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Orogeny and Geochemistry

By *Tom. F. W. Barth* (Oslo)

Geological forces exist in the interior of the earth. They are physical and chemical forces, and not until the geologist learned to apply the exact laws of physics and chemistry to geological phenomena, did he meet with any success in the interpretation of these forces. We are still in the very beginning of what I may call interpretative geology.

The geologist can tell us much about the mechanism and the results of erosion and sedimentation, but he knows little about the ultimate causes. Why do mountains rise? Why do synclinal areas sink?

These fundamental queries have been broached by geophysicists and geochemists: Three chief theories have been advanced:

a) Adaptation of the solid crust to the contraction of the cooling interior.
b) Folding and drag due to the continental drift.
c) Shear stresses associated with convective currents below the crust.
d) A fourth alternative, which never has been specifically discussed before, is the effect of degassing of the earth.

In order to make a choice between these rival theories, one has to go far back into the history of the earth. It is readily seen that phenomena like a cooling interior, internal convections, or degassing, are intimately connected with cosmogony: with the conditions that obtained in the young earth and with its earliest development.

Research in geology, geophysics, and astrophysics has shown that the earth is not homogeneous, but made up of concentric shells: There is a central iron core, apparently liquid; with a radius rather more than half that of the earth as a whole and with a sharp boundary. It is surrounded by concentric layers of successively lighter silicates, until, at the surface of the solid crust, we pass into the hydrosphere and, eventually, into the atmosphere which constitutes the outermost tenuous layer that is wrapped around the whole earth.

Our first query is: Was the earth created as a concentric ball with a ready-made iron core followed by consecutive shells of silicates and finally by water and air? Or was it made as a more homogeneous object in which the concentric structure gradually developed through redistribution of the original matter?

For the purpose of this paper we shall choose to believe that the earth grew from a primeval tenuous solar nebula through gradual emergence by accretion. (Theory of WEIZSÄCKER and others).

It is generally believed that during the early accumulation of gas and cosmic dust, all iron was present as oxide. The cosmic abundance of oxygen is much higher than that of iron (in terms of atoms there is about 30 times as

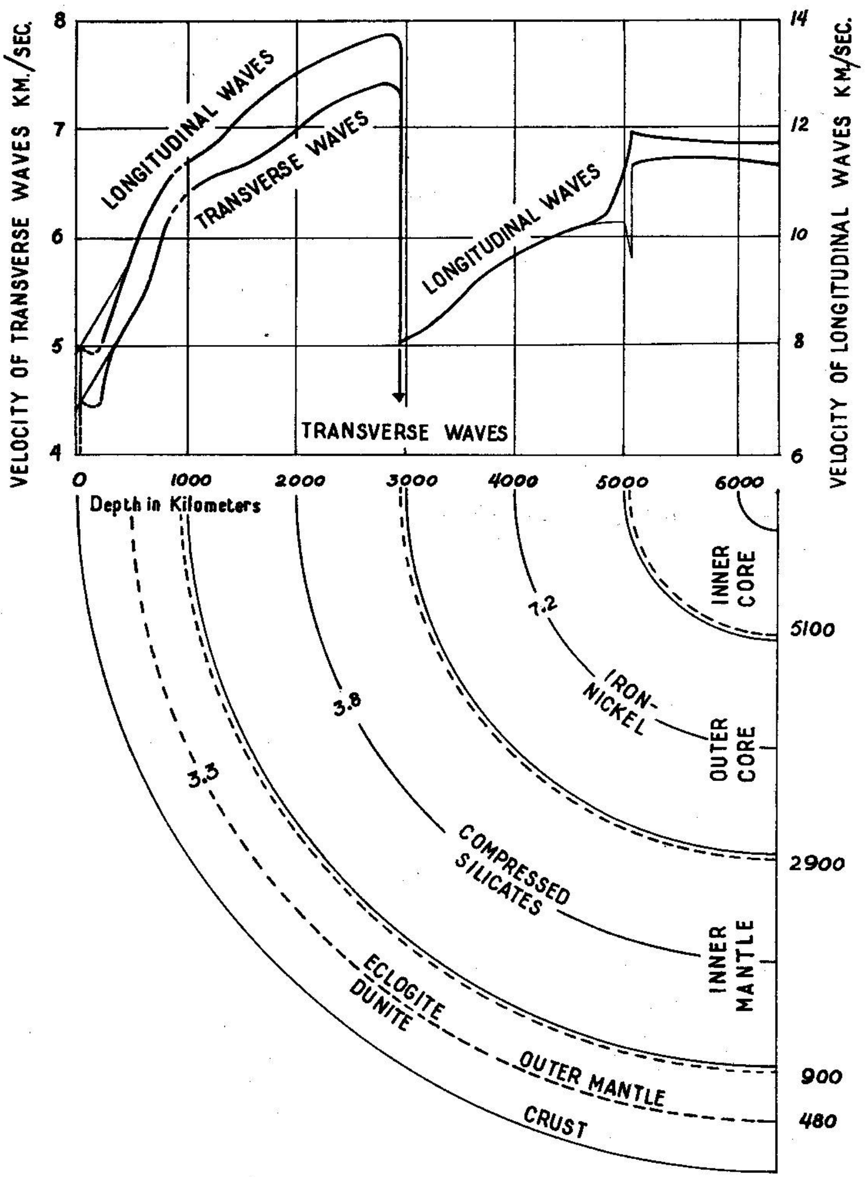

Fig. 1. Upper half: Velocity of propagation of earthquake waves from the surface to the centre of the earth. Lower half: The concentric structure of the earth. The discontinuity between the silicate mantle and the iron-nickel core is indicated by the discontinuity in the wave velocities.

much oxygen), therefore iron oxides and iron silicates, but not metallic iron, were the first ferriferous constituents of the earth. It is reasonable to believe that not until the planet condensed, the temperature thereby rising and the "squeeze" on the oxygens increasing, did reduction of the iron oxides occur and the loss of oxygen begin.

It is possible to investigate into the probability of these assumptions by comparing the earth with the other planets. In particular the moon and Mars constitute convenient objects of comparison. This comparison takes us into the realm of celestial mechanics. But it is sufficient for the present purpose to discuss, in a non-mathematical way, the data of Table 1.

Table 1. *Comparison between the Earth, Mars, and the Moon* (most data after H. C. UREY).

	Moon	Mars	Earth
Mass	0.01	0.11	1.00
Gravity	0.17	0.40	1.00
Reduced Density	3.3	4.0	4.4
Oblateness, ϵ	(x)	1/192	1/297
ϵ/Φ	(x)	1.20	0.98
Structure	uniform	uniform	concentric
Hydrosphere	none	none	present
Atmosphere	none	A? (very thin)	O_2, N_2, A, etc.
Fold-Mountains	none	?	present

The "reduced density" is the density that would have obtained without gravitational compression. The oblateness, ϵ, is the difference between the equatorial and polar radii divided by the mean radius; it results from a combination of the centrifugal force at equator and the gravitational force of the planet, as expressed by the quantity, Φ, which is the ratio of the centrifugal force to the gravitational force. The value of ϵ/Φ depends upon the internal structure of the planet. It should be 1.25 for a planet of uniform density with Mars' rotation (but even if Mars were chemically homogeneous, gravitational compression should slightly decrease this value). It should be 1.02 for Mars if it has an iron core similar to that of the earth. The observed value for Mars is 1.20 with an uncertainty of ± 0.04. This value excludes the existence of an iron core and indicates strongly that Mars is a planet of uniform chemical composition.

The figure of the moon is irregular, with a probable "bulge" in the direction of the earth, and does not correspond to equilibrium conditions. It indicates that isostatic equilibrium does not exist, and that the moon is a solid, relatively cool body. The low mean density excludes an iron core, and indicates a rather uniform chemical composition.

Thus the evidence is strong that neither Mars nor the moon was made with an iron core and concentric structures. The inference is that the earth likewise was created without iron core and concentric structure, but that these features slowly developed through geochemical migrations. The opposite way of evolution is impossible. The concentric structure with the heavier matter concentrated in the core corresponds to thermodynamical equilibrium. The evolution must therefore have been from a homogeneous body toward a concentric body not the other way.

In a recent paper Leo Brewer has examined in detail the equilibrium distribution of elements in a gravitational field. If we disregard the chemical forces the relation is simple: the heaviest matter will concentrate in the core, and toward the crust concentric shells of successively lighter material will form. This simple arrangement will be modified for certain elements by the chemical bonding energies. But it does not alter the fact that if one starts with a homogeneous earth, a vertical transport of the various components will take place with some rising and some sinking in an attempt to attain the equilibrium conditions required in the gravitational field. Many compounds, e. g. iron oxide, will not be stable at great depths — a simple calculation shows that somewhere around 1000 km (depending upon the temperature) all oxides of iron will become unstable, the chemical bonds will break and iron will concentrate at lower depths, while oxygen will concentrate in the opposite direction.

All mechanisms will tend to produce the equilibrium conditions which must be the final state of the earth if sufficient time is allowed.

The Degassing of the Earth

For the purpose of the present paper it is particularly interesting to discuss the migration of the very light elements and compounds that were present in the original homogeneous earth.

Let us turn to the hydrosphere and the atmosphere. They are parts of the concentric structure of the earth — they are the outermost earth-shells of the lowest density. Several lines of evidence indicate that they, too, are of secondary origin and slowly developed with geological time by degassing of the earth.

The most convincing evidence is here geochemical in nature: The noble gases — xenon, krypton, argon and neon — are from 10^6 to 10^{10} times less abundant on the earth than in the atmosphere of the stars, the lighter gases showing the greater discrepancies, indicating that they have been lost at a rate directly related to the molecular weight of the species.

Table 2. *Ratio of Rare Gases to Silicon* (after HARRISON BROWN)

	Cosmos	Earth	Cosmos/Earth
Ne	4×10^0	4×10^{-10}	1×10^{10}
A	1×10^{-1}	1×10^{-7}	1×10^{8} 1)
Kr	2×10^{-4}	2×10^{-11}	1×10^{7}
X	2×10^{-6}	2×10^{-12}	1×10^{6}

Other compounds and elements in the gaseous state and of the same molecular weights — water, nitrogen, carbon oxides, and oxygen — would have been lost in the same proportion if they too had existed as gases when

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1) One of the argon isotopes, A^{40}, is radiogenically formed from K^{40} and its terrestrial abundance is therefore out of proportion to its cosmic abundance. In the calculation of this ratio the radiogenic A^{40} has been neglected.

the earth was formed. The fact that water, nitrogen, etc. are present in considerable quantities on the earth today is evidence that they were not retained as gas, but retained chemically or occluded in rocks during the earth's formation.

During all subsequent time, these elements have been supplied to the atmosphere and ocean gradually through degassing of the crust and of the interior of the earth. I see no escape from the conclusion that the concentric earth-shells have grown gradually. And if we admit this, the degassing follows as a necessary accompaniment. Thus I advance the dictum: No concentric shells, no degassing, strong concentric layering, strong degassing.

The geological degassing of a shell of igneous rocks, less than 40 km thick, would account for the entire volume of water in the present ocean.

Let us assume that the primitive rocks through degassing during all geologic time have lost 3% H_2O.

The present ocean contains 1.46×10^{24} g H_2O.

The upper crust, 33 km deep, representing a mass of 49×10^{24} g would yield 1.46×10^{24} g H_2O, i.e. exactly the mass of the present ocean.

But the degassing undoubtedly has worked deeper. In order to account for the large quantity of argon^{40} in the present atmosphere, Kulp has been forced to assume that a very deep degassing — possibly right down to the iron core — has been going on throughout geologic time. — A^{40}, being radiogenically derived from K^{40}, is several hundred times too abundant in the atmosphere compared to A^{36} based on their cosmic abundances.

The degassing of water may be assumed to have taken place at least as deep as the maximum depth to which deep-focus earthquakes are recorded. The total mass of this subcrustal matter down to 700 km is about 1040×10^{24} g, which, upon degassing, would yield 30×10^{24} g H_2O, or more than 20 times as much water as exists today in the ocean.

Other volatile substances in addition to water are likewise subject to degassing. Much chlorine must have been expelled from the subcrustal matter; a large fraction of it is now stored in sea-water. The order of magnitude of the process is shown by the following data:

Total chlorine in the ocean is about 266×10^{20} g. The generally accepted figure for the concentration of chlorine in massive rocks is 314 parts per millon. If this concentration is representative for the deeper crust we find that an earth-shell, 57 km thick, contains as much chlorine as the ocean.

The escape of water, chlorine, and of other common "volatile" compounds from the interior of the earth is a simple process which for obvious reasons must take place. Likewise oxygen will escape; indeed, the necessary thermodynamical data are at hand to calculate the depth at which oxygen is squeezed out of the lattice of iron oxides.

It is an interesting fact that, today, there is not enough oxygen to saturate the iron in the earth. This can be elucidated by a simple computation. The mass of the atmosphere is approximately 51×10^{20} g, and the mass of free oxygen in the atmosphere is therefore only 11.5×10^{20} g. The mass of free iron in the core is about 1.3×10^{27} g, or a million times more than the weight of free oxygen. If this enormous mass of iron had been available for oxidation, the atmosphere would have been depleted of oxygen in a short time. But fortunately for us who live on this earth the iron core cannot become oxidized, and the air will continue to sustain life.

Let us summarize the processes of degassing: In the beginning there was no iron core, the earth was more homogeneous than today. But slowly did the heavier compounds sink into the core and the lighter compounds rise to the crust. And as the iron oxides sank, a gradual reduction took place, oxygen slowly percolating upward. Perhaps this process was brought near completion before the beginning of the geologic history. If so, most of the degassing of oxygen was over at a very early stage. But like all such processes, the degassing must be asymptotic in time, and therefore some oxygen — although the amount may be very small as compared with the mass of iron — still is present at great depths, and even in the core of the earth.

Let us now turn to the various theories advanced to explain the orogenic movements, and let us analyze them in light of the new cosmogonic knowledge:

1. The theory of contraction on cooling is fraught with many difficulties. The most serious objection is probably that it is by no means certain that the earth has cooled. One rather has to assume an approximate balance between the rate of cooling and the rate at which heat is generated; if anything, the earth would seem to heat up, rather than to cool.
2. The theory of continental drift has so far received no satisfactory explanation.
3. The theory of convection currents assumes, of course, that the currents are driven by atomic heat, possibly more directly by the difference in temperature between sub-oceanic and sub-continental material.
4. The degassing is associated with a general and large — scale radial diffusion — a disperse flow of atoms and ions leading to geochemical adjustments in the composition of the earth's shells; this flow is aided by "entrapped solar gases (hydrogen)" (VAN BEMMELEN)[2]. Thus energy and water, together with other volatiles, will leave the depths of the earth and percolate upward.

And the degassing thus means a shrinking of the earth — enormous quantities of volatiles must have been expelled during the geologic ages. The effect on the crust would be folding, thrusting, and, generally, mountain building. It is a significant fact that no folded mountains exist in either Mars or the moon.

The degassing goes on steadily, it has been going on since the beginning of the earth. At any one time it is apt to follow certain zones or avenues of least resistance. In this way global strain is being generated along certain zones, as far as we can observe today, at a constant rate. It takes of course a certain activation energy to release the strain. This harmonizes with the observations of BENIOFF (see (6), Colloquium on Plastic Flow) that the strain is released in shallow earthquakes only during intervals when the "fault-locking" is reduced. Likewise the deep quakes are found to be related in a

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[2] In supplementary papers VAN BEMMELEN has shown how not only physical but also chemical processes are important factors in orogenesis (e.g. Gravity field and orogenesis in the West-Mediterranean region, Geol. and Mijnbouw, nr. 8, pp. 306—315, 1952). See also H. RAMBERG. The thermodynamics of the Earth's crust. Norsk Geol. Tidsskr. vol. 25, pp. 307—326, 1945.

single stress system in which a compressional elastic creep strain is accumulating and releasing.

I have the hope that further work along the lines that I have indicated above may bring a reasonable solution to these enigmatic problems. It would seem that both folding and deepstructure patterns are related to degassing, radial diffusion, and the development of the concentric structure of the earth.

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