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# The Role of the Atmosphere and the Hydrosphere in Crustal Evolution [and Discussion]

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## The role of the atmosphere and the hydrosphere in crustal evolution

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The physical and chemical properties of the Earth's crust have been shaped by the interaction of endogenic and exogenic processes during the course of history. The nature of this interaction between 4.6 and 3.8 Ga B.P. is still uncertain. Since then the nature of erosional processes, of transport, deposition, and the cycling of sea water through the ocean crust, has remained reasonably constant. However, variations in the nature and in the intensity of these processes due to changes in the endogenic cycle, due to biological evolution and probably due to variations in the input of solar energy have left easily discernible marks in the nature of the crust.

### INTRODUCTION

It is a truism that the present state of the Earth's crust has been shaped by the interplay of endogenic and exogenic processes. The endogenic processes have been driven largely by the original heat content of the Earth and by heat generated in the decay of short- and long-lived radioisotopes. The exogenic processes have been driven largely by solar energy. The two sources of energy differ greatly in their intensity. The flux of solar energy exceeds the flux of internal energy by about a factor of  $10^4$ . Surficial processes therefore tend to be much more rapid and to owe very little of this rapidity to the flow of heat from the Earth's interior. This imbalance between the two energy sources must have existed during all but the very earliest period of Earth history, when surface temperatures could have reached several thousand degrees centigrade.

In spite of the enormous difference between the rate at which continents move and the rate at which air and water masses normally flow, the slow horizontal and vertical motions of continental masses do yield mountain ranges and ocean deeps, features that can persist for periods of  $10^7$  a after cessation of crustal movement. When the elevation of a continent is more than a few hundred metres above sea level, the effects of mechanical erosion tend to overshadow those of chemical weathering, and it is likely that this has been true for much of geological time. Mechanical and chemical processes have both played important roles in the evolution of the Earth's crust. The best estimate for the present rate of removal of material from the continents is approximately  $2 \times 10^{16}$  g/a (Holeman 1968). At this rate the entire continental crust could be eroded in about 1 Ga. During the course of Earth history the crust could therefore have been cycled through the erosional process about four times. This calculation is, however, somewhat misleading. At present the stand of the continents is unusually high above sea level. The average erosion rate may therefore be somewhat more modest than today's rate. Furthermore, the upper parts of the continental crust are much more vulnerable to repeated erosion and re-sedimentation than are the lower parts of the crust. Garrels & Mackenzie (1971) have suggested that most sedimentary rocks have a mean half life for destruction by erosion of only a few hundred million years. Nevertheless, many

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of the rock units in the deeper parts of the continental crust show evidence of having passed through at least one cycle of erosion, transport and deposition, and it is abundantly clear that these processes have deeply influenced the evolution of the Earth's crust.

Weathering, transport, and deposition can act to homogenize differences in the physical and chemical properties of the several parts of a mountain range. They can also serve to separate initially homogeneous terrains into heterogeneous packets of sediments. Many of our most valuable natural resources have been produced by physical and chemical sorting accompanying weathering, transport and sedimentation. Aluminium ores are products of weathering, and most major ores of iron, potash, halite, gypsum, phosphate and lime, as well as many large uranium ore deposits and all commercial accumulations of coal, oil and natural gas owe their origin to the concentrating power of processes related to sedimentation.

All this has been known for many years. During the past two decades the circulation of meteoric water through continental rocks near recent intrusives has been shown to play an important role in the formation of many hydrothermal ore deposits. Even more recently it has been shown that the circulation of sea water through mid-ocean ridges is probably a major geological process, one that is almost certainly responsible for significant changes in the chemistry of the oceanic crust and in the chemistry of sedimentary rocks, and probably for the formation of massive volcanogenic sulphide deposits.

#### EFFECTS OF THE ATMOSPHERE AND HYDROSPHERE DURING THE LAST 3.8 Ga

The interaction of the crust with the atmosphere and the hydrogen has been reasonably constant during the past 3.8 Ga. However, there have clearly been variations with time, and it is very likely that more variations remain to be discovered. The driving force for endogenic processes has decreased significantly during Earth history. The rate of heat production has decreased by approximately a factor of 4 during the past 3.8 Ga. It is not yet clear just how this decrease has affected the mechanisms of heat loss, but the difference in tectonic style between Archaean and Proterozoic provinces is well established and presumably reflects differences in patterns of mantle convection during these two periods of Earth history.

The driving forces for exogenic processes have also varied with time. If current theories of stellar evolution are valid, the intensity of solar radiation reaching the Earth has increased by about 25 % during the past 3.8 Ga. It is not clear whether this increase has been quite steady, or whether notable excursions in the solar constant have taken place. The causes of the repeated periods of glaciation during the past 2.5 Ga are not really understood, but it is sure that the interaction of the crust with the atmosphere and hydrosphere during glacial periods differs significantly from their interaction during non-glacial periods.

The nature of exogenic processes has also been affected by changes in the biota. The evolution of life itself, the invention of the photosynthetic production of free oxygen, the development of animals, the evolution of siliceous and carbonate tests, and the development of the higher land plants have all left their mark in the record of the interaction of the atmosphere and of the hydrosphere with the crust.

The oldest dated rocks, those at Isua in west Greenland, are some 3.8 Ga old (Moorbath *et al.* 1973). They contain a large deposit of banded iron formation (Appel 1979), which could only have been deposited in water, and a metapelite unit whose chemistry is very similar to

metapelites in younger rocks (Allaart 1976). Its high  $\text{Al}_2\text{O}_3$  content and its depletion in  $\text{CaO}$ , except where  $\text{CaO}$  is balanced by bound  $\text{CO}_2$ , can only mean that chemical weathering was active during Isua time. Enough  $\text{CO}_2$  must have been present in the atmosphere and in surface waters to decompose silicate minerals, and  $\text{CaCO}_3$  was apparently being deposited in the Isua basin (Holland 1976). Nothing is known about the distribution of water on the face of the globe during Isua time, but the evidence at Isua is certainly consistent with an Earth in which hydration and carbonation reactions were already proceeding apace. Little can be said about oxidation reactions. The iron oxide in the Isua iron formation is dominantly magnetite (Appel 1979), but the degree of metamorphism of the Isua metasediments is so high that post-depositional reduction from haematite or goethite to magnetite cannot be ruled out.

Carbonation reactions have remained similar since Isua time. However, the last 3.8 Ga can be divided roughly into three parts on the basis of the carbonates contained in sedimentary rocks. Archaean carbonates appear to be mainly limestones (Veizer 1979); Proterozoic and Palaeozoic carbonates contain a great deal of dolomite; Mesozoic and Cainozoic carbonates are again mainly limestones (see, for instance, Holland 1978). Such differences could be due to a variety of causes; these include variations in post-depositional dolomitization and differences in the balance between  $\text{CO}_2$  demand during weathering and  $\text{CO}_2$  supply by volcanism (Holland 1976). At present it seems most likely that the decrease in the proportion of dolomite during the past 200 Ma is related to a decrease in the areal extent of carbonate platforms with sabkha environment. At present much of the river-borne magnesium that enters the oceans is removed from sea water by cycling through mid-ocean ridges. During the reaction of sea water with basalt, magnesium is removed from sea water, largely in exchange for calcium from basalt; this reaction proceeds at all temperatures above, perhaps,  $10^\circ\text{C}$ . It has been observed in interstitial waters above the basalt–sediment interface, as well as in warm and hot springs where sea water has reacted with the oceanic crust (Edmond *et al.* 1979*a, b*). The total magnesium loss from sea water is therefore a rough measure of the total volume of sea water cycling through the oceanic crust. Estimates of this rate based on the heat flow deficit in the vicinity of mid-ocean ridges suggest that about  $10^{11}\text{ m}^3$  of sea water cycles annually through the oceanic crust, and that the entire ocean cycles through the oceanic crust in approximately 15 Ma.

During the Proterozoic and Palaeozoic eras much of the river-borne magnesium was apparently removed from sea water by penecontemporaneous dolomitization of calcium carbonate. The mass balance of magnesium in the oceans was probably preserved by a correspondingly smaller rate of magnesium loss to mid-ocean ridges. This smaller loss rate could have been due to a smaller rate of seawater cycling or to a lower concentration of magnesium in sea water. The second alternative is the more likely (see below).

The behaviour of several other elements also suggests that seawater cycling is and has been an important geological process. An excess of lithium in sedimentary rocks was observed by Wedepohl (1968) and has been confirmed by Styr (1977). This excess is readily explained by the cycling of about  $20\text{ Pg}\dagger$  of sea water per year at a temperature in excess of *ca.*  $150^\circ\text{C}$  through the oceanic crust. A similar excess of zinc in sedimentary rocks was reported by Brehler & Wedepohl (1978), and it seems likely, but as yet unproven, that high-temperature cycling also accounts for this excess.

†  $1\text{ Pg}$  (petagram) =  $10^{15}\text{ g}$ .

There is no definite time trend in the lithium content of sedimentary rocks. This suggests that either the rate of seawater cycling through mid-ocean ridges has been reasonably constant during much of geological time or that variations in this rate have been coupled to the rate of erosion via the intensity of tectonic and volcanic processes.

The role of living organisms during Isua time is still obscure. A few graphitic lenses occur in the Isua supracrustals (J. Boak, personal communication 1979). It is likely that these are the metamorphic equivalents of sediments that contained the remains of microorganisms. The sedimentary rocks of the Barberton Mountain area are approximately 3.4 Ga old, are nearly unmetamorphosed, and contain rather convincing morphologic evidence for the presence of fossil microorganisms (Knoll & Barghoorn 1977). Whether these organisms were bacteria or blue-green algae is not clear, but the evidence for the presence of some atmospheric oxygen at the time is strong, and is consistent with the presence of oxygen producing microorganisms more than 3 Ga ago.

The precise level of atmospheric oxygen more than 2 Ga ago is still hotly debated. Uraninite in the very large uranium deposits at Blind River, Ontario, and in the Witwatersrand and Dominion Reef series of South Africa is almost certainly detrital (see, for instance, Smith & Minter 1980), and it is at present difficult to understand the resistance of this mineral to oxidative weathering if the oxygen content of the atmosphere during the formation of these deposits was more than a small percentage of its present level (Grandstaff 1976). The occurrence of detrital pyrite in the same sediments reinforces this observation, and the formation, between 2.5 and 1.8 Ga ago, of the enormous banded iron formations of the type found at Lake Superior can be understood much more readily if the oxygen content of the atmosphere was considerably lower than at present (Holland 1973). Just why the oxygen content of the atmosphere was apparently lower than today is not yet clear. A variety of reasonable explanations can be advanced, but so little is known about the biota and the Earth's palaeogeography in the Archaean and early Proterozoic eras that these explanations are little more than conjectures.

The extensive silica deposits in the banded iron formations of the type found at Lake Superior are presumably related to a higher concentration of dissolved silica in the Precambrian than in the present oceans. The silica concentration in the Precambrian oceans is impossible to gauge precisely, but it is most likely that the present, low concentration of dissolved silica was attained during the Phanerozoic era, after the development of silica-secreting organisms.

The deposition of calcium carbonate has probably been less affected by evolutionary processes than has the deposition of silica. The inorganic precipitation of  $\text{CaCO}_3$  requires only modest degrees of supersaturation with respect to this compound, and apparently occurs even today in warm areas where some evaporative concentration of sea water has taken place.

Extreme evaporative concentration of sea water leads to the formation of marine evaporites. These are well represented in the Phanerozoic record but have not been found in sedimentary rocks more than 1 Ga old. Casts of gypsum and halite are, however, common in older rocks, and indicate that evaporites were once present but have been removed by selective dissolution. The presence of thick evaporites in Phanerozoic sediments and their absence in nearly all Precambrian sediments is of some importance in determining differences in their mechanical behaviour during structural deformation. Décollements, salt domes and salt diapirs are features of many young terrains, but they are virtually ruled out where Precambrian sediments have recently been structurally deformed.



SOME SPECULATIONS REGARDING THE FIRST  
0.8 Ga OF EARTH HISTORY

Before finishing, I would like to comment briefly on the possible effects of the atmosphere and hydrosphere on the Earth's crust during the first 800 Ma of Earth history. If J. Hutton had visited Isua, he would surely have been confirmed in his belief that these oldest of terrestrial rocks show 'no vestige of a beginning', and yet we are convinced that only about 800 Ma separate the deposition of these rocks from the beginnings of the Earth. The pre-Isua Earth must have been a very different and, in some ways, a much more exciting place than the Earth today. If lunar history is a guide to our own, the Earth was extremely hot during and shortly after accretion. It is hard to see how a gaseous envelope could fail to have developed around such a growing planet. The distribution of volatiles between the primordial atmosphere and lava oceans can be calculated with some certainty, but the release of these volatiles from the mantle after the formation of a stable crust is difficult to model in a convincing fashion. It seems likely that life began during the first few hundred million years of Earth history, and it is still much easier to propose a logical sequence of steps leading to the development of the first replicating organisms if the atmosphere-ocean system is assumed to have been chemically reducing rather than mildly oxidizing. However, the stability of a reducing atmosphere-ocean system still remains to be studied in the required detail. Even if these studies show that the earliest atmosphere-ocean system could have been modestly or highly reducing, proof of the existence of such an atmosphere-ocean system must surely await confirmation in the chemistry of rocks from this period of Earth history. A search for such rocks is eminently worthwhile, even if its success if anything but assured.

SUMMARY AND CONCLUSIONS

Let me now draw together the four major points that I have tried to make regarding the role of the atmosphere and the hydrosphere in crustal evolution.

(i) An atmosphere and a hydrosphere have been present on Earth since at least 3.8 Ga ago.

(ii) Erosion, transport and deposition, together with a variety of endogenic processes, have shaped the chemical and physical properties of the Earth's crust.

(iii) The operation of exogenic processes has been rather uniform during the past 3.8 Ga. However, sedimentary rocks do record changes in the interaction of the atmosphere and hydrosphere with the crust. Chief among these are changes related to fluctuations in the intensity and patterns of tectonism and magmatism, to the evolution of living organisms, and possibly to variations in the solar constant.

(iv) The atmosphere-ocean-crust system must have been quite different during the earliest history of the Earth. In the absence of a rock record from the first 0.8 Ga of Earth history, reconstructions of the interaction between the atmosphere, hydrosphere and crust during this period are quite speculative. However, it is still true that the development of life is more easily explained if the atmosphere-ocean system is considered to have been reasonably reducing during part of the period between 4.6 and 3.8 Ga ago.

## REFERENCES (Holland)

- Allaart, J. H. 1976 In *The early history of the Earth* (ed. B. F. Windley), pp. 177–189. London: John Wiley.
- Appel, P. W. U. 1979 *Econ. Geol.* **74**, 45–52.
- Brehler, B. & Wedepohl, K. H. 1978 In *Handbook of geochemistry*, vol. 2, pt 3 (ed. K. H. Wedepohl), ch. 30. Berlin, Heidelberg and New York: Springer-Verlag.
- Edmond, J. M., Measures, C., McDuff, R. E., Chan, L. H., Collier, R., Grant, B., Gordon, L. I. & Corliss, J. B. 1979a *Earth planet. Sci. Lett.* **46**, 1–18.
- Edmond, J. M., Measures, C., Mangum, B., Grant, B., Sclater, F. R., Collier, R., Hudson, A., Gordon, L. I. & Corliss, J. B. 1979b *Earth planet. Sci. Lett.* **49**, 19–30.
- Garrels, R. M. & Mackenzie, F. T. 1971 *Evolution of sedimentary rocks*. New York: W. W. Norton.
- Grandstaff, D. E. 1976 *Econ. Geol.* **71**, 1493–1506.
- Holeman, J. N. 1968 *Water Resour. Res.* **4**, 737–747.
- Holland, H. D. 1973 *Econ. Geol.* **68**, 1169–1172.
- Holland, H. D. 1976 In *The early history of the Earth* (ed. B. F. Windley), pp. 559–567. London: John Wiley.
- Holland, H. D. 1978 *The chemistry of the atmosphere and oceans*. New York: Wiley-Interscience.
- Knoll, A. H. & Barghoorn, E. S. 1977 *Science, N.Y.* **198**, 396–398.
- Moorbath, S., Allaart, J. H., Bridgewater, D. & McGregor, V. R. 1977 *Nature, Lond.* **270**, 43–45.
- Smith, N. D. & Minter, W. E. L. 1980 *Econ. Geol.* **75**, 1–14.
- Styrt, M. 1977 B.Sc., Harvard University.
- Veizer, J. 1979 In *Yb. Res. School Earth Sci., Aust. natn. Univ., Canberra*.
- Wedepohl, K. H. 1967 In *Origin and distribution of the elements* (ed. L. H. Ahrens), pp. 999–1016. Oxford: Pergamon Press.

*Discussion*

SIR KINGSLEY DUNHAM, F.R.S. (*Charleycroft, Quarryheads Lane, Durham DH1 3DY, U.K.*). I invite Professor Holland to enlarge on the question of the deposition of the pre-Cambrian banded ironstone formations, surely the greatest repositories of concentrated oxides of iron in the continental crust under oxygen-deficient atmospheric conditions.

H. D. HOLLAND. The origin of the pre-Cambrian banded ironstone formations is still somewhat obscure. Their origin can be understood most easily if oxygen-deficient atmospheric conditions prevailed more than 1.9 Ga ago. If the oxygen content of the atmosphere before 1.9 Ga B.P. was lower by one or two orders of magnitude than it is today, much of the deeper part of the oceans would probably have been mildly reducing. The concentration of dissolved iron in these waters could then have been as high as several milligrams per kilogram. Upwelling of such deep waters could have led to the precipitation of a variety of iron minerals and the formation of banded ironstones.