Geological reasoning: making sense of making sense[1]

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Abstract

Advances in information technology (IT) alter the mechanisms supporting geoscience reasoning. IT can help us to integrate types of information and modes of thinking. Instead of perpetuating the constraints of pen, paper and printing press, we can use what brain science reveals of the working of our minds to build new structures. As scientists, our findings must ultimately be testable against the real world. They are likely to be based on analogies and a diversity of qualitative interpretations and interacting models: direct; inverse; episodic; spatial; quantitative; reductionist where appropriate, but recognising unpredictability from emergent systems and missing evidence. Individual reasoning processes manage such models in a top-down context, set in a generalised view of the geoscience paradigm, detailed within the specialised area. The process of research from observation to explanation to communication can be seen as one of generalization and abstraction, reducing detail through ascending hierarchies of objects, processes and events. But each investigation (of, say, one kind of geohazard in one area) selects what is salient and important from a specific viewpoint based on objectives, training, experience, and mind-set. IT increases the interactions between groups, and integrates the results of investigations to serve wider purposes. Consequently, the need to reconcile viewpoints grows in importance. Review of the mechanisms for reconciliation, including publication procedures, standards committees and information communities, may now be appropriate, to take advantage of the opportunities to support scientific progress more efficiently. We need to study the reasoning processes of geoscience in order to design better systems.

Keywords: geoscience reasoning, information technology, models, explanation, reconciliation

Introduction

It was my custom, about once a month, to go to an outcrop, any outcrop, and look at it, intently. It served to remind me of the ridiculous mismatch between the complexity of the real world I could see and the simplicity of the computer programs on which I was labouring. Meanwhile, Information Technology (IT) developed, as did its role in geological research. Its value lies in enabling us to do new things, not just to replicate existing products. To control its changing role, geoscientists must think of what they do.

Take an example. Geological surveying is a mature field, where the productive worker takes for granted the well-established procedures that produce a familiar, predictable style of map. In contrast, as spatial models impinge on geological survey, they call out for diversity, originality, and trial and error, based not on inherited rules of thumb but on reconsidering the underlying reasoning. But reconsider cautiously, for reasoning research is prone to failure. Remember the introverted centipede that wondered, 'which leg moves after which, and fell exhausted in the ditch, not knowing what to do.'

Aspects of georeasoning research, as introduced by Pshenichny (2003), have long preyed on my mind. I went through the quantitative, statistical phase and was converted. I read works by philosophers, but their words seemed to lengthen with the radii of their arguments, and my mind wandered. I read the erudite and readable account of Geographic Information Science in Raper (2000) but could not wholly relate theory and example. I looked at the fascinating account of the georeasoning discussion group (Pshenichny, 2003), and heard echoes of my misgivings when listening to database enthusiasts – *C'est magnifique, mais ce n'est pas la géologie*. I kicked the nearest rocky outcrop.

Still, how we handle IT deeply affects the way we reason in geoscience and vice versa, so I wrote a book (Loudon, 2000), on which this polemic is partly based, and felt better. Actually it was in hybrid serial and book format (a seriook?) issued also in *Computers & Geoscience* and so available electronically in subscribing libraries. Multiple formats ease access, but fail to free the content from the container. To take content outside the box of pen, paper and printing press, we must look inside our heads.

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Better, let brain scientists do it, with non-invasive techniques (Pinker, 1997). They tell us of our accurate short-term memory, used for direct comparisons, maybe leading to a quantitative database; our less reliable but longer-term episodic memory where we concoct stories (and scientific explanations) maybe leading to text accounts; our spatial memory, handling spatial configuration and pattern, maybe leading to maps and diagrams; and semantic memory where we build our background understanding of what we regard as true and significant, maybe leading to textbooks, standards and metadata. Much knowledge is tacit, acquired through practice but not articulated, known but not expressed. The brain scientists have mapped the processing and memorising of these information types to discrete areas of the brain – a map of our very own armoury of mental skills.

Models

Most geoscientific explanation is designed to be ultimately testable against the real world (see Popper, 1996). I cannot prove it, but suspect that most of us accept a distinction between the activities that go on within our brains (to which we give names like explanation, interpretation, modelling and reasoning) and the real, external world beyond. The brainwork may lead us to expect that certain procedures that interface with the real world (such as observation, experiment or measurement) will result in a predictable, specific outcome. Thus, when kicking an outcrop, prepare to say 'ouch'. Effective reasoning relies on models that survive widespread testing of their predictions against observations of the real world.

Imagine yourself leading a field excursion and consider how, when explaining your reasoning, you integrate various modes of thought: think how you bring together words, images, stories, directed observations and demonstrations in order to communicate ideas by analogy (like we saw back there), modelling (that process would produce something like this), passing on tacit knowledge (try doing it this way), and testing the interpretation (look, just as we expected). Your account could be more instructive and informative than a conventional publication, and you might therefore welcome new ways to communicate it. IT can offer metadata, database, GIS, computer models, visualisation, hypertext, and hypermedia; should be able to deploy and integrate our full armoury of information skills; and can record and archive the results with immediate global communication. Its new mechanisms for handling ideas must have a bearing on the reasoning process.

Leatherdale (1974) suggested that we discover the truly fruitful facts about nature by reasoning from analogy (looking at parallel cases, where some things are similar and so others may be) and, indeed, that explanation involves an inescapable use of analogy. One powerful form of analogy (or model) is between properties or processes observed in the real world and the properties of symbols and numbers when manipulated according to the rules of mathematics or formal logic. It is one more weapon to coordinate with the others in our armoury, and is particularly convenient for computer implementation. Such quantitative models are put in context (and their relevance determined) within an episodic, text explanation.

Some geoscientific reasoning deals with processes affecting objects of known composition and properties and predicts the outcome. This is the direct problem of establishing a forward model. Because geology is a historical science (Gaylord Simpson, 1963), we are more often looking at the outcome of past events, and trying to work backwards to understand the processes that brought it about. This is the inverse problem of establishing an inverse model. Typically, an inverse model has no unique solution (Chamberlin, 1897), but the larger our armoury of techniques, the more we can bring to bear independent lines of reasoning, which narrow down the range of possible solutions (see for example Gorbachev, 1995). We need all the weapons we can get, for what we are trying to understand is extraordinarily complicated.

Many models take a reductionist approach. This explains complicated phenomena by reducing them to simple parts controlled by mechanical processes governed by the deterministic laws of physical science. But we also have to deal with complex and emergent systems, which show pattern that appears to develop spontaneously by self-organisation, that is, through the interaction of adjacent parts according to simple rules without any central control (see, for example, Bar-Yam, 2003). Feedback effects mean that these systems cannot be explained by analogies with linear equations where effect is proportional to cause.

“Which of the possible configurations the system will settle in will depend on a chance fluctuation. Since small fluctuations are amplified by positive feedback, this means that the initial fluctuation that led to one outcome rather than another may be so small that it cannot be observed. In practice, given the observable state at the beginning of the process, the outcome is therefore unpredictable.” (Heylighen, 2001, section 3.7). A clear result from an inverse model depends on the availability of direct models. Emergent systems suggest that we must cope with fundamentally unpredictable elements and inverse models that are inevitably incomplete.

Top down abstraction

Individual models are generally invoked from a top-down view or gestalt (an analysis working down from the structure of the whole to its relations with its constituent parts and their characteristics). At each stage of the reasoning, geoscientists must look carefully at all relevant aspects of what they know so far, imagining an entire situation and seeing how ideas can fit together. Analysis of items in isolation cannot provide a full understanding as their significance may depend on their place, role and function in the system as a whole.

As individuals, we focus only on what is relevant, for our mental limitations restrict our gestalt to a specialist area in which we can reason in detail. As we move outwards from our specialised knowledge, we rely on a vague and increasingly generalised impression of the work of others, hoping to detect pointers to anything else we ought to consider. Out there, lurking in the background, is the shared paradigm (Kuhn, 1962) – the generally recognised exemplars that determine the current framework for reasoning in any aspect of science.

An important aspect of the geoscientists’ paradigm is the general geoscience spatial model. It refers at all levels of detail to the three-dimensional disposition and configuration of the present-day objects of geoscience, to their observed and interpreted properties and composition, and also to their history throughout geological time, including the processes that created them and are crucial to their interpretation. It structures the answers to questions a young child might ask on looking into a dark cupboard: What is in there? What is it called? Where is it? What does it look like? What is it made of? What does it do? How did it get there? How do I know? This model is vast beyond representation, sparsely populated with information and so largely unknown. It is inevitably incomplete, for most of it is unknowable, the evidence destroyed long ago by geological reworking. Yet it is essential, for it holds together reasoning across many fields of geoscience.

To deal with the complexity, geoscience research and reasoning relies on a process of abstraction, reducing the volume of information under the influence of the current paradigm. From the unimaginable detail of the real world, we observe salient points. As trained geoscientists we classify our impressions in categories, lumping them together as things of interest (objects), arranged in hierarchies of object classes (Coad and Yourdon, 1991). Through observation, we describe occurrences or instances of the real-world objects. The description is itself an interpretation, abstracted from reality in the light of our trained expectations. It confirms or amends our view of the properties and behaviour of the classes of object to which the instances belong, influencing future observation and interpretation.

The more important observations are interpreted further and recorded, and eventually reworked and summarised as published articles and maps, boiling down the detail to explanations that focus on significant pattern rather than specific details. Maybe the information changes its nature as it is digested, abstracted, recorded and shared more widely, passing from our short-term memory (data?) to episodic memory (interpretation?) to semantic memory (concepts, knowledge and metadata?), but terminological boundaries in a continuous spectrum of abstraction are fuzzy and contrived.

Reconciliation

Throughout the abstraction process, we decide what is salient and important according to our personal viewpoint or our interpretation of agreed guidelines. In practice, we can relate our work only to a tiny fragment of the general model, seen from a viewpoint determined by objectives, training, experience and mind-set. We might model different types of geohazard, for example, from separate, incompatible viewpoints.

Models are concepts that simplify reality from a selected viewpoint for a particular purpose. They thus differ from reality by definition, often in incompatible ways. Think, for example, of the continuous, smooth surfaces depicted on a contoured model (or map) or the notion that formation boundaries model sharp breaks in the properties of the rock continuum. Then consider the expostulations of Mandelbrot (1982) that continuity is an unlikely feature of natural surfaces at any scale, and think of his ensuing fractal models. We simplify with varied and incompatible criteria. Yet our inconsistent simplifications enable us to visualise complex pattern by using the skills we acquired from human evolution and a lifetime of learning by looking about. They enable us to conceive (for a particular purpose) objects and processes with which we can reason, predict and verify.

Kent (1978) gives a sympathetic view of this world where we try to reason within a jumble of conflicting concepts, where we must assess and balance many aspects and sources of information, and reconcile a diversity of inconsistent views. He points out (pages 202-203) that people adopt different views of reality that change with time, extending from the meaning of a word to the acceptability of a paradigm. But the views overlap, and so can be reconciled with varying degrees of success to serve different purposes. "By reconciliation, I mean a state in which the parties involved have negligible differences in that portion of their world views which is relevant to the purpose in hand." He points out that reconciliation is growing in importance as technology increases the interaction between people, and integrates processes to serve more and more purposes.

We invent mechanisms to support reconciliation. On the one hand, we seek standards for shared representations that underpin our ability to communicate and moderate our tendency to reinvent the wheel. We record metadata and try to formalise the gestalt (Pshenichny, 2003). Committees in areas like stratigraphy (Hedberg, 1976) provide standard classifications and nomenclature based on precedence and practicality. Groups, such as POSC with their Epicentre Model (POSC, 2003), encourage conformity of usage by defining metadata in data dictionaries and data models, and supporting IT standards. Long-standing information communities, notably geological surveys, provide a coherent account of regional aspects of the general geoscience model reconciled across many sources, with object stores that are securely archived and curated, and internal controls to maintain consistency and safeguard the reputation of their brand name.

On the other hand, we seek evolution of ideas or memes (Blackmore and Dawkins, 2000) as the basis of scientific progress. Evolution depends on diversity and selection, exemplified in the scientific literature: diversity encouraged by editors seeking papers with original ideas; selection by peer review, citation, quotation and discussion. Criteria for selection include relevance to the paradigm, conformance to appropriate standards, and the agreement of testable predictions with the ultimate arbiter – the real world. The exceptional phenomenon of paradigm shift (Kuhn, 1962) has ubiquitous smaller-scale counterparts, leading to paradigm drift as viewpoints alter, driven by the hierarchy of evolving memes, including those involving standards committees and information communities.

Conclusion

Our mechanisms for reconciling viewpoints developed for the most part before modern IT and the emergence of computer-based knowledge systems. Their design therefore needs review, in general and in detail. They must continue to encourage efficiency (supported by standards) and scientific progress (supported by diversity and selection). But computers lack human insight and process information differently. They need more formal identification and documentation of objects, their relationships and behaviour. Clarification of our models can help us to reconcile the objects they create. Better understanding of geoscience reasoning will help us to benefit from IT and its promise of instant communication, worldwide analogies, quantified results, and their application in coherent models of broader scope.

The subject matter is complicated – look at any outcrop. The achievement of geoscience has been to make sense of the whole (in outline) and of fragments (in detail), allowing us to make useful predictions about the real world, not least about geohazards. New approaches must build on existing geological insights, not blind us to their value. Only geoscientists can ensure this happens – our responsibility as custodians of a legacy from countless years of scientific endeavour.

References

Bar-Yam, Y., 2003, Significant points in the study of complex systems. http://www.necsi.org/projects/yaneer/points.html

Blackmore, S. and Dawkins, R., 2000, The meme machine. Oxford University Press, Oxford. 264 p.

Chamberlin, T.C., 1897, The method of multiple working hypotheses. Journal of Geology. Reprinted in 1995, Journal of Geology v. 103, p. 349-354.

Coad, P., and Yourdon, E., 1991, Object-oriented design. Yourdon Press, Englewood Cliffs, NJ, 197p.

Hedberg, H.D. (editor), 1976, International stratigraphic guide: a guide to stratigraphic classification, terminology and procedure. Wiley-Interscience, New York, 200p.

Heylighen, F., 2001, The science of self-organization and adaptivity, in: The Encyclopedia of Life Support Systems. EOLSS Publishers Co. Ltd. (in press). http://pespmc1.vub.ac.be/Papers/EOLSS-Self-Organiz.pdf

Gorbachev, Y.I., 1995, Well logging: fundamentals of methods. John Wiley & Sons Ltd., Chichester, 324p.

Kent, W., 1978, Data and reality. North-Holland Publishing Company, Amsterdam, 211p.

Kuhn, T.S., 1962, The structure of scientific revolutions. The University of Chicago Press, Chicago, 172p.

Loudon, T.V., 2000, Geoscience after IT: a view of the present and future impact of information technology on geoscience. Elsevier, Oxford. 142 p. Also available as *Computers & Geosciences*, Special Issue, v. **26,** no. 3A, p. A1-A142.

Leatherdale, W.H., 1974, The role of analogy, model and metaphor in science. North-Holland, Elsevier, Amsterdam, 276p.

Mandelbrot, B.B., 1982, The fractal geometry of nature. Freeman, San Francisco, 460p.

Pshenichny, C.A., 2003, A draft for complex formal approach in geoscience. In press.
See: http://groups.yahoo.com/group/geo-reasoning

Pinker, S., 1997, How the mind works. Norton, New York, 660p.

Popper, K.R., 1996, Conjectures and refutation: the growth of scientific knowledge. Routledge, London, 431p.

POSC, 2003, POSC specifications – Epicentre 2.2. Petrotechnical Open Software Corporation, Houston, Texas. http://www.posc.org

Raper, J., 2000, Multidimensional Geographic Information Science. Taylor and Francis, London, 300p.

Simpson, G.G., 1963, Historical science, in Albritton, C.C. (editor), 1963. The fabric of geology. Freeman, Cooper & Co, Stanford, p. 24- 48.