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Why are the chemical compositions of living organisms so similar?

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ABSTRACT

The partition of elements between seawater and the marine solid phases (organisms and pelagic clays) is basically controlled by the same surface adsorption mechanisms as between soil pore water and the land solid phases (plants and soils). However, the elements in living organisms are separated into 'biophile' and 'biophobe' groups.

By compiling many chemical composition data of marine and non-marine plants and animals, Bowen (1966) noticed a remarkable similarity among them. The new compilation by Bowen (1979) again confirms this observation. Figure 1 gives some examples of the good linear relationship among the mean concentrations of elements in marine brown algae and several other organisms. All the elemental concentration data are from Bowen's (1979) Tables 6.1 and 6.2 (ppm in dry weight), and additional data from his early compilation (Bowen, 1966).
The marine brown algae is chosen as a reference material in Fig. 1 simply because it represents a primitive life form and it has been analyzed extensively for many elements (phytoplankton is ideal but with fewer elemental analysis). As shown in Bowen's (1979) Table 6.1, the elemental compositions among marine brown algae, red algae and green algae are very similar (except brown algae has much higher I, Br, and As concentration), therefore the green algae data for Au, Re and W were also adopted as brown algae's. Single La datum for brown algae is doubtful and is omitted. The horizontal and vertical lines in Fig. 1A represent the ranges of concentrations given in Bowen's tables. The filled circles, therefore, represent the geometric means of the ranges if a range was given. For clarity of figures, the ranges of concentration for the marine brown algae are not given in other plots of Fig. 1. The two parallel dashed lines in each plot of Fig. 1 are one order of magnitude apart, enclosing as many data points as possible, and have a slope of one. The slope of one in the log-log plots of Fig. 1 means that the elemental compositions of all living organisms are linearly related to each other (within one order of magnitude out of the total ranges of nine orders of magni-

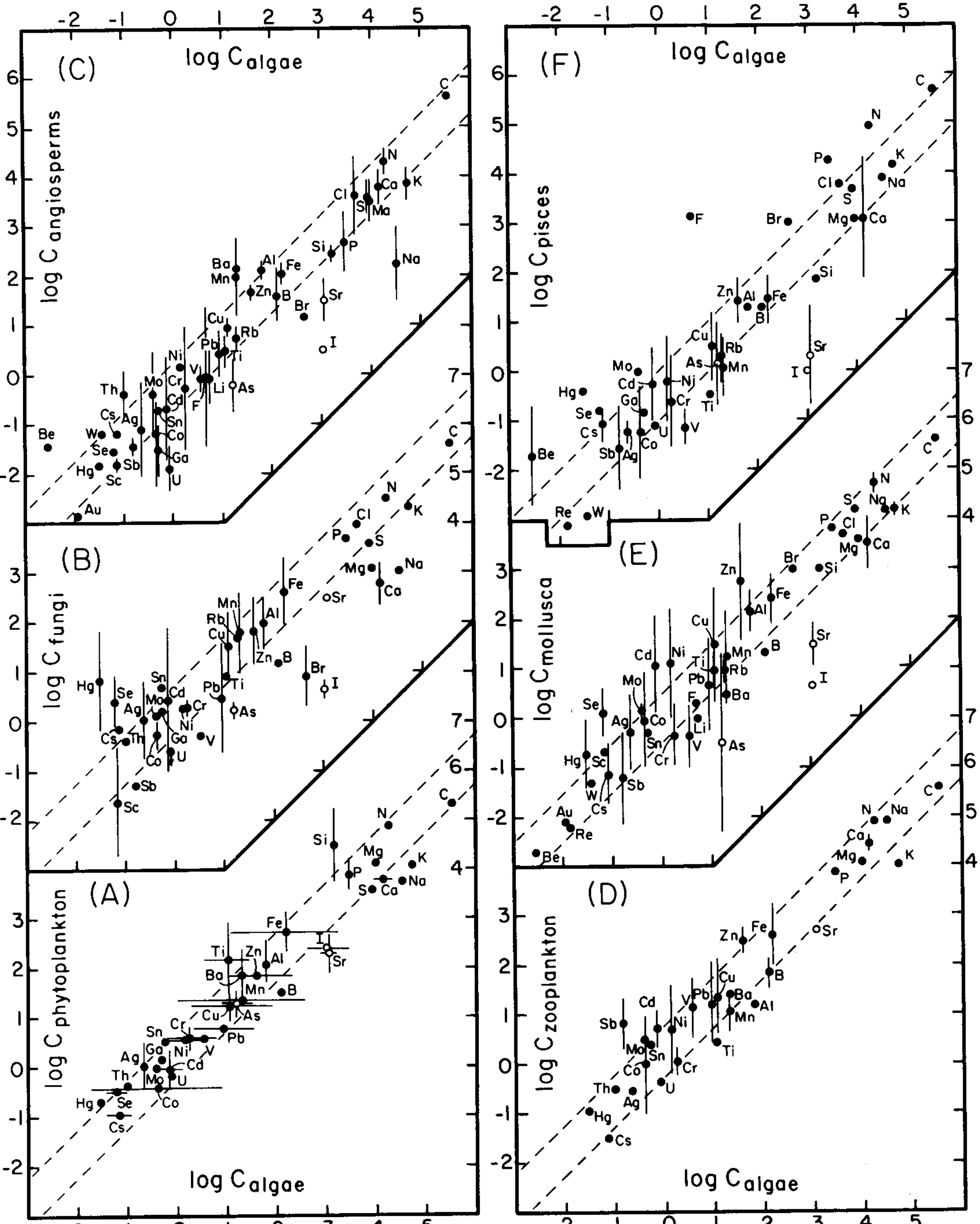

Figure 1. The log-log plots of the chemical composition data of marine brown algae against that of A) marine phytoplankton, B) Fungi, C) woody Angiosperms, D) marine zooplankton E) marine mollusca, and F) marine fishes.

tude) with the exception of a few elements. For example, the elements I, Sr and As are are abnormally high in marine brown algae as compared with other organisms. If compared with marine brown algae (excluding I, Sr and As) phytoplankton are high in Si and Ti (Fig. 1a) due to the inclusion of siliceous skeletons; Mollusca concentrate Zn, Cu, Ni, Cd, Se and Hg (Fig. 1e); Fishes (Pisces) are enriched in F, P (related to fish bone formation), Hg and probably Be (also could be a bad datum); Fungi are enriched in Hg, Se and depleted in Na, Mg, Ca, Br, B, V and U; trees (angiosperms) are enriched in Mn, Ba, Be and depleted in Na, Br and U (the apparent enrichment of Th is probably due to bad data, because woody gymnosperms and ferns do not show Th enrichment in Bowen's tables).

One may argue that one can easily obtain a false apparent correlation between two sets of data in any log-log plot. However the important constraint is the slope of the correlation line. A slope value other than one means a power relationship ($y = ax^b$, not a linear relationship of $y = ax$) and has no simple straightfoward physical meaning. The next question is why the living organisms have such a similar elemental composition. Since the relative elemental composition of marine brown algae is similar to all other living organisms (Fig. 1 and Bowen's Tables 6.1 and 6.2), the following conclusions drawn by marine brown algae can be equally applied to all other living organisms.

Since brown algae grow in seawater, one may expect some kind of relationship between the elemental composition of algae (C_{algae}) and seawater (C_{sw}). However, the plot of C_{algae} vs. C_{sw} (Fig. 2a) gives only a weak non-linear relationship. Taking Na or Cl as a reference point (dashed lines in Fig. 2a), most of the elements are variably enriched in

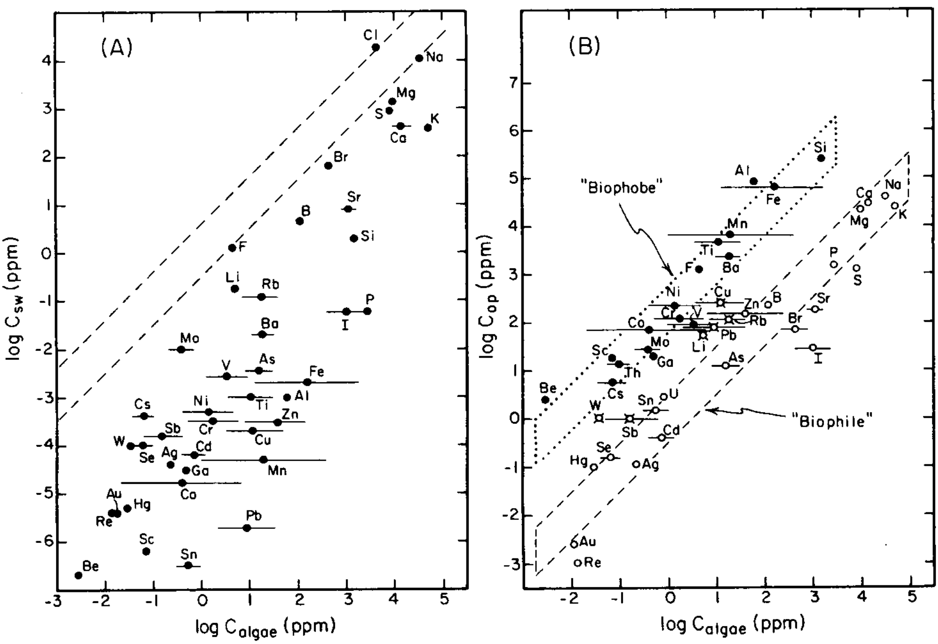

Figure 2. The plots of the elemental concentration data of marine brown algae against that of A) seawater, and B) oceanic pelagic clays.

algae as compared to seawater. It is not convincing to use the weak non-linear relationship between living organisms and seawater as an argument for the origin of life from the ocean (e.g. Banin and Havrot, 1975). The seawater data are from the recent compilation by Li (1982). However, the concentration of Sn should be replaced by 0.5 ng/kg (Byrd and Andreae 1982). The most recent compilation by Quinby-Hunt and Turekian (1983) is in general agreement with Li's.

On the other hand, if the marine algae (as well as all other marine organisms) and oceanic pelagic clays, as solid phases in the ocean, are both in some kind of adsorption equilibrium with seawater (Balistrieri et al., 1981; Li, 1981), then one may expect a one-to-one linear relationship between the chemical composition of algae (C_{algae}) and pelagic clays (C_{op}). Fig. 2b seems to indicate this to be the case. The oceanic pelagic clay data are from the recent compilation by Li (1982), but one should obtain the original Ca and Sr concentration data from Turekian and Wedepohl (1961). Another exception is the iodine value. I adopted the value of 28.8 ppm for Pacific surface red clays given by Shishkina and Pavlova (1965). As noted by Bennett and Manuel (1968), the value of 0.05 ppm by Turekian and Wedepohl (1961) is too low.

There are two distinct groups of elements in Fig. 2b. One group is tentatively named 'biophile' (open circles) and the other 'biophobe' (solid circles). The paired parallel lines are again on one order of magnitude apart (enclosing as many data points as possible) and have a slope of one. If one choose the 'biophile' element Si as the normalizing element, the enrichement factor E^i_{Si} (= $[C_i/C_{Si}]$ organisms/$[C_i/C_{Si}]$ pelagic clay) for 'biophile' group elements in marine brown algae falls mostly in the range of 10^2 to 10^3 and for 'biophobe' group elements around one. A few elements (e.g., Rb, Pb, Li, and Sb) fall between these two groups.

The systematic enrichment of 'biophile' (or depletion of 'biophobe') elements in living organisms does not itself imply essentiality (or dispensability) of each elements for growth but it may imply the same underlying physicochemical processes.

Figure 3 is another way to look at the data given in Fig. 2a and 2b. The enrichments of the 'biophile' and 'biophobe' group elements in oceanic pelagic clays and in algae relative to seawater (C_{op}/C_{sw} vs. C_{algae}/C_{sw}) are again linearly related. The observed variation of C_{op}/C_{sw} ratios of elements has already been adequately explained by the adsorption model of surface complex formation (Li, 1981). For example, the higher the chemical bond strength between the hydrated cation and the oxygen of hydrous oxide surfaces of red clays (or the higher the first hydrolysis constant of cation), the higher the C_{op}/C_{sw}. Therefore, the C_{algae}/C_{sw} ratios should also be controlled by the same adsorption processes or mechanisms, except that the adsorption surface is now organic cell membrane and the algae cell separates the elements into the 'biophile' and 'biophobe' groups. The probable cause of the separation will be discussed later. Since C_{op}/C_{sw} is inversely proportional to the mean oceanic residence time (τ) of an element (Li, 1982), one should expect a linear relationship between $C_{organisms}/C_{sw}$ and $1/\tau$ as shown by Yamamoto (1972) for marine algae, phytoplankton and zooplankton data with 10 to 20 elemental analysis.

One may take the similarity of the chemical composition between marine and land organisms as evidence for the evolution of land organisms from marine organisms. However, one can explain the biological similarity equally well by the similarity of the chemical composition between oceanic pelagic clays and soils. The chemical composi-

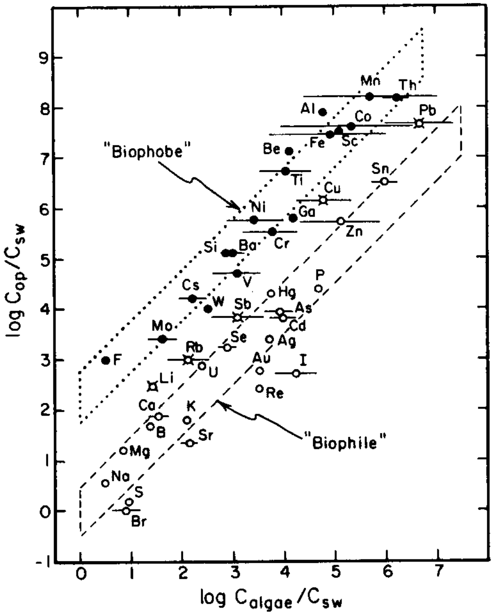

Figure 3. The plot of the elemental concentration ratios of algae and seawater (C_{algae}/C_{sw}) against that of oceanic pelagic clays and seawater (C_{op}/C_{sw}).

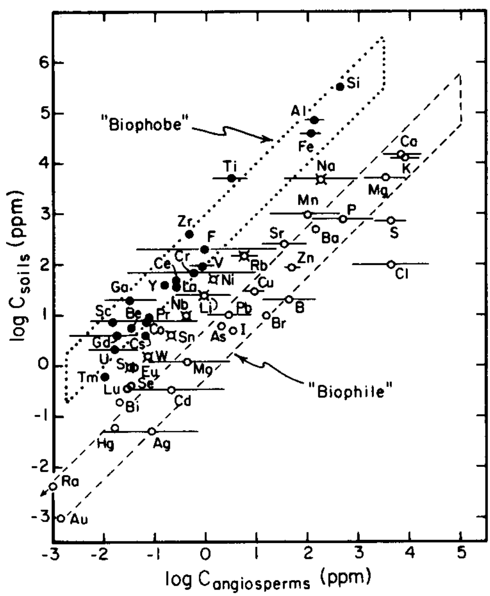

Figure 4. The plot of the chemical composition data of angiosperms against that of soils.

tion of land plants and soils can be linked through soil pore waters by the same surface adsorption processes. In any case, the similarity between the plots of the chemical composition of angiosperms vs. soils (Fig. 4) and marine algae vs. oceanic pelagic clays (Fig. 2b) are outstanding. The soil data are mainly from the compilation by Bowen (1979) which retains many data originally given by Vinogradov (1959). The mean Be concentration datum of soils listed by Bowen is too low as compared to other geological rock types. Therefore, Vinogradov's original Be datum was preferred here. The lists of 'biophile' and 'biophobe' group elements in land trees (Fig. 4) and marine algae (Fig. 2b) are very similar. The 'biophile' elements of trees include K, alkaline earths minus Be, halogens minus F, B-type metal cations (Cu, Ag, Au, Zn, Cd, Hg, Sn, Pb, Sb, Bi, Se, As) Mn, Mo, S, P, B, Re, and B. In addition to Cs, Be, and F, the 'biophobe' elements include, tri- and tetra-valent cations such as Al, Si, Sc, Ti, V, Cr, Ga, Y, Zr, rare earths, Th and U, which all have very high hydrolysis constants, hence have high affinity to solid particles (Li, 1981). The elements Mn, Mo, Ba, Cu and Pb are 'biophile' in land trees but fall on the 'biophobe' field in marine brown algae (Fig. 2B), probably caused by the unusual enrichment of these elements in red clay as compared with soils. Na and U are 'biophobe' in land trees (Fig. 4) but become 'biophile' in marine organisms due to their very high concentrations in seawater. Li and Rb fall between 'biophile' and 'biophobe' groups. One interesting observation is that the heavy rare earth elements (e.g., from Eu to Lu) tend to be enriched, relative to the lighter ones, (La, Ce and Pr) in trees.

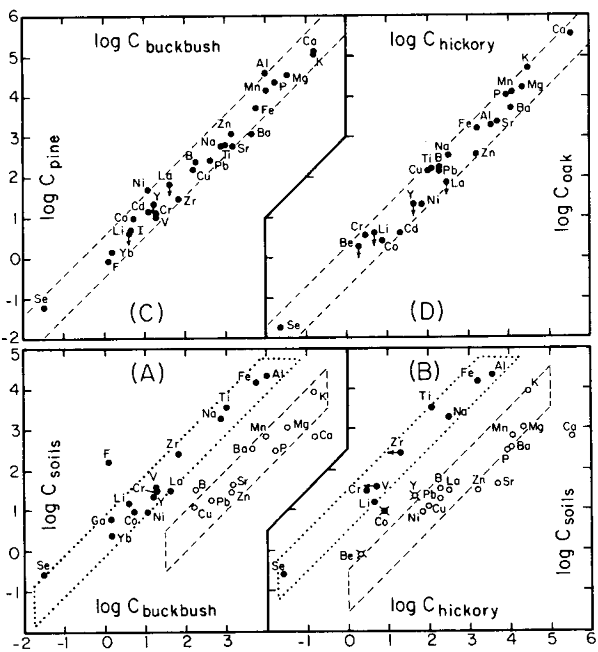

Figure 5. The correlation plots of the elemental composition data of a) buckbush and soils, b) hickory and soils, c) buckbush and pine and d) hickory and oak.

The list of 'biophobe' group elements suggest that all living organisms may have been contaminated by fine inorganic particles (soils, dust, pelagic clays etc.), or actively incorporate these elements form solution in dissolved or particulate forms. It is hard to distinguish which mechanism is the dominant one. However the linear relationship of the elemental compositions among all living organisms (Fig. 1) may favor the active role of organisms instead of a passive contamination. Certainly further studies are needed.

Finally, Erdman et al. (1976) specifically measured the chemical composition of native plants and associated soils from major vegetation-type areas in Missouri, to investigate their relationship. Figures 5a and 5b are examples of the good linear relationship between the chemical composition of trees (buckbush and hickory) and associated soils, from the oak-hickory-pine forest area, for 'biophile' and 'biophobe' group elements separately. The similarity among Figures 2b, 4, 5a and 5b are, again, remarkable. However, there are always a few exceptions: Se is 'biophile' and La, Ni are 'biophobe' in Figures 2b and 4 but not in Figures 5a and 5b. Apparently, hickory and oak trees are accumulators of La and Ni. Figures 5c and 5d along with Figures 5a and 5b again demonstrate the generally good linear relationship among the composition of various trees grown in the same area (all from the oak-hickory-pine area of Missouri). The pessimistic conclusion by Erdman et al. (1976), that there is only a weak relationship between the chemical composition of trees and associated soils is not warranted.

Summary

The chemical composition data of marine organisms and plants, red clay, sea water, land plants and soil was plotted to find linear correlations. Relative enrichments and depletions of elements in different organisms and plants are found to be of similar magnitude, but only weakly related to the chemical composition of sea water. Living organisms separate elements into 'biophile' and 'biophobe' groups. The relative abundance of 'biophile' and 'biophobe' group elements in living organisms is linearly but separately related with those in oceanic pelagic clays and soil. The observed linear relationship can be best explained by the surface adsorption equilibrium between sea water and marine solid phases (marine organisms and pelagic clays) and between soil pore waters and land solid phases (land plants and soils). The separation mechanisms in general and the mechanisms of unusual enrichment of certain elements in accumulator plants (Peterson, 1971, Bowen, 1979) in particular need to be investigated further.

ZUSAMMENFASSUNG

Die chemische Zusammensetzung von marinen Organismen und Pflanzen, Tiefseetone, Meerwasser, Landpflanzen und Böden wurde auf lineare Zusammenhänge hin geprüft. Es wurde gefunden, dass die relative Anreicherung und Abnahme der Elemente in den verschiedenen Organismen und Pflanzen von ähnlicher Grössenordnung ist, aber nur schwach mit der chemischen Zusammensetzung des Meerwassers korreliert. Lebewesen reichern die Elemente entweder an («biophile» Elementgruppe) oder vermindern sie («biophobe» Elementgruppe). Das relative Vorkommen von «biophilen» und «biophoben» Elementen in Organismen korreliert linear mit demjenigen in Tiefseetonen oder in Böden. Dieser hier beschriebene Zusammenhang wird mit der Oberflächenkomplexierung von marinen Partikeln (z. B. Organismen oder Tiefseetone) oder Feststoffen in Böden (Pflanzen und Bödenpartikel) durch in Wasser gelöste Jonen erklärt. Die Aufnahmemechanismen und die ungewöhnliche Anreicherung von gewissen Elementen in Akkumulatorenpflanzen (Peterson, 1971; Bowen, 1979) bedürfen allerdings weiterer Untersuchung.

RÉSUMÉ

La composition chimique des organismes, plantes, et argiles marins, de l'eau de mer, des plantes et du sol des continents a été étudié en cherchant des correlations linéaires. On a trouvé que l'enrichement et l'appauvrissement relative des élements dans des organismes et plantes est semblable, mais n'est pas correlée très bien avec la composition chimique de la mer. Des organismes vivants sont enrichis de quelques élements (élements «biophiles») ou appauvris (élements «biophobes») des autres. L'abondance relative des élements «biophiles» et «biophobes» dans de organismes est correlé linéairement avec l'abondance relative dans des argiles de la mer et du sol. Cette corrélation est expliqué le mieux par le modèle de complexation des surfaces des particules naturels par des ions dissous dans des environnements marins (organismes ou argiles marins) en continentales (plantes ou particules des sols). Le méchanisme d'enrichissement et l'enrichissement des plantes accumulateurs obligent des recherches davantages.

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