Interactive Visualization to Advance Earthquake Simulation

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Abstract

The geological sciences are challenged to manage and interpret increasing volumes of data as observations and simulations increase in size and complexity. For example, simulations of earthquake-related processes typically generate complex, time-varying datasets in two or more dimensions. To facilitate interpretation and analysis of these datasets and evaluate the underlying models, and to drive future calculations, we have developed methods of interactive visualization with a special focus on using immersive virtual reality (VR) environments to interact with models of Earth’s surface and interior. Virtual mapping tools allow virtual “field studies” in inaccessible regions. Interactive tools allow us to manipulate shapes in order to construct models of geological features for geodynamic models, while feature extraction tools support quantitative measurement of structures that emerge from numerical simulation or field observations, thereby enabling us to improve our interpretation of the dynamical processes that drive earthquakes. VR has traditionally been used primarily as a presentation tool, albeit with active navigation through data. Reaping the full intellectual benefits of immersive VR as a tool for scientific analysis requires building on the method's strengths, that is, using both 3D perception and interaction with observed or simulated data. This approach also takes advantage of the specialized skills of geological scientists who are trained to interpret, the often limited, geological and geophysical data available from field observations.

Interactive Visualization of Geoscience Data

The human brain excels at visually identifying patterns, and as a result the best interpretations arise when scientists can fully visualize their data. As the expert on informational graphics Edward Tufte wrote two decades ago, “At their best, graphics are instruments for reasoning about quantitative information. Often the most effective way to describe, explore, and summarize a set of numbers – even a very large set – is to look at pictures of those numbers” [Tufte, 1983]. Earth science datasets have now increased in size and complexity to the extent that they can no longer be represented adequately in numerical form [Erlebacher et al. 2001; Cohen, 2005]. Although statistical distributions and correlations can yield insight, by definition such an approach reduces the amount of information conveyed. As it becomes increasingly easy both to model interacting, non-linear processes and measure natural systems, developing new ways of understanding and interpreting these expanding datasets is critical to making significant scientific advances [Foster, 2006; Butler, 2006] and responding to natural disasters [Nourbakhsh, 2006]. Using our innate abilities to interpret vast amounts of very complex visual information and focus our attention on the most salient features is the best technique for gaining the scientific insights that produce breakthroughs in difficult problems. Advanced visualization technology allows scientists to use their full visual capacity, helping them to identify previously unrecognized processes and interactions in complex systems [see e.g. Carlson, 2006 for a discussion of recent advances in imaging geological materials].

A fully immersive environment is highly desirable for interaction with complex datasets [Kreylos, 2006; Kreylos et al. 2006] and has demonstrated benefits over single screens for identification of features [Billen et al. 2006]. Single 3D projection surfaces limit the detail in which datasets can be fully explored because the edges of the viewing table or wall restrict peripheral vision restricting observations to the center of the visual range. Thus, it is difficult to interpret connections between processes acting at different spatial or temporal scales because objects cannot be viewed in both detail and context. In contrast, viewing with three or more projection surfaces permits full peripheral vision, thereby improving understanding of multiscale data. Geologists and geophysicists are trained in the interpretation of 3D Earth structure and 4-D (space plus time) reconstructions of geological processes. Immersive visualization enables geoscientists to fully utilize their training to interpret computational datasets.

To advance beyond viewing and navigating through datasets, we are developing new interaction tools that allow scientists to create and modify objects within the immersive environment. For example, complicated surfaces or materials with specific elemental distributions can be built and modified rapidly using intuitive tools such as hand-held, tracked wands or electronic data gloves [Kreylos 2006]. These objects can then be exported to serve as initial or boundary conditions in numerical simulations. When natural processes can be modeled in real time, such interactive tools allow scientists to manipulate an object and see the resulting effects immediately. This rapid feedback helps scientists identify the most interesting and important features in their data and thus concentrate their efforts on understanding critical processes rather than finding the conditions that allow them to be investigated.

An immersive visualization system is ideal for Earth scientists: Earth processes are intrinsically complex; nonlinear systems and critical phenomena associated with earthquake simulation alone typically span more than 6 orders of magnitude in spatial scales with abrupt variations in behavior both in space and through time (Figure 1). For example, the deformation during an earthquake takes place on a distinctly human scale of time and space: ruptures of a fault can take seconds to minutes and cause shaking over a few to many kilometers. Models such as TeraShake require large-scale computing resources to simulate the shaking [Olsen et al. 2006]. In contrast, the interseismic deformation, measured by geodetic methods, occurs at much lower rates. Crustal deformation at the intermediate to long time scale can be modeled using numerical simulation: for example, interaction of large scale fault systems [Rundle et al. 2006] generates sequences of slip events over time, while simulations of damage in the crust [e.g. Manaker et al. 2006] generates a full stress and strain-rate field for the modeled system. The entire earthquake process is driven by plate motion, which takes place over millions of years and thousands of kilometers. Simulations hold some hope of providing insight into how these processes are linked.

Current observations and models push the limits of available interpretive methods. Yet new, larger observational datasets are rapidly becoming available, providing the opportunity to significantly advance our understanding of how the Earth works. In such a data-rich environment, rapid advances in knowledge are commonly limited by ideas rather than information. New modeling techniques are poised to provide the means to interpret this data, when coupled to increases in computational power and efficiency that have been gleaned using advanced IT methods. Visualization is already used to convey knowledge obtained from data and models from the scientific and engineering community to the general public. Use of fully immersive 3D visualization is beginning to substantially change our perspective of these datasets and models in much the same way that going from presenting data as still images to movies fundamentally changed our scientific focus from the characterization of static distributions of parameters to understanding the dynamics of how distributions change.

In this paper, we describe an interdisciplinary approach to exploring earthquake-related geoscience data using an immersive, 3D visualization and data manipulation environment. The work is motivated by the need to understand specific scientific problems that span many orders of magnitude in space and time, from millimeters to thousands of kilometers, and from seconds to billions of years. The three investigations described here include using VR as a tool for mapping geologic structures in remote, inaccessible locations, using immersive visualization to construct models of a subducting slab from earthquake locations in preparation for a full dynamical simulation, and using Tripod-based Light Detection and Ranging (T-LIDAR) to model structures and extract time-sequences of deformation. These applications are linked by the need to understand the multidimensional evolution of complicated boundaries interacting with larger and smaller systems.

VR in Neotectonic Mapping and Interpretation of Earth's Structure

Neotectonic geologists use field-based observations, digital elevation data and multi-spectral satellite or photographic imagery to record, measure, and reconstruct geologic structures such as faults and folds from using deformed geomorphic features such as stream channels, abandoned shorelines, fluvial and marine terraces, or abandoned alluvial fan surfaces. Such reconstructions of geologic features are used to interpret present and past deformation of the Earth's crust as it responds to the forces of plate tectonics and is modified by processes of erosion and deposition. The recent availability of almost global coverage of intermediate (10—90 m) and high (1—10 m: U.S. Geological Survey EROS data center: http://seamless.usgs.gov/) resolution digital elevation and imagery data has created new opportunities to study regions of the world inaccessible to the neotectonic geologist due to the scale of the structures of interest (e.g., thousands of kilometers long), or due to the remoteness of the locality (e.g., the Tibetan Plateau, the ocean floor, or another planet). At the same time this wave of new data poses a formidable challenge to available VR methods.

The goal for the neotectonic geologists working with digital terrain data sets is to use remote-sensing data to observe and measure the detailed features (10-100 m long) that attest to active deformation of the Earth's surface over areas spanning an entire continental collision zone or active plate margin (~$1x10^5$ to $1x10^6$ km^2). We therefore require a highly efficient, yet sensitive system to enhance analysis and interpretation of data collected through field mapping – an experience that normally includes viewing the region of interest from many perspectives and at different scales, detailed study and analysis of focus regions, and direct measurement of the location and orientations of often complex planar and undulatory 3D structures, defined solely by their intersection with the 3D surface topography.

A group of us [Bernardin et al. 2006] developed the *Real-time, Interactive Mapping System* (RIMS) to allow geologists to visualize and map structures in an intuitive and natural 3D space (Figure 2). RIMS provides interactive, textured height field rendering capability for very large terrain data sets (tens of gigabytes) with full roaming and viewpoint manipulation and mapping of attributed points, polylines and polygons directly onto the terrain model. RIMS renders terrain data employing view-dependent, level-of-detail (LOD) and out-of-core data management techniques, using preprocessed quadtrees of the elevation and texture data. Google Earth is a similar tool that uses variable resolution and has been used, for example, by USGS scientists to provide a "virtual tour" of the 1906 San Francisco Earthquake [USGS, 2006]. In contrast to Google Earth and other such software, RIMS is unique in its ability to provide users a tool for efficiently mapping and directly measuring structure on the 3D terrain models. In particular, users can attribute and then edit geo-referenced mapping elements using points and poly-lines, measure the orientation of surfaces such as bedding or folded alluvial fan surfaces using a virtual compass (an adjustable plane that tracks its own orientation with respect to geographic north and dip angle), and generate interpolated surfaces to facilitate geometric reconstructions using deformable surfaces. While these tools were developed with the terrestrial earth scientist in mind, RIMS can also be used to explore high-resolution seafloor-bathymetry data and has potential applications for planetary geology data.

To interpret the 3D geometry of a surface (for example, a folded sedimentary layer) based on its intersection with the surface of the earth, geologists traditionally construct many 2D cross sections along vertical slices through their map data, projecting the data into the plane of the cross section. Using RIMS, the geologists can generate and manipulate curved or planar surfaces through their mapping of the structure at the surface, and thus display surfaces that would otherwise only be mentally imaged. Such structure matching tools provide quantitative constraints on the minimum amplitude of the fold, which in turn can be interpreted physically as the minimum amount of deformation (shortening) in the region of the fold. Figure 2 illustrates this process in action. The bottom row of images shows the steps involved in measuring the shape of a fold. Image (1) shows the intersection of a distinct layer of rock mapped along opposite sides of a ridge. In image 2, an automatically generated reconstructed surface intersects topography where the layer is no longer present because it has been removed by erosion of the crest of the fold, indicating that this initial model is in error and that the fold amplitude must be larger than the reconstructed surface. To correct this, the surface is adjusted manually (3) to appropriately represent the amplitude of the fold.

Volume Rendering in Geodynamics Models

Geodynamical modeling [Tackley, 2000; Billen et. al., 2003; McNamara and Zhong, 2005] seismological models [e.g. Romanowicz 1991] and geodetic observations [e.g. Rundle et al., 2002] all generate large, multidimensional datasets that require analysis and interpretation. Carrying out high-resolution numerical models of geodynamics in 3D presents a number of technical and scientific challenges that require numerical methods capable of handling extreme changes in rheology, vector and tensor data such as velocities and stress, and development and evolution of complex, heterogeneous structures. Moreover, we do not typically know the initial or boundary conditions (stress state, temperature) within the Earth, yet computer simulations are typically solving initial and boundary value problems that require specifying both *a priori*. A common approach is to carry out repeated simulations using different starting conditions to determine how sensitive results are to variations in the initial and boundary conditions. It would therefore increase the efficiency of the modeling process if we could use interactive tools to rapidly generate and evaluate starting models from which to run each geodynamical calculation. Furthermore, during a calculation or in post-processing analysis, we typically need to track a deforming interface to understand the progress of a calculation. Interactive feature extraction tools allow the measurements of specific features, such as the morphology of deformed surfaces, to facilitate comparison with seismic models and other geophysical datasets.

Many subduction zone plate boundaries (the location of many great earthquakes) are characterized by geometry of the subducted plate that varies both along strike and with depth [Tassara et al. 2006; Miller and Kennett 2006; Miller et al. 2006]. Processes such as surface deformation in the overriding plate and flow patterns in the underlying mantle may be sensitive to the 3D geometry of the slab, particularly where the slab dip is shallow in the first process, or where the slab contains a cusp or edge in the latter process [Fischer et. al., 2000; Billen et. al., 2003]). Thus, adequately representing the 3D shape of the plates at plate boundaries is likely important to understanding the processes the govern deformation in these regions of the Earth. However, rendering smooth input for 3D finite element models while maintaining the complexity of the geological system under study poses a challenge. The use of a 3D immersive environment such as the CAVE greatly improves the efficiency with which input for geodynamic models based on complex shapes can be generated and refined as well as the efficiency with which model output can be visualized and understood.

As an example, here we show how the 3D visualization software is used to visualize input for a 3D finite element model (FEM) of a subduction zone, where the geometry of the subducted plate changes along the length of the subduction zone. In the model, the initial shape of the subducted plate is based on seismic observations [Page et al., 1989; Brocher et al., 1994; Gudmundsson and Sambridge, 1998; Doser et al., 1999; Ratchkovski and Hansen, 2002]. Superposition of the seismic data and the smoothed slab surface enables visualization of the fit between the data and the idealized, yet complex, initial slab shape (Figures 3a and 3b). To visualize the initial temperature and viscosity fields associated with the FEM model, we have developed the program Visualizer, which we use to extract isosurfaces and 2D slices of these values (Figures 3c and 3d). The 3D environment of Visualizer enables rapid assessment of the character and quality of the input data; these illustrations apply equally to the assessment and visualization of the model output as well.

In a recent study designed to assess the effectiveness of visualization tools in geodynamics applications [Billen et al. 2006] we asked a group of researchers and students to search for specific features in a model of a subducting slab using two different visualization methods on two different platforms. The study compared Visualizer, the KeckCAVES-developed software that can be used in a variety of 3D VR environments (e.g., GeoWall, ImmersaDesk, CAVE, desktop computer), to a commercial visualization package, TecPlot (http://www.tecplot.com). TecPlot was used on a desktop system, while Visualizer was used both on a desktop and in a fully immersive environment, the CAVE (Cave Automatic Virtual Environment). Using Visualizer on both platforms allowed us to assess the experience of immersive visualization independent of the software. The users evaluated a model prepared as initial conditions for the finite element program CitComT [Zhong et al., 1998; Billen et al., 2003], a widely used code designed for mantle convection models [e.g. Moresi and Parson, 1995].

The user study showed that Visualizer used in the CAVE made data exploration (navigating, identifying and locating features) the easiest and was the easiest to learn and use overall. Visualizer used on the desktop also made data exploration easier than TecPlot, although users found Visualizer more difficult to learn initially. A key feature of Visualizer is the ability of users to create seeded slices and surfaces located and oriented arbitrarily using a handheld input device, in contrast to most commonly available software packages, in which users must typically decide *a priori* where to place a slice or an isosurface, often by entering values into a menu on a keyboard. The interactivity provided by Visualizer is a much more effective means of exploring data when the location and characteristics of features of interest are yet to be discovered. Movies showing a user creating slices and isosurfaces with Visualizer using geophysical datasets are available on the KeckCAVES project web site http://www.keckcaves.org/movies.

Tripod-LIDAR

Light Detection and Ranging measurements taken from the ground using a tripod (T-LIDAR) provide the capability to rapidly acquire ultra high-resolution surface (sub-millimeter) data on the outcrop scale (1 m^2 to 10 km^2), complementing space-based and airborne geodetic measurements including data acquisition underway and being planning by EarthScope [www.earthscope.org] and GeoEarthScope. T-LIDAR has impressive potential as a tool for neotectonics, quantitative geomorphology, and geological hazards assessment by allowing rapid, high-resolution measurements of a changing landscape [Bawden et al. 2004]. A T-LIDAR instrument bounces light off surfaces, recording a "data cloud" of points that together make a 3D image of the landscape. A complete view is created by collecting data from multiple directions. This new technology rapidly generates millions of scattered points from which features must be extracted and interpreted, but the development of analytical software to manipulate and analyze the data lags behind the hardware technology. We have developed a VR LIDAR viewer, which rapidly displays and allows navigation through large T-LIDAR datasets. Thus for example, the user can view the landscape from a perspective that would not be obtainable from the field. By adapting the feature extraction tools described above in the context of the RIMS software package to LIDAR data, we enable the user to rapidly identify features, select sets of points that are of interest, such as the landscape being mapped, (Figure 4) while leaving behind irrelevant points (such as vegetation covering the landscape).

Feature extraction allows the user to fit geometric objects to a subset of the data and to make quantitative measurements. For example, fitting a plane to a wall, or fitting cylinders to fenceposts, within a sequence of LIDAR images taken over a period of time allows the user to determine offset and strain of a structure that crosses a fault plane. Thus, repeated T-LIDAR scans following an earthquake can be used to understand the 4-D deformation field. Fitting best-fit surfaces to select features in the T-LIDAR imagery (planes to building walls, vectors to fence post, cylinders to posts and bridge supports, etc) improves the position accuracy of the target feature and provides a unique method for tracking how features move in 3D space over time (Figure 4). A movie showing a user exploring and analyzing a sample dataset, a high-resolution tripod LIDAR laser scan of part of the UC Davis campus, using the multiresolution point set visualization program, is available on http://www.keckcaves.org/movies. The visualized point set contains about 4.7 million 3D points with intensity values that randomly sample all surfaces in the scanned area. The program uses a 3D paintbrush interface (the yellow sphere) to allow a user to select subsets of points and determine low-degree analytically defined approximations such as planes, cylinders, spheres, etc.

Conclusions

We have discussed how VR technology can benefit diverse geological applications for characterizing faults and simulating earthquake. These applications have in common the need for the human interaction with data to make scientific progress on all aspects of earthquake simulation, from identifying seismogenic faults and their properties to constructing fully dynamical models. By taking advantage of the skills of geoscientists and also exploiting the full capabilities of a VR environment, we have produced new approaches to visualization that are especially applicable to earthquake simulation. We emphasize that the methods that make data exploration possible are not confined to state-of-the-art VR systems, but are adapted to a wide range of other VR systems. Previously developed VR software has largely been limited in portability to VR systems with similar input devices, limiting the ability of a research group with a low-end visualization system to scale up in a cost-effective manner. The value of immersive, interactive data exploration is growing more important with the explosion of large datasets created by imaging, large observational efforts, and high-resolution computer simulations. The ability to rapidly create complex objects for use in models allows the use of more realistic boundary conditions and objects in earth science modeling. One of the most difficult aspects of developing forward models and simulations of earth science processes is identifying the spatial distribution of critical behaviors and the temporal framework of changes. Proper resolution is critical to modeling realistic behaviors in fault zones. An ability to interactively adjust critical parameters in 3D models substantially increases the appropriateness of boundary conditions during model development, promoting rapid advances in model sophistication, accuracy, and relevance to earthquake processes.

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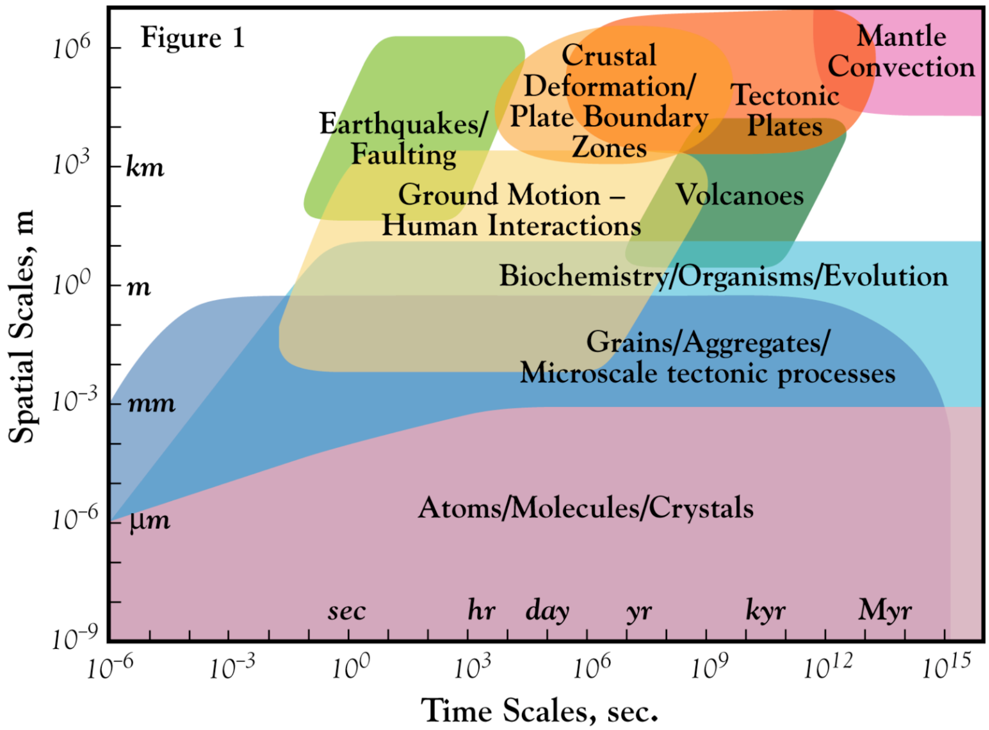

Figure 1: Time and spatial scales of earthquake-related processes that benefit from interactive visualization.

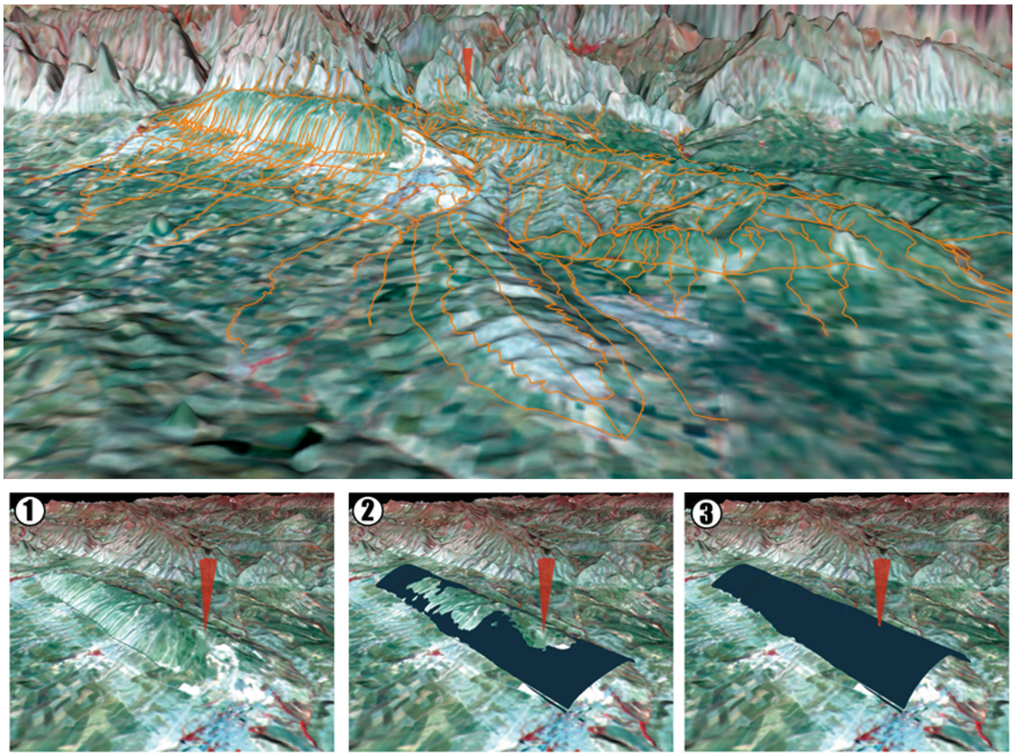

Figure 2. Top: Using the 3D view of RIMS with a twofold vertically exaggerated textured DEM, structures were more easily identified and could be directly mapped out. Bottom: Interpreting the 3D geometry of a surface (a fold). Modified after Bernardin et al. (2006)

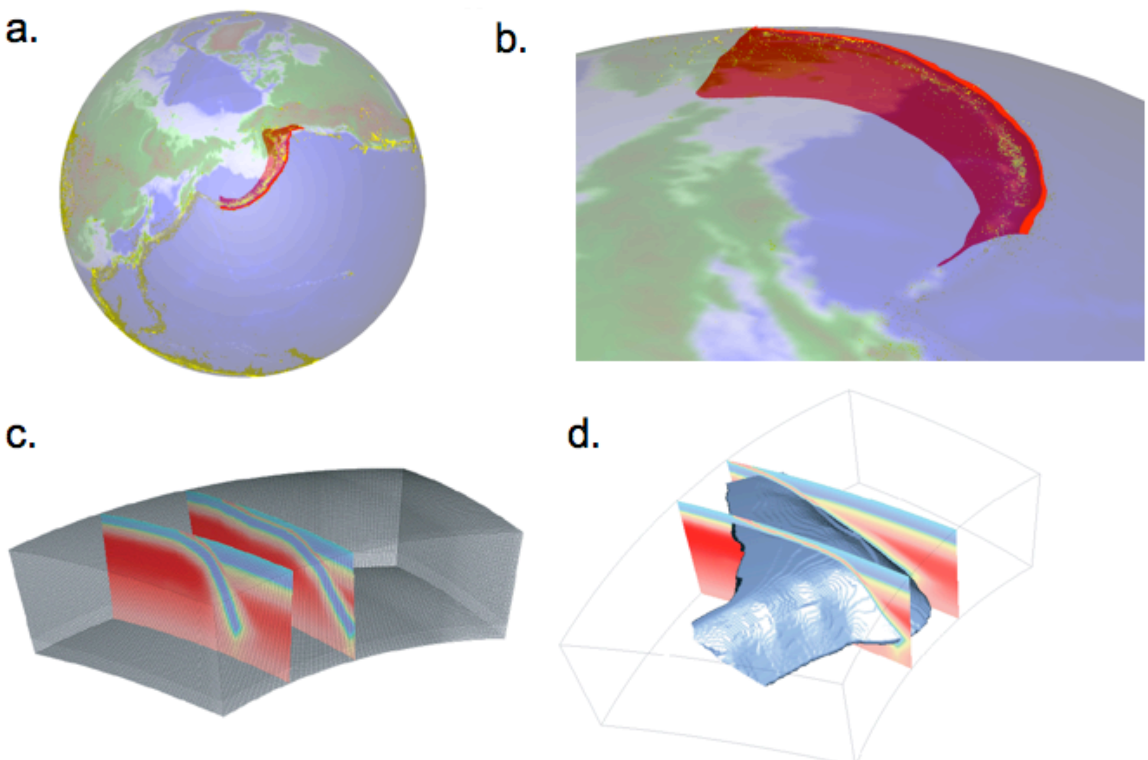

Figure 3. Constructing, viewing, and refining a model of a slab (adapted from the work of Jadamec and Billen 2006). (a) Global earthquake distribution in a transparent globe. (b) Slab surface constructed from seismic data (see text for references). (c) Arbitrary slices taken through a finite element model of a slab using the slicer tool. (d) Seeded isosurface with slices.

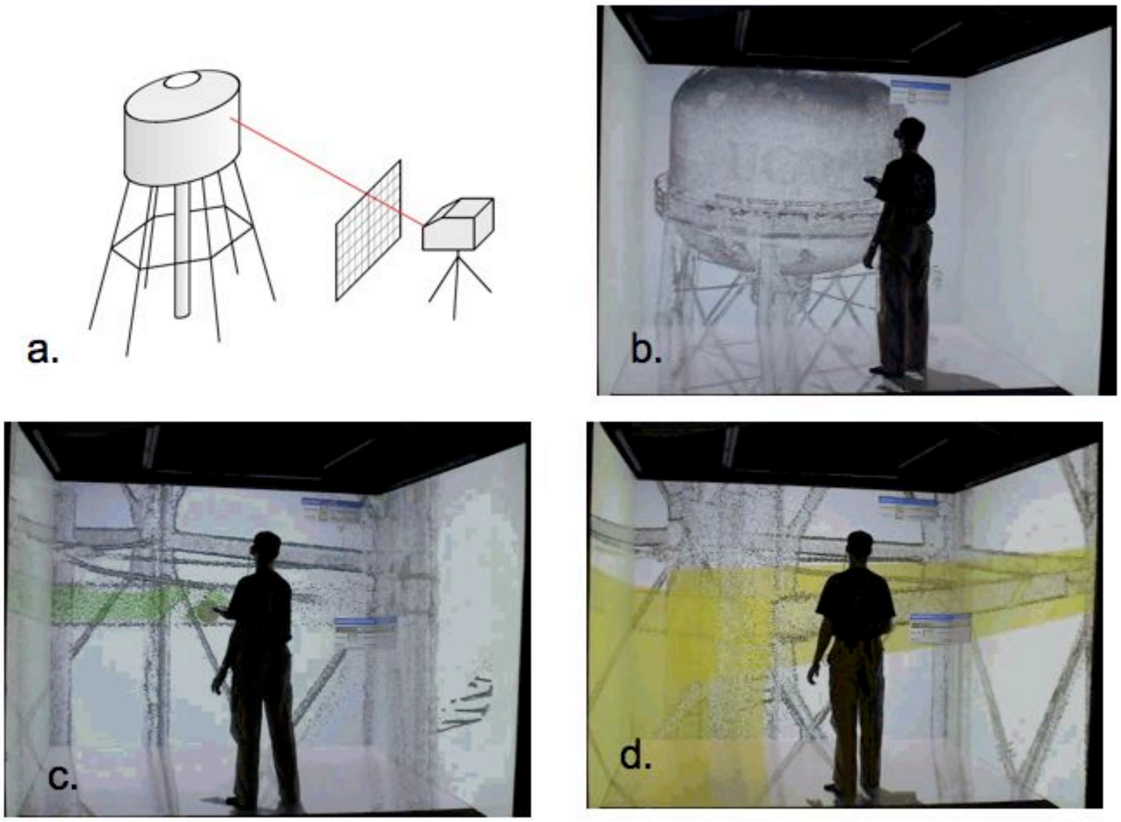

Figure 4. Working with tripod LIDAR (T-LIDAR) data in an immersive interactive visualization environment. (a) Schematic of tripod LIDAR data acquisition on, in this example, an engineered structure. (b) T-LIDAR scan of a watertower on the UC Davis campus: the user can take an otherwise unobtainable perspective next to the structure (c) A tool allows the user to select parts of the structure (here, a beam). The selection tool is represented by the sphere at the end of the hand-held wand (in the user's right hand). The selected points are green. (d) The final step in creating a model involves fitting a geometric function (a plane) to the selected points. Here two planes (yellow) have been fitted to points selected on two beams.