SPATIAL AND TEMPORAL REASONING IN GEOLOGIC MAP INTERPRETATION

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ABSTRACT

In this paper, we describe a way of extending and combining several AI techniques to attack a class of problems exemplified by a problem known as geologic map interpretation. We use both a detailed and an abstract model of elementary geology, combined with both local and global reasoning techniques to achieve the system's expertise.

In particular, a new technique called *imagining* allows us to find global inconsistencies in our hypotheses by causally simulating a sequence of "instructions". Imagining makes use of both our detailed and abstract models of the world.

I INTRODUCTION

A recent trend in expert systems research has been toward systems which reason from descriptions of causal processes in the domain, rather than from the surface effects. This is the "causal model" versus "empirical association" distinction presented in [2]. Typically, this involves creating a detailed model of the physical processes which underly the domain. This model must support inferences about how the processes affect the world, and how they interact with one another.

One problem with such models is that they are often too complex to allow the relevant inferences to be made in a reasonable amount of time. Hence, representations and methods of reasoning which abstract or compress detail are very useful for much of the problem solving process. The full model may be used when these less detailed methods fail, but that should occur infrequently in the problem solving process as a whole.

This research explores the issues of reasoning from both a detailed and an abstract model of the domain, using as a testbed a problem from geology known as map interpretation. In this paper, we outline the types of geologic knowledge needed to represent and reason about the geologic environment. We illustrate the use of both a detailed model of geologic processes and a more abstract model employing diagrams. We also discuss the types of reasoning needed to solve the problem, with particular emphasis on a new technique called *imagining*. Imagining allows one to "visualize" the effects of a sequence of processes, and detects any global inconsistencies in that sequence.

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II MAP INTERPRETATION

In geologic map interpretation, one is given a diagram representing a vertical cross-section of a region, plus a legend identifying the various rock formations. The problem is to reconstruct a plausible sequence of geologic events which could have formed that region. A simple map example is shown in Figure 1.

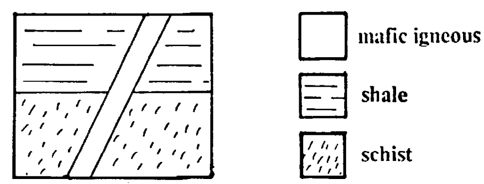

Fig. 1. Simple Geologic Map Interpretation Problem

A geologist would approach this problem by noting that, since the **mafic igneous** crosses the schist,* it intruded through (i.e. forced its way through) the schist and hence is younger. The geologist would use the same reasoning to infer that the **mafic igneous** also intruded through the **shale**. Thus the shale and the schist were both in place before the **mafic igneous** intruded through them. To determine in what order the **schist** and the shale appeared, the geologist would infer that, since sedimentary deposits are deposited from above onto the surface of the Earth, the shale was deposited on top of the **schist.** The **schist** was created from existing rock by the process of metamorphism. However, metamorphism occurs in rocks buried deep in the Earth and deposition occurs on the surface, so somehow the **schist** must have gotten from the depths to the surface to be deposited upon. A combination of the processes of *uplift* and *erosion* would suffice to bring the schist to the surface. Thus, the final sequence of events is:

1. Metamorphism of **schist**
2. Uplift and erosion of **schist**
3. Deposition of shale on **schist**
4. Intrusion of **mafic igneous** through **schist** and **shale**

Solving the map interpretation problem is typically taught in introductory geology courses. This indicates that the problem is solvable with an elementary knowledge of geology, together with

* Our geologic knowledge includes the facts that schist is a *metamorphic* rock, mafic igneous is *igneous*, and shale is a *sedimentary* deposit.

some common sense physical knowledge. The fact that only elementary geologic knowledge is needed means that many of the details of a complete model of geology need not be represented. On the other hand, the domain is fairly complex because one must reason about continuous processes and their interacting effects on an environment. We feel that since the domain is both bounded and complex, it is a good problem choice for studying the use of imagining and the use of detailed and abstract models.

III TYPES OF KNOWLEDGE USED

We have used three basic types of knowledge in solving the above example: knowledge about the nature of geologic processes, temporal knowledge to create sequences of events, and knowledge of diagrams as abstractions of the geologic model.

A. Geologic Process Knowledge

Geologic process knowledge forms the basis of the geologic model, which is used throughout the problem solving process. We will need to represent basic geologic knowledge such as "schist is a metamorphic rock", and knowledge about processes that would allow us to infer, for example, what effect erosion would have on the environment. We also need to represent how processes interact. For instance, in step 2 of the example, uplift and erosion happen simultaneously. We intend to use the Qualitative Process Theory [4] as the basis of our approach because it enables us to represent qualitative knowledge about processes and knowledge about how those processes interact.

We need to reason about the geologic processes in both a *synthetic* and *analytic* mode. In the synthetic mode we reason from the causes, simulating processes to determine their effects on the environment. In the analytic mode we reason from the effects, analyzing the difference between two situations to hypothesize the existence of a geologic process which could account for those differences.

B. Temporal Knowledge

There are a number of different problems in creating sequences of geologic events. For example, we need a mechanism for composing geologic processes. We also need to formalize what causes an attribute of an object to change and to reason about enduring attributes - those whose values do not change over a particular temporal interval. We have not yet done substantial research on these topics, but we believe that the Qualitative Process Theory, with its idea of a *history*, is a step in the right direction.

C. Diagrammatic Knowledge

In this system, diagrams are used as an abstraction of the geologic model. Diagrams facilitate spatial inferences for two reasons. First, they abstract away irrelevant details, such as internal structure of formations. Second, unlike other representations of the same knowledge, diagrams are spatially organized, that is, the position of an entity in space is directly related to its position in the diagram. The adjacency, position, and orientation of geologic features such as formations can be readily inferred by "viewing" the diagram.

A key technique in this research is to represent the effects of geologic processes as diagrammatic transformations. For instance, the process of erosion can be visualized in a diagram (Figure 2) by drawing a horizontal line at the level of the erosion, erasing all *faces* which are above the line, and erasing the line where it cuts through air. Because geologic processes primarily have spatial effects, the diagrammatic transformations can be more easily carried out than the corresponding inferences in the geologic model. That is, to ascertain the effects of geologic processes, it proves to be more efficient to transform the diagram and "view" it than it is to reason about the processes directly.

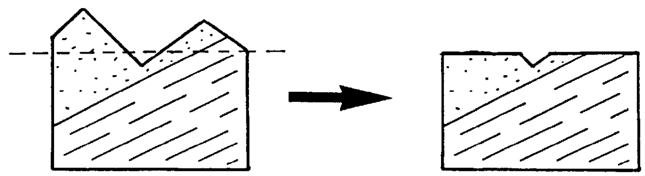

Fig. 2. Diagrammatic Effects of Erosion

This diagram transformation facility has been implemented. The underlying representation for the diagram is based on the wing-edge structure of [1]. This representation facilitates geometric and topological inferences. The interface between the diagram sub-system and the rest of the system is based on a small vocabulary of terms such as *faces, edges*, sidedness relations between them (e.g. *above, left-of*) and adjacency relations (e.g. which lines make up a face, which face is on the other side of an edge and a face). There are also transformation commands, such as drawing a line, rotating the diagram, or merging two faces.

IV TYPES OF REASONING

One way to view this problem is as a standard search. We have an initial state of the world (e.g. the "void"), and operators to be applied (i.e. all possible geologic processes). It becomes clear in this view that unconstrained forward search is not a plausible approach.

A. Scenario Matching

In order to make the problem tractable, we reason backwards from the effects of processes to their causes using a process we call *scenario matching*. A scenario is a pair consisting of a diagrammatic pattern and a set of sequences called *interpretations* which could have caused that pattern. For example, in solving the example in Figure 1 we used the following scenario twice:

pattern	*interpretation*
<rock> igneous <rock>	igneous intruded through the **<rock>**

The patterns represent local effects of processes and involve the boundaries between two or three formations. An *interpretation* is a sequence of events which is a possible causal explanation for the pattern's occurrence. Each pattern may have several plausible interpretations. Note that scenarios affect a translation from the presentation language (diagrams) to the causal language (geologic processes).

By matching scenario patterns throughout the diagram and combining the local interpretations, we generate sequences which purport to explain how the region was formed. However, these sequences might not be valid explanations for two reasons. First, local consistency does not imply global consistency. Second, the evidence for the occurrence of some physical processes might no longer exist in the geologic record (i.e. the diagram). For instance, there is no evidence in Figure 1 for the occurrence of the processes of uplift and erosion of the schist, because the erosion has removed whatever once covered the schist. To detect both types of inconsistencies, a method of global reasoning is needed.

B. Imagining

We are developing a new technique called *imagining* to handle this situation. An outgrowth of the notion of *envisioning* [3], imagining takes as input an initial environment, a goal state which is the final environment (a diagram), and a sequence of geologic processes. The imaginer simulates each of the processes in turn, producing a final environment which is then compared with the goal environment to see if they qualitatively match. Although we noted that *unconstrained* forward search is not practical in this domain, imagining, by using a sequence of plausible operators, constrains the search sufficiently to avoid the combinatorics problem.

The imaginer must determine if each process of the sequence, viewed as an operator, can be applied to the current environment. If the imaginer cannot continue, it returns an explanation of the problem encountered. This explanation consists of the process which the imaginer could not simulate, and the difference between the state which would be needed in order to simulate that process and the state actually produced by simulating up to that process. This imagining process should suffice to detect both types of inconsistencies mentioned above.

The imaginer works by transforming diagrams in accordance with the diagrammatic interpretation of the geologic processes outlined in the previous section. Detecting if a geologic process can be simulated involves inferences from both the geologic and diagrammatic models. For instance, if the geologic process was "deposit A on B", the geologic model would be checked to see if A is a sedimentary rock, and the diagram would be checked to see if B is on the surface.*

The imaginer must be able to infer the parameters of the geologic processes. The description of the processes in the input sequence is qualitative, but quantitative parameters are needed to do the diagrammatic transformations. In addition, these parameters must be approximately correct if the imaginer is to produce a final diagram which is similar to the goal diagram. For example, in order to simulate "deposit A on B" the imaginer would have to know the width of A, at least within some definite range. The imaginer uses measurements taken from the diagram, plus knowledge of geologic processes to determine these parameters. For instance, from Figure 1, we can measure the width of the schist deposit, and since we also know that part of the schist was later eroded away (in step 2), the original width of the formation was greater (by some unknown amount) than the measured width in the diagram.

* The use of diagrams is not intrinsic to the concept of imagining, which merely implies causal simulation of a sequence of "instructions". The imaginer *could* work on the geologic model alone.

C. Gap Filling

If the imaginer detects a "gap" between the state needed for some process to occur and the actual state of the environment,* we need to hypothesize some sequence of events to fill the gap. The imaginer indicates why it could not continue in terms of the difference between two states, and from that one can reason about which process or sequence of processes would have the effect of minimizing or eliminating that difference. This is means-end analysis [5] used in a restricted context.

* as would have occurred if we had not inferred the presence of the uplift and erosion in Figure 1.

V CONCLUSION

We have described a way of extending and combining several AI techniques to attack a class of problems exemplified by the map interpretation problem. We have used both a detailed and an abstract model of elementary geology, combined with both local and global reasoning techniques.

In particular, imagining allows us to find global inconsistencies in our hypotheses by causally simulating a sequence of "instructions". Imagining makes use of both our detailed and abstract models of the world.

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