# The Future of Earth Imaging

Victor C. Tsai
Department of Earth, Environmental and Planetary Sciences
Brown University, DEEPS, Box 1846
Providence RI, 02912, USA

**Abstract**

Imaging of Earth's interior has led to a large number of successful discoveries of plausible structures and associated geophysical processes. However, due to the limitations of geophysical data, Earth imaging has many tradeoffs between the underlying features, and most approaches apply smoothing to reduce the effect of such tradeoffs. Unfortunately, this smoothing often results in blurry images that are not clear enough either to infer the geologic processes of interest or to make quantitative inferences about the various geologic properties. Here, we first summarize some of the basic issues that make Earth imaging so difficult and explain how Earth imagers must choose between more open-ended discovery oriented goals and more specific, scientific inference oriented goals. We discuss how the choice of the optimal imaging framework depends crucially on the desired goal, and particularly on whether plausible discovery or inference is the desired outcome. We argue that as Earth imaging has become more mature, sufficiently many plausible structures have been imaged that it is becoming more crucial for Earth imaging to serve the inference goal and would benefit from an inference oriented imaging framework, despite the additional challenges in posing imaging problems in this manner. Examples of inference oriented imaging frameworks are provided and contrasted with discovery oriented frameworks. We discuss how the success of the various frameworks depends critically on the data quality and suggest that a careful balance must be struck between the ambition of the imager and the reality of the data. If Earth imaging is to move beyond presenting qualitatively plausible structures, it should move towards making quantitative estimates of the underlying geologic processes, inferred through a self-consistent framework.

## Introduction

The inaccessibility of the Earth's interior has led to much speculation about its nature, including many myths, science fiction stories, and scientific debates. Myths include the hell of Dante's Inferno (Alighieri, 1472), or earthquake-causing subterranean turtles or catfish (SCEC, 2014; Nur, 2008). Science fiction stories include Jules Verne's *Journey to the Center of the Earth* (Verne, 1864), Lewis Carroll's *Alice in Wonderland* (Carroll, 1865), many other subterranean world novels (Fitting, 2004), and the movie *The Core* (Amiel, 2003). More interesting from a science perspective are the numerous scientific debates about the Earth's interior. These include the 1690's-1930's debate over whether the Earth's interior was solid, fluid, gaseous or hollow (Halley, 1692; Franklin, 1793; Brush, 1980), and the more recent debate about whether narrow mantle plumes can be confirmed to exist or not (Montelli et al., 2004; van der Hilst and de Hoop, 2005).

Due to its inaccessibility, many inferences about geophysical processes and the structure of Earth's interior have come through imaging techniques, especially seismic imaging (e.g., Dziewonski and Anderson, 1981; Grand et al., 1997), but also imaging with other geophysical data like gravity (Oldenburg, 1974), electromagnetic (Naif et al., 2013), muon (Tanaka et al., 2009) and neutrino (Donini et al., 2019) data. The fact that the Earth has a core (Brush, 1980; Muir & Tsai 2020a), that high-pressure mineral phases like Bridgmanite and Wadsleyite exist (Ringwood & Major, 1966; Dziewonski & Anderson, 1981; Ringwood, 1991), and that subducting plates likely impinge upon the lower mantle (Grand et al., 1997) have been indicated primarily with seismic imaging.

However, despite the past successes of seismic imaging, there remain many debated interpretations of seismic images, and it is often unclear from a science philosophy standpoint whether certain Earth features claimed to be imaged are true beyond reasonable doubt, likely, plausible, or simply false. As Earth imaging matures, we argue that insufficient attention has been paid to the critical inference related aspects needed for such imaging to make a lasting impact on our knowledge of the Earth's interior. We begin with a discussion of the critical reasons that Earth imaging is challenging. While previous studies have commented on some of the same issues of non-uniqueness and underdeterminism (e.g., Jackson, 1972; Zelt, 1999), most studies still approach the problem within the standard discovery driven approach. Next, we describe how imaging approaches can be framed as either being discovery oriented or inference oriented and that these approaches have fundamentally different scientific philosophies and goals. Finally, we describe some of the emerging ideas for posing inference oriented Earth imaging and how they contrast with discovery oriented approaches.

**The Challenge of Earth Imaging**

Imaging is the use of observed data to produce a picture of the object of interest. In the case of standard, light-based imaging, relatively high quality images are produced even with cheap mobile phone cameras (see Fig. 1a). The success of standard imaging is well known (e.g., by amateur photographers; Audubon, 2022) and can be attributed to the fact that (1) photons are generally abundant, (2) the wavelength of visible light is relatively short (400-900 nanometers) leading to sub-micron resolution, (3) air is minimally refractive so that photons usually travel directly from the subject to the detector, and (4) modern cameras have millions of pixels that fit easily into mm-sized semiconductor sensors. An example of such success is the photo of a cow shown in Figure 1a, where it is clear that the subject is a cow. From an epistemological standpoint, the viewer can have great confidence that the subject is a cow rather than a pig or a walrus. Moreover, one can identify important characteristics of the cow, the relative sizes of the cow's features can be measured quantitatively, and one could determine whether any features are unexpected in size or shape.

Imaging also has many scientific applications (see Fig. 1). We can obtain detailed images of flow in the interior of the sun (e.g., Fig. 1b, Gizon et al., 2010), we can image an 8-week human fetus in utero the size of a peanut (Fig. 1c, Jauniaux et al., 2005), and we can even image the structure of a single protein (Fig. 1d, Dubochet, 2018). In an Earth context, Figure 1e shows an example seismic image that has been interpreted to show the subducted Farallon plate in the lower mantle (Grand et al., 1997).

Perhaps surprisingly, in some ways it is more difficult to obtain clear images of the Earth's interior than it is to image the sun's interior, the peanut-sized fetus or a single protein. Earth imaging is difficult for the same considerations that make standard imaging easy. First, the geophysical data that are most sensitive to the Earth's deep interior, namely seismic wave data, are limited given the paucity of large enough seismic sources to illuminate regions of the Earth's interior of interest. Second, the wavelength of seismic waves used is relatively long (10's-100's of km), resulting in resolvable features of similar length scales for global (Hosseini et al., 2020) and regional problems (Fichtner et al., 2009). Third, the Earth's interior is highly heterogeneous, with geologic structures ranging from the micron to the hundreds-of-km scale that contribute to significant refraction and reflection of seismic waves (Lay & Wallace, 1995). Finally, although the number of sensitive, globally distributed seismic stations is impressive (e.g., Hosseini et al., 2020), the few thousand broadband seismometers pales in comparison to the millions of sensors in an iPhone camera, with major station coverage gaps in the oceans, Russia and Africa. All of these reasons create tradeoffs that conspire to cause seismic images to be generally blurrier than desired to make clear inferences about what structures exist in the Earth's interior and what their characteristics are. Other geophysical data such as electromagnetic, gravity, muon and neutrino data are even more limited than seismic data, and suffer many of the same non-uniqueness problems. This explains why researchers have often struggled to use geophysical imaging to go beyond suggesting that structures exist to clearly distinguishing between different hypotheses about the existence and sizes of various structures and geophysical processes.

**Discovery Versus Inference**

The dichotomy between the simultaneous success of Earth imaging in discovering plausible features and yet the difficulty of using it to make clear inferences highlights the importance of identifying its scientific purpose. Importantly, whether the result is successful or not depends on the researcher's perspective and purpose, rather than there being an absolute metric of success. Specifically, there is a significant difference between the goal of discovering plausible features versus the goal of inferring specific characteristics (including about existence of features).

A simple example helps demonstrate the difference between the ‘discovery’ and ‘inference’ goals. We return to the cow image (repeated in Fig. 2b) and ask whether Figure 2a (a blurry but traditional photo) or Figure 2c (a cartoon cow impression with certain specific features estimated) would be preferable if the ‘true’ Figure 2b were unavailable (setting aside for now how these images would be obtained). The answer depends on one’s goal. If no prior information were available and the purpose is to determine what is plausible, you may prefer Figure 2a, where no assumptions were made about possible features. Although the image is blurry, it is unbiased and has a wide range of possible outcomes, an advantage if one has no idea what to expect. In contrast, if you know there is a cow and your purpose is to determine the various cow features, you may prefer Figure 2c, where it is much clearer than from Figure 2a that the cow has 4 legs, 2 ears, spots, and even 4 teats on its udder and a red tag (all of measurable sizes). This example underscores how the goal of unbiased discovery (or exploration) of plausible structures is distinct from the goal of inferring specific characteristics of a hypothesized object, and implies different preferences in approach. Interestingly, while Figure 2b has 3.7 million pixels and thus 11.0 million parameters (RGB values), the number of effective parameters needed for Figure 2a is about 2300 (smoothed ~70x) and only about 600 for Figure 2c (~270 points plus colors). This is important if, for example, only 3000 pieces of information were available. In this case, Figure 2b could not be produced, but Figure 2a and 2c may be, depending on the structure of that information. Finally, we note that for Figure 2c, one needs to propose a set of possible cow characteristics to test; using the wrong features would lead either to no features or misinterpretations of other features.

This example highlights two related problems that plague scientific imaging and especially Earth imaging, but which are not usually problems for traditional imaging. As already noted, Earth imaging is data poor in that there is never enough data to constrain all details of geologic structure that should exist in the Earth's interior. For example, geologic outcrops have important structure at the sub-meter scale (Waldron & Snyder, 2020), and the Earth's volume is approximately $10^{21}$ $m^3$, meaning $10^{21}$ pieces of independent information (a zettabyte of information) would be needed to determine Earth structure at a 1-meter resolution, an impractical amount of data (equivalent to the global annual internet traffic). Even with a growing amount of Earth data, Earth imagers will always be forced to make difficult decisions about what features to focus on. Much like in the cow example with 3000 pieces of information, the Earth imager simply cannot capture Figure 2b regardless of method, and must embrace the strategy behind either Figure 2a, Figure 2c or some alternative that similarly uses less than 3000 pieces of information. Thus, the choice between discovery-mode (Fig. 2a) and inference-mode (Fig. 2c) approaches is apparent, and the Earth imager does not have the luxury of avoiding the choice.

The fact that high-resolution Earth imaging problems have significant tradeoffs and are therefore non-unique or underdetermined is well known (Jackson, 1972; Jordan, 1979) but, to date, discovery-mode solutions to the Earth imaging problem have dominated. As elsewhere, Earth imaging often uses pixels, grids, splines, spherical harmonics or other cell type structures as the fundamental building blocks. These mathematical objects are chosen to be as general as possible in order to accommodate the flexible discovery philosophy. Furthermore, in designing the smoothing or regularization to reduce the number of effective parameters, there has usually been a preference towards flexible mathematical regularization approaches. Tikhonov regularization is one such common smoothing used in Earth imaging (Aster et al., 2013), and is a good example of a very general approach to stabilizing an inversion that has too many grid cells for a robust unregularized inversion. Tikhonov regularization results in the typical smoothing of underdetermined images that is common, for example in Figure 1e. Other mathematical approaches for addressing the same regularization problem can produce somewhat different results, but still share the same philosophy regarding flexibility. For example, sparsity regularization (e.g., Candes & Wakin, 2008), also known as compressive sensing, lasso or L1 regularization, is a recently popular alternative where fewer jumps in parameter values between adjacent grid cells are preferred and used to effectively reduce the number of free parameters. The underlying structure is otherwise unchanged, making sparsity regularization useful when one expects a small number of sharp boundaries between discrete, homogeneous objects but one still wants to maintain flexibility in the outcome. As such, sparsity regularization takes a small step in the direction of interpretability for objects with sharp boundaries but keeps most of the discovery philosophy. Similarly, other mathematical regularization approaches, such as using large Voronoi cells to sample an ensemble of possible models through a sub-space approach (Bodin & Sambridge, 2009), share the same philosophy and accomplish a similar goal. A number of such mathematical approaches exist (e.g., Rudin et al., 1992; Capdeville et al., 2010; Fichtner et al., 2021) and all fundamentally share the same philosophy, while incorporating a small amount of a priori information.

The focus of Earth imaging on discovery and exploration was sensible, especially in the early days of Earth imaging, when little was known about the Earth's interior. Discovery-mode Earth imaging approaches have successfully led to a large number of Earth images with various qualitative interpretations for what geologic structures exist and what their properties might be. However, just like it is difficult to say anything quantitative using the blurry cow image in Figure 2a, the vast majority of Earth image interpretations remain qualitative rather than providing quantitative estimates either of the likelihood of correctness or of the physical characteristics. Given the prior discussion, this is unsurprising, but this highlights the need for Earth imaging to move in the direction of quantitative inference, particularly for regions that already have discovery-mode images. Inference-mode imaging has a number of challenges that discovery-mode imaging does not, including the difficulty of asking the right questions and the extra technical expertise needed to correctly pose the problem and efficiently solve for the important features (Tsai et al., 2023). But it is the only way in which Earth imaging will be able to truly answer scientific questions posed about the appropriate geophysical processes operating within the Earth. Thus, despite the challenges, it is time for Earth imagers to embrace the inference philosophy more fully.

**Inference-Mode Imaging Approaches**

Just as there are a variety of discovery-mode approaches to Earth imaging, there have been a number of suggested inference-mode approaches to Earth imaging, each with its pros and cons, and some of which more completely embrace the inference goal than others. Many of these approaches build upon discovery-mode approaches, including using them as starting points. Here, we explain some of the differing approaches, with a focus on the differences in philosophy and the implications for quantitatively answering geophysical questions.

***Early examples of inference-mode imaging***

The idea that imaging can benefit from an inference framework is an old one that can be traced back at least to the earliest experiments on the nature of light and specifically whether light is a wave or a classical particle. Young's double-slit experiment (Young, 1804) was designed to test whether the observed pattern would be the interference pattern predicted of the wave theory or whether it would have the classically predicted two peak pattern. The goal of the imaging is not to determine the detailed structure of the light pattern but rather to test between 2 very specific hypotheses and determine which provides a better explanation of the observed data (see Fig. 3).

This general idea has been used in Earth imaging, with Harold Jeffreys being one of the first to clearly articulate (Jeffreys, 1939) what is now known as a Bayesian framework for how different proposed models (with different parameter values) can be tested against observed geophysical data. The general idea behind all such approaches is familiar to students of inverse theory in that a prediction of each piece of data is made given a model framework and a range of parameter values, and the model is preferred based on how closely the model predictions (forward model) fit the observed data (Tarantola, 2005; Aster et al., 2013). Within a Bayesian context, the data misfit provides a quantitative assessment for how reasonable the model is and specifically the probability that the model is correct. When applied to model frameworks with different parameters, this comparison between models is more difficult and requires use of a model selection criterion to weigh the importance of accuracy versus simplicity (e.g., Sambridge et al., 2006), but otherwise has a similar philosophy.

Nataf & Ricard (1996) was one of the earliest studies to embrace a forward modeling philosophy in whole Earth imaging problems, with a direct prediction of seismic wave speeds using a geodynamical model. Unlike strictly Bayesian studies, they only computed the predicted data for a single best-guess geodynamical model and declined to adjust the geodynamical parameters to fit observed seismic data, but the idea was that their model could be used by future imagers by doing so. Khan et al. (2008) took this concept one step farther, and into a Bayesian framework, by directly estimating the mineralogy of the mantle using a comparison of a seismic model (Dziewonski & Anderson, 1981) with an ensemble of predictions from mineral physics models. This study was a significant conceptual step forward and suggested a different mineralogy from what was commonly assumed, but limited in its comparison of strictly one-dimensional (depth) structure, and therefore only average bulk properties of the Earth. Koelemeijer et al. (2018) took this approach an additional step farther, testing seismic predictions of three-dimensional geodynamical models with and without post-perovskite directly against seismic tomographic images. The philosophy taken here is close to the inference end-member discussed above. Unfortunately, a challenge of such an approach is whether or not the model predictions can explore the full range of plausibly realistic models, and whether the data are good enough to distinguish robustly between the numerous possibilities or whether significant tradeoffs exist (see next section).

In a parallel line of research, Zelt (1999) pointed out that there are different strategies and goals in imaging. Contrasting with the discovery-mode approach, he described what he called a 'minimum-parameter, prior-structure model' that includes strong prior information about what physics or geometry exist, and in which imaging data is used to estimate a small number of parameters related to these strong priors. This approach results in simple estimates of geometric structures defined by prior ideas for what structures are reasonable. Similarly, Magistrale et al. (2000) used various geophysical data including tomographic imaging data to construct a simple rule-based model of seismic velocities in Southern California. In this work, limitations on data availability necessitated the use of simple empirical constraints on sedimentary basin velocities to construct a complete model across Southern California that included such shallow basins. The resulting Southern California Earthquake Center (SCEC) Community Velocity Model (CVM) Version 2 has been used by many researchers, but has since been subsumed by more complex discovery-driven tomographic models like the SCEC CVM Version 4.26 (Lee & Chen, 2016). While these early works of Zelt (1999) and Magistrale et al. (2000) were simplistic in their assumed structures and ambitions, in many ways later work described below builds upon the same philosophy but allowing for more sophisticated models and hypotheses.

***Recent examples of inference-mode earth imaging***

More recently, there has been a resurgence in the number of studies advocating for a variety of different types of inference approaches to Earth imaging. We group these into 3 philosophically distinct end-member contributions, which are exemplified by the works of Astic and Oldenburg (2019), Arnold and Curtis (2018), and Tsai et al. (2023). Each of these involve inference as an important principle and are archetypical of the range of modern approaches to inference-mode imaging which are framed with modern data-quality constraints, available methodologies, and uncertainty quantification. These emerging frameworks should help pave the road for future inference-mode Earth imaging work.

The work of Astic and Oldenburg (2019) exemplifies a type of inference-based imaging in which there are a small number of categories of structures with clearly distinct properties within an arbitrarily complex spatial landscape. Their work demonstrates how 2 or 3 categories of known (or modestly unknown) electrical conductivities can be determined from resistivity data more robustly with a petrophysically and geologically guided inversion (PGI) compared with a Tikhonov regularization approach. Importantly, this work is designed to offer maximum flexibility regarding the spatial variability of the structures, using the data misfit and clustering algorithms (e.g., Sun and Li, 2015) to converge close to a realistic geologic model. Other work embraces a similar philosophy, though with different underlying methodologies and imaging applications. For example, Linde et al. (2015) review how hydrogeological systems can be categorized; Sun and Li (2015) demonstrate how to use gravity and crosswell seismic data to identify distinct geologic units through clustering; Giraud et al. (2017) discuss how to use geologic classification constraints to reduce the tradeoffs in gravity and magnetic inversions through uncertainty estimation; and Muir and Tsai (2020b) show how seismic data can be used to solve for geometrically distinct subsurface units using an Ensemble Kalman Inversion (EKI) approach. Other similar applications are summarized by Moorkamp et al. (2016).

In their ‘interrogation theory’ framework, Arnold and Curtis (2018) take a different approach in which they frame the entire geophysical imaging problem with a single overarching science question that the imaging is designed to answer and which is ‘interrogated’ with the geophysical imaging data. The philosophy taken is analogous to that of Young’s double slit experiment (see Fig. 3), where a single hypothesis is addressed and the imaging data is analyzed only with respect to this hypothesis. Zhao et al. (2022) show how interrogation tomography can be framed using different algorithms to answer the question ‘What is the volume of a subsurface body?’ using seismic travel time data. The interrogation framework formalizes the earlier approaches of Khan et al. (2008) and Koelemeijer et al. (2018). Those works could be framed as asking the questions ‘What is the average depth-dependent mineralogy of the mantle?’ and ‘Does post-perovskite exist in the deep mantle?’, respectively.

In yet another distinct approach to the inference problem, Tsai et al. (2023) advocate for parametrizing imaging problems in terms of the geophysical processes and structures most pertinent to the expected geologic setting, an approach they call ‘geological tomography’ (Fig. 4). They present a few examples of using idealized models of sedimentary basin formation, subduction zone processes, and continental-scale architecture to directly parametrize models for inverting seismic imaging data. This work intentionally reduces the flexibility of the possible imaging results in favor of geologic interpretability of each parameter. A key feature and simultaneous challenge is that the realisticness of the outcome depends on the quality of the data and the modeling sophistication and ambition of the imager. Furthermore, due to the different physical processes, data quality and a priori information, each application is expected to require its own independent evaluation of how to pose the inference problem such that the idealized model is commensurate with the data. In an analogy to the cow imaging problem, the number of pieces of information and structural complexity of the cow cartoon should be simpler when less information is available, and can be more realistic when more information is available, as schematically shown in Figure 5a-e. This philosophy applies similarly to geological tomography (subduction example in Fig. 5f-j; shallow subsurface example in Fig. 5k-o), not just to features but also to the underlying geophysical processes and deformation which can be included explicitly in the model parametrization if warranted. The geological tomography framework formalizes the old but never fulfilled goal of Jordan (1979) of performing structural geology of the global Earth's interior, and applies the 'simplifying, specific modeling' approach discussed by van Zelst et al. (2022) to Earth imaging problems rather than the ad hoc geometric approach of Zelt (1999). The philosophy is a pragmatic one that embodies the Einsteinian 'as simple as possible, but not simpler' mantra (Dyson, 2004), with the result being explicit quantitative estimates of exactly those physical parameters that the imager deems worthy of investigation.

## Future Outlook for Inference-Mode Earth Imaging

As Earth imaging moves beyond pure exploration and towards learning more precise information about the Earth, it will be necessary for researchers to grapple with the challenges of thinking about the purpose of imaging and how the framework used has important implications for how successful the result will be in addressing the imager's goals. 'Discovery-mode' imaging will always be useful in leading to hypotheses but 'inference-mode' frameworks are crucial for robust discovery of hypothesized features, e.g., as used classically by Young to discover the wave nature of light (Fig. 3) and also by Le Verrier (1846) to discover the planet Neptune. Given the recent frameworks exemplified by Astic and Oldenburg (2019), Arnold and Curtis (2018) and Tsai et al. (2023), the Earth imaging field is well prepared to take the next steps towards inference. These and other recent inference oriented imaging studies have just scratched the surface in terms of possible applications, but a set of possible directions has been set for the Earth imaging community to follow. While inference-mode imaging has many technical challenges that traditional imaging does not (e.g., Tsai et al., 2023) and can easily be biased by the use of non-independent data (a form of data dredging), it is exciting to see the field mature to the point where robust conclusions about the mysteries of the Earth's interior may finally see the light of day. Whether we reach this point may be a matter of whether we, as a community, have the ambition, patience and education to follow this challenging path.

## Data and Resources

No data were used in this paper.

**Declaration of Competing Interests**

The author declares no competing interests.

**Acknowledgments**

The author thanks the US Department of Agriculture, Laurent Gizon, Pulin Li and Alden Tsai, Seychelle Vos, and Suzan van der Lee for graciously providing the images in Figure 1; Daniel Bowden, Colleen Dalton and Andreas Fichtner for helpful suggestions; and editor Allison Bent for shepherding this paper through review. This work was partially supported by NSF grant EAR-2011079.

**References**

Alighieri, D. (1472). *La Comedia di Dante Alleghieri*, Johann Numeister and Evangelista Angelini da Trevi, Foligno.

Amiel, J. (Director) (2003). *The Core* [Film], David Foster Productions.

Arnold, R., and A. Curtis (2018). Interrogation theory, *Geophys. J. Int.* 214, 1830-1846.

Aster, R.C., B. Borchers, and C.H. Thurber (2013). *Parameter Estimation and Inverse Problems*, Elsevier, New York, 2nd edition.

Astic, T., and D.W. Oldenburg (2019). A framework for petrophysically and geologically guided geophysical inversion using a dynamic Gaussian mixture model prior, *Geophys. J. Int.* 219, 1989-2012.

Audubon (2022). *The 2022 Audubon Photography Awards: The Top 100.* https://www.audubon.org/news/the-2022-audubon-photography-awards-top-100

Bodin, T., and M. Sambridge (2009). Seismic tomography with the reversible jump algorithm, *Geophys. J. Int.* 178, 1411-1436.

Bourgeois, A., M. Bourget, P. Lailly, M. Poulet, P. Ricarte, and R. Versteeg (1990). Marmousi, model and data, *EAEG workshop-practical aspects of seismic data inversion*, cp-108-00002, EAGE publications, May 1990.

Brush, S.G. (1980). Discovery of the Earth's core, *Am. J. Phys.* 48, 705-724.

Candes, E.J., and M.B. Wakin (2008). An introduction to compressive sampling, *IEEE Signal Process. Mag.*, Mar 2008, 21-38, doi:10.1109/MSP.2007.914731.

Capdeville, Y., L. Guillot, and J.-J. Marigo (2010). 2-D non-periodic homogenization to upscale elastic media for P-SV waves, *Geophys. J. Int.* 182, 903-922.

Carroll, L. (1865). *Alice's Adventures in Wonderland*, Macmillan Publishers, London.

Donini, A., S. Palomares-Ruiz, and J. Salvado (2019). Neutrino tomography of Earth, *Nature Phys.* 15, 37-40.

Dubochet, J. (2018). On the development of electron cryo-microscopy (Nobel lecture), *Angew. Chem. Int. Ed.* 57, 10842-10846.

Dyson, F. (2004). A meeting with Enrico Fermi, *Nature* 427, 297.

Dziewonski, A.M., and D.L. Anderson (1981). Preliminary reference Earth model, *Phys. Earth Planet. Int.* 25, 297-356.

Fichtner, A., B.L.N. Kennett, H. Igel, and H.-P. Bunge (2009). Full seismic waveform tomography for upper-mantle structure in the Australasian region using adjoint methods, *Geophys. J. Int.* 179, 1703-1725.

Fichtner, A., A. Zunino, L. Gebraad, and C. Boehm (2021). Autotuning Hamiltonian Monte Carlo for efficient generalized nullspace exploration, *Geophys. J. Int.*, 227, 941-968.

Fitting, P. (2004). *Subterranean Worlds: A critical anthology*, Wesleyan University Press, Middletown.

Franklin, B. (1793). Queries and conjectures relative to magnetism, and the theory of the Earth, in a letter from Dr. B. Franklin, to Mr. Bodoin, *Trans. Am. Phil. Soc.* 3, 10-13.

Grand, S.P., R.D. van der Hilst, and S. Widiyantoro (1997). Global seismic tomography: A snapshot of convection in the Earth, *GSA Today* 7, 1-6.

Halley, E. (1692). An account of the cause of the change of the variation of the magnetic needle; with an hypothesis of the structure of the internal parts of the Earth, *Phil. Trans. Royal Soc. Lond.* 195, 563-578.

Hosseini, K., K. Sigloch, M. Tsekhmistrenko, A. Zaheri, T. Nissen-Meyer, and H. Igel (2020). Global mantle structure from multifrequency tomography using P, PP and P-diffracted waves, *Geophys. J. Int.* 220, 96-141.

Jackson, D.D. (1972). Interpretation of inaccurate, insufficient and inconsistent data, *Geophys. J. R. Astr. Soc.* 28, 97-109.

Jauniaux, E., J. Johns, and G.J. Burton (2005). The role of ultrasound imaging in diagnosing and investigating early pregnancy failure, *Ultrasound Obstet. Gynecol.* 25, 613-624.

Jeffreys, H. (1939). *Theory of Probability*, Oxford University Press, Oxford, 1st edition.

Jordan, T.H. (1979). Structural geology of the Earth's interior, *Proc. Natl. Acad. Sci.* 76, 4192-4200.

Koelemeijer, P., B.S.A. Schuberth, D.R. Davies, A. Deuss, and J. Ritsema (2018). Constraints on the presence of post-perovskite in Earth’s lowermost mantle from tomographic-geodynamic model comparisons, *Earth Planet. Sci. Lett.* 494, 226-238.

Khan, A., J.A.D. Connolly, and S.R. Taylor (2008). Inversion of seismic and geodetic data for the major element chemistry and temperature of the Earth’s mantle, *J. Geophys. Res.* 113, B09308, doi:10.1029/2007JB005239.

Lay, T., and T.C. Wallace (1995). *Modern Global Seismology*, Academic Press, San Diego.

Le Verrier, U.-J. (1846). Recherches sur les mouvements d’Uranus, *Les Comptes Rendus de l’Academie des Sciences* 22, 907-918.

Lee, E.-J., and P. Chen (2016). Improved basin structures in Southern California obtained through full-3D seismic waveform tomography (F3DT), *Seismol. Res. Lett.* 87, 874-881.

Magistrale, H., S. Day, R.W. Clayton, and R. Graves (2000). The SCEC southern California reference three-dimensional seismic velocity model version 2, *Bull. Seismol. Soc. Am.* 90, S65-S76.

Montelli, R., G. Nolet, F.A. Dahlen, G. Masters, E.R. Engdahl, and S.-H. Hung (2004). Finite-frequency tomography reveals a variety of plumes in the mantle, *Science* 303, 338-343.

Moorkamp, M., P.G. Lelievre, N. Linde, and A. Khan (2016). *Integrated Imaging of the Earth: Theory and Applications*, Vol. 218, John Wiley and Sons.

Muir, J.B., and V.C. Tsai (2020a). Did Oldham discover the core after all? Handling imprecise historical data with hierarchical Bayesian model selection, *Seismol. Res. Lett.* 91, 1377-1383.

Muir, J.B., and V.C. Tsai (2020b). Geometric and level set tomography using ensemble Kalman inversion, *Geophys. J. Int.* 220, 967-980, doi:10.1093/gji/ggz472.

Naif, S., K. Key, S. Constable, and R.L. Evans (2013). Melt-rich channel observed at the lithosphere-asthenosphere boundary, *Nature* 495, 356-359.

Nataf, H.-C., and Y. Ricard (1996). 3SMAC: an a priori tomographic model of the upper mantle based on geophysical modeling, *Phys. Earth Planet. Inter.* 95, 101-122.

Nur, A. (with Burgess, D.) (2008). *Apocalypse: Earthquakes, Archaeology, and the Wrath of God*, Princeton University Press, Princeton.

Oldenburg, D.W. (1974). The inversion and interpretation of gravity anomalies, *Geophys.* 39, 526-536.

Ringwood, A.E. (1991). Phase transformations and their bearing on the constitution and dynamics of the mantle, *Geochim. Cosmochim. Acta* 55, 2083-2110.

Ringwood, A.E., and A. Major (1966). High-pressure transformations in pyroxenes, *Earth Planet. Sci. Lett.* 1, 351-357.

Rudin, L.I., S. Osher, and E. Fatemi (1992). Nonlinear total variation based noise removal algorithms, *Physica D* 60, 259-268.

Sambridge, M., K. Gallagher, A. Jackson, and P. Rickwood (2006). Trans-dimensional inverse problems, model comparison and the evidence, *Geophys. J. Int.* 167, 528-542.

SCEC, 2014. The turtle story, a native American account of earthquakes. *YouTube*, uploaded by SCEC, 10 Jan 2014, https://www.youtube.com/watch?v=8_83ppaxT74.

Tanaka, H.K.M., T. Uchida, M. Tanaka, H. Shinohara, and H. Taira (2009). Cosmic-ray muon imaging of magma in a conduit: degassing process of Satsuma-Iwojima Volcano, Japan, *Geophys. Res. Lett.* 36, L01304.

Tarantola, A. (2005). *Inverse Problem Theory and Methods for Model Parameter Estimation*, SIAM.

Tsai, V.C., C. Huber, and C.A. Dalton (2023). Towards the geological parametrization of seismic tomography, *Geophys. J. Int.* 234, 1447-1462, doi:10.1093/gji/ggad140.

van der Hilst, R.D., and M.V. de Hoop (2005). Banana-doughnut kernels and mantle tomography, *Geophys. J. Int.* 163, 956-961.

van Zelst, I., F. Crameri, A.E. Pusok, A. Glerum, J. Dannberg, and C. Thieulot (2022). 101 geodynamic modelling: how to design, interpret, and communicate numerical studies of the solid Earth, *Solid Earth* 13, 583-637.

Verne, J. (1864). *Voyage au Centre de la Terre*, J. Hetzel et Cie, Paris.

Waldron, J., and M. Snyder (2020). *Geological structures: A practical introduction*, University of Alberta, Alberta. https://openeducationalberta.ca/introductorystructuralgeology/

Young, T. (1804). The Bakerian lecture. Experiments and calculation relative to physical optics, *Phil. Trans. Royal Soc. London* 94, 1-16.

Zelt, C.A. (1999). Modelling strategies and model assessment for wide-angle seismic traveltime data, *Geophys. J. Int.* 139, 183-204.

Zhao, X., A. Curtis, and X. Zhang (2022). Interrogating subsurface structures using probabilistic tomography: an example assessing the volume of the Irish Sea basins, *J. Geophys. Res.* 127, e2022JB024098.

**Full Mailing Address for Each Author**

Victor C. Tsai

Department of Earth, Environmental and Planetary Sciences

Brown University, DEEPS, Box 1846

Providence RI, 02912, USA

**Figure Captions**

**Figure 1**. Five imaging examples at different scales. (a) An image of a cow taken with a cheap standard camera. (b) An image of the sun from helioseismic Doppler imaging (colors denote magnetic field strength, arrows denote horizontal velocities up to 300 m/s). (c) Fetal ultrasound image showing a live 8-week fetus (~1 cm) plus yolk sac (~3 mm) within the uterus. (d) Image of an RNA polymerase protein reconstructed using cryo-electron microscopy. (e) Image of the subducted Farallon plate underneath North America from seismic data. Images from (a) reprinted from ars.usda.gov/oc/images/photos/k5176-3/, (b) reprinted from arXiv:1001.0930 and courtesy of Laurent Gizon, (c) courtesy of the author, (d) courtesy of Seychelle Vos, (e) courtesy of Suzan van der Lee.

**Figure 2.** Comparison of different approaches to imaging. (b) represents the truth and contains 11.0 million pieces of information (assumed unavailable in the example). (a) is a version of (b) that is blurry due to smoothing by a factor of 70 in both directions, resulting in ~2300 pieces of information. (c) is an image constructed out of cow features (head, udder, legs, spots, eyes, ears, tag) and uses ~600 pieces of information. The smoothed image in (a) is most useful in discovery mode. The featured image in (c) is most useful in inference mode.

**Figure 3**. Young's double slit experiment with 2 distinct imaging hypotheses. (a) The classical theory predicts 2 lines. (b) The wave theory predicts a central peak and a large number of adjacent lines of different intensities depending on the wavelength. The purpose of the experiment is to test the 2 specific hypotheses.

**Figure 4.** Example geologic parametrizations for imaging. (a) Example sedimentary basin parametrization with 14 parameters, characterizing 2 graben forming and 2 deposition geologic events. (b) Example subduction zone parametrization with 8 parameters, including cooling of the mantle wedge by the subducting plate. Adapted from Tsai et al. (2023).

**Figure 5**. Schematic showing how models of a cow (a-e), a subduction zone (f-j) and a shallow subsurface structure (k-o) can be simpler or more realistic and encode less information or more information, respectively. The approximate number of pieces of information required to produce the cartoon in each panel is provided below each image. (a) A 'spherical cow' cartoon. (b-d) Intermediate complexity cartoon cows. (e) A realistic cartoon cow that approximates the cow in Fig. 2b. The geologic models in (f-o) are not just composed of arbitrary geometric objects but instead represent various geophysical processes and assumed deformation rules when used for 'geological tomography'. Structure in (k-o) inspired by the Marmousi model (Bourgeois et al., 1990).

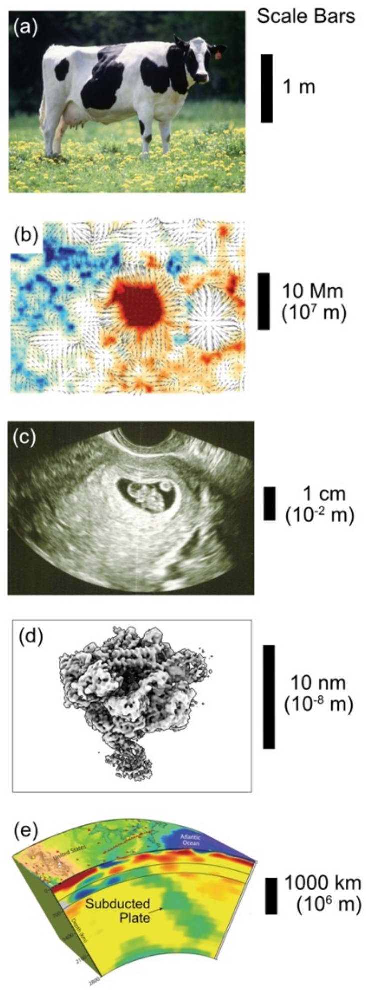


**Figure 1**. Five imaging examples at different scales. (a) An image of a cow taken with a cheap standard camera. (b) An image of the sun from helioseismic Doppler imaging (colors denote magnetic field strength, arrows denote horizontal velocities up to 300 m/s). (c) Fetal ultrasound image showing a live 8-week fetus (~1 cm) plus yolk sac (~3 mm) within the uterus. (d) Image of an RNA polymerase protein reconstructed using cryo-electron microscopy. (e) Image of the subducted Farallon plate underneath North America from seismic data. Images from (a) reprinted from ars.usda.gov/oc/images/photos/k5176-3/, (b) reprinted from arXiv:1001.0930 and courtesy of Laurent Gizon, (c) courtesy of the author, (d) courtesy of Seychelle Vos, (e) courtesy of Suzan van der Lee.

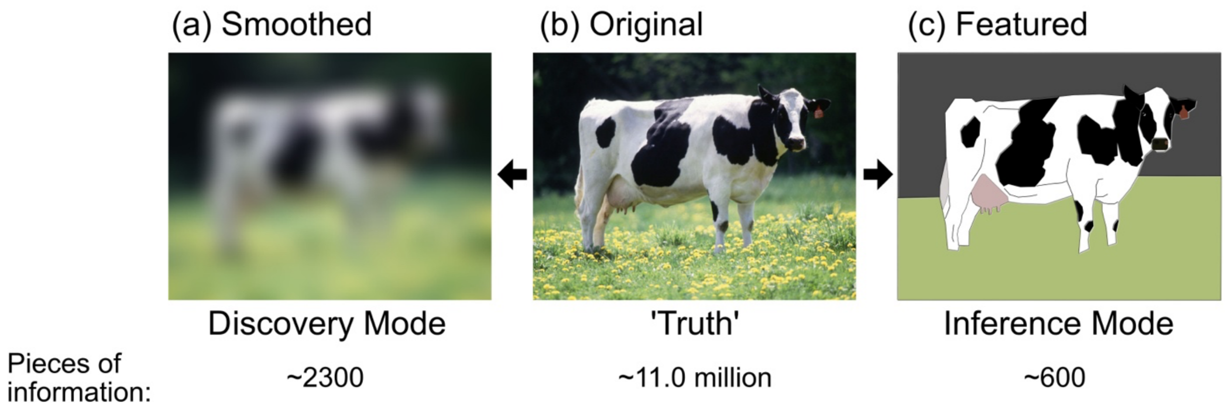


**Figure 2.** Comparison of different approaches to imaging. (b) represents the truth and contains 11.0 million pieces of information (assumed unavailable in the example). (a) is a version of (b) that is blurry due to smoothing by a factor of 70 in both directions, resulting in ~2300 pieces of information. (c) is an image constructed out of cow features (head, udder, legs, spots, eyes, ears, tag) and uses ~600 pieces of information. The smoothed image in (a) is most useful in discovery mode. The featured image in (c) is most useful in inference mode.

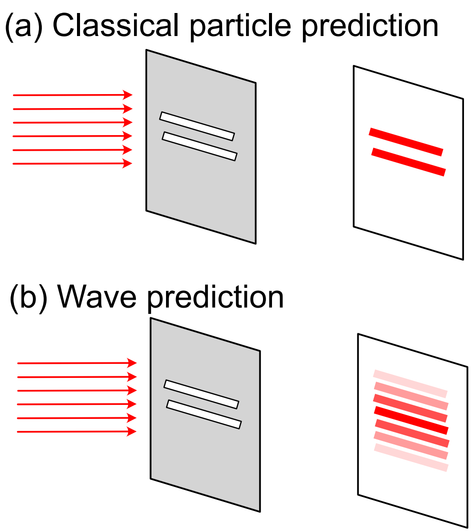


**Figure 3**. Young's double slit experiment with 2 distinct imaging hypotheses. (a) The classical theory predicts 2 lines. (b) The wave theory predicts a central peak and a large number of adjacent lines of different intensities depending on the wavelength. The purpose of the experiment is to test the 2 specific hypotheses.

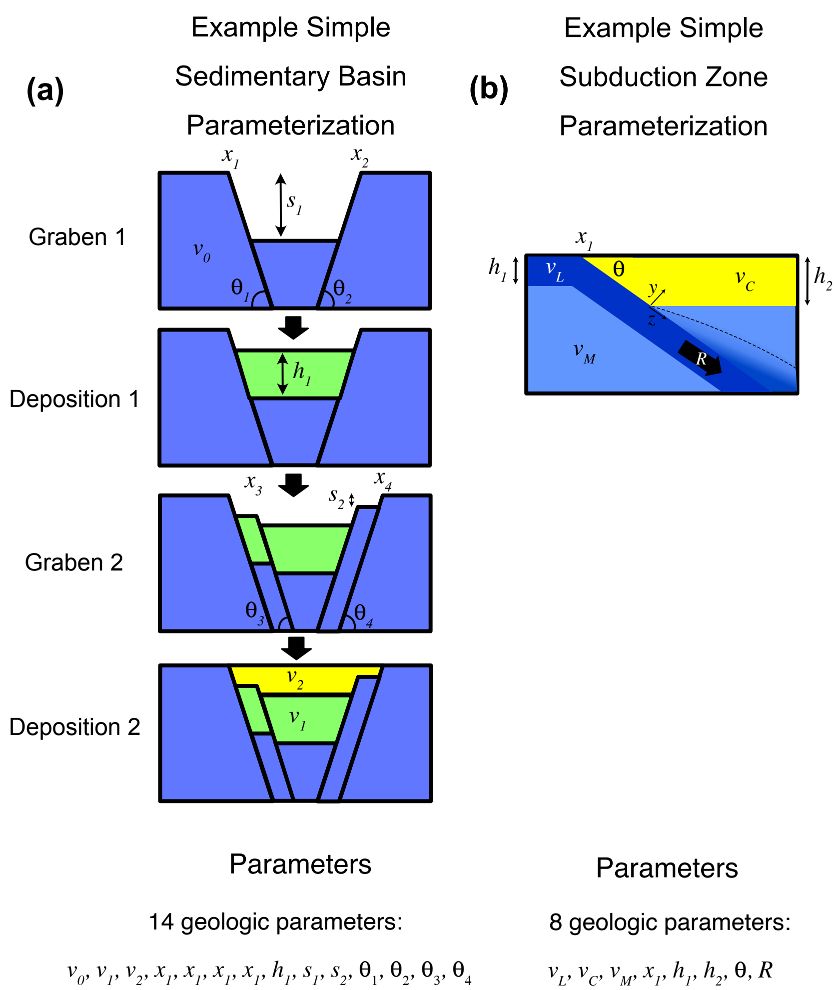


**Figure 4.** Example geologic parametrizations for imaging. (a) Example sedimentary basin parametrization with 14 parameters, characterizing 2 graben forming and 2 deposition geologic events. (b) Example subduction zone parametrization with 8 parameters, including cooling of the mantle wedge by the subducting plate. Adapted from Tsai et al. (2023).

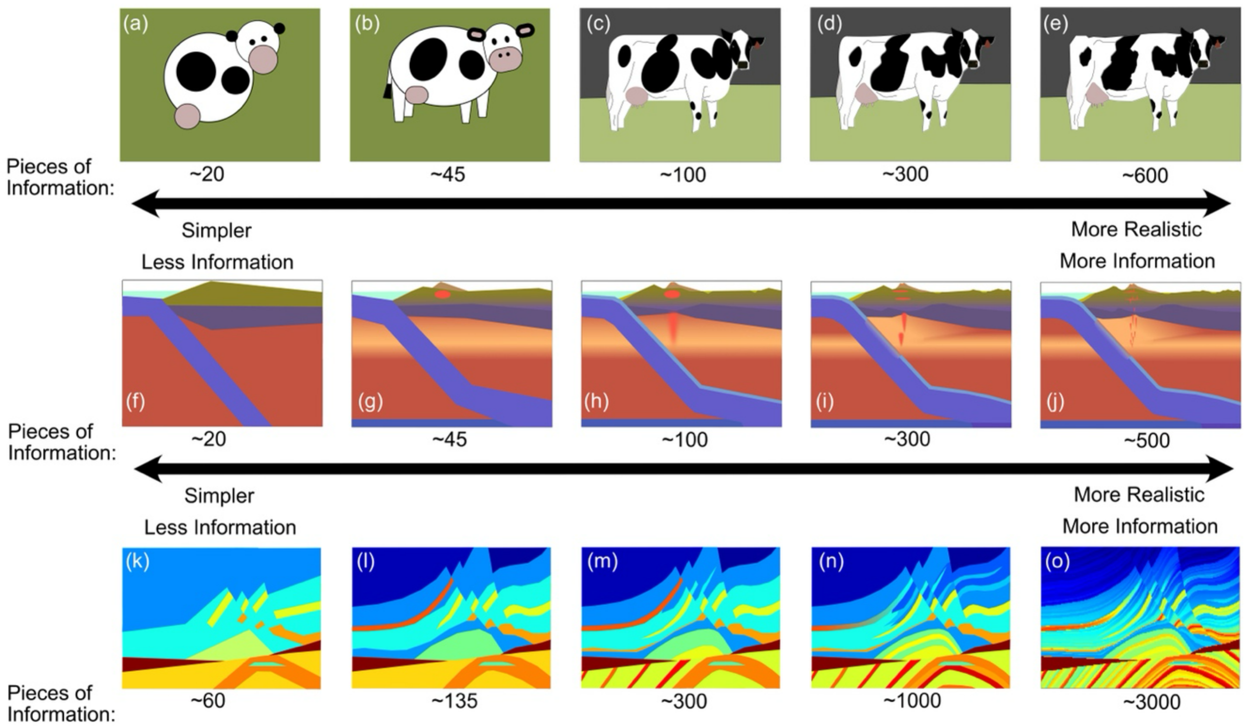


**Figure 5**. Schematic showing how models of a cow (a-e), a subduction zone (f-j) and a shallow subsurface structure (k-o) can be simpler or more realistic and encode less information or more information, respectively. The approximate number of pieces of information required to produce the cartoon in each panel is provided below each image. (a) A 'spherical cow' cartoon. (b-d) Intermediate complexity cartoon cows. (e) A realistic cartoon cow that approximates the cow in Fig. 2b. The geologic models in (f-o) are not just composed of arbitrary geometric objects but instead represent various geophysical processes and assumed deformation rules when used for 'geological tomography'. Structure in (k-o) inspired by the Marmousi model (Bourgeois et al., 1990).