Figure 1. Photo of the Sage Hen Flat looking southward.

Sage Hen Flat pluton, California, and Increasing Trust by Communicating Uncertainty and Salience

Thomas F. Shipley,[1] Basil Tikoff,[2,*] and Ellen M. Nelson[2]

Geology logline: *Uncertainty in geological data exists because of inaccuracies in perception and variations in Earth patterns and processes; uncertainty in geological models exists because of the uncertainty in underlying geological data and the prioritization of some data in the construction of models. The result is that both geological data and models are best considered in a probabilistic framework.*

Cognitive science logline: *Collecting information about both the uncertain world and the uncertain mind facilitates the collection of less biased data and cooperative science; it also communicates an important part of the geologist's workflow.*

"To know what you know, and what you do not know, that is true knowledge"

—attributed to Confucius

Sage Hen Flat, in the White Mountains of eastern California, USA, is different from the other locales in this essay series; it is neither widely known nor a place accepted by the discipline as influential (Fig. 1). If it is known at all, it is because of its proximity to the bristlecone pine and a high-elevation University of California field station. Sage Hen Flat, however, became our testing ground for how cognitive science and geoscience could be integrated by externalizing what was already going on in the geologists' minds (Tikoff et al., 2023) and providing new tools to communicate and collaborate (Nelson et al., 2024). In this sense, it thoroughly changed our perspective on the geological mind. In this essay, we try to convey this new view and its implications for geoscience research and training future geoscientists.

Geologically, the Jurassic Sage Hen Flat pluton is interesting because the granitic rock intruded a thick Precambrian–Cambrian section of metasedimentary units without noticeably altering the surrounding bedding orientations (Fig. 2A). Cognitively, the area is interesting because there are two geological maps from the same area with contradictory interpretations for the subsurface geometry (Ernst and Hall, 1987; Bilodeau and Nelson,

*basil@geology.wisc.edu
[1] Temple University, Philadelphia, Pennsylvania 19122, USA
[2] University of Wisconsin–Madison, Madison, Wisconsin 53706, USA

CITATION: Shipley, T.F., Tikoff, B., and Nelson, E.M., 2025, Sage Hen Flat pluton, California, and increasing trust by communicating uncertainty and salience: GSA Today, v. 35, no. 7, p. 36–42, https://doi.org/10.1130/GSATG110GM.1.

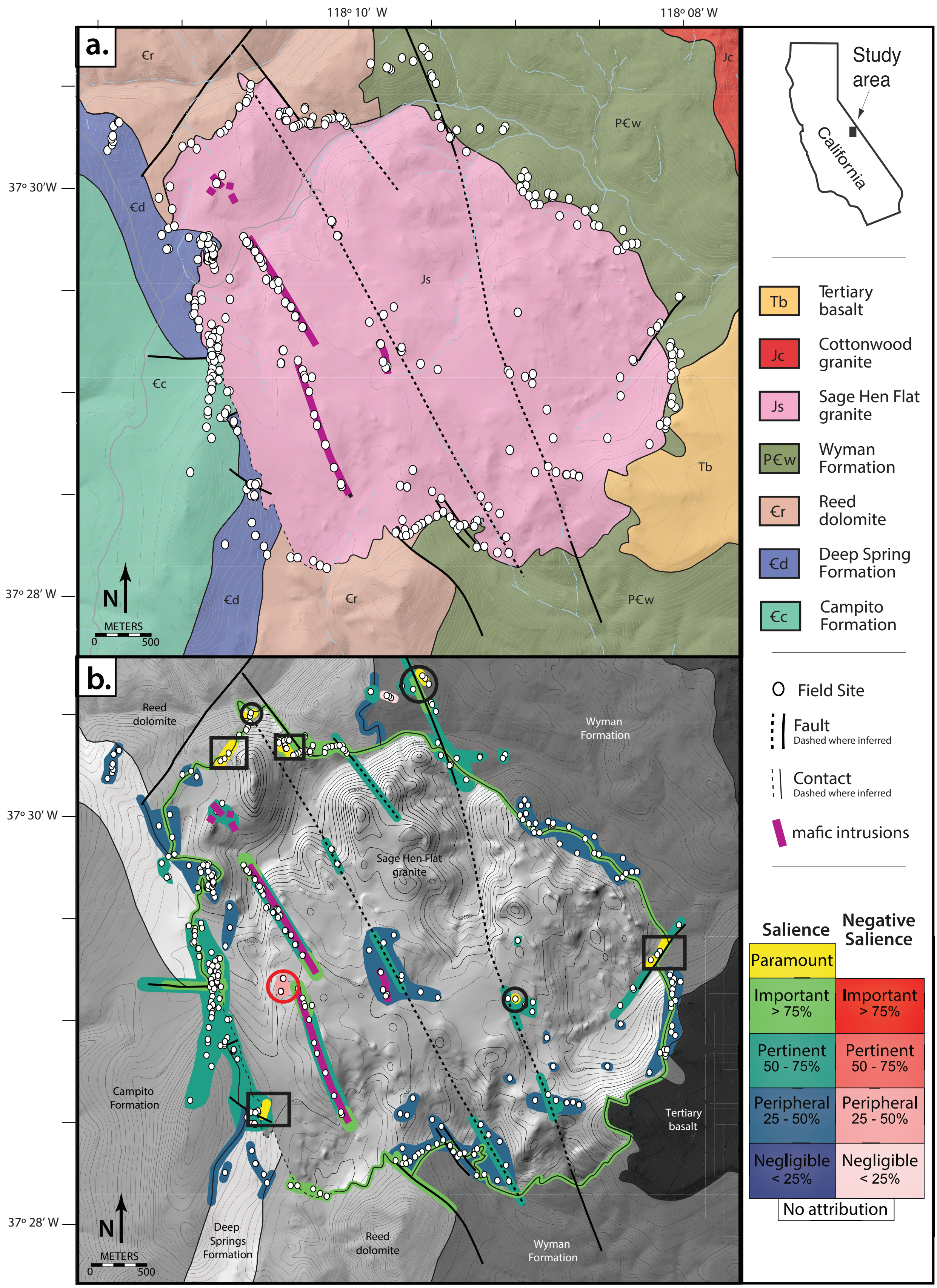

Figure 2. (A) Geologic map of the Sage Hen Flat region, California. (B) Salience map for the horizontal sheet model of the Sage Hen Flat pluton for the same area as shown in A. The salience values for each point are color coded. Four places where the pluton/wall-rock contact is exposed have thxe highest positive salience, highlighted by black boxes. Positive high-salience areas along exposed normal faults are highlighted by black circles. Figure is after Nelson et al. (2024).

1993). We hypothesized Sage Hen Flat to be a region where observational uncertainty was high and could provide insights into geological thinking by considering the cognitive processes that managed uncertainty in individual scientists' practices.

We introduce the Sage Hen Flat pluton as an example of how observations and theories interact when there is uncertainty. We first utilize cognitive science insights about human perception and thought as probabilistic, rather than deterministic. Using these insights, we explore the possibilities of field-based data collection being improved by: (1) recording the probabilistic nature of perception of the world and the variability of Earth patterns and processes through the use of uncertainty; and (2) recording salience to capture the alignment of observations with an interpretation of the world. Using both uncertainty and salience together provides a protocol to de-bias observations and thereby do better science. Communicating these parameters can potentially increase trust among scientists and between scientists and the general public.

PERCEPTUAL, OR OBSERVATIONAL, UNCERTAINTY

Early efforts in psychology to understand perception assumed a deterministic experience where sensory inputs led to specific perceptual experiences. Perception researchers assumed that scientific laws, similar to those discovered for physics, would be revealed to connect sensory input (cause) to experience (effect). That is, researchers expected a direct and simple relationship between what was in the world and what was in the mind. This approach ultimately failed because sensory inputs yielded neither a consistent nor a simple output.

Rather, the same sensory input yielded different perceptual reports in different people. Moreover, even the same person reported different experiences at different times. This variability was initially assumed to be the result of measurement error and/or noise imposed on an underlying deterministic process. It was not until the advent of the field of signal detection, part of the larger field of decision making, that conceptions of perceiving changed from deterministic processes to probabilistic processes. The recommended reading by Green and Swets (1966) discusses how this field initially arose from work on radar operators detecting planes in World War 2 (Marcum, 1947).

A person's everyday experience of the world—seeing, smelling, touching, and hearing—may not feel probabilistic because it is so often correct. Moreover, when perception is incorrect, it is quickly corrected with additional input. However, awareness of this probabilistic reality becomes heightened when our perception is based on imperfect data. For example, a field geologist is sometimes confronted with a complex or chemically altered rock for which the lithology is not clear. In this circumstance, any lithological decision is a likelihood of an observation matching the true state of the world, rather than a certain identification. Thus, what is recorded and reported as an observation will reflect the probable, but not certain, state of the world.

If perception is both uncertain and variable, how can we evaluate how well something is known? Studies in cognitive science indicate that people can reliably assess the quality of evidence for a perceptual decision (Preston and Colman, 2000). The record of their uncertainty is therefore scientifically valuable as an indicator of the likelihood that an observation matches the state of the world. Consequently, the probabilistic nature of perception provides an opportunity to record and share the degree of uncertainty.

UNCERTAINTY: CHARACTERIZING THE PROBABILISTIC NATURE OF PERCEPTION OF THE WORLD

We return the narrative to Sage Hen Flat, California, where we attempted to address the issue of perceptual decision making in a geological field setting. The results for field-based uncertainty are reported by Tikoff et al. (2023). We used a six-point ranking system (no evidence, permissive, suggestive, presumptive, compelling, certain) for the determination of the properties of any outcrop, where properties included certainty of attachedness, lithology, geometry, and kinematics. These categories were chosen because they integrate evaluation of both variation in perception and variation in Earth patterns and processes. To illustrate, consider the concept of attachedness, which we defined as the likelihood that an outcrop was fully attached to the underlying bedrock. It is somewhat difficult to tell if many of the outcrops at Sage Hen Flat are connected to the subsurface. Typically, the decisions about attachedness involved either size (e.g., bigger was more convincing) or consistency (e.g., fabrics had the same orientation in nearby, isolated outcrops).

In our experience, recording the uncertainties required minimal extra time because the geologists were already evaluating this information. That is, experts were already determining the observational evidence for whether a geologic property was present, but now they had a systematic and rapid way of recording the information. Moreover, the experts did not want to mix low-quality and high-quality data without a way to distinguish them in the data set. Thus, for the geologists, the main effect of using the uncertainty ranking system was that additional stops were recorded for outcrops that would have been bypassed otherwise due to their low quality.

Recording and communicating uncertainty are not new aspects in expert practice. A well-known field example is the use of solid versus dashed contacts on geological maps, in which dashed contacts are an assessment of uncertainty. Uncertainty, however, can be applied to all field measurements. In fact, early digital mapping systems allowed uncertainty to be assigned to most attributes (e.g., Walker et al., 1996; Pavlis et al., 2010).

Geologists routinely record and report the variability in all other tools (e.g., instruments) they employ in the field. If so, why is uncertainty of observations not routinely reported in field geology? The answer likely has three parts. First, the mind was not seen as the purview of geologists. We hope by now in this essay series you are thinking, "but of course it is." Second, there was no community tradition or shared vocabulary for evaluating the many facets of uncertainty in field-based observations. Third, there was no mechanism for storing and sharing these observations with the community. The use of digital databases now makes sharing these types of data possible (e.g., Walker et al., 2019).

RECORDING OBSERVATION UNCERTAINTY IN PRACTICE AND TEACHING

Recording uncertainty increases the transparency of the observer's perception in the recorded observation; a workflow that includes uncertainty could lead to a decrease in bias. One way to decrease bias is simply to be more mindful, which typically includes slowing down. Slowing down to reflect on a decision and the evidence for the decision has been found to reduce errors in medical decision making (Pinnock et al., 2021), and slowing down to consider regional histories has been found to reduce errors in seismic profile interpretations (Macrae et al., 2016). These improvements likely arise from active reflection that reduces the influence of expectations on pattern recognition. Thus, reflecting on uncertainty is likely to lead to a reduction in bias.

A familiar way to decrease uncertainty is to make additional measurements, for three reasons. First, when you record more observations, you are less likely to record a single observation that is based on its fit with existing theory. Second, increasing the amount of data collected yields an estimate that is proportionally more robust and therefore more trustworthy. However, optimal aggregation should factor in quality; this is where recording the level of uncertainty becomes critical. Third, variable data are most valuable when there is a lot of data, as aggregation offers a converging estimate of the underlying signal. If more is better, identifying when one has reached a point of diminishing returns becomes important, and that point will depend on the level of uncertainty. Deciding how much data are necessary requires both an understanding of perceptual experience and an understanding of how much variability is typically found in the Earth pattern or process being observed (which can come from prior knowledge).

Instructors could easily build on the well-known concept of uncertainty in mapping contacts to teach students to think more carefully and broadly about different types of uncertainty. All measurements carry a level of uncertainty associated with the measuring instrument. However, there is also a conceptual issue relating to uncertainty: How sure are you that you are really measuring the feature you think that you are? Some areas and rock types are difficult for students when they are getting started. For example, distinguishing between bedding versus rock cleavage in slate belts is quite challenging. Recording both the observation and the uncertainty of the observation facilitates better measurements because it supports reflection about a measurement. Effectively, it promotes the separation of what is known from what is not known. Additionally, in our experience, some students concerned about being wrong may be reluctant to measure geological features, but they will do so if they know that they can evaluate their measurement as uncertain.

ATTENTIONAL LIMITS AND MODEL UNCERTAINTY

The level of uncertainty is not the only characteristic that influences the value of data. Some data are inherently of higher relevance to a model. Using field geology, examples of high-relevance outcrops include those that expose contacts, clearly show gradients (e.g., sediment grain size), or illustrate a process or history (e.g., offset of intersecting faults). These are informally referred to by some as "Rosetta" outcrops because they uniquely constrain interpretations

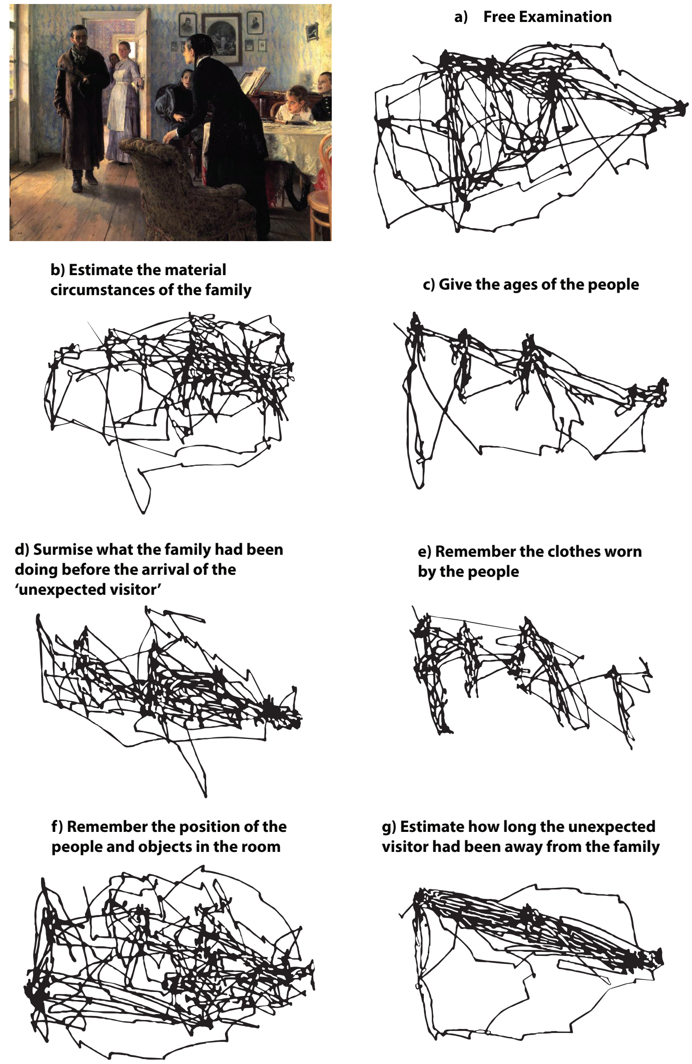

Figure 3. Eye-path looking records, from Yarbus (1967). Adapted from Wikimedia Commons/public domain.

of data in other areas of the field site. In the absence of a Rosetta outcrop, multiple interpretations of the patterns observed in the remaining outcrops would be permissible.

To address why some data are particularly relevant to constructing a model, we return to human perception. Humans can only attend to, and therefore think about, a few things at a time; all else is filtered out. You have but to look up from reading this text to become aware of things happening around you that you had not noticed while focused on reading. The fact that the term "attentional economy" has come into modern parlance reflects the competition for humans' limited attention from a host of sources attempting to monetize viewers' attention (e.g., social media apps). Limited attention is highly functional as it allows the mind to work with a manageable amount of information to guide rapid action, such as avoiding drivers or pedestrians whose attention is distracted.

Cognitive scientists have documented that human capacity to take in perceptual information is limited. Despite the sense of a visually rich 140° view of the world, only a tiny portion (approximately a thumb's width at arm's length) has high-resolution information at any moment. The earliest research on eye tracking found reliable patterns about where people focused on picking up details. For example, when confronted with a picture of people in a room (Fig. 3), most of the viewer's attention was focused on the faces and where each person was looking (Yarbus, 1967). If asked to estimate the wealth of the family, eye tracking indicated that the pattern changed, and people now spent more time on the objects in the room. That is, people literally changed how they were looking at the world, depending on what question they were asked. Observers attend to high-importance (e.g., salient) details and ignore parts that have lower importance. What one looks at—and therefore what one sees—is strongly influenced by an object or event's relevance to the observer's goals.

Attention to a small number of observations can quickly lead to an interpretation. In the case of Figure 3, the interpretation is a narrative of what might be going on in the moment of the image. However, these interpretations guide future looking (data gathering). Thus, the consequence of limited attention is that we produce mental models (interpretations) that guide where to next direct one's attentional resources (Neisser, 1976). While such interpretations are often correct, they are not inevitably correct. The key point is that the initial interpretation of the world around us, and generally all interpretations, is inherently probabilistic and contains some degree of uncertainty.

The same is true for scientific investigations. All scientists have experienced the failure of an initial conceptual model, based on limited data. Moreover, all scientists ignore some data that they think is anomalous or incorrectly collected. Expressed generally, uncertainty in geological models directly arises from the limited observations that were given priority to form the interpretation. Although scientists recognize the need to distinguish levels of data importance with terms such as permissive or compelling, what has been missing is the framework for recording, discussing, and sharing the weighting factor that we give data.

SALIENCE: CHARACTERIZING THE PROBABILISTIC NATURE OF THE MIND WHEN INTERPRETING THE WORLD

Salience is defined as the level of support that a specific observation offers for a specific interpretation. For the scientist, salience informs how interpretations were reached by linking data to an interpretation. As such, salience explicitly acknowledges the mental and practical limits on formulating an interpretation, because not all data enter into the formulation of a model or hypothesis. Recognizing this human limitation can be valuable for understanding why some types of data were collected and others not.

Nelson et al. (2024) proposed the use of salience in a scientific workflow at Sage Hen Flat such that these decisions would be recordable, sharable, and practically evaluated. An observation could be highly important because it either supports a model or is inconsistent with a model. To capture this dichotomy, we diverge from the cognitive science usage of salience as ranging from low (near zero) to high. Rather, we adopt assigned salience with both positive and negative scales. Negative salience values indicate increasing importance due to increasing inconsistency with a model. By including negative salience, it is possible to be explicit about how all evidence influenced the final interpretation, reflecting the preponderance of evidence. Practically, this means that evidence of increasing salience against an interpretation must be balanced by stronger, more compelling evidence for the interpretation.

Salience in this conceptualization can be accumulated and communicated as values or as a map layer for spatial observations. Figure 2B is a salience map for a horizontal sheet model of pluton emplacement in the Sage Hen Flat area (Nelson et al., 2024). We assessed salience at Sage Hen Flat using the "what if it magically disappeared" criterion. That is, when constructing our salience map, we determined the salience of an outcrop by assessing how much the support for the model would suffer if the outcrop was removed. The four places where the pluton/wall-rock contact is exposed have the highest positive salience (highlighted by black boxes on Fig. 2B), as do places that exposed a normal fault (black circles). The pluton at Sage Hen Flat is relatively well exposed, and thus the salience for any of the granitic outcrops was relatively low because of the inherent redundancy. The one area of high negative salience is a vertical, E-W–oriented fault on the west side of the pluton that is on strike with a fault in the wall rock ~0.5 km away (red circle). We observed it, but it does not fit well into our model of the area. A salience map allows a complete account of how all data "map" (in a literal sense) onto a model, which is otherwise not possible because of practical limitations on space in scientific journals and readers' attention.

The salience map is only for a particular model for a particular purpose. We anticipate that the previous published maps of the region (e.g., Ernst and Hall, 1987; Bilodeau and Nelson, 1993) would have had different salience maps. Those studies were more focused on regional geology, rather than pluton emplacement, although the interpretations constrained the geometry of the pluton at depth. However, even another study that explicitly shared our focus on the process of pluton emplacement would likely have a different salience map. The difference between two salience maps would uniquely identify the data that different groups are using to constrain their models.

Similar to uncertainty, the concept of salience is not new to expert practice. Positive salience is implicit in the observations that are mentioned in a scientific report in support of an interpretation. This concept is also central to a familiar practice of showing a visiting colleague around a field area, taking them to the important (positive salience) outcrops that support an interpretation. Perhaps less common, but still part of scientific practice, is to invite colleagues to the baffling (negative salience) outcrops that do not make sense in the context of a particular interpretation.

> *"How do you know what you know?"*
>
> ***—attributed to Socrates***

RECORDING SALIENCE IN PRACTICE AND TEACHING

Recording and sharing salience is not new but could become shared more broadly, and with greater precision, with formalized methods. Experts with a shared understanding of a model, or interpretation, will have a shared sense of what is and is not consistent with the model. Salience as a shared resource thus empowers cooperation, even among individuals with differing interpretations of an area. If salience were part of formal data sharing, it would support reproducibility by pointing those in the field to revisit key locations and "see for themselves." It would also allow community review to confirm the implications of data for an interpretation.

Negative salience is an important, and unexpected, conceptual outcome of this work—unexpected in the sense that we had not previously recognized how contradictory evidence was managed by individuals in the field but rarely shared with the community. Moreover, these nonconforming observations might be extremely valuable for reformulating interpretations. In this sense, negative salience is more important than positive salience. The key to progress is to communicate the nonconforming observations, so that the inconsistencies with a particular model—and hence the opportunities for improvement—are clearly communicated to future researchers.

We think the introduction of salience to students could help to illuminate a hidden part of becoming a professional geologist: understanding the nature of scientific models. A naïve view of science is that scientific models are either right or wrong. However, scientific models are tentative and subject to change because they contain uncertainty and are thus probabilistic. Changes to scientific models occur because salience may be incorrectly assigned, or important observations may have been overlooked. A more powerful and predictive explanation might be possible with a different interpretation using some of the same data, in which the weighting of what data are important (e.g., salience) changes. On topics of active scientific debate, one model or another may be prioritized, depending on which data set is prioritized (for an example, see Tikoff et al., 2025).

In this view, scientific models are part of a process rather than an end state. This recognition is both liberating and powerful. As a first year Ph.D. student, Basil was advised by the senior U.S. Geological Survey geologist Paul Bateman: "You don't need to be right, you do need to be consistent with your data." Including salience in a workflow shifts the focus from a correct end product to refining models to be consistent with the most salient data.

HOW UNCERTAINTY AND SALIENCE FIT TOGETHER: A PROTOCOL FOR DE-BIASING MODEL-DRIVEN SCIENCE

Uncertainty and salience are a package deal. Together, they reflect the reciprocal nature of data and models: Data constrain models, and models guide data collection and interpretation. This interplay creates a significant problem, often pointed out by historians of science (e.g., Oldroyd, 1996): Data and models are not independent, and therefore scientists are biased. Scientific training allows careful collection of complex data, and that complex data afford complex models. Those complex models in turn guide biased data collection. Yet, both perception and the process of science are self-correcting and together will approach a coherent, underlying reality. For geology, correction occurs because data and models are both grounded in Earth's patterns and processes.

High-quality models require converging data, which can be conceived of as redundancy in geological patterns. Salience can be seen as a way to record where to look for data that can be interpreted by taking advantage of such convergence and how uncertain that inference is. With uncertainty to record the noise and salience to record which data are being used, the two together can capture the probability that science has understood the world. Viewed this way, science can become significantly more efficient at self-correcting if both uncertainty and salience are recorded.

In efforts such as field mapping, the utility of the combined uncertainty-salience approach may be clear. Consistent with our geological mapping on Sage Hen Flat, we communicated what outcrops were most important in constraining the models (cross sections, in this case). We were aware of other models (e.g., Ernst and Hall, 1987; Bilodeau and Nelson, 1993), and we utilized multiple working hypotheses (e.g., Gilbert, 1886) to try to collect data that could support any of these models.

In reflecting on our own workflow at Sage Hen Flat, we realized that having multiple hypotheses focused our attention on specific areas. Many of the benefits of using multiple working hypotheses are also available using the uncertainty-salience approach. The act of evaluating the uncertainty in the data and the relevance of that data to a model required continuous assessment by the geologist, and thus resulted in de-biasing data collection. In our experience of working within a framework of assigning positive and negative salience, we were more likely to notice and thus record data that were inconsistent with the working model(s). In other field areas, we have used a single-model (or model-driven) approach. Model-driven science efficiently guides field time. However, it has the tendency to prioritize data that fit into one's model, which inherently yields biased data. The uncertainty-salience approach is particularly useful in cases where a single model is being tested. In such cases, de-biasing occurs as a result of increased awareness of context in making decisions about uncertainty (e.g., how does this outcrop compare to surrounding outcrops) and consideration of the entire data collection for consistency (e.g., recording negative salience).

UNCERTAINTY, SALIENCE, AND TRUST

It is often the role of the scientist within society to offer understandable guidance, based on evidence, and also communicate what is uncertain. The aspects of a topic that are uncertain are liable to change with the accumulation of further evidence, but so too are the high-salience data that matter for the practical guidance regarding any specific topic. In the absence of a clear articulation of both uncertainty and salience, any changes in policy based on data will seem arbitrary. This understanding is important to scientists and the general public alike. Reporting of salience allows multiple independent minds to consider the relationship between observation and interpretation.

Trust, in large part, comes down to effective and transparent communication about how you know what you know and how you know that it is likely correct. Increasing trust is a major reason for characterizing uncertainty and salience. Field scientists who have not been to a particular area are effectively trusting those scientists reporting on an area to be accurate (uncertainty). Telling people how the data were weighted to build a model (salience) further increases trust. Clear scientific communication also requires reporting what is not known. Negative salience provides the opportunity to report an important unknown, data that are nonconforming to a specific model. Future research efforts can effectively be directed at areas of negative salience, leading to new observations and new models.

In conclusion, why did Sage Hen Flat change our minds? The answer lies partly in the nature of Earth patterns here: It is where we could see how uncertainty in observations allowed experts to have differing but reasonable conclusions. Perhaps it is a "sweet spot": Less uncertainty and everyone would map the same way; more uncertainty and a definitive interpretation would not be possible. Similarly, the sparse outcrops meant that some of the outcrops played a greater role than others in guiding reasonable interpretations. Although we started with a more typical attempt to adjudicate between different interpretations, we realized that there was an opportunity to change our workflow, and thereby our minds. It was Sage Hen Flat, itself, that allowed us to confront the interrelationships between data and models, and the opportunity afforded by communicating uncertainty in both.

ACKNOWLEDGMENTS

Alix Davatzes, Aryssa Mahrt, and Sarah Trevino provided informal reviews of this essay. Formal reviews by T. Pavlis, an anonymous reviewer, and Editor A. Egger significantly improved the manuscript. Art Sylvester facilitated this collaborative effort and was generous with his field time in California. The Crooked Creek facility of the White Mountain Research Station provided lodging, and we are grateful to the staff for their support. National Science Foundation support for T. Shipley (2311820) and B. Tikoff (2311822) is acknowledged.

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This essay series is a joint effort of the National Association of Geoscience Teachers (NAGT) and the Geological Society of America (GSA). Anne Egger, Executive Director of NAGT, served as the associate editor.

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