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Explaining the Past in the Geosciences

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Abstract Abductive reasoning is central to reconstructing the past in the geosciences. This paper outlines the nature of the abductive method and restates it in Bayesian terms. Evidence plays a key role in this working method and, in particular, traces of the past are important in this explanatory framework. Traces, whether singularly or as groups, are interpreted within the context of the event for which they have evidential claims. Traces are not considered as independent entities but rather as inter-related pieces of information concerning the likelihood of specific events. Exemplification of the use of such traces is provided by dissecting an example of their use in the environmental reconstruction of mountain climate.

Keywords Geoscience · Bayesian · Abduction

Geosciences, which encompass geology, physical geography, ecology and other field-based studies, as well as modelling and simulation studies of the physical environment, have long looked to the 'hard' sciences for their philosophical basis (e.g. Harvey 1969; Haines-Young and Petch 1986; von Engelhardt and Zimmerman 1988). Explanation is usually expressed in terms of a tri-form structure (Tucker 2004a). The tri-form structure of explanation consists of, firstly, a description of the event that is to be explained, the *explanandum*, secondly, a description of events that explain the event, the *explanans*, and, thirdly, something connecting the two together, be it a process, a mechanism or a 'law' or even a probabilistic relation or statistical generalization. This explanatory structure, and in particular, its development within a critical rationalist framework (Haines-Young and Petch 1986) has been seen by some researchers as being *the* way to understanding even though field investigations have tended to fall short of the ideals of this approach. Specifically,

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geosciences are rarely, if ever within a critical rationalist framework, able to reduce the potential competing theories to one they are not able to falsify. Just two of the problems encountered in applying this philosophical framework to the reality of the field are the difficulties in singular translations of theoretical concepts to workable hypotheses as well as the shifting status of evidence.

In explaining the past geoscientists have tended to study and try to reconstruct individual events. The objective of this study has been to understand the individual event hence their focus on the concrete rather than the abstract of universals. Although most geoscientists do not recognise the ancestry of this debate, their concerns are very much in line with the division of sciences and appropriate methodology outlined by Rickert (1986). Rather than having the subsuming of the individual event under some universal explanation as their goal, the reduction of an individual event to a 'law' (Leighton 1904), geoscientists wish to understand and interpret reality in its singularity and individuality. The preoccupation of geoscientists with history means that, although they may refer to the 'laws' of physics and chemistry in their explanations, their aims and methods of explanation are peculiar to an historical science, a science concerned with the concrete (Rickert 1986).

There have been debates within the geosciences concerning appropriate modes of explanation (e.g. Chamberlin 1890; Johnston 1933; Simpson 1963). Recently, this debate has intensified (Frodeman 1995; Baker 1999; Rhoads and Thorn 1993, 1994, 1996; Lane and Richards 1997; Cleland 2001; Inkpen 2005) as practitioners search for an alternative to the aping of the 'hard' sciences of physics and chemistry. Recent philosophical trends in this debate have noted a move away from a naive realist view of reality to a subtler view of reality as a system of signs (Baker 1999; Frodeman 1995) or reality as stratified and differentiated (Richards 1990). There have even been debates concerning whether the geosciences should be concerned with physical forms and materialism or look for a more process-based view of reality (Rhoads 2006). This move has been accompanied by a greater interest in detailed case studies (Lane 2001). From these intensive studies of how processes are mediated within a specific context, researchers have tried to achieve a greater understanding of how general relations or laws are linked to specific instants. Similarly, debates concerning the nature of the entities that form the basis for analysis have moved from a naïve realism towards a view that accepts the duality of a real and socially constructed reality (Baker 1999; Hacking 1999; Inkpen 2005).

Given the limited philosophical basis available within geosciences, practitioners have tended to focus on the practice of doing the field work, collecting the data, carrying out the analysis and getting an answer they are comfortable is relevant to the question. In environmental reconstruction, for example, the focus remains on the identification of traces of the past and their construction into a plausible description of the past and how it has changed. The philosophy is seen as something that can be worked out later if anyone is really that interested. Such practice must follow, or be underlain by, a set of philosophical principles to determine identification of entities, the nature of acceptable evidence and the nature of an adequate explanation, but the formalization of these principles is rarely articulated. Implicit in practice is a history of tradition guiding the hand of operator and requiring no further scrutiny. Previous practice provides the template for current success. Practitioners have tended to

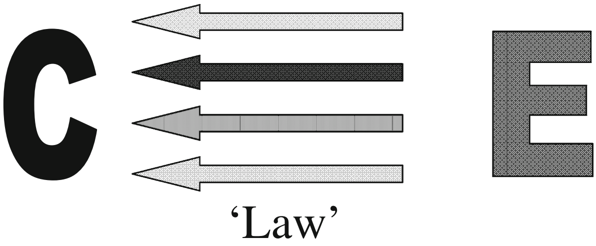

Fig. 1 Abductive reasoning as a tri-form structure. Effect (*E*) linked to cause (*C*) through application of potential ‘laws’, relations or probabilistic relations. The belief or certainty a researcher has in each ‘law’ is indicated by the *shading of the arrows*

explain their subject matter and view its philosophical debates as *“remarkably barren and irrelevant”* (Elton 1969, quoted in Tucker 2004a, p.190).

Although it is accepted that the above is a brief caricature of the use of philosophy in the geosciences, the philosophical debates outlined above are rarely explicitly enunciated. Rarer still is the illustration of how philosophy can be applied to the development of an explanation and how its consideration can aid or improve that explanation. This short paper outlines a key working method of the geosciences, abduction. This paper tries to express this method using Bayesian terms to clarify its explanatory framework and how evidence is interpreted within it. Using this clarification, the implicit use of this form of reasoning is illustrated using a study of environmental reconstruction.

Abduction as a Working Method

Abductive reasoning can be viewed as being structured as in Fig. 1. Argument operates from effect to cause. Effects are known, then ‘laws’, be they deterministic or probabilistic, are applied and a range plausible links made from effect to the cause indicated by the ‘law’. The belief in these links will vary and so researchers investigate the plausibility of the links that each explanation suggested. For reconstructing events in past environments, Fig. 1 could be redrawn as Fig. 2. This represents the main thrust of many papers on environmental reconstruction: the identification of the nature of a past event and the detailed differentiation of that event.

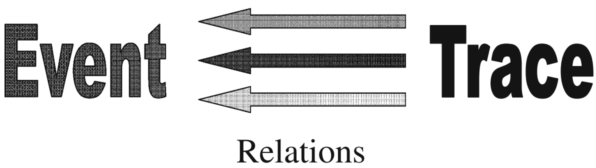

Fig. 2 Abductive reasoning in environmental reconstruction. *Trace* is linked to *Event* through the assumed relations (deterministic and probabilistic) that should exist if the trace is the result of the event. Knowledge of thee relations is derived from contemporary studies of environments

Abductive arguments can be biconditional, where a cause can result in only the effect observed, or conditional, where a cause can have an effect, but that effect does not necessarily occur and that effect can be potentially produced by other causes. In other words, conditional abductive arguments contain doubt as to the necessity of effect following cause. Goodman (1958, 1967) suggested that when considering these different explanations, preference should be given to the simplest, although what is meant by 'simplicity' may be contextual defined.

For past events and entities the researcher can undertake neither direct observation nor manipulate entities to produce new effects by which the nature of the entities could be deduced. Explanation of the past relies upon understanding contemporary analogies of past events and entities and a matching of traces produced these contemporary events to the traces left by the past. Past events and entities, therefore, act as unifiers of phenomena, integrating within them information about the nature of a past environment. Identifying and unravelling the information associated with these traces is a key part of abductive reasoning.

Restatement of Abductive Method

Relating Bayesian concepts to abductive reasoning requires a consideration of the event or effect that is the focus of study and the relationship between explanation and evidence. The meaning of the term 'event' needs to be clarified to make the focus of abductive reasoning clearer. Any event will consist of a set of entities and pathways linked through a causal network of relations. This causal network identifies the general or type level of an event, whilst the actual instance of a particular event, the parts of the causal network activated, is the token level (Pearl 2000; Inkpen 2005). Knowledge of the type-level can only be gained through the study of the token-level. The more instances of an event, the more the causal network of the type level is illuminated and the more the general characteristics of this level are defined. Similarly token-level events are only identified as belonging to the type-level by comparison with other token-level events already classified as being of that type. Taking landslides as an example (Inkpen 2005), a researcher will have a concept of what a landslide is and how they expect it to operate. Researchers will have a concept of how the variables that represent a landslide fit together to form a system that defines the landslide and its behaviour. This is the type level: the general, conceptual level at which an event, the landslide, is understood. Constructing the type level, however, requires identification and abstraction of properties and behaviour from observations and previous knowledge of individual landslides themselves; the individual landslides are the token level. There is a continual interplay between the token and type level, with the type level providing the means to classify and understand specific landslides, whilst the token level informs a researcher of problems or gaps in the nature of the causal system identified by the type level.

In explaining an event, it is not the complete event that is either explained or even considered. It is the description of the event for which explanation is sought and often this description is guided by viewing the event as a token of a type-level event. Without this interplay, events would be totally unique and not explainable within science (Tucker 1998). Reconstruction of past events relies on the description of the past and so upon its identification of past events as token-level events and relating them to contemporary type level events.

It should not be assumed that there is only a single, possible description of an event as noted by Tucker (2004b).

> Explanations of descriptions of events explain aspects of a token event that are picked out by a description.... This is not a problem as long as it is clear that different explanations explain different descriptions of the same event, and are not confused with each other. (Tucker 2004b, p.574.)

An event under study is not usually treated as an entity for which the traditional covering law model of critical rationalism is appropriate; the event is treated as a whole instead. Explanation, for events such as sea-level rise for example, lies not in the tri-form structure, but in reference to evidence that the event transmits and which is available for assessment by the researcher. The event requires these traces for both its identification and construction of its explanation. Sea-level rise, for example, produces specific types of changes in beach morphology, in biological communities and in ratios of oxygen isotopes to name but a few. The nature of changes in these traces as well as their perseveration is central to construction the explanation of sea-level rises. Event, evidence and explanation are linked as a holistic unit (Tucker 2004b).

Reconstructing the past then is not about finding a general covering law for all events, but instead finding a 'law' or a relation that integrates a holistic explanation of a description of an event with the evidence for that event. Conflict arises when there is more than one holistic explanation, and by implication more than one set of connecting 'laws' or relations, that can explain the range of evidence. It is the assessment of these competing explanations that is the purpose of abductive reasoning in reconstructing the past.

In explaining the description of events abductive reasoning refers to the evidence and, what Tucker (2004b) denotes as 'the background of information theories', by which he means the theories explaining how information from the past event has been preserved, transmitted and interpreted in the present study. Evidence for past climates, for example, can be preserved in peat bogs, but the traces will have to survive the harsh, acidity environment. Reaching such spatially distinct localities of preservation, the peat bogs, will involve the movement of traces through a landscape and potential alteration and removal of information. Preservation of information is always partial. Such differentiation preservation means that only limited information retained in the traces will be preserved in peat bogs and so limit the attributes of the past environment that can be reconstructed. It is these sets of relations, between preservation, transmission and interpretation, which form the basis for connecting event description and evidence. The abductive method is concerned with integrating the event and the evidence into a complete and plausible narrative. This means that the description of events is not explained by reference to some set of covering laws, but by reference to scenarios of evidence generation, transmission and interpretation. It is the relative probabilities of these scenarios that are compared, often qualitatively and implicitly, within the abductive framework.

The abductive method can be recast as judgements about relative probabilities within a Bayesian framework. The abductive method outlined above can be restated using Bayesian terminology. In Bayesian terms the relationship between evidence, *e*, and a hypothesis, *h*, which might explain the evidence can be expressed as:

$$P(h|e) = P(e|h)P(h)/P(e)$$

The hypothesis in this case is that a specific event is the cause of the evidence. The conditional probability of *h* given *e* can be regarded as the degree of belief in the hypothesis given the evidence. The expression $P(h|e)$ is the 'posterior probability', the probability of the hypothesis given the evidence. $P(h)$ is the 'prior' probability, the probability of the hypothesis before the evidence is considered (Howie 2002, p.30–1). Bayesian theory relates the posterior probability to the prior probability, but does not indicate how to determine the prior probability.

A single event (E_1) of the fairly recent past that is describable by a great number of properties ($P_1 ... P_n$). A particular description of the event will pick out particular properties as being indicative of that event, whilst other descriptions will pick out other properties, not necessarily mutually exclusive ones, as being indicative of the event. It is only by using the analogy of contemporary events and their properties that the properties of past events can be postdicted. The range of properties associated with a contemporary event will be limited to those that can be identified and described by contemporary science. These properties will produce changes in the environment that mark the event out as a distinct spatio-temporal entity. Such changes are only noticed as changes through the alterations in the environment they cause. It is these alterations that become the traces of the contemporary event and to which traces of the past are compared.

Significantly, a range of properties will be expected to define the nature of an event rather than a single property. A drop in temperature, for example, will be expected to produce snow, limit growing seasons and alter the blooming time of flowers to name but a few. In other words, an event will have a multitude of properties associated with it, not just a single one, although a single property may be sufficient to identify it as a key event; Cleland's (2001) elusive 'smoking gun'. This idea of a single property identifier has been advanced as key feature of past reconstruction and found expression in the example of the mass extinction at the end of the Cretaceous using the evidence of the global iridium trace (Alvarez et al. 1980). A specific event with an identifier trace held up as 'the' singular cause.

Traces reflect the properties of the event but are not necessarily the properties themselves. Periods of cooler temperatures such as the 'Little Ice Age', for example, may define a particular event of interest to climatologists. Traces of the property of temperature can be found such as paintings of frost fairs on the Thames, which reflect a property of the event, but are not the property itself. Survival, transmission and interpretation of traces will vary depending on the nature of the traces, the context of the traces and the techniques used to identify and extract them. The theories underlying the generation, preservation, transmission and interpretation of traces, the theories that link the past event to contemporary analysis serve as vital links or relations between the traces and events.

A single trace, as illustrated in Fig. 2, can be related to a particular event, but it is unlikely it can be related to only that event. There are likely to be other possible relationships that can be identified that would link this single trace to other events. As the number of traces increases it is unlikely that relations can be found that consistently link all the traces to different events (Fig. 3). It is more likely that the coincidence of traces points to a particular event being a common cause of their existence. In Bayesian terms, the single trace does not aid in much in deciding if a particular hypothesized event is the cause of the trace. The likelihood of the event as the cause of the trace is a possibility, but with only one trace, there are other possible events that could also cause the trace. As the number of traces increases, the likelihood of different events as causes alters. A trace is judged, not only in its own right, but also in combination with other traces that are expected to exist if a particular type of event was the cause. Traces can therefore be related to each other. The occurrence of a specific trace is likely to imply the occurrence of other traces, as they are all related to a common cause.

Traces, such as those discussed below, can occur as *trace clusters*. The presence of a specific trace indicates that other traces are likely to be present. These other traces share similar properties that ensure their co-survival through deposition and post-depositional alterations (diagenesis). The occurrence of a trace cluster becomes a persistent feature in the environment and it is a surprise to the researcher if only an isolated, single member of the cluster is found. Comparison of the nature of each trace in the cluster, such as their relative magnitudes, can also provide additional information that single traces alone can not provide.

Illustration of Abductive Method

Illustration of the implicit application of this type of reasoning in practice would be useful to highlight that researchers reconstructing the physical past are working with a consistent conceptual basis. The paper of Mazzucchi et al. (2003) studies the reconstruction of Holocene climatic change in British Columbia, Canada by using

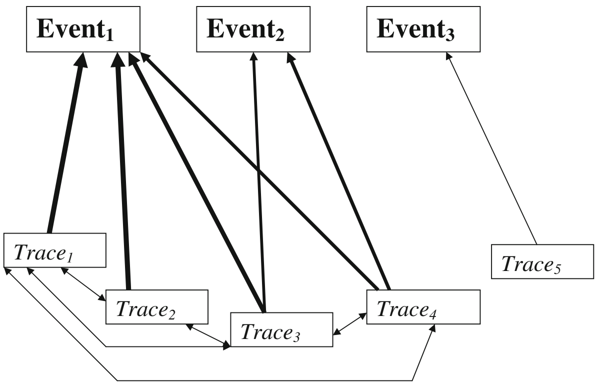

Fig. 3 Traces have many possible relations linking each to different event with differing degrees of belief or certainty (represented by the *thickness of the arrows*, *thicker arrows* implying increased certainty). Traces also linked to each other in the sense that contemporary studies find such traces occurring together. The occurrence of specific trace ensembles may be the necessary outcome of the operation of contemporary processes and so by implication identify the same processes as having had occurred. The figure suggests that *Event$_1$* is the common cause. *Event$_2$* is possible as a common cause but with less belief or certainty as less traces are related to it and with a lower degree of certainty for all traces. *Event$_3$* is only related to *Trace$_5$* which itself is an unexpected trace as it is unrelated to the other four traces

multiproxy sediments from Pyramid Lake. The aim of their paper was to identify the variability of Holocene climate in the northwestern Cordillera using a range of traces found in lake sediments. The location of the Pyramid Lake meant that variations in the timberline, the limit of tree growth on a mountain, could be identified in the sediment. Contemporary studies had identified that the timberline responded very rapidly to changes in climate. In other words, the researchers aimed to identify events of changes in timberline using traces of those events preserved and transmitted in the lake sediment. Additionally, it was thought that high-magnitude precipitation events could have left a specific trace in the sediment that the researchers also searched for. The high-magnitude precipitation events were thought to be caused by changes in summer atmospheric circulation patterns. Once again analysis of contemporary high-magnitude precipitation events suggested this relationship and its impact upon sediment that should, the researchers believed, leave a trace in the sediment.

Transmission of traces meant that it had to be assumed that the sediment had been undisturbed since its deposition. This meant that the deposition followed a strict chronological sequence, so that depth equated to age. Absolute dating of the sediment was obtained through beta-counting and radio-carbon dating of wood remains within specific sedimentary layers. Relative dating of the sediment used two layers of sand and 15 layers of inorganic graded layers. Contemporary studies suggested that depositional processes associated with such sediment produced almost instantaneous deposition of layers. The presence of these layers could be used to correlate layers between cores collected at different locations in the lake as well as being used to construct sedimentation rate curves using a standard, referenced procedure. Analysis of these derived curves implied that a relatively uniform rate of sedimentation had occurred in the lake. All this initial dating of the sediment is to ensure that the temporal framework of the sediment within which the traces sit is as certain as it can be given current scientific practices. If there is confidence in this temporal framework, then the information provided by the sediment can be related to a specific temporal order of events.

All procedures, from sample collection through to sample preparation, identification and counting of pollen and macrofossils, followed standard and referenced procedures. Similarly, other information about the sediment such as the physical properties of the sediment (clast size, charcoal abundance, magnetic suspectibility, loss on ignition, bulk density and grain size distribution) were collected using standardized techniques. This ensured comparability of the results with other studies; they ensured that the traces and their values could be believed both by the researchers and the wider scientific community. In following the standard procedures, the characteristics of the traces themselves could not be open to doubt, so the only source of uncertainty, the researchers believed, lay in relating the traces to the event or events.

The time period covered by the sediment cores was divided into four zones (1–4) based on the timberline pollen assemblages found in them. Focusing on the two zones at the base of the cores, zones 1 and 2, helps to illustrate the reasoning used by the researchers in interpreting the traces. In zone 1, the zone closest to the base of the sediment cores, there was little pollen, too little to distinguish locally derived pollen from pollen transported into the lake from the whole region. In terms of belief about events, there is no specific event identified because there are no traces of vegetational change that can be distinguished in the sediment. There is pollen in the sediment, but it is from species that could either be from other sources outside of the local area or of a type that could be found in both timberline communities and other communities. In other words, past events, as defined by vegetation communities, have not left traces that can be used to distinguish the different communities. The authors admit this when they state that:

> The paleoenvironmental significance of pollen percentages within zone 1 cannot be inferred reliably.

Mazzucchi et al. 2003, p. 525.

Zone 2 has pollen from tree, shrubs and herbs but in differing proportions as depth decreases. The researchers interpret this as evidence of plant colonization and establishment of a mixed spruce and pine trees. The reasoning behind this interpretation is set out in Fig. 4. The high concentration of pollen and other traces within the sediment in this zone means that there are enough traces to permit a set of relations to be established to a potential cause. Contemporary studies of vegetation assemblages as well as reference to the theory of vegetation succession means that four traces, grass and sedge, moss and fern spores occurring together can be linked as indicative of the colonization of the lake by vegetation. It is the combination of the traces that reinforce the belief in the evidence for a colonization event. If only

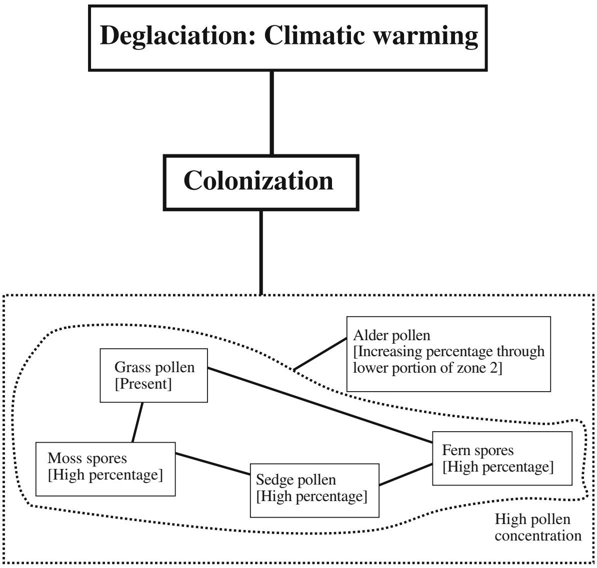

Fig. 4 Colonization, the event, is known through the traces in the *boxes*. The traces are only identifiable because of the high pollen concentration in the sediment. The properties of the traces, *in square brackets*, indicate that the lake area is undergoing colonization. Together these traces form a distinct trace cluster as identified by their enclosure in a *dotted polygon*. The additional trace of increasing alder pollen concentration indicates that this process is not static as the area is undergoing increasing colonization by tree species as the soil becomes stable and more able to support higher plants. The event itself is undergoing a change in its nature as indicated by the relative magnitude of each trace within the trace cluster and by the change in the percentage of alder pollen

one of these traces had been present, then the researcher would have needed to provide a plausible explanation as to why the other traces were not present. Evidence of preferential preservation and other plausible accounts from the theories associated with the transmission of pollen through sediment would need to be referenced.

The addition of alder pollen in the sediment and its variation in concentration as the sediment get younger indicates a dynamism to the colonization that is predictable from existing theories of plant succession. This variation in the magnitude of this trace is expected to occur in the sediment if climatic conditions have remained stable or improved. The alder trace is linked to the whole ensemble of traces indicating colonization rather than to a specific individual species (the four boxes enclosed within the area of the dashed shape). Both the traces of colonization and the traces of changing colonizing communities indicate that climate has changed to a warmer environment that has been stable or increasing in temperature.

As climate improved, tree communities were able to establish themselves and traces in the sediment indicate this event (Fig. 5). The nature of the event the traces infer has altered, although the climate itself may remain the same or warmed. The increased presence of tree species and the decreasing percentage contribution of the colonizing species indicates that tree species have established themselves within the lake catchment. Once again it is the combination of traces that provides this belief. The relationship between colonizing species and the percentage rise in tree species pollen indicates the establishment of tree communities in contemporary environ-

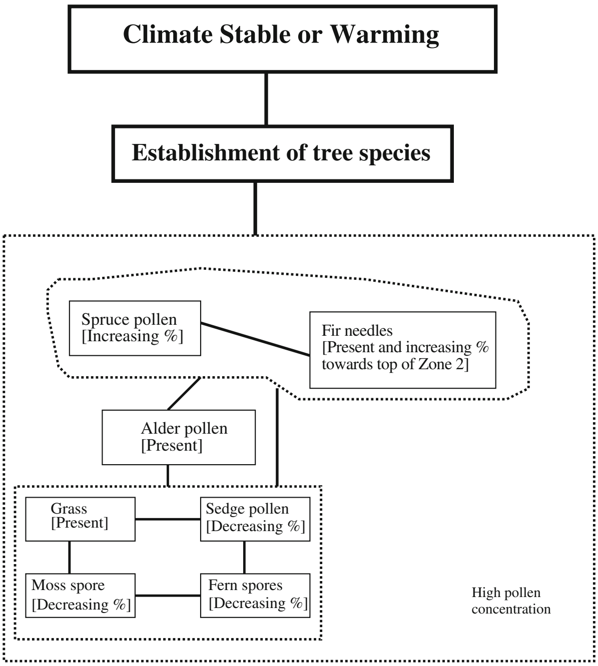

Fig. 5 The traces of colonization are decreasing in their percentage of the pollen in the sediment indicating a change in the nature of the event. The presence of alder indicates that tree species are present, whilst the increasing percentage of spruce and increasing presence of fir needles indicates the establishment of tree species in the lake catchment

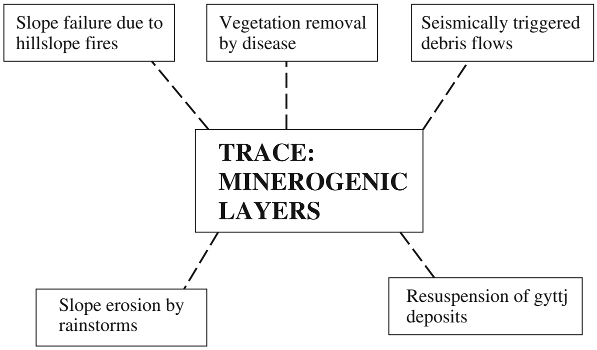

Fig. 6 Five possible events that could be the cause for the trace of minerogenic layers. Each is plausible given the environment but the plausibility of each needs to be assessed by reference to the properties of the minerogenic layers, other traces in the sediment and observation of contemporary processes hence the uncertain nature of the link from events to trace (*broken lines*)

ments. The relative contribution of each species reflects the maturity of the tree communities. Only by understanding the relationship between traces as indicated by theory and contemporary studies can the event inferred.

The researchers also looked at the 15 thin minerogenic layers in the sediment. They assumed, based on analogies with contemporary observations, that these layers were deposited in a single rain event of a magnitude greater than 85 mm. The trace itself, however, was potentially produced by more than one cause (Fig. 6). It was the use of the accompanying pollen evidence plus the other traces from within the minerogenic layers that reduced the belief in these other potential causes (Fig. 6).

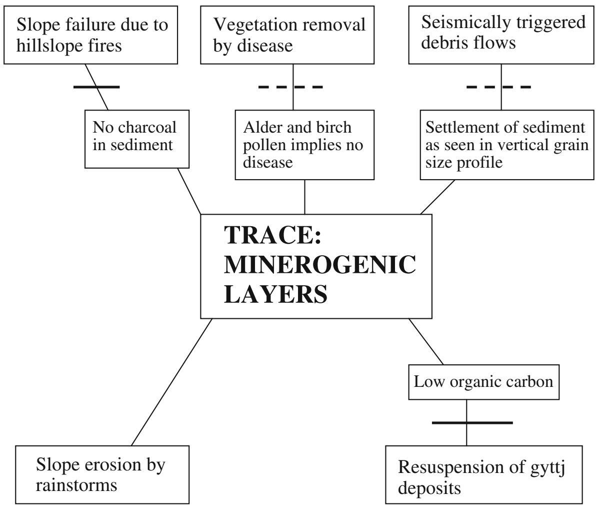

Fig. 7 Use of properties of minerogenic trace and other traces in sediment to narrow down the likely event that caused the minerogenic layers. The *horizontal bars* represent the discarding of that cause or event. The *dashed lines* represent the uncertainty associated with the elimination in some cases. Although four of the five potential events are tested as in classic critical rationalism, two are not eliminated, but rather seen as highly unlikely. The fifth, rainstorms, is not tested but assumed to be the most likely relative to the unlikely nature of the other possible causes

Interestingly, the researchers do not try to relate the physical nature of the microgenic layers to the magnitude of the causative past rain event as they note other researchers had done. Their reasoning is laid out in Fig. 7. They regard the properties of the rain event that could influence the physical properties of the layers as untraceable from the evidence in the sediment. This is an illustration of abductive reasoning permitting researchers to identify the limits of interpretation within their evidence.

Conclusion

Abductive reasoning is vital to reconstructing the past in the geosciences. Traces of the past can only be interpreted as part of a framework of evidence that involves both theory and practice. Traces, both singular or, more commonly, as groups or clusters, are interpreted and weighed as evidence in relation to the event or events they are claiming to be associated with. Assessment of traces involves the researcher in an intricate and often implicit process of evaluation based on degrees of belief in both the theory behind the event and the evidence itself. Exemplification of the process of abductive reasoning shows how trace clusters are important in developing belief in a particular reconstruction. Often these traces clusters are based on contemporary understanding and observations of environments. Linking past trace clusters to contemporary ones is one basis for increasing the belief in a particular reconstruction. Recognition that reconstructing past environments is based upon this form of reasoning could be of use in assessing the explanations put forward by different researchers. Assessing likelihoods rather than asserting the reality of relationships provides a basis for accepting the provisional status of explanations. Similarly, the focus on the whole event rather than specific parts or traces, provides a more appropriate framework for assessing the value of evidence.

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