
47 Immersive Visualization for the Geological Sciences

AQ1

*William R. Sherman, Gary L. Kinsland,
Christoph W. Borst, Eric Whiting, Jurgen P. Schulze,
Philip Weber, Albert Y.M. Lin, Aashish Chaudhary,
Simon Su, and Daniel S. Coming*

CONTENTS

47.1	Introduction	1228
47.2	Common Geology Data Types.....	1229
47.2.1	Terrain Elevation Data.....	1230
47.2.2	Satellite Imagery.....	1230
47.2.3	2D Fields (e.g., Gravity and Magnetism).....	1231
47.2.4	3D Material Property Data (Tomogram Volumes).....	1233
47.2.5	Ground-Penetrating Radar (GPR) Data.....	1233
47.2.6	Well Log Data.....	1233
47.2.7	Vector Geometry Objects with Attributes.....	1234
47.2.8	Breadcrumb Trail.....	1234
47.2.9	Point Cloud Data.....	1234
47.3	Geology Visualization	1234
47.3.1	Relevant Issues in Geology Visualization	1235
47.3.2	Applying Standard Visualization Techniques to Geology	1235
47.3.3	Visualization Techniques for Geology	1236
47.3.4	Temporal Data	1237
47.3.5	Benefits to Geologic Visualization from the Immersive Interface.....	1237
47.4	Exemplar Applications and Lessons Learned	1238
47.4.1	Applications for Exploration of Terrains, Associated Geophysical Data, and Well Logs at the University of Louisiana at Lafayette	1239
47.4.1.1	Rendering and Interaction for Terrain Interpretation	1239
47.4.1.2	Well Log Visualization	1240
47.4.1.3	3D Lens Immersive Interface Technique.....	1241
47.4.2	LidarViewer: An Immersive Point Cloud Visualization Tool	1243
47.4.2.1	Visualization Techniques.....	1244
47.4.2.2	Immersive Interface Techniques.....	1245
47.4.2.3	Idaho National Laboratory LidarViewer Workflow.....	1246
47.4.2.4	Outcomes and Lessons	1246
47.4.3	Visualization of Multimodal Geophysical Survey Data.....	1247
47.4.3.1	Visualization Techniques.....	1248
47.4.3.2	Immersive Visualization Application	1249
47.4.3.3	Benefits Derived.....	1251
47.4.4	DRI Lancaster Sand Dune Layers	1252
47.4.4.1	Visualization Techniques.....	1253

1227

47.4.4.2 Immersive Interface Techniques.....	1253
47.4.4.3 Outcomes and Lessons	1253
47.5 Benefits	1255
47.6 Future and Conclusion	1256
References.....	1257

47.1 INTRODUCTION

One characteristic of geologists is their ability to think in 3D. Whether this ability is developed as they advance as geologists or they were drawn to geology because they possessed this ability is an open question. However, experienced geologists possess this ability to such a degree that two or more geologists may verbally communicate about a complex 3D, real-world problem—each of them building and modifying a 3D image in their mind as they receive information from the others. They can verbally query the image of another and as a group may actually change perspective in the virtual/mental 3D image. That is, they are capable of agreeing to look at the 3D problem from different positions in space...or time. They often need to trace the development of a particular geologic situation through geologic time. The group is capable of coming to consensus and running a very similar 3D *movie* in their individual minds. This *movie* is tweaked by evidential or opinion input from those involved, developing a cause and effect–based plausible explanation of the present geological situation. Similarly, the group may run this movie into the future to make predictions. Using immersive tools for visualizing the data is, therefore, both natural and powerful for geologists. Immersive 3D computer graphics technologies are tools that combine an intuitive 3D viewing environment with easily learned interaction mechanisms. These advanced 3D tools represent a natural operating platform for geologists who of necessity must think in 3D.

The following statement may be a tautology; however, it is worth specifically stating for its relevance to the use of immersive visualization: “All interpretation occurs in the mind.” The specific point is that before interpretation can proceed, information must get into the mind. In the example earlier, the information is communicated verbally. In many other cases, information enters the mind visually. Often, this information is in the form of 2D images. In the mind, 2D images from several different perspectives and at different scales are often (in the case of geologists...very often) constructed into 3D spaces. These 3D spaces, then, are the basis for making interpretations. While geologists are quite good at assembling 3D spaces from various input formats, it is more efficient to have the information enter the mind as already correctly constructed 3D images. This is one great advantage of immersive visualization for geologists.

AQ2 Another advantage is the ability of one or several geologists to freely move about in the 3D volume. The effect on the geologist of being immersed in their data is similar to being in the field where curiosity drives movement, inspection, and analysis. To geoscientists, this type of interaction is often intuitive—if, while in the field, the geoscientist wants to look at some feature that has aroused curiosity, he or she simply walks over there and looks at it (as part of the education and experience, most geoscientists have had some field work). Contrast this with what happens in many other environments wherein the investigator must make decisions, consciously or unconsciously, related to effort versus reward. That is, decisions must be made as to whether investigation of the curious feature is worth the effort of gathering the additional data necessary to reach a conclusion. Of course, in this process, the conclusion is estimated, perhaps incorrectly, and compared to the cost. One member of our team (Kinsland) experienced this firsthand: he had written and published a paper using 2D representations of aerial topographic light detection and ranging (LIDAR) data to interpret the evolution of a particular river. Later, he has presented the LIDAR data impressively, allowing him to move, interact, and continuously query as to latitude, longitude, and elevation. Within just a few minutes of *mindlessly* but curiously moving about in the data he said, “I have to write another paper. I have found an alternative explanation.” He had poured over the 2D data for many months before he wrote the original paper. Less than 20 min of walking within the data, as if he were in the field, resulted in

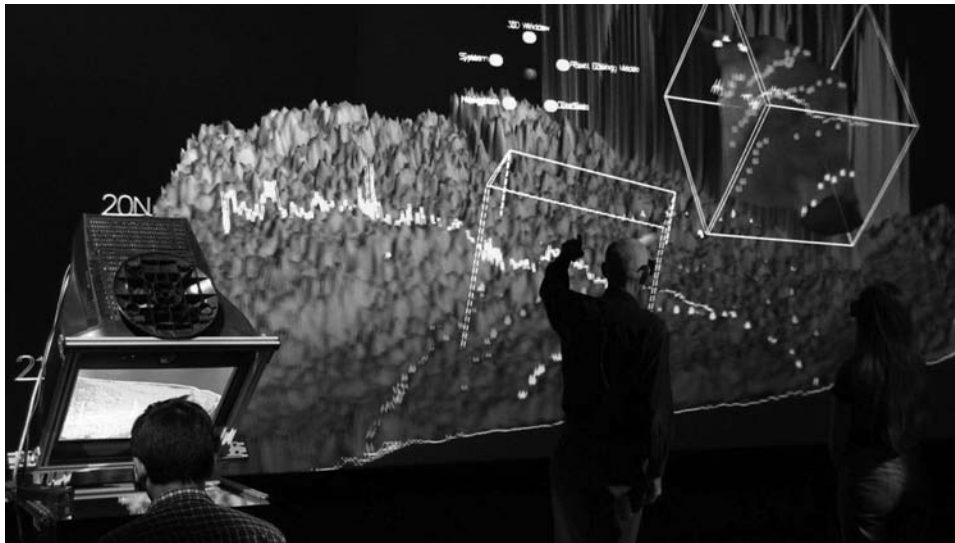


FIGURE 47.1 (See color insert.) A variety of immersive technologies (aka VR interfaces) enable the creation of new methods of interaction useful for geologists to inspect and interact with their data. Here, Gary Kinsland and students from the University of Louisiana at Lafayette collaboratively explore the Chicxulub crater with a reach-in style (a) and large rear projection (b) technologies. (See Section 47.4.1 for more details.)

AQ3

the basis for another paper, which was also published. Another example comes from the work done with data over the Chicxulub impact crater (the one that perhaps killed the dinosaurs) (Figure 47.1). For several years, Kinsland made 2D contour maps of the topographic data, making pseudo-3D maps of the data with color-coded elevation representations. All were useful in building the mental 3D image. However, in discussing the day he was reintroduced to his data in a head-mounted display (HMD) and allowed to walk about within his data, he relays that “I was totally enthralled and stayed in the HMD longer than I later was told I should have. To this day, years later, my mental 3D image of the topography over the Crater is largely that which I saw that day in the HMD.”

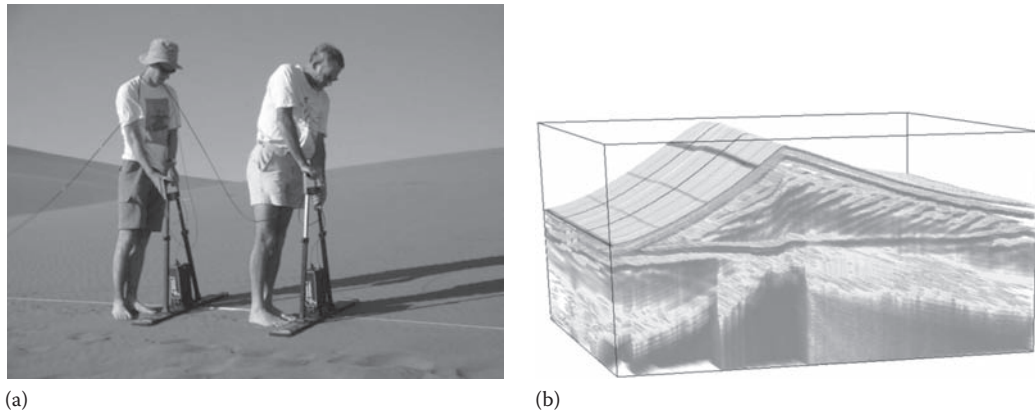
AQ4

One of the weaknesses of the human mind when dealing with multiple 3D datasets from the same geographical area is in getting the georeferencing done correctly. That is, it is difficult to mentally compare two overlapping 3D datasets such as topography and magnetic intensity. The interpreter is quite capable of inspecting and interpreting each 3D mental image from various perspectives and at various scales. However, it is often useful to query the correlation of features between the two. For example, does a valley in the topographic data correlate spatially with a particular anomaly (outstanding feature) in the magnetic data? *Georeferencing* of datasets is well handled by computers, which can blend the data into a single coordinate system. The two images may then be immersively viewed, compared, and interpreted simultaneously using any of several techniques described in this chapter.

In short, the world is 3D, and geologists think in 3D. Why reduce the 3D world to 2D images for communication into minds where 3D images must then be reconstructed and interpreted? Immersive environments are the key to accurate 3D thinking and offer improved understanding of almost all geology-related datasets.

47.2 COMMON GEOLOGY DATA TYPES

Data for the geological sciences of course are centered on the Earth and other planetary bodies. Nevertheless, there are still many different forms that geological data can take. Geology data can be 1D, 2D, or 3D; it can be static or time varying; and it might be spaced at regular intervals or be entirely unstructured.



AQ5 **FIGURE 47.2** Geologists collecting GPR data over a sand dune (a) and the associated visualization (b). (See Section 47.4.4 for more details.)

In this section, we briefly describe sources of geologic data and the forms those data take in terms of traditional visualization techniques (Figure 47.2).

47.2.1 TERRAIN ELEVATION DATA

A fundamental data type for geology is the height field of a terrain. Specifically, the term *terrain* (or *bare earth model*) generally refers to the actual ground surface of the planet, whereas *surface* often includes natural (e.g., forests) and man-made (e.g., buildings) objects protruding above the ground. The expressions *digital terrain model* (DTM) and *digital surface model* (DSM) are often used to explicitly indicate what has been measured. However, digital elevation model (DEM) data are ambiguous and may refer to either.

Terrain data are often collected using remote sensing technologies such as RADAR (collected via satellite) or space shuttle or airborne that passes over the region of interest taking LIDAR scans and other readings. Terrain data may also be collected using classical surveying techniques or even by GPS tracking. For the most part, the measuring technologies will capture the height of many points on the surface, but these points are irregularly spaced. Often, these points are processed into a regular, 2D (aka *raster*) pattern. The DEM format as specified by the U.S. Geological Survey (USGS) is a 2D *raster* data format with elevation values specified in a regular grid. Modern sources of DEM data include the Shuttle Radar Topography Mission (SRTM) data collected in 2000 (Farr & Kobrick, 2000; Farr et al., 2007) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data released in 2011 (Yamaguchi, Kahle, Tsu, Kawakami, & Pniel, 1998) (Figures 47.3 and 47.4).

47.2.2 SATELLITE IMAGERY

Images captured by orbiting satellites are another quintessential (pun intended) data type for geology. In the cases of imagery, the data are generally captured as regular 2D *raster* fields of spectral response. Captured spectral fields generally span from the infrared, through the visible colors and into the ultraviolet regions of the electromagnetic (EM) spectrum.

Due to the nature of an orbiting object scanning a curved surface, the image data require reprojection to *warp* the image to match either a Cartesian or polar mapping.

While we will see that there are many opportunities for registering and viewing different sources of data into a single representation, it is natural to begin by combining imagery data with elevation data to create a basic reconstruction of the real world. Even with no other data added, this in itself can be a good tool for reconnoitering geologic expeditions into the field to prepare a better plan for where to gather data (Figure 47.5).

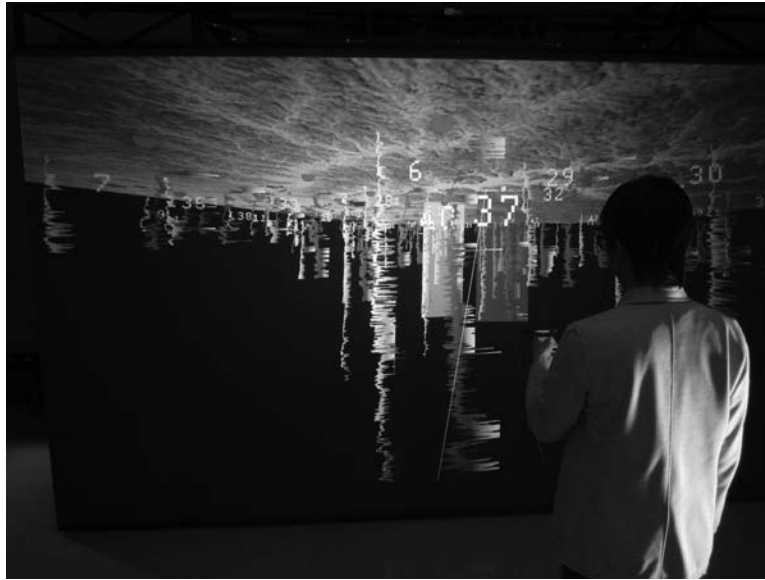


FIGURE 47.3 Geophysical logs of wells are *hung* from a surface generated from SRTM terrain data from North Louisiana. In this system, the virtual *wand* may be used to highlight and toggle a well icon located on the terrain. Toggling turns the well log representation on/off underneath the icon of the well. In the illuminated well data here, yellow is SP and blue is the resistivity. Though not yet implemented, correlation of features in these logs while within the 3D environment promises to facilitate and improve the interpretation of such subsurface data when compared to 2D methods of correlation. (See Section 47.4.1 for more details.)

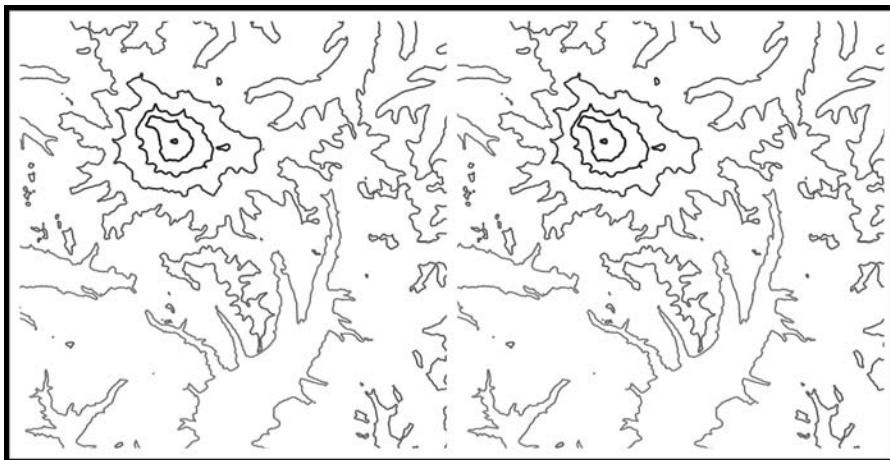


FIGURE 47.4 A stereo pair representing terrain contours near Mount Rainier. Using a stereoscope, viewers can see the relief of the terrain elevations.

47.2.3 2D FIELDS (E.G., GRAVITY AND MAGNETISM)

In addition to the obvious terrain-height data, or even spectral imagery, that correspond with latitude and longitude, there are other fields that map to the 2D surface of the planet. These data may be collected as an input stream recorded by a moving craft such as an airplane or boat, or they may be collected on the surface by moving measurement equipment to areas of interest. Two fields of particular interest to geology are gravity and magnetism.



FIGURE 47.5 Here, a user modifies an Esri shapefile from within the virtual environment, presented in a four-sided CAVE system.



FIGURE 47.6 Well log. This is a log of a well as typically utilized in the petroleum industry to investigate the properties of the subsurface. The header, at the far left, contains information about the location of the well, date logged, well owner, etc. The log extends from left to right from the shallowest to the deepest data and is usually viewed and interpreted vertically (rotated 90 degrees clockwise). The measurements represented by the *squiggly lines* are identified at the ends of the lines as are the scales for the values. The values in this log are (from bottom to top in this image) SP, resistivity, and conductivity (calculated from resistivity).

Magnetic data are typically collected through airborne instruments flown in a pattern over the region of interest (such as the Chicxulub crater presented earlier). Airborne collection of gravity data, however, lacks sufficient precision to be useful for detailed analysis. Thus, gravity data are more typically collected by laboriously moving measurement instruments on the surface from location to location. The irregularly sampled data may then be interpolated into a regular *raster* format more convenient for some visualization techniques—for example, using the Kriging interpolation technique as done in the case study in Section 47.4.1.

Each of these, and other, fields (e.g., radioactivity, resistivity, chemical, heat flow) is interpreted based on knowledge of the regional geology of the survey and the likely types of subsurface materials, which would lead to *anomalies* in the data. *Anomalies* are areas of the data that have values distinct from their surroundings—implying that in the subsurface, there are materials that are distinct from their surroundings (Figure 47.6).

47.2.4 3D MATERIAL PROPERTY DATA (TOMOGRAM VOLUMES)

Tomography techniques can be used to determine a property of material within a volume by passing a signal through the volume. There are several signal types that can be used to reveal different properties (and which have different effective ranges and resolutions). In medical imaging, we generally think of CT scans that use x-ray signals. CT scans can also be performed on soils and minerals to analyze properties such as porosity. On a larger scale, seismic tomography is performed with sound waves (sent from well to well). RADAR and many other wave sources can also be used to produce 3D tomogram volumes. For example, Muon absorption tomography is being used to image the interior structures of volcanoes (Tanaka et al., 2007).

Seismic volumes are tomograms collected using seismic reflection surveying, whereby signal sources and receivers are located on the surface with the signal reflecting off horizons in the subsurface. Processing the received signals yields representations of the distribution of various seismic properties within the subsurface. The most common property represented is the *reflection coefficient*—a measure of differences in velocity and density between adjacent rock layers.

47.2.5 GROUND-PENETRATING RADAR (GPR) DATA

Specialized radar devices use transmit and receive antennas separated on the order of 1 m from one another sending and receiving a signal aimed downward into the ground and measuring the returned/reflected time-response signal caused by changes in the dielectric constants when transitioning between materials. Often, the contrasts in the dielectric constant will correlate with the acoustic impedance contrasts of a seismic reflection survey.

AQ6

The result of a single sounding is a 1D signal response measured over time, where that time correlates with depth, though not necessarily in any specific ratio. The general means of visualization is to show 2D vertical images (e.g., *fence diagrams*) comprised of regularly spaced soundings of the data (e.g., where that data may be processed to remove low-frequency effects). Thus, the real-time signal from the receiver is plotted against distance along the surface line. A recent trend in some domains has been to create a 3D tomogram volume constructed by performing a 2D survey over a surface, respectively, versus a 1D survey for the fence diagrams.

Ground-penetrating radar (GPR) is used as a tool for a variety of fields such as archaeology, environmental site characterization, hydrology, concrete and road inspection, sedimentology, and glaciology. It is a nondestructive subsurface measurement technique that, in addition to preserving the site, is less difficult and expensive than excavation or drilling (Bristow, Duller, & Lancaster, 2007).

47.2.6 WELL LOG DATA

Data collected while a well hole is bored may be captured. This may be during an active process of accessing a reserve of natural resources, or the collection of the data may be the entire goal of the boring operation (such as when searching for the increased presence of a material such as gold). These *well logs* or perhaps *multivariate well logs of physical properties down a borehole* (Fröhlich, Barrass, Zehner, Plate, & Göbel, 1999) are 1D in space but sample many different properties along the path. It should be noted that with modern drilling technology, these wells are not necessarily in a straight-line path, but can be directed in different directions along the length of the well path.

Similar to other *ground-penetrating* techniques, an accumulation of data from multiple wells can be used to produce a regional layout of the subsurface structure or as control points to constrain and improve models of subsurface volumes.

47.2.7 VECTOR GEOMETRY OBJECTS WITH ATTRIBUTES

AQ7 There are many geological applications that make use of geometric data specified on a 2D manifold (i.e., surface) using points, edges/lines, and polygons/polylines to indicate places and regions on the surface. There also are many applications of these data that are less than scientific in nature, such as for political or engineering purposes. Attributes are typically assigned to the points, lines, and space within a polygon. Additionally, as the original 2D manifold (e.g., the surface of the Earth) is frequently not planar and *metadata* (data about the data) are kept of properties such as which projections used in mapping the data from the physical 3D space onto a flat *map*. Vector geometry data for geology might include features such as topographic levels represented as contour lines, along with natural and man-made features such as rivers, roads, forests, and dams.

Among the common formats of *geospatial vector data* is the Esri *shapefile*. Although Esri products are commercial, the format of the shapefile is broadly available, and many other commercial as well as free software tools are able to read and write them. There are other common formats as well, including the WKT/WKB formats (aka well-known text/binary). There are also web markup languages with vector geometry aimed as geospatial data representations such as Geography Markup Language (GML) and Keyhole Markup Language (KML).

47.2.8 BREADCRUMB TRAIL

AQ8 Collecting location data as a subject moves and performing a survey and collecting samples along a pathway or just capturing the path itself are examples of survey traverses. In many respects, a breadcrumb trail can be considered a form of vector geometry (aka *geospatial vector data*) where the attributes are the samples collected at points along the path. One additional attribute is that of *time*. The time attribute can then be used to determine rate of movement along the path.

Typically, a GPS system is used to capture and log the trail. An autonomous differential GPS can be used to achieve 1 m vertical resolution and 1 m horizontal resolution.

47.2.9 POINT CLOUD DATA

Point cloud data are a collection of specific locations in space (vertices) generally with additional information for each recorded point, such as intensity. Frequently, the point locations exist where there is solid or liquid matter. This is a consequence of the data typically being captured by scanning devices that report the location of surfaces struck by the scanning beam. A further consequence is that for scans of solid objects, the points will all be on the surface of that object and thus can be used to derive a geometric shape from the points.

Features of point clouds are that they are irregular, and not constrained to a 2D manifold as vector geometries typically are. Each point can be multivariate. That is, each point can have many attributes such as intensity, color, temperature, as well as categorical data such as *vegetation* or *road*. Point cloud data are most effective when they are rendered in great numbers.

A common method of capturing point cloud data is through LIDAR technology. A LIDAR scan consists of radially captured data as a laser mounted on a rotating platform with a spinning mirror sends and receives the light signal. The speeds of the mirror and platform rotation affect the resolution of the data collected. LIDAR scans easily capture millions to billions of point data in a single scan.

The LAS (American Society for Photogrammetry and Remote Sensing, 2013) format is an effort by the Imaging and Geospatial Information Society (IGIS) to try to facilitate a standard format for LIDAR data exchange between users.

47.3 GEOLOGY VISUALIZATION

Many sciences work with specific datasets collected simultaneously, or simulated as a group, the result of all being in the same coordinate space. This scenario is atypical for geologists, who

generally gather data in a variety of ways and at different times, resulting in data that can be difficult to correlate and thus properly visualize. The goal might be to model and characterize a reservoir of natural resources or to “determine the stratigraphy from a drill hole” (Fröhlich et al., 1999). In this section, we discuss the relationship of geological data to standard and specialized visualization techniques, leading up to techniques specific to immersive interface technologies.

47.3.1 RELEVANT ISSUES IN GEOLOGY VISUALIZATION

Geology has particular needs when it comes to visualizing data for analysis. This is not to imply that the techniques used to meet these needs are necessarily unique to geology, but there are particular issues of great importance to geologists, and there are particular visualization methods that address them better.

A major issue with geology analysis is: “where is that?” For example, an anomaly might be evident in the data, but determining where that anomaly is in the physical world (*in the field*) can be difficult. Also, geologists and particularly geophysicists work with physical phenomena that occur hidden from view—under the surface of the earth—and thus are more difficult to measure and more difficult to *see*. The limited ability to take subsurface measurements also leads to irregular collections of data—not only spaced irregularly, but data with holes in it, and collected at varying times.

Perhaps the most significant issue is registering data collected by different technologies, at different times, and from different locations such that comparisons of attributes can be made with datasets aligned to one another. Bringing multiple geology datasets such as mineral content, water content, and magnetism together is an important means for comparing datasets in search of features linked between them. Also, the differing frames of reference will often be mapped into Cartesian space using different mathematical projections. Thus, the data must be reprojected into a common projection as well as translated/scaled/rotated to be coregistered. We can take this one step further and align them to a standard earth-based frame of reference, which is referred to as *georeferencing* the data.

47.3.2 APPLYING STANDARD VISUALIZATION TECHNIQUES TO GEOLOGY

The sciences share many attributes, such as the use of mathematics to explain (and predict) observed phenomena. Thus, it is not surprising that there are many *standard* scientific visualization techniques that work well for analyzing and explaining geological data.

A common technique for geology is the use of height-field maps (or warping) whereby a 3D surface is created from scalar values used to displace an otherwise flat plane proportionate to the data field. The displacement is performed orthogonal to the plane in either positive or negative directions. The most intuitive use of this is to map terrain-height data to height mapping, but any 2D scalar field can be represented this way in order to quickly identify peaks, valleys, and gradients. Another 2D technique used with scalar values is to apply a mapping from data into colors. In some cases, the colors may come from actual photographic capture and represent the physical appearance of the terrain. This need not be the case of course, and mapping an arbitrary selection of colors onto a representation is thus referred to as *pseudocoloring*. Further, a 2D coloring of one data field can be draped over a 2D height-mapped field of another dataset, allowing the researcher to more easily compare the relationship between the two values.

For 3D scalar fields, such as those created through tomographic techniques or building up a volume from 1D signals such as GPR, there are three common visualization techniques: isosurfaces, volume rendering, and slices.

Isosurfaces are an extension of the isocontour line technique that produces a surface within a 3D volume over which all the values are constant. As with contour lines, there may be many disjoint surfaces of the given value. Also, multiple values can be selected to show more of the internal structure of the data, as is done with terrain contour lines. Isosurfaces can be used to show boundaries between subsurface layers or perhaps to show the shape of a subsurface reservoir.

Volume rendering is an alternative 3D visualization technique that can be used to see multiple features within a volume. As opposed to isosurfaces, where the 3D data are converted into solid structures within the volume, volume rendering treats the data as a nebulous cloud. The view through the *cloud* contains colors based on the values along the line of sight. Colors as well as opacities are mapped onto specific data values. This is referred to as the *transfer function*. Through the use of partial opaqueness (i.e., partial transparency), particular values within the data can be highlighted to differing degrees, which thus lead to the nebulous-style rendering.

Reducing the volume to specific *slices* through it is another way to peer into a 3D volume. A common visualization method is to slice through one of the cardinal planes (i.e., orthogonal to one of the primary axes). A slightly more complex algorithm can be used to slice through the data at any angle. In either case, in interactive visualizations, the user is generally given the opportunity to move the slice around, giving a better perception of the entire dataset. A method more specific to geology visualization is to take a slice along a traverse (see Section 47.3.3).

Point cloud data can be converted into geometric shapes with techniques such as *alpha shape and Delaunay triangulation* (Edelsbrunner & Mucke, 1994). But with modern hardware rendering capabilities, a more common method has become to simply render all, or a large subset of, the points themselves. Each point may be colored by any of the associated multivariate data (actual color, time of flight, classification, etc.).

The coloring technique discussed earlier with the 2D visualization techniques can equally be applied to 1D and 3D scalar fields as well. The choice of how to map values into colors is a very important one, though all too often, a default *rainbow* color mapping is used. Poor choice on *color mapping* can disguise important features or create the appearance of an interesting phenomenon that doesn't exist (Rogowitz & Trenish, 1998).

The representation of vector data such as from flow or gradient fields can be done in a handful of ways, affected by whether the field is in steady state or changes over time. A common and easy to comprehend flow field representation is *moving particles* that are released from strategic locations and advected through the field. *Streamlines* and *streaklines* represent the paths that particles follow over time or paths of particles that are infinitely fast. *Line interval convolution* (LIC) is a technique that shows the entirety of a steady-state flow field by warping a white noise texture. The LIC technique works best as a 2D technique (perhaps on a 2D slice through a 3D field), whereas the other techniques work equally well for 3D data.

AQ9

47.3.3 VISUALIZATION TECHNIQUES FOR GEOLOGY

The nature of geological phenomenon taking place below the planet's surface (though sometimes made visible through geologic or human activity) is primarily reflected by means of data collection and then subsequently how to link subsurface visualizations to recognizable surface landmarks.

Given that some features of a planet's geology are reflected in the topography of the surface, an early visualization technique was the use of *isocontour lines* drawn at regular intervals to give both a quantitative measure of the height of the terrain as well as a qualitative view of the gradient of the surface. This was also extended to be an early use of stereoscopic data analysis through the creation of stereo-pair topographic contour maps (Blee, 1940; Gay, 1971) and before that aerial photography (Bagley, 1917; MacLeod, 1919). (Although the use of stereo to view terrain features has since become commonplace, the use of standard [*flat*] *topographic contour and terrain maps* remains prevalent.)

The *vector geometry objects with attribute* data discussed in Section 47.2.7 also lead to specific visualization techniques that can be thought of as cartographic in nature. Different polygonal *shape* regions might be colored differently based on vegetation, land use, or geologic era.

The nature of well log or GPR data (at least when looking at a single transmission and return) maps easily into representations of the data as a signal similar in nature to the recording of a single seismic trace—a *1D needle vibration movement plotted over time*. Of course, for well log or GPR

data, the data are sensory responses plotted over depth. The 3D nature of the measured object begins to become apparent through multiple plots of well logs or GPR recordings.

Fence diagrams, which are 2D data slices taken along a surface traverse, are a geological visualization technique that is used to view subsurface data that cuts across an important terrain feature. As mentioned earlier in Section 47.3.2, fence diagrams are similar to some standard *slice* visualization techniques used in other fields of research. Because we know that data on either side of the slice will generally be similar to the slice itself, it allows the researcher to make overall conclusions regarding the neighboring geologic material.

Techniques that *cut away* part of the solid representation of the planet's surface are clearly very important when working with data measured from beneath the terrain surface. Similar to how some medical visualizations might show an otherwise complete external view of a person, with certain layers of skin, muscle, etc., removed to show the internal organs in a particular location, the same can be done for the Earth or other celestial body. We can strip away the topsoil to see what's beneath. Often the edges of the *hole* created by the cutaway will themselves show subsurface data, using the slice techniques described earlier. Then internally, techniques such as isosurfaces or volume rendering might show reservoir formations or mineral content.

47.3.4 TEMPORAL DATA

While it's easy to jump to the conclusion that the time scale of geologic processes limits the need for datasets involving more than a single time step, this is of course not the case. For starters, there are geologic events that happen in human-scale time: active volcanic activity, earthquake shifts, landslides, as well as slower erosive activities to name four. Furthermore, there are unbounded areas in which geologic processes might be computationally simulated, allowing for the prediction of how land masses, etc., change in much larger time scales. Small simulations might have hundreds of time steps, and given sufficient compute resources, thousands or more time steps might be produced.

We think of *time-lapse* movies as ones where slowly changing phenomena are brought to life through long-interval photography presented back in rapid succession. In this way, we can more easily see behavior and flow that was difficult to perceive at real time. Likewise, geologic and other scientific data can be collected over time with large time intervals between collections, and these data can be viewed in rapid presentation. Two areas where this is more common in the geologic sciences are in *time-lapse seismic survey data* and multiple LIDAR captures used for detecting and measuring changes such as before and after earthquakes and landslides. The application in the case study in Section 47.4.2 (*LidarViewer*) is frequently used with just this type of data.

But in geology, even static data represent change over time. Deposited sediments built up over long periods of time forming underground rock layers and other phenomena. Working through the layers, geologists draw conclusions, which then allow the creation of temporal models of geological activity. One such example is highlighted in the case study in Section 47.4.4 where the changes in sand dunes are analyzed through an application with an immersive interface and tools that specifically make use of the 6-DOF inputs afforded by that interface. Similarly, archaeologists generally correlate the depth in which an artifact is found with increase in age as exemplified in Section 47.4.3.

AQ10

47.3.5 BENEFITS TO GEOLOGIC VISUALIZATION FROM THE IMMERSIVE INTERFACE

There are both general and specific ways in which immersive technologies can benefit the visualization of scientific data. Some of the general benefits derive merely from the accidental properties of a general immersive system: substantial compute power and display size and resolution, whereas the benefit of perspective rendering is specifically part of the nature of immersive systems.

Perspective rendering is what makes immersive systems (virtual reality [VR]) unique. It is the means by which, when an immersed viewer moves their head, the world responds as though it were

actually there before them. This feature provides improved perception of the relationship between objects based on that ability of moving one's head to see the world from a new perspective.

Most immersive display systems have a larger *field of regard* than a typical desktop or laptop display. The field of regard is a measure of how many directions you can look to see the virtual world. Larger screens, multiple screens, and screens that follow you are typical ways of increasing the field. Increased field of regard benefits visualization tools by providing more real estate to place the data. Geologically scaled simulations can often generate large datasets, and having the ability to put as much data in *space* as possible can be helpful. Related to that, when focused on a particular phenomenon, it can be helpful to see it in its larger context. The large screen *space* allows for the larger context while placing important details in front and center, especially for higher-resolution systems. On the other hand, when surrounding the user with data, it can become difficult for them to find the user interface. Some systems therefore allow the user to control the placement of the interface, as with the LidarViewer application in Section 47.4.2. Another solution is to use an interface that is always front and center when summoned, such as the radial menu discussed in Section 47.4.1.

The other *accidental* benefit of using immersive systems is the increased computation and rendering capabilities that are often included as part of the integrated solution. Thus, more data can be held in memory, processed, and rendered than with a typical laptop or desktop computer.

There are a myriad of specific user interface features that can be added to an immersive application. At this point, there has been only minimal coalescence around common user interface techniques or libraries. This stew of interfaces is not necessarily a good thing in the long run, but as the still quite nascent technology evolves, this flexibility provides opportunities for new and quite useful innovations. Some of these innovative user interfaces are discussed in the case studies of Section 47.4. In Section 47.4.1, the use of *3D magic lenses* is demonstrated as a means to correlate information from differing but spatially overlapping datasets. In Section 47.4.2, a handheld *painting* operation is provided in order to quickly, yet specifically, select points that belong to a particular grouping. In Section 47.4.4, a *virtual Brunton compass* was created to mimic the utility of the real article but applied within the virtual world.

47.4 EXEMPLAR APPLICATIONS AND LESSONS LEARNED

As immersive technologies began maturing in the late 1990s, opportunities for visualization researchers to work with geologists began to materialize. Two good examples were reported at the 1999 conference on visualization hosted by the IEEE (Institute of Electrical and Electronics Engineers). These examples include work by Fröhlich et al. (1999), which provided a unique interface for geologists to view seismic volumes, and well logs using isosurface, and slice-plane techniques controlled by a newly created 6-DOF input device dubbed the Cube-Mouse. The other related project from the 1999 visualization conference is by Winkler, Bosquet, Cavin, and Paul (1999) where they extended an existing geoscience visualization program to work in an immersive display system. Experimentation continued in the first decade of the new millennium as exemplified by a borehole drilling planning application (Dorn, Touyinhthiphonexay, Bradley, & Jamieson, 2001), as well as the use of GPR to construct an underground ant colony network based on the boundary between soil and air under the surface (LaFayette, Parke, Pierce, Nakamura, & Simpson, 2008).

In the subsections that follow, we will take a quick look at four applications that make use of immersive technologies to assist in the process of gaining insight into data above and below the planetary surface. These applications were written in collaboration with research geologists who were seeking better ways to understand their data. In general, we'll give a little background information, discuss the visualization techniques used, present the specific ways immersive technologies were used, and discuss some of the benefits and other outcomes of the project.

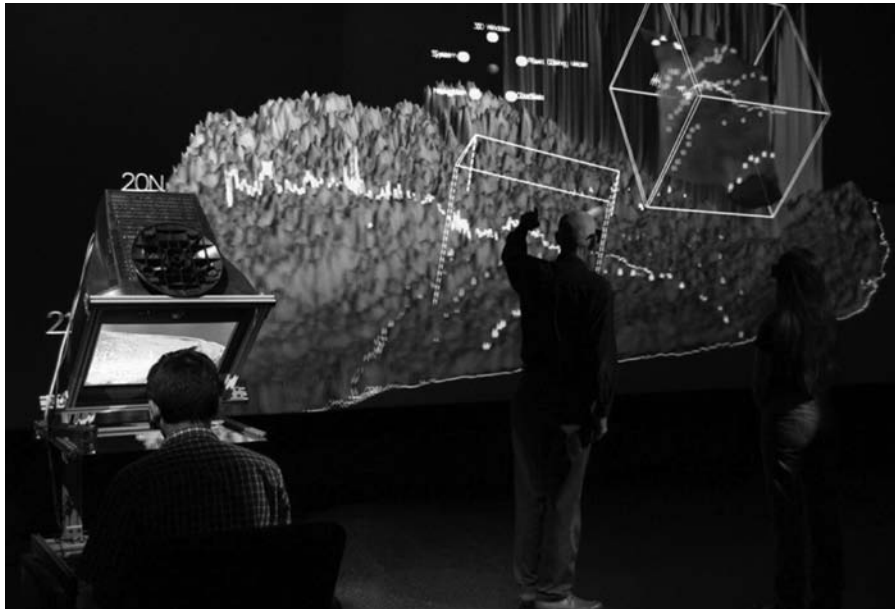


FIGURE 47.7 Users viewing Chicxulub crater data. Two displays are shown: a large projection display at the Louisiana Immersive Technologies Enterprise (LITE) and a *fishtank* display (left) that allows a user to reach into a 3D volume with a haptic stylus under a mirror. The two systems were networked for a demonstration at the Gulf Coast Association of Geological Societies (GCAGS) 2006 geology convention. Two movable boxes are visible in the main display: one selects a source region of the main mesh, and the other shows a secondary dataset from that source region. A radial menu can be seen near the top center. Annotative marks of various colors appear, arranged along concentric arcs near the standing users.

47.4.1 APPLICATIONS FOR EXPLORATION OF TERRAINS, ASSOCIATED GEOPHYSICAL DATA, AND WELL LOGS AT THE UNIVERSITY OF LOUISIANA AT LAFAYETTE

Borst and Kinsland applied VR environments to explore geoscience datasets including (1) a collection of 3D datasets over the Chicxulub impact crater—for example, Borst and Kinsland (2005); (2) data for insight into water drainage in the Lafayette, Louisiana region (Kinsland, Borst, Best, & Baiyya, 2007); and (3) well log data from the North Louisiana Coalbed Methane database—for example, Kinsland, Borst, Tiesel, and Bishop (2008). They visualized these datasets in HMDs, single-wall stereoscopic projection displays with tracked viewpoint, a CAVE-like display, a *reach-in*-style *fishtank* display (a desktop display that provides a haptic stylus tool in a fishtank-sized display volume), and a low-cost 3DTV-based environment. The systems have been used both for geological investigations by Kinsland and colleagues as well as for educational purposes in geology classes (see Figure 47.7).

47.4.1.1 Rendering and Interaction for Terrain Interpretation

AQ11

Graphical rendering and display of these datasets for VR was relatively simple compared to supporting user interaction. Early versions of the systems achieved real-time rendering with mesh tiling and culling, careful use of graphics card features, and reduced-resolution meshes textured with colors and shading from higher-resolution versions. Toolkits such as OpenSceneGraph (Wang & Qian, 2010) and VR Juggler (Bierbaum et al., 2001) provided common graphics operations and access to standard VR devices in a portable manner (with extensions necessary for the fishtank devices). Toolkits for 3D interaction and 3D interaction techniques, in general, are less developed, leading to trade-offs between interface quality and development time. For general system control,

a menu toolkit was developed as a compromise between naïve interfaces (e.g., functions mapped to many buttons) and specialized 3D interaction techniques (e.g., direct or widget-based manipulation of objects). User studies of the ray-based menu interaction support the use of large radial layouts, contextual location of menus at objects of interest, and automatic scaling for constant projected size (Das & Borst, 2010a, 2010b). Contextual location can cause menu placement behind other objects, so the menus were rendered in a way that reveals them through occluding objects, with reduced intensity.

The ability to directly move through the data with natural navigation techniques is of prime importance for data exploration. Kinsland notes a personal affinity for navigation with natural movement (head motion and walking) in HMD and CAVE displays. This is augmented with wand-based flying, *grab the world*, and scaling interactions to provide a greater range of movement. Unconstrained navigation can lead to uncomfortable views, especially when objects are too close to the viewer, where stereoscopic images are difficult to fuse. Thus, when the user wants to see a location on the terrain in more detail, it can be better to scale up the scene about the point of interest than to fly closer. The difference is not always clear to, or adequately controlled by, users—especially those not accustomed to stereoscopic viewing. In single-sided displays, ranging from small-scale fishtank displays to larger projection walls, good distance and dataset orientation can be maintained with *center of workspace*-style constraints (Ware et al., 2001). In Borst and Kinsland's systems, this is achieved in part by a constrained grab where translations are constrained to lateral sliding in a workspace-centered dataset-aligned coordinate frame and rotations are constrained to fit an azimuth elevation model for the centered frame.

With a good navigational scheme in place, the next feature of importance is the ability to place and adjust annotative markers. In the impact crater and LIDAR terrain systems, users place and edit markers on surfaces to annotate interesting features. The approach varied depending on display type. In a single-wall display, the marking and editing usually involved ray-based pointing at targets. In earlier CAVE and HMD implementations, users moved their hand (wand) directly over targets to drop markers in place. The ray-based manipulation requires less navigation, as the user can be further from the target, but it is less precise at a given dataset scale due to fundamental problems of the imprecision of long-range ray pointing. In the fishtank display configuration, annotations can be more sophisticated and precisely placed: its pen-like tool has stable mechanical tracking and can be used to draw directly on datasets. The pen also supports force feedback that allows users to feel virtual surfaces. It was shown that the force feedback improves performance of users tracing paths on terrains, particularly when paths follow terrain features rather than cross over bumps (Raghupathy & Borst, 2012). Researchers previously suggested various ways for force feedback to aid interaction in geoscience-type applications—for example, Harding, Kakadiaris, Casey, and Loftin (2002) and Komerska and Ware (2004). For example, force cues could support point or terrain editing, menu selection, and interactive 3D *widgets*. Others have discussed various benefits of fishtank configurations over fully immersive displays (Demiralp, Jackson, Karelitz, Zhang, & Laidlaw, 2006; Mulder & Boschker, 2004). They have relatively low-cost and space requirements, high angular resolution, and (for the *reach-in* approach) a focal plane suited to hand-based interactions with visualized objects.

47.4.1.2 Well Log Visualization

In the well log visualization system, users view vertical plots of resistivity and spontaneous potential (SP) under a terrain and can select a plot or well to move markers along its axis. All or any subset of the well logs may be displayed simultaneously. Their vertical scale is adjustable so that the user might investigate the signatures of the individual logs or of a selection of logs at various scales to highlight features. Correlation markers that were determined for each well in a separate 2D system are also displayed in this system.

This system, as it is, serves to convey 3D relationships of the wells in a way that pseudo-3D renderings may not. When inside the data, a geologist feels more as if they are viewing and interpreting

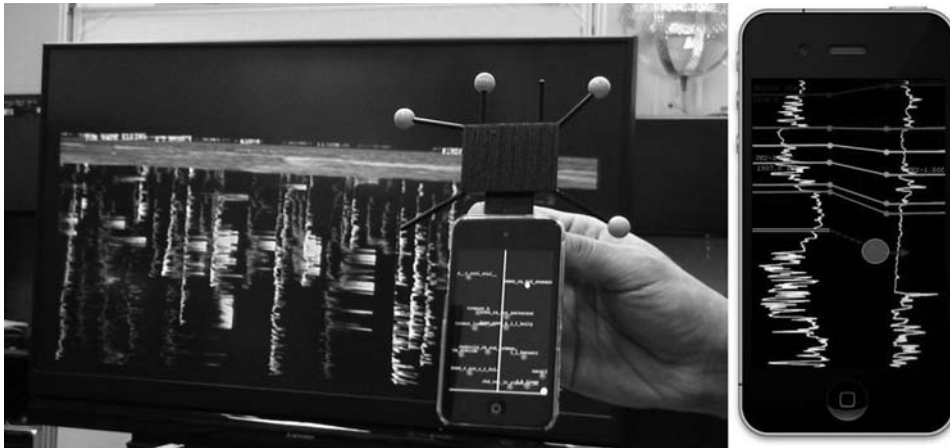


FIGURE 47.8 Low-cost well log visualization system (Mitsubishi 3D DLP TV and iPod Touch with markers for OptiTrack camera-based tracking) showing well logs (curves) hanging underneath a terrain generated from SRTM data. The iPod Touch presents an overview of the well log scene that resolves occlusion in the main view and supports rapid touch-based selection. A middle vertical line represents a virtual ray in the main view, which is locked during a selection step after coarse ray pointing. Right: (Constructed conceptual illustration) Well log *picks* illustrated as horizontal lines with associated depth and text annotation. A highlighted pick on the left log is being associated with a pick on the right log by a drag gesture.

from within the earth. If many well logs are visible simultaneously at various depths, the stereoscopic visuals may help disambiguate overlapping plots. Being able to overview multiple well logs can be helpful for determining subsurface structures, lithologies, fluid contents, faults, etc., based on plot features across well logs. In the future, segments of multiple wells could be selected, moved, and scaled for comparison (correlation). Correlation points marked on multiple wells could influence a computer-generated 3D surface or volume interpolated/extrapolated throughout the dataset to aid further investigation (this type of interpreter/computer interaction is common in packages that aid interpretation of seismic data volumes). VR would help preserve, correct, and maintain constant visibility between geospatial relationships of features, reducing mental transformations between 2D physical images and 3D mental images.

To get an overview of underground features, a user can view many plots at once. This presents a problem for ray-based selection when desired targets are partially or fully occluded by other plots. To aid this selection, the researchers developed *Handymap*, which uses thumb motion on the touch surface of a tracked iPod Touch to allow more precise targeting and selection depth control (Prachyabrued, Ducrest, & Borst, 2011). This approach is additionally motivated by its benefits for low-cost VR environments with reduced tracking accuracy: it does not require very precise or stable tracking (Figure 47.8). The touch surface could additionally be useful for tasks such as menu selection or symbolic input (text entry).

47.4.1.3 3D Lens Immersive Interface Technique

While developing the systems described earlier, Borst and Kinsland explored 3D lens-based techniques for managing multiple dataset views and filtering options in VR systems for interpreting geoscience data. In 2D desktop interfaces, windowing systems are a well-established standard for organizing multiple views, for example, showing a dataset in multiple views or with multiple visualization options, multiple related or colocated datasets, collaborative views that communicate information from remote collaborators during networked operation, or multiple temporal views (different time points or animated views). This motivated various researchers to incorporate related mechanisms into 3D interfaces. Plumlee and Ware (2006) explained how such windowing can reduce

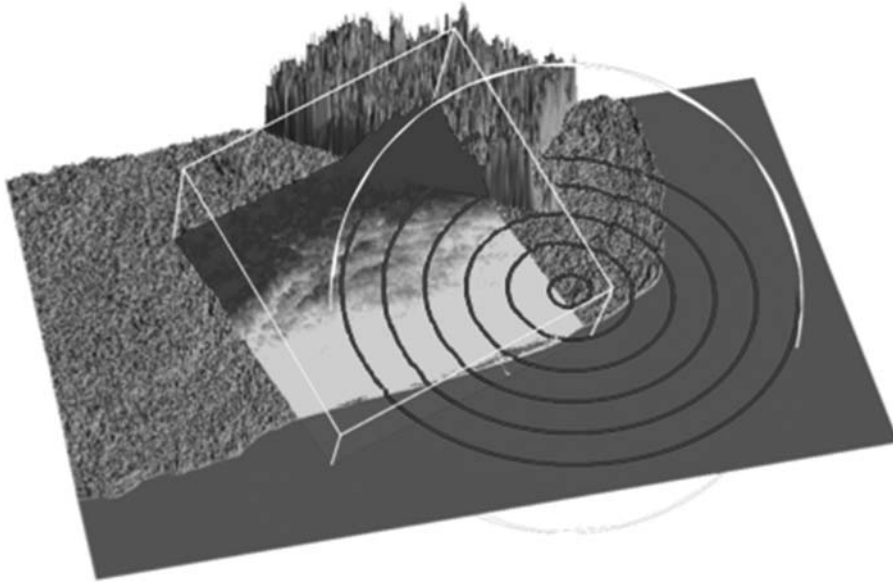


FIGURE 47.9 Two lenses apply effects in constrained regions on a terrain. A box-shaped lens applies a colormap, and a distance tool lens adds concentric contours about its center. For clarity, the lenses are large and the main view is zoomed out.

errors related to visual working memory limits when compared to alternative navigation techniques such as zooming.

Some basic approaches to windowing in stereoscopic 3D environments include placing 2D-style windows into 3D spaces—for example, *Task Gallery* (Robertson, et al., 2000)—or using portal-like windows into other 3D scenes or views as with the *SEAMS* project (Schmalstieg & Schaufler, 1999) or tunnel windows (Kiyokawa & Takemura, 2005). Another approach is Itoh et al.'s *3D WorldBottles*, which are containers for separate scenes that are each drawn on their container surface (Itoh, Ohigashi, & Tanaka, 2006). *WorldBottles* supports operations such as transporting objects between bottles and transporting users into bottles.

In contrast, Borst and Kinsland extended rendering methods and application of volumetric (3D) lenses, originally introduced by Viega, Conway, Williams, and Pausch (1996) as a 3D version of 2D lens techniques (Bier, Stone, Fishkin, Buxton, & Baudel, 1994; Perlin & Fox, 1993). Described simply, these 3D lenses are boxes containing 3D objects different from the main scene rendering. A *lens* effect is apparent when the chosen content appears to modify the surrounding main view, for example, when the lens contains a version of the main dataset with a different colormap applied (Figure 47.9). The most recent rendering techniques for such lenses in 3D include mechanisms for composing effects when multiple lenses intersect, for example, combining a colormap with a magnifying effect. A comparison of lens rendering techniques is given in Borst, Tiesel, and Best (2010).

In addition to lens-type effects, 3D lenses can be used more generally as containers for secondary datasets or views, leading Borst et al. to use the term *volumetric windows* (Borst, Baiyya, Best, & Kinsland, 2007). A similar term, *volume windows*, was previously used to refer to a 3D windowing system proposed for holographic displays (Kurtenbach, Fitzmaurice, & Balakrishnan, 2002). Volumetric lenses can also be used to *cut out* portions of environments, resembling clipping volumes—for example, Weiskopf, Engle, and Ertl (2003). Lenses configured to contain miniaturized versions of a 3D environment resemble world-in-miniature techniques (Stoakley, Conway, & Pausch, 1995).

Compared to other secondary view techniques, volumetric lenses may better preserve viewing and interaction for 3D environments. Stereoscopic and motion parallax effects are present, unlike

for 2D-in-3D windows. Compared to portals or flat lenses in 3D, a volumetric lens view can be more stable because the same dataset region is affected by (contained in) the lens regardless of view-point. Raghupathy and Borst (2011) explained that this simplifies placement of secondary views in a terrain-marking application. They demonstrated performance and subjective improvements with a box view compared to portal- or mirror-type views in a small-scale VR environment for drawing on terrains. Their evaluation also underscores the importance of direct interaction in secondary views: users should be able to annotate visualized features directly in secondary views rather than use them only as a visual guide while annotating in a main view.

Borst and Kinsland initially applied 3D lenses to deal with multiple datasets over a single region. Kinsland's geology research task was to mark extrema and ridges (e.g., low points from limestone sinkholes) on a terrain and check for corresponding features in a gravity data surface. Interpretive marks placed on one dataset were projected to the other to help check consistency of features. Prior to incorporating multiple views, much time was spent switching between datasets, manipulating viewpoints, and toggling filtering options. For example, to examine minima, Kinsland applied large-magnitude negative scale or flipped a mesh upside down to view the bottom. Long and repeated sequences of such manipulations occurred as Kinsland sought the best marker placement. A lens system was added that allowed users to *see through* one dataset to another with a lens, grab and move copies of dataset regions in boxes to arrange multiple views in the scene, change filtering and view options in lenses individually, and reach into any of the lenses to place or adjust annotative marks. Based on informal observations, there was some time spent setting up the lens views, but during consistency checking, this subsequently reduced the switching and manipulation of datasets. The ability to fine-tune annotative marks was enhanced because the user could immediately reach into any of multiple views to adjust markers. Kinsland notes that *seeing through* one mesh to another in a movable lens supports comparison between datasets with little overall distraction or focus shift: the lens box can be moved back and forth while the user remains focused on the area of interest and the surrounding context is largely preserved.

Other tasks handled by windows of conventional 2D visualization systems may be addressed in 3D by 3D lens systems. For example, 3D lenses may be useful for communicating a remote collaborator's filtering options or view of a dataset. However, differences between local and remote viewing geometry in head-tracked immersive visualization make it difficult to replicate a remote user's view precisely while still providing stereoscopic viewing and perspective appropriate to the local viewer. Recently, Borst et al. have rendered *time warp* lenses that navigate time-varying datasets by allowing a user to select time, relative time offset, or animated playback inside of constrained regions selected by lens volumes (Borst, Tiesel, Habib, & Das, 2011) (Figure 47.10). Future work can improve 3D lens and window systems with better interaction and arrangement techniques and integration into scene graph tools.

47.4.2 LIDARVIEWER: AN IMMERSIVE POINT CLOUD VISUALIZATION TOOL

The *LidarViewer* application (Kreylos, Bawden, & Kellogg, 2008) is a LIDAR data visualization tool that runs on a wide range of hardware platforms supported by the Vrui VR integration library (Kreylos, 2008). *LidarViewer* depends on the Vrui VR integration toolkit for its immersive functionality support, which integrates display configuration with 3D interaction devices. When properly configured, the Vrui toolkit layer allows the *LidarViewer* application to provide the same functionality on either a desktop platform or VR platform (CAVE-style or head-based display) (Figure 47.11).

LidarViewer was developed under the auspices of the KeckCAVES lab at the University of California, Davis, Department of Geology. Not surprisingly, the KeckCAVES lab is dedicated to the visualization and analysis of geologic data through the use of immersive interfaces and other advanced techniques. The lab serves clients within the UC Davis Department of Geology and from other organizations such as the USGS.



FIGURE 47.10 A user in a projection environment uses ray-based interaction to set up a relative time warp lens. The color in this particular lens indicates increased rainfall 6 h beyond the context.



FIGURE 47.11 Data from an airborne LIDAR scan capturing the path of a powerline grid are presented using LidarViewer in a CAVE display.

47.4.2.1 Visualization Techniques

LIDAR capture devices generate a large set of points—a *point cloud*—with the 3D location of the optical signal return along with other data such as intensity and time of flight. Often, color data are captured through a secondary sensor and assigned as an attribute to a location data point. LidarViewer then presents these point clouds using an optimized rendering technique that builds an octree structure from the dataset bringing points into the scene as needed to present the full resolution within the nearby field of view (Figure 47.12).

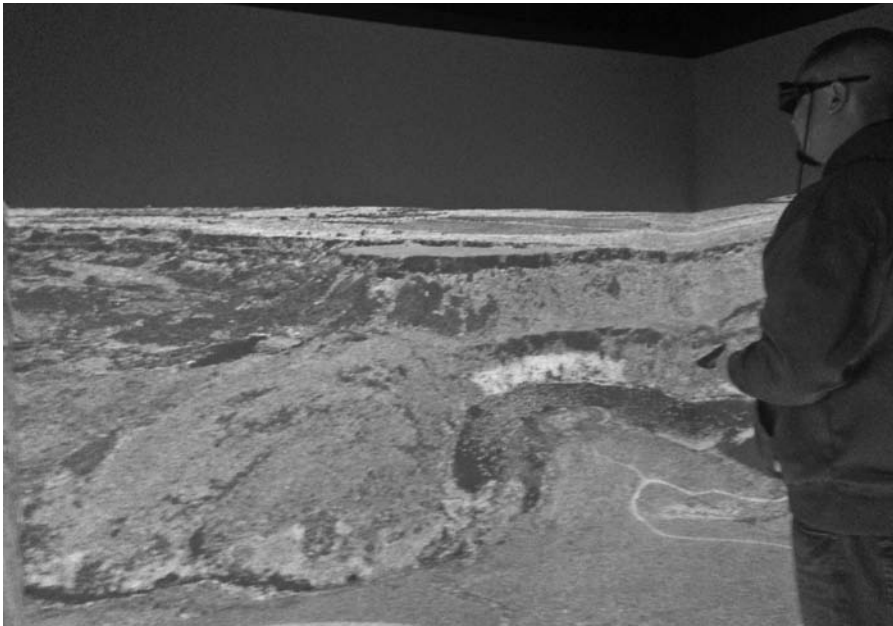


FIGURE 47.12 Using LidarViewer in a CAVE system to view changes in terrain from natural events, seasonal changes, and human activity. Airborne LIDAR scans from two time frames are represented, with points from the initial scan in red and points from the subsequent scan in green.

AQ12

With the data loaded and visible in the 3D immersive environment, the user can select a subset of data points, determine the distance between points or planes, as well as perform real-time 3D navigation through the dataset. These data interaction and visualization techniques provide the user with a true immersive experience. The user visualizes the data as though actually present in the location where the data were collected, thereby providing the user with insight into their data not otherwise possible.

In preparation for using the immersive data visualization tool, LidarViewer provides a pair of data conversion and preprocessing utilities. The *LidarPreprocessor* utility comes with dozens of optional directives and converts a standard LIDAR data format into a binary format suitable for the octree rendering algorithm. Data processed into LidarViewer format can be further enhanced with the *LidarIlluminator* utility. The primary enhancement performed by LidarIlluminator is the calculation of normals for each of the points in the cloud. The *normal* data can then be used by the LidarViewer rendering algorithm to produce improved lighting effects.

Menus within LidarViewer enable the user to control shading and other rendering options. Shading options include rendering points at their given intensity level, using any RGB values that may have been assigned to the points or a pseudo sun reflection model that makes it easier to see surface features such as roughness. Points can also be colored based on their distance above an assigned *ground* plane. Additionally, the number and size of the points can be controlled in order to balance between rendering quality and rendering speed.

47.4.2.2 Immersive Interface Techniques

Written with the Vrui VR library, LidarViewer inherits several standard Vrui interaction modes, including a built-in menuing system, which includes a choice of methods for navigating through the world. The Vrui menus and widgets are designed to work reasonably well in configurations ranging from a desktop workstation up to large-scale CAVE immersive systems. LidarViewer uses the menu system to bring up dialog controls for shading and other effects, but LidarViewer also has interaction specific tools that make use of the immersive interface.

A key feature of LidarViewer is the ability to select points using 3D painting and selection gestures. All points within a certain region of the handheld controller are highlighted as they are added to the selected group of points. The size of the selection region can be adjusted through a menu dialog. It is also possible to remove points from the selection as desired. Once an acceptable set of points have been selected, a mathematical description of the points can be calculated. The description is based on a set of simple primitive shapes such as a plane, a sphere, or a cylinder. The mathematical description can then be used to make measurements or other annotations within the data.

47.4.2.3 Idaho National Laboratory LidarViewer Workflow

As an open-source project, LidarViewer is also used at other immersive visualization centers. One such group is the Center for Advanced Energy Studies (CAES) in Idaho Falls, Idaho, who have successfully used LIDAR data and immersive environments to better understand and quantify geological change. One successful method involves overlaying georeferenced LIDAR datasets acquired at different times, coloring the time-series point clouds to highlight changes over time.

The LidarViewer application creates a dramatic immersive scene allowing viewers to gain insights for a variety of geologic and natural resources including the following:

1. Land mass change due to natural earth movement such as landslides, earthquakes, erosion, or similar changes (Glenn, Streutker, Chadwick, Thackray, & Dorsch, 2006)
2. Mechanical man-induced changes such as excavation, construction, or road building
3. Seasonal vegetation changes such as those experienced in agriculture and wildland fire
4. Short- and long-term changes in vegetation canopy of a given forest or rangeland due to natural growth, fire, beetle infestation, or forestry operations
5. Changes in water levels such as lakes, ponds, rivers, or snowfields

These changes have been observed in time-series datasets from airborne LIDAR, as well as terrestrial laser scanning (TLS) data. These datasets can also be fused to provide both high-resolution (mm to cm) point clouds (from the TLS), coupled with the large geographic extents (from airborne LIDAR) (Murgoitio, Shrestha, Glenn, & Spaete, 2013). Additionally, LIDAR datasets can be fused with high-resolution digital imagery, including hyperspectral data to provide both true and false-color perspectives of the point cloud (Moore et al., 2011; Olsoy et al., 2012). The unique capability of immersive environments to view this 3D point cloud data in its native 3D format makes this representation very intuitive for exploring, understanding, and quantifying change (Figure 47.13).

AQ13

The capability of demonstrating time variance using traditional geographically oriented LIDAR datasets leads to an exciting extension of this technology in the change detection of buildings, infrastructure, bridges, and other important features. The ability of LIDAR to capture highly accurate data regarding current state and then capture feature evolution through subsequent scans opens the door to a whole new world of very important historical preservation activities. The CAES has acquired a very-high-fidelity scan of the nearby Experimental Breeder Reactor No. 1 National Historical Landmark. The first scan will serve as the baseline, while subsequent scans will be studied for change detection activities.

Researchers affiliated with CAES have successfully combined LIDAR data from airborne sensors with terrestrial-based sensors, thereby creating an impressive multiresolution representation of a forest. The air-based scans give the overall perspective and orient the viewer to the surrounding area, while the ground-based scan provides a unique view of details in areas where details are required.

47.4.2.4 Outcomes and Lessons

The experience at Idaho National Laboratory and Idaho State University is just one site that makes use of the LidarViewer application to interact with point cloud data. Researchers at KeckCAVES



FIGURE 47.13 A user explores a wooded area captured by high-resolution LIDAR scans presented in a CAVE with LidarViewer.

and the USGS have analyzed and measured phenomenon such as the shift caused by earthquake activity or the movement of structures whose foundations have been compromised by landslide activity.

In the case of earthquake analysis, a site along the San Andreas Fault for which LIDAR scans had been taken both before and after a large earthquake allowed scientists to calculate before and after measurements of various surface features (Gold, Cowgill, Kreylos, & Gold, 2012). In the landslide usage case, a house with much of the foundation washed away was measured from the same location on a daily basis, and by determining the mathematical description of the near wall, the movement of the house could be determined to millimeter accuracy (Kreylos et al., 2006).

The ability to visit, or revisit, sites of interest in and of itself is a great benefit to the geologist whose *laboratory* can be anywhere on the planet, including sites that can be expensive and otherwise impractical to visit on a recurring basis. Thus, the ability to virtually visit these sites with considerable detail is a great boon. And while measurements can be directly obtained while in the field, the ability to take them in the immersive environment is far easier (given that it's possible to fly or rescale the world) and also can be more accurate through the assistance of basing measurements on a large collection of points. Consequently, LidarViewer is not just for revisiting geological and other sites, but can be better than those visits by allowing the visitor to take more measurements, explore the site faster, and leave behind annotations of intriguing discoveries.

47.4.3 VISUALIZATION OF MULTIMODAL GEOPHYSICAL SURVEY DATA

Recognizing that geophysical exploration produces large amounts of data, generated by a variety of acquisition devices, a team of archaeologists and computer scientists at the California Institute for Telecommunications and Information Technology (CALIT2) created a project to fuse aerial and satellite imagery and elevation; infrared, magnetic, and EM surface data; GPR; photographs of artifacts and man-made structures; and a database with information about found artifacts (such as 3D location, type, radiocarbon dates, and pictures; Lin et al., 2011). Some of the acquired data were further

processed into derived data products: extensive image sets of 3D structures on the ground have been processed with a structure-from-motion (SfM) algorithm (University of Washington's Bundler; Snavely, Seitz, & Szeliski, 2006) to derive a colored 3D point cloud of the structure, and 3D models were created manually for structures that no longer exist but are assumed to have existed in the past.

Archaeologists can often verify their hypotheses by digging up what they believe to be buried somewhere. This principle does not hold for CALIT2's archaeologists working in Mongolia to find Genghis Khan's tomb and other historical sites, because the Mongolian government does not allow them to excavate. This means that they have to rely entirely on what is readily accessible from the surface and data that can be acquired about subsurface objects.

The StarCAVE (DeFanti et al., 2009) at CALIT2 is a 34-megapixel immersive VR system and a unique tool for archaeologists, because it allows them to not only visit a site of interest on another continent without traveling to it but also to show all the available data about the site in its geospatially correct locations. The goal of this effort is to explore the use of the StarCAVE to enable noninvasive *virtual excavation* through the 3D VR reconstruction of geophysical survey data of an archaeological site that has been investigated since July 2010 as a component of the Valley of the Khans project, a noninvasive remote sensing survey for burial sites in Northern Mongolia.

For the archaeologists, working with this VR tool gives them the unique ability to view not only a spatially correct visualization of their data but also one that fuses all the data types they generate. This is because no off-the-shelf tools exist that solve this problem for them. Understanding spatial correlations between the multitude of data types the archaeologists collect is key to making new discoveries.

There are no off-the-shelf solutions for VR systems, which can display all of the data types this system supports. AEGIS Easy 3D (Aegis Instruments, 2013) supports GPR data but does not run in a CAVE. Existing GPR visualization software for VR, such as Billen et al. (2008), does not allow point visualization with the data points following the terrain under which they are located (needed for a precise analysis of the data). Commercial tools such as EON's software suite (EON Reality, 2013) or VTK (Kitware, Inc. VTK, 2013) are not flexible enough to support all the data types and visualization modes, with the required scalability due to the size of the data.

47.4.3.1 Visualization Techniques

The general idea of the visualization tool is to display all the data in their respective locations on a virtual reconstruction of the site of interest. In order to display geospatial data correctly on a terrain map, we had to get accurate terrain height. This was done by processing the height data from a Trimble VX Spatial Station to tessellate a terrain surface. This provided a terrain elevation as the missing coordinate for the 3D display of any dataset arrays. One visualization mode (*Hill*) shows the terrain with a height map on it, where a terrain height is color coded onto the surface.

Magnetic (Aitken, 1958; Becker, 1995) and EM (Fröhlich & Lancaster, 1986; Tabbagh, 1986) conductivity are 2D data types, as they result in surface maps of variations of their respective physical properties. A magnetic survey is a passive detection of contrasts in the magnetic properties of differing materials, whereas EM measures the conductivity and magnetic susceptibility of soil. A derived data type is based on the density of artifacts found in 3×3 m grid cells around the surveyed site, defined by the locations of measurement probes, and displayed as a false colormap on the terrain. In each case, a suitable color gradient is used to map the data values to colors.

GPR (Goodman, Nishimura, & Rogers, 1995; Novo, Grasmueck, Viggiano, & Lorenzo, 2008) and electrical resistivity tomography (ERT) (DOE, 2000) generate 3D data arrays. GPR transmits an EM pulse and measures a reflected signal that is dependent upon the dielectric properties of subsurface material. ERT derives subsurface structures of resistive materials from electrical measurements made by electrodes. The archaeologists use a 1 m grid for the electrodes. Note that the depth information in both data arrays is for distance from the surface, which means that neighboring data samples with the same depth value are not normally on the same plane but follow the curvature of the terrain.

Another important data type used in this work is photographs. Pictures of the probes and their surrounding areas are displayed on the ground in their respective locations. Locations of the various artifacts that were found in the area are represented as blue or red cubes. The red cubes represent artifacts that have been radiocarbon dated (with dates shown above the cube). Both types of cubes can be clicked on, which will display a picture of the artifact in a window floating in front of the user.

Two of the objects at the site were digitized with an SfM approach: many overlapping photographs were taken from different viewing angles, and then the Bundler algorithm analyzed the pictures and computed the camera positions they were taken from in 3D space (Snavely et al., 2006). This allowed the PMVS2 algorithm (Furukawa & Ponce, 2009) to calculate a dense, colored point cloud indicating the geometry of the digitized object. One of these objects is a collection of bricks found on the ground; the other is a modern shrine built by local residents. The latter serves more as a landmark than to understand history.

Finally, a 3D modeling tool was used to create a typical temple from the Yuan Dynasty, which existed at the site around the time the radiocarbon dates indicate. The temple was placed and oriented on a particularly dense collection of bricks and subsurface material to indicate that this is the likely location of such a structure.

47.4.3.2 Immersive Visualization Application

This immersive visualization tool was implemented as a plug-in for the VR middleware software CalVR (Schulze, Prudhomme, Weber, & Defanti, 2013). CalVR is based on the OpenSceneGraph API (Wang & Qian, 2010) and runs on Linux-based visualization clusters.

Figure 47.14 shows the application displayed in CALIT2's StarCAVE. The image on the left shows the site with the magnetic data surface layer (mostly green, with some yellow and red areas), the 3D temple model (white), and the probe site images. It can be seen that the probes were arranged on a 3×3 m grid. The picture on the right shows the point cloud of a modern shrine on the site, which serves as a reference point for the archaeologists. This point cloud was not tessellated in order to stay as true to the acquired data as possible.

AQ14

Figure 47.15 shows two views of the subsurface data. Both show GPR points. Every sphere corresponds to a sampled data point. The colors indicate value, normalized to a color range from green to yellow to red. The image on the left was taken from a viewpoint on the surface, showing only the GPR data points at a certain depth (set with a 3D menu). The image on the right shows all available data points from a camera position below the ground.

AQ15

An artifact location cube indicating a carbon dated artifact, along with its dated time range, is shown in the left picture of Figure 47.16. This picture also shows the 3D digitized ground structure,

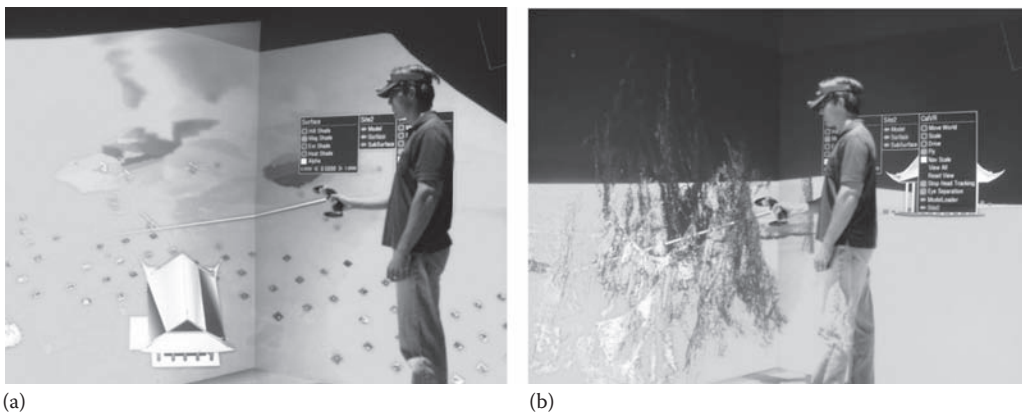


FIGURE 47.14 StarCAVE user high above the archaeological site (a) and looking at the shrine model (b).

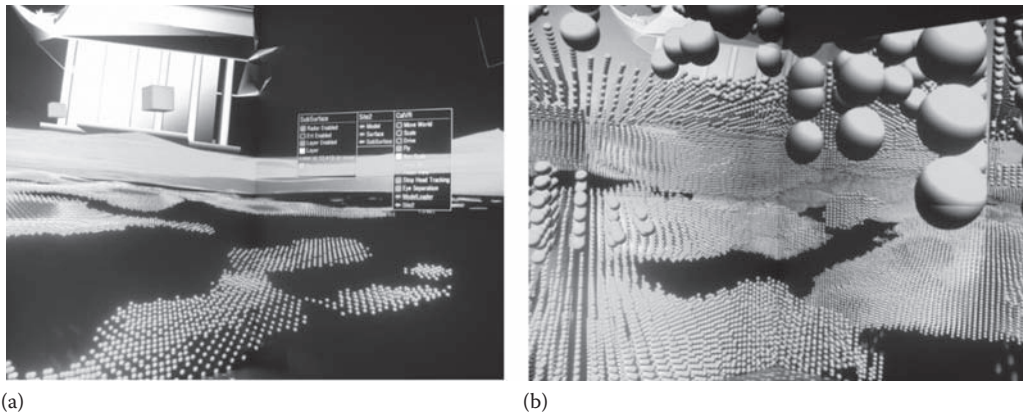


FIGURE 47.15 Ground-penetrating data visualized as colored spheres (a). Warmer colors indicate higher measured density (b).

done with the Bundler algorithm. In the picture on the right, one can see the photograph of a probe location on the ground and the photograph of the selected artifact in the top left corner of the image. Artifacts are selected by pointing and clicking on them. Selecting an artifact updates the picture in the fixed frame at the top left. The frame itself can be moved around by clicking and dragging it with the input device. The picture on the right also shows what a translucent ground texture with underlying GPR spheres looks like. The transparency level can be set in the menu with a slider.

The application's VR menu is shown in Figure 47.17. The three subimages show three different submenus of the application. The leftmost picture shows the Model submenu, the middle the Surface submenu, and on the right the Subsurface submenu. In each submenu, the user can toggle the display of the respective visual elements as well as set their parameters. In the Surface menu, the transparency level for the surface texture can be set. The Subsurface menu allows selecting a layer of spheres to display or to show all spheres. The Density option in this menu allows setting a cutoff point, which hides all spheres with a density below that value. Rendering all spheres creates a very densely packed grid, because our data consist of about 20 million GPR and 400,000 ERT data points.

All menu adjustments result in immediate visual feedback. The application loads all required data into memory at startup and, thanks to optimized rendering algorithms, do not suffer from

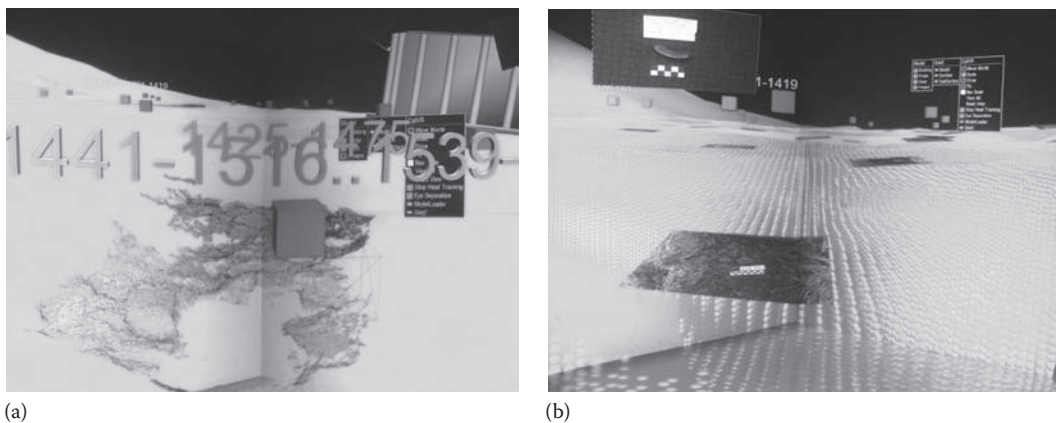


FIGURE 47.16 SfM and radiocarbon dates (a), images of the magnetic probes, and artifact photograph (b).

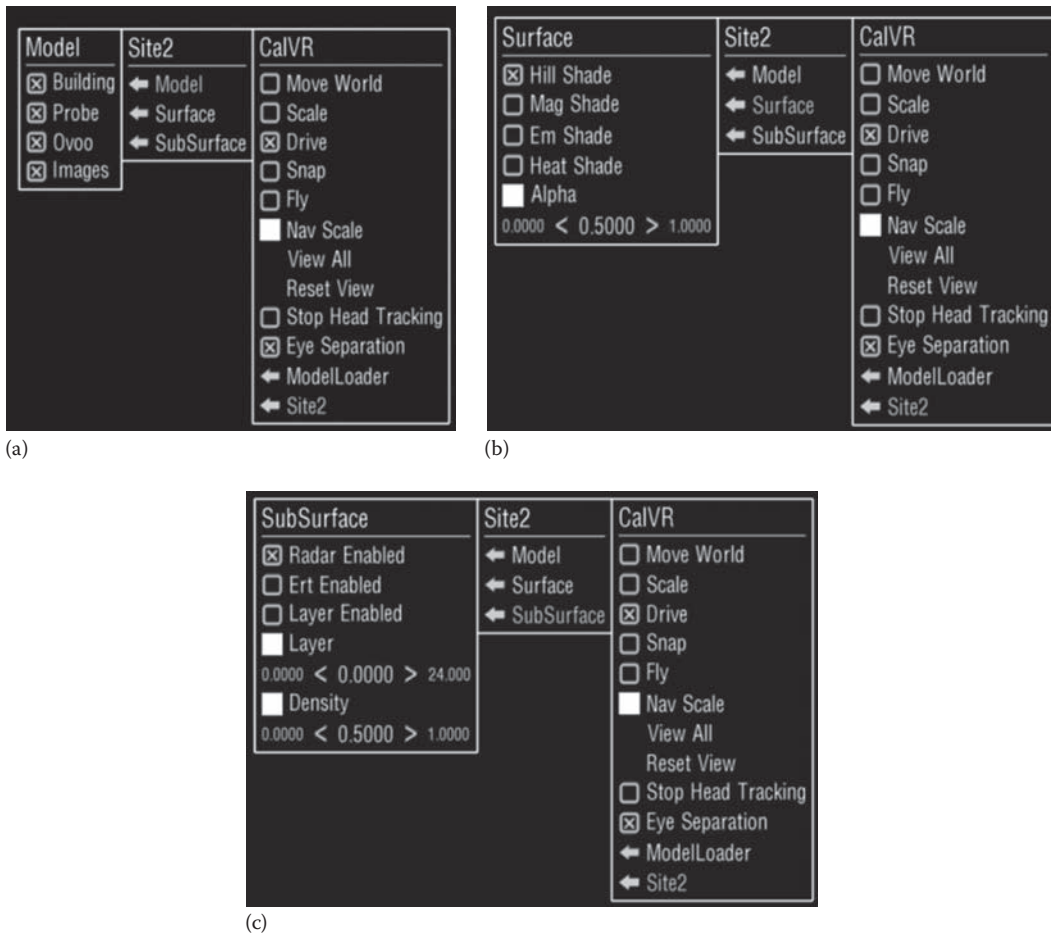


FIGURE 47.17 (a–c) Three submenus of the VR application.

loading lag or other delays once the data have been loaded. This is possible by downsampling the photographs to sizes they typically are displayed at and a fast, shader-based point rendering algorithm for the GPR data. The terrain is not complex enough to require sophisticated terrain rendering algorithms and can be loaded into memory in its entirety.

The menu allows selecting one of the four surface types and one of the two subsurface types, and it allows displaying any number of 3D models and pictures desired. This is because the latter can coexist without occlusion, whereas the former two data types would occlude one another.

47.4.3.3 Benefits Derived

This successful VR software application for geologists and archaeologists fuses 12 different data types in one interactive visualization tool. The ability to see all these data types georeferenced on the same terrain and get an idea of the age of the found artifacts as well as their 3D locations is new for the domain scientists. It is very valuable for them to be able to spatially correlate all these different data types, which is more intuitive through the immersive interface than with their existing desktop software tools. Additionally, the ability to see the data *to scale* is very useful, as is the ability to navigate through the data space with a 3D input device. Both geophysicists and archaeologists like that using the application in CALIT2's StarCAVE, which can accommodate up to 10 people who can collaboratively explore the dataset.



FIGURE 47.18 A real Brunton compass and the virtual version in use.

Future goals for this application are to support additional data types, such as LIDAR point data, and datasets that are larger than the size of the computers' RAM. This will require integrating existing out-of-core approaches, which could perhaps be improved by optimizing spatial access for multiple different data types.

47.4.4 DRI LANCASTER SAND DUNE LAYERS

Sgambati et al. also applied immersive visualization and analysis to GPR data (Sgambati, Koepnick, Coming, Lancaster, & Harris, 2011)—in this case, data capturing the subsurface layers within sand dunes. They began with the immersive tool Toirt Samhlaigh (O'Leary, 2010) to volume render stacks of GPR images in four-sided CAVE and six-sided CAVE-style displays and on a low-cost immersive display. During their collaboration with geologist Nick Lancaster, they introduced an immersive widget called a virtual Brunton compass (Figure 47.18) for measuring dip and strike (orientation) of features inside the volume and also visualized these measurements and the ground surface in context with the volume.

Gathering data with GPR works well on sand dunes because sand has a high resistivity, allowing for good penetration of EM energy. This enables researchers to look deep into the large-scale sedimentary structures below the surface (Bristow et al., 2007). Analysis and annotation of the underground structures helps researchers understand and present how given sand dunes evolved over time. Building on this data, researchers can extrapolate information on past climates and wind directions over the region. Deposits of ancient sand dunes also occur in the rock record. Many of these ancient Aeolian sandstones are important reservoirs for hydrocarbons.

Characterizing the sediments of modern sand dunes in order to understand the conditions under which they were formed benefits from taking measurements of the angle and direction of dip of primary and secondary sedimentary structures. Airflow over the dunes affects their shape, and thus by measuring the shape of ancient dunes, the wind flow patterns of the past can be deduced. Working in the field, geologists measure the dip and strike of surfaces using a Brunton compass. Unfortunately, most desktop GPR visualization tools do not offer a good user



FIGURE 47.19 Using the measurement feature of Toirt Samhlaigh, a researcher simultaneously measures the length, height, and width of the sand dune slope.

interface allowing the geologist, accomplished in the use of a real Brunton compass, to transfer this skill to using a virtual version of the tool.

47.4.4.1 Visualization Techniques

The project team leveraged Toirt Samhlaigh for its immersive volume visualization capabilities. They created a 3D tomogram volume of the data from the stack of 2D subsurface cross-section images from the GPR (see also Figure 47.19 and Section 47.2.5). Working with the 3D volume, the geologist (Lancaster) manipulated the visualization controls to highlight features of scientific significance—that is, he manipulated the transfer functions, lighting parameters, and slice plane’s positions to best view the data. A semitransparent ground surface provides context. Finally, the virtual Brunton compass tool was added to allow measurement and annotation of the dip/strike across the data. These markings then provided a visualization of the nonuniform vector field, indicating direction with a cone pointing in the direction of the steepest gradient.

47.4.4.2 Immersive Interface Techniques

Leveraging the Toirt Samhlaigh immersive volume-rendering tool, the project team had a firm footing on which to add features specifically for visualization of GPR-sourced data volumes. Addressing the shortcoming of most desktop GPR visualization tools, the virtual Brunton compass was added to enable users to efficiently and precisely measure dip and strike of features. The interface comprises a virtual plane, with a dynamic dip line, attached to a 6-DOF wand that the user aligns with features to measure orientation. With one click and a small hand motion, the user aligns the next measurement and, with a second click, saves that measurement. The collection of all the dip and strike measurements is then saved for off-line (on the desktop) analysis (Figure 47.20).

47.4.4.3 Outcomes and Lessons

Lancaster, the geologist on the project, stated that this “application improves current tools used by researchers or practitioners who are interested in these datasets.” He tested this application in a high-resolution (1920 × 1920) six-sided CAVE-like display, on a standard resolution (1050 × 1050) four-sided CAVE, on a low-cost 3DTV-based immersive display (67" with 1080p using checkerboard stereo) similar to the IQ-Station (Sherman, O’Leary, Whiting, Grover, & Wernert, 2010), and on a standard nonimmersive (mouse and keyboard only) computer. All were usable for basic visualization and data exploration. The 6-DOF interaction offered by the immersive displays demonstrated an advantage over the mouse/keyboard interface in the interactive use of the virtual Brunton

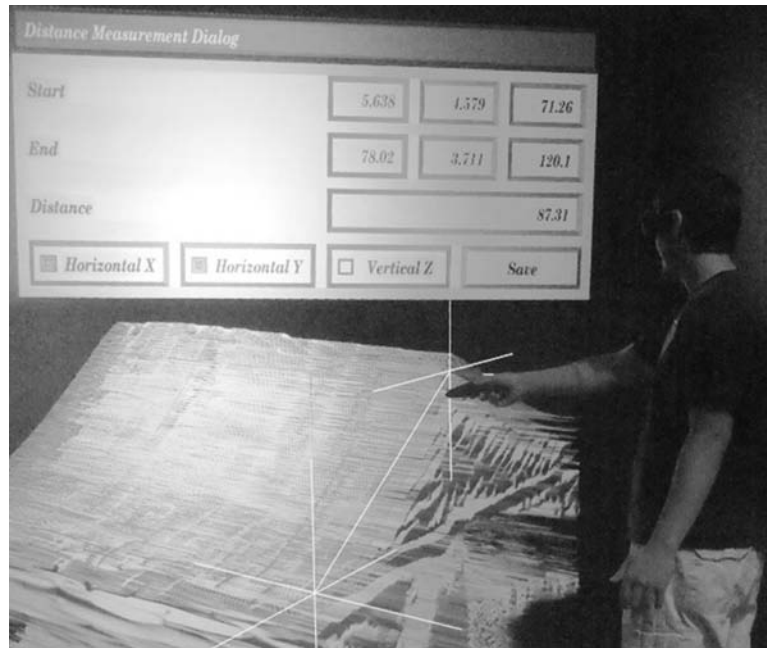


FIGURE 47.20 A user interacting with a volume dataset using the Toirt Samhlaigh application running on a portable and low-cost IQ-Station.

compass and virtual ruler for taking dip, strike, and distance measurements. Lancaster noted major positives that included the ability to quickly view the dataset from different viewpoints in addition to being able to intuitively collect quantitative information on dip and strike.

Specifically, Lancaster noted that interactive tools “enable extraction of quantitative information from dataset” and that “Compared to field investigations, working in the CAVE is a lot easier and quicker.” In comparing the taking of measurements in the real versus virtual worlds, he said: “to perform actual measurements of strike and dip on the beds and surfaces imaged by these data, we would have to excavate the dune and expose these features, which would be logistically difficult and not feasible in most cases.” While using the immersive tools, he would frequently change viewpoints to confirm and refine placement of the Brunton compass markers. During his sessions in the various immersive systems, the visualization scientists on the team noted the differences in how much he was able to take advantage of their unique qualities. In particular, they found that the wider field of view of the CAVE-style displays over the low-cost 3DTV-based systems afforded the scientist the ability to place more user interface elements in the world without interfering with the visualization, whereas the 3DTV-based display became increasingly cumbersome to use as the smaller screen became cluttered.

Lancaster also pointed out some deficiencies in the tool. In particular, determining the scale of the data was difficult, which led to some *uncertainty in dip and strike measurements*. Perhaps not surprisingly, taking angle measurements on a nonuniformly scaled volume can be disconcerting. Even if calculations are correct, results are nonintuitive. This shortcoming could perhaps be reduced through greater practice or by improving the interface. Another deficiency emanates from the use of 2D menus and controls (widgets) contained within a 3D world. This problem is exacerbated when attempting to control small features with shaky position tracking. One possible solution is to move the 2D widgets onto a tablet, matching the 2D nature of the touch interface, though this could then add a fatigue factor from prolonged holding of the tablet.

Back on the positive side, basic computer graphics lighting also turned out to be important in understanding the structure of the data. The ethereal nature of volume rendering is often difficult

to fuse and reduces the effectiveness of stereoscopic rendering. Motion parallax is still helpful, but through the use of GPU lighting effects, features within the volume can come to life more, providing some hooks that the brain can connect with, and make the 3D object more compelling. Also, the manipulation of lighting parameters in and of itself can provide structural cues as shading on surfaces changes.

Contrasted against the difficulty of manipulating 2D widgets in a 3D space, using the 6-DOF position tracking to place and orient the virtual Brunton compass proved to be a very big win. But even some of the 2D interfaces provided benefits not available in other tools. In particular, the Gaussian transfer function editor of Toirt Samhlaigh was much easier to use than the standard piecewise linear transfer function editor. This benefit results from the unique Gaussian curve editor that requires fewer precise selection actions by the user to obtain a desired curve. Sliding the Gaussian around by its center provides a quick way to explore a new dataset for salient features.

One feature of the immersive GPR visualization tool that is not splashy, but crucial, is the basic ability to save and restore the state of the visualization. Not only does this allow the researcher to return to work where they left off, but this also allows them to save a particularly interesting scenario to share with colleagues.

Overall, the geologist found great benefit from the GPR visualization tool, which was based on a volume visualization application with specific extensions for geology visualization, including a virtual Brunton compass widget with natural 6-DOF manipulations. In anecdotal comparisons of various display types, the visualization researchers note how the increased real estate of a four- or six-sided CAVE display provided the space needed to place controls without interfering with the data representations.

47.5 BENEFITS

While not universal, there are demonstrable benefits from the use of immersive technology in many areas, including the visualization and analysis of scientific data from the geological sciences. But demonstrable benefits are not a sufficient criterion in determining whether a new immersive visualization program or tool will pay dividends. Even the most proven tool must overcome the hurdle of breaking into the regular workflow of the researcher. For larger immersive displays, this problem is exacerbated by the distance the researcher must travel to make use of the system. Smaller immersive systems can be available in the lab, and while their benefits may fall between desktop and location-based immersive systems, proximity to the research can make them much more valuable.

A single favorable anecdote indicates that an immersive system *can* be useful, and there are several such anecdotes, some discussed in Section 47.4. For example, in Section 47.4.1, within 20 min in a CAVE system, geologist Kinsland discovered something new in data he had been poring over. In Section 47.4.2, researchers were able to explore that which could not otherwise be explored—hidden data under the surface at a site for which digging was prohibited. Also they found that seeing their data *at scale* was much more useful than viewing a small model on a computer desktop. In Section 47.4.3, the LidarViewer application has been shown to be valuable for several researchers in its ability to naturally select a group of points and then measure them precisely. And in Section 47.4.4, the immersive interface was helpful through the natural placement techniques used to annotate the dip/strike within the subsurface data, which also was from a site that would have been too big (and deep) to dig.

But beyond anecdotes, there is also experimental evidence that demonstrates advantages in using immersive technologies for scientific visualization. In the realm of geosciences, Gruchalla et al. demonstrated an improved ability in navigating through a complex well-path landscape (Gruchalla, 2004). In the wider field of immersive visualization, Prabhat's experiment on analyzing fluid flow through a heart found immersive technologies provided increased performance over desktop tools (Prabhat, Forsberg, Katzourin, Wharton, & Slater, 2008), and Brady et al. described tasks

(following indistinct fibers through volume data) found to be nearly impossible to perform on the desktop were doable in a CAVE display (Brady et al., 1995).

Of course, there are fields related to the geosciences in their need to visualize data within the context of the physical world that also benefit from these and similar immersive tools. Archaeology has already been mentioned, plus other areas such as community planning, which has been used at the CAES facility using the same LidarViewer tool described in Section 47.4.2.

The benefits are not automatic, however—purchasing a new CAVE is not sufficient to guarantee great results. Acquiring the hardware is only part of the process. There is good software available, but not to an overwhelming degree, and expertise is required to get the software installed, configured, and put to use. In some cases, there won't be a software package that directly meets the scientists' needs, and so custom software will be needed, requiring more expertise as well as more time. And then once again, only if the hurdles to use are low enough, will scientists be fully engaged.

The observation of Marshall McLuhan "*I wouldn't have seen it if I hadn't believed it*" serves as another cautionary consideration. The ability to vary scales (e.g., human versus continental) or select how data are filtered offers the possibility to see features that aren't obvious in the field or when observing the unfiltered data. But to avoid perceiving what isn't there, it is also important to go back to the field or to the unfiltered data. For example, a subtle fault whose areal extent isn't visible in the field becomes identifiable as a fault by its horizontal form and extent in LIDAR data viewed immersively. Back in the field, the subtle topography can be confirmed to clearly identify a fault.

In the end, VR is a medium that can assist our search for details revealing the nature of our planet. As we pointed out in the introduction, most geology is intrinsically 3D. Interpreting and communicating about 3D data is thus most effectively (quickest, most accurate, etc.) done in 3D, physically immersive, viewing. While geologists have learned how to interpret 2D representations into 3D, by presenting the data directly in three living dimensions, it becomes easier for the mind to ingest. We also largely avoid the pitfalls of preconceptions that can unintentionally cloud the interpretation.

47.6 FUTURE AND CONCLUSION

Interest and excitement around immersive technologies—*Virtual Reality!*—ebbs and flows over the course of time. In general, it has followed the typical pattern of the Gartner's technology hype curve (Fenn, 1995) in that after an initial spark, there was huge interest and media exposure, surpassing the accomplished merit of the time. For VR, this *peak of inflated expectations* occurred in the mid-1990s. Following that, during the *trough of disillusionment*, the pendulum generally swings too far to the negative, and many give up on the technology. Those who continue and others who gradually join the effort may persevere through the *slope of enlightenment*, perhaps to eventually reach the *plateau of productivity*.

Presently, we can consider the technology of immersive interfaces (VR) to be somewhere on the *slope of enlightenment* with value gradually being demonstrated to more and more users. That does not mean that there are not those who test the technology and find it insufficient for their needs, for that is the nature of all technology. But we are seeing an increasing number of scientific researchers who have found value in immersive technologies, several in fields related to geologic research.

One trend bolstering immersive technologies is the increasing availability of needed technologies through consumer channels. Most prominently, the availability of 3D television displays has made the prospects of building a low-cost immersive system possible. The ubiquitous nature of 3D acceleration in just about every computing device enables interesting virtual worlds, and the last major piece of the puzzle is position tracking, which can range from home brew using Wii™ remote controls or PlayStation Move™ controllers to professional tracking systems costing one or two orders of magnitude more. But even professional systems are significantly less expensive and perform better than what was available a decade ago. Integrating a low-cost immersive system can be

done on an individual or small group basis, but there are benefits to be gained by working together in a community. The IQ-Station (Sherman et al., 2010) project is one such effort whereby an open recipe for the hardware is provided and refined, taking into account the changing availability of consumer products (IQ-Station Consortium, 2013).

Another precursor to wider usage of immersive technologies for visualization as well as other uses comes from the growth of end-user software that is quickly usable. This growth can be fostered in two ways. One way is through the adoption of immersive, or VR, options to existing visualization software—particularly software that is already in use by the user community. Some examples of visualization tools that provide this option include the commercial packages Avizo (Visualization Sciences Group, 2013) and EnSight (Computational Engineering International, Inc., 2013), as well as open tools such as ParaView (Kitware, Inc. ParaView, 2013).

The other primary way to spur growth is to provide a user interface that is not only easy to use but widely adopted. When there is inconsistency between how to use immersive software tools, then more effort is required for end users to become familiar and fluent with each tool. Consistency allows users to quickly move between applications, and when tools become available with needed features, users can readily jump to the new (and probably improved) tool. This ability to keep on the forefront of software technology will better hold the interest of those who use the technology because it helps them improve their research.

The ebb and flow in the amount of usage and attention garnered by immersive technologies will likely continue. But even now, overall, the evidence suggests that there is value in immersive systems benefiting many in the scientific communities, including the geological sciences. We anticipate that as proliferation of the technology continues to spread, the audience will grow steadily, the hardware and software systems will improve, and some will be available ready-to-use right from the time of purchase.

All these advances, coupled with the ascension of new scientists with technology usage, engrained in their lives, looking to take advantage of any technology that provides dividends, and we can expect usage of immersive technologies in the geosciences over the coming years to be even more fruitful.

REFERENCES

- Aegis Instruments. (2013). *Easy 3D-GPR visualization software*. Retrieved August 1, 2013, from <http://www.aegis-instruments.com/products/brochures/easy-3d-gpr.html>
- Aitken, M. J. (1958). Magnetic prospecting: I—The water Newton survey. *Archaeometry*, 1, 24–29.
- American Society for Photogrammetry and Remote Sensing (ASPRS). (2013). *LASer (LAS) file format exchange activities*. Retrieved August 1, 2013, from <http://asprs.org/Committee-General/LASer-LAS-File-Format-Exchange-Activities.html>
- Bagley, J. W. (1917). *The use of the panoramic camera in topographic surveying: With notes on the application of photogrammetry to aerial surveys* (U.S. Geological Survey Bulletin #657). Washington, DC: Government Printing Office.
- Becker, H. (1995). From nanotesla to picotesla—A new window for magnetic prospecting in archaeology. *Archaeological Prospection*, 2, 217–228.
- Bier, E. A., Stone, M. C., Fishkin, K., Buxton, W., & Baudel, T. (1994). A taxonomy of see-through tools. In *ACM CHI* (pp. 358–364).
- Bierbaum, A., Just, C., Hartling, P., Meinert, K., Baker, A., & Cruz-Neira, C. (2001). VR juggler: A virtual platform for virtual reality application development. In *VR '01 Proceedings of the Virtual Reality 2001 Conference* (p. 89).
- Billen, M., Kreylos, O., Hamann, B., Jadamec, M., Kellogg, L., Staadt, O., & Sumner, D. (2008, September). A geoscience perspective on immersive 3D gridded data visualization. *Computers & Geosciences*, 34(9), 1056–1072.
- Blee, H. H. (1940). Third dimension maps. *Military Engineer*, 32, 187–190.
- Borst, C. W. & Kinsland, G. L. (2005). *Visualization and interpretation of 3-D geological and geophysical data in heterogeneous virtual reality displays: Examples from the Chicxulub impact crater*. Paper presented at the Transactions: Gulf Coast Association of Geological Societies (Vol. 55), New Orleans, LA.

- Borst, C. W., Baiyya, V. B., Best, C. M., & Kinsland, G. L. (2007). Volumetric windows: Application to interpretation of scientific data, shader-based rendering method, and performance evaluation. In *The 2007 International Conference on Computer Graphics and Virtual Reality* (pp. 72–78).
- Borst, C. W., Tiesel, J.-P., & Best, C. M. (2010, May/June). Real-time rendering method and performance evaluation of composable 3D lenses for interactive VR. *IEEE Transactions on Visualization and Computer Graphics*, *16*(3), 394–410.
- Borst, C. W., Tiesel, J.-P., Habib, E., & Das, K. (2011). Single-pass composable 3D lens rendering and spatiotemporal 3D lenses. *IEEE Transactions on Visualization and Computer Graphics*, *17*(9), 1259–1272.
- Brady, R., Pixton, J., Baxter, G., Moran, P., Potter, C. S., Carragher, B., & Belmont, A. (1995, October). Crumbs: A virtual environment tracking tool for biological imaging. In *1995 Proceedings of IEEE Biomedical Visualization* (pp. 18–25).
- Bristow, C., Duller, G., & Lancaster, N. (2007). Age and dynamics of linear dunes in the Namib Desert. *Geology*, *6*(35), 555–558.
- Computational Engineering International, Inc. (CEI). (2013). *Ensign virtual reality*. Retrieved August 1, 2013, from <http://www.ceisoftware.com/virtual-reality-vr>
- Das, K., & Borst, C. W. (2010a). An evaluation of menu properties and pointing techniques in a projection-based VR environment. In *IEEE 3D User Interfaces (3DUI)* (pp. 47–50).
- Das, K., & Borst, C. W. (2010b). VR menus: Investigation of distance, size, auto-scale, and ray-casting vs. pointer-attached-to-menu. In *ISVC (Visual Computing)* (pp. 719–728).
- DeFanti, T. A., Dawe, G., Sandin, D. J., Schulze, J. P., Otto, P., Girado, J., ... Rao, R. (2009, February). TheStarCAVE, a third-generation CAVE and virtual reality OptiPortal. *Future Generation Computer Systems*, *25*(2), 169–178, Elsevier.
- Demiralp, C., Jackson, C. D., Karelitz, D. B., Zhang, S., & Laidlaw, D. H. (2006). CAVE and Fishtank virtual-reality displays: A qualitative and quantitative comparison. *IEEE Transactions on Visualization and Computer Graphics*, *12*(3), 323–330.
- AQ18 DOE: U.S. Department of Energy, Offices of Environmental Management and Science and Technology. (2000, June). *Electrical resistance tomography for subsurface imaging* (Innovative Technology Summary Report, DOE/EM-0538).
- Dorn, G., Toussinhthiphonexay, K., Bradley, J., & Jamieson, A. (2001). Immersive 3-D visualization applied to drilling planning. *The Leading Edge*, *12*(20), 1389–1392.
- Edelsbrunner, H., & Mucke, E. P. (1994). Three-dimensional alpha shapes. *ACM Transactions on Graphics (TOG)*, *13*(1), 43–72.
- EON Reality, Inc. (2013). *Experience more with virtual reality*. Retrieved August 1, 2013, from <http://www.eonreality>
- Farr, T. G., & Kobrick, M. (2000). Shuttle Radar Topography Mission produces a wealth of data. *American Geophysical Union EOS*, *81*, 583–585.
- Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., ... Alsdorf, D. (2007). The Shuttle Radar Topography Mission. *Reviews of Geophysics*, *45*, RG2004. doi:10.1029/2005RG000183.
- AQ19 Fenn, J. (1995). *When to leap on the hype cycle* (Gartner ID: SPA-ATA-305).
- Fröhlich, B., & Lancaster, A. (1986). Electromagnetic surveying in current Middle Eastern archaeology: Application and evaluation. *Geophysics*, *51*, 1414–1425.
- Fröhlich, B., Barrass, S., Zehner, B., Plate, J., & Göbel, M. (1999). Exploring geo-scientific data in virtual environments. In *Proceedings of IEEE Visualization '99* (pp. 169–173).
- AQ20 Furukawa, Y., & Ponce, J. (2009). Accurate, dense, and robust multi-view stereopsis. In *IEEE Transactions on Pattern Analysis and Machine Intelligence*.
- AQ21 Gay, S. P. (1971). Morphological study of geophysical maps by viewing in three dimensions. *Leading Edge (Journal)*, *36*, 396–414, Tulsa, OK, ISSN: 1070-485X, 04/1971.
- Glenn, N., Streutker, D., Chadwick, D., Thackray, G., & Dorsch, S. (2006). Analysis of LiDAR-derived topographic information for characterizing and differentiating landslide morphology and activity. *Geomorphology*, *73*(1), 131–148.
- Gold, P. O., Cowgill, E., Kreylos, O., & Gold, R. D. (2012). A terrestrial lidar-based workflow for determining three-dimensional slip vectors and associated uncertainties. *Geosphere*, *8*(2), 431–442.
- Goodman, D., Nishimura, Y., & Rogers, J. (1995). GPR time slices in archaeological prospection. *Archaeological Prospection*, *2*, 85–89.
- Gruchalla, K. (2004, March). Immersive well-path editing: Investigating the added value of immersion. In *IEEE Proceedings of 2004 Virtual Reality* (pp. 157–164).
- Harding, C., Kakadiaris, I. A., Casey, J. F., & Loftin, R. B. (2002). A multi-sensory system for the investigation of geoscientific data. *Computers & Graphics*, *26*(2), 259–269.

- IQ-Station Consortium. (2013). *Open-recipe low-cost immersive display*. Retrieved August 1, 2013, from <http://iq-station.org>
- Itoh, M., Ohigashi, M., & Tanaka, Y. (2006). WorldMirror and WorldBottle: Components for interaction between multiple spaces in a 3D virtual environment. In *IEEE Tenth International Conference on Information Visualization, 2006 (IV, 2006)* (pp. 53–61).
- Kinsland, G. L., Borst, C. W., Best, C. M., & Baiyya, V. B. (2007). *Geomorphology and Holocene Fluvial Depositional History in the Mississippi River Valley near Lafayette, Louisiana: Interpretations of LIDAR data performed in 3D virtual reality*. Paper presented at the Gulf Coast Association of Geological Societies 2007 Convention. AQ22
- Kinsland, G. L., Borst, C. W., Tiesel, J. P., & Bishop, C. E. (2008). Imaging digital well logs in 3D virtual reality: Investigation of northern Louisiana Wilcox fluvial/coal strata for coalbed natural gas. *Gulf Coast Association of Geological Societies Transactions*, 58, 517–524.
- Kitware, Inc. (2013). *ParaView/users guide/CAVE display*. Retrieved August 1, 2013, from http://www.paraview.org/Wiki/ParaView/Users_Guide/CAVE_Display
- Kitware, Inc. (2013). “VTK—The visualization toolkit” software. Retrieved August 1, 2013, from <http://www.vtk.org>
- Kiyokawa, K., & Takemura, H. (2005). A tunnel window and its variations: Seamless teleportation techniques in a virtual environment. *HCI International*.
- Komerska, R., & Ware, C. (2004). Haptic state–surface interactions. *IEEE Computer Graphics and Applications*, 24(6), 52–59.
- Kreylos, O. (2008). Environment-independent VR development. In Bebis, G. et al. (Eds.), *Lecture Notes in Computer Science (LNCS): Vol. 5358. 2008 Proceedings of the International Symposium on Visual Computing (ISVC), Part I* (p. 901). Berlin, Germany: Springer-Verlag. AQ23
- Kreylos, O., Bawden, G., Bernardin, T., Billen, M. I., Cowgill, E. S., Gold, R. D., ... Sumner, D.Y. (2006). Enabling scientific workflows in virtual reality. In *Proceedings of the 2006 ACM International Conference on Virtual Reality Continuum and Its Applications* (pp. 155–162).
- Kreylos, O., Bawden, G. W., & Kellogg, L. H. (2008). Immersive visualization and analysis of LiDAR data. In Bebis, G. et al. (Eds.), *Lecture Notes in Computer Science (LNCS): Vol. 5358. 2008 Proceedings of the International Symposium on Visual Computing (ISVC), Part I* (pp. 846–855). Berlin, Germany: Springer-Verlag.
- Kurtenbach, G., Fitzmaurice, G., & Balakrishnan, R. (2002). Volume management system for volumetric displays. U.S. Patent application 10/183,966. AQ24
- LaFayette, C., Parke, F. I., Pierce, C. J., Nakamura, T., & Simpson, L. (2008). Atta texana leaf cutting ant colony: A view underground. In *ACM SIGGRAPH 2008 Talks* (Vol. 53, p. 1).
- Lin, A. Y.-M., Novo, A., Weber, P. P., Morelli, G., Goodman, D., & Schulze, J. P. (2011). A virtual excavation: Combining 3D immersive virtual reality and geophysical surveying. In Bebis, G. et al. (Eds.), *Lecture Notes in Computer Science (LNCS): Vol. 6939. 2011 Proceedings of the International Symposium on Visual Computing (ISVC), Part II* (pp. 229–238). Berlin, Germany: Springer-Verlag.
- MacLeod, M. N. (1919, June). Mapping from air photographs. *The Geographical Journal*, 53(6), 382–396. <http://www.jstor.org/stable/1780414>
- Moore, C., Gertman, V., Olsoy, P., Mitchell, J., Glenn, N., Joshi, A., ... Lee, R. (2011, December 5–9). *Discovering new methods of data fusion, visualization, and analysis in 3D immersive environments for hyperspectral and laser altimetry data*. San Francisco, CA: American Geophysical Union.
- Mulder, J. D., & Boschker, B. R. (2004). A modular system for collaborative desktop VR/AR with a shared workspace. In *IEEE Proceedings of 2004 Virtual Reality* (pp. 75–82).
- Murgoitio, J., Shrestha, R., Glenn, N., & Spaete, L. (2013). Airborne LiDAR and terrestrial laser scanning derived vegetation obstruction factors for visibility models. *Transactions in GIS*, 18(1), 147–160. doi:10.1111/tgis.12022.
- Novo, A., Grasmueck, M., Viggiano, D., & Lorenzo, H. (2008). 3D GPR in archaeology: What can be gained from dense data acquisition and processing. *Twelfth International Conference on Ground Penetrating Radar*, Birmingham, U.K.
- O’Leary, P. (2010). “Toirt-Samhlaigh” software. Retrieved from <http://code.google.com/p/toirt-samhlaigh/>
- Olsoy, P., Gertman, V., Glenn, N., Joshi, A., Mitchell, J., Whiting, E., ... Spaete, L. (2012, March). Interactive exploration and data fusion of multimodal remote sensing data. In *ASPRS Annual Conference* (pp. 19–23). Sacramento, CA. AQ25
- Perlin, K., & Fox, D. (1993). Pad: An alternative approach to the computer interface. In *Proceedings of SIGGRAPH 1993* (pp. 57–64).
- Plumlee, M., & Ware, C. (2006). Zooming versus multiple window interfaces: Cognitive costs of visual comparisons. *ACM Transactions on Computer-Human Interaction*, 13(2), 179–209.

- AQ26 Prabhat, Forsberg, A., Katzourin, M., Wharton, K., & Slater, M. (2008). A comparative study of desktop, fish-tank, and cave systems for the exploration of volume rendered confocal data sets. *IEEE Transactions on Visualization and Computer Graphics*, 14, 551–563.
- Prachyabrued, M., Ducrest, D., & Borst, C. W. (2011). Handymap: A selection interface for cluttered VR environments using a tracked hand-held touch device. In Bebis, G. et al. (Eds.), *Lecture Notes in Computer Science (LNCS): Vol. 6939. 2011 Proceedings of the International Symposium on Visual Computing (ISVC), Part II* (pp. 45–54). Berlin, Germany: Springer-Verlag.
- Raghupathy, P. B., & Borst, C. W. (2011). Investigation of secondary views in a multimodal VR environment: 3D lenses, windows, and mirrors. In Bebis, G. et al. (Eds.), *Lecture Notes in Computer Science (LNCS): Vol. 6939. 2011 Proceedings of the International Symposium on Visual Computing (ISVC), Part II* (pp. 180–189). Berlin, Germany: Springer-Verlag.
- Raghupathy, P. B., & Borst, C. W. (2012). Force feedback and visual constraint for drawing on a terrain: Path type, view complexity, and pseudohaptic effect. In *3DUI 2012* (pp. 157–158).
- Robertson, G., van Dantzich, M., Robbins, D., Czerwinski, M., Hinckley, K., Risden, K., ... Gorokhovskiy, V. (2000). The task manager: A 3D window manager. In *CHI* (pp. 494–501).
- Rogowitz, B. E., & Trenish, L. A. (1998). *Why should engineers and scientists be worried about color?* Retrieved from <http://www.research.ibm.com/people/lloyd/color/color.HTM>
- Schmalstieg, D., & Schaufler, G. (1999). Sewing worlds together with SEAMs: A mechanism to construct complex virtual environments. *Presence: Teleoperators and Virtual Environments*, 8(4), 449–461.
- Sgambati, M. R., Koepnick, S., Coming, D. S., Lancaster, N., & Harris, F. C. Jr. (2011). Immersive visualization and analysis of ground penetrating radar data. In Bebis, G. et al. (Eds.), *Lecture Notes in Computer Science (LNCS): Vol. 6939. 2011 Proceedings of the International Symposium on Visual Computing (ISVC), Part II* (pp. 33–44). Berlin, Germany: Springer-Verlag.
- Sherman, W. R., O'Leary, P., Whiting, E. T., Grover, S., & Wernert, E. A. (2010). IQ-Station: A low cost portable immersive environment. In Bebis, G. et al. (Eds.), *Lecture Notes in Computer Science (LNCS): Vol. 6454. 2010 Proceedings of the International Symposium on Visual Computing (ISVC), Part II* (pp. 361–372). Berlin, Germany: Springer-Verlag.
- Schulze, J. P., Prudhomme, A., Weber, P., & DeFanti, T. A. (2013, March 4). CalVR: An advanced open source virtual reality software framework. In *Proceedings of SPIE 8649, The Engineering Reality of Virtual Reality 2013* (pp. 864–902). doi:10.1117/12.2005241
- Snavely, N., Seitz, S. M., & Szeliski, R. (2006). Photo tourism: Exploring image collections in 3D. *ACM Transactions on Graphics (Proceedings of SIGGRAPH 2006)*.
- Stoakley, R., Conway, M., & Pausch, R. (1995). Virtual reality on a WIM: Interactive worlds in miniature. In *ACM CHI* (pp. 265–272).
- Tabbagh, A. (1986). Applications and advantages of the slingram electromagnetic method for archaeological prospecting. *Geophysics*, 51, 576–584.
- Tanaka, H. K. M., Nakano, T., Takahashi, S., Yoshida, J., Takeo, M., Oikawa, J., ... Niwa, K. (2007, November). High resolution imaging in the inhomogeneous crust with cosmic-ray muon radiography: The density structure below the volcanic crater floor of Mt. Asama, Japan, *Earth and Planetary Science Letters*, 263(1–2), 15, 104–113. <http://dx.doi.org/10.1016/j.epsl.2007.09.001>
- Viega, J., Conway, M. J., Williams, G., & Pausch, R. (1996). 3D magic lenses. In *ACM UIST* (pp. 51–58).
- Visualization Sciences Group (VSG). (2013). *Avizo extensions*. Retrieved August 1, 2013, from <http://www.vsg3d.com/avizo/extensions>
- Wang, R., & Qian, X. (2010, December). *OpenSceneGraph 3.0: Beginner's Guide*. Packt Publishing, ISBN: 1849512825.
- Ware, C., Plumlee, M., Arsenault, R., Mayer, L. A., Smith, S., & House, D. (2001). GeoZui3d: Data fusion for interpreting oceanographic data. In *Oceans 2001* (pp. 1960–1964).
- Weiskopf, D., Engel, K., & Ertl, T. (2003). Interactive clipping techniques for texture-based volume visualization and volume shading. *IEEE Transactions on Visualization and Computer Graphics*, 9(3), 298–312.
- AQ27 Winkler, C., Bosquet, F., Cavin, X., & Paul, J. C. (1999, October). Design and implementation of an immersive geoscience toolkit (case study). In *IEEE Proceedings of Visualization '99* (pp. 429–432). IEEE Computer Society Press.
- Yamaguchi, Y., Kahle, A. B., Tsu, H., Kawakami, T., & Pniel, M. (1998). Overview of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). *IEEE Transactions on Geoscience and Remote Sensing*, 36(4), 1062–1071.

AUTHOR QUERIES

- [AQ1] Please check whether the citations for Figures 47.1 through 47.6, 47.11 through 47.13, 47.19, and 47.20 are appropriate.
- [AQ2] Please check if edit to the sentence starting “To geoscientists, this...” is okay.
- [AQ3] Artwork of Figures 47.1 and 47.7 are same. Please check.
- [AQ4] Please confirm the inserted citation for Figures 47.1–47.6, 7.11–7.13, and 7.20.
- [AQ5] Please confirm the inserted part labels in the caption of Figure 47.2.
- [AQ6] Please check if edit to the sentence starting “Specialized radar devices...” is okay.
- [AQ7] Please check the sentence starting “Additionally, as the original...” for completeness.
- [AQ8] Please check if edit to the sentence starting “Collecting location data...” is okay.
- [AQ9] Please check if edit to the sentence starting “Streamlines and streaklines...” is okay.
- [AQ10] Please provide the expansion of “6-DOF,” if appropriate.
- [AQ11] Please confirm the identified headlevels.
- [AQ12] Please check the mention of color in Figure 47.12.
- [AQ13] Please note that the year in Moore et al. (2012) is changed as per list.
- [AQ14] Please check the mention of color in the sentence starting “The image on...”
- [AQ15] Please check the mention of color in the sentence starting “The colors indicate...”
- [AQ16] Prabhat (2008) has been changed to Prabhat et al. (2008) as per the reference list. Please check.
- [AQ17] Please provide editor group and publisher details for the following references: Bier et al. (1994), Bierbaum et al. (2001), Borst et al. (2007), Brady et al. (1995), Das and Borst (2010a,b), Fröhlich et al. (1999), Gruchalla (2004), Itoh et al. (2006), Kreylos et al. (2006), LaFayette et al. (2008), Mulder and Boschker (2004), Perlin and Fox (1993), Raghupathy and Borst (2012), Robertson et al. (2000), Sgambati et al. (2011), Sherman et al. (2010), Schulze et al. (2013), Stoakley et al. (1995), Viega et al. (1996), Ware et al. (2001).
- [AQ18] Please provide publisher details and also confirm the inserted report number for DOE (2000).
- [AQ19] Please provide publisher details for Fenn (1995).
- [AQ20] Please provide volume number and page range for Furukawa and Ponce (2009).
- [AQ21] Please confirm the inserted volume number and page range for Gay (1971). Also confirm journal title for the same.
- [AQ22] Please provide location for Kinsland et al. (2007), Kiyokawa and Takemura (2005), Murgoitio et al. (2013), Schulze et al. (2006), Wang and Qian (2010).
- [AQ23] Please confirm the edit made to Kreylos (2008), Kreylos et al. (2008), Lin et al. (2011), Prachyabrued et al. (2011).
- [AQ24] Please provide publisher details for Kurtenbach et al. (2002), if applicable.
- [AQ25] Please provide publisher name and editor group for Olsoy et al. (2012).
- [AQ26] Please provide initials for Prabhat.
- [AQ27] Please provide editor group and location for Winkler et al. (1999).