Adviser: Immersive Field Work for Planetary Geoscientists

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The Adviser prototype system makes it possible for planetary geologists to conduct virtual field research on remote environments such as Antarctica and Mars. Among Adviser's interactive tools are mission-planning and measurement tools that let researchers generate new data and gain interpretive insights. Five case studies illustrate the system's applications and observed benefits.

Geologists primarily explore the Earth through fieldwork and by analyzing the geological record at various points on the Earth's surface (see Figure 1a). They then integrate individual data points about the Earth's surface by means of more synoptic analyses. To aid this analysis, they often use image and topographic data that satellites acquire from Earth's orbit. One of the authors, who has decades of field experience in widely varying terrain—from recent volcanic eruptions[1] to the Earth's sea floor[2] to Antartica's Dry Valleys[3]—has demonstrated this strategy's value and shown how to augment it using images from helicopters or remotely operated vehicles.

In contrast, planetary geoscientists commonly work in the reverse order: Given the time and distances involved, flybys and orbital spacecraft acquire the initial data from individual moons and planets. In some cases, more detail might come later through lander and rover deployments, or—in the Moon's case—through human explorers. These opposite approaches result in a huge difference in local analysis of the Earth and other planets. While Earth geoscientists can employ 3D in situ strategies, most planetary geoscientists use static or interactive 2D visualizations for their analyses (see Figure 1b). Although these 2D visualizations are highly developed and often effective, for tasks involving subtle 3D spatial judgments, we expect that interactive 3D visualizations will likely lead to a more complete understanding of the data—and in some cases to recognition of features missed altogether in 2D visualizations.

Our goal is to enhance planetary geologists' ability to do field work as effectively on other planets as they can on Earth. We also want to enhance the exploration of remote and potentially hazardous Earth environments, such as Antarctica. Guided by multiple questions about Mars's geological evolution, as well as by future mission objectives, we're developing the Advanced Visualization in Solar System Exploration and Research system.[4] As Figure 1c shows, Adviser lets geologists virtually enter the field by recreating remote sites using laser altimetry, camera, atmospheric, and other data. In developing Adviser, we face the challenges of

- developing algorithms that interactively render a rich 3D environment that combines multiple large data sources;
- building tools that aid geoscientists in their research; and
- running formal usability studies to evaluate the system relative to alternative approaches.

Here we describe our system and present observations based on five case studies of its application.

System overview

Our prototype Adviser implementation operates in a four-wall Cave using the model-view-controller design pattern to organize data, visualizations, and interactions. The Adviser system contains topography, camera data, simulated data, and user annotation layers. We visualize the model using OpenGL and, in particular, the Real-Time Optimally Adaptive Meshes 2 (ROAM-2)[5] to render topography and camera data interactively.

In terms of performance, an $8,192 \times 8,192$ heightfield renders at 80 stereo frames per second using an Nvidia GeForce 3000G graphics card. The heightfield can register multiple high-resolution inset camera images, although each inset incurs a frame-rate penalty. The user can toggle insets on and off to find a balance between information and frame rate. Geologists generally display three inset images, with samples ranging from $1,000 \times 1,000$ to $15,000 \times 14,000$. The Cave pro-

Published by the IEEE Computer Society 0272-1716/06/$20.00 © 2006 IEEE

Related Work

Many researchers are currently working on geovisualization systems. Following are the systems most closely related to Adviser.

Desktop systems

NASA's World Wind system (see http://worldwind.arc. nasa.gov) lets users interactively explore a wide variety of terrain and image data. Google Earth (see http://earth. google.com) lets users look at high-resolution images, annotated data, and 3D models of some structures. The osgPlanet viewer (see http://www.ossim.org/tiki-read_ article.php?articleId=3) can visualize large geospatial data sets and import GIS data via the Web Mapping Server standard (see http://portal.opengeospatial.org/files/ ?artifact_id=5316).

Immersive environments

Immersive systems have been developed for a range of specific tasks. Wright and colleagues developed a system for creating and visualizing 3D terrain for the Mars Pathfinder missions.[1] Powell and colleagues developed a data fusion and visualization system for rover data acquired during Mars exploration.[2]

Although both systems have proven useful for investigating topographical features within a small area, we're interested in planetary-scale data visualization and exploration. In that respect, research focused on exploring large data sets [3,4] is closely related to our own. While all the immersive systems provide excellent features, Adviser focuses on tasks and tools specific to geological exploration. In addition to its immersive experience, Adviser offers research-oriented tools that let geologists do fieldwork inspired tasks.

Algorithms

Our choice of terrain-rendering algorithm was guided by several requirements:

- strict real-time performance for large data sets,
- open-source code availability,
- ease of integration with our software, and
- utilization of the latest graphics hardware features.

While several excellent algorithms were potential candidates for integration—including Geometry Clipmaps,[5] Batched Dynamic Adaptive Meshes (BDAM),[6] the Virtual Terrain Project's Terrain Library (http://www. vterrain.org/Doc/vtlib.html), and chunked Level-of-Detail (LOD; http://tulrich.com/geekstuff/chunklod.html) we chose Real-Time Optimally Adaptive Meshes 2 (ROAM-2) because it provides interactive terrain rendering and view-frustum culling for large data sets. While high-performance texture and terrain-paging extensions are also available, we have yet to integrate them into our system.

References

1. J. Wright, F. Hartman, and B. Cooper, "Immersive Environments for Mission Operations: Beyond Mars Pathfinder," *Proc. Int'l Symp. Space Mission Operations and Ground Data Systems* (SpaceOps 98)*, The Space Operations Organization, 1998; http://www-dial.jpl.nasa.gov/~john/papers/SpaceOps98/SpaceOps98.pdf.
2. M. Powell et al., "Scientific Visualization for the Mars Exploration Rovers," *Proc. Int'l Conf. Robotics and Automation*, Jet Propulsion Laboratory, NASA, 2005; http://hdl.handle.net/2014/37614.
3. L.E. Hitchner, "The NASA Ames Virtual Planetary Exploration Test-bed," *Proc. IEEE Wescon*, vol. 36, IEEE Press, 1992, pp. 376-381.
4. D. Koller et al., "Virtual GIS: A Real-Time 3D Geographic Information System," *Proc. IEEE Visualization Conf.,* IEEE CS Press, 1995, pp. 94-100.
5. F. Losasso and H. Hoppe, "Geometry Clipmaps: Terrain Rendering Using Nested Regular Grids," *Proc. ACM Siggraph,* ACM Press, 2004, pp. 769-776.
6. P. Cignoni et al., "BDAM—Batched Dynamic Adaptive Meshes for High Performance Terrain Visualization," *Computer Graphics Forum*, vol. 22, no. 3, 2003, pp. 505-514.

duces an immersive effect that lets geologists feel like they're at the site; they achieve interaction—such as 3D navigation and point specification—using a tracked handheld wand-like device. They also can use a Tablet PC for 2D line and gestural input.

Typically, geologists create a session in the laboratory, using their target data elements, then access the session in the Cave. They can also create new data within the Cave and store it in a networked database that they can subsequently access from anywhere using a Web portal.

1 Different types of planetary geoscience analysis. a) Glacial geologist Dave Marchant analyzes sublimation till fabrics in the Antarctic Dry Valleys. This local data will be integrated with regional air photos and satellite images to provide a broad view of the Mars-like Antarctic glacial processes. b) Studying 2D maps of Martian topography and camera data. c) Virtually studying topography on Mars with Adviser.

2 Two tools for teaching geological sciences. Students (a) in the classroom and (b) in the Cave, using Adviser to visit Tharsis Montes on Mars.

Case studies

Researchers are using Adviser to address multiple science themes through specific applications. Case studies 1 (general exploration) and 5 (wind visualization) support a wide variety of tasks. In contrast, case studies 2, 3, and 4 support graduate-level research, and the researchers helped build them to suit their specific needs.

While we've included images here to offer a general sense of what users see, these narrow-field-of-view, monoscopic images hardly capture the immersive experience of using Adviser in a Cave. In such an environment, the wide field of view and head-tracked stereo viewing greatly enhance the sense of being present and, in particular, of perceiving spatial relationships.

Case study 1: going virtually into the field

One of Adviser's basic capabilities is that it lets users freely explore a terrain in 3D. It is our belief that moving through a 3D environment makes it easier to understand an environment's intricacies than simply studying a 2D map. Establishing 3D relationships among geologic units and structures is particularly important when geologists are reconstructing the geological history of a region or planet. In this context, vantage point is particularly important; the different perspectives obtained when researchers constantly shift vantage points and return to previous ones are essential. During this process, having a continuously available field toolkit lets researchers make and record valuable, detailed measurements.

Currently, we're using Adviser to explore 3D environments for both research and education.

Research tool. Geoscientists have used Adviser to explore Mars and make useful observations about its features in a context that would be difficult or impossible to achieve with a nonimmersive 2D tool. Using Adviser as a tool to help understand the evolution of Mars has let researchers accomplish several key tasks. They have, for example,

- stood inside large craters on Mars and considered illumination conditions and solar insulation, and their role in the formation and preservation of the crater's ice deposits;[6]

- assessed the polar layered deposits' characteristics and distribution, which let them make thickness and geometry measurements to understand the planet's recent climate history;[7]
- planned and verified candidate rover traverses (or paths) for a proposed NASA mission to explore the North Pole's cap;[8] and
- assessed the general circulation of Martian atmosphere in different areas and on different time scales.

In addition, researchers previewed the Antarctic Dry Valley field area by flying through a 3D reconstruction of its topography with overlaid camera data. This experience helped field season candidates to train for geography, geology, and safety in this harsh and unforgiving region. Finally, Adviser let researchers place data collected over multiple trips to the Antarctic Dry Valley into a much broader context, using the same frame of reference that researchers developed in the field. This helped resolve many problems that emerged in the field, but had proven insoluble without the context Adviser provided.

Educational tool. Instructors have successfully used Adviser in a range of classes, from introductory-level courses to graduate seminars. For example, in "Geological Sciences 5: Earth, Moon, and Mars," more than 100 students per year study Mars, choose an area of it in which to pursue a specific scientific question or investigation, and then use Adviser to visit Mars and explore their chosen region in immersive VR. Figure 2 illustrates the difference between traditional classroom visuals and those possible in the Adviser environment. Students uniformly report a positive and rewarding experience that gave them new insights into the geology and topography of Mars and a better appreciation for its spatial relationships.

Discussion. The large class size and time constraints meant that each student group had just 15 minutes to learn Adviser's user interface and complete the assignment. To minimize training time, we disabled all Adviser tools except for navigation. This seemed reasonable, as navigation controls appeared to be the primary functional requirement for completing the assignment. However, we found that the constraint led students to
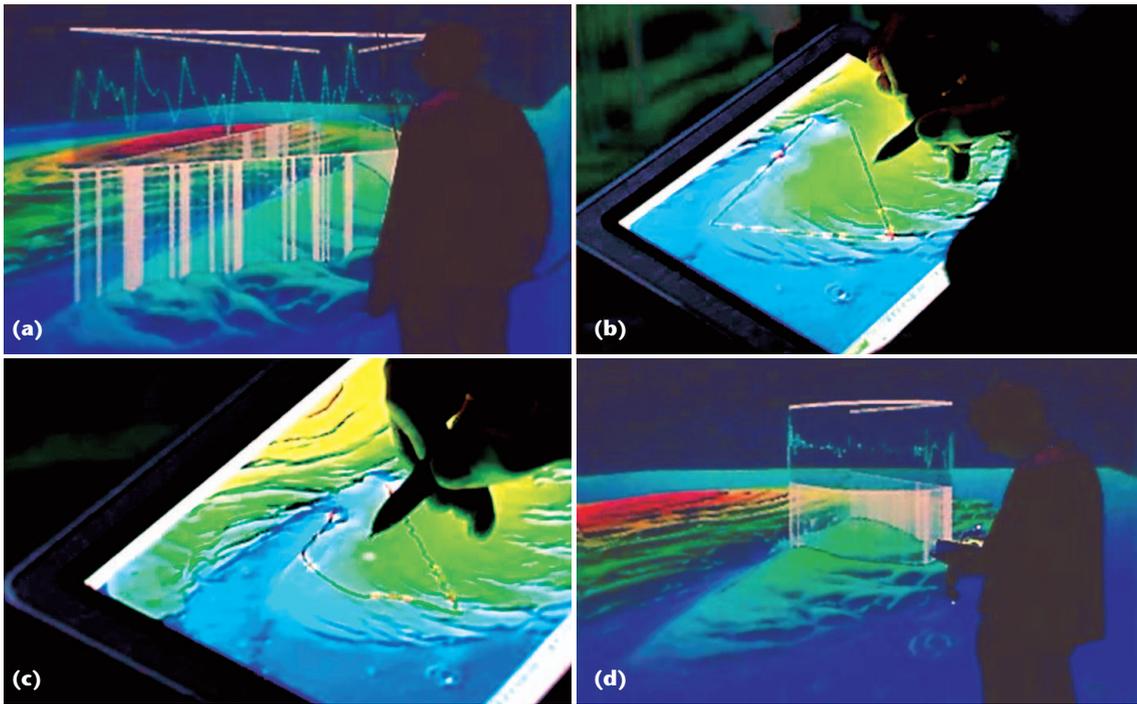
3 Traverse planning. (a) Initial rough triangular traverse is visualized in the Cave by a line that snaps to the terrain and vertical bars that connect it to a graph of slope. (b) The Tablet PC's view of the initial traverse. (c) The user sketches a new traverse, after which (d) the system updates the traverse and slope visualization.

describe capabilities and tools they believed would have also been valuable. Among the students' requests were maps for navigation, high-resolution overlays, and additional visuals or tools for judging the size of features. From the research and exploration-planning perspective, all participants had a uniformly positive experience using Adviser. One said, "It's like going to a foreign country rather than reading about it in a book!"

Case study 2: traverse planning for rover missions

We're currently collaborating with NASA scientists on the Palmer Quest mission's concept development. Among other things, the mission plans involve landing a rover on Mars's North Pole and studying the polar layered deposits' surface properties and structure. Selecting candidate traverses in advance is vital in mission planning, because path constraints (slope, distance, and so on) can be important in determining the mission's scope. Traverse planning is a complex activity involving close interactions among multiple groups.

Facilitating collaboration. In our work, we targeted collaboration between engineers (who are intimately familiar with the rover design constraints) and geologists (who are knowledgeable about the domain science). These two parties' design goals are often contradictory: the rover engineers generally prefer a traverse that navigates relatively flat terrain, whereas the geologists might prefer a traverse over steep slopes in order to investigate deposit textures and layer outcroppings.

The Adviser system provides an integrated environment in which the two groups can collaborate effective-

ly. For example, the system lets users input roughly sketched traverses with important waypoints. It then overlays the traverses on the 3D topography and presents them in the context of the camera image overlays. Engineers can choose to evaluate a target variable (such as slope) along the traverse, and can also provide some thresholds (such as a maximum slope of 30 degrees). The system then computes path segments that don't satisfy the constraint and presents the information to users in both the Cave environment (see Figure 3a) and on a handheld Tablet PC device (see Figure 3b). Using such a device, geologists can sketch new or modified paths (see Figure 3c); the system then updates the traverse and slope visualization (see Figure 3d).

Collaborators can now examine alternate routes to bypass problematic regions. We adapted the fluid inking system (www.cs.brown.edu/publications/techreports/reports/CS-05-10.html) to provide a natural interface for editing 2D traverses. With it, users can zoom into a target area on the Tablet PC and simply sketch over problematic segments. Adviser reevaluates the slope function on the new path accordingly and immediately presents the results in the immersive environment and the Tablet PC. The collaborators iterate until a traverse that satisfies the constraints is produced; they can then export the final traverse for more sophisticated analysis.

Discussion. Presenting traverse information in 2D with different overlays requires users to merge disparate sources of information. The typical 3D presentation makes the traverses easier to comprehend, but is rarely done in a collaborative mode. Because Adviser presents
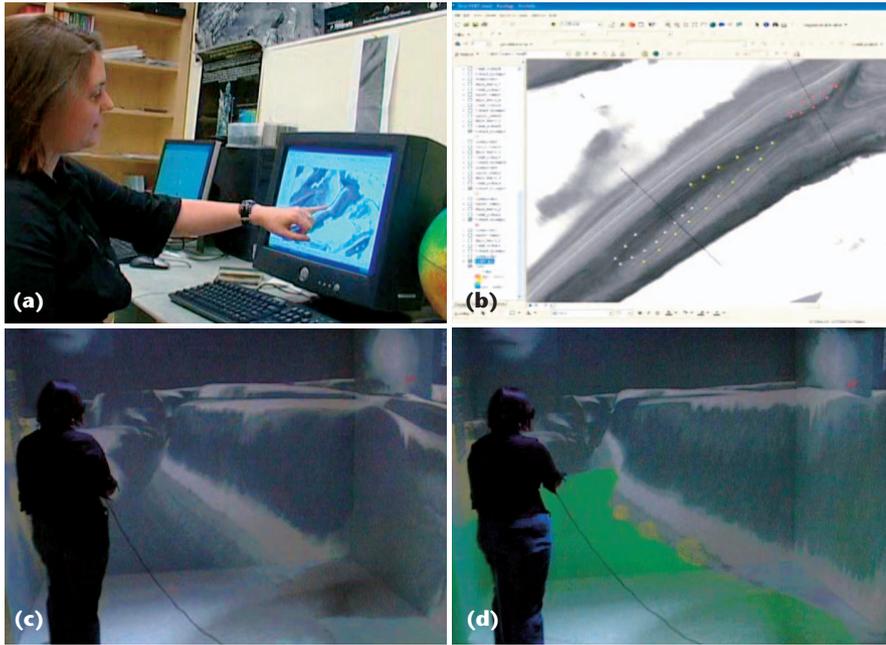
4 Analyzing layered geometry using strike and dip measurements. (a) A geologist uses a desktop ArcGIS system to take strike and dip measurements. (b) A close-up of the user-specified points on a layer, which show the layer's ambiguous positioning with reference to the cliff. (c) The same area as viewed stereoscopically by the user in the Cave immediately resolves the confusion. (d) The geologist places multiple yellow points along the exposed layer and Adviser computes a green best-fitting plane (planar to the head-tracked user).

traverses in the context of the 3D topography and images, it noticeably enriches collaborator discussions.

In addition, geologists typically see topography with substantial vertical exaggerations (scale factors of 15 to 30 are common). This is useful for enhancing important topographical features characterized largely by elevation changes, but which are diminished when visualized over a vast area (similar to the way a nonplanar terrain appears flat when viewed from an airplane). The rover engineers, however, need terrain presented proportionally so they can make accurate visual judgments. Adviser's ability to present the data with and without exaggeration interactively enhances the analysis and mutual understanding between the scientists and engineers.

Finally, to remove problematic traverse segments, we decided to use 2D stroke gestures on a Tablet PC, rather than marking a 3D path directly on the terrain. The 2D input device seemed much simpler, because it leveraged precise line-drawing skills and would thus avoid occlusion and accuracy problems that users might encounter by drawing 2D lines in a 3D environment. We plan to evaluate this conjecture more formally in a user study.

Currently, Adviser computes a predetermined class of functions, and we're planning to incorporate function expressions from the MathPad[2] system.[9] Associating the 3D and MathPad[2] variables will present a UI challenge.

Case study 3: strike and dip measurements

On Mars, the North Pole's layered terrain is composed of water ice and dust, and the individual layers' thickness and brightness are keys to the planet's recent cli-

mate record. In addition, the layer spacing and 3D configuration are important for understanding their emplacement and evolution. Do they represent a flat plane when they're emplaced? Or, are they warped—either during formation (deposited on rough terrain) or after due to post-emplacement deformation? The terrain's ice and dust layers are visualized by combining data from two sources. The Mars Orbiter Camera offers high-resolution images that reveal alternating dust and ice layers, while the Mars Orbiter Laser Altimeter topographic data lets us calculate an individual layer's thickness and geometry.

Layer analysis. Recent work suggests that these ice and dust layers encode a distinctive climate signal related to the same orbital parameter variations—such as periodic changes in obliquity and eccentricity—that cause the Earth's ice ages.[7]

To analyze the geometry of this climate record's individual layers, we're using strike and dip measurements. Field geologists use such measurements to describe subsurface layers' orientation and structure. The geologist typically identifies multiple, surface-exposed points along the same layer and then computes a best-fit plane from the points. The intersection of this plane with the horizontal plane forms a line; the angle between this line and the North Pole is the strike and the plane's inclination is the dip. Taking multiple strike and dip measurements along a layer can reveal whether the layer is flat or distorted beneath the surface.

As Figures 4a and 4b show, our group's geologists use ArcGIS (see http://www.esri. com/software/arcgis) to place points along a layer on a desktop system. They calculate strike and dip value for a set of points. To aid point placement, ArcGIS presents a 2D topography colormap in conjunction with the camera image. Adviser presents the layer data on a 3D terrain (see Figure 4c). Users can change the gray-scale images' contrast settings to enhance layer details and use a wand to specify points in 3D. As the user places more points, Adviser displays and updates the best-fit plane, which is a rough approximation to the local layer structure. Adviser also presents standard strike and dip representations (glyphs and numbers), which users can record in the virtual field notebook.

Discussion. Contrast enhancement is particularly important for visualizing layers in the Cave as most projector output quality lags behind conventional desktop display capabilities. We compute reasonable default values based on the mean and standard deviation of a camera image's intensity distribution, and give users controls to selectively map the input gray-scale intensities to the entire spectrum; this effectively enhances our current Cave projectors' limited brightness and resolution capabilities.

Another key operation is layer disambiguation. Without the topography information, a 2D layer view can be confusing and ambiguous. Such a view also complicates users' ability to establish the presence of layers relative to topographic features. Presenting layers on a 3D terrain helps disambiguate their structure and positioning.

Finally, users have commented that layer anomalies were easier to detect in the Cave environment, and that Adviser helped them select sites for strike and dip measurements with much greater confidence. Assuming finite time and resources to conduct such measurements, the Cave system appears to be a better environment than the 2D ArcGIS desktop for preselecting areas with interesting layering.

In terms of future work, we want to improve how some interactions are done in the Cave. For example, users can place points on a layer precisely using a desktop system's mouse input device. However, Cave users sometimes find placing points using the virtual laser pointer tiring and inefficient. We're considering whether we can improve this technique and whether a hybrid technique—using a laser pointer for rough positioning and a joystick for fine positioning—would be more effective.

Case study 4: angle measurements in Antarctica

Our group's field geologists undertake research expeditions to Antarctica's Dry Valleys. The Dry Valleys' geological environment is a hyperarid cold polar desert; its conditions resemble those on Mars more closely than any other place on Earth.

Polygon analysis. In one field experiment, geologists are studying contraction-crack polygon formation and how their structure varies along the debris-covered glaciers.[10] One of their operations measures angles between intersecting polygon margins that indicate the presence of a crack or trough. Because mobility constraints limit the number of field observations possible while in Antarctica, researchers follow field trips with desktop-based analyses of image data, such as the Cambot image in Figure 5a. As Figure 5b shows, researchers typically use Adobe Photoshop to mark points (indicating polygons) on the high-resolution cambot images without using topographic information. They then compute the angle value between the polygon margins. Multiple measurements yield statistics that can provide insight into the polygons' spatial layout and relationships.

The Adviser system lets geologists perform the same measurements. Geologists can bring up high-resolution Cambot images on the topographic base and perform contrast enhancement to reveal the polygons (see Figure 5c) . They can then use a wand to select points on the polygon margins (see Figure 5d), yielding an angle value. To present overall statistics, Adviser bins the angle values and computes a histogram, which it can optionally display on a Cave wall. Users can immediately download the angle data created in the Cave in comma-separated-value format on a standard desktop computer; they can then further process the data in applications such as MathWork's Matlab or Microsoft Excel.
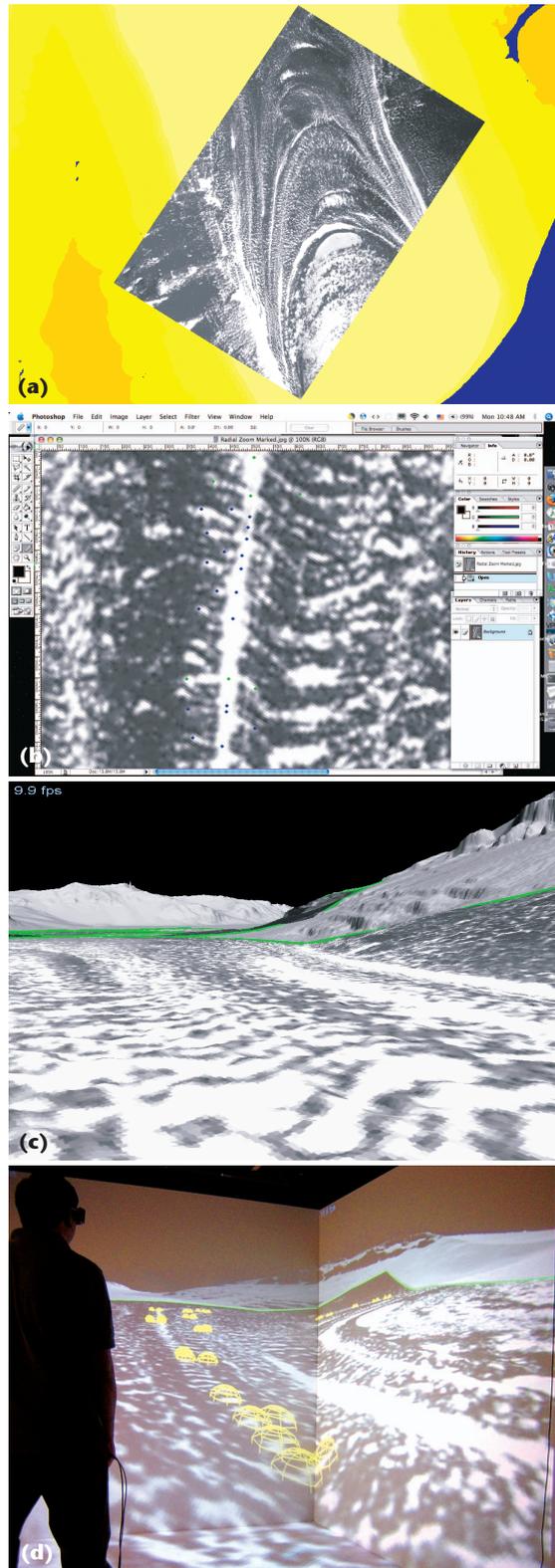
5 Studies of contraction-crack polygon formation in the Mullins Valley, Antarctica. (a) Topography colormap and Cambot image in ArcGIS. (b) In Adobe Photoshop, researchers use blue points for angle measurement. (c) The data set presented in the Cave and (d) examples of groups of three user-specified yellow points that Adviser uses in angle measurement calculations.

6 Wind data from the Mars Climate Database. The data as presented in (a) 2D and (b) in Adviser's 3D visualization.
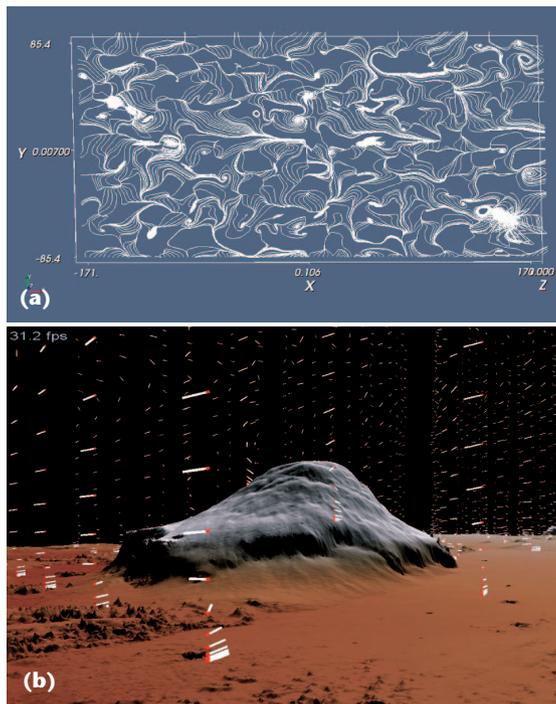
Discussion. Using Adviser in this context offers several benefits.

First, our field geologists find it easier to see the Cambot images' glacial lobe structures in the Cave than on the desktop systems; they've noted that subtle correlations between topography and camera data jump out to the eye. For example, one user detected a new chevron-shaped trough pattern that he hadn't seen before.

Second, users feel an enhanced sense of presence in the Cave environment. For example, being in the immersive environment reminded one geologist of thoughts and questions that had occurred to him during his field season six months earlier. This is particularly significant because he'd already been looking at the same Cambot images on the desktop for months following the Antarctica trip.

Third, the geologists said that the Dry Valleys' lighting variation was fascinating when they physically visited the area, so we provided an interface that let them interactively vary the time, day, and month to update the solar illumination. They found this extremely useful in understanding solar insolation's role in polygon and glacier development.

Finally, users reported that using Adviser helped them find new interesting places to take angle measurements. They also reported that after this experience they would like to conduct additional measurements with their 2D tools in those new target areas. As with the strike and dip measurements, however, there's no observable advantage to placing markers on the 3D terrain. In fact, using a 6 degree-of-freedom virtual laser pointer to specify points makes the process somewhat harder.

As for future work, our system's current illumination model uses an OpenGL diffuse Phong lighting model. Computing shadows would make the scene look more realistic and help in gauging solar effects.

Case study 5: global climate model simulations

Our group is interested in studying Mars's Tharsis Montes region because it contains geologically recent tropical glaciers, emplaced when climatic conditions were considerably different from today.[11] Our ability to study and interpret this area is critical to determining the causes of the climate changes involved in forming tropical mountain glaciers. Key to this understanding is the atmosphere's behavior and general circulation under these conditions.[12] By visualizing the atmosphere's characteristics and evolution in the context of the surface geology, we should be able to gain the insights necessary to understand how these tropical mountain glaciers are formed.

One of Adviser's primary goals here is to provide an integrated environment for viewing multiple scientific data sets. Thus far, these data sets have primarily included topographic information from Mars Orbiter Laser Altimeter and Light Detection and Ranging (Lidar) and image data from Mars Orbiter Camera, High Resolution Stereo Camera (HRSC), and Cambot. We've begun preliminary work to incorporate Forget and colleagues' excellent General Circulation Model (GCM) simulations.[13] The simulations provide accurate predictions of several quantities (such as wind, solar radiation, and surface pressure) for Mars under a range of input scenarios (such as dust conditions and obliquities). Although the simulation resolution is thus far relatively low (5.675×3.75 degree longitude-latitude grid) compared to the other data sources, the results are state of the art and provide valuable insight into the climatic conditions involved in the planet's evolution.

In our preliminary work, we've imported wind data for different time steps from the Mars Climate Database (see Figure 6a). Adviser displays the wind data at discrete grid points as 3D glyphs (see Figure 6b). The system gives users a time control to cycle through the time steps. This has provided an initial appreciation of the seasonal atmospheric changes' rate and scale in this area, and their possible role in climate evolution.[12]

Discussion

Among the commonalities we've observed in the case studies are:

- Using 3D topography to analyze surface features (such as striations and troughs) in camera imagery can be more powerful than viewing the 2D imagery alone.
- An immersive environment like the Cave can facilitate collaboration among disparate groups, especially when the goal involves a 3D spatial task.
- Immersive exploration of planetary data can be an effective medium for teaching students about planetary geological processes.
- Immersive visualization is a promising enhancement to the planetary geoscientist's conventional research process; we've observed an enrichment of both the discussion quality and the resulting insights.

We recognize the importance of conducting formal user studies to substantiate our observations. While pur-

suing such an evaluation in future works, we must overcome unique challenges. Some research tasks require subjects with specialized skills, such as geologists who have significant field experience in Antarctica or who are studying polar deposits on Mars. It might be possible to simplify the tasks to increase our subject pool, but this would be at the expense of the domain-specific insights that geologists have reported from using Adviser.

Conclusion

Geologists report that Adviser is more than just an exciting and stimulating experience: it gives them a clearer understanding of the 3D terrains. It also helps them

- make better spatial judgments,
- see details overlooked or underappreciated in 2D data visualizations, and
- make quantitative measurements effectively.

Further, students report a considerably enhanced learning experience from their Cave exploration expeditions.

In the future, we plan to extend Adviser to additional geology research tasks on Earth and Mars in service of the science themes. Additionally, we plan to:

- formally evaluate the system's mature components
- better integrate Adviser with the geologist's existing working environment, and
- support data sets on the order of terabytes.

We also plan to make Adviser's capabilities available for wider use in the research community. ∎

References

1. J.W. Head and L. Wilson, "Lava Fountain Heights at Pu'u O'o, Kilauea, Hawaii: Indicators of Amount and Variations of Exsolved Magma Volatiles," *J. Geophys. Res.*, vol. 92, 1987, pp. 13715-13719.
2. J.W. Head and L. Wilson, "Deep Submarine Pyroclastic Eruptions: Theory and Predicted Landforms and Deposits," *J. Volcanology and Geothermal Research*, vol. 121, 2003, pp. 155-193.
3. D.R. Marchant and J.W. Head, "Equilibrium Landforms in the Dry Valleys of Antarctica: Implications for Landscape Evolution and Climate Change on Mars," *Lunar and Planetary Science 36,* CD-ROM, abstract 1421, Lunar and Planetary Inst., 2005.
4. J. Head et al., "Adviser: Immersive Scientific Visualization Applied to Mars Research and Exploration," *Photogrammetric Eng. & Remote Sensing*, vol. 71, no. 10, 2005, pp. 1219-1225.
5. L.M. Hwa, M.A. Duchaineau, and K.I. Joy, "Real-Time Optimal Adaptation for Planetary Geometry and Texture: 4-8 Tile Hierarchies," *IEEE Trans. Visualization and Comp. Graphics*, vol. 11, no. 4, 2005, pp. 355-368.
6. P. Russell, J.W. Head, and M.H. Hecht, "Evolution of Ice Deposits in the Local Environment of Martian Circum-Polar Craters and Implications for Polar Cap History," *Lunar and Planetary Science 35*, CD-ROM, abstract 2007, Lunar and Planetary Inst., 2004.
7. S.M. Milkovich and J.W. Head, "North Polar Cap of Mars: Polar Layered Deposit Characterization and Identification of a Fundamental Climate Signal," *J. Geophys. Res.*, vol. 110, no. E01005, 2004, doi: 10.1029/2004JE002349, pp. 1-21.
8. F.D. Carsey et al., "Palmer Quest: A Feasible Nuclear Fission 'Vision Mission' to the Mars Polar Caps, Lunar and Planetary," *Lunar and Planetary Science 36,* CD-ROM, abstract 1844, Lunar and Planetary Inst., 2005.
9. J. LaViola and R. Zeleznik, ""MathPad^2: A System for the Creation and Exploration of Mathematical Sketches," *ACM Trans. Graphics,* vol. 23, no. 3, 2004, pp. 432-440.
10. J. Levy, J. Head, and D. Marchant, "The Origin and Evolution of Oriented-Network Polygonally Patterned Ground: The Antarctic Dry Valleys as Mars Analogue," *Lunar and Planetary Science 36*, CD-ROM, Lunar and Planetary Inst., 2005.
11. D.E. Shean, J.W. Head, and D.R. Marchant, "Origin and Evolution of a Cold-Based Tropical Mountain Glacier on Mars: The Pavonis Mons Fan-Shaped Deposit," *J. Geophys. Res.*, vol. 110, no. E05001, 2005, doi:10.1029/2004JE002360.
12. F. Forget et al., "Formation of Glaciers on Mars by Atmospheric Precipitation at High Obliquity," *Science*, vol. 311, no. 5759, 2006, pp. 368-371.
13. F. Forget et al., "Improved General Circulation Models of the Martian Atmosphere from the Surface to Above 80 km," *J. Geophys. Res.*, vol. 104, no. E10, 1999, pp. 155-176.

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