only contribution from India was from S. M. NAQVI of NGRI Hyderabad who traced the physico-chemical conditions during Archaean as indicated by Dharwar geochemistry. On the basis of chemical data collected by him he argued that the Archaean crust was thin unstable oceanic type. It was only in late Archaean and early Proterozoic that the craton got stabilised through granitisation. This cratonisation was marked by the appearance of alkali-olivine basaltic dykes (2100 m.y.). He pointed to the marked chemical differences between the Archaean and Proterozoic basalts.

R. A. BINNS of W. Australia describing the metamorphic pattern in the Eastern Yilgarn granite-greenstone terrain of W. Australia pointed out that the observed large-scale metamorphic pattern was apparently unrelated to areas of granite or gneiss, nor was it related to simple stratigraphic burial. A major change in geothermal regime and partly in heat flow at about 2650 m.y. appeared responsible for both metamorphism and the voluminous production of mantle-derived granitic magma.

ARCHAEAN TECTONICS

The fourth day's deliberations were confined to a consideration of Archaean tectonics and Metallogeny. J. SUTTON of the Imperial College, London, who led the discussion pointed out that changes in global tectonics developed towards the end of Archaean time presumably reflected changes in the earth's thermal regime. Two aspects of these changes were emphasised (1) the diachroism of the change over from a structure characteristic of the Archaean such as greenstone belts to those characteristic of early Proterozoic times when several extensive linear structures had begun to form, (2) the extent to which late Archaean structures influenced Proterozoic tectonics. According to Sutton some features in Proterozoic were markedly influenced by older structures first established in the Archaean.

According to K. BURKE and others of the State University of New York, continental masses were more numerous but hundred times smaller in Archaean. Because heat generation rates were three times higher than now, there was greater ridge activity. The lenticular style of greenstone belts was characteristic signature of rapid horizontal movements and consequent arc and microcontinental collision.

R. M. SHACKLETON of Leeds University, who had been to India earlier, devoted his talk to a description of shallow and deep exposures of Archaean crust in India and Africa. In parts of Karnataka, he said, he saw a gradation from amphibolite to granulite facies, while in other parts presence of mylonite zones pointed to uplift of granulites many km relative to the greenschist. He envisaged uplift of the order of 25 to 30 km. He proposed two models to account for the observed distribution of granulites and low grade metamorphic rocks: (1) the granulite facies metamorphism and the emplacement of the anorthosite complexes were of the same date as the orogenic belts, and (2) granulites were older pre-orogenic rocks which represented uplifted samples of sub-Conrad lower crust which also underlie the low grade rocks exposed on the cratons. According to him where the granulites outcrop, the crust was thickened perhaps to twice the thickness normal at that time and was eroded following isostatic recovery, until the thickness was restored to normal. Such crustal thickening pointed to a substantial crustal shortening across southern India. The presence of shallow water current-bedded orthoquartzites at intervals throughout the volcanic succession in Karnataka according to Shackleton was evidence that the greenstone belts accumulated on continental crust and that the sea remained shallow as subaerial basalts and sediments accumulated. He considered the matrix of Kaldurga conglomerates as a tillite.

EVOLUTION OF THE ARCHAEAN CRUST

The fifth day was devoted to the consideration of the nature and evolution of the Archaean crust. A. M. Goodwin of the University of Toronto, Canada, who initiated the discussion, projected a number of slides to show the asymmetric crescentic distribution of continental crust. By analogy with the moon this apparent crustal asymmetry was attributed to giant meteorite impact. He postulated that Earth experienced mega impacting synchronous with and greatly similar in style and pattern to giant impacts causing lunar maria. Three consecutive partly overlapping building stages of continents were proposed (1) Nucleal stage (mainly Archaean time) involving development of numerous small island or proto-continents (2) Craton or Platform stage (mainly Proterozoic time) by segregation of the sialic nuclei to form stable shield with granulite in deeper central parts, and (3) Extensional stage (mainly Phanerozoic time) featuring periodic fragmentation, drifting and regrouping of continental fragments by the process of modern plate tectonics.

R. St. J. Lambert of the University of Alberta, Canada, conceived of the Earth's history as being divisible into the following stages:

1. 3800 m.y. *Chaotic phase*, very high heat generation, 'impact' tectonics.
2. 3800-(?) 3300 m.y. *Anarchic phase*, highly mobile upper mantle and crust, locally differentiated.
3. (?) 3300–2600 m.y. *Archaean proper*: thick basalt crust, slow stabilisation; thin lithosphere or scum tectonics.
4. 2600–600 m.y. (?1000 m.y.) Proterozoic; thick basalt crust with substantial continents, whole lithosphere mobile with respect to mantle; single-plate tectonics with intermittent stability.
5. <600 m.y. (?<1000 m.y.): Multi-plate tectonics as at present.

Geochronology and isotope geology of the Early Archaean was summarised by S. Moorbath from Oxford. According to him by about 3800 m.y. ago surface cooling and geochemical differentiation of the Earth had progressed sufficiently to produce continental crust of unknown extent and thickness, but comprising a wide variety of igneous, sedimentary and metamorphic rocks, mostly characteristic of the well known Archaean bimodal 'granite-greenstone' association. Isua region of West Greenland was the best preserved and geochronologically documented crustal segment of this age. Rocks in the age range *ca.*2600–2900 m.y. occurred in all continents. It was possible that about 50 per cent in area of the present continental crust already existed at that time, with a thickness closely comparable with modern continental crust.

Moorbath felt that studies of initial strontium and lead isotope ratios of Archaean granite gneisses and greenstone assemblages demonstrated that they could not have originated by reworking or partial melting of older sialic crust, but were most likely derived from upper mantle source regions.

EVOLUTION OF ATMOSPHERE AND HYDROSPHERE

The last two days of the conference were appropriately earmarked by the organisers for a consideration of the evolution of the atmosphere and hydrosphere and of life on Earth. These proved to be most informative giving glimpses of current research being carried out on these subjects.

M. SCHIDLOWSKI from Max Plank Institute of W. Germany spoke about the Archaean atmosphere and evolution of the terrestrial oxygen budget. Of the main constituents of the present atmosphere, nitrogen was thought to have accumulated through time. Carbon dioxide was considered fixed at modern levels. The evolution of atmosphere therefore was mainly concerned with the build up of the present oxygen pressure. The reason adduced for the build up of oxygen was the photochemical effect (either organic or inorganic). The equation $CO_2 + H_2O \rightarrow CH_2O + O_2$ represented the photosynthetic pedigree of the oxygen budget.

Discussion on this paper brought out the fact that the iron formations of the Archaean were mostly quartz-magnetite rocks while haematite rich jaspers and red beds appeared between 2800-2000 m.y. They were largely the result of the scavenging action of life.

The evolution of the Archaean ocean was the subject handled by H. D. HOLLAND from Harvard University, USA. According to him the chemistry of the earliest ocean was quite unknown. The oldest unmetamorphosed rocks indicated that weathering was already intense more than 3000 m.y. ago, that atmospheric CO_2 was at least as abundant as now and that the oceans were saturated with respect to calcite and probably with respect to amorphous SiO_2. As regards salinity of the oceans Holland thought the presence of gypsum and halite casts in Proterozoic rocks indicated that the chemistry of the oceans 2000 to 3000 m.y. ago did not differ greatly from that of present day. The oxidation state of the ocean atmosphere system prior to 2000 m.y. was considerably lower than now. This was attributed to the progressive decrease in volcanism during geologic time.

M. M. KIMBERLEY and E. DIMROTH from Canada did not agree with the hypothesis which insisted on a reducing ocean as a source of iron formation. According to them the cherty iron formations were formed by early diagenetic replacement of aragonitic sediment. Similarity of sedimentary tectonics of iron formation and limestone, massive evidence for intense diagenetic alteration in iron formations and in particular for precipitation, were put forward as evidences for subscribing to the above hypothesis.

What was one of the best lectures in the series, a model in scientific presentation, was that of J. W. SCHOPF of the University of California. His was a critical appraisal of the antiquity and evolution of Archaean life. The evidences for the existence of Archaean life were evaluated under three main headings:—consistent, suggestive and compelling. The evidences of Archaean life were considered meagre and difficult to interpret. Some of the early micropalaeontological and organic geochemical interpretations were probably in error. There were no microfilaments in the

Archaean and many of the microspheroids had proved to be non-biologic in origin. Schopf therefore pleaded for a reevaluation of Archaean fossils.

The Precambrian was divided by him into two major portions: the *Archaean* dating from the time of deposition of the oldest known sedimentary rocks (3760 m.y.) to the first appearance of widespread cratonal, platform type deposits (2500 m.y.), and the *Proterozoic*, extending from the close of the Archaean to the first appearance of widespread invertebrate metazoans that marked the beginning of the Phanerozoic.

M. D. MUIR of the Imperial College, London gave an account of the microfossils discovered in the Onverwacht Group of S. Africa. Organic matter in black cherts occurred in three forms: 1) as amorphous flat lying laminations 2) as structurally preserved microfossils showing a variety of forms, and 3) as some coccoid microfossils forming small domical stromatolites. According to Muir, evidence from the microfossils and the $\delta^{13}C$ ratios supported the conclusion that most of the structures encountered are genuine microfossils.

The discussion on the subject was brought to a close by Preston Cloud. He illustrated by means of well chosen slides how difficult it is to interpret microstructures from Archaean as organic.

With the concluding remarks and thanks giving by Professor Sutton, the conference came to a close on the afternoon of 11th April.

CONCLUSION

The conference was a resounding success bringing together probably for the first time a large number of active workers on the Precambrian from different parts of the world and exposing them to the new thinking in solving current problems. One could not but recognise the remarkable similarities and close parallels in the oldest rocks from different regions of the world. A good amount of interest was shown in the study of the Indian Precambrian. The relation between the low grade and high grade regions was nowhere better exemplified than in India. Windley advocated cooperative projects with Indian scientists for carrying out trace element and isotopic studies. Cooperative projects similar to lunar studies were suggested whereby a number of laboratories could study Indian material.

The Indian shield does hold a preeminent place in the shield areas of the world and a detailed study of its geology, structure and geochemistry is sure to provide information of great value to all those engaged in understanding the Early History of the Earth. The time appears most opportune to initiate such studies with vigour, taking help wherever necessary from organisations outside the country who have the equipment and resources to carry out such studies and who have expressed willingness to enter into collaboration arrangements.

'Every question answered raises ten new ones and only new observations and more refined techniques coupled with man's ingenuity will permit progress.'

In conclusion I wish to express my thanks to Dr. A. Y. Glikson and Prof. B. F. Windley for their invitation to attend the Conference and for providing me with a unique opportunity of enlarging my vision and sharing the knowledge with my fellow scientists in India.

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