

The Interdisciplinary Entanglement of Characterization and Explanation

Max Dresow and Alan C. Love

Philosophers have traditionally focused on the nature of scientific explanation while ignoring the process by which features of the world are formulated as discrete explanantia and explananda. However, the characterization of phenomena is an important activity in its own right, and is intertwined with evaluations of the appropriateness and sufficiency of explanatory strategies. We explore this entanglement of characterization and explanation using an extended case study from deep time: research into the Cambrian explosion. Our analysis focuses on three spheres of research that together illustrate key features of characterization for complex phenomena, including open-endedness, interdisciplinarity, and a concern with explananda and explanantia alike. In addition, they suggest a pair of substantive claims: (1) characterizations of complex phenomena are frequently contested along several dimensions of descriptive understanding, and (2) the dynamics of characterization for complex phenomena are poorly described by models that treat recharacterization primarily as a response to explanatory failures.

1. Introduction

There is no such thing as the ‘received view’ of scientific characterization, but if there were, it might go something like this. Scientists characterize phenomena in order to explain them. For some, this means developing an explanatory theory; for others, it means describing the mechanism underlying a phenomenon of interest (Bogen and Woodward [1988]; Craver and Darden [2013]). Scientists must characterize phenomena early in an investigation, since characterizations tell researchers what to attend to, as well as what exactly needs explaining (Bechtel and Richardson [2010]). Inevitably, these characterizations need to be revised. Perhaps an ostensible phenomenon is really two phenomena, or perhaps a phenomenon does not exist at all—at least as it was initially described (Craver and Darden [2013]; Colaço [2018b]). Still, for most researchers, most of the time, characterizations themselves are not objects of active scrutiny. Instead, they are taken for granted in ongoing research: a status that

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reinforces the view that characterization is an activity separate from, and subordinate to, explanation.¹

Our purpose in this paper is to demonstrate that the ‘received view’ fails to capture important features of characterization for complex phenomena.² These features include how characterization is often done for its own sake and not solely for the purpose of facilitating explanation; how it tackles multiple dimensions of a phenomenon simultaneously, often requiring the coordination of several disciplinary inputs; and how it interacts with the construction of explanatory models throughout the career of a research project.³ This last feature is important enough to warrant a name: the ‘entanglement thesis’. Characterization and explanation display a complex entanglement in ongoing research. Thus, characterization is not just preparatory work that sets the table for the ‘real business’ of scientific inquiry (explanation and associated aims like prediction and hypothesis testing). Instead, the traffic between characterization and explanation is continuous and bidirectional. Sometimes work on explanatory models prompts researchers to revise their characterizations (Bechtel and Richardson [2010]). Sometimes ongoing characterization shapes explanation by introducing new adequacy conditions or growing the roster of explanatory resources (Dresow [2021a]). Here we explore this bidirectional traffic and assess its implications for philosophical models of scientific characterization. This involves both illustrating the entanglement thesis and scrutinizing its consequences for our understanding of scientific practice.

An allied goal is to challenge the idea that characterization is a disciplinary or field-specific undertaking. For example, an influential account of scientific characterization holds that to ‘describe a phenomenon is to characterize it in the language of a given field and to implicitly call up the host of explanatory concepts [...] known to a field at a time’ (Craver and Darden [2013], p. 52). An implication of this view is that fields undertake their own characterization work for proprietary phenomena and, crucially, that the researchers engaged in characterization are also engaged in attempts to explain target phenomena. Although claims of field specificity can be softened by pointing to the interdisciplinary nature of certain fields, an emphasis on circumscribed communities of inquiry obscures the fact that researchers engaged in characterization often belong to entirely different disciplinary communities than

¹ In describing a ‘received view’, our aim is to isolate those commitments that we regard as central to much philosophical discourse on scientific characterization. These commitments do not constitute a mutually entailing package, but there is value in isolating a central tendency in philosophical perspectives on characterization.

² We use the term ‘complex’ generically to designate phenomena that are produced by multiple, interacting variables and manifest over many spatial and temporal scales. Philosophical discussions of scientific phenomena sometimes stipulate that phenomena result from the interaction of a ‘manageably small number of causal factors’ (Bogen and Woodward [1988], p. 317). Complex phenomena are generated by a larger number of causal factors and therefore require special strategies to achieve manageability.

³ Colaço ([2020], p. 14) reaches a conclusion similar to our first point: ‘Characterizing a phenomenon is not always, let alone solely, done in the effort of explaining it’. Allied positions can also be found in (Feest [2017]; Bollhagen [2021]).

those engaged in formulating explanatory models. It also overlooks the challenges this division of labour can generate, since scientists engaged in characterizing a phenomenon may rarely collaborate, or even communicate, with scientists interested in explaining that phenomenon.

To explore the entanglement thesis and its corollary of interdisciplinarity, we develop an extended case study from the sciences of geohistory: research into the Cambrian explosion (hereafter, CE). Beginning about 540 million years ago (Ma), a complex evolutionary transition took place that saw the first appearance of abundant and diverse bilaterian animals in the fossil record (Erwin and Valentine [2013]).⁴ This transition was superimposed upon major changes in the oceans and atmosphere, making the CE a complex phenomenon par excellence.⁵ Our account focuses on several spheres of research that target distinct aspects of this phenomenon. Together, they illustrate important features of characterization for complex phenomena, including open-endedness, interdisciplinarity, and a concern with explananda and explanantia alike. In addition, they suggest a pair of substantive claims: (1) characterizations of complex phenomena are frequently contested along several dimensions of descriptive understanding, and (2) the dynamics of characterization for complex phenomena are poorly described by models that treat recharacterization primarily as a response to explanatory failures.

In section 2, we provide a brief digest of the scattered philosophical literature on characterization, with an eye to extracting latent assumptions. Section 3 presents a detailed case study that puts pressure on these assumptions and points to an enriched view of characterization for complex phenomena. Section 4 explores this view in relation to the themes of entanglement and interdisciplinarity, and defends our two substantive claims. Finally, section 5 summarizes our analysis and identifies several new questions arising from it.

2. Philosophers on Characterization

Characterization is an important scientific activity, yet philosophers have shown relatively little interest in it until fairly recently. Because of this, observations about characterization have accumulated in scattered places throughout the literature, including discussions of ‘data-to-phenomena reasoning’, studies of mechanistic explanation, and accounts of exploratory experimentation. In this section, we provide a brief digest of some claims made about characterization in these disparate locations.

⁴ The Cambrian period began around 541 Ma, following the long Proterozoic eon (2500–541 Ma). The CE is usually thought to have begun shortly thereafter (but see below), with the greatest burst of diversification happening between about 530 and 520 Ma (Erwin and Valentine [2013]).

⁵ We regard ‘phenomena’ as an ontologically diverse category that includes ‘particular objects, objects with features, events, processes, and states’ (Bogen and Woodward [1988], p. 321). The CE therefore qualifies as a phenomenon, even though it can also be described as a singular event. For a congruent view of ‘phenomena’, see (Ankeny and Leonelli [2020]).

To speak of characterization is to raise the question of what exactly scientists aim to characterize. The literature on characterization tends to presuppose that the answer to this question is ‘phenomena’ (Craver and Darden [2013]; Colaço [2018b], [2020]).⁶ Although philosophers disagree about what phenomena are, as well as how to differentiate them from data, most agree that phenomena are stable or otherwise salient features of the world; that they are important targets of scientific explanation; and that they are known from data, ‘which play the role of evidence for the existence of phenomena’ (Bogen and Woodward [1988], p. 305). Characterization thus involves a kind of ‘data-to-phenomena reasoning’ in which the existence and properties of phenomena are inferred from patterns in data. The challenge of characterization arises from the noisiness and inherent idiosyncrasy of these patterns (McAllister [1997]; Woodward [2010]). Data are unique and local; phenomena are more general features of the world. It follows that scientists must use a variety of methods to remove or mitigate the idiosyncratic features of data, including techniques of data reduction and analysis (Leonelli [2019]; Bokulich [2021]). When successful, this permits scientists to distinguish real features of the world from artefacts and thereby to establish the existence of phenomena in the face of apparently ambiguous or contradictory data.

Studies of data-to-phenomena reasoning do not specify a preferred method of data production and for this reason do not presuppose a privileged role for experiments in characterization. By contrast, philosophical studies of mechanistic explanation tend to do just this. For example, Craver and Darden ([2013], p. 57) claim that characterizing a phenomenon requires ‘some experimental means of determining whether or not the phenomenon in question is present or absent at a given time’. This is because characterizing a phenomenon in the context of mechanism discovery involves identifying the conditions under which the phenomenon occurs, and this is best achieved through experimental intervention.⁷ Craver and Darden ([2013], p. 57) further stipulate that characterization must be mostly completed before a ‘mechanism schema’ is formulated, since this ‘prunes the space of possible mechanisms [. . .] and loosely guides the construction of [a] hypothesis space’. So, even though mechanists recognize that phenomena ‘might [need to] be recharacterized or discarded entirely as one learns more about the underlying mechanisms’, a preliminary characterization needs to be in place before explanatory efforts can proceed (Craver and Darden [2013], p. 62). ‘[To] characterize a phenomenon correctly and completely is a crucial step [in mechanism discovery]’ (Craver [2007], p. 128); the phenomenon then becomes

⁶ This is presumably because phenomena are widely regarded as the staple scientific explananda (Bogen and Woodward [1988]; Craver and Darden [2013]). Older accounts (for example, Hempel [1965]) make this identification explicit, labelling the explanandum in a scientific explanation the ‘explanandum phenomenon’.

⁷ Colaço, who is critical of other elements of Craver and Darden’s account, shares this experimental orientation. Writing of the distinction between phenomena and data, he states that ‘data [. . .] are the empirical findings collected in experiments that are used to infer the characteristics of a phenomenon’ (Colaço [2018b], p. 33).

the explanandum for a mechanism sketch and, eventually, a fully articulated mechanistic schema or explanation.⁸

The idea that characterization is undertaken as a means to explanatory ends is mirrored in discussions of exploratory experimentation: a style of inquiry in which researchers aim to characterize experimental systems as opposed to testing explicit hypotheses. For example, in Steinle's ([1997], p. S70) influential account, exploratory experimentation 'typically takes place in those periods of scientific development in which—for whatever reason—no well-formed theory or even no conceptual framework is available or regarded as reliable'. This claim is based on the assumption that hypothesis testing must take place against the backdrop of a well-formed theory or settled conceptual framework. Absent this, the best researchers can do is engage in exploratory experimentation—that is, characterize systems with an eye to future hypothesis testing. But this pattern is chock-full of exceptions. Franklin-Hall ([2005]), for example, observes that the advent of high-throughput technologies in biology has made exploratory experimentation a more efficient research strategy in some contexts than traditional hypothesis testing. This suggests that, in certain areas of the life sciences, exploratory experimentation is here to stay (see also Colaço [2018a]). Similarly, Burian ([2007]) argues that practices of hypothesis testing will not supplant exploratory experimentation in biology, owing to the extreme complexity and heterogeneity of living systems.

These recent contributions evince a clear understanding that exploratory experimentation is not confined to the early stages of research projects. However, they fail to challenge the presumption that researchers undertake characterization largely or exclusively as a means to explanatory ends. For example, Franklin-Hall ([2005]) discusses exploratory experimentation via high-throughput methods as a heuristic activity that facilitates the identification of difference makers for causal analysis. Similarly, for Burian ([2007], p. 286), the ongoing need for exploratory experimentation arises because theory alone cannot yield adequate predictions for biological systems: 'No systems for generating general hypotheses and no bodies of fundamental biological or chemical theory, supplemented by appropriate boundary conditions plus general background knowledge, are able to predict both in general and in detail genotype-phenotype relations, or structure-function relations for wide ranges of important biological molecules'.

These analyses locate the value of characterization work in its capacity to further the ends of intervention, prediction, and causal analysis. And they are right that this is an important benefit that this work can provide. But it is not the only rationale for pursuing projects of characterization. As a recent editorial in *Nature Human Behaviour*

⁸ Notably, some philosophers have criticized the view that experimental scientists are largely in the business of explaining well-delineated phenomena by identifying potential explanantia (Feest [2011], [2017]; Bollhagen [2021]). This is complementary to the position advanced in this paper. Although we are not here concerned with the experimental sciences, we think that much empirical work in the observational and historical sciences is concerned with 'making taxonomic constructs and attempting to describe the features of the (purported) objects in their extension' (Feest [2017], p. 1167).

([2021]) states, it is a mistake to regard description as ‘valuable only insofar as it provides the starting point for causal inference’. Or, to render this as a motto: characterization is not just preliminary work.⁹

Our brief observations give only a taste of the scattered philosophical commentary on characterization, but they suffice to illustrate several points. First, philosophers tend to assume that characterization plays a preliminary role in scientific inquiry because it constitutes an early stage in the discovery of mechanistic explanations or serves as a means to the end of identifying difference makers for intervention, prediction, and causal analysis. Second, many philosophers regard characterization as a subordinate aim of researchers whose ultimate aims are explanatory; there is little explicit recognition that characterization supplies the principal goal for much research, and that researchers engaged in characterizing phenomena frequently belong to different communities than those engaged in formulating explanatory models. Finally, philosophers tend to see characterization as involving the authentication and demarcation of phenomena, as opposed to their open-ended and multi-dimensional elaboration. Our case study puts pressure on all of these points. Attempts to characterize the CE supply the primary focus for many research groups and are pervasively entangled with the construction of explanatory models, even though a significant portion of this work is not undertaken with explanation in view. In addition, researchers seek to elaborate the phenomenon in an open-ended way (for example, through the iterative application of new methods and tools), and not merely to authenticate and delineate it.

3. Characterizing the Cambrian Explosion

Efforts to characterize the CE do not lend themselves to a simple narrative. Given this, we have organized our analysis around three spheres of work that seek to characterize the following: the ‘explosiveness’ of the CE, its temporal structure, and a potential causal factor—ocean ventilation. These spheres of work intersect with attempts to explain the CE (the ‘entanglement thesis’) and are associated with different disciplinary specialties (the corollary of interdisciplinarity).

3.1. Just how explosive was the Cambrian explosion?

No one seems to know who first called the events of the early Cambrian period the ‘Cambrian explosion’. But whatever the story, it is easy to understand why this colourful metaphor stuck. The CE has been called one of six ‘really important events in the history of life on earth’ (Erwin [1993], p. ix). In a remarkably short time, most

⁹ In sciences concerned with evolutionary history, the reconstruction of pattern is often distinguished from the reconstruction of process. This might suggest a sequence of scientific inquiry: ‘Characterize the pattern first, then explain the causal processes responsible for the pattern’. However, as we show in section 3, this sensible schema does not accurately describe scientific practice. We thank an anonymous referee for reminding us of the salience of the pattern/process distinction in this context.

major groups of animals made their first appearance in the fossil record in a burst of apparent innovation that also saw the rise of animal-dominated ecosystems (Erwin et al. [2011]). To call this development an ‘explosion’, then, seems a perfectly apt expression.

But just how explosive was the CE? The question is significant since much of the interest that attaches to the event owes to the idea that it was very explosive indeed—a riot of morphological innovation unmatched in the history of life. Should the CE turn out to be more muted, then scientists will have a different explanandum on their hands—one that imposes different demands on would-be explainers. Moreover, if characterizations of the event shift frequently in response to ongoing research, communities of explainers must track a moving target, with all the difficulties this entails.

Views about the explosiveness of the CE have traced a complicated arc since the middle of the twentieth century. At that time, many scientists believed the ‘explosion’ was a mere artefact, the result of a highly imperfect fossil record that contained few traces of Precambrian life (Shevyrev [1964]). However, beginning in the 1970s, this outlook began to give way to the view that the early Cambrian had witnessed an explosion of the first magnitude. A thorough investigation of the middle Cambrian Burgess Shale seemed to indicate that the range of designs present in the Cambrian oceans may have exceeded that of today—a shocking conclusion that led some to posit a burst of innovation mushrooming beyond current anatomical limits (Brasier [1979]; Gould [1989]; Valentine et al. [1991]). No less important was the recognition that the Precambrian fossil record was not as impoverished as researchers had once believed. By 1960, members of the Precambrian ‘Ediacaran fauna’ had been discovered on several continents, suggesting that conditions for the preservation of soft-bodied fossils were widespread prior to the Cambrian period (Glaessner [1959]). Later, it was suggested that these fossils contain few obvious ancestors of extant phyla, further supporting the idea that something special happened around 600 Ma—then believed to be the age of the Precambrian-Cambrian boundary (Seilacher [1984], [1989]).¹⁰

Not everyone was convinced. In 1989, the palaeontologists Derek Briggs and Richard Fortey restudied the evolutionary relationships among Burgess Shale arthropods using the methods of cladistic analysis (Brysse [2008]).¹¹ Briggs and Fortey

¹⁰ This claim suppresses some historical complexities. For several decades following the identification of soft-bodied macrofossils in the Ediacara Hills and elsewhere, many regarded these fossils as primitive members of living animal groups (Glaessner [1959], [1961]). However, beginning in the mid-1980s, an ‘open season [was] declared on [...] interpretations [of this sort]’ (Brasier [2009], p. 171). This problem remains under active scrutiny, although it is now thought likely that at least some Ediacaran taxa are bona fide animals that branched off early in the history of major groups (stem lineages; see note 12).

¹¹ Cladistics is an approach to classification that groups organisms on the basis of shared derived characters: characters found in a particular group because they were inherited from a common ancestor that first evolved those characters. Its widespread adoption revolutionized taxonomic practice beginning in the 1970s, and it began making waves in palaeontology during the 1980s and 1990s (Hull [1988]; Velasco [2013]).

were interested in whether all the presumptive arthropods of the Burgess Shale could be accommodated within a phylogenetic tree that assumed a single evolutionary origin for the group (a 'monophyletic tree'). This was significant because a popular scenario for the origin of arthropods held that the group had evolved multiple times from separate Precambrian ancestors, including some bizarre Cambrian fossils that seemed to defy description in conventional groups. Yet Briggs and Fortey ([1989], p. 241) also recognized that the problem of arthropod phylogeny went beyond matters of classification, and affected 'our understanding of the nature of the Cambrian radiation [itself]'. If all the Cambrian arthropods could be accommodated within a single monophyletic tree, then it would be possible to interpret even the most bizarre forms as primitive members of living clades (in technical parlance, as members of 'stem' as opposed to 'crown groups').¹² But if no such tree existed, then these strange organisms would be better interpreted as 'taxa of equivalent rank and independent origin from the major arthropod groups' (Briggs and Fortey [1989], p. 241). The latter scenario—but not the former—supports the view that the early Cambrian saw a singular radiation over-spilling the limits of conventional anatomical designs: a true evolutionary 'explosion'.

Using a database of twenty-eight taxa and forty-six characters, Briggs and Fortey ([1989]) showed that the great majority of Cambrian arthropods can indeed be accommodated in a plausible monophyletic tree. Later studies using more sophisticated character sets and an expanded collection of taxa lent additional support to this result. Wills et al. ([1994]) used a database consisting of twenty-four Cambrian and twenty-four Recent taxa, each scored for 118 distinct morphological characters, to build a consensus tree that accommodated both Cambrian and modern forms. Scrutiny of the tree revealed that the bizarre forms are not sister groups to recognized classes: a position that might have warranted the erection of new class- or phylum-level taxa to accommodate them. Instead, they fall largely within established clades, making it 'difficult to argue that there are any high-level [body plans] in the Cambrian [that are] not represented today' (Wills et al. [1994], p. 117). In addition, trilobites—long believed to be primitive arthropods—appear as highly derived forms: advanced 'twigs' on the arthropod tree. This suggested that a sizable period of arthropod evolution preceded the CE and failed to leave a record in the rocks (Fortey et al. [1996]).

Suggestions of a long cryptic history for animals seemed to receive powerful support from the results of early molecular clock studies. These studies compare DNA sequences of living taxa, calibrated against divergence times inferred from the fossil

¹² A 'crown group' is a monophyletic clade (a group consisting of an ancestral species and all its descendants) containing all the living members of that clade, their most recent common ancestor, and any extinct descendants of that ancestor. A 'stem group' is a paraphyletic clade (a group consisting of some, but not all, descendants of a common ancestor) containing extinct members of a monophyletic clade that are not part of the crown group. Because of their position on a phylogenetic tree, stem groups are sometimes described as 'intermediates' between a crown group and its closest monophyletic sister group (see Budd and Jensen [2000]).

record, to estimate divergence dates for lineages under study. And early molecular clock studies of animal evolution had stunning implications. Animals had apparently diversified some 400–600 million years before the fossil record seemed to indicate: between 1 and 1.2 billion years ago, by one estimate (Wray et al. [1996]). Other studies produced different results, but all of them suggested a long cryptic history for major animal groups, leading some palaeontologists to declare that the ‘Cambrian explosion hypothesis’ had been conclusively debunked (Bromham et al. [1998]).¹³ The view was not a consensus, however, with other palaeontologists preferring a more literal interpretation of the fossil record that made an anomaly of the molecular clock results (Conway Morris [2000]).

Thus, during the 1990s, two lines of characterization work found themselves at loggerheads: attempts to characterize patterns in the fossil record (which suggested a genuine CE) and attempts to estimate divergence times based on phylogenies and molecular data (which suggested an ‘explosion of fossils’ only). For a time, it appeared that the sceptics had gained the upper hand. What needed to be explained was not a spasm of innovation exceeding everything in the fossil record, but rather the relatively late appearance in the fossil record of groups that had originated in the Precambrian.¹⁴ More recently, though, advocates of the ‘Cambrian explosion hypothesis’ have again gained the advantage. Problems with early molecular clock studies invalidated many of the most scandalous estimates of divergence times, like those that placed the origin of animals over a billion years ago (Sperling and Stockey [2018]). More recent estimates place the dawn of animals around 780 Ma and the origin of the bilaterian body plan around 650 Ma, close to the earliest fossil evidence for bilaterians (Erwin et al. [2011]). This has functioned to dispel many of the most serious objections to the ‘Cambrian explosion hypothesis’ (Cunningham et al. [2016]). Still, revised molecular clock studies continue to suggest a deep history for the animal clade, much of which is absent from the rock record (Sperling and Stockey [2018]). New models of the CE are therefore tasked with explaining both the absence of a robust Precambrian fossil record for complex animals and the rapid divergence of animal crown groups near the base of the Cambrian—a different explanandum than any previously entertained.

What all of this means is that ongoing characterization has rendered the CE a moving explanatory target. Following the restudy of the Burgess Shale fauna in the 1970s, many regarded the CE as an episode of rapid diversification associated with the initial divergence of major animal groups. It was thought to be phylogenetically explosive (generating a spread of anatomical variation perhaps exceeding that of the modern oceans) and geologically rapid (taking place over a few million years

¹³ By ‘Cambrian explosion hypothesis’, Bromham et al. mean the hypothesis that most phyla and classes of living animals originated in a rapid burst at the beginning of the Cambrian period, or at most 10–15 million years before the Cambrian boundary.

¹⁴ Notice that none of this implies that the CE is not a real phenomenon. Rather, it implies that the CE represents the nearly simultaneous appearance in the fossil record of animals capable of forming fossils: a different kind of phenomenon, but a phenomenon nonetheless.

or less). But later innovations in phylogenetic analysis and molecular dating cast doubt on several aspects of this picture. These made it seem that what needed to be explained was not a period of heightened evolutionary innovation, but the sudden appearance in the fossil record of lineages capable of forming fossils. More recently, advances in molecular dating and intensive fieldwork have rehabilitated the view that the CE was morphologically explosive: ‘the most dramatic interval of metazoan morphologic innovation in the history of life’, according to one estimate (Darroch et al. [2018], p. 655). Yet, in contrast with the older picture, this burst of morphological innovation is not thought to be associated with the initial divergence of major animal clades. Now the CE is thought to represent a diversification of crown group bilaterians within clades that diverged much earlier. This means that explanatory models for the CE are presently tasked with explaining both this crown group radiation and the considerable lag between the origin of major clades and their diversification in the early Cambrian: a new explanatory target.

3.2. Cambrian explosion or Ediacaran-Cambrian radiation?

While palaeontologists laboured to erect phylogenetic frameworks and evolutionary biologists tinkered with molecular clocks, stratigraphers and geochronologists were hard at work constructing a more adequate temporal framework for the events of the Cambrian and Neoproterozoic (late Precambrian).¹⁵ Such frameworks are important for two reasons. First, they enable researchers to order events in time and, with the aid of radiometric dating techniques, to constrain their absolute ages and total durations (Bokulich [2020]). Second, they enable researchers to compare evolutionary events with changes in the physical environment that may be related as causes. Here we consider research aimed at locating events in time. Then, in section 3.3, we consider efforts to characterize a particular change in the physical environment: the ventilation of the oceans in the Neoproterozoic and early Cambrian.

Historically, the rocks of the Cambrian system were divided into early, middle, and late series, but difficulties in identifying stratigraphically useful fossils made the early Cambrian something of a black box. Identifying the base of the Cambrian posed a particular problem, owing to the ‘general paucity of early Cambrian fossil evidence, [. . .] absence of late pre-Cambrian fossils which can be used for correlation, and [. . .] inadequacy of recorded field evidence and knowledge of [biostratigraphic] zones in many areas’ (Cowie [1967], p. 28). A breakthrough came in the 1960s, when Soviet geologists subdivided early Cambrian rocks in Siberia into four stages (Raaben [1981]). The tentative global correlation of these stages enabled palaeontologists to document, for the first time, fine patterns in the structure of the CE. However, many ‘of the important sections [proved to be] incomplete at critical

¹⁵ The Neoproterozoic era is the last major division of the Proterozoic eon, spanning the interval from 1000 to 541 Ma (fig. 1). The term ‘Precambrian’ is an informal category referring to the whole of Earth’s history prior to the Cambrian, including the Proterozoic eon.

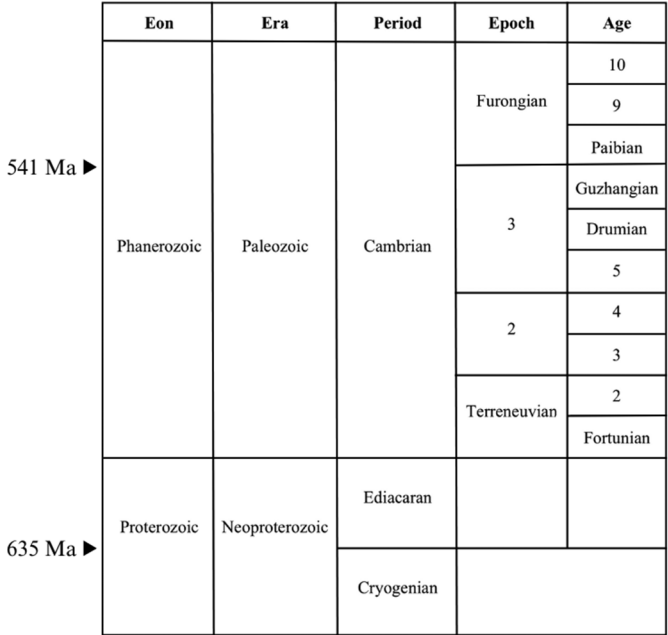


Figure 1. A timescale for the terminal Proterozoic (late Precambrian) and early Phanerozoic. Names and dates reflect current understandings and conventions.

horizons’ (Erwin and Valentine [2013], p. 17).¹⁶ As a consequence, recent stratigraphic work has adopted a novel periodization of the Cambrian consisting of four series/epochs and ten stages/ages (see fig. 1).¹⁷ The formal definition and international correlation of these units remains a focus of ongoing research (Wood et al. [2019]).

If the early Cambrian posed problems for stratigraphers, they were nothing compared to the problems posed by the Neoproterozoic (Knoll [2000]). For much of this interval, there were no large organisms to speak of and thus no body fossils to use for stratigraphic correlation. Large multicellular organisms make their first appearance in the record during the last stretch of Neoproterozoic time, today called the Ediacaran period. Still, these have limited utility for correlation and were traditionally thought to have been absent for millions of years leading up to the Precambrian-Cambrian boundary. Their absence could hardly have been more unfortunate. To better understand the CE (including its causes), researchers needed to reconstruct

¹⁶ Correlation refers to the practice of establishing correspondence between widely separated rock units. It is how geologists synthesize information from local sections into regional and ultimately global frameworks for the purpose of reconstructing geohistory (Dresow [2021b]).

¹⁷ ‘Series’ and ‘stage’ are terms for rock units; ‘epoch’ and ‘age’ are terms for corresponding time intervals.

the changes that ushered in the Phanerozoic world: changes in climate, ocean chemistry, tectonic activity, and so forth. But in the absence of a dense fossil record, researchers lacked the most reliable way of constructing a high-resolution timescale for the interval. This left the roots of the CE shrouded in darkness.

In 1989, the International Committee on Stratigraphy set up a working group on the Terminal Proterozoic period, and its task was to establish a refined temporal framework for understanding the events of the late Neoproterozoic. Some progress had been made in unravelling regional geological histories through the use of radiometric dating methods. However, most rocks are not susceptible to radiometric dating, 'and even well dated sections cannot be correlated with anything like biostratigraphic precision' (Knoll and Walter [1992], p. 673). The challenge was thus to establish the temporal relationships between distantly located rocks when the ages of these rocks could not be determined by direct dating. Two lines of evidence proved to be instructive in this connection. The first was morphologically diverse microfossils, especially the small, capsule-like structures known as acritarchs. By 1992, over twenty distinct assemblages of acritarchs had been described from Neoproterozoic rocks, and they provided 'an independent framework for evaluating the stratigraphic ranges of early animals and for correlating rocks in which no [animal] fossils are known' (Knoll and Walter [1992], p. 675). The second was the carbon isotope record, which records changes in the composition of seawater. By characterizing isotopic fluctuations in carbonates and organic matter, researchers were able to correlate distantly separated rocks lacking fossils, and ultimately to 'establish a framework for understanding the geological and biological events associated with the early diversification of animals' (Erwin and Valentine [2013], p. 14).

Work on this framework generated more than a few surprises. As noted, a distinctive feature of the late Neoproterozoic fossil record was the presence of a sizable gap separating the youngest fossils of the Ediacaran biota from the oldest fossils of the Cambrian fauna. The gap was believed to span about 30 million years, with the oldest Ediacarans dated to around 600 Ma, and the Cambrian boundary dated to about 570 Ma. However, in 1995, work on the Neoproterozoic rocks of Namibia revealed that Ediacaran fossils continued right up to the Precambrian-Cambrian boundary, whose age researchers constrained to between 543.1 ± 1 Ma and 539.4 ± 1 Ma (Grotzinger et al. [1995]). The Ediacaran and Cambrian radiations—once separated and presumed to be causally decoupled—had suddenly been squished together.

Even more surprising was the evidence that they may not have been discrete events. By the 1980s, researchers had located trace fossils suggestive of bilaterian locomotion well beneath the Precambrian-Cambrian boundary, implying that bilaterians existed alongside the enigmatic soft-bodied fossils of the Ediacaran biota. A statistical study of Ediacaran fossils further complicated the picture by showing that the biota was composed of three temporally and faunally distinctive assemblages with a peak of diversity in the middle (Waggoner [2003]). Combined with the elimination of the stratigraphic gap, this led some to suggest that the CE may have begun in the

Ediacaran period when the diversity of Ediacaran forms began to decline, apparently in synchrony with the diversification of bilaterian trace fossils (Darroch et al. [2018]). Others have gone still further, arguing not only that the CE has its roots in the Ediacaran, but also that ‘a discrete Cambrian explosion event’ may be impossible to isolate (Wood et al. [2019], p. 535). Perhaps the CE was just a phase of a longer transition—a genuine radiation, but one that must be understood as integrally related to the events immediately preceding and following it. Apropos of this suggestion, the term ‘Ediacaran-Cambrian radiation’ has begun to gain currency as a means of identifying this transformative event in the early history of animal life (see Meert and Lieberman [2008]; Erwin [2015]; Darroch et al. [2018]).

In summary, the development of a high-resolution temporal framework has considerably sharpened our picture of the CE, imposing a range of new demands on candidate explanantia (see section 4). Additionally, extensive fieldwork at Precambrian-Cambrian boundary sections has challenged the notion that the Cambrian and Ediacaran worlds were separated by a bright line. Absent this line, a range of factors become relevant to explanatory modellers, including the waxing and waning of the Ediacaran biota itself as well as any factors that may have contributed to this process (for example, climate change, evolutionary innovation, and competition). This suggests that characterization not only shapes the requirements for adequate explanations but also reveals relationships of potential explanatory relevance between explananda and associated phenomena.

3.3. What sparked the Cambrian explosion?

For complex phenomena, characterization is rarely limited to the target (explanandum) phenomenon alone. Instead, a large amount of time is spent on characterizing associated phenomena, often by multiple disciplinary specializations and for their own sake (independent of being candidate explanantia). In the case of the CE, such phenomena are legion and include ‘changes in the physical environment, the establishment of new ecological relationships, and the evolution of developmental systems’ (Erwin and Valentine [2013], p. 8).¹⁸ Here we consider just one of these, ocean ventilation, which for many decades has been a locus of characterization research for scientists interested in the early diversification of animals.

The idea that animal evolution was suppressed by an absence of dissolved oxygen has a long pedigree (Mills and Canfield [2014]). Early speculation proposed that a critical threshold was surpassed only during the late Precambrian, after which time complex animals evolved with great rapidity (Berkner and Marshall [1964]). This threshold was thought to be about 1% of present atmospheric oxygen levels (PAL),

¹⁸ It remains an open question whether explanatory models for the CE must contain all, or only some, of these causal factor types (Love and Lugar [2013]). Yet, most researchers today agree that no single factor is likely to explain the entire complex phenomenon (Marshall [2006]; Erwin and Valentine [2013]).

based on attempts to characterize the oxygen concentration at which facultative anaerobes switch to aerobic (oxygen-burning) metabolism (Mills and Canfield [2014]). But the argument that an oxygen threshold was breached near the Precambrian-Cambrian boundary hinged on the fact that no animal fossils were known from earlier rocks, and was accordingly circular (Sperling and Stockey [2018]). Sedimentary structures called ‘banded iron formations’ provided an independent line of evidence that the early earth contained little oxygen. However, in the absence of direct evidence for increased ocean ventilation near the Precambrian-Cambrian boundary, the date of the supposed breach was difficult to constrain. The eminent palaeontologist Preston Cloud speculated that the earth may have passed 1% PAL as early as 2 billion years ago (Cloud [1976]), although he admitted that more direct lines of evidence were needed to settle the issue.

The first direct evidence for increased ocean ventilation during the Neoproterozoic was supplied by work on variations in the carbon isotopic composition of sedimentary carbonates and organic materials (Knoll et al. [1986]).¹⁹ This showed that the burial rate of organic carbon spiked during the late Neoproterozoic; and because photosynthesis produces organic matter and oxygen, whereas aerobic respiration consumes them, oxygen levels are expected to rise whenever organic matter is shielded from respiring organisms. Unfortunately, carbon isotopes cannot yield quantitative estimates of Neoproterozoic oxygen concentrations, so this line of evidence does not indicate when the 1% PAL threshold was breached. It also is uninformative about whether 1% PAL is in fact a significant threshold, and during the 1970s, new work on oxygen requirements suggested that early animals may have required oxygen levels in excess of 6–10% PAL to support their active lifestyles (Rhoads and Morse [1971]; Runnegar [1982]).

A major breakthrough in the study of Neoproterozoic oxygenation came from researchers involved in constructing models of Proterozoic ocean chemistry. In a pioneering paper, geologist Donald Canfield ([1998]) argued that oxygenation of the deep ocean lagged behind that of the atmosphere by over a billion years. Several lines of evidence implied that the earth experienced a ‘great Oxygenation event’ about 2 billion years ago, but according to Canfield ([1998], p. 451), this failed ‘to create an aerobic [well oxygenated] deep ocean’. Only in the Neoproterozoic did oxygen levels rise beneath a surface layer of water oxygenated by exchanges with the atmosphere. Happily, this is when multicellular organisms first appeared in the fossil record, which suggests that this second oxygenation event may have triggered an acceleration of animal evolution. Canfield et al. ([2007], p. 92) later speculated that a ‘prolonged stable oxic environment may have permitted the emergence of bilaterian animals some 25 million years [after the final Neoproterozoic glacial event, which ended about 580 Ma]’. Notably, these inferences were possible

¹⁹ These are the same variations that provided crucial evidence for researchers interested in unravelling the Neoproterozoic rock record (see section 3.2).

because refined temporal frameworks enabled researchers to make comparisons between changes in the physical environment and events known from the fossil record—an illustrative case of characterization directly facilitating causal inference.

In the last decade, more sophisticated methods for reconstructing the redox state of ancient oceans have become available (Lyons et al. [2014]).²⁰ These have uncovered extensive evidence for marine anoxia in the Proterozoic, matching the expectations of Canfield's model (Sperling and Stockey [2018]). They also have corroborated the idea that redox conditions remained highly variable between 750 and 560 Ma, which could account for both the absence of complex bilaterians from the fossil record before 560 Ma and their apparently rapid diversification afterwards (Erwin [2015]). However, not all evidence matches this picture. A recent analysis of iron geochemical data found no support for an Ediacaran oxygenation event and is consistent with the hypothesis that no statistically significant increase in oxygen took place during the Ediacaran or Cambrian periods (Sperling et al. [2015]). Other studies have found evidence that oxygen levels in the oceans may have exceeded 1% PAL as early as 800 Ma (Sperling et al. [2013]) or that atmospheric oxygen may have exceeded 4% PAL over a billion years ago (Zhang et al. [2016]). In conjunction with new experimental work on the oxygen requirements of simple organisms, these results hint that a lack of oxygen may not have played a major role in suppressing the early diversification of animals (Knoll and Sperling [2014]).

Much uncertainty continues to surround the redox state of the Neoproterozoic ocean and its relationship to biological evolution (Lyons et al. [2014]). Nonetheless, ongoing research has overturned old ideas and moved inquiry in new directions, 'reflecting novel approaches from paleontology, geochemistry and comparative physiology' (Knoll and Sperling [2014], p. 3908). For example, a recent article has suggested that environmental instability may actually incubate evolutionary novelties (Wood and Erwin [2017]). If this is correct, then the low oxygen conditions of the Ediacaran may have facilitated the developments of the CE (in contrast to the traditional picture, where novelty is associated with an oxygen breakthrough). Other work suggests that early metazoans may have preferred low oxygen environments, even when higher oxygen environments were available (Hammarlund et al. [2017], [2018]). If true, an important development in the diversification of animals was the evolution of the capacity to withstand high oxygen environments (Hammarlund [2020]). Whoever is right, progress on the problem of oxygen's role in the CE will hinge on refined characterizations of the redox landscape of the Neoproterozoic ocean, the environmental preferences of early metazoans, and the temporal relationships between evolutionary events and changes in ocean chemistry (Sperling and Stockey [2018]; Wood et al. [2019]).

²⁰ 'Redox' stands for 'oxidation-reduction'; oxygen is an oxidizing agent.

4. Analytical Implications of Ongoing Characterization and Interdisciplinary Entanglement

The CE provides a rich case study for exploring philosophical issues related to characterization and explanation. This section explores some of these issues in relation to the themes of entanglement and interdisciplinarity (section 4.1), and then defends two substantive claims (section 4.2).

4.1. Features of interdisciplinary entanglement

As noted at the outset, the characterization of complex phenomena exhibits three distinctive features. First, it is often done for its own sake and not solely for the purpose of facilitating explanation or prediction. Second, it tackles multiple dimensions of a phenomenon simultaneously (including explananda and potential explanantia), often requiring the coordination of multiple disciplinary inputs. And third, it involves an interaction with the construction of explanatory models throughout the career of a research project (the entanglement thesis). We now consider explicitly how the strands of research described in section 3 illustrate these features, particularly the entanglement thesis and its corollary of interdisciplinarity. In addition, we draw out the implications of our analysis for philosophical reconstructions of scientific practice by defending two claims: (1) characterizations of complex phenomena are frequently contested along several dimensions of descriptive understanding, and (2) the dynamics of ongoing characterization for complex phenomena are poorly described by models that treat recharacterization primarily as a response to explanatory failures (section 4.2).

Philosophers have tended to regard characterization as a kind of preparatory work that serves as a means to the end of the main (explanatory) business of science (section 2). We emphatically dispute this. For complex phenomena like the CE, characterization is ongoing, open-ended, and takes place alongside the construction of explanatory models. Attempts to explain complex phenomena must therefore track a moving target, and since moving targets are more difficult to hit, this feature of characterization imposes a range of challenges on would-be explainers.

The CE has moved a great deal since it began to garner serious attention during the 1970s. Prior to the cladistic revolution, it was thought to represent the initial divergence of major animal groups, and the challenge was to account for the apparently rapid origin of nearly the whole of the ‘modern’ marine fauna. Yet, with the advent of cladistic and molecular clock methods, this picture began to shift. To an increasing number of researchers, the CE seemed to be an explosion of fossils only—the delayed expression in the fossil record of a long and cryptic history of body plan evolution. The challenge was thus to explain how animal groups that diverged in the Precambrian only entered the fossil record in a giant pulse in the Cambrian or slightly before. More recently, refined clock methods have brought estimates of divergence times

more closely in line with the fossil record, suggesting that the CE was more than simply an explosion of fossils. Today, researchers tend to regard the CE as a diversification of crown group bilaterians within clades that diverged in the Neoproterozoic: a view that requires would-be explainers to account for both the burst of crown group diversification and the lag between the origin of major clades and their eventual radiation. And there is no indication that the CE is done moving (see Wood et al. [2019]). As Brasier ([1979], p. 148) observed in 1979, ‘One suspects there can be no final word on the Cambrian radiation’.

Thus, characterization can shift researchers’ attitudes about what needs to be explained. Yet, it also can shape views about how a target phenomenon should be explained: for example, by revealing relationships of explanatory relevance or supplying adequacy conditions for explanatory models (Dresow [2021a]). Regarding adequacy conditions, we documented in section 3.2 how stratigraphic research into the temporal structure of the CE revealed its temporal proximity to the Ediacaran radiation. Further research aimed at characterizing patterns in the fossil record showed that these events were unlikely to have been wholly distinct and may in fact have been stages of an integral process. This has led some to argue that the events need to be understood together if they are to be understood at all. To explain the CE means placing it in the context of the larger ‘Ediacaran-Cambrian radiation’ (Wood et al. [2019]). But this is just to say that an adequate explanatory model for the CE must be a model of the Ediacaran-Cambrian radiation or, alternatively, that any model seeking to explain the CE as an isolated phenomenon is bound to be inadequate. In this way, ongoing characterization has shaped evaluations of the appropriateness and sufficiency of explanatory strategies by imposing particular demands on explanatory models.

Regarding explanatory relevance, extensive fieldwork at Precambrian-Cambrian boundary sections showed that the Ediacaran and Cambrian biotas were not wholly distinct (section 3.2). Many complex behaviours once thought to be restricted to the Cambrian actually arose in the Ediacaran period (Darroch et al. [2018]). In addition, some researchers have claimed that elements of the Ediacaran biota may have survived into the Cambrian, further blurring a once-bright line (Wood et al. [2019]). However, if the Ediacaran and Cambrian biotas are intermingled—and especially if the CE began during the Ediacaran period—a range of factors become relevant to explaining the CE, not the least of which is the waxing and waning of the Ediacaran biota itself. Perhaps the CE was ignited when early bilaterians began to out-compete the previously dominant Ediacaran forms. Or perhaps a change in redox conditions facilitated bilaterian diversification by incubating evolutionary novelties or precipitating an Ediacaran die-off. Whatever the case, ongoing characterization of the Ediacaran-Cambrian transition has served to establish or corroborate the potential explanatory relevance of a range of factors whose further characterization, often pursued for their own sake, may pay explanatory dividends.

At this point, it becomes relevant that the characterization of complex phenomena tends to target a range of allied factors and processes, including phenomena that may serve as explanantia in explanatory models (see also Feest [2017]). One such phenomenon is the redox structure of the Neoproterozoic oceans (section 3.3). Ocean redox is a major focus of inquiry in its own right, but it has long been recognized that it is potentially relevant to the early history of animal diversification. By characterizing the history of ocean redox, researchers have developed this record as an explanatory resource. They have shown, for example, that shallow oceans remained mostly anoxic until at least 560 Ma, which potentially accounts for the lag between the initial divergence of major animal clades and their diversification during the Ediacaran and early Cambrian. In addition, they have shown that oxygen levels may have risen significantly in the mid-Ediacaran (compare Sperling et al. [2015])—a date that roughly coincides with a number of important biological events. Finally, ongoing work on the role of oxygen in animal evolution has raised new questions, such as the nature of the relationship between dynamic redox conditions and biological innovation. Together, these features illustrate two more ways that characterization can influence explanation: by growing the roster of explanatory resources and by raising questions relevant to the development of explanatory models.

The entanglement between characterization and explanation is complex, but it is also multidisciplinary. Section 3 documented how various disciplines have contributed to characterizing diverse features of the CE and associated phenomena, often at the same time. It also showed that different disciplines have made contributions of different kinds: for example, furnishing new explanatory resources (as geologists and geochemists did when constructing new models of ocean redox) and revealing relationships of explanatory relevance (as stratigraphers did when refining stratigraphic frameworks for the late Neoproterozoic). Such a complex, interdisciplinary entanglement can be expected whenever a phenomenon is sufficiently complex that characterizing it requires the coordinated contributions of several disciplinary specialties. And to reiterate, not all of these contributions were made with explanatory ends in view. While much characterization work is relevant to explanatory projects, this is not to say that it is undertaken for the purpose of testing explanatory hypotheses, or furnishing resources for explanatory models.

Overall, the case of the CE illustrates that characterization is often done for its own sake and not just for the purpose of facilitating explanation; that it tackles multiple dimensions of a phenomenon, often requiring the coordination of several disciplinary inputs; and that it is pervasively entangled with explanation. This entanglement, in turn, has several noteworthy features: first, it is open-ended, which renders the explanandum a moving target; second, it can shape evaluations of the appropriateness and sufficiency of explanatory strategies; and third, it can establish the potential explanatory relevance or actual explanatory value of a range of associated phenomena. All of these features are marked by interdisciplinarity and involve

contributions from diverse disciplinary approaches that play a variety of epistemic roles.

4.2. Implications for accounts of characterization

A conspicuous feature of the ‘received view’ of scientific characterization is that phenomena must be well characterized as a preparatory step in the process of building explanatory models. Many philosophers assume that characterizations are largely taken for granted unless empirical findings call the adequacy of these characterizations into question. In the case of complex phenomena like the CE, however, characterizations are rarely taken for granted and never regarded as complete. Instead, they are treated as works in progress and are perpetually contested along one or more dimensions of descriptive understanding. Marshall ([2006]) lists five features that need to be accounted for in any adequate model of the CE: (1) the burst of disparity (or spread of morphological variation produced), (2) the increase in diversity, (3) the time of onset, (4) the total duration, and (5) the uniqueness of the event. At least four of these features are presently contested. Along with persistent questions about how morphologically explosive the CE was, ‘the “roots” [time of onset] of the Cambrian explosion are greatly contested’, rendering its duration uncertain as well (Wood et al. [2019], p. 528). Its uniqueness has also been called into question, for if ‘a discrete Cambrian explosion event is difficult to temporally isolate, or indeed to define’, then the case for its uniqueness is greatly complicated (Wood et al. [2019], p. 535).

It is important to emphasize that the contested nature of the CE is not a recent development and is not evidence that the term is heading for the scrap heap. Rather, the CE has always been contested and has remained contested even as our picture of the phenomenon has been sharpened by developments in disciplines ranging from evolutionary biology to geochemistry. As Erwin ([2016], p. 279) writes, ‘Since 1989 almost every aspect of our understanding of the early history of animals and the Cambrian explosion has been fundamentally altered’. If the CE has survived these ‘fundamental’ alterations, there is no reason to regard its demise as imminent, even as challenges continue to arise. We submit that this is a general feature of characterization for complex phenomena: they are habitually contested along several dimensions of descriptive understanding.

Our second claim is that the dynamics of characterization for complex phenomena are poorly described by models that treat recharacterization largely as a response to explanatory failures. According to these models, recharacterization is a response to frustrated explanatory ambitions that occurs whenever attempts to fill out a mechanism schema show a prevailing characterization to be empirically inadequate (Craver and Darden [2013]; Colaço [2018b]). Craver and Darden mention three kinds of mistakes that can frustrate mechanism discovery and therefore elicit recharacterization—what Colaço ([2018b], p. 32) calls the ‘rejection of a

characterization of a phenomenon'. The first is claiming that a phenomenon exists when it does not. The second is inappropriately lumping two phenomena together. And the third is inappropriately splitting a single phenomenon into multiple phenomena. In the first instance, recharacterization consists in a process of authentication, which may discover that a phenomenon is fictional or needs to be recharacterized as a different kind of thing than previously suspected. In the second and third cases, it is a process of delineation that seeks to redraw the boundaries around the phenomenon to accord with new empirical information.

There are two problems with this model of recharacterization when applied to contested phenomena like the CE. First, while ongoing research may enjoin major revisions in researchers' understandings of a phenomenon (see section 3.1), these revisions arise from sustained efforts to more adequately characterize that phenomenon, often independent of any explanatory model.²¹ This means that recharacterization (the process) is not a sporadic occurrence induced by explanatory failures. Instead, complex phenomena are being characterized all the time. In the case of the CE, work on phylogenetic, stratigraphic, and environmental frameworks has been pursued for more than fifty years, and researchers openly discuss them as 'works in progress' (see, for example, Wood et al. [2019]). Some of this work has produced major revisions in the prevailing characterization of the CE, and these 'recharacterizations' (regarded as products) may be seen as sporadic. Our point is that the process of recharacterization is ongoing and non-sporadic. Moreover, there is no clear association of recharacterization effort with explanatory failure.

Second, there is more to recharacterization than authentication and delineation. Although researchers certainly worry about the authenticity and contours of target phenomena (see section 3.2), a more prominent theme of ongoing characterization is elaboration: the open-ended exploration of diverse features of a phenomenon, often based on diverse methodological approaches and lines of evidence. As Feest ([2017], p. 1167) states, for research in the cognitive and behavioural sciences, 'when we put ourselves in the epistemic position of practicing scientists, it is clear that they are not (or at least not exclusively or even primarily) in the business of explaining some already clearly delineated phenomenon. Rather, much of their empirical work is directed toward figuring out what they are actually investigating'. In Feest's [2017], p. 1166) useful language, research objects in the sciences are often epistemically blurry—'their nature and identity conditions are not well-understood'.²² We agree and think more philosophical attention should be devoted to this process of grappling with epistemically blurry phenomena, which motivates and organizes large swathes of scientific inquiry independent of explanation, often at the juncture of multiple disciplines.

²¹ For similar cases, see (Colaço [2020]; Bollhagen [2021]).

²² To this we would add that their internal structure and boundary conditions are also frequently blurry.

We lack the space to attempt a thorough analytical account of elaboration, but it is important to observe that elaboration does not just involve the progressive disclosure of more and more features of a phenomenon, like filling in the blank spaces in a proverbial map of the world. In addition, it involves the application of new measures and tools to known features of phenomena: going over the same ground again with different or improved resources. This might be discussed under the heading of ‘re-characterization’, but the crucial point is that elaborative recharacterization need not be—and often is not—mobilized by failures of explanation. Instead, it is a form of ‘epistemic iteration’ in which researchers seek to refine initial, provisional models of phenomena by the application of new tools and approaches to familiar research objects. In the case of the CE, iteration of this sort is ubiquitous (Chang [2004]; Elliott [2007]). New phylogenetic methods replaced the old, and were further refined by the application of the stem and crown group distinction. New methods of subdividing and correlating rocks led to a progressive refinement of the stratigraphic framework, while advances in geochronology increasingly constrained the time-scale. And new methods from isotope geochemistry sharpened researchers’ pictures of the redox landscape of Neoproterozoic and Cambrian oceans. All of these examples fit a standard definition of epistemic iteration: they are processes by which ‘scientific knowledge claims are progressively altered and refined via self-correction and enrichment’ (Elliott [2007], p. 378). Characterization as elaboration therefore involves an iterative dimension driven by the development or recruitment of new resources for grappling with the multidimensional spread of complex phenomena.

5. Closing Reflections

Although philosophers have tended to regard characterization as an auxiliary to explanation or prediction, there are reasons to reject this conception for complex phenomena. In contrast to simple objects of inquiry, complex phenomena are routinely subject to ongoing processes of characterization independent of explanatory aims, often from multiple disciplinary vantage points. The same holds true for associated phenomena, including those phenomena marshalled as explanantia in explanatory models. For both explananda and explanantia, worries about authentication and delineation account for only a small part of the scientific effort expended, which is undertaken continuously rather than confined to special moments of explanatory crisis. Moreover, they interact continuously with the formulation of explanatory models for target phenomena (the entanglement thesis) and do so across disciplinary boundaries (the corollary of interdisciplinarity). As we have shown, this interdisciplinary entanglement is amply illustrated by the spheres of work aimed at characterizing the ‘explosiveness’, temporal structure, and environmental context of the CE.

In closing, we note several conceptual questions that our analysis makes salient. First, if the default state of characterization work is dynamic and open-ended, the stability of particular characterizations of phenomena becomes a feature of scientific

reasoning in need of explanation (Feest [2011]). What has traditionally been taken for granted now requires an account: Under what conditions do we expect phenomena to exhibit a stability of characterization in multidisciplinary investigation? Does the language used, including metaphors like ‘explosion’, play an important role in establishing forms of stability for a research object through time? Second, the prevalence of interdisciplinary entanglement demands increased scrutiny of the evaluative standards operative when characterizations of phenomena are contested along some dimension of descriptive understanding (Powers [2015]). To what degree are forms of consilience important, such as when molecular clock estimates were brought into closer alignment with fossil evidence of early animal diversification? In the case of the CE, a reconciliation between two disciplinary approaches was nurtured through a happy convergence of distinct lines of evidence (Cunningham et al. [2016]). But what happens when lines of evidence remain incongruous? How are different sets of evaluative standards weighed against one another?

Third, despite the wide range of views and disciplinary approaches involved, researchers have continued to organize their labours around the idea of a discrete event, even when stratigraphic developments encourage seeing it as bound up with earlier and later events. This commitment does not arise from a shared theoretical orientation, a single consensus model, or a continuity in methodological approach, since there are no viable candidates for this office in a richly interdisciplinary environment (Love and Lugar [2013]). Something else constitutes the epistemic glue that binds researchers together in studying different facets of this event. Other analytical units, such as problem agendas, might be better suited to account for these patterns in ongoing research and offer ways to both measure and track the kind(s) of progress that attend the ongoing characterization of complex phenomena (Love [2014], [2024]). Although these three broad questions do not exhaust the space of possibility opened by our analysis, they clearly indicate that philosophers of science have their own projects of characterization to undertake.

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Max Dresow
Department of Philosophy
Minnesota Center for Philosophy of Science
University of Minnesota
Minneapolis, MN, USA
dreso004@umn.edu

Alan C. Love
 Department of Philosophy
 Minnesota Center for Philosophy of Science
 University of Minnesota
 Minneapolis, MN, USA
 aclove@umn.edu

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