Chapter 13: U.S. Geological Survey: A Synopsis of Three-dimensional Modeling

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Mission and Organizational Needs

The U.S. Geological Survey (USGS) is a multidisciplinary agency that provides assessments of natural resources (geological, hydrological, biological), the disturbances that affect those resources, and the disturbances that affect the built environment, natural landscapes, and human society. Until now, USGS map products have been generated and distributed primarily as 2-D maps, occasionally providing cross sections or overlays, but rarely allowing the ability to characterize and understand 3-D systems, how they change over time (4-D), and how they interact. And yet, technological advances in monitoring natural resources and the environment, the ever-increasing diversity of information needed for holistic assessments, and the intrinsic 3-D/4-D nature of the information obtained increases our need to generate, verify, analyze, interpret, confirm, store, and distribute its scientific information and products using 3-D/4-D visualization, analysis, modeling tools, and information frameworks.

Today, USGS scientists use 3-D/4-D tools to (1) visualize and interpret geological information, (2) verify the data, and (3) verify their interpretations and models. 3-D/4-D visualization can be a powerful quality control tool in the analysis of large, multidimensional data sets. USGS scientists use 3-D/4-D technology for 3-D surface (i.e., 2.5-D) visualization as well as for 3-D volumetric analyses. Examples of geological mapping in 3-D include characterization of the subsurface for resource assessments, such as aquifer characterization in the central United States, and for input into process models, such as seismic hazards in the western United States.

The USGS seeks to expand its 3-D/4-D capabilities in monitoring, interpreting, and distributing natural resource information, both by adopting and/or developing new 3-D/4-D tools and frameworks and by promoting and enabling greater use of available technology.

Everything that shapes the Earth or affects its functions does so in 3-D space: water flowing over rocks, through aquifers, or as ice in glaciers; plants growing up into the atmosphere and down into the soil; the movement of animal life and pathogens within ecosystems; the movement of tectonic plates driven by deep convection beneath the crust; volcanic eruptions, floods, debris flows, and fires; the extraction, sequestration or migration of carbon, nutrients, contaminants, biota, minerals, energy, and other resources. Until recently, the computational and visualization power necessary to understand these complex systems was limited to a handful of supercomputing centers or industrious scientists. This situation has now changed: personal computers equipped with fast video cards and vast storage allow wide access to 3-D/4-D tools and visualization.

Business Model

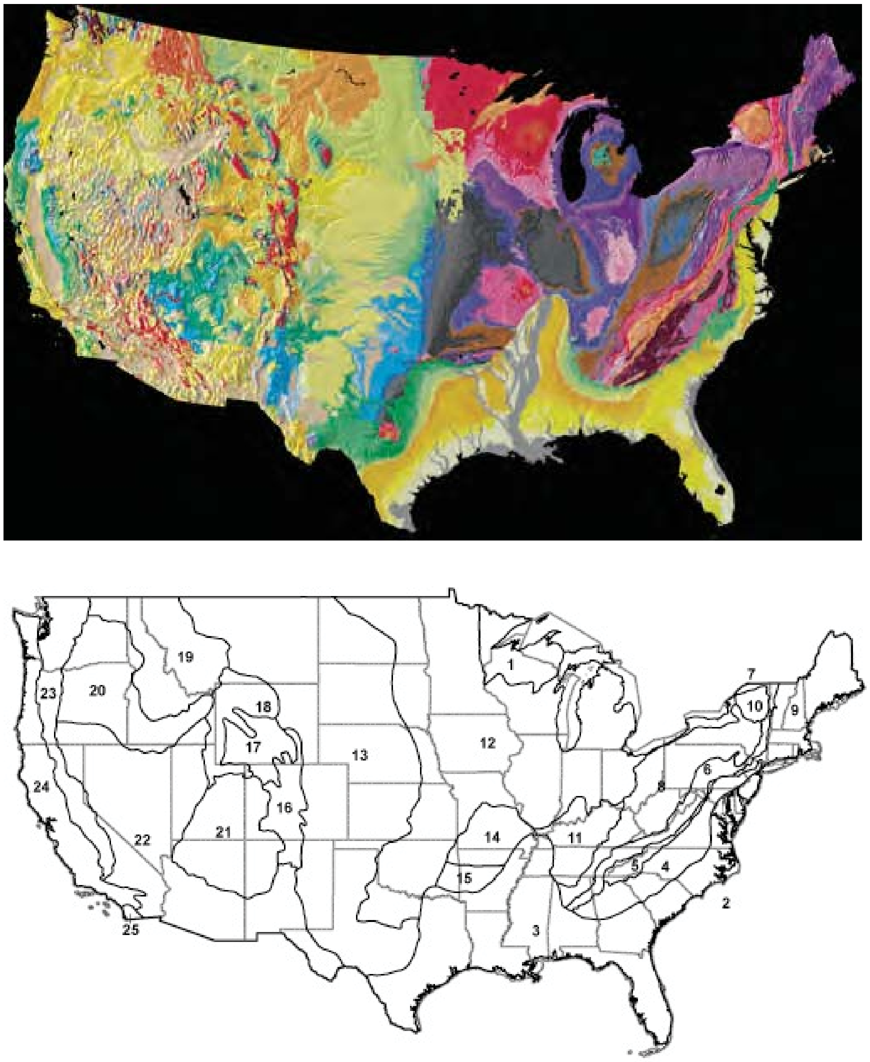
The annual USGS budget is approximately US$1 billion from federal appropriations. The bureau also receives about US$500 million from outside entities such as other federal agencies, foreign governments, international agencies, U.S. states, and local government sources. More than half of the outside funding supports collaborative work in water resources across the country, and the balance of the funding supports work in the geological, biological, and geographic sciences and information delivery.

The USGS has a workforce of approximately 9,000 distributed in three large centers (Reston, Virginia; Denver, Colorado; Menlo Park, California) and in numerous smaller science centers across the 50 states. Scientific work is organized into "projects" run by principal investigators (PIs) who have significant latitude in planning and conducting research, including acquisition of the resources (e.g., equipment, computers, software) needed to carry out their studies. Due to the distributed nature of management and personnel and due to the independence of the PIs, finding common organizational solutions is often a challenge. For example, concerns regarding optimal use of 3-D/4-D technology within the USGS include these:

- Many tools and solutions are expensive.
- The user community is not well coordinated and sometimes does not buy or share software licenses as a group. Buying power is not currently maximized.
- Pockets of specialists are emerging, but there are few forums for sharing ideas and expertise.
- Staying abreast of rapidly evolving technologies is difficult.

Geological Setting

The United States has a large variety of geological terranes that record more than 2 billion years of geological history (Figure 13-1). The complexity of U.S. geology ranges from horizontal stacking of sediments in the Great Plains, Colorado Plateau, and Coastal Plain Physiographic Provinces to overprinting of compressional, extensional, and transform tectonics of the Pacific Border Province of the western United States (Figure 13-1). These varied geological terranes present a challenge to



1. Superior Upland
2. Continental Shelf
3. Coastal Plain
4. Piedmont
5. Blue Ridge
6. Valley and Ridge
7. St. Lawrence Valley
8. Appalachian Plateau
9. New England
10. Adirondack
11. Interior Low Plateaus
12. Central Lowland
13. Great Plains
14. Ozark Plateaus
15. Ouachita
16. Southern Rocky Mtns
17. Wyoming Basin
18. Middle Rocky Mtns
19. Northern Rocky Mtns
20. Columbia Plateau
21. Colorado Plateau
22. Basin And Range
23. Cascade – Sierra Mtns
24. Pacific Border
25. Lower California

Figure 13-1 Simplified version of the King and Beikman (1974) geologic map of the conterminous United States. Colors indicate age of rock formations. Detailed explanation and digital versions are available at http://tapestry.usgs.gov and http://mrdata.usgs.gov/geology/kb.html.

3-D modeling of divergent and convergent plate boundaries, strike-slip fault zones, and the stable craton. Also, surficial geological processes of the last several million years have left variable unconsolidated deposits, including the voluminous deposition of glacial materials in New England and the northern conterminous United States.

The oldest rocks of the United States are igneous and metamorphic rocks that occur in the Adirondacks of New York and the Superior Uplands of Minnesota. These rocks contain complex fracture systems that can be modeled for water and mineral resources, but also have metamorphic fabrics inherent from high heat and pressures that occurred over many millions of years.

The United States contains fold and thrust belts that record several continental plate collisions. Examples of these are the Valley and Ridge, Blue Ridge, and Piedmont Provinces in the eastern United States where rocks were folded and faulted during four plate collision events between 1 billion years ago and 300 million years ago. The Rocky Mountains Province in the western United States records a collision event from about 40 million years ago. Along with overprinting of several tectonic events, these terranes include complex fold relationships and zones of intense faulting that must be taken into account in models. Linear trends of folds and faults are characteristics of these provinces.

Strike-slip fault systems, such as the San Andreas fault system of the Pacific Border Province in California, are regions of particularly complicated geology. As continental plates or structural blocks move past one another in a horizontal direction, complex compression and extensional structures occur. In this setting, rocks are translated great distances horizontally. These offsets are superimposed on a Mesozoic to Paleogene history of subduction, accretion, batholith formation, and extensive extensional attenuation. Understanding structural control and associated seismic hazards along strike-slip fault zones such as the San Andreas fault system requires the fusion of traditional geological mapping, geophysical measurements, seismology, structural geology, and state-of-the-art visualization and modeling techniques to produce detailed 3-D and 4-D geologic maps.

Extensional tectonic events are recorded in Triassic and Jurassic basin sediments within the Piedmont Province of the eastern United States and the Basin and Range Province of the western United States. In both regions, compressional tectonics resulted in folded and faulted rocks that were later torn apart and that developed basins that were filled with sediments shed off highlands. In the Piedmont of the eastern United States, this extension was associated with the opening of the Atlantic Ocean. For the Basin and Range Province, extension is related to back-arc spreading behind the Coast Range and Cascades Provinces.

Volcanic terranes occur in the western U.S. Cascades and Sierra Nevada Provinces. Large masses of intrusive igneous rock represent the deeply eroded roots of a Mesozoic volcanic arc and its Mesozoic and Paleozoic country rock in the Sierra Nevada and an active volcanic arc in the Cascades where the Juan de Fuca plate in the Pacific Ocean is being subducted beneath North America.

The sedimentary rocks of the Interior Plains and Atlantic and Gulf Coastal Plains reflect numerous periods of transgressing and regressing seas. These provinces are generally flat lying to gently dipping marine sediments that show complex facies changes over time. The Atlantic and Gulf Coastal Plain contains marine and terrestrial sediments that span more than 100 million years. In some areas, terrestrial river systems have also deposited sediments within these provinces, such as the Mississippi River in the Gulf Coastal Plain.

Several major glacial advances covered New England and the northern United States from 2.6 million years ago to about 11,000 years ago. The deposits that the melting glaciers left behind are quite variable and include silt, clay, sand, and till. These sediments have complex intertonguing relations that make 3-D modeling a challenge.

Major Clients and the Need for Models

Based on the needs of its clients and of the U.S. public, the USGS has identified seven major science strategy directions: ecosystems, wildlife and human health, climate change, energy and minerals, natural hazards, water availability, and data integration (U.S. Geological Survey 2007). Major users of USGS data and information include federal and state agencies, foreign governments, multinational agencies (e.g., International Atomic Energy Agency, World Meteorological Organization, Food and Agriculture Organization), and national and international nongovernmental organizations.

Because of its long-term monitoring data and resource assessments and the national and international scope of its science, resource and land management agencies use USGS science in developing policies that help them meet their stewardship responsibilities. For example, agencies in the U.S. Department of the Interior and the U.S. Department of Agriculture rely on USGS science to manage federal lands and resources. Other agencies, such as the U.S. Environmental Protection Agency, rely on USGS assessments of anthropogenic contaminants across the landscape to develop and enforce regulations. The USGS provides information that helps other agencies develop policy and provide warnings or mitigation strategies relating to hazards such as volcanoes, fire, floods, and earthquakes. The USGS is developing an ecosystem and global change (climate variability and land-use change) framework that will provide a context for its science and for its clients, such as regulatory and resource management agencies and public safety agencies.

Within the USGS, the greatest needs and applications of 3-D modeling and visualization have been emerging in geological, hydrogeologic, and biologic modeling and visualization. Specific needs include

- displaying, checking raw scientific data collected in multi-dimensional frameworks, and performing mathematical and statistical operation on the data, often all in real time;
- displaying temporal changes in primary scientific information in an “animated” 4-D framework (e.g., energy or material fluxes, disruptions in 3-D structures or boundaries, or changes in the intensities of given distributed characteristic properties);
- integrating diverse types (e.g., point, line, areal, volumetric) of primary spatial-temporal information for any given property (e.g., porosity, permeability, or any physiochemical property) in a 3-D/4-D visual environment that can display not only the information but also the associated uncertainties;
- inverse, statistical, geostatistical, stochastic, or other types of modeling to create 3-D/4-D realizations of natural phenomena;
- interpolating and extrapolating spatial and temporal values from data using a variety of methods and using interpreted and modeled information to build 3-D/4-D information frameworks, such as geological mapping frameworks, that maximize the use of the knowledge available for a given issue or given spatial system;
- maximizing our ability to use the information for given interpretive or predictive studies, simulations, and assessments; and
- using animations, fly-throughs, and data-discovery tools that help researchers individually or collaboratively conduct science and communicate results and their implications to each other, decision makers, and the public.
- providing example models.

Currently, the USGS employs a myriad of 3-D modeling and visualization programs (Table 13-1).

3-D/4-D Visualization for Geological Assessments

The USGS 3-D geological mapping efforts occur on a project-by-project basis. In addition to geological knowledge, at least one member of the staff has expertise in GIS and 3-D software. Others may have expertise in software specific to their discipline. The primary software packages used for, or in support of, 3-D geological mapping in the USGS are EarthVision, 3-D GeoModeller, Move, RockWorks, ArcMap, Oasis montaj, SGeMS, Encom PA, and in-house software for geophysical modeling. Recently published 3-D geologic maps (Faith et al. 2010, Pantea et al. 2008, Phelps et al. 2008) at the USGS incorporate new methods and proper-

Table 13-1 The 3-D modeling and visualization software programs used by the USGS.[1]

Software	Developer	URL
3D GeoModeller	Intrepid-BRGM	http://www.geomodeller.com/geo/index.php
3DMove ™	Midland Valley	http://www.mve.com/Move/advanced-structural-modelling-software-move.html
ArcGIS©	ESRI	http://www.esri.com/software/arcgis/index.html
ArcHydro©	AquaVeo TM	http://www.aquaveo.com/archydro-groundwater
ArcView, ArcMap	Rockware	http://www.rockware.com/product/overviewSection.php?id=189&section=54
Argus ONE	Argus Holdings, Ltd.	http://www.argusint.com/
COMSOL ™	COMSOL	http://www.comsol.com/
EarthVision®	Dynamic Graphics, Inc.	http://www.dgi.com/earthvision/evmain.html
Encom PA	Encom	http://www.encom.com.au/template2.asp?pageid=16
Erdas Imagine	Erdas	http://www.erdas.com/
Fledermaus	IVS 3D	http://www.ivs3d.com/products/fledermaus/
IDL/ENVI	ITT Visual Information Solutions	http://www.ittvis.com/
LiDAR Viewer	University of California Davis	http://www.keckcaves.org/software/lidar/index.html
Model Viewer	USGS	http://water.usgs.gov/nrp/gwsoftware/modelviewer/ModelViewer.html
MODFLOW, GWT, SUTRA, PHAST, MODELMUSE,USGS groundwater codes and visual interfaces	USGS	http://water.usgs.gov/software/lists/groundwater/ http://en.wikipedia.org/wiki/MODFLOW
Oasis montaj	GeoSoft	http://www.geosoft.com/pinfo/oasismontaj/keyfeatures.asp
PolyWorks®	InnovMetric Software, Inc	http://www.innovmetric.com/
Quick Terrain Modeler	Applied Imagery	http://www.appliedimagery.com/
Rockworks ™	RockWare	http://www.rockware.com/product/overview.php?id=165
SGeMS	Stanford University	http://sgems.sourceforge.net/?q=node/20
Voxler®, Surfer®	Golden Software	http://www.goldensoftware.com/products/products.shtml

[1]Use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

ties that go beyond the traditional 2-D geologic map:

- completing descriptions of characteristics of all significant geological features in a map (e.g., units, faults unconformities, structures, physical, and chemical properties), and the methods and techniques used to map them (Descriptions are necessary because 3-D geological mapping relies on a variety of unique mapping methods, whereas 2-D geological mapping uses a standard set of mapping techniques defined from more than a century of prior work.);
- defining some map features solely on the basis of geophysical expression;
- including a discussion of the data model used to construct the map;
- publishing the 3-D map in an open source format in addition to an encrypted proprietary format; and
- publishing geological features such that they can be individually extracted from the map for general use as stand-alone features.

3-D geological framework applications in the USGS include these examples:

- geological models for earthquake assessments and assessments of past tectonic displacements and predictive modeling of the potential impacts of given fault-slip scenarios;

- geological modeling for resource assessments (oil and gas, minerals, geological sequestration of carbon);
- inverse modeling of anomalous geophysical properties;
- visualization of magmatically driven bulging in volcanic areas and predictive modeling of eruption types and timing; and
- visualization and detection of surface structures and landscape changes, such as faults, landslides and debris flows, paleofloods, glaciers, and impact craters.

3-D/4-D Analyses and Use of LiDAR Imagery in Geological Modeling

Geomorphic and surface structure analyses are commonly conducted during mapping and modeling exercises. Indeed, 3-D/4-D analyses of earthquakes can provide valuable insights into the types of events that occurred, their impacts in modifying the land surface, and the likely stability or potential for post-event slip in the near future. For example, 3-D/4-D imagery analysis of precisely relocated earthquakes following the San Simeon earthquake in central California helped characterize the post-seismic slip and fault kinematics of the complex double blind thrust fault system (McLaren et al. 2008). Through 3-D surface contouring of time-varied earthquakes, common earthquake features were identified, mapped, and visualized, revealing the migration and rotation of the transient post-seismic strain migration as a function of time and depth. In another example, repeat ultra-high resolution (sub-centimeter) 3-D ground-based LiDAR imagery was collected in the days and months following the magnitude 6.0 Parkfield earthquake in central California. Immersive virtual reality 4-D analysis (Kreylos et al. 2006, Kellogg et al. 2008) of the land surface and engineered structural features illuminated small active tectonic geomorphic features that would have been overlooked in 2-D analysis. Furthermore, mathematical surface models of a bridge crossing the San Andreas fault near the epicenter showed over 7 cm of post-seismic slip in the 10 weeks after the main shock and bending of the steel support beams holding up the deck of the bridge.

Airborne and ground-based LiDAR have also contributed significantly to 3-D (and sometimes 4-D) geological mapping, particularly of potentially hazardous faults. Airborne LiDAR bare-earth models are especially helpful in heavily vegetated areas with little bedrock exposure. For example, large-scale LiDAR imaging and vegetation removal in the Puget Sound region of Washington state illuminated previously hidden faults and geomorphic expressions of past glacial epochs (Haugerud et al. 2003, Haugerud 2008). Similarly, a 37-km-long active fault was identified north of Lake Tahoe (California) within 500 m of a reservoir dam. The 4-D analysis of high-resolution T-LiDAR imagery determined that the fault was active and slipping at a rate of 0.5 mm/yr, which necessitated a reevaluation and reengineering of the reservoir construction (Hunter et al. 2010, Howle et al. 2009). Similarly, the 3-D/4-D fusion of ground-based and airborne LiDAR was used to measure offset in faulted glacier moraines in the eastern Sierra Nevada. Immersive virtual reality tools were then used to assess the quality of the merged products of the two different data types, allowing for detailed analysis and understanding of the seismic hazards of the newly identified fault system. 3-D/4-D hazard response analysis has also been used to assess structure and surface stability after landslides (e.g., the 2005 Laguna Beach landslide in southern California), rock slides, and debris flows (e.g., following major fires in steep terrain). Detailed 3-D/4-D analyses are used to characterize these events, understand their driving mechanisms, and provide rapid situation awareness to local authorities regarding the post-event stability of the land surface. Immersive 3-D/4-D virtual reality analyses often allow scientists to evaluate hazards in areas that are inaccessible because of ongoing safety concerns.

Case Study: The Hayward Fault—An Example of a 3-D Geological Information Framework

The 3-D geologic map of the Hayward fault in California was constructed to support modeling of earthquake hazards. Models that attempted to predict potential damage from various earthquake scenarios have until recently treated faults as vertical planes in semi-infinite half-spaces, primarily because of technological limitations. The 3-D geologic map of the Hayward fault was one of the first attempts to move away from simplified models and toward incorporating geology into the hazard scenarios. This change allows researchers to study the effect of fault curvature and rheology on fault movement and the resulting energy waves that travel across the landscape. Current research, based on this mapping effort, indicates that both fault curvature and changes in rheology across the fault can significantly affect its behavior (Barall et al. 2008).

The Hayward fault is considered to be the most dangerous fault in the San Francisco Bay region, located in central California (Figure 13-2). There is a 27% chance of a magnitude 6.7 or greater earthquake on this fault over the next 30 years (Working Group on California Earthquake Probabilities 2003). The Hayward fault cuts through several cities that form a densely populated urban area, making it even more dangerous than the nearby, better known San Andreas fault. Earthquakes generated along the fault threaten structures and critical lifelines that include conduits for transportation, power, and water.

A team of geologists and geophysicists explored various approaches of combining geologic map data with subsurface data to develop a 3-D earthquake hazard model of the Hayward fault. The team addressed geological questions regarding tectonics, structure, stratigraphy, and history of the region. The team also addressed broader issues related to mapping in 3-D in general,

Figure 13-2 Map showing the location of the San Francisco Bay region (inset). The red line demarcates the surface trace of the Hayward fault, and the blue rectangle shows the planimetric boundary of the 3-D map of the Hayward fault zone.

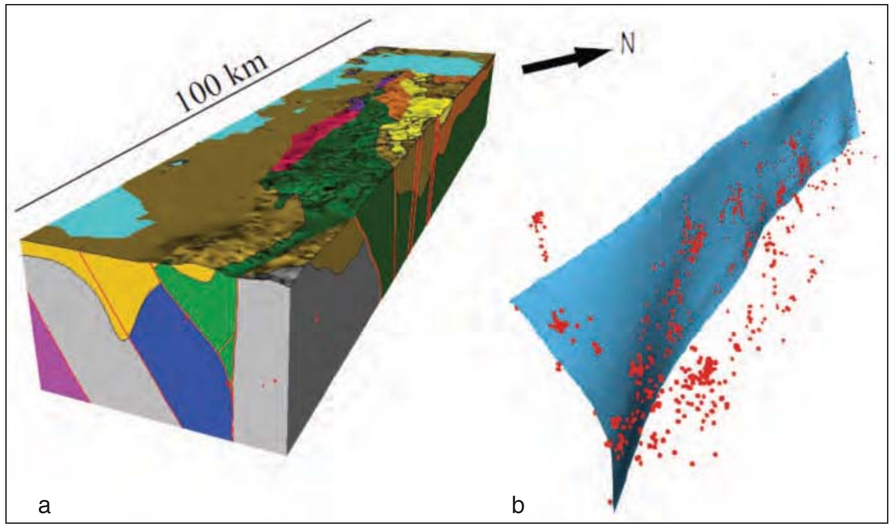


Figure 13-3 (a) Three-dimensional geologic map of the Hayward fault zone and (b) the Hayward fault surface extracted from the map, shown with accompanying earthquake hypocenters.

such as new mapping methods, resolution, uncertainty, database design, and publication options. The resulting 3-D map can be downloaded at http://pubs.usgs.gov/sim/3045. Correlations with fault behavior are discussed by Graymer et al. (2005).

The 3-D geologic map of the Hayward fault includes a volume of 100 × 20 × 14 km^3, with the fault approximately bisecting the long dimension (Figure 13-3). The Hayward fault is an oblique right-lateral strike-slip fault with a compressive component of about 10%. The mapped volume is geologically complex, formed of two contrasting amalgamated suites of Mesozoic terranes and overlying Cenozoic strata that have been juxtaposed by late Miocene and younger right-lateral offset of as much as 175 km. Consistent stratigraphy can usually be determined within the fault-bounded blocks but cannot be traced between them. The terranes themselves are fault-bounded packages of rocks emplaced, folded, faulted, and partially exhumed during subduction and subsequent extensional unroofing and faulted and translated during strike-slip faulting.

The structural style imposed by the complex tectonics of the San Francisco Bay region disallows the regular use of standard geological mapping tools, such as stratigraphic position and down-dip projection. In order to map geological units in 3-D, researchers had to define simplified mappable units, for the most part corresponding to entire terranes. The region lacked relevant well data, so ample use was made of geophysical data to define the subsurface shape of the critical geological features.

Model Construction Methodology

Several somewhat independent modeling efforts mapped individual geological features. The Hayward fault itself was mapped as a single surface using a combination of seismic data and cross sections. Several of the other faults in the model were mapped at the surface and projected downward based on the grain of local and regional geology. Two basins within the model were defined on the basis of their gravitational signature. A subsurface unit, thought to be volcanic, was defined on the basis of its magnetic signature. Geological terranes were mapped at the surface and constrained at depth by faults, their magnetic signature, and other modeled geological features.

These individually modeled features were combined into a unified 3-D geologic map in the proprietary software EarthVision. In the EarthVision data model, faults are surfaces that have precedence over (truncate) all other surfaces. Faults are specified in a hierarchy to determine which faults cut which other surfaces. Unconformities are surfaces that truncate other nonfault surfaces, and depositional surfaces onlap onto other surfaces. Modeled geological features were defined in EarthVision by their bounding surfaces according to the data model. Property information for geological unit volumes, such as formation name, are stored internally but can be queried interactively by modifying the unit volume color based on a property or by interactively clicking on a volume to retrieve the properties.

Once the model was constructed, it was evaluated by project members and received two scientific reviews external to the project. The reviewers interactively explored the map itself and examined the accompanying map pamphlet to look for geological inconsistencies in a manner similar to the review process for printed USGS geologic maps. Review comments were resolved through further collaborative modeling and mapping.

Output

The final publication contains a digital 3-D geologic map, an accompanying informational pamphlet, and a map plate that displays various views of the 3-D map. The map is published in two formats. The first is available in a free version of the 3-D viewer from the proprietary software EarthVision. The map can be viewed in a variety of ways but cannot be modified. The second format makes the fault surfaces and boundaries of the geological units available as a series of files stored in the open-source t-surf format. A user can reconstruct part or all of the features in the Hayward map from the surfaces, and this format has a lifespan longer than the free 3-D EarthVision viewer, which will become increasingly out of sync with newer operating systems. It is also expected that these geological features will be integrated with other data sets including lifeline and infrastructure data.

The pamphlet includes a discussion of the geological setting and history, a description of map features, including map units, map structures, and the data and modeling methods used to generate each feature in the model (feature-level metadata).

Observations, Suggestions, and Best Practices

The diminishing amount of data with depth has several implications:

- Resolution decreases dramatically with depth, geological units in 3-D may be simplified compared with units mapped at the Earth's surface, geophysics is important for modeling and constraining geology at depth, and a range of expertise is needed to process and model various data types.
- Geological mapping can be expanded to include mapping based on geophysical models of geological features in the subsurface. Rather than a description of the rock's appearance in outcrop, a description of the geophysical characteristics and geological and geophysical context is provided.
- Features in the geological map are often themselves the result of an individual modeling effort; the 3-D geological map is an amalgamation of models brought together to form a coherent geological map.
- When constructing the map, critical features (faults and unconformities) that will form the framework of the map need to be identified and built in first to allow the structural and topological relationships to be more easily seen, corrected, and verified early in the mapping process.
- The map should maintain both geological and database integrity; that is, geological rules should not be violated, topological rules should not be violated, and any associated tables should maintain database integrity.
- Putting the "best available data" into a 3-D map is not always practical. Although in theory digital geologic maps can accommodate scales from the microscopic to continental, in practice current software limitations prevent a wide range of resolutions within a map. For example, LiDAR could not have been used as the model of the Earth's surface in the 3-D geologic map of the Hayward fault zone because the data volume could not be supported.
- The 3-D map can exist in its entirety only on a computer; as such, a 3-D viewing tool that can spin, slice, take apart, and query features in the map is a necessity.

Several steps can be taken to alleviate dependence on a particular software package:

- Describe the data model in the text.
- Publish an open-source version of the 3-D map.
- Ensure that eatures within the map can be extracted so that they can be studied independent of the map.
- Ensure that the software can accommodate complex structures that have multiple z-values, including oblique-slip faults, overturned folds, and diapirs.

Case Study: Santa Fe, New Mexico, 3-D Modeling as a Data Integrator

Many geological mapping projects at the USGS involve the development of regional geological frameworks to serve as the basis for understanding groundwater, geological hazards, and natural resources. Project goals focus on extrapolating geological mapping from the surface to depths greater than 1 km over large areas where little borehole information exists. To extrapolate below ground, we acquire airborne geophysics, fill in existing gravity coverage, and collect ground-based geophysics in critical areas. Each of these geophysical data sets provides information on diverse aspects of different physical properties of the Earth, which then must be interpreted in the context of the geology of the area.

In a study near Santa Fe, New Mexico, USA, Grauch et al. (2009) found that 3D GeoModeller was well suited to integrating such diverse types of input in a 3-D world (Figure 13-4). An important objective of the study was to model the position of the surface representing the bottom of the sedimentary section. This surface was needed to assess the aquifer and for groundwater modeling. Using a mixed data-driven and expert-controlled 3-D modeling approach, 3D GeoModeller allowed simultaneous data integration, synthesis, and geological interpretation of geophysical data in conjunction with 3-D geological mapping. Advantages to 3D GeoModeller are that it (1) directly incorporates geological field and borehole data, such as mapped contacts, borehole lithologic contacts, and strike and dip measurements, (2) ensures that the model follows known geological relationships in the area in 3-D, (3) allows indirect input of derivative geophysical products and geological concepts as guides to the geological modeling, (4) provides geophysical forward and inverse modeling to check for geophysical validity, and (5) allows an individual to work in either a 2-D (cross section) or 3-D (points-in-space) environment.

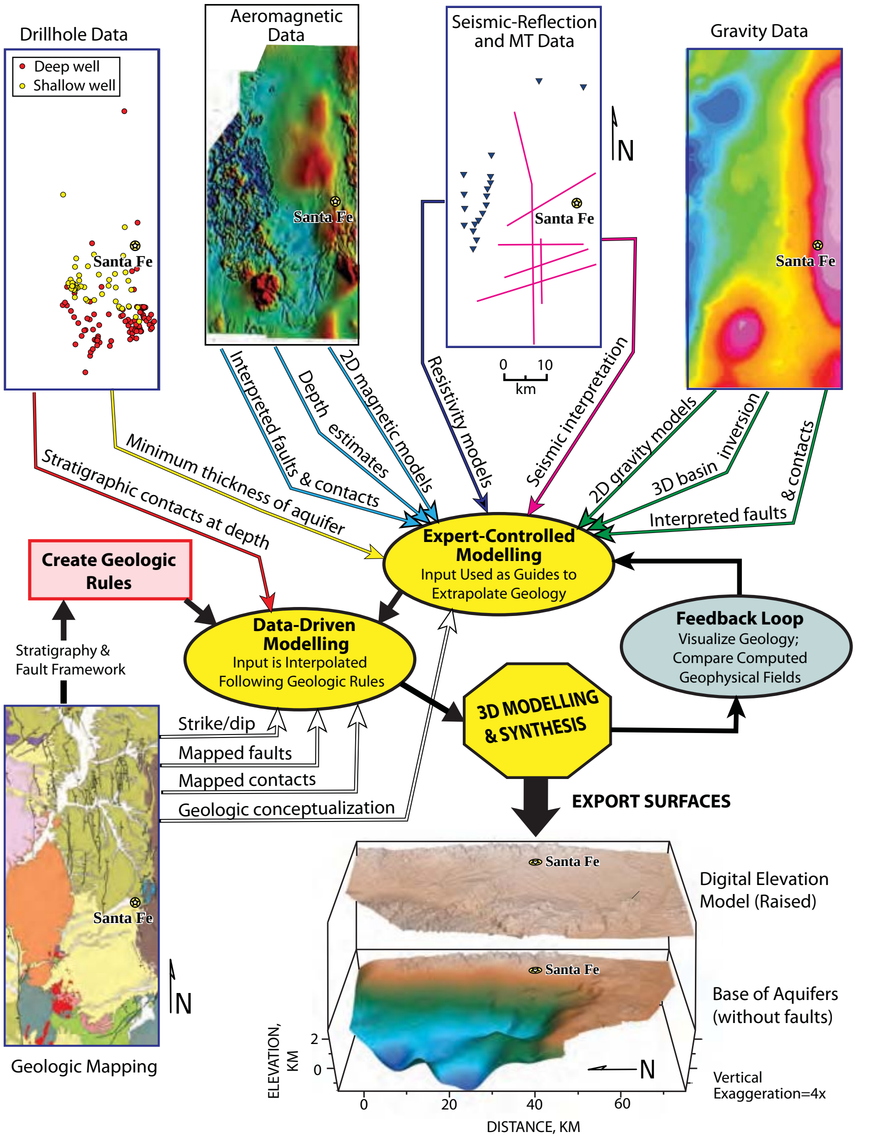


Figure 13-4 Work flow that uses 3-D modeling to integrate and synthesize diverse types of geological and geophysical information for a basin study near Santa Fe, New Mexico, USA (Grauch et al. 2009). Although 3D GeoModeller (BRGM-Intrepid Geophysics) was used for the synthesis (yellow workflow steps), a variety of other software packages were used to analyze geophysical data beforehand, including Oasis montaj and GM-SYS (Geosoft), Geotools MT (AOA Geophysics, Inc.), and methods and software developed by the USGS (Jachens and Moring 1990, Phillips 1997). 3-D visualization is from Oasis montaj.

3-D/4-D Visualization and Geological Modeling for Hydrologic and Biologic Assessments

The need to display and integrate increasingly large data sets and the need to analyze, often collaboratively, a wide variety of multidisciplinary information necessitates using the most advanced visualization tools available, such as 4-D immersive virtual reality systems. Traditional 2-D analyses and rudimentary 3-D analyses (e.g., stereoimages on ordinary 2-D computer screens) are inefficient and do not measure up to the complexity of the interdisciplinary analyses and interpretations that are required. Collaboration among scientists, who often do not have the same scientific disciplinary backgrounds and therefore lack a common scientific language, can be made significantly easier through the use of advanced 4-D immersive visualization systems. These systems utilize the spatial-temporal skills innately developed in people as they interact with their environment and help scientists communicate with each other. This section provides a "walkthrough" of example applications of 3-D/4-D technology in the hydrologic and biologic sciences, from the atmosphere to the subsurface.

Visualizing and representing atmospheric hydrologic processes are essential to the USGS mission. The USGS must be able to understand how orographic processes can affect precipitation, specifically types of precipitation (rain, hail, snow) as well as duration and intensity, over a spectrum of spatial and temporal scales. Visualizing, understanding, and predicting the focusing of precipitation and consequent impacts can help mitigate the damages caused by flooding, landslides, or debris flows. Visualization tools, coupled with "before and after" landscape surveys (e.g., through remote sensing or LiDAR), are being used to benchmark current landscape conditions and to help characterize and model the magnitude and extent of atmospheric events in terms of natural hazards, water availability, ecosystem response, and long-term climatic variability.

The interrelationship of temperature and topography affects our landscapes, their associated ecosystems, and their evolution in time. For example, visualizing and predicting temperature distributions across a mountainous landscape or watershed helps understanding of biologic habitats and how they may change. Understanding and visualizing topographic and climatic drivers can help predict the movement and intensity of fires, the spread of pests or invasive species, and/or the migration or extinction of species. USGS scientists also routinely collect high-resolution 4-D snow depth change data and combine the data with climate models to estimate daily snow melt runoff as a function of solar radiation and incident angle at various elevations. Climate forecast models using 4-D climate data and different global warming scenarios help us understand how ecosystems and water availability might change in the future.

Visualization in 4-D is needed to plan and manage water resources, their availability, and their quality and to plan the investments needed for their sustainable and balanced use and protection. Visualization is needed to understand the effects of (1) climate change on the storage and release of water at higher elevations, (2) land-use change on groundwater recharge, particularly at lower elevations, and (3) climate, land-use, and anthropogenic changes and natural system dynamics on the timing and intensity of the water cycle and its spatial distribution. Groundwater withdrawals not only impact water sustainability in arid or semi-arid environments but can also produce substantial land subsidence, damage infrastructure, and irreversibly decrease an aquifer's ability to store water (Figure 13-5). Repeat satellite InSAR (Synthetic Aperture Radar Interferometery) imagery of active hydrocarbon fields can show how the land surface responds over time to hydrocarbon pumping and CO_2 and water injection. The 3-D/4-D visualization can help show what areas are at the greatest risk and can be used in optimization modeling to more efficiently manage and distribute pumping and recharge in a given area.

The USGS also conducts work visualizing and predicting the impacts of sea level rise and salinity intrusion on coastal habitats (human and natural). Although fixed-level 3-D flooding maps are useful as a first cut interpretation of the consequences of floods or sea level rise, the USGS also uses 4-D dynamic visualization of flood waves, storm surges, tsunamis, tidal surges, and outflows. Deterministic, predictive models, based on mathematical descriptions of both the operative physical processes and mass and energy conservation relations, are often displayed using advanced visualization systems to enhance dynamic patterns that would not otherwise be apparent.

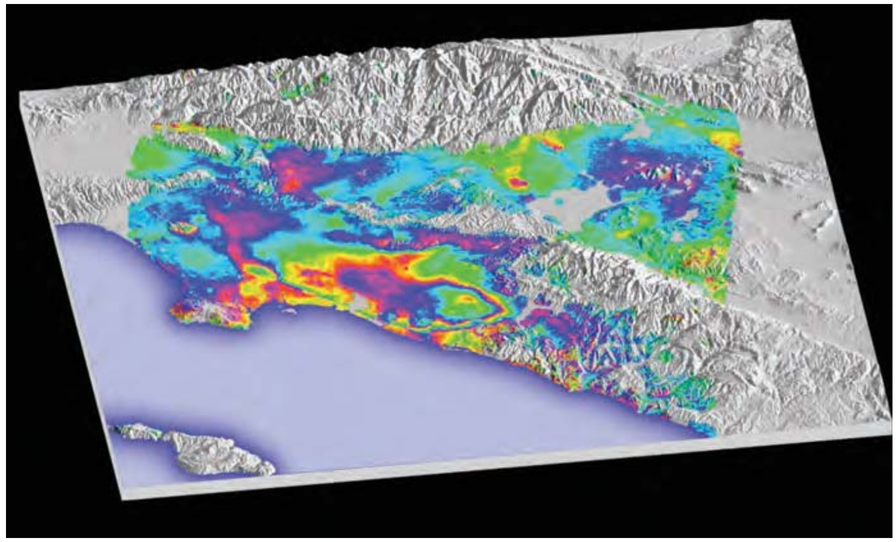


Figure 13-5 Perspective view of the greater Los Angeles region with InSAR imagery showing greater than 6 cm of groundwater pumping-induced subsidence over a region 40 km x 20 km in extent (Bawden et al. 2001).

The USGS extensively uses 3-D/4-D visualization tools (non-stereo) in the representation and modeling of subsurface flow and contaminant transport. In these studies, 3-D/4-D visualization is essential in

- representing and checking the available data and information in a geological context;
- assessing relevant geological structures, as well as the spatial distribution and temporal evolution of the hydrogeological (Figure 13-6) and chemical properties of those structures, i.e., the porosity, permeability, mineralogy, and chemistry associated with various geological units, their matrix, and structural features (open, closed, or partially filled), such as active faults, fractures, joints, channels, and macropores;
- using integrative hydrologic, chemical, or geophysical response information to help determine, through "inverse modeling" numerical simulations, the spatial distribution of hydrogeological or geological properties in various subsurface zones; and
- using predictive or "forward" modeling to numerically simulate the potential movement of water, solutes, contaminants, colloids, viruses, or bacteria in the subsurface and the coupled evolution of the hydrogeological environment.

Hydrogeological studies have focused primarily on the shallow subsurface, which is usually the primary provider of groundwater resources for irrigation or drinking water. Most groundwater contamination studies have also focused on the shallow subsurface because of the importance of its human use and because of its high vulnerability to contamination. Hydrogeological studies and visualization of deeper environments have until recently been mainly confined to studies of sites that might be suitable for the disposal of nuclear wastes (Figure 13-7) or the injection of other industrial wastes. The potential for using geological formations, specifically former oil and gas reservoirs, coal seams, and saline aquifers for the geological sequestration of supercritical CO_2, will likely result in a much greater number of hydrogeological studies investigating the deeper regions of the subsurface. If geological sequestration of CO_2 becomes widely implemented, we expect an exponential increase in

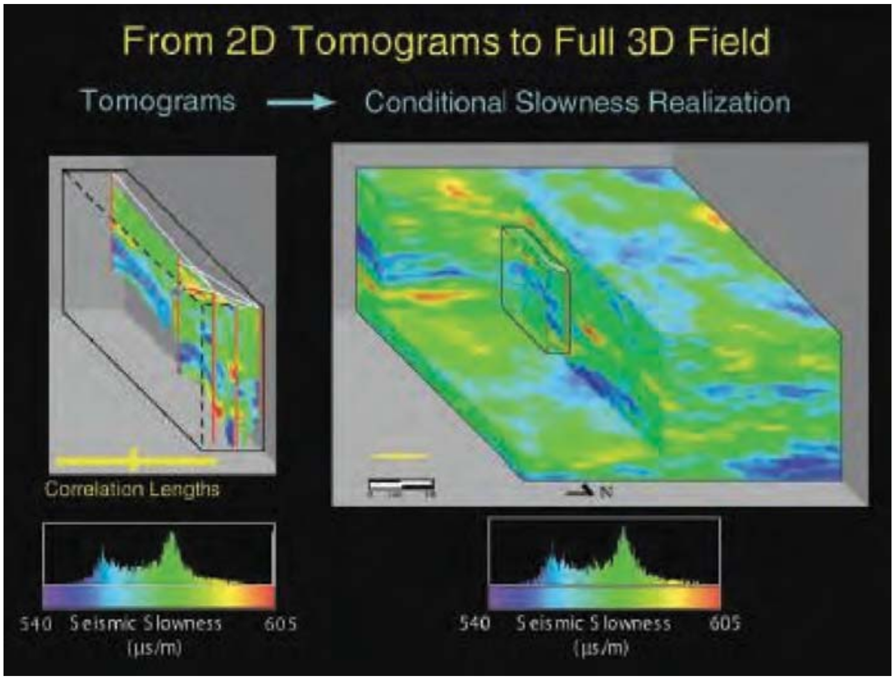


Figure 13-6 Three-dimensional images from seismic surveys of the speed of shock waves through sediment (Hyndman et al. 2000). The speed of waves is controlled partly by the compressibility of the sediment, which is related to the hydraulic conductivity. Therefore, it may be possible to use seismic images to better map heterogeneity in unconsolidated aquifers (from Sanford et al. 2006).

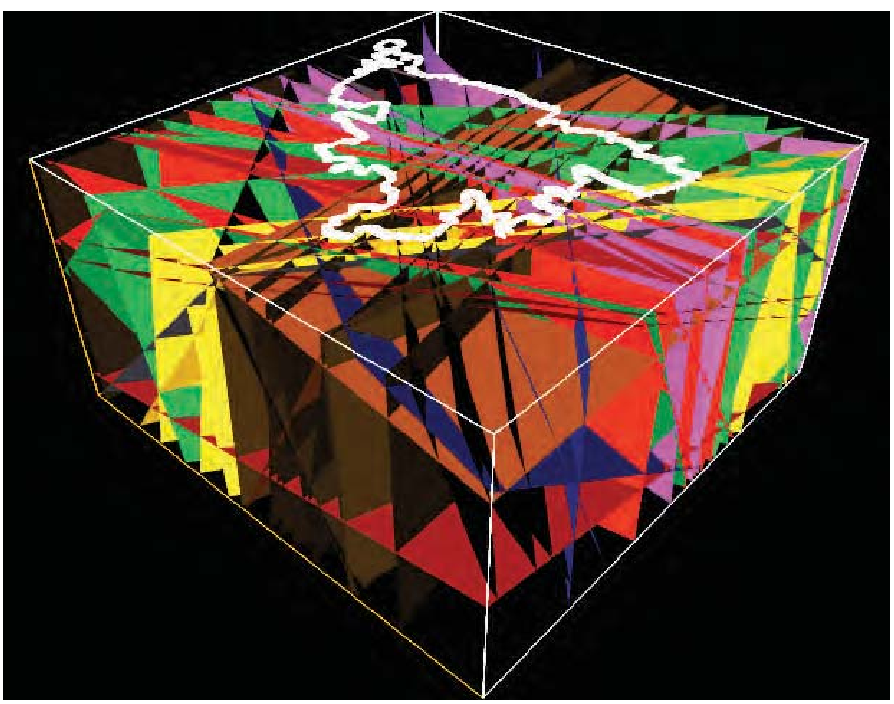


Figure 13-7 Fracture model of the Äspö Hard Rock Laboratory (SKI SITE-94 1997, Glynn and Voss 1999).

studies and geological and hydrologic information obtained for subsurface environments. Once again, having ready access to 3-D/4-D visualization and information frameworks and interpretive tools will be key in making well-informed assessments and decisions based on clearly represented, understood, and quality-controlled data and information.

Lessons Learned

In 2010, a small group of USGS managers and scientists recognized that individual researchers and teams were acquiring 3-D technologies across the USGS with little to no knowledge of other similar efforts. The group also observed that thousands of dollars were being spent on individual licenses across the bureau with no coordination, and, although many scientists were adding 3-D applications as analysis tools, there were few forums for sharing ideas and knowledge of emerging technologies. These findings led to efforts to endeavor to increase communication and coordination across the bureau via workshops; a user-survey; development of a database of 3-D systems, requirements, and users; and use of community-of-practice tools, such as a wiki.

Workshops

A workshop called "3D Visualizations of Geological and Hydrogeological Systems," held during an annual USGS Modeling Conference, drew almost 50 participants primarily from federal agencies and academia. The purpose of the workshop was to preview state-of-the-art 3-D characterization software and hardware to expand the reach of geological and hydrogeological assessments. Vendors were invited to demonstrate 3-D visualization products, and participants contributed their requirements and knowledge of 3-D visualization tools. Also, a diverse cross section of USGS researchers who are experienced users of 3-D systems was convened to discuss USGS requirements and share knowledge. The result of the meeting was an action plan to better coordinate future purchases, stay in step with technological advances, define and increase opportunities for data integration, and champion communities of practice.

User Survey

The USGS will conduct a Web-based survey of staff identified as using or having an interest in using 3-D applications. The goal of the survey is (1) to identify the areas of scientific study that employ 3-D/4-D technologies, how the technologies are applied in research, what barriers might exist preventing scientists from applying these technologies, and (2) to raise awareness of a new community designed to broaden the availability of 3-D/4-D technology and the knowledge surrounding it. The survey results will also be used to construct the 3-D systems database.

3-D Systems Database

The USGS is developing a Web-based database to serve as a shared resource for exploring the various 3-D visualization systems used throughout the bureau. This storehouse will contain detailed information regarding hardware configurations, visualization systems, software packages, costs, available licenses and/or available hardware, and requirements for use. Points of contact are provided along with any relevant videos that help convey the types of applications that have been developed using 3-D technology. Additional information is provided in the form of documents, Web sites, and slide presentations. Users will be encouraged to add comments, opinions, and observations to help make the 3-D resources useful to both new and experienced users to enhance their knowledge and help them research new software and hardware platforms.

Synopsis of Current Three-dimensional Geological Mapping and Modeling in Geological Survey Organizations

Editors

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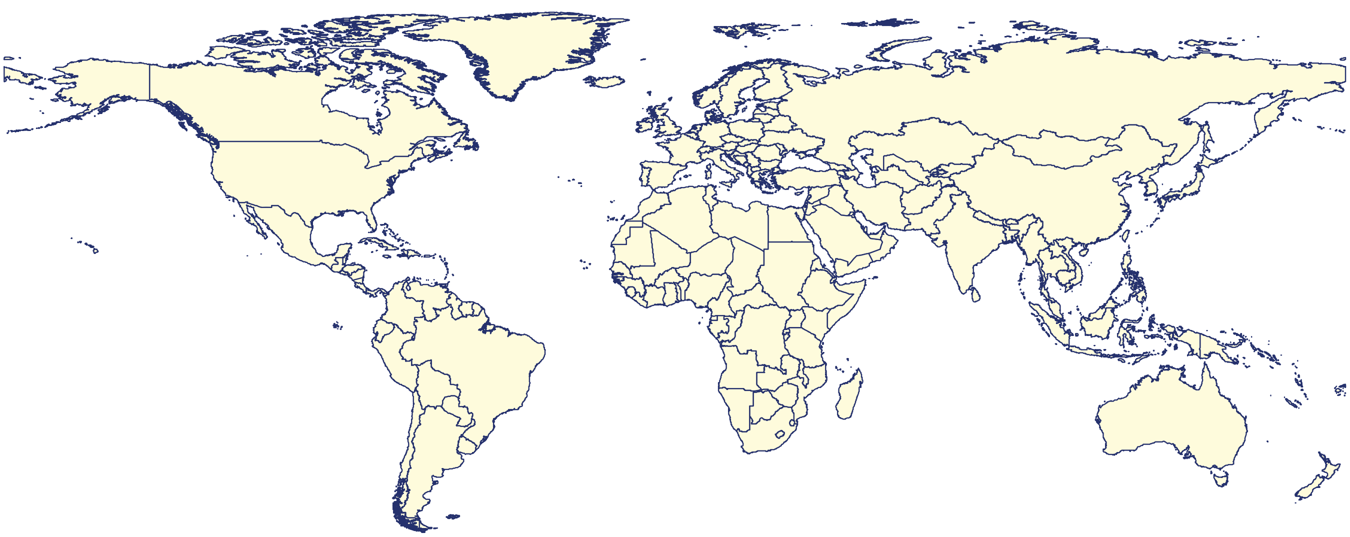

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Front Cover: *GCS_WGS_ 1984 projection of the world.*

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DISCLAIMER: Use of trade names is for descriptive purposes only and does not imply endorsement.

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