Sketch-based Spatial Reasoning in Geologic Interpretation

Panrong Yin, Maria D. Chang and Kenneth D. Forbus

Qualitative Reasoning Group, Northwestern University,
2133 Sheridan Road, Evanston IL 60208
{pennyyin, maria.chang}@u.northwestern.edu, forbus@northwestern.edu

Abstract

Geologic interpretation is the process of determining a sequence of geological events that could have caused a particular geologic formation. This paper describes a model for geologic interpretation of sketches, which are collected and represented with our open-domain sketch understanding system, CogSketch. The spatial relations that CogSketch computes are combined with a domain theory for geology to support *state-to-state inference*, which allows the system to make inferences about geological processes that may have occurred as well as spatial features of the previous geologic state. State-to-state inference involves three steps. First, spatial relations are used with *proposal rules* to infer the set of all geological processes that may have caused the geologic state depicted in the sketch. Second, spatial and temporal constraints are applied to refine this list of candidate processes. Third, candidate processes are used to infer facts about the prior state which are tested through *verification rules*. The model has been successfully tested on 7 sketches which involve the six basic physical principles geologists use for determining the relative age of rocks. These results also highlight several opportunities for improvement.

Introduction

Geologic interpretation is the process of determining a sequence of geological events that could have caused a particular geologic formation. In addition to extensive knowledge about geological processes, geologic interpretation requires spatial reasoning and inference over a depiction of the given (i.e. resultant) geologic state. Typically, models of geologic interpretation use cross-sectional diagrams of geologic states or reconstructions of real images [Simmons 1983] [Roberto & Chiaruttini 1999]. Sketching is a fast, natural method for conveying spatial information that is heavily used in geoscience. Sketching is especially useful in educational settings, where pen strokes may not need to be precise, but the spatial relations and conceptual information are critical. With sketches people tend to focus less on the physical details and more on the spatial relations between drawn objects. This enables effective qualitative analysis of spatial changes, without the distraction of irrelevant details. Indeed, sketching is often required in geology courses to improve the learning of spatial concepts. Despite the advantages of sketching, including its pervasive use in geoscience practice, we are unaware of any computational models of geologic interpretation that use sketched input.

This paper proposes a sketch-based reasoning model for geologic interpretation. Our motivation is creating sketch-based educational software, such as Sketch Worksheets [Yin et al 2010], for a variety of science, technology, engineering, and mathematical (STEM) subjects, including geoscience. The domain-specific geologic knowledge is encoded in a declarative ontology and inference rules. The rules use spatial relations in the sketched geologic state to infer a set of possible geological processes that may have caused that state. While this paper focuses on geoscience, we hope that similar ways of constructing qualitative, causal explanations will be useful in a variety of STEM subjects.

We start with a review of geologic interpretation and CogSketch, our open-domain sketch understanding system. Then we describe the knowledge representations for geological objects and processes and outline the proposal and verification rules which enable state-to-state inference. Lastly, the results of the evaluation are given, followed by related and future work.

Background

We start with a brief introduction to geologic interpretation and CogSketch.

Geologic Interpretation Problem

Given a depiction of a geologic state (i.e. a region at a certain moment in time), the goal of geologic interpretation is to infer a sequence of events that could have caused that state to exist. Geological depictions can be diagrams or real images. These depictions may be a 2D cross-section, a 3-dimensional perspective drawing, or a map viewed from above. Typically, geologic interpretation starts with cross-sectional diagrams because they show rock layer boundaries, which provide evidence about the relative age of rock layers. From a cross-sectional diagram of rock layers, geologists and geology students locate the *geologic record*: layers of rock stacked one atop the other like pages in a book. The geologic record can be divided into eonothems, erathems, systems, series, stages and zones, just as authors organize books according to sections, chapters and pages. Detecting the rock layers in the geologic record and understanding their spatial organization is critical for geologic interpretation.

Geologic interpretation skills are typically taught in introductory geology classes to help students understand the relationship between the spatial characteristics of the geologic region and the time course of geological processes. Figure 1 shows an example sketch that describes a geologic region. Each geologic object in this sketch has been labeled with a concept, indicating that it is an instance of that concept (e.g. *rock1* is labeled with "Igneous rock" and *rock2, rock3 and rock4* are labeled with "Sedimentary rock").

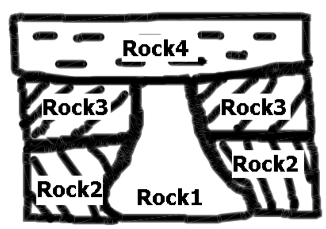


Figure 1: A sketch example showing the geologic interpretation problem

To interpret this sketch, geologists would first observe the spatial relations between objects in the sketch, and then think about the possible geological processes that could have caused the observed spatial relations. For example, since the igneous rock, *rock1,* crosses *rock2* and *rock3*, they would infer that an intrusion process might have happened and that *rock1* is younger than *rock2* and *rock3*. Also, the fact that *rock4* is the top layer implies that an erosion process or a deposition process might have happened. Geologists can use spatial relations in the image to determine the temporal ordering of processes as well. For instance, because *rock4* is ***above*** *rock3* and *rock1,* the geologist would infer that *rock4* was eroded or deposited on *rock3* and *rock1*, ***after*** the intrusion process (because sedimentary rocks are deposited from above onto the surface of the top layer rock). This same line of reasoning allows the geologist to infer that *rock3* is younger than *rock2.* For each possible candidate geological process, geologists would reconstruct the prior state and update the spatial arrangement of rocks accordingly. For instance, in the reconstruction of the state prior to the deposition of *rock4, rock4* would no longer be the top layer and the sedimentary rock *rock3* would be the top layer. Thus, a possible sequence of processes is:

1. Deposition of *rock2*
2. Deposition of *rock3*
3. Intrusion of *rock1* into *rock2* and *rock3*
4. Erosion of *rock1* and *rock3*
5. Deposition of *rock4*

The corresponding solution sequence of sketches is shown in Figure 2. This sequence of sketches represents one possible sequence of events that resulted in the formation shown in Figure 1. In general, there can be multiple possible interpretations.

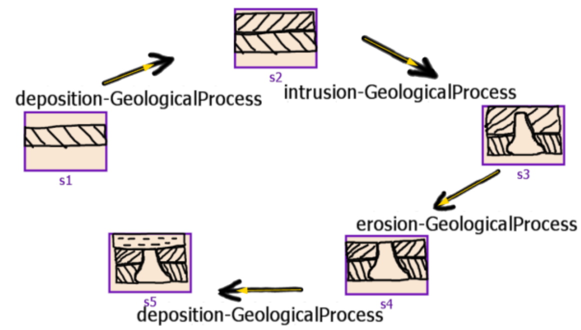


Figure 2: A sketch-based solution to the geologic interpretation problem

CogSketch

In many spatial domains, such as geology, experts and students use hand-drawn sketches to communicate ideas and to solve problems. Therefore, we built our model of geologic interpretation on CogSketch [Forbus et al 2008], an open-domain sketch understanding system.

Most sketch understanding systems treat understanding as a matter of recognizing a limited number of predefined symbols [Alder&Davis 2004]. However, in geological reasoning there are no conventional symbols that can be recognized entirely by their shape, so recognition-based approaches are not relevant for this problem. In contrast, CogSketch is designed with the insight that in human-to-human sketching, recognition is a catalyst, not a requirement [Forbus et al 2008]. Sketching does not require precise artistry, and people use language to conceptually label what they are drawing. CogSketch's interface supports providing conceptual labels without requiring recognition.

The basic building block in CogSketch sketches is the *glyph,* which is used to represent entities and relations. Users draw *entity glyphs* to represent geologic objects (e.g. a particular layer of rock). Users can also draw *relation glyphs* to represent non-spatial relations between two entities depicted via glyphs (e.g. A causes B). The user specifies what object or relation a glyph represents by providing a *conceptual label* (e.g. Sedimentary rock, Causes). The conceptual labeling system is inspired by the fact that humans often use language to explicitly label the contents of their sketches. However, it is important to note that spatial relations (e.g. intersection, containment) are automatically computed by CogSketch; users do not explicitly draw or label spatial relations. Glyphs are drawn within a *subsketch* and one or more *subsketches* make up a *sketch*. For our model of geologic interpretation, each subsketch corresponds to a geologic state.

Large-scale Knowledge Base. The conceptual labels are drawn from an OpenCyc[1]-derived knowledge base (KB) with over 58,000 concepts, including our own additions to support visual, spatial, qualitative and analogical reasoning. Concepts are modeled in the KB as *collections*, which are linked into a hierarchy by the `genls` relation. With hierarchical organization, concepts can inherit properties from parent concepts (e.g. `SedimentaryRock` is a specialization of `GeologicalRockUnit`). Because the KB is huge, the contents of the knowledge base are partitioned into *microtheories* to provide contextualization. For our model, we created a microtheory called `GeoscienceMt` to hold all geological concepts and inference rules. Microtheories are also hierarchically organized and are related by `genlMt`. For example, `(genlMt GeoscienceMt GeographicalRegionGMt)` indicates that every fact believed in `GeographicalRegionGMt` is also believed in our `GeoscienceMt`.

Reasoning System. The FIRE reasoning system [Forbus et al 2010] provides several types of reasoning and planning services, including analogical reasoning and learning. Our domain theory is implemented via inference rules, encoding the semantics of the geological processes that are described here.

Representing Geological Objects and Processes

Simmons [1983] defined three categories of geological objects: boundaries, rock units, and points. We extended the OpenCyc ontology with three concepts for these, `GeologicalBoundary`, `GeologicalRockUnit` and `GeologicalPoint` respectively. These serve as the superordinate collections for the rest of the objects we needed. For example, under `GeologicalRockUnit`, there are three sub-collections: `SedimentaryRock`, `IgneousRock` and `MetamorphicRock`, which represent the three basic rock types. The collection `GeologicalBoundary` has a sub-collection `Fault-Topographical`, under which there are more detailed sub-collections of fault categories. In the sketched geologic state, each glyph representing a geologic object will be labeled by a concept from the above collections.

Based on an analysis of standard textbooks and consultation with professional geoscientists, we identified five fundamental geological processes relevant to geologic interpretation, which are shown in Table 1. The processes identified in Table 1 are not exhaustive, but they do cover a broad and basic set of geologic interpretation problems. They are also the critical geological processes to be introduced to students in geosciences classes and textbooks. Detecting these processes requires all of the six physical principles [Marshak 2008] used by geologists to determine the relative age of rocks in a geologic record. These principles are: original horizontality, original continuity, superposition, inclusion, cross-cutting and unconformities. Other more detailed sub-categories of geological processes (e.g. normal faulting by tension, thrust/reverse faulting by compression, or folding by compression) are left for future exploration.

Once these five processes were identified, we developed functions to denote processes, where the arguments are the participants in the process. In addition to this fine-grained representation, we also provide a coarse-grained representation in terms of binary relations between geologic states. We use subsketches to represent geologic states, so using binary predicates such as `deposition-GeologicalProcess` allow us to draw relationships between subsketches to indicate hypothesized interpretations (as shown in Figure 2).

Table 2: Knowledge representation for five geological processes

(Deposition-GeoProcessFn <rock> <TheSet <rock1> <rock2>...>) • A deposition process which caused <rock> to deposit horizontally atop a set of other rocks in <TheSet>.
(Faulting-GeoProcessFn <fault> < TheSet <pair1> <pair2> …>) • A faulting process which created a fault and caused a set of rocks to split into pairs of separate rocks <TheSet (pair1) (pair2) …>. Relative motion between each pair of rocks is also caused.
(Tilting-GeoProcessFn < TheSet <rock1> <rock2> …> <x> <y>) • A tilting process which causes at least one non-top rock layers in <TheSet> to rotate toward the direction (<x> <y>).
(Intrusion-GeoProcessFn <rock> <TheSet <rock1> <rock2> …>) • An intrusion process which causes igneous rock to intrude into a set of other rocks in <TheSet>.
(Erosion-GeoProcessFn < TheSet <rock1> <rock2> …>) • An erosion process which causes the top layer of rock in <TheSet> to decrease.

Inferring Process Sequences from Geology

The input consists of a sketched representation of a geologic state. First, spatial relations (which are described in greater detail below) are computed. These relations characterize the spatial organization of the objects (i.e. rocks) in the sketch, which provide evidence as to which geological processes may have occurred. Next, a set of candidate geological processes are constructed, using rules in the domain theory. Candidate geological processes are the *most recent* processes that may have *directly* caused the geologic formation depicted in the sketch. In terms of the geologic interpretation problem in Figure 1 (and a possible solution in Figure 2), the set of candidate geological processes would include deposition of *rock4* (step 5) but not the earlier processes (steps 1-4). Thus, candidate geological processes are inferred one state at a time.

[1] http://www.cyc.com/opencyc

Finally, properties of the previous state are inferred, both to verify the reasonableness of the hypothesized cause and to provide information that can be used to continue inferring causality back through a sequence of states. This section describes this process in more detail, using as a running example the cross-section illustrated in Figure 1.

Computing Additional Spatial Relations

CogSketch automatically computes RCC-8 relations, which is a set of eight mutually exclusive relations that describe all possible topological relations between two 2D closed shapes. Some positional relations and visual/conceptual relations are calculated as well, e.g. `above`, `rightOf` and `SpatiallyIntersects`. The relation `above` typically implies vertical movement, and `rightOf` often implies horizontal movement from the cross-section view.

However, the above relations were not enough to describe intrusion, so we created a new spatial relation `intersectsConvexHull` to represent it. `intersectsConvexHull` is different from `spatiallyIntersects` in that the former is true when a glyph and the convex hull of another glyph intersect, while the latter is based on the intersection of the exact boundaries of both glyphs. For example, Figure 3 shows an example of intrusion. The two glyphs do not intersect according to `spatiallyIntersects`, so that relation cannot be used to sufficiently detect intrusions. However, the relation `intersectsConvexHull` will detect the intersection caused by the intrusion. Additionally, in the event that intrusion occurs in different directions (e.g. igneous rock that intrudes from the top or from the side) `intersectsConvexHull` will detect it. To avoid brittleness, given the imprecision of hand-drawn sketches, we require that the extent of overlap extend beyond a depth threshold.

Figure 3: An intrusion example showing one glyph intrudes into another concave glyph

Generating Candidate Geological Processes

Occurrences of geological processes which could explain how the current state came to be are generated by *proposal rules*. Proposal rules analyze the physical structure implied by the sketch to propose geological processes that may have directly caused these structures. They produce terms denoting one of the five process types introduced in Table 1.

To identify what processes could lead to the current state, both spatial and conceptual constraints are defined for every geological process. To demonstrate how these constraints work, let us walk through the inference on the sketch shown in Figure 1.

First, we consider the proposal rule for the deposition process. According to the principle of superposition [Marshak 2008], the deposited younger rock layer must be at the top, while the older rock layers are at the bottom. Therefore, when one rock layer is above all others, the system infers that a deposition process may have taken place and that the top rock layer was deposited. Also, because deposition is the process by which sediment settles out of the transporting medium, the deposited rock should be sedimentary rock. In the sketch shown in Figure 1, the sedimentary rock *rock4* is above all other rocks. Consequently, the system infers that a deposition process (where *rock4* was deposited) may have preceded the current state.

The proposal rule for intrusion is used as well, because the fact that *rock1* intersects *rock2* and *rock3* can be determined by the spatial relation `intersectsConvexHull`. The principle of cross-cutting [Marshak 2008] says that any feature that cuts across a rock or body of sediment must be younger than the rock or sediment it cuts across. Therefore, the system infers that an intrusion process involving the igneous rock *rock1* may have resulted in the current state. It can also infer that *rock1* is younger than *rock2* and *rock3*.

Top rock layers are almost always susceptible to erosion and the goal of proposal rules is to cover all possible occurrences of geological processes. Therefore, the list of candidate geological processes leading to the current state includes an erosion process under many circumstances. In Figure 1, the sedimentary rock *rock4* is the top layer, thus an erosion process involving *rock4* is inferred. Note that we are only considering geological processes that may have *directly* resulted in the state depicted in Figure 1, so the system can only infer erosion on *rock4* because it is the only top layer. If we were to consider the geologic formation of a prior state, when *rock1* and *rock3* were the top layers, then the system would have inferred erosion of *rock1* and *rock3*.

Based on these proposal rules, the set of geological processes that may have directly caused the state in Figure 1 are: deposition, intrusion and erosion. However, the spatial relations may inform temporal constraints as well. According to the cross-cutting and superposition principles, if a layer of sediment buries a fault or an intrusive rock, the sediment must be younger. In this case, because the top rock layer (i.e. *rock4*) is involved in the deposition and the intrusion process involves objects (e.g. *rock1*) beneath the top layer, the proposal rules can infer that the deposition occurred after the intrusion process. Thus, temporal constraints prune the intrusion process from the set of processes that may have directly caused the state in Figure 1.

As a result, the inference produces the following candidate processes that could have preceded the current state:

- (Erosion-GeoProcessFn <rock4>)
- (Deposition-GeoProcessFn <rock4> (TheSet <rock1> <rock2> <rock3>))

Here, we show candidate geological processes that refer to the labeled rocks in Figure 1. In actual code, these are replaced by internal object names (as used in the section below) that are protected from user edits and potential naming conflicts.

Producing Facts about the Prior State

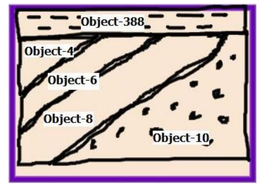
Once a set of candidate geological processes has been inferred, the model can infer facts about the previous geologic state via *verification rules*. Verification rules examine whether the transition from the prior state to the current state is caused by a particular geological process. For example, in Figure 1, one of the candidate geological processes is deposition, so some hypothetical facts about the top rock layer *rock4* in the prior state are produced based on the verification rule for the deposition process. In the meantime, these hypothetical facts are verified by the constraints for the transition. This is how facts about the prior state are produced. These generated facts become the spatial and conceptual constraints for a sketch of the prior state. Therefore, the state-to-state inference can be conducted back through a sequence of states by turning the prior state into the current state, until no facts about the prior state can be generated.

Currently, the reasoning model has a proposal rule and a verification rule for each geological process. This set of five proposal rules and five verification rules define the constraints for spatial changes for every geological process.

Experiment

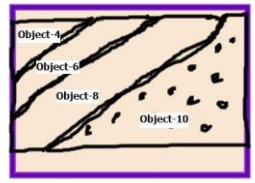
In the simulation test, 7 out of 12 process-combination sketches were chosen from *Laboratory Manual in Physical Geology* [Busch&Tasa 2000] to evaluate the robustness of the reasoning model. The 7 sketches constitute a set that involves the six basic physical principles geologists use for determining the relative age of rocks. Each of these sketches involves two or three kinds of possible geological processes and all of the five processes defined in the paper are included. The other 5 sketches contain combinations of geological processes that are already included in the 7 sketches.

Table 2: Simulation results are shown with the list of candidate geologic processes below each sketch example.



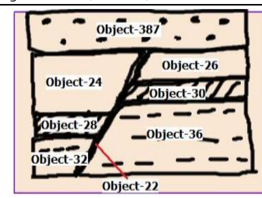
Deposition1

- (Erosion-GeoProcessFn (TheSet Object-388))
- (Deposition-GeoProcessFn Object-388 (TheSet Object-6 Object-8 Object-10 Object-4))



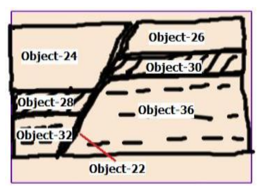
Tilting

- (Erosion-GeoProcessFn (TheSet Object-4 Object-10))
- (Tilting-GeoProcessFn (TheSet Object-6 Object-4 Object-8 Object-10) 1 1)



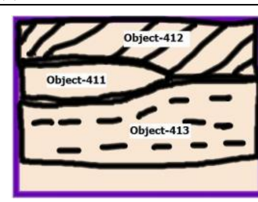
Deposition2

- (Deposition-GeoProcessFn Object-387 (TheSet Object-24 Object-26))
- (Erosion-GeoProcessFn (TheSet Object-387))



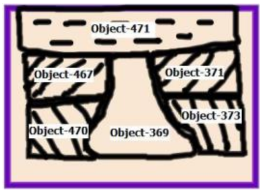
Faulting

- (Erosion-GeoProcessFn (TheSet Object-24 Object-26))
- (Faulting-GeoProcessFn Object-22 (TheSet (Object-24 Object-26) (Object-32 Object-36) (Object-28 Object-30)))



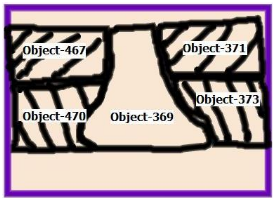
Intrusion1

- (Intrusion-GeoProcessFn Object-411 (TheSet Object-412 Object-413))
- (Deposition-GeoProcessFn Object-412 (TheSet Object-413))
- (Erosion-GeoProcessFn (TheSet Object-412))



Deposition3

- (Erosion-GeoProcessFn (TheSet Object-471))
- (Deposition-GeoProcessFn Object-471 (TheSet Object-371 Object-369 Object-467))



Intrusion2

- (Erosion-GeoProcessFn (TheSet Object-467 Object-369 Object-371))
- (Intrusion-GeoProcessFn Object-369 (TheSet (Object-470 Object-373) (Object-467 Object-371)))

Table 2 shows the set of candidate geological processes generated for each of the 7 sketches. For each sketch, the model uses spatial and temporal constraints to arrive at the set of candidate geological processes. For example, according to the spatial relations in the `Deposition2` sketch, deposition, erosion and faulting could have occurred at some point in time. However, the principle of superposition prunes the possibility that faulting was the most recent and direct cause of the current state, so the model correctly omits a faulting process.

Inferred results also include the objects undergoing the geological process. For example, when the system infers a deposition process, it determines which rock was deposited and the rock(s) on which it was deposited. This is very useful for automatically inferring the positional arrangements of rocks in the previous geologic state.

Each sketch has more than one candidate geological process because there are often several different geologic interpretations for a given state. The ordering of the candidate processes does not matter, since they do not represent a sequence of processes, but rather the most recent process of many different possible sequences. For example, the candidate processes generated for the `Faulting` sketch indicate that the process directly preceding this state could have been an erosion process *or* a faulting process.

There was only one case where our model generated a candidate process with missing arguments. For the `Tilting` sketch, the argument list of the inferred erosion process is incomplete. The two intermediate layers `Object-6` and `Object-8` were not taken into account for erosion. This is because a spatial constraint of erosion was applied to avoid non-top rock layers from being involved in erosion. However, this sketch also involves tilting, thus the intermediate layers are also eligible for experiencing erosion. This problem can be solved by determining whether there is a consistent operation on a stack of rock layers or not (e.g. tilting) and then incorporating the missing rock layers into the relevant objects.

The `Intrusion1` sketch unexpectedly inferred a deposition process, where `Object-412` is deposited on `Object-411` and `Object-413`. However, this is not necessarily incorrect as the sketch is ambiguous. This geologic state may have resulted from an intrusion process *or* a deposition process. Our system infers three candidate geologic processes (intrusion, deposition and erosion) and thus demonstrates the ability to detect several different (but sensible) interpretations.

Related Work

A number of researchers have investigated the geological interpretation problem. Previous work has focused on segmentation, detection and inference over images and diagrams. However, our model is the first to use sketched input, which lends itself to natural communication in educational settings.

Zhen Zhang and M. Simaan [Zhang & Simaan 1987] designed a rule-based interpretation system for segmenting seismic images. The texture analyzer extracted discriminant features from the texture-like signal image and assigned a vector of initial certainty factors as representations. In [Pitas & Venetsanopoulos 1987], a knowledge-based system was proposed to detect the position of hydrocarbon reservoirs from the seismic cross-sections. The knowledge base in this system was used to search for various elements of the seismic image.

Roberto and Chiaruttini [Roberto & Chiaruttini 1999] thoroughly investigated the reconstruction of 3-D geologic profiles using spatial and temporal analyses on a set of underground images. Here, the knowledge base mainly contained concepts from topology and graph theory. The domain concepts were represented as geometric primitives and relations among them. During the inference process, the reconstruction was built by assembling simpler components.

The earliest system that used qualitative reasoning in geologic interpretation was by Simmons [Simmons 1983] [Simmons & Davis 1987]. The input to his system was a perfectly formed line drawing of a cross-section. Given such a diagram, his *imagining* technique combined qualitative simulation with diagram modification operators to construct a sequence of diagrams. Our approach is inspired by his work, but we use a more general ontology and we have tackled the problem of dealing with messy, hand-drawn sketches, with promising results. How well our techniques work with users “off the street” remains an open question at this point.

Discussion and Future Work

This paper describes a computational model for geologic interpretation of hand-drawn geologic sketches. Given a geologic state depicted by a sketch of a cross-section, the system is capable of inferring previous geological processes as well as facts about previous states.

While these results are encouraging, there are several opportunities for improvement:

Richer geoscience knowledge: Currently, our system has the ability to infer five geological processes. But, the variations of these processes are not fully covered. For example, the faulting process can be caused by different types of stress and generate different fault types. Additionally, we have included the three main rock categories, but adding greater detail (e.g. sandstone, shale, etc) will enable the system to represent more complex geologic formations. Improving the depth and coverage of our system's geoscience knowledge will increase its applicability as a tool in geoscience instruction as well.

Richer qualitative reasoning: Currently, our system was only evaluated using sketches involving two or three kinds of geological processes. Some examples involve many more layers and more complex combinations of processes (e.g. the formation of folds via compression). Handling such sketches will require extending both the proposal and verification rules.

Automatic sketch generation: To visualize the results of the interpretation process, ideally a system would generate its own sequence of sketches, compatible with the inferences it drew about the prior states. Since only partial information about prior states can typically be inferred, multiple sketches may need to be introduced and subsequently reasoned about to capture the full range of possible explanations.

Integration with Sketch Worksheets: Sketch Worksheets are a simple form of sketch-based educational software, where students are given feedback on their sketches. As noted above, the geological interpretation model here is motivated by geoscience education concerns. One worksheet design we are planning involves the system using its ability to construct qualitative causal explanations to test student explanations, providing them feedback as to whether or not their proposed explanation (described via sequence of linked sketches, as per Figure 2) is correct and/or complete.

Acknowledgements

This research was supported by the Spatial Intelligence and Learning Center, NSF SLC Grant SBE-0541957.

References

Adler A., and Davis R. 2004. *Speech and Sketching for Multimodal Design.* In Proceedings of the 9th International Conference on Intelligent User Interfaces.

Busch, R. and Tasa, D., 2000. *Laboratory Manual in Physical Geology*. Fifth edition. American Geological Institute and National Association of Geoscience Teachers.

Kumar, V. 1992. *Algorithms for Constraint Satisfaction Problems: A Survey*. AI Mag., pp. 32–44, Spring 1992.

Forbus, K., Hinrichs, T., Kleer Johan., Usher J., Klenk, M., Lovett, A., and Paritosh, P. 2010. *The FIRE Manual Version 3.0.* Qualitative Reasoning Group, Northwestern University.

Forbus, K., Usher, J., Lovett, A., Lockwood, K., and Wetzel, J. 2008. *CogSketch: Open-domain Sketch Understanding for Cognitive Science Research and for Education.* In Proceedings of the Fifth Eurographics Workshop on Sketch-Based Interfaces and Modeling, Annecy, France.

Marshak, S. 2008. Earth: Portrait of a Planet, The Third Edition.

Pitas, I. and Venetsanopoulos, A. N. 1987. *Toward A Knowledge-Based System for Automated Geophysical Interpretation of Seismic Data*, Signal Process., vol. 13, no. 3, pp. 229–253.

Pittman J., Smith I., Cohen P., Oviatt S., and Yang, T. 1996. *Quickset: a Multimodal Interface for Military Simulations.* In Proceedings of the Sixth Conference on Computer-Generated Forces and Behavioral Representation, pp. 217-24.

Roberto, V. and Chiaruttini, C. 1999. *Modeling and Reasoning Techniques in Geologic Interpretation*. IEEE Trans on Systems, Man and Cybernetic, Part A: System and Humans, Vol. 29, No.5.

Simmons, R.G. 1983. *Representing and Reasoning about Changes in Geologic Interpretation.* MIT AI Tech. Rep. **749**.

Simmons, R.G. and Davis, R. 1987. *Generate, Test And Debug: Combining Associational Rules and Causal Models*. In Proceedings of IJCAI'87, pp.1071–1078.

Yin, P., Forbus, K., Usher, J., Sageman, B., Jee, B. 2010. *Sketch Worksheets: A Sketch-based Educational Software System*. In the Proceedings of the Twenty-Second Innovative Applications of Artificial Intelligence Conference (IAAI).

Zhang, Zh. and Simaan, M. 1987. *A Rule-Based Interpretation System for Segmentation of Seismic Images*. Pattern Recognition., vol. 20, no. 1, pp.45–53.