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Possible Correlation between Species Extinction, Evolution and Plate Adjustments to Continental Erosion

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ABSTRACT: Data from continental erosion and from fluctuations in sea level are offered as a correlation with species extinction reported by Raup. Such data suggest a model for long term punctuate evolution.

A recent article by Raup (1) forces serious physical theoretical attention to the causal implications of its thesis of rapid periods (e.g. under 10 million years – My) of familial 'cohort' extinctions of living species alternating rather regularly with extended periods (perhaps 20–100 My, averaging near 25–40 My) of little extinction for the entire Phanerozoic epoch of the past 600 My, beyond a few individual periods of 'large' extinctions. Together with the note that one is looking at an evolutionary process in which there are only a few million species alive (at present perhaps 3–10 M) out of a surmised history of developmental diversity of perhaps a few hundred million to a few billion species (2), and the plausible inference that new species might likely evolve (evolution into niches made newly available) to at least make up for the number of species that have disappeared (3), this must confront physically founded science with the requirement to establish a dynamic theory for the evolutionary history of a number of complexly interacting and competing processes within the solar system (4).

In discussing possible causes of extinction, Raup mentions changes in sea level, climatic deterioration, and comet or asteroid scenarios. He points out, validly, that the establishment of cause and effect is difficult and requires careful assessment of probabilities in complex time series. Raup himself has highlighted such study of living species. For example in the paper under discussion, he provides an extensive graphing (from his colleague) for survivorship of 2316 families of marine animals during the past 600 My. The graph presents the trajectories of disappearance in time of clusters of these families as such clusters newly appear during that epoch.

These data indicate an extinction of each of these family clusters (aggregated as "pseudocohorts" – these are not defined) in a period of about 300 My (ranging from 150 to 400), by approximately 10 flat steps alternating in time more sharply with descending ramps. That is, the individual trajectories of disappearance are not smooth. The 'flat' steps of little extinction range from about 20 to 100 My, probably averaging in the 25 to 40 My range; the rapid extinction ramp drops average less than 10 My. Each initial 'pseudocohort' drop, when it first appears (at 100% in magnitude), tends to be rapid. Loosely speaking, with a few notable exceptions, the families cover the space uniformly and nest without crossing. That is, the family of curves, of appearance and decay, tend to conform, to be isochronous. New 100% clusters originate at a rate of about 1 pseudocohort per 8 My. There is also some clustering of dropping trajectories shown, indicating a few periods of sharp general extinctions.

Raup points out the comet-asteroid theory and the possible periodicity induced on comet showers by astrophysical processes which have both received considerable recent publicity. He also alludes, in passing, several times to climatic and sea level disturbances as a commonly citied cause of mass extinction. Since the latter case is not so well spelled out in most readers minds, this opportunity is taken to contribute to this controversy on the basis of some of the results derived in a NASA study a few years ago (4). In addition to the results so far alluded to, Raup's assertion is accepted that the half-life of a biological species is rather short (e.g. less than 10 My – from Schopf (2) more plausibly like 1 My); also the notion is premised that species appearance, in some approximate fashion, has to be congruent with species demise, on the basis that availability of new niches would hasten their filling by new founder groups.

Our earlier study (4) was a thermodynamic characterization of the interaction of six earth systems: the lithosphere, the meterological, hydological, geochemical, biochemical earth systems, and modern man. Much of that preliminary effort was devoted to the hydrological character of continents and their rivers. Some results from that study can be abstracted on the erosion of continents, and the processes involved in the long term regulation of sea level for the past 2.5 billion years (By).

Wear and Movement of Continents

It was shown, independently confirming some other estimates (see Elder (5)), by having developed a theory of ground water drainage, water table, and river runoff, that there were two major continental erosion processes – mechanical erosion accounting for about 80,000 kg, and chemical erosion accounting for about 35,000 kg, for a total of about 120,000 kg per year per square km of earth's surface. Reckoning the height of continental features to be in the range of km and their rock density to be about 2.8 gr/cubic cm would result in loss of features at a scale of about 25 My or more.

It was also shown, making use of the then newly available sea level fluctuation data of Vail and colleagues (6), that there seemed to be three major long term scales for such sea level and associated land level changes: about 3–8 My, 30–40 My, and 300–600 My process changes with the latter process likely associated with convection cell rolls in the upper mantle with such long rolls estimated by Turcotte and Burke (7) to be about 300 My in scale.

With a little more geological detail (see, for example, Encyclopaedia Brittanica – Earth, Geological History of; Continents, Development of (8); Elder (4); Vail (6); Wood (9); Gass and Wright (10), based on the assumptions: that the solid surface of the earth is made up of a crust consisting of a patchwork of plates interacting plastically-elastically that float on a highly viscous hot fluid-like mantle layer (the asthenosphere); that the continents comprise thickened portions of such plates; that the oceans covering about 2/3rds of the earths surface lie above thinner plate crust portions; that molten magma, near continuously and periodically, wells up at plate margins by a number of volcanic processes; that the plate movements and such volcanic action are driven largely by the thermal and momentum inhomogeneity of the underlying convective rolls and thermal plumes; that in the current epoch, one of the most prominent examples of such motion and volcanism is the Atlantic mid-oceanic rifting and spreading, we can also assume the following measures:

average ocean depth 4.5 km, density 1 gr/cm^3;
crust thickness under oceans 5 km, density 2.85 gr/cm^3;
average continental thickness at sea level 28 km;
average continental thickness 35 km;
upper continental density (sial) 2.7 gr/cm^3;
lower continental density (sima) 2.85 gr/cm^3;
upper mantle density 3.3 gr/cm^3;
elastic rebound of mountains (buoyancy) requires 5.6 km of continental removal per km of continental surface.

It may be plausibly assumed that most, if not all, of continental crust was formed by about 2.5 Bya (9; 10). Thus substantially all the earth's crust (which is viewed as making up the component parts of the so-called geological column) has been reworked since that time. The prototypic unit of that column, in the form of a slab of sedimentary deposits, may be estimated to be about 45 km thick (2/3rds of the earth's surface is water, but the ocean crust, 5 km, is only 1/6th of the thickness of continental crust. Thus the amount of reworked crust in ocean plates is about 1/3rd of that in continental plates. This increases the effective reworked continental crust thickness by about 10 km). This unit notion is supported by (or supports) the compatible assumption that sea level has been effectively regulated essentially constant for the past 2.5 By (9).

Thus a unit scale for turnover of the entire earth's crust (continents and ocean plates by continental erosion, subduction, volcanism, and isostatic rebalance) is about 1 By or some substantial fraction thereof (e.g., 1–2 thirds). This is a unit measure that subsumes (a) the general erosion process scale; (b) the near isostatic balance of the crustal plates; (c) their turnover by some slow and weak dynamic process.

The result that we inferred in (4) was that the processes making up long term sea level regulation could likely be accounted for from the 300 My mantle convection cells, and that their weak coupling to the earth's crust would be expected to totally turn over the earth's crust by a number of discrete roll processes, in a few, e.g., 2 or 3, Raleigh-Benard roll time constants associated with the mantle convection of heat. As the chapter author, Beloussov, states (8) in referring to tectonic cycles: "Precambrian metamorphism was preferentially confined to certain intervals of time. These time intervals (Bya) are . . . 3.0–2.8; 2.6–2.5; 2.2–2.0; 1.8–1.6; around 1.2; 1.0–0.9; and 0.6–0.5. These figures show that Precambrian metamorphism recurred at discrete intervals of 300,000,000 to 600,000,000 years".

Actually if instead of extracting a 'primary' long cycle from Vail's sea level variation data by filtering, as he (6) and we (4) did, one repeatedly subtracts the rapid (discontinous) falls in sea level from the otherwise continous record, e.g., by subtracting the piecewise discontinuities, one obtains a moderately smooth monotonic cycle with a period of about 600 My. Thus we are now willing to infer that the large scale convection rolls succeed in largely tuning the process and turning the crust over in about two rolls, through the detailed erosion process and repeated rebalancing by continental reformation; that this process has been going on since the first (or second) cycle of producing sedimentary rocks 3.8 Bya, so that the earth now is marked by about 6 (of 7) overturns of about 35 km, making up a geological column of about 210 km or so, in conformity with other estimates. This modelling also implies the Beloussov picture (also see (10)) in that the crust material is substantially conserved, added to only in very modest amounts, but periodically metamorphosed by subduction and exposure to 40 km depths (1000° C granitic melting temperatures). The fact that the tuned erosion cycle is monotonic but not perfectly uniform in erosion rate may represent an associated long term process of continental clumping and separation. This then represents the outline of a tectonic model of crustal surface at global scale. Now we turn to a more local, continental, scale.

We surmise that the second more rapid scale, marked by rapid changes (falls) in sea level, is a time scale for specific continent turnover driven presumably by mantle rolls, volcanic spreading, and erosional imbalance. Since these sea level falls are associated with land rises, we surmise that the process is more likely scaled specifically associated with a density difference (of about 0.5 gr/cubic cm) of about 1/6th of the density involved in the total crust erosion process, and representing a change in scale height of perhaps half the continental thickness. Thus one might expect that more rapid scale to be closer to 80 My (1/12th of 1 By) rather than 1 By (or more precisely to 25–50 My rather than 300–600 My).

Examining the Vail et al. data (6), if one assumes the discontinuous breaks (falls) in sea level to be emergent isostatic plate adjustments, e.g. represented both by tilting and rocking subductions as well as lateral shifts, that take place 'suddenly', less than a My, one finds there to have been perhaps 50 odd such shifts over 600 My. These scale uniformly as 'relaxations' from perhaps a few to hundreds of My, with a median relaxation period of about 50 My. If these relaxations are viewed as constituting a 'smooth' distribution, they tend to cluster in the few to 40 My range.

The tail of this distribution likely represents an even faster rolling instability (e.g., subduction near continental margins) which can be imagined as associated with the even smaller differential instability due to the difference between sedimentary materials gathered in geosynclinic troughs near continental margins and the underlying continental margin itself. These margins, because of their lack of support as well as being subject to considerable volcanism, are thus both elastically and plastically mobile. Assessed as an isostatic unbalance, their response might be represented by the differential order of magnitude difference in density of 0.05 gr/cubic cm and an effective erosion of a fraction of the continental margin thickness of 28 km, perhaps 7–15 km. Thus that fast scale might be perhaps 3–5 My. This is the fast scale found in the Vail et al. data.

Now obviously we have not argued the actual hydrodynamic form of the processes that drive these three time scales except to suggest some plausibility arguments for their existence and for further exploration, namely that they result basically from the vorticity and thermal inhomogeneity drives associated with the mantle, with gravitational imbalances resulting from small density differences, with thermodynamic state changes emergent from volcanism, and from hydrodynamic erosion. The three scales are then associated with earth system crustal processes, with local continental processes including a considerable amont of lateral as well as vertical plate movement, and with continental margin processes. In particular, we surmise that the two more rapid processes exhibit sharp rapid processes of geological discontinuity. It is these two effects that we wish to relate to biological evolution.

Dynamics of Species

We find that the statistics of rapid change in species number to be comparable for the Raup data of species extinction (1), and for the Vail et al. data of sea level fluctuation (6). To bring some compatibility between their functioning, we view these processes as related in the following manner. The rapid material rearrangements of sediments and shelves associated with rapid sea level adjustments have to have significant effect on existing living species (appearing, as it were, as 'nuclear winters' in the oceanic atmosphere). that is we believe the appearance of new 'pseudocohorts', Raup's term (e. g., scaled at perhaps 8 My), is comparable with marginal adjustments (scaled at perhaps a comparable 3–8 My scale), and that the dissappearance of such pseudocohorts (at perhaps a 50 My scale) is comparable to continental tectonic adjustments (at perhaps a 25–40 My scale).

Our nominal modelling view is that rapid continental margin adjustments (e. g., sea level rapidly falling consequent to a marginal adjustment of sediment and a rise of the land margin as rapid as a million years, taking place every 5 My or so at one or more plate margins) makes possible the appearance of new large biological 'families' in niches which have been significantly denuded. It is our surmise that these newly appearing groupings are at the level of classes and orders, almost of phyla and classes (our interpretation of Raup's "pseudocohort" – note, for example, that most of the monera kingdom, representing about 16 phyla in Margulis, Schwartz' classification (11), and about 100 to 200 orders that we surmise will be ultimately found in the fossil record, likely evolved in the 3.8–2.5 By period according to Margulis' schema (12); or their kingdom of protoctista, represented by about 27 phyla, and about 200 to 400 orders that we again suspect will be found in the fossil record, likely evolved in the 1.1–0.8 By period. The point is that the punctuate character of these earlier more primitive evolutionary epochs really does not differ from its comparable nature during the more recent Phanerozoic. The evolution of punctuation does not take place at the species level, but at the level of class and order).

But then at the next continental scale, there is premised a great deal more synchrony among plate adjustments. Again following rapid fall in sea level, not only as a more local margin adjustment but as an entire continental plate and tectonic system adjustment, the continental plate erosion cycle at about the 25–40 My scale begins. At this slower scale at which the ecology is only gently affected, there is very little evolutionary change (point mutation within species responding to local selection pressure), and so speciation becomes local, much less abrupt. But of course the following (or preceding) tectonic adjustment makes for a rapid change in speciation. Namely the more frequent marginal adjustments continue to produce large and rapid evolutionary change (of orders, classes, and phyla in under a million years) to fill denuded or newly available niches, and the less frequent whole plate adjustments result in relatively rapid (few million years) synchronic disappearance of species of all taxa. It is such a mix of processes which makes the notion of species so perplexing.

However in this mixed scale sense, one finds the statistics of step and decay of species exhibited by Raup and the slow decay and fast rise of sea level exhibited by Vail et al. to be quite compatible, even if their agreement is not sharp enough to test the precise details of phasing. At least this model thus offers a plausible account for scaling speciation and disappearance of species with geophysical-geochemical processes of erosion and change rather than requiring external – stellar or meteoric – events.

One must note that from geological study beginnings, much of what geologists know is tied up with correlations between such sedimentary strata and fossils. It is timely to begin an even more detailed calendric correlation.

References and Notes

1) Raup, D.: Biological extinction in earth history. Science, 231, 1528–1533 (1986)

2) The composite comments of Simpson, G.: How many species? Evol. 6, 342 (1952); Cailleux, A.: How many species? Evol. 8, 83–84 (1954); Schopf, T.: A critical assessment of punctuated evolution. 1. Duration of taxa. Evol. 36, 1144–1147 (1982) make some such numbers plausible as an order of magnitude estimate. That is, such a number far exceeds the number of currently estimated species.

3) While the argument under consideration has to do with species extinction, the larger problem of evolution – whether gradual or episodic – has to deal very detailedly with the fossil record. There is the latent assumption that the fluctuation in the total number of species available at every point in time is lesser in measure – more slowly varying – than the fluctuations in, say, extinctions. If this is the case, then new niche filling species, e. g., a small group point evolution, has to follow extinction with relatively short delays, such as delays significantly less than a few My.

4) The work that my colleagues and I have pursued in developing a physics of complex systems, homeokinetics (see Soodak, H.; Iberall, A.: Homeokinetics: A physical science for complex systems. Science 201, 579–582 [1978]), led us to the conjecture that a unified earth science could only be developed on the basis of the interacting thermodynamics of six earth systems – the lithospheric earth, the hydrosphere, the atmosphere, the geochemical earth, the biochemical earth, and modern man. Obviously acceptance of our thesis encountered a great deal of resistance, even though now it has become fashionable coin of the realm (see Washington embraces global earth sciences. Science 233, 1040–1042 (1986). The limited effort that we were able to receive support for is available as Iberall, A.; Cardon, S.: NASA Contractors Reports, Contract NASW-3378, prepared by Gen. Tech. Serv. Inc., May, Aug., Nov. 1980, Jan. 1981 for NASA-Washington. Continental erosion by rivers, continental uplift, and sea level variations are discussed in the Nov. 1980, Jan. 1981 reports.

5) Elder, J.: The bowels of the earth. Oxford U. Press, London 1976.

6) See Vail, P. et al.: Seismic stratigraphy and global changes of sea level. AAPG Memoir 26, 49–212 (1977); Vail, P.; Mitchum, R.: Global cycles of relative changes of sea level from seismic stratigraphy. AAPG Memoir 29, 467–472 (1979).

7) Turcotte, D.: Burke, K.: Global sea-level changes and the thermal structure of the earth. Earth Plan. Sci., Lett. 41, 341–346 (1978).

8) Encyclopaedia Britannica, 15th Ed. 1975.

9) Wood, R. M.: The fight between land and sea. New Sci. 87, 512–515 (1980).

10) Gass, I.; Wright, J.: Continents old and new. Nature 284, 217–218 (1980).

11) Margulis, L.; Schwartz, K.: Five kingdoms. Freeman and Co., San Francisco 1982.

12) Margulis, L.: Origin of eukaryotic cells. Yale U. Press, New Haven 1970. Symbiosis in cell evolution. Freeman and Co., San Francisco 1981.