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What is Philosophy of the Geosciences?

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Abstract

The philosophy of the geosciences is an emerging subfield in philosophy of science. Although past and present geoscientific disciplines differ substantially, we argue that they frequently face common epistemological and ethical problems. We survey several of these problems that have already attracted sustained philosophical interest, related to the use of measurements, data, and models to study relatively inaccessible target phenomena, responses to (epistemic) injustices, and the management of epistemic risks.Philosophy of Science

1 | INTRODUCTION

Philosophers of science have become increasingly interested in the geosciences. The geosciences have potential implications for wellbeing, and raise epistemological questions about how complex and inaccessible planetary processes can be studied.

Here, we survey key topics in this burgeoning field.[1] We first discuss demarcating the geosciences (section 2). Attempts to demarcate the geosciences by means of a definition or a list of constituents are unsatisfactory. Nevertheless, there are philosophical themes that unify the geosciences. First, geoscientists study objects and processes that are difficult to access — the deep past, the interior of the Earth, distant planets — which necessitates creativity in construction and use of measurement techniques, data, and models. Sections 3-5 discuss recent philosophical work on these three sets of practices. Second, the geosciences are implicated, historically and today, in unethical political projects and research practices, including extractive, exploitative, or (neo)colonial endeavors (section 6). While we encourage future work in philosophy of the geosciences on other topics, we think it is not accidental that current philosophers of the geosciences have generally focused on these four subjects. Geoscientists themselves are also interested in improving their practices in these areas, providing ample opportunity for philosophers to get involved and impact scientific practice.

Like any survey, the following overview required curatorial choices. The literature and case studies focused on herein are (unsurprisingly) those with which the authors are most familiar. The result should be read as an initial guide, rather than a finalized map, which will hopefully lend itself to being revised and extended in the future. We look forward to seeing the philosophy of the geosciences co-evolve with changing societal needs and a better understanding of past and present scientific practice.

2 | DEMARCATING THE GEOSCIENCES

Philosophy of the geosciences faces a question of scope: what, if anything, demarcates the geosciences from other sciences? To demarcate sciences in general, or a specific subset of them, one may specify demarcation criteria. For example, we might say the biological sciences are demarcated by subject matter — objects that are/were alive. Similarly, we could demarcate chemistry by method — techniques for composing and decomposing substances.

An intuitive starting point is to look at historical and contemporary definitions used by practitioners. In the geosciences, such discussions predate current labels. "Geoscience" is a relatively recent invention, barely used before the 1940s. Even "Earth sciences" was common only after the early twentieth century. The urge to identify a distinct field of science concerned with the Earth, and various physical, biological, and chemical processes and properties at a planetary level goes back much further; for example, Martin's *Philosophical Grammar* (1735, 11) already contains a section on "geology" (Howarth, 2001, p. 4). Such early attempts to synthesize the geosciences did not reflect any methodological or theoretical unity. More generally, competing umbrella terms proliferated, ranging from the abovementioned "geology" to the narrower "geophysics," and including now-forgotten terms like "geognosy" and "geogony" (Howarth, 2001, p. 15).

Methodological heterogeneity still characterizes our current geosciences, which are usually defined based on the objects that geoscientists study. For example, the American Geosciences Institute defines geosciences as "sciences studying the Earth," while the current Wikipedia entry speaks of "sciences related to the Earth." These definitions are generally followed by lists of the sciences presently and/or historically considered geosciences (e.g., paleontology, seismology, geochemistry, or geodesy), and a disclaimer that the field also studies extraterrestrial planets. Good (1998) likewise describes current geosciences as the product of contingent historical developments. The boundaries of the geosciences continue to develop today, evidenced by the flourishing subsections within major geoscientific societies.

Object-oriented definitions correctly highlight that geoscientists treat planetary properties and processes as epistemic objects in their own right, rather than background conditions for other phenomena. This captures an important unifying feature of most geoscientific research, but is an unsatisfactory demarcation criterion. Whether a discipline should be considered geoscientific, according to such a criterion, would depend on whether its practitioners study planets. This criterion faces many counterexamples and is unavoidably vague; e.g., human social development is a planetary-scale process on Earth, but sociology and social history are (intuitively) not geosciences. Given methodological diversity in the geosciences, we cannot alleviate this worry by qualifying *in what sense* geoscientists study planets.

Perhaps it is more fruitful to look for *philosophically* salient similarities between the geosciences. While object-oriented definitions characterize most of the geosciences well, they also fail to offer a single demarcation criterion. Even if the geosciences do not possess theoretical or methodological unity, however, they still pose several common problems, which arise because the various objects studied in the geosciences are relatively inaccessible. Inaccessibility is an epistemic notion, referring to the background assumptions needed to justify empirical inferences (see Smith, 2007). For example, compared to human observers and instruments, planets are exceedingly large, making it difficult to reproduce phenomena in laboratory settings. Additionally, several of the geosciences' most widely studied phenomena depend on processes in the planetary deep interior or deep past, inevitably locked away from direct measurement or experimental manipulation (Turner, 2007). Furthermore, geoscientific phenomena are incredibly complex, such that individual measurements or experiments are of little value.

This focus on epistemic accessibility tracks problems shared across geoscientific fields as diverse as geology, geodynamics, climate science, volcanology, oceanography, atmospheric chemistry, and many branches of astrophysics. It also generalizes a key motivation in debates about the epistemic status of the historical sciences. The positions previously advocated for here include (1) that the historical and experimental sciences are methodologically distinct, but not in such a way that makes either epistemically superior to the other (Cleland, 2001, 2002, 2011, 2013); (2) that the historical and experimental sciences are methodologically distinct, such that the historical sciences are epistemically inferior to the experimental sciences (Turner, 2005, 2007, 2016); and (3) that the historical and experimental sciences are not methodologically distinct, and so it doesn't make sense to ask whether either is epistemically superior to the other (Currie, 2018; Forber & Griffith, 2011). Underlying all of these positions is an interest in the specific epistemic problems faced in the historical sciences. Means for probing assumptions in other geosciences (such as about planetary interiors, climates, or dynamics) — whether these means are experimental or otherwise — are similarly scarce and presupposition-heavy. This scarcity must *not* threaten the credibility of geoscientific results. Rather, it invites us to assess the alternative methods and inferences underwriting geoscientific knowledge. As we illustrate in the following sections, this focus aligns rather naturally with existing work in philosophy of the geosciences.[1]

Geoscientists have responded to their common epistemic problems in interesting ways. When constructing quantitative models of inaccessible phenomena, geoscientists often determine their parameters through theory- and model-mediated measurements (Miyake, 2017a, 2017b; Ohnesorge, 2022; Smith, 2007). Such practices are ripe for philosophical analysis. Geoscientists also rely on analogical inference for producing, storing, and repurposing data, challenging received views of the evidentiary relationship between data, models, and theories (e.g., Bokulich, 2020b, 2021a; Bokulich & Oreskes, 2017; Lloyd, 2012; Parker, 2020b). Finally, geoscientists are innovative in gaining empirical access by scaffolding diverse forms of evidence relative to contextually specific purposes, a strategy that Currie (2018) calls "methodological omnivory" (see also A. Wylie, 2017).

Beyond epistemology, the geosciences also share a common history as extractive, military, or "survey" sciences (Schaffer et al., 2017). Gathering data to draw conclusions about the Earth's defining features is a laborious and costly enterprise; modern geoscientific practices only became feasible when sufficiently resourceful institutions such as governments, colonial trading companies, and industrial conglomerates realized their value for pursuing global trade, industrial-scale agriculture, conquering territory, extracting natural resources, and projecting power across continents, oceans, and the atmosphere. As a consequence, geoscientific research has long served the aims of these institutions. Geoscientists, in turn, sometimes actively exploit the political and economic utility of their research to obtain financial support.

This ongoing history of the geosciences makes them an ideal context for addressing central questions in the ethics and political philosophy of science. Moreover, the imprint that military and industry interests leave on geoscientific practice can inform debates about permissible and impermissible roles for non-epistemic values in science. Geoscientists also face unique challenges in providing genuinely global policy advice, raising questions about the ways in which scientific advice should respond to historically grown, highly asymmetrical distribution of data between the Global North and the Global South.

In short, instead of demarcating the geosciences in a strict sense, we are better advised to focus on philosophically salient problems shared across the different disciplines studying planetary processes. In sections 3-6, we address each of these philosophically-salient features related to: measurement, data, models, and research ethics.[2]

3 | MEASUREMENT

To measure some property of a target system, scientists use instruments to determine that property's magnitude in terms of standardized units. The data that measurements produce allow scientists to compare the target property across time and space, justify inferences about related properties of the target system, or test theories and models. By measuring an earthquake, for example, seismologists can compare that earthquake to past and future earthquakes, infer the size and displacement of earthquake faults, and test competing models of fault displacements or theories about the transmission of seismic waves (Howell, 2005, chap. 5; Miyake, 2017a, 2017b).

Inferring information from measurement procedures requires scientists to assume that they satisfy scale-specific relational conditions (e.g., Luce & Suppes, 2002). Quantitative scales presume that their underlying procedures invariantly rank their outcomes *and* the ratios between their intervals. Testing these conditions in geoscientific measurements is incredibly difficult. For example, seismologists recorded ground motion for several centuries while neither managing to agree on a unit-invariant scale, nor the correct definition of the property under measurement (Miyake, 2017a). Some measurements in mineralogy, sedimentology, geochemistry, and paleontology are believed to still fail these formal conditions. In many cases, scientists concentrate instead on developing specialized statistical tools for jointly analyzing non-quantitative data and quantitative data (Bialik et al., 2021).

Such difficulties have led philosophers to suspect that geoscientific measurement is particularly challenging. This suspicion can be motivated by contrast with classic textbook cases of measurement, which usually involve target attributes that can be directly observed and experimentally shielded from confounding perturbations.[3] Take measurement theorists' favorite cases: measuring rods and fulcrum balances. It is relatively easy to notice and correct disturbances that arise from, say, thermal expansion. Even in cases of indirect measurement philosophers have focused on procedures that involve experimental control over the measurement process.[4] Consider, for example, measuring the strength of gravitational force by observing the acceleration of a pendulum bob. Here, scientists need to theoretically derive along which path a pendulum oscillates harmonically. They can subsequently ensure that the bob follows such a path by manually constraining the bracket of the string (Yoder, 1989). Given the size and layered structure of planets, the intended targets of many geoscientific measurements (e.g., the magnitude of force released in a seismic event or the composition of the Earth's outer core) — and the link between these targets and the measurement instruments (e.g., the transmission and seismometer recording of seismic waves or the strength and gradient of Earth's magnetic field between its outer core and a surface magnetometer[5]) cannot be experimentally shielded from perturbations.

Assessing whether geoscientists are measuring actual quantities or merely curve-fitting error-ridden data often involves at least two distinct problems, which Miyake (2011) refers to as (i) “theory-mediation” and (ii) “combining of effects.” Problem (i) applies if scientists need to assume one plausible theory about the target to infer its magnitude. Consequently, the measurement in question depends on assumptions that cannot be tested independently. Problem (ii) applies if scientists need to rely on theory to decompose jointly occurring effects of their target property and other properties. These problems overlap and reinforce one another, as they both result from the inaccessibility of geoscientists' target systems. Ohnesorge (2022) argues that this overlap exacerbates problems of coordination — co-dependencies between theory and instrumental procedures that are characteristic of indirect measurement.[6] If scientists' access to the measurement process is reliant on theory, it becomes harder to avoid vicious circularity and underdetermination. Perhaps not *all* geoscientific measurements are theory-dependent in one or both of the senses sketched above (Dresow, 2021b), but such problems occur more frequently given persistent inaccessibility.

Geoscientists' solutions to difficult measurement problems contain valuable lessons about building indirect measurements. For example, Smith (2007) shows how seismologists measured the parameters of the Preliminary Earth Reference Model (PREM). PREM provides a description of the Earth's internal attenuation, pressure, density, gravity, and elasticity. Despite the problems specified by Miyake, seismological measurements of PREM's parameters license reliable inferences about the Earth's interior. Seismologists succeeded by first applying theories of wave-propagation to simple models of its structure and successively correcting discordant outcomes by incorporating increasingly detailed features of the Earth's interior.[7] Ohnesorge (2022) stresses an alternative methodology at work in the first convergent measurements of Earth's ellipticity. Scientists only accounted for relevant sources of error when they employed several alternative measures and repeatedly revised their respective modeling assumptions in light of numerical conflicts. Studying research on the formation of the Moon, Fox (2021) shows that geoscientists can become even more creative, using not only theories but also story-lines to link present-day measurement indications to quantitative properties in the deep past.

Despite their difficulties, geoscientific measurements can have evidential payoffs. For example, Smith (2007) stresses how PREM accounted for long-standing discordances in seismological measurements that arose from irregularities and anisotropies in the Earth's outer mantle. By successively explaining such discordances, seismologists can test the theories underlying these measurements with increasing stringency. Bokulich (2020a) shows that a similar logic can be discerned in the calibration of geochronological standards.[8] In her study of recent discordances between radiometric clocks, she stresses the importance of studying the sources of discordances before recalibrating the different measures. Scientists only recalibrated uranium-lead and argon-argon clocks after they had identified the physical sources of their long-standing discordance. This careful study of discordances strengthened the evidence for the clocks' reliability and the standardly used Geological Time Scale.[9]

Much philosophical work on geoscientific measurement remains to be done. Crucially, little is written about measuring parameters of other planets in flyby missions, a remarkable problem of gaining empirical access based on extremely limited data (e.g., Stevenson, 2020). A second promising topic is the widespread use of ordinal measurement in the geosciences (Bialik et al., 2021). As Larroulet Philippi (2021) points out, existing work focuses exclusively on Moh's hardness scale and pays little attention to how the scale is used in scientific practice.

4 | DATA

Practices regarding the production, storage, interpretation, and use of data are also central to the geosciences. For example, data in the historical geosciences are uncovered in the “natural archive” constituted by the sedimentary layers of the Earth, and geoscientists have developed strategies to cope with how Earth's history and processes are imperfectly recorded therein. Philosophers of the geosciences have made notable contributions in philosophy of data — e.g., concerning data ontology and data evaluation — by examining geoscientific data practices.

Fossil data, for example, are crucial for many research programs in paleontology. Paleontology is an uncontroversial example of a geoscience, but is notable for its focus on biological processes (especially evolutionary and taphonomic processes) in addition to physical or geological processes. Paleontological data primarily consist of preserved organisms that lived in the past, and enable reconstructions of past life. However, fossils represent an imperfect, unrepresentative sample: not all organisms are equally likely to be preserved (some organisms live in sedimentary environments that are more conducive to fossilization) and not all fossilized organisms are equally likely to be discovered by researchers (only fossils not destroyed by erosion or subduction will be discovered). Furthermore, processes that occur between deposition and discovery of a fossil affect the fossil data that are uncovered. For example, fossilization can involve material conversion of organic remains into rock; only “hard parts” of organisms (skeletons, shells) are likely to be preserved; and rock beds move around over long periods of time, making it difficult to reconstruct the original location at which the organism lived.[10]

Geoscientific data can also be digital, rather than specimen-based. For example, the Paleobiology Database (https://paleobiodb.org) is a popular source of data for paleobiologists. Paleontologists have developed sophisticated statistical techniques to account for imperfections in fossil data, which they can apply to digitized data. These techniques rely on the presence of detailed and reliable metadata.[11] More recently, paleontologists have noticed the importance of metadata about the “data journeys” (*sensu* Leonelli & Tempini, 2020) a fossil undergoes *after* it is extracted. C. Wylie (2021) points out that the decisions and practices of fossil preparators — skilled technicians who "prepare" fossils, for example by scraping away irrelevant rock matter — are seldom documented, although these decisions are important for the eventual interpretation of the fossil.[12] C. Wylie (2019) demonstrates how the eventual fossil data used by paleontologists is underdetermined by the extracted specimens (cf. Currie, 2021), and Bokulich (2021a) argues that fossil preparation can be viewed as a data processing or data modeling practice. Paleontologists also must reckon with legacies of colonialism and how unequal distributions of scientific authority affect patterns of fossil collection (we return to data ethics in section 6).

Examination of data practices in the geosciences has contributed to several novel philosophical insights. First and foremost, the geosciences accentuate the role of models in producing and processing data (as well as the use of data in constructing models); we return to this in section 5. Second, inspired by Parker's (2009, 2010, 2020c) adequacy-for-purpose view of model evaluation, according to which models should be evaluated by reference to a research purpose rather than the model's representational accuracy, Bokulich and Parker (2021) advocate for evaluating data by their adequacy for particular research purposes. Bokulich and Parker thereby highlight that other features of data (such as its spatial or temporal resolution, what available metadata there are, etc.) might be more important for evaluating data than the data's truth or accuracy. Such pragmatism saturates the geosciences, in which dealing with imperfect or distorted records is standard practice. Third, philosophers of the geosciences emphasize the importance of *time* for data. Using Leonelli (2018)'s discussion of how both "phenomena-time" and "data-time" exert important influences on data and the claims for which they serve as evidence, Currie (2019) emphasizes that all data, not just data in the historical sciences, have an important, historical component.[13] Fourth, Bocchi et al. (2022) identify several specifically "datic" challenges encountered when comparing paleodata with contemporary data on biodiversity (see also Bocchi, 2022; Dresow, 2021a). Finally, several philosophers of the geosciences pick up a problem first discussed by Laudan (1987) by addressing questions about taxonomy and the relationship between these taxonomies and the data needed to support them, including taxonomies of geologic time (Bokulich, 2020c; Santana, 2019b) and mineral taxonomy (Cleland et al., 2021; Santana, 2019a).

There are many more philosophical topics regarding data in the geosciences that are ripe for future research. For example, quantification and communication of uncertainty is a very important topic that requires further analysis (although see Lewandowsky et al., 2015; Parker & Risbey, 2015; Oreskes, 2015b). Several philosophers have also become increasingly interested in the use of proxy data and measurements in the geosciences (e.g., Boudinot & Wilson, 2020; Page, 2023; Watkins, n.d.-a; Wilson & Boudinot, 2022). More generally, the fact that the geosciences often rely on many different types of data and subsequently complex methods of data analysis requires more philosophical attention.

5 | MODELS

Given the complexity and inaccessibility of their objects of study, geoscientists often rely on the use of models, including computer simulations, mathematical models, and concrete models.[14] For example, Currie (2018) argues that historical scientists "manufacture their own evidence" using models: because historical scientists typically cannot generate their own data experimentally but are limited to data they find in the field, they can supplement these data with simulated data.[15] Doing so removes any potential misunderstanding of the epistemic limitations of the historical sciences, because the historical sciences actually have access to the same kinds of evidential support that the experimental sciences do. Currie's point holds more broadly. Because geoscientists are often limited in how they can study their targets — whether because these targets are temporally distant, spatially large, or buried deep below the surface of the Earth — these scientists must be creative. And their creativity often involves supplementing field and lab studies with the use of models.

For example, philosophers of climate science[16] have focused on the use of climate simulations. Climate simulations are massive, computationally expensive computer simulations made by several research groups that are used to detect contemporary climate change, attribute it to human activity, and make predictions about the trajectory of climate change under different future emissions scenarios. Climate simulations are able to address counterfactual claims (for example, what would the global average temperature have been in the twentieth century in the absence of human-generated emissions?) that cannot be addressed experimentally using the Earth's actual climate. So, it is because the climate itself is experimentally intractable — too large, too difficult to influence intentionally, there is only one of them — that climate scientists rely on climate simulations in order to study climate change.[17]

Philosophers of climate science have engaged productively in several debates in philosophy of modeling. For example, concerning model evaluation: what makes a climate model better or worse than another? Philosophers disagree on this issue. For example, Lloyd (2009) argues that models that fit the data better are better models, and Kawamleh (2022) thinks models with dynamics similar to actual climate dynamics are better models. These views of model evaluation prioritize accuracy over other possible features of the model. On the other hand, Parker (2009, 2010, 2020c) argues that climate models can only be evaluated by reference to a particular purpose, and that, consequently, sometimes models which (intentionally) misrepresent their target systems are better than more accurate models.[18]

Another important debate concerns the practice of using multiple climate simulations in conjunction with one another. Philosophers of climate science have asked what significance it has when climate models agree (or disagree).[19] Does agreement between climate models have any *evidential* value, above and beyond the evidential value of the individual models themselves? Lloyd (2010, 2015) argues yes, with the caveat that the confirmation provided by model agreement is not confirmation of the models' outputs, but confirmation of the common causal structure shared by these models (see also O'Loughlin, 2021). Parker (2011, 2018) disagrees, persuasively rejecting several plausible arguments for the confirmatory nature of model robustness. Climate scientists often *do* check for agreement or disagreement among sets of climate models — for example, the Intergovernmental Panel on Climate Change (IPCC) relies on Coupled Model Intercomparison Projects (CMIPs) — so it is of the utmost importance whether or not these comparative projects are evidentially significant.

As alluded to in section 4, one widely received contribution by philosophers of the geosciences has been documenting and justifying the practice of using models to correct data and also using data to construct models. Philosophers of the geosciences argue that this reciprocal relationship between models and data — called "model-data symbiosis" (Edwards, 2010) — is not always viciously circular (Parker, 2020a, 2020b). Furthermore, Lloyd (2012) argues for "complex empiricism," whereby models can correct and validate data (and vice versa). Bokulich (2021a) documents how models are used to correct data in paleobiology, and Bokulich (2020b) provides a helpful taxonomy of how data can be model-laden (influenced by or constructed using models), using examples from the geosciences. A nuanced view of the relationship between models and data is directly tied to geoscientific practice, in which uncertainty, error, or incompleteness in the data generate the need for models to process and supplement the data.

Future philosophical research on models in the geosciences would benefit from examination of additional examples of models used in other geosciences. For example, do other geosciences treat model agreement or disagreement in the same way as climate scientists do? What is the relationship between models and data in these areas of research? Additionally, many of the topics recommended for future research in the context of measurement and data, such as related to error and uncertainty, should also include an analysis of models, given that models play a central role in these practices.

6 | ETHICS AND POLITICS

The geosciences have a history of ethically and politically contested research practices, continuing into the present. In this section, we address this legacy (section 6.1) and the often related task of incorporating considerations of risk and value into the geosciences (section 6.2).

6.1 | Facing up to injustices

Several geosciences, such as geology and paleontology, developed in tandem with extractive industries that involve mining and prospecting, including the fossil fuel industry (e.g., Monarrez et al., 2021). Additionally, “survey sciences” like geodesy or oceanography are deeply embedded within the military infrastructure of colonial and expansionist political projects (Edney, 1997; Oreskes, 2021; Schaffer et al., 2017). These historical developments shaped geoscientific practice and produced or deepend inequalities in access to natural resources, cultural artifacts, knowledge, and habitable environments.

This legacy of the geosciences points to important philosophical questions, many of which are being debated actively by geoscientists and activists (e.g., Cisneros et al., 2021, 2022; Dunne et al., 2021; Kempf et al., 2023; Monarrez et al., 2021; Raja et al., 2022). For example, Cisneros et al. discuss “scientific colonialism,” referring to two power asymmetries resulting from the geosciences' colonial history. A first class of power asymmetries structures research conducted in low-income regions by scientists from high-income countries (we call these “epistemic process asymmetries”); a second class of power asymmetries structures the accessibility of research outputs (we call these “epistemic access asymmetries”). Cisneros et al. criticize both asymmetries based on their moral, political, and epistemic consequences. Philosophers of the geosciences have much to learn and contribute by drawing connections to social epistemology, normative ethics, and political philosophy of science.

Many philosophers share a concern for epistemic process asymmetries, which are often studied using Fricker's (2007) notion of testimonial injustice.[20] Researchers in the geosciences, similarly, highlight that historically grown power asymmetries lead to some researchers' credibility being dismissed or downplayed based on discriminatory misconceptions. They not only criticize such injustices on political and ethical grounds, but stress their epistemic impact (e.g., Raja et al., 2022 discusses resulting sampling biases in paleodiversity research). These lines of reasoning echo arguments from feminist social epistemology concerning the intimate connection between the social structure and epistemic reliability of scientific research (Longino, 1990, 2002).

There is also growing philosophical interest in epistemic access asymmetries, which form the core of Irzik and Kurtulmus's (2021) theory of “distributive epistemic (in)justice.” Distributive epistemic injustice occurs if “epistemically basic” public institutions (universities, schools, etc.) do not fairly produce and disseminate knowledge about citizens' fundamental needs or do not adequately educate citizens to use such knowledge.[21] While the epistemic resources deemed fundamental vary across theories of justice, Irzik and Kurtulmuş argue they will generally include “epistemic needs that bear on people's health and the quality of their environment” (p. 9). The geosciences deal with many such needs: responding to earthquakes, toxic environmental pollution, extreme weather events, etc. While Irzik and Kurtulmuş’s account is restricted to epistemic injustice in *individual* societies, Elabbar (2023) proposes to extend it to *global* injustices. Like others, he focuses on the distribution of high quality climate data across world regions, but the argument may well be extended to other fields (Brönnimann & Wintzer, 2019).[22] As North et al. (2020) stress, historically grown epistemic access asymmetries also result in an acute scarcity of geoscientific research into “food security, health, water, minerals, energy” on the African continent (p. 2).

Ethical and political concerns are of course not limited to *epistemic* injustices, i.e., those which pertain to the scientific process and its epistemic outputs. The geographical distribution of expertise and environmental and human costs in extractive and military research has massively shaped the global and regional distribution of material and cultural resources. While philosophers disagree about which demands in-country and global distributive injustices place on particular institutions, it is an important task to locate (geo)scientific institutions in such discussions (e.g., Dresow, 2023; Castillo Brache, n.d.). Not least, because understanding the implications of past injustices can shape how scientists and philosophers engage with present controversies about geoscientific research on indigenous land and the geosciences' possible roles in space exploration (e.g., Cooper, 2021; Smiles, 2020).

6.2 | Epistemic risk

The geosciences — like all sciences with practical consequences — also have to contend with *epistemic risks*. Philosophers of science recognize that deciding to accept, reject, or defer judgment about hypotheses involves a weighing of their respective non-epistemic consequences (Douglas, 2000; Rudner, 1953; Wilholt, 2013). Beyond such "inductive risks" in drawing inferences, other types of non-epistemic consequences are at stake across different aspects of scientific inquiry; say, choosing a model or defining a theoretical concept (Biddle & Kukla, 2017; Harvard & Winsberg, 2022). Since many geosciences have complex ramifications for welfare and the environment, handling risks is an important and difficult task.

Philosophers of climate science argue that societal values impact which policy-relevant conclusions scientists' adopt (e.g., Parker & Lusk, 2019; Parker & Winsberg, 2018; Winsberg, 2012, 2018). For example, in models that attribute severe weather events like hurricanes and wildfires to anthropogenic climate change (rather than natural variation), different attribution methods lend themselves to different evaluative preferences (Winsberg et al., 2020). The "storyline" method (which seeks to explain the origins of singular events) reduces the possibility of falsely claiming that weather events are not attributable to climate change, whereas "risk-based" methods (which seek to estimate the overall risk of extreme weather events in the presence and absence of anthropogenic climate change) are less likely to result in false claims that do attribute these weather events to climate change. As Oreskes (2015a) argues, similar problems are widespread across other geosciences as the "perhaps most significant topics in earth science research today address…not only the functioning of physical systems, but the interaction of physical and social systems" (p. 247; see also Chakrabarty, 2009, 2019, 2021). Zanetti and Chiffi (2023) also develop an account of how values feature in the design and application of models in seismology. Such models are crucial to predict the potential damage of earthquakes and hold construction firms and politicians legally accountable. Similar problems occur in the study of other natural hazards, pointing to important avenues for future research.

How to best incorporate values into the geosciences remains a subject of debate, challenging existing ethical frameworks for policy advice. Both climate scientists and seismologists are increasingly aware of the role that value judgements play in their work, and are discussing how to ensure these values affect scientific research in a constructive way (e.g., Pulkkinen et al., 2022; Zanetti & Chiffi, 2023). Much of the philosophical debate about managing epistemic risks focuses on the practices of the IPCC. For instance, Betz (2013) defends a value-free approach to policy-relevant science by arguing that climate scientists can and should defer value-judgements to policy makers by heavily qualifying their conclusions, and John (2015, 2017) defends the IPCC's approach of adopting fixed high evidential thresholds to avoid any ethical grounds for skepticism. Elabbar (2023) and Elabbar (forthcoming) criticizes this approach by invoking global epistemic distributive injustices. He draws on the uneven global distribution of high-quality evidence and argues this provides political justification for varying evidential standards across regions; if some regions are less able to produce high-quality results that bear on fundamental interests, the IPCC needs to ensure their representation by accommodating lower-quality data. Relatedly, Jebeile and Roussos (2023) discuss the problem of "usability" of climate information, which is typically at a global scale and therefore not helpful in a policymaking context.

7 | CONCLUSION

In this article, we have traced the contours of philosophy of the geosciences as it currently stands, while gesturing toward directions it would be fruitful to pursue in the future. In summary, we argue that although it is difficult to unify the geosciences by subject matter or methodology, they are somewhat *philosophically* unified by difficulties having to do with measurement and data collection, a reliance on models as an inferential tool, and a set of concerns related to research ethics.

We believe it will continue to be productive for philosophers of the geosciences to focus on these broad areas, and we provide some guidance for interesting questions for future analysis, including: measurements in solar system geophysics, ordinal measurements, quantification and communication of uncertainty, proxy data and measurements, combining multiple types of data in geoscientific contexts, distributive epistemic justice, and epistemic risks in the study of natural hazards. A careful focus on the scientific practices related to each of these topics is sure to produce relevant insights and enrich future work in philosophy of the geosciences.

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ENDNOTES

[1] Geoscientists have of course thought about the foundations of their disciplines long before the recent wave of scholarship documented in this paper. Arguably, some of C.S. Peirce's philosophy of science was informed by his geodetic work for the US Coast and Geodetic Survey and he wrote several manuscripts on the methodological development of the field (Bokulich, 2021b; Lenzen, 1972); see also the various papers on "gravity" and "Earth's figure" at the Harvard Houghton Library, Peirce Papers, BMS Am 1632, n.d. The acceptance of continental drift also sparked philosophical attention and motivated a 1978 Philosophy of Science Association conference session on scientific revolutions in the geosciences, including papers by Rachel Laudan (1978), Michael Ruse (1978), David B. Kitts (1978), and Henry Frankel (1978). Individual publications such as Rachel Laudan's (1987) epistemological history of geological taxonomy were also widely received. Recent scholarship differs from such earlier trends because it led to *sustained* discussions across many successive conference symposia and workshops. While we cannot do justice to the rich history of the philosophy of the geosciences, we believe that it holds many lessons for future research, some of which are already being picked up in recent work (cf. the discussion of taxonomy in section 4).

[2] By focusing on these features we are deliberately departing from the areas highlighted by Kleinhans et al. (2010), who concentrated on types of inference, reducibility, and explanation in the geosciences. These issues are important and Kleinhans et al.'s focus on abduction bears similarity to the epistemic accessibility problems stressed here (less epistemic access, one might expect, leads to a stronger reliance on abductive inferences). We are giving less prominence to the three issues since none of them have been at the heart of recent debates in the field, which rather focus on concrete practices of measurement, modeling, and data management.

[3] Following standard usage in mathematical perturbation theory, we use "perturbation" to refer to discrepancies between a target system and an initial model of that target system. Perturbations in measurement refer to discrepancies between the initial model of the measurement process and the actual performance of the measurement, which may result from misrepresenting properties of the measurement target, context, or instruments.

[4] There is a long debate in philosophy of measurement on how to properly differentiate "direct" from "indirect" and/or "derived" measurements. For contemporary proposals, see Parker (2017), Elder (n.d.).

[5] The history of geomagnetic measurement has been studied in much detail (e.g. Good, 1988; Multhauf & Good, 1987), but its epistemological significance remains little discussed, the explorative work by Good (2011) being the prime exception.

[6] This evidential co-dependence has been referred to as the "problem of coordination" (Mach, 1900; Tal, 2011; van Fraassen, 2008) or "problem of nomic measurement" (Chang, 2004).

[7] Teru Miyake illustrates that seismologists similarly tested many idealized models that mediate between such theories and actual measurements (2017a, 2017b), which, among other things, were instrumental in establishing unit-invariant quantitative scales of earthquake size.

[8] Regarding radiometric dating in archaeology, see Chapman and Wylie (2016).

[9] Ohnesorge (2021), though, stresses the importance of other epistemic aims besides theory- or model-testing, showing how measurements can support fruitful research into sources of residual error *without* increasing the evidence for its underlying theories or models.

[10] For an excellent introduction to some of these issues in paleontology, see Shipman (1981) and Holland (2016).

[11] Relevant metadata might include pictures or descriptions of the orientation at which bones in a bone bed were originally found or details about the methods used to date the surrounding strata; regarding the importance of metadata in general, see Boyd (2018).

[12] For discussion, see Carrera and Watkins (2023).

[13] Watkins (n.d.-b) discusses how the various processes that shape fossil data actually put pressure on extant accounts of data ontology; part of her argument is that the temporal aspect of the processes that shape these data makes it difficult to say when the specimens *become* data (before or after they are extracted).

[14] See Bokulich and Oreskes (2017) for a review of models in the geosciences.

[15] See Jeffares (2008), though, for some examples of standard experimentation used to test "midrange theories" in the historical sciences.

[16] We take climate science to be a geoscience, according to the characterization of the geosciences provided in section 2.

[17] Climate scientists also use other sources of evidence to inform their climate projections, such as information from paleoclimatology (Page, 2021; Watkins, 2023a, 2023b, 2023c; Wilson, 2023). More philosophical work needs to be done on these other methods as well as on climate simulations.

[18] These debates relate to larger philosophical debates concerning the relative importance of accuracy compared to more pragmatic considerations, and the general role of idealizations or falsehoods in model-based science (e.g., Bokulich, 2009; Elgin, 2004; Potochnik, 2017; Rice, 2021; Wimsatt, 1987).

[19] This debate harkens back to the different views espoused by Levins (1966) and Orzack and Sober (1993).

[20] As Leticia Castillo Brache pointed out to us, Fricker's notion is of course not the only available lens for assessing epistemic process asymmetries. A similar notion is "epistemic violence," which Dotson (2011) defines as "the failure of an audience to communicatively reciprocate, either intentionally or unintentionally, in linguistic exchanges owing to pernicious ignorance." Dotson's definition requires that the audience's ignorance causes harm to agents (i.e., that it is "pernicious"), rather than that it results from discriminatory misconceptions. Since discrimination misconceptions arguably *are* materially or psychologically harmful forms of ignorance, we treat these notions as similar in spirit for the purpose of this article.

[21] Epistemic injustices can occur on a primary level — directly concerning citizens — or a secondary level — concerning legitimate public officials responsible for citizens.

[22] A similar point can also be made about climate models (e.g., Jebeile & Crucifix, 2021; Parker & Winsberg, 2018).

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