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The Call for a New Definition of Biosignature

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Abstract

The term *biosignature* has become increasingly prevalent in astrobiology literature as our ability to search for life advances. Although this term has been useful to the community, its definition is not settled. Existing definitions conflict sharply over the balance of evidence needed to establish a biosignature, which leads to misunderstanding and confusion about what is being claimed when biosignatures are purportedly detected. To resolve this, we offer a new definition of a biosignature as *any phenomenon for which biological processes are a known possible explanation and whose potential abiotic causes have been reasonably explored and ruled out.* This definition is strong enough to do the work required of it in multiple contexts — from the search for life on Mars to exoplanet spectroscopy — where the quality and indeed quantity of obtainable evidence is markedly different. Moreover, it addresses the pernicious problem of unconceived abiotic mimics that is central to biosignature research. We show that the new definition yields intuitively satisfying judgments when applied to historical biosignature claims. We also reaffirm the importance of multidisciplinary work on abiotic mimics to narrow the gap between the detection of a biosignature and a confirmed discovery of life.

1. Introduction

Scattered throughout the literature in astrobiology is a term central to the search for extraterrestrial life, that is, *biosignature*. This term, however, has been defined inconsistently by different individuals at different times. Taken in a very general sense, a biosignature is a phenomenon which signals the presence of life (extraterrestrial or terrestrial). Although many in the scientific community and elsewhere have a general conception of what the term biosignature refers to, its widespread adoption as a technical term belies a fundamental ambiguity. Is a biosignature supposed to represent tentative evidence, strong evidence, or overwhelming evidence (a true "signature") for life? In other words, is the detection of a biosignature only the beginning of the process of discovering extraterrestrial life, or is it the successful conclusion of it? Without some consensus on this basic question, the term may be positively unhelpful, obscuring more than it reveals about the quality and finality of the evidence to which it is applied. Given recent calls for clearer communication about life detection (Green et al., 2021; Malaterre et al., 2023), now seems an opportune moment to revisit and reunify the disparate definitions of a biosignature.

To provide a motivating example of this disparity, the often-cited definition from the NASA Astrobiology Roadmap (Des Marais et al., 2003) states that: "A biosignature is an object, substance, and/or pattern whose origin *specifically requires* a biological agent" (p.234, emphasis added). This definition implies a very strong condition for any candidate biosignature: something is a biosignature if and only if life has created it. Explicitly rejecting this in favor of a weaker definition with a wider domain of applicability, Catling et al. (2018) preferred to stipulate that "a biosignature is any substance, group of substances, or phenomenon that provides evidence of life" (p.710). Similarly, Pohorille and Sokolowska (2020) defined biosignatures as "chemical species, features or processes that provide evidence for the presence of life." Any observation that merely hints at the presence of life would fall within the scope of these modest definitions. This ambiguity over the strength of a biosignature is problematic because it leads to misunderstanding and confusion about what is being claimed when biosignatures are purportedly detected.

Hence, this paper provides a critical account of the term *biosignature* from a philosophical and methodological point of view and ultimately proposes a new definition that circumvents the shortcomings of existing definitions. Presently, §2 surveys the numerous definitions of biosignature in the relevant literature. This comprises both weak and strong definitions. Their various shortcomings will be discussed in turn. In response to the multitude of definitions, §3 argues that a pluralist approach to biosignature definitions cannot be sustained. Hence, §4 both makes and responds to the call for a single definition of biosignature that avoids some of the limitations saddled on previous definitions. The resulting definition is a pragmatic one that recognizes the epistemic limitations of current biosignature research. §5 then applies the new definition to three significant historical biosignature claims; it is found that the new definition is in line with intuition. Some broader implications of the new definition are then discussed in §6 with a focus on multidisciplinary research and, finally, §7 summarizes the key arguments of the paper.

2. Working Definitions of Biosignature

The term "biosignature" appears increasingly in academic journals and popular science magazines alike. With this growing popularity, however, comes a growing catalogue of discrepant definitions (e.g., Thomas-Keprta et al., 2002; Des Marais et al., 2003, 2008; Catling et al., 2018; Pohorille and Sokolowska, 2020). All definitions involve an inferential relationship from the detection of a biosignature to the existence of life. The strength of that inference is, however, ambiguous. In the present study, we classify the various definitions in the relevant literature according to the strength of this inferential link, as follows.

2.1. Definitions with Weak Biosignature-to-Life Inferences

A modest definition of biosignature was defended by Catling et al. (2018). These authors proposed that "a biosignature is any substance, group of substances, or phenomenon that provides evidence of life" (p.710). Similarly, Pohorille and Sokolowska (2020) defined biosignatures as "chemical species, features or processes that provide evidence for the presence of life." The broad requirement that a biosignature *provide evidence* of life is significant in allowing any number of observations, with sliding scales of life-confirmation, to enter the ranks of biosignature. Now, this weakening of the term is deliberate and is done so that the term can be confidently used in practice, given that the science of life detection necessarily relies on data of limited quality and completeness. By allowing biosignatures to include observations that provide less than complete confidence in life, the term is made useful and escapes redundancy.

This pragmatic approach to biosignatures is seen also in the work of Schwieterman et al. (2018). They discussed the validity of considering a signal to be a biosignature when there is a non-zero probability that it had a non-biological origin. Correspondingly, Schwieterman et al. recognized that a definition of biosignature that allows for no leeway when regarding possible abiotic causes would always need to be prefaced with *potential.* No known or immediately foreseeable signal in exoplanet spectroscopy could be regarded as a biosignature on such a definition, only a *potential* biosignature. Schwieterman et al., therefore, provided an alternative definition of biosignature as "the presence of a gas or other feature that is indicative of a biological agent" and hence "a gas may be a biosignature gas, even if the gas may have nonbiological sources (2018, p.666)." The authors pointed out that such a relaxed definition of biosignature guards against overconfidence by acknowledging the uncertainty inherent in life detection science. But do we really want even *very weak* evidence to count as a biosignature? This seems to stray from the intuitive conception of the term.

Consider, for example, Percival Lowell's sensational interpretation of apparent markings on Mars' surface. Lowell attributed these markings to canals built by an ancient Martian civilization (Lowell, 1908, 1906, 1895). In his popular books, Lowell illustrated hundreds of these alleged canals, and he advanced the theory that they were created to transport water from Mars' polar caps to its equator. Lowell would use his canal theory to argue for the existence of life on Mars, concluding (somewhat meanderingly) "That Mars is inhabited by beings of some sort or other we may consider as certain as it is uncertain what those beings may be" (Lowell, 1906, p.376).

On the definitions offered by Catling et al., Pohorille and Sokolowska, and Schwieterman et al., Lowell could have justifiably insisted that his canals were biosignatures, since his observations did provide some (ultimately refuted) evidence for the existence of life. But most of Lowell's scientific contemporaries dismissed his views because more mundane alternative explanations involving geological features or optical illusions had not been ruled out (e.g., Evans and Maunder, 1903; Wallace, 1907); such mundane alternatives were ultimately vindicated. It is intuitively unacceptable for any observation whatsoever to count as a biosignature if it is merely consistent with the presence of life when alternative (plausible) explanations have not been ruled out.

Another study suggesting only a weak inference from biosignature to life is that of Neveu et al. (2018). These authors characterized biosignatures as follows: "Biosignature measurements directly seek features characteristic of life (such as complex organic matter not known to be formed through only chemical reactions or concentrations of biologically necessary or useful elements) as evidence of ongoing or past biological processes." (Neveu et. al., 2018, p.1). The two examples after the "such as" are, however, very different. The first suggests a definition stronger than the Catling et al., Pohorille and Sokolowska, and Schwieterman et al. definitions with the requirement that the measurement not be known to form through non-biological reactions alone. But the second, by permitting observations of concentrations of biologically necessary or useful elements to rise to the ranks of biosignature, suggests a considerably more liberal definition. Although Neveu et al. stressed the importance of context in evaluating whether the observation may have an abiotic explanation, it is hard to see how concentrations of oxygen, or phosphorus, or any biologically useful element could be considered a biosignature in themselves (rather than just evidence of habitability as we might prefer to say) except on a very broad definition that would encompass a multitude of possible observations only weakly suggestive of life. Overall, then, the Neveu et al. definition faces the same limitations as the Catling et al., Pohorille and Sokolowska, and Schwieterman et al. definitions. A definition for biosignature that is more restricted in its conditions is required to exclude observations that should not be considered even passably good evidence for life.

2.2. Definitions with Strong Biosignature-to-Life Inferences

The widely cited NASA Astrobiology Roadmap (Des Marais et al., 2003) definition of biosignature states that "A biosignature is an object, substance, and/or pattern whose origin specifically requires a biological agent" (p.234)." Hence, the substance is a biosignature if and only if life has caused it: the discovery of a biosignature inescapably implies the existence of life itself in the environment under scrutiny. Such a strict definition is not vulnerable to the charge of having too low a bar for what constitutes a biosignature. Certainly, there is no risk of false positives sneaking into the list of NASA Astrobiology Roadmap (Des Marais et al., 2003) biosignatures. But might the bar actually be too high?

This strong definition, in practice, could almost never be used on account of the uncertainty that shrouds prospective biosignatures. The stipulation that the observation specifically requires a biological agent necessitates that all possible abiotic origins for the observation have been ruled out. It might seem at least possible to rule out all *known* abiotic alternative explanations, but how does the community go about ruling out the unknown ones? This "problem of unconceived alternatives" — explored more generally by Stanford (2001, 2006) — surfaces continually within philosophy of science literature. Briefly, the problem concerns how a community can be certain of the truth of their current hypotheses if unforeseen alternative hypotheses may well be equally or more successful. Such underdetermination is worrisome as it throws into question the validity of any particular theory.

The problem of unconceived alternatives is particularly salient in the discovery and interpretation of signs of life (Vickers et al., 2023). Astrobiology is a relatively immature field; breakthrough discoveries (in terms of observations, technology, and theory) are frequent. The field is growing, and potential research areas are rich. The implication is that there exists a vast pool of alternative candidate hypotheses that have yet to be explored. In particular, there may be innumerable abiotic processes that mimic evidence of life of which we cannot yet conceive. These abiotic processes might include mechanisms that create organized and complex pseudofossils (McMahon and Cosmidis, 2022), or a stable and significant disequilibrium of oxygen and methane (as long as a suitable energetic process is able to sustain such a disequilibrium, it would not violate the laws of physics).

The NASA Astrobiology Roadmap (Des Marais et al., 2003) definition fails to account for the intellectual modesty required by the problem of unconceived alternatives. Unless, of course, advocates of this strong definition are content only to use the term with a prefacing qualifier such as *weak*, *modest*, *strong*, or *potential*. Indeed, the 2003 Astrobiology Roadmap offers a separate definition for a *potential* biosignature: "A *potential biosignature* is a feature that is consistent with biological processes and that, when it is encountered, challenges the researcher to attribute it either to inanimate or biological processes. Such detection might compel investigators to gather more data before reaching a conclusion as to the presence or absence of life" (Des Marais et al., 2003, p.234). This definition for potential biosignature captures the possibility of life as the cause but acknowledges that more data are needed for a conclusive determination of biogenicity. The requirement for the feature to "challenge" the researcher excludes trivial observations that are merely consistent with life without being seriously suggestive of it, assuming that "the researcher" is reasonably well informed about both "inanimate [and] biological processes." Hence, this definition is practicable and — an additional strength — seems implicitly to encourage the driving forward of science to increase confidence in a potential biosignature.

However, the question remains as to how — or whether — a potential biosignature can graduate to an *actual* biosignature as investigators gather more data. Under the two definitions provided by the 2003 Astrobiology Roadmap, it is apparent that this transition occurs only when there is complete confidence that the feature in question "specifically requires a biological agent," a threshold that may be extremely difficult to meet in practice regardless of how much data are gathered (not least because of the problem of unconceived alternatives). The term "potential biosignature" seems to be applicable to candidate life-detections with all degrees of confidence in biogenicity up until the limiting case of complete confidence (in which case the word "biosignature" is arguably redundant since what has been found is just *life*). A more lenient definition of biosignature that can work more effectively in tandem with "potential biosignature" is still needed.

Gargaud et al. (2009) also criticized definitions of biosignature that require the ruling out of all possible abiotic explanations. They recognized that this cannot, in practice, be done. As a result, Gargaud et al. remarked that "the word bio-signature is frequently used in an abusive way" (2009, p.595), and therefore they advocated for the term "bio-indices" instead. Bio-indices would have a lower threshold for confirmation than the NASA Astrobiology Roadmap (Des Marais et al., 2003) definition of biosignature. However, this term would fall within the class of weaker definitions subject to the same issues raised in §2.1. Moreover, introducing a new term to do the work of an existing term is cumbersome; perhaps all we need is a considered and unified repackaging of what it is to be a biosignature.

3. Should we embrace a plurality of definitions?

The above discussion has critiqued the popular definitions of biosignature to be found in the literature. It has been shown that these definitions exist along a scale of increasing exclusivity to observations that can be explained solely by the presence of life. The weaker of these definitions might deem a biosignature an observation that could be caused by life but could also be caused by abiotic processes, such that the observation in question is only weakly indicative of life. Conversely, stronger definitions require the total ruling out of abiotic causes, leaving the presence of life as the sole explanation. One might respond to this multitude of definitions by taking a pluralist view, on which different definitions of biosignature are appropriate to different measurement contexts and can thus coexist unproblematically. The consequence of this would be that no individual definition of biosignature should be universally preferred over any other. Moreover, apparent flaws in each definition might be neutralized given the specific context of applicability.

A parallel example is the pluralist approach to the definition of life. Even within science, the term has a multiplicity of definitions, but a popular one emerged from a committee gathered by NASA to discuss the possibility of life in the cosmos: "Life is a self-sustaining chemical system capable of undergoing Darwinian evolution" (Joyce, 1994). This definition is intuitive, precise, and widely cited. However, alternative conceptions of life in the disciplines of evolutionary biology, molecular biology, synthetic life, and the origins of life have been widely discussed (e.g., Machery, 2012; Mix, 2015).

Each discipline calls for a different focus on what constitutes life, and each discipline uses the term for its own ends. Any attempt at a unified definition would fail to do the work that each discipline needs (Machery, 2012). To argue that there is or should be an absolute and single definition of life would betray how the word is used, and therefore a pluralist definition of life is motivated on these grounds. The differing definitions need not be competing; rather each is suitable within its own context.

These differing definitions of life are justified insofar as the differences exist between disciplines, not within them. To prevent miscommunication, there needs to exist a shared language within research fields and thus a shared understanding of which definition of life is being employed. There indeed exists lively and fruitful debate about the most suitable definition of life within the field of astrobiology (e.g., Benner, 2010) — definitions that center on metabolism, for example, are popular. Such disagreement might be attributed to the varied fields that contribute to astrobiology, but many within the discipline clearly feel the need for a shared definition. So, to summarize, pluralism about the definition of life is justified, but with the general maxim of one definition per field.

Pluralism about the definition of a "biosignature" within astrobiology fails for the same reason. All discussed definitions of biosignature are applied within the astrobiology community, where those seeking evidence of life in different contexts communicate frequently with each other through the same meetings and journals (and are often simply the same people). Hence, a pluralist account of the term is likely to create more problems than it solves. To have a multitude of definitions for a single term in the same field would incite confusion and misinterpretation. One subset of astrobiologists may proclaim that the conditions for deeming an observation to be a biosignature have been met, only to be challenged by scientists from an adjacent area of astrobiology with stricter conditions. It is easy to imagine interpretation of evidence being blamed for the confusion when something as simple as misaligned definitions — an unnecessary semantic disagreement — is at fault.

4. The New Definition

The unity of astrobiology calls for a single definition of biosignature. Previous definitions discussed in this paper, however, have either allowed the admission of *any* observation that could result from life or been found impractical on the grounds of the problem of unconceived alternatives. With these considerations in mind, we propose the following definition of biosignature:

A <u>biosignature</u> is any phenomenon for which biological processes are a known possible explanation and whose potential abiotic causes have been reasonably explored and ruled out.

The first half of the definition requires that life be a possible explanation for the observation. This includes the requirement that the environment in which the phenomenon originated was habitable at the time. Regarding the second half, the definition does not require absolute confidence in a biotic origin, but it does capture the requirement that the accessible (given the scientific understanding of the time) abiotic alternative explanations be uncovered and disqualified. What is more, unconceived alternative abiotic explanations that are not readily in reach need not be ruled out (which, of course, they cannot be). As a result, the above definition is stronger than the widely cited Catling et al. definition but not as strong as that of Des Marais et al. (2003).

There are two significant features of this definition that should be explored: the first concerns the phrase "reasonably explored and ruled out" and the other addresses the gap between a biosignature and life. To better pin down and understand the implications of the proposed definition, these features will be discussed in turn.

4.1. "Reasonable" Exploration and Ruling Out

The requirement that the potential alternatives be *reasonably* explored and ruled out must be explicated. Much discussion has been devoted to the inability to rule out all the unknown abiotic explanations (§2.2

of this paper, and, e.g., Vickers et al., 2023). This problem is avoided when focusing just on the known ones, but it is still not possible to rule out all known alternative explanations *with absolute certainty*. Such certainty is rare in any science, let alone in the rapidly developing field of astrobiology. Nonetheless, a high bar must be set to ensure that the term *biosignature* carries weight. For the alternative non-biological explanations to be reasonably explored and ruled out, three considerations should be made; these concern time, attention, and consensus. Concerning time and attention, these are necessary to attempt to lessen, though unlikely close, the gap between the list of known alternative explanations and the list of unknown ones. Giving time and attention to a biosignature claim will ideally reveal additional hypotheses about possible non-biological origins that were not initially considered, and these further lines of enquiry can then be explored and closed (Green et al., 2021).

On the path to a phenomenon being categorized as a biosignature, it may enter an intermediate phase where 1) life has been identified as a possible cause of a phenomenon, 2) there does not currently exist a complete abiotic explanation, but 3) the community has not yet given the time nor attention needed to reasonably explore and rule out abiotic alternatives and consequently a consensus has not been met. This is where the term *potential* biosignature would be most appropriate. We might even define a potential biosignature as follows:

A <u>potential biosignature</u> is any phenomenon for which biological processes are a known possible explanation but whose potential abiotic causes have not yet been reasonably explored and ruled out.

This proposal is in good alignment with the NASA Astrobiology Roadmap (Des Marais et al., 2003) definition of potential biosignature.

The adoption of our definition for biosignature would enable debates about whether something is a biosignature to focus on the science rather than the semantics. To justify classifying a given phenomenon as a biosignature, a researcher need only conclude that the accessible alternative explanations have been reasonably explored and ruled out. Those who think they have not been ruled out will disagree that the phenomenon is a biosignature. This is a substantive disagreement that will drive the science forward, not a fruitless semantic one. Nevertheless, if there is significant disagreement in the community about whether alternative explanations have been reasonably ruled out, this in and of itself would tend to suggest that they have not. Thus, particularly for non-experts or journalists hoping to evaluate whether something is or is not justly called a biosignature, the state of consensus in the field is significant.

An appeal to the level of consensus in the scientific community as a gauge to confidence in a scientific statement is not novel. The Intergovernmental Panel on Climate Change (IPCC) employs a metric where broad scientific agreement increases confidence in statements about climate change (Mastrandrea et al., 2010). The theoretical backdrop to the framework is that increasing consensus tracks with decreasing uncertainty. Transferring this framework to ascertaining confidence in biosignature claims has already been proposed and motivated (Vickers et al., 2023).

It is expected that the level of consensus will grow over time and the rate of this will depend on various relevant factors. The amount and quality of evidence would be influential: as would availability of relevant theory and technology. Some scientists would be willing to call an observation a biosignature before others, but it is when there is significant consensus in the community that the possible abiotic explanations have been reasonably explored and ruled out, that an observation should be called a biosignature.

4.2. The Gap Between Biosignatures and Life

Let us imagine that an observation meets the requirements for a biosignature, under this definition. This is to say that the abiotic alternative explanations have been reasonably explored and ruled out. The question will naturally arise of how certain one can be of its biotic origin. Could the community attempt to quantify their confidence in a biotic cause; might they ascribe 30%, 50%, or 70% confidence? Unfortunately, the choice of quantifier is itself unlikely to be robustly underpinned by available evidence. To assert that we are, say, 70% certain of the biotic origin of a biosignature is to suggest that we have exhaustively explored the causal possibility space for the biosignature and have determined that the abiotic causes have a 30% chance of providing the cause, and a biotic origin has a 70% chance. Yet, as noted previously, there is an acute problem of unconceived alternatives in astrobiology: we have not exhaustively explored the causal possibility space in any of the contexts where biosignatures are sought.

NASA-affiliated researchers have proposed a confidence ranking with a seven-point scale – the "confidence of life detection" (CoLD) scale (Green et al., 2021). The purpose of the CoLD scale is to standardise the stages that a potential biosignature moves through as its biotic origin is tested. The certainty that any observation derives from life increases as the observation moves up the scale, with level seven corresponding to "confirmation of the presence of biology" (Green et al., 2021, p.577). Significantly, level four requires that "all known non-biological sources of signal shown to be implausible in that environment" (p.577). This is indeed a realistic and achievable goal and the new definition of biosignature is in line with this. However, the CoLD scale quietly closes the gap between having ruled out all the *known* alternatives and having ruled out all the *possible* alternatives. To arrive at level seven, with the confirmation of biology, an assumption is made that the known alternatives at this point comprise the complete set of alternatives. Clearly, the gap between level four and level seven may be very large or very small depending on the extent to which the alternatives have been explored, and this ambiguity undermines the usefulness of the scale (see the discussion in Section 3 of Vickers et al. 2023).

The limitations of our knowledge of the relevant possibility space are made salient in McMahon and Cosmidis' "False biosignatures on Mars: anticipating ambiguity" (2021). Speaking specifically about geological biosignatures on Mars, they recognize that, to rule out abiotic mimics, not only do the mimics need to be discovered in the first place (which typically happens by serendipity rather than forethought), but the mechanisms of these mimics need to be understood in enough detail to predict how and when such mimics will arise (p.28). It is simply not the case that we sufficiently understand all possible abiotic mimics: "given the haphazard and unsystematic way in which varieties of false biosignature have so far been identified, we can only assume that many others remain undiscovered" (McMahon and Cosmidis, 2021, p.29).

With levels of confidence dependent on the evaluation of a possibility space that is simply not wholly accessible to us, quantifying the certainty of an observation's biotic origin becomes tricky. What is instead achievable is assessing how thoroughly we have ruled out the known abiotic mimics. We have argued that, for any given phenomenon to qualify as a biosignature, we should require that the known abiotic causes have been reasonably explored and ruled out. The jump from there to the conclusion that the phenomenon is most likely caused by life remains just that – a jump. The most that can be done is to assess whether the conditions for a biosignature have been met and to acknowledge that this is simply our best guess at the validity of any life-detection claim. There is therefore an epistemic gap between something being classified as a biosignature and that thing being caused by life. As our understanding of abiotic mimics and the conditions of habitable worlds progresses, this gap might be narrowed, but it should nonetheless be made explicit.

5. Applying the New Definition

Having motivated a new definition, it remains to apply the definition to past claims of biosignature detection to assess how the term might be used in practice and how it might have helped mitigate the bumpy and revisionist history of biosignatures. Despite the lack of consensus in the evidentiary criteria of a biosignature, biosignature claims have been abundant throughout the history of astrobiology; with the hasty retraction of such claims being almost equal in number.

5.1. ALH84001

A prominent case study to test the proposed definition of biosignature comes from the Martian meteorite discovered in Antarctica 1984: Allan Hills 84001 (ALH84001). In a paper in *Science* in 1996, McKay et al. argued that the evidence supports a conclusion that Martian microorganisms lived on the meteorite. The authors highlight three key observations regarding apparent fossil structures on the meteorite and conclude that "although there are alternative explanations for each of these phenomena taken individually, when they are considered collectively, particularly in view of their spatial association, we conclude that they are evidence for primitive life on Mars" (McKay et al., 1996, p.929). The likelihood of an abiotic cause that neatly explained all three lines of evidence seemed, to the researchers, much smaller than explaining one of them alone, whereas the presence of life on Mars appeared to account for the three observations well.

Having said this, the Martian microorganism hypothesis was not uncontroversial even in 1996. Alternative explanations including volcanic activity, impact events, and hydrological exposure were suggested but were unable to be convincingly demonstrated as the cause at the time (e.g., Harvey & McSween, 1996). However, a series of progressive refutations over the following 25 years provided abiotic explanations for each of the three key observations (see, for example: Golden et al., 2001, 2004, 2006 and Bell, 2007). Most recently, Steele et al. (2022) showed that mineral carbonation and serpentinization reactions on an early Mars explain the occurrence of organic matter in the meteorite. Importantly, it is recognized that advancements in relevant technology made this discovery possible. The claim that ALH84001 harbored fossilized Martian microorganisms was largely debunked and its status as a biosignature invalidated. How, though, would this event have played out if the new definition of biosignature were employed? Should the structures on ALH84001 have been classified as a biosignature?

The answer to this depends on whether the accessible (*at the time)* non-biological alternative explanations were reasonably explored and ruled out. In this example potential abiotic causes were suggested before they could be fully tested (in part because methodological advancements were needed). Nonetheless, such limitations in technology should not validate a total bypassing of the exploration of any suggested abiotic explanation. In the case of the structures on ALH84001, fruitful lines of enquiry remained open. Potential abiotic causes were not reasonably ruled out and consequently, the structures on ALH84001 should not have been considered a biosignature, either in 1996 or subsequently.

5.2. Stromatolites 3.7 Billion Years Old

Consider now a terrestrial biosignature claim. Astrobiology, broadly construed, also encompasses the study of early life on Earth and the term *biosignature* is also correspondingly used for terrestrial life. Among the oldest accepted biosignatures are stromatolites in the East Pilbara Terrane, dating back to around 3,500 – 3,400 million years ago (e.g., Walter et al., 1980; Van Kranendonk et al., 2008; Baumgartner et al., 2019). However, Nutman et al. (2016) argued for the existence of yet older stromatolites in 3,700 million-year-old rocks in the Isua supercrustal belt of southwestern Greenland. Nutman et al. offered both a positive account for how life could have produced these structures, and a negative account of the competing abiotic explanations: after considering four features which particularly evaded non-biotic explanation, they concluded that "we rule out an abiogenic origin for Isua stromatolites" (2016, p.3).

However, only two years later, Allwood et al. (2018) challenged the biotic explanation and instead offered an abiotic cause for the proposed stromatolites. Allwood et al. attributed the apparent stromatolites to structural deformation and geochemical alteration of the rock. The debate continues: Nutman et al. (2019, 2021) responded to Allwood et al. (2018), and the discussion remains lively (e.g., see also Zawaski, et al., 2020). So how might these potential stromatolites in be best categorized? A biotic account has been provided. Abiotic explanations, however, are still actively under investigation. and there is a lack of consensus. The term "potential biosignature," as defined in §4.1, is therefore most appropriate in this case.

5.3. Petroleum

The story of Earth's major crustal petroleum accumulations offers an example of a terrestrial biosignature claim whose biogenicity has historically been controversial. Towards the end of the 19th century, it was concluded by various North American geologists that petroleum originated from the remains of marine animals and plants; they began to recognize organic-rich, fossiliferous shales as the source rocks (e.g., Hunt, 1963; Lesquereux, 1866; Newberry, 1873). By the middle of the 20th century, it was clear that many of the molecular constituents of petroleum could be traced back to specific biomolecules such as porphyrins and bacterial membrane lipids (Treibs, 1936).

Nevertheless, the hypothesis of a non-biological origin of petroleum was maintained by a vocal minority of Soviet and American scientists in the late 20th century who argued that oil is produced by non-biological chemical reactions at high temperatures and pressures in the deep crust or mantle (e.g., Kudryavtsev, 1951). They argued that biological molecules in the oil were simply contaminants. These dissenting voices were prominent particularly in the Soviet Union; in the West, they notably included the astrophysicists Fred Hoyle and Thomas Gold (Hoyle, 1955; Gold, 1985). The theory of abiotic petroleum seemed to be supported by evidence for hydrocarbons on other planetary bodies in our solar system, such as asteroids and comets (Cronin et al., 1988).

The origin of oil is now exceptionally well understood. Each stage of the production of petroleum from organic biomass via natural processes of decay, diagenesis, and catagenesis has been explored in the field and in the laboratory (e.g., He, 2018). We know that sedimentary rocks rich in biological organic matter are effective source rocks for oil, and we can explain the origin of all the world's major economic petroleum reserves very well on the biological model. Abiotic hydrocarbons, especially methane, do occur naturally but do not contribute significantly to the world's known petroleum resources (Sherwood Lollar et al., 2002; Walters, 2017). Petroleum contains a suite of biomarker molecules that only biological processes could generate in such quantities and distributions, and these molecules derive overwhelmingly from the same source as the oil itself, that is, ancient biomass (e.g., Grantham & Wakefield, 1988). There is no longer any doubt that the vast majority of the world's oil derives from this. This understanding has been extensively tested and put into practice by oil companies and geologists.

From the suggestion of petroleum as biotic in origin, up to its wide acceptance as such, petroleum could aptly have been described as a *potential* biosignature. Life was recognized as a coherent explanation, but time was needed to investigate the abiotic alternatives. Field and experimental evidence in the late 20th and early 21st centuries settled the debate. Petroleum with a composition like that of the major oilfields on Earth (which is markedly distinct from abiotic hydrocarbon accumulations) now stands as a biosignature under the proposed definition.

5.4. Table of Categorization

The three case studies considered above show how the new definition might be used in practice and how it might help avoid hasty conclusions regarding the presence of life. Examples of neither biosignature nor potential biosignature (structures on ALH84001), potential biosignature (3.7Gyr stromatolites), and biosignature (petroleum) have been discussed. The following table sorts a wider selection of terrestrial and extraterrestrial biosignature claims throughout recent history into these three categorizations. A brief explanation for the categorization is provided, though the decision over biosignature status is only the opinion of the authors and should alternatively, in practice, be arrived at collectively by the scientific community.

Phenomenon	Biosignature	Potential Biosignature	Neither	Justification
Combined features of meteorite ALH84001 (McKay et al., 1996)			✓	Some possible abiotic causes were known at the time, but could not be ruled out (e.g., due to technological limitations).
3.7 Gyr Stromatolites (Nutman et al., 2016, 2019, 2021; Allwood et al., 2018)		✓		Life has been proposed as a convincing explanation for these candidate stromatolites (Nutman et al., 2016). However, the debate is lively with possible abiotic explanations suggested (Allwood et al., 2018), alongside counter arguments (Nutman et al., 2019, 2021).
Petroleum (major accumulations)	✓			A biotic explanation exists, and any abiotic explanations have been well considered and ruled out.

"Sinton bands" indicating life on Mars (Sinton, 1959)			✓	The abiotic cause of telluric water vapor (Rea et al., 1965) was reasonably within reach at the time, yet was not ruled out.
Viking Labelled Release experiment		✓?	✓?	Abiotic explanations have been suggested (see, for example, Navarro-González et al., 2010), but there is still a lack of consensus; no account is completely satisfying as yet. Such grey-area cases are to be expected.
Oumuamua as an alien artefact		✓		A (somewhat outlandish) biotic explanation exists (Loeb, 018; Bialy and Loeb, 2018) to explain Oumuamua's unusual properties. However, an abiotic explanation is in development (Bergner & Seligman, 2023); debate remains lively.
3.8 Gyr Carbon Isotopes		✓		A biotic explanation is available, but debate is ongoing, and the picture is unclear (see e.g., Lepland et al., 2005)
Venusian Phosphine (Greaves et al., 2021)			✓	Although phosphine above a certain abundance on Venus might well be considered a potential biosignature, its presence in the cloud decks of Venus has been disputed (Villanueva, 2021).

Table 1: Selection of biosignature claims and their suggested categorisation as either a 1) biosignature, 2) potential biosignature, or 3) neither, under the proposed definition of biosignature.

6. Broader Implications of the New Definition

The new definition requires the explicit exploration and ruling out of non-biological explanations for the term *biosignature* to be used. The examples in Table 1 of phenomena that are *not* biosignatures show that non-biological explanations often arise from differing areas of science. For example, the fossil-like structures on ALH84004 were elucidated by research into the conditions on an early Mars and the effects of fluids on rocks; open questions regarding Oumuamua's non-biological origin concern the outgassing of exotic volatiles and comparisons with the trajectories of unusual comets like 2P/Encke; and, in the case of Sinton bands, the prevailing explanation came from atmospheric science and physics.

What these varied explanations show is that an unconceived alternative explanation may be hiding in any domain of science. If we are truly to rule out the known or accessible abiotic causes of any observation, a multidisciplinary effort is required. Possible explanations need to be pulled from broad fields and explored collaboratively. Such an approach will more effectively uncover new abiotic processes, leading to a more complete exhaustion of the causal processes at play in astrobiology. More generally, if the epistemic gap between a biosignature and life is to be narrowed, a multidisciplinary approach to abiotic explanations will be essential. The narrowing of the gap between known abiotic mimics and possible abiotic mimics will lead to the narrowing of the gap between a biosignature and an actual detection of life. Hence, the new definition reaffirms the widely held view that, for astrobiology to flourish, collaboration between its composite disciplines is essential.

7. Conclusions

This paper has presented and discussed the various definitions of the term *biosignature* extant in the literature. Definitions that require all possible (known and unknown) abiotic causes for the observation to be ruled out are impracticable, particularly given the problem of unconceived alternatives. Definitions that simply require life to be *a* possible explanation are too weak to justify the term *biosignature*. We have considered a pluralistic account of the term but argued that astrobiologists working on the search for life in different contexts constitute a single community in which a multiplicity of definitions for the same term is bound to cause unnecessary confusion. We, therefore, claim that a single definition of biosignature is needed. We repeat here the definition we have proposed and defended:

A biosignature is any phenomenon for which biological processes are a known possible explanation and whose potential abiotic causes have been reasonably explored and ruled out.

This definition acknowledges the problem of unconceived alternatives: the need to rule out all *unknown* abiotic causes before identifying something as a biosignature is removed and the proposed definition is sympathetic to the call for a pragmatic definition pursued by Schwieterman et al. (2018) that strikes the balance between exclusivity and usability. The proposed definition has been applied to historical cases to illustrate how the definition would work in practice.

Finally, we have acknowledged that discovering a biosignature is not the same as discovering life itself; biosignatures are limited, observable proxies for life and are inherently uncertain. Definitions of biosignature that overlook this gap (e.g., NASA Astrobiology Roadmap, 2003) are impracticable. For any observation, this gap should narrow as a greater understanding of abiotic processes builds and these abiotic alternative explanations can be explored and ruled out. The proposed new definition encourages such progress by requiring that, for something to be a biosignature, potential abiotic causes must have been reasonably explored and ruled out.

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CG wrote the article with input from all authors.

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