The major elemental abundance differences between life, the oceans and the Sun

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***Abstract*—As we begin to understand the origin and evolution of life on Earth and investigate the possibility of extraterrestrial life, the need to scientifically approach fundamental questions such as 'What is Life?' increases. In beginning to answer such questions we can look at the ingredients of life on Earth. Here we present an overview of our understanding of the composition of life on Earth. At the level of chemical elements, the major ingredients are carbon, hydrogen, oxygen, nitrogen, sulphur and phosphorus along with trace amounts of elements like sodium, potassium, iron and copper.**

Here we present the correlation between the elemental composition of life (humans and bacteria), the Sun and sea water. Some elements like carbon, nitrogen and phosphorus are more abundant in life than in sea water, while others like chlorine and sodium are more abundant in sea water than in life. We quantify differences in elemental abundances in life, relative to sea water and attempt to interpret them in terms of chemical constraints on metabolic activities and harnessing energy. We discuss how future investigations could further our understanding of the origins and evolution of life on Earth.

While natural philosophers[1] believed all matter to be made of four elements: fire, air, water and earth, we now recognise that all matter in the universe is made of atoms of chemical elements.[2]

The first chapter of De Courcey's 1857 book [1] is titled: "A chemical analysis of the elements which are found to exist in the human frame - thus showing the natural origin of man." It is perhaps one of the earliest records where one has examined the composition of life in terms of chemical elements. De Courcey mentions that vegetable and animal matter are essentially composed of carbon, hydrogen, oxygen and nitrogen in addition to sulphur, phosphorus, iron and small quantities of "saline matter" (for example sodium and potassium).

He goes on to give us relative proportions of these elements in "fibrin - the lean part of animals, which is composed of 18 parts of carbon, 14 of hydrogen, 5 of oxygen and 3 of nitrogen."

Upon examining the elements that make up the environment of the vegetables and animals, he concludes that the atmosphere, water and vegetables are composed of the "same elementary principles" and that "the Earth and the animal organization of the human frame is composed of the same agencies."

Today we have a much better knowledge of the composition of life and its environment, primarily due to the suite of analytical techniques available to accurately measure the concentrations of elements in a sample.

The 'bulk' elements oxygen, carbon, hydrogen and nitrogen make up 96.8 ± 0.1 % of the mass of living matter[3] and phosphorus and sulphur make up 1.0 ± 0.3 %. 2.2 ± 0.2 % is dominated by potassium, sodium, calcium, magnesium and chlorine, while the remaining mass (0.03 ± 0.01 %) is attributed to 'trace' elements like iron, copper and cobalt.

Many of these trace elements are known to play a variety of biological roles as electrolytes and as enzyme cofactors and often the amounts and proportions of these elements are important in achieving successful functioning of the metabolic pathways in an organism. Davies and Koch [4] have noted that "of the 90 kinetically stable elements that occur in nature, about 36 are essential to some form of life."

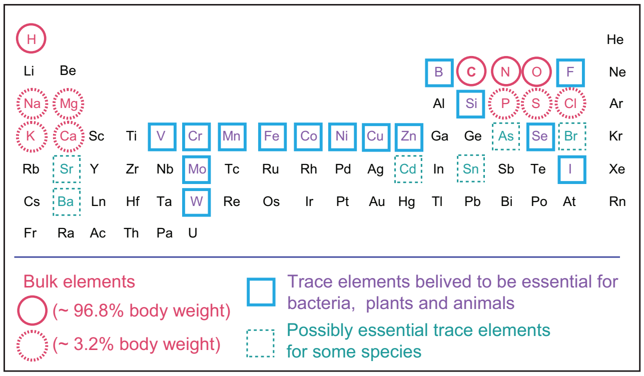

Fig. 1. The distribution of elements considered 'essential' for life in the periodic table. Adapted from [5].

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[1] Empedocles proposed *circa* 450 BC that the four classical "roots" known to pre-Socratic philosophers, made all the structures in the world. The term "elements (stoicheia)" was first used by Plato *circa* 360 BC in his dialogue *Timaeus*.

[2] Excluding the case of dark matter, whose nature and composition is still in question.

[3] Values were derived from averaged elemental abundances in humans and bacteria, as presented in [2] and [3] respectively. The uncertainties largely reflect the range of abundances among humans and among bacterial species rather than instrumental uncertainties.

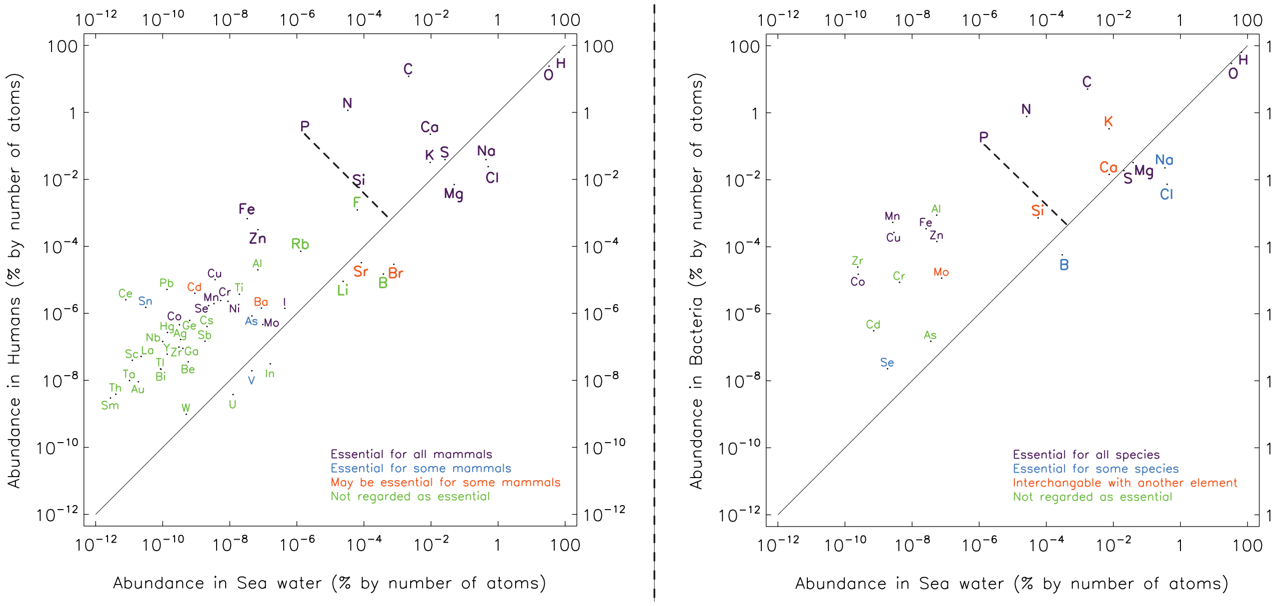

Fig. 2. Life vs. Sea water - The positive correlation between elemental abundances (by number of atoms) in humans and bacteria relative to 'boiled' sea water, which contains the same percentage of water (by number of H and O atoms in water) as in the life form. 'Essentiality' of elements for mammals and bacteria are colour coded as suggested in [6] and the appropriateness of the criteria to establish 'essentiality' is discussed later.

A number of authors including Davies and Koch [4] and Bowen [6] have presented the relative proportions of the chemical elements in organisms like humans[4] and bacteria[5] and noted the similarity in their compositions. Bowen [6] has also noted that the elemental abundances in these species show strong correlation with the elemental abundances of sea water[6]. We have graphically illustrated the tabulated data from [6] in Fig. 2.

Life forms show many commonalities but also differ in their composition and usage of elements because of the different environments they live in. It is clear that any life form can only be made of the elements available to it from its environment. If element X is non-existent in an environment then any life in that environment will not be composed of element X. It is interesting to examine to what extent the ingredients of life reflect the relative proportions of the elements in its environment.

Although humans do not currently live in the oceans or drink sea water, the composition of our diet is much more similar to sea water than it is to the Earth's crust which is mainly composed of aluminium and magnesium silicates. The first 90 % of our evolution, approximately 4 billion years ago to 400 million years ago, took place in sea water and our metabolic process have evolved around nutrition that was available in sea water.

Our bodies are made of the diet we eat. If we take sea water as an approximation to our diet then from Fig. 2 we can infer that 'we are what we eat' but also that 'we are not *exactly* what we eat.' That is, although the data points are positively correlated to the $y = x$ line, there are some interesting outliers.

The relatively high abundance of hydrogen and oxygen in life is primarily due to the water (H_2O) that makes up about 65.9 % (by number of H and O atoms) of humans[7] and about 83.6 % (by number of H and O atoms) for bacteria such as *Escherichia coli* [3]. The lower number of data points for bacteria (25 elements) than for humans (58 elements) in Fig. 2 and Fig. 4, relates to the fact that bacteria have not been analysed to the same extent as humans have been for their elemental composition.

The uncertainties in the elemental abundances quoted in Fig. 2 have not been quantified by the authors who compiled the data that we have used here. Since measurements were made before the availability of high precision analyses offered by analytical techniques today, it is possible that the errors associated with elements with low abundances are large, even in the range of a few orders of magnitude.

Further, the nature of the data set[8] means that the abundances do not necessarily reflect the true composition of the life form or the environment in general.

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[4] Human abundances are from [2]. The study involved about 150 individuals.

[5] Bacteria abundances are from [3] and the values are representative of 7 - 40 species depending on the element.

[6] Sea water abundances are from [7] and are based on empirical models that estimate the composition of normal surface sea water with a chlorinity of 19 which corresponds to approximately 34.5g of salt per litre of solution.

[7] Oser [8] suggests that human body water content can range from 56 % for obese individuals to 70 % for lean individuals and here we have used the mid-point value of 63 % by mass.

[8] A number of publications such as [6], [8]–[16] have presented data sets of elemental abundances in a variety of life forms and environments. However, these data sets are either based on the same primary source as the data sets used here or focused on the elemental abundances of carbon, nitrogen and phosphorus and specific elements such as magnesium and calcium that were of use to ecological studies but inappropriate for our analysis where we desire abundances of a large number of elements.

For example, about 150 individuals were used for the human body analysis and due to logistical constraints, the abundances of some elements were determined from only a handful of individuals. The abundances for bacteria are representative of 7 - 40 species depending on the element. The composition of oceans changes with geographical location, temperature and depth and the abundances quoted here are based on empirical models that estimate the composition of normal surface sea water with a chlorinity of 19^6. Nevertheless, even with the uncertainties that may be associated with the abundances, it is unlikely that the strong qualitative correlations that have been noted here will become significantly weaker.

Unlike humans and bacteria, sea water is almost entirely composed of hydrogen and oxygen (hydrogen and oxygen in H_2O makes up 99.1 % of the atoms in normal surface sea water) with relatively negligible amounts of other elements that make up the ‘sea salts’. To allow valid comparisons of the relative elemental abundances in life forms and the sea, we have reduced the quantity of H_2O in sea water such that the percentage of water (by number of H and O atoms) was equivalent in the life form and sea water. The treatment is analogous to ‘boiling’ sea water and concentrating the salts.

Due to the logarithmic axes used in Fig. 2, hydrogen and oxygen appear to have a small deviation below the equilibrium value (as indicated by the y=x line) compared to other elements. However, the absolute deviations of hydrogen and oxygen below the line are much greater and account for the apparently large deviations in the opposite direction exhibited by the low concentration elements like cerium and lead.

It was surprising to find that if we ‘boiled’ sea water to the extent that no hydrogen and oxygen was present as H_2O, and similarly ‘boiled’ the life form (humans or bacteria) by reducing the water content to 0 %, we would still have a higher proportion of hydrogen and oxygen in seawater than in the life form. That is, there are more atoms of hydrogen and oxygen present as salts (such as bicarbonates and sulphates) and gases dissolved in sea water, than there are hydrogen and oxygen atoms in the non-water component of humans and bacteria.

As expected, the most abundant elements in sea water after hydrogen and oxygen are chlorine and sodium that upon evaporation of sea water yield sodium chloride crystals that constitute common salt. Sea water is not just a solution of sodium chloride and water, but rather is a mixture of virtually every element on Earth. Anything that can be washed downstream eventually finds its way to the seas, and is incorporated into the solution of the oceans [17].

In Fig. 3, we have changed our reference environment for life from the sea (as in Fig. 2) to the Sun. All atoms that are or have been part of living matter on Earth have either been produced during big bang nucleosynthesis [18] or in different processes of the stellar nucleosynthetic pathways that take place in stars [19]. Our Sun was formed out of a collapsing molecular cloud that was polluted by earlier stellar processes and the proto-planetary disk that was made of the remaining dust eventually gave rise to terrestrial planets like the Earth.

The composition of solar system objects including other planets and asteroids reflects to a large extent the composition of the Sun, except that the Sun has a large excess of hydrogen and helium. When the Sun formed from the solar nebula, 4.5672 (± 0.0006) billion years ago [20], the solar wind caused the depletion of volatile elements such as hydrogen and helium from the region of the solar nebula where terrestrial planets formed. Rocky planets like Earth, accreted from the fractionated nebular condensate whose composition (particulary C1 chondrites) closely resembles the solar composition, except for the abundances of volatile elements [21].

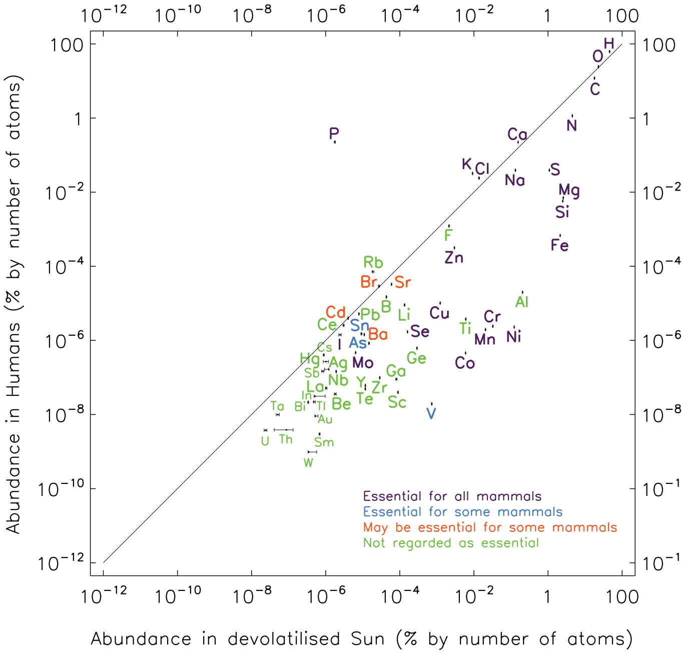

Fig. 3. Life vs. Sun - The elemental abundances in life, as represented by humans, is positively correlated to devolatilised solar abundances and supports the idea that ‘we are made of star dust’.

In order to make a valid comparison between life and the Sun, it is necessary to account for the excess of hydrogen and the noble elements in the sun and we have used devolatilised solar abundances which reflect the elemental composition of the Sun [22], which has lost all noble gases and has a reduced hydrogen content.

We have reduced the abundance of hydrogen such that for every atom of oxygen we have two atoms of hydrogen, in effect assuming that all hydrogen and oxygen in the Sun is bound as water (H_2O).

Let us assume that humans represent all life on Earth and take sea water as the reference environment for all life. The alternative of using bacteria to represent all life may be more appropriate as microbial prokaryotic life was the dominate life form for most of life's existence on the Earth[9]. However, the limited number of data points for bacterial elemental abundances means that our confidence in our interpretations will be compromised. Nevertheless, we have performed similar analyses for humans and bacteria and present both results here. We note that our interpretations remain valid for both life forms.

The relatively high abundance of 'essential' elements in humans, bacteria and sea water in Fig. 2 suggests that life on Earth does not have strong elemental preferences and is based on the most abundant elements in the environment. Although devolatilised solar abundances in Fig. 3 are different to sea water abundances, given that the uncertainties in the solar abundances are negligible on the scales we have used, our conclusion that life is based on the most abundant elements remains valid.

We observe that the composition of life is not exactly the same as its environment. Some elements like carbon, nitrogen and phosphorus are more abundant in life than in sea water while other elements like chlorine and sodium are more abundant in seawater than in life. An increased abundance of an element in life, relative to its abundance in sea water (for example carbon and phosphorus in Fig. 2), is a measure of life's concentration of the element from the environment. Elements like tungsten or uranium, which are not regarded as 'essential' to life appear to have similar abundances in life and in sea water and appear along the diagonal line in Fig. 2. It is tempting to suggest that life concentrates 'essential' elements from its environment while 'non-essential' elements occur in equilibrium abundances in life and its environment. However, a number of elements not regarded as 'essential' like aluminium, germanium and cerium, are also in high abundance in life relative to sea water.

We also observe that elements recognised as 'essential' are not necessarily concentrated in life like sodium and magnesium which are more abundant in sea water. Some elements may not be 'essential' for an organism but are concentrated in the organism as a consequence of sequestration of another element. For example, Pb^{2+} ions have similar binding preferences to Ca^{2+} and Zn^{2+} ions in the metal centres of proteins as they all have similar effective ionic charge to radius ratios. It is difficult for metabolic pathways to distinguish between ions of these elements and the toxic effects of lead poisoning are attributed to displacement of Ca^{2+} and Zn^{2+} ions by Pb^{2+} ions in metalloenzymes [25], [26]. In humans, lead is found incorporated into the mineral matrix of calcium rich bones.

The criteria to establish the essentiality of an element X for an organism, are formulated by Bowen [6] as:

- The organism can not grow or survive without X.
- X is involved in a metabolic pathway.

Such a criteria has a selection bias such that only elements in high enough concentrations in a life form and within the detection capabilities of biochemists, will be candidates for determining their essentiality. It requires the invalid assumption that elements in low concentration will not be involved in a metabolic pathway. For example, until recently bromine, which is in relatively low abundance in life and its environment and requires specialised analytical techniques for analysis, was not regarded as essential to life. It is now known that a wide variety of brominated metabolites are produced by marine sponges for defence strategies, many of which are being investigated for their pharmaceutical activity [27].

The essentialities of elements to life have been defined by their essentiality in selected plant and animal species that were popular in biological laboratories and so do not necessarily represent their essentiality for life in general. Dioxygen which was believed to be a universal requirement for respiration for all life forms is now recognised as being toxic for many anaerobic species. Similarly, iron was believed to be the sole element capable of oxygen transport until the discovery of copper performing the role in some marine species. The metabolic roles of elements like nickel and vanadium in animals were identified only in the 1970s [28].

We suggest an alternative view towards essentiality of an element to life that could apply to life in general and be more appropriate in terms of quantifying the extent of essentiality of an element.

We plot the magnitude of deviation of each element's abundance in life from the equilibrium value relative to sea water, which we define as 'perpendicular distance', multiplied by the element's absolute abundance in sea water (Fig. 4). This is a measure of the distance of each element from the diagonal line, as illustrated by the length of the dashed line for phosphorus in Fig. 2. We observe that 'essential' elements are associated with higher values and 'non-essential, elements are associated with lower values.

An interesting feature in Fig. 4 is the change in slope of the dotted trend lines in the plot for humans and marks the transition from 'bulk' elements (see Fig. 1) that are essential to all mammals (like calcium, carbon, sodium and magnesium) to the 'trace' essential elements (like iron, copper, vanadium and cobalt).

Perhaps it is the chemical nature and/or the high abundance of these elements that makes them suitable for use in the fundamental or obligatory metabolic pathways of life.

Although, elements like iron and copper are classified as essential to all mammals by Bowen [6], they have y-axis values (in Fig. 4) less than -6, suggesting that these elements are suitable only for metabolic pathways that require low amounts of these elements. Most elements not regarded as essential by [6] have y-axis values less than -8 and perhaps are only involved in facultative metabolic reactions.

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[9] Controversial isotopic evidence by Rosing [23] suggests the presence of autotrophic organisms 3.7 billion years ago. Bacteria have existed for at least 3.4 billion years, as indicated by stromatolite fossils [24] and microbial life was the only form of life until ∼2 billion years ago. Animals appeared ∼600 million years ago and the *Homo* genus that includes modern humans has existed for ∼2.5 million years.

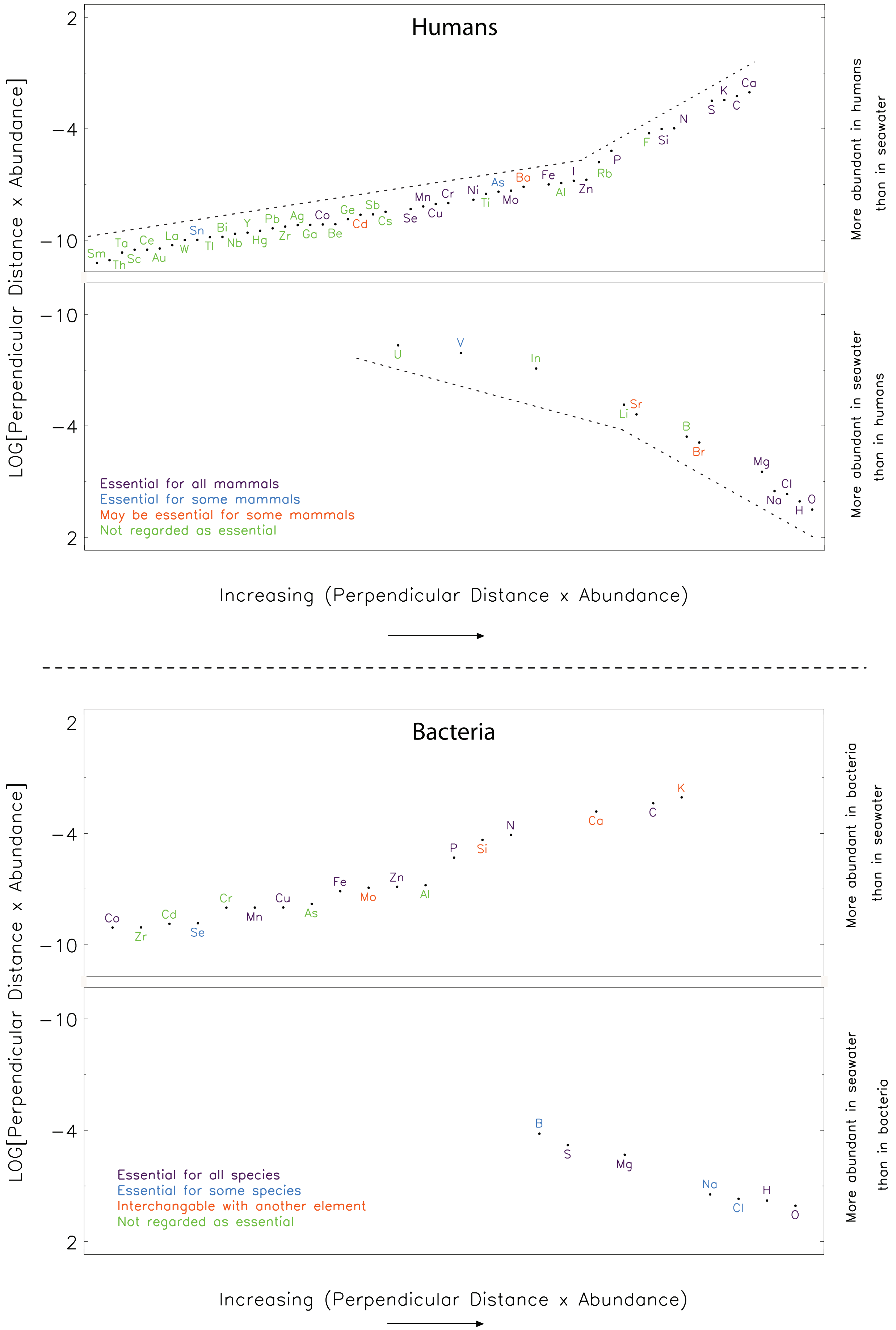

Fig. 4. Magnitude of the deviation of each element’s abundance in life from the equilibrium value relative to ‘boiled’ sea water (see dashed lines in Fig. 2). Essential elements are associated with higher values and non-essential elements are associated with lower values.

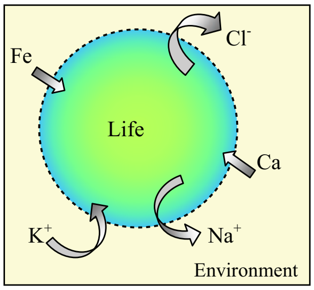

Fig. 5. Life pulls in some elements like calcium, potassium and iron from the environment while it pushes out elements like chlorine and sodium.

It will be important to increase the confidence in these trends through future analyses of the elemental composition of more bacterial species but if these observations remain valid for humans, bacteria and archea, representatives of each of the domains of life on Earth, then the trends presented here could be interpreted as being a universal correlation in life on Earth and lend support to the idea that life is a system which manipulates elemental abundances away from their equilibrium abundances in its environment, to perform its metabolic activities and harness energy.

Imagine that life begins as a bag containing the same elements in the same proportion as in the external environment. Then life somehow learns to pull in some elements from the outside world and concentrates them inside the bag and push out other elements as illustrated in Fig. 5. We can now define life as a chemical system away from equilibrium with its environment. The disequilibrium established by the unequal abundance of an element in life relative to its environment is used by life to perform its metabolic activities.

We are not suggesting that organisms are bags of independent elements. Organisms are chemical entities and are produced, maintained, and propagated by chemical reactions, in the form of highly complex coupled networks, which are the product of evolution over the past approximately 3.5 - 4 billion years.

Elements such as fluorine and boron exhibit relatively large deviations in their abundance in humans from the equilibrium value relative to sea water. The 'essentiality' of these elements in humans is not confirmed as their metabolic roles have not been identified. If our interpretation is correct then these elements are likely to be involved in facilitating metabolic processes in humans.

In the future, we plan to perform elemental analyses of various species using analytical techniques that offer much higher precision than ever before, and hope to remedy the lack of quality data for other life forms (not just humans and bacteria). Widespread studies looking at all forms of life on Earth would be required to work towards our ultimate goal of understanding the origins and evolution of life. However, given that our approach is at an early stage, we must have a modest realisable target that will eventually help us assemble the big picture. This will be achieved by focusing on the root of the phylogenetic 'Tree of Life' illustrated in Fig. 6.

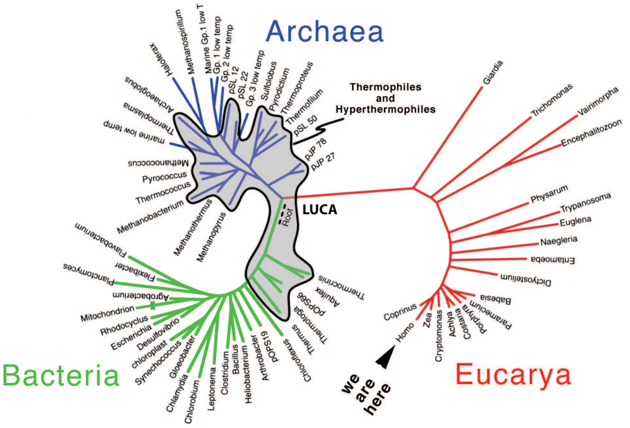

Fig. 6. The Phylogenetic Tree of Life based on comparisons of 16s rRNA sequence of extant organisms. For clarity, only a few known lines of descent are shown (www.astro.washington.edu).

We plan to study the elemental composition of archea and bacteria that have been the dominant forms of life for most of life's existence on the Earth and are probably more closely related to the Last Universal Common Ancestor (LUCA) than are eucaryotes.

The elemental composition of an organism may be a highly conserved feature of life on Earth, allowing us to relate deeply branched extant species by their elemental composition and in turn infer the composition of the Last Universal Common Ancestor and its environment. Such knowledge will further our understanding of the possible sites for the origin and early evolution of life on Earth.

Using branch lengths as a proxy for time, analyses of the elemental compositions of species with various branch lengths across the phylogenetic tree will be used to determine if there are any identifiable trends of life using a larger suite of elements as a function of time.

This approach also lends itself to identifying evolutionary steps linked to changes in the bioavailability of elements. For example, oxygenation of the atmosphere approximately 2.34 billion years ago caused substantial decrease in the availability of the biologically active form of iron in the oceans (from soluble Fe^{2+} to Fe^{3+} which forms insoluble $Fe(OH)_3$).

The oxygenation also oxidised another biologically active metal, copper from its Cu^{+} to Cu^{2+} state [29]. Williams and Fraústo da Silva [30] have suggested that this change in the environment may have triggered the development of new metabolic pathways which harnessed the electrochemical potential of the higher oxidation state of copper, often in roles previously performed by iron.

Advancements in molecular biology, bioinformatics and elemental analysis over the last decade mean that we now have the tools to perform our investigations successfully.

De Courcey [1] observed the similarities in the elements that make up life and its environment and reasoned that "…man was created from the dust of the Earth." 150 years on, we are examining both the similarities and the differences in the elements that make up life and its environment and our interpretations will allow us to better understand the origins and the evolution of life on Earth and quite possibly elsewhere in the universe.

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