

A postulate to assess ‘habitability’

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Abstract: One principal challenge in biology is defining a postulate by which the habitability of other planets can be assessed. Current assessments suffer from two potential weaknesses. With respect to other planets, either assumptions are made about the physical and chemical conditions of environments that err on the side of biological optimism without empirical constraint by spacecraft observations or novel physiologies of microorganisms are invented to fit extraterrestrial environmental conditions with no demonstrated microbiological counterparts on Earth. Attempts to assess the habitability of the early Earth suffer from similar problems. We discuss the following postulate: ‘the proposition that a planet is or was habitable requires that the physiological requirements of microorganisms on Earth known at the time of assessment match the empirically determined combined physical and chemical conditions in the extraterrestrial or early Earth environment being assessed’ as a means of evaluating ‘habitability’. We use as tests for our postulate the early Earth and the cloud deck of Venus (a habitat that has been a source of optimistic debate for forty years). We conclude that, although the early Earth was habitable, Venus is a dead world.

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Introduction

A pervasive problem in biology is assessing the habitability of planets for which there is a limited data set. The expense and logistical difficulty of launching missions to other planets and moons necessitates drawing biological conclusions based on vastly fewer data than are available for habitats on Earth. As we will show, any ‘mission’ to the early Earth also suffers from the limited availability of data.

The assessment of habitats on Earth as either ‘habitable’ or ‘uninhabitable’ can be approached by two means:

- (1) Direct human exploration of the region in question (e.g., Takami *et al.* 1997; Pimenov 2000). As most regions of the Earth are accessible multiple times within the budgets that can be acquired through research grants, it is possible for scientists to assess the habitability of environments directly. Initial datasets can be reviewed by returning to the site of interest.
- (2) Environments can be assessed by using as analogies environments that have been explored previously and that are known to possess very similar physical and chemical characteristics. For example, impact-shocked rocks in impact craters can be postulated to be a habitat for life on the basis that shocked rocks in certain craters on Earth are shown to be colonized (e.g., Cockell *et al.* 2002). Thus, a comparison of certain unexplored habitats to similar explored habitats on Earth allows an extrapolation of ‘habitability’ criteria (surfaces for

growth, liquid water, nutrients, light, etc.) to other habitats.

The assessment of actual or past habitats on other planets poses quite different problems for a number of reasons:

- (1) It is, for the time being, logistically difficult for scientists to physically visit extraterrestrial sites of interest.
- (2) The data that do exist are limited and may have been acquired by just a few spacecraft or by observations from Earth, thus greatly limiting the empirical basis of assessment of habitability.
- (3) The data gathered do not necessarily have a biological focus, because that might not have been the focus of the missions in the first place. For example, the concentration of the major macronutrient, nitrogen (in its various biologically accessible states) in the Martian regolith is still unknown, despite the numerous landers that have been to Mars and the obvious biological importance of this measurement.
- (4) Extraterrestrial environmental conditions are often very different to conditions known to support life on the present Earth, frustrating any analog parallels that can be used to assess the possibility for life. An obvious example is surface atmospheric pressure and composition, which is different for Mars, Venus and Earth.

In this exercise, we use the present-day Earth as our point of reference. However, the Earth itself evolved through time and so did its habitability. In this respect, the early Earth can be regarded as a different planet and the problems associated

with the assessment of its habitability are similar to those that challenge us regarding the other terrestrial planets. These problems are related to the fact that, although we have unlimited access to the locations where the oldest (3.5 Ga), well-preserved rocks occur, the data set is limited because, (i) there are only two localities where these ancient rocks are exposed (the greenstone belts of Barberton in South Africa and the Pilbara, Australia); (ii) these ancient terrains are already relatively young, having formed a billion years after the formation of the Earth; and (iii) the evidence for potential life in these rocks is disputed and, consequently, so is the habitability of the Earth at that time (Brasier *et al.* 2002; Schopf 2003; Westall & Folk 2003). The scarcity of the data points is related to the dynamics of a tectonically active planet where the process of lateral plate tectonics has caused the destruction of the oldest rocks.

In view of the inherent complexities in making comparisons between present-day Earth and other planets, including early Earth, one useful approach to the problem is to define a biological postulate that can be used to guide attempts to make comparisons and to arrive at conclusions on 'potential habitability' and the likelihood of life. In this paper we derive such a biological postulate and apply it to the habitability of the early Earth and the cloud deck of Venus as just two examples of locations that have been postulated to be sites for life.

A postulate for habitability

Owing to the different environmental conditions occurring on other planets compared to the Earth, and to the limited number of datasets available from spacecraft and Earth observations, it is necessary to create a bridge between what we know about habitats on Earth at present and the extraterrestrial or early Earth environment under consideration. In the case of early Earth the 'astrobiological gap' in the assessment of habitability can be filled by visiting the remnants of early Earth or in the case of extraterrestrial environments, by visiting the planet under study. Thus, the questions that remain about the habitat being studied can be directly addressed. However, if the database is poor, as in the situation of the early Earth, or if it is not logistically easy to visit the planet in question, the gap must be filled by using the existing data. Historically, in the literature, this gap has been bridged in two ways Fig 1.:

- (1) *Habitat assumptions.* Assumptions can be made about the physical and chemical characteristics of the early Earth or the environment on the planet under study. The problem with this approach is that it can, without conscious effort, err on the side of biological optimism, especially with respect to extraterrestrial environments. We can use, as an example, nitrogen as a limiting nutrient. Nitrogen is essential for the biosynthesis of proteins and nucleic acids. We know that nitrogen existed in the environment of the early Earth (Beaumont & Robert 1999; Pinti & Hashizume 2001), but we do not know in what biologically-available form it occurred. Likewise for

Mars, although the concentration of biologically available nitrogen in the Martian regolith is not known (Mancinelli 1996), there is nitrogen in the atmosphere. One might assume that this nitrogen could have been abiotically fixed into biologically-available nitrogen compounds during the past history of Mars. However, without direct observation of nitrogen in the regolith we empirically do not know whether it exists and therefore we cannot empirically assess the habitability Mars at present (although we could use models, but this is still not an empirical, biologically-motivated measurement of the amount of nitrogen available for life). As a result of these uncertainties there is a temptation to succumb to 'biological optimism' – making extrapolations from the particular environment being investigated that are most suited to proving life.

- (2) *Assumptions on life.* Theoretical life forms can be matched with the known or inferred conditions on the early Earth or in the extraterrestrial environment. This method of bridging the astrobiological gap is the most pervasive in the literature. In the case of extraterrestrial habitats, its inherent problem is the temptation to resort to 'invented physiologies'. Because of a desire to show that the habitat can support life, new physiologies with no counterparts on Earth are invented to show that life might be possible with a new innovation. The problem with this line of reasoning is that it requires a transgression from science into science fiction. With respect to the early Earth, the 'invented traits' reflect the various scenarios for the origin of life and the evolutionary steps from the first primitive cell to Last Universal Common Ancestor (LUCA). Or, moving further along the line of evolution, confounding the concept of microbial mat and stromatolite development with the necessary existence of oxygenic photosynthesisers, such as cyanobacteria.

The purpose of a postulate for habitability is to bridge the gap between the known and the hypothesised whilst attempting to reduce the chances of 'biological optimism'.

The principles are self-evident, but they need to be enunciated. One attempt at the enunciation of a habitability postulate might be:

'the proposition that a planet is or was habitable requires that the physiological requirements of microorganisms on Earth known at the time of assessment match the empirically determined combined physical and chemical conditions in the extraterrestrial or early Earth environment being assessed'.

How does this postulate help to reduce 'biological optimism'? First, we will take the case of habitat assumptions. The second part of the postulate ('the empirically determined combined physical and chemical conditions in the extraterrestrial or early Earth environment being assessed') requires us to confine ourselves purely to direct observations that have been made by spacecraft or from Earth. Thus, in the absence of a measurement of biologically-available nitrogen on the Martian surface we must conclude, 'we do not know whether Mars is presently habitable and we cannot

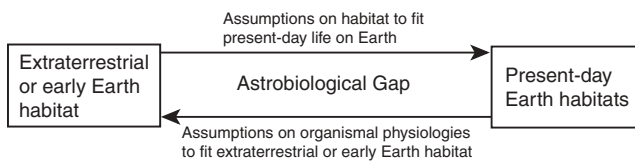


Fig. 1. The gap in knowledge between Earth and extraterrestrial or early Earth habitats is sometimes bridged with biological optimism.

know this until we know the concentration of biologically-available nitrogen'. Thus, until such measurements are made, any hypothesis concerning the presence of active life on Mars must remain a biological speculation. Likewise, for measurements of all other known macro and micro-nutrients required for life. Thus, the assessment of an extraterrestrial habitat as being conducive, or not as the case may be, for life requires the empirical measurement of *all* factors that are *currently* known to be critical to the kind of life being considered as a potential inhabitant.

The situation with respect to the early Earth is empirically somewhat rosier, but the actual data are subject to great debate. A lot more is known about the environment of the early Earth in general, than about Mars. However, the fact that interpretations have to be made indirectly from analyses of very ancient rocks that have undergone moderate to severe alteration leaves room for ambiguity and discussion. There are a number of reasons for this. (i) In the first place, as noted above, there are only two, localised, data points where the rocks are sufficiently well-preserved to represent the whole planet, (ii) The early Earth was significantly different to the present-day Earth in many environmental respects. Comparisons and contrasts need to be made using not only the terrestrial rocks, but also modelling and comparative planetology based on an understanding of the geological evolution of other planets, such as Mars and Venus. Direct measurements of potential nutrients that were in the early Earth environment cannot be made and we have to rely on proxy measurements of elements, such as nitrogen, or the isotopic ratios of such elements, that are trapped in mineral species (cf. Beaumont & Robert 1999; Pinti & Hashizume 2001).

The requirement to measure all the currently known nutrients in an extraterrestrial or early Earth environment may be a little too stringent. Models can provide realistic insights. However, in the absence of total knowledge of all physical and chemical parameters known to influence life, we are left with gaps. For example, models used to assess the ultraviolet radiation environment on Mars are an excellent example of where habitability is assessed using models rather than direct field observations. In this case light penetration through a CO₂ atmosphere is simple enough to be confident that these models give realistic insights on the UV flux at the Martian surface or on the early Earth (e.g. Kuhn & Atreya 1979; Cockell *et al.* 2000; Patel *et al.* 2004), but even they must be treated with caution as we do not know precisely the absorption properties of the ubiquitous Martian dust.

How does the postulate help us to reduce biological optimism in the assumptions on life? The most parsimonious way to prevent biological optimism is not to make assumptions regarding the biochemistry and physiologies of extraterrestrial life and to use only those physiologies currently demonstrated to exist on Earth. This is required in the first part of the postulate ('requires that the physiological requirements of microorganisms on Earth known at the time of assessment'). This seems intuitive, but for the case of Venusian exobiology 'biological optimism' has been a pervasive problem, as we will illustrate later. Even if a postulated physiology appears to be thermodynamically possible, it does not necessarily mean that it is biologically likely. There are costs and benefits to different modes of living. Thermodynamically plausible modes of existence in energy acquisition, motility, UV protection etc. may not occur if there are some unknown biological or biochemical reasons why such a physiology cannot exist (Haynie 2001). A possible example of such organisms is thermosynthetic organisms that use temperature differences as a source of energy (Muller 2003). These organisms seem thermodynamically possible, but they have never been observed on Earth. Their existence is therefore, by definition, science fiction at this time.

Thus, using the above suggested constraints, it is possible to bridge the astrobiological gap in assessing the possibility of life on other planets and in habitats on early Earth whilst at the same time minimizing the chances of falling prey to 'biological optimism', i.e., matching the environment to fit life or *vice versa*. If the postulate does not hold, the planet or the micro-environment is uninhabitable at the time of assessment. For the environment to become habitable either: (1) new information about the extraterrestrial or early Earth environment must be obtained that brings the previously 'uninhabitable' environment into the physical and chemical hyperspace for life, the classical Hutchinsonian 'ecological n-dimensional hyperspace' (Hutchinson 1957) or (2) new organisms must be discovered on Earth that could potentially grow in the previously 'uninhabitable' environment, i.e., new organisms must be discovered that fall within the physical and chemical hyperspace defined by the extraterrestrial or early Earth environment under consideration.

Life on Venus – test case I

The habitability of the clouds of Venus has been a matter of discussion in the exobiology community since the 1960s. The clouds of Venus provide an example of the way in which exobiological thinking develops in favour of life and it illustrates the potential value of a postulate on habitability. We will briefly review the life on Venus debate and apply the postulate as a test case.

The habitability of Venus has been a matter of speculation since the turn of the 20th century. Arrhenius (1918) speculated that the planet was covered in microbially-dominated swamps. Seckbach and Libby (1970) speculated that acidophilic algae lived in hot Venusian oceans near the poles.

Similarly, Ichinose and Folsome (1973) considered the habitability of Venus.

These early speculations were afflicted by the lack of knowledge about the environment of Venus at that time and limited knowledge about the range of microbial physiologies found on Earth. In the strictest sense, they do not conform to the second part of the postulate discussed here because at the time of assessment it was known that microbes required nitrogen, phosphorus, liquid water and a range of other macro- and micro-nutrients. Since at the time of assessment there was no empirical knowledge of the abundance of such elements and compounds on Venus, it was not possible to determine whether the physical and chemical environment fitted the physiologies of organisms known on Earth at that time. Thus, 'we do not know if the planet is habitable, we require more measurements' would have been a stance consistent with the postulate discussed here.

The conclusions of these scientists can be defended on the basis that models of the environmental conditions on Venus at that time did support the potential for Earth-like organisms (the greenhouse effect on Venus had not been revealed) and so it was reasonable for them to infer that liquid water existed and perhaps, knowing that Venus was rocky, other elements for life as well. These early authors did stay consistent with the first part of the postulate in that they only used organisms empirically known on Earth. Arrhenius considered swamps. Seckbach, on the other hand, was more specific and assessed Venus using the acidophilic alga, *Cyanidium caldarium*, concluding that it could grow. In that sense they did not succumb to biological optimism in their assumptions on life.

As models and observations of Venus improved, it became apparent that the surface is not conducive to life. The temperature of the surface is almost globally isothermal at 464 °C (see Marov and Grinspoon 1998 for a review). This is at least 340 °C higher than the currently known upper temperature limit for life (Kashefi and Lovley 2003) and there is no liquid water on the surface. Because of this apparent hostility, the clouds of Venus then became a focus of astrobiological studies, and have remained so to this day.

Morowitz and Sagan published a paper in 1967 in which they speculated on the existence of hydrogen-evolving float bladders in the atmosphere of Venus (Morowitz and Sagan 1967). They proposed that these organisms would float through the Venusian cloud layer and would be of size 75 microns to 4 cm. The paper was the first suggestion of a life form for the Venusian clouds. The problem with the hydrogen-evolving float bladders is that they do not exist in the cloud deck of Earth, although there are marine organisms, such as the nautiloids, that use buoyancy to regulate their position in the oceans of Earth (Odor *et al.* 1993). Thermodynamically, hydrogen-evolving float bladders might seem plausible, but the lack of them on Earth forces us, under the conditions of the postulate proposed here, to reject them on Venus. The paper, although presenting a beautiful idea, tried to bridge the astrobiological gap by conceiving of entirely new organisms to fit the extraterrestrial environment being

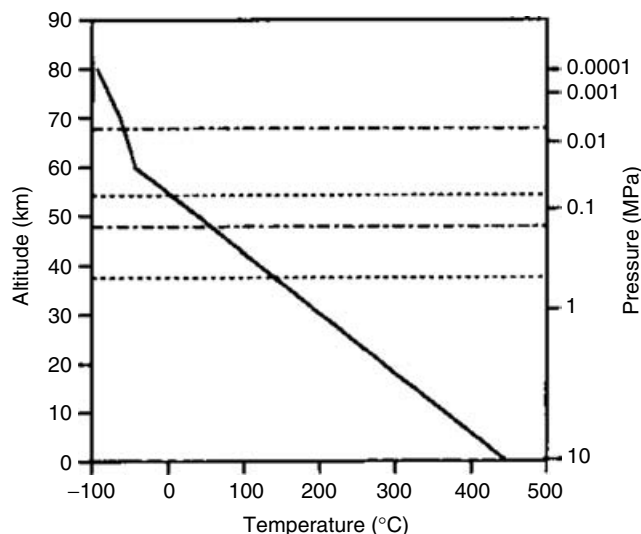


Fig. 2. The cloud deck of Venus has regions thermally favourable for life, but the other physical and chemical extremes in a cloud state have no counterparts in terrestrial clouds (dotted line marks region between 0 and 150 °C in the atmosphere and dash-dot line shows region of the Venusian clouds) (adapted from Cockell, 1999).

considered, and thus it falls foul of the first part of the postulate.

Since these early papers were written, a great deal of knowledge about the Venusian cloud layer has been gathered. The Venusian cloud layer contains sulphuric acid of concentrations between 81 and 98% (Marov & Grinspoon 1998). These concentrations present an extreme problem for osmoregulation in any putative cloud biota. Between 48 and 55 km the temperature and pressures within the clouds are similar to ground conditions on Earth, however (Figure 2). The UV flux at the top of the cloud layer, because of Venus's closer proximity to the Sun, is higher than on the surface of the Earth, although deeper in the clouds it is likely to be significantly reduced by CO₂ scattering and the presence of UV absorbers in the atmosphere.

There are a number of ways around the sulphuric acid problem. One could hypothesize the existence of micro-organisms that can tolerate this level of sulphuric acid that have not yet been discovered. However, the assumption of an entirely new physiology that has not been demonstrated on Earth requires a transgression into science fiction and is not tenable under the first part of the postulate. Another approach might be to assume that there are regions of the Venusian clouds that do not have sulphuric acid and are long-lived. However, this has not been empirically demonstrated at the time of writing. Thus, this assumption would also require a transgression into science fiction at the time of writing and it is not tenable according to the second part of the postulate.

The cloud deck was discussed as an abode for life by Cockell (1999). He concluded in a synthetic review that anaerobic sulphate-reducing chemoautotrophic organisms fitted the habitat most closely on account of the presence of sulphate as an electron acceptor, hydrogen as an electron

donor and the abundance of carbon dioxide and other elements such as phosphorus and nitrogen in an essentially oxygen-free environment. But the paper did not suggest the organisms were actually there. Cockell stated, 'Here, it is not proposed that organisms inhabit the clouds of Venus' and went on to examine microbial physiologies against the known physical and chemical parameters of the cloud deck as a 'theoretical exercise'. There is a small literary difference, but a large practical difference between examining extraterrestrial environments to see how close they come to being habitable and actually suggesting they are inhabited.

More recently there have been new proposals for organisms in the clouds of Venus that consider new types of physiologies for growth and survival in the cloud layer (Schulze-Makuch & Irwin 2002; Schulze-Makuch *et al.* 2004). Thus, the debate about life on Venus continues and it illustrates the breadth of discussions in assessing the environments of other planets and the potential value of a postulate.

At the time of writing what we empirically know about the cloud deck of Venus is that there is sulphuric acid at concentrations between 81 and 98% suspended as droplets. We know there is very little water in the clouds. One positive observation for life that we can make is that temperatures and pressures are favourable in certain regions. As we do not know *at the time of assessment* of any microorganism on Earth that naturally grows under these *combined* conditions in the aerosol state permanently in clouds, we should conclude, if we use the postulate formulated above, that Venus is a dead world. This is not to say that Venus *is* a dead world, but that *at the time of assessment* (in other words at the time this paper is being written) we must conclude that it is a dead world.

The early Earth – test case 2

The use of modern life on Earth as an analogy for ancient life has both positive and negative aspects. Obviously, dinosaurs and the weird but wonderful Ediacaran fauna have no modern analogues. But what about relatively simple organisms, such as bacteria? Using the theory of uniformity, the 'present is the key to the past', propounded by the 18th century Scottish geologist James Hutton, the first observations of microfossils in very ancient rocks described microorganisms in the 1.9 Ga Gunflint Formation of Canada that resembled the microbial mat and stromatolites-forming, oxygenic photosynthetic cyanobacteria (Barghoorn & Tyler 1965). Since then, a plethora of investigations reported a wide variety of microfossils (identified often down to species level) from increasingly older rocks up to the highly metamorphosed, 3.8 Ga Isua Greenstone Belt in SW Greenland. In the latter case, cyanobacteria-like and even yeast-like species were described (Pflug 1979; Pflug & Jaeschke-Boyer 1979; Robbins 1987). The well-preserved 3.5 Ga chert horizons of the Barberton (South Africa) and Pilbara (NW Australia) Greenstone Belts yielded many species of cyanobacteria, according to Schopf and Walter (1983), Schopf and Packer (1987), Walsh (1992), and Schopf (1993; 1998). The identification of

these organisms stimulated a closed cycle of further studies of modern cyanobacterial mats and the continued search for such organisms in the ancient rocks. The result of nearly 50 years of such investigations is the creation of a framework of understanding and search methodology that is rigidly locked into the identification of fossil cyanobacteria. Although cyanobacteria are wide ranging in morphology, they tend to be much larger than most other types of bacteria and exhibit the kind of cell differentiation that does not occur in other prokaryote groups. This makes them relatively easy to observe and identify with simple, optical microscopic methods. Moreover, the use of a more efficient energy-producing metabolism, that of oxygenic photosynthesis led to (1) a vast increase in the biomass and (2) an important influence on the precipitation of calcium carbonate. The prominent stromatolites so typical of the later Precambrian are a result of these two factors. Microbial mats formed by non-cyanobacterial microorganisms are, on the other hand, more subtle in terms of size, morphology and volume importance. They, and the microorganisms that form them, also require more sophisticated methods of observation, such as electron microscopes (Westall 1999; Westall *et al.* 2000).

The existence of cyanobacteria and yeasts in these very ancient rocks would imply very rapid evolution of life since oxygenic photosynthesis is a very sophisticated method of obtaining energy, while the yeasts belong to the eukaryote group. This produced a dichotomy regarding the environment of the early Earth because modelling, as well as the geochemical analyses of the rocks, suggested that the early environment was very poor in oxygen (Kasting 1993; Rye *et al.* 1995; N.B. Ohmoto (1999) contends, on the contrary, that oxygen levels were as high as they are today). The dichotomy can, however, be resolved very simply. It has been shown, for example, that the yeast-like and cyanobacterial microfossils from the Isua rocks are actually recent wind-blown or endolithic contaminants in the cherts (Westall & Folk 2003). With respect to the 3.5 Ga cherts from Barberton and the Pilbara, it has been suggested that the fossil cyanobacteria are most likely artefacts (Westall *et al.* 2001; Brasier 2002). Westall (2003a) demonstrates that, although life was relatively abundant in the Pilbara and Barberton cherts, it consisted of small microorganisms that formed mats in non-oxygenic environments. These microfossils, with extremely rare exceptions (e.g. Walsh 1992) are individually not visible with the optical microscope, although the mats that they form are (Walsh 1992; Westall *et al.* 2001; Westall 2003a).

Was the identification of cyanobacteria in the very ancient cherts simple biological optimism? Did it go against the biological postulate that the physiologies of the microorganisms should match the combined physical and chemical conditions? In fairness to the original interpretations, little was known about the environment of the early Earth and, thus, the interpretation of oxygenic photosynthesizers could be defended (the existence of sophisticated eukaryotes, such as yeasts, was rather surprising, however). The continued identification of such organisms in these rocks (e.g. Altermann & Kazmierczak 2003; Schopf 2003) might, on the other hand, be

an example of biological optimism and would be contrary to the postulate presented here. The problems involved in studying the most ancient habitats on Earth have obvious relevance to the study on actual and ancient habitats on other planets, such as Mars (Westall 2003b).

Conclusion

The assessment of environments on other planets or the early Earth as being 'habitable' or 'uninhabitable' needs a postulate that allows the environments and potential life to be evaluated with the minimum chance of 'biological optimism'. We have proposed such a postulate here. The postulate suggests firstly that the physical and chemical conditions determined by (in)direct analysis of rocks in the case of ancient terrestrial environments, and by Earth or spacecraft observations in the case of other planets are used as a basis to evaluate the environment as an abode for life. Secondly, the physiologies of known organisms should be used as the basis to assess the plausibility of a potential physiology capable of tolerating those conditions. When applied to Venus, it suggests that the planet is lifeless. With regard to the early Earth, it argues for a more realistic approach to the interpretation of early life and ancient microfossils. In view of the increasing number of worlds coming under scrutiny and the possibility that even the environmental conditions on the surface of Earth-like extrasolar planets might one day be empirically determined, the debate on the definition of 'habitable' and 'uninhabitable', and if habitable, by what type of life, has become a useful one for standardising approaches for the biological evaluation of other planets.

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