Chapter 26: Status of Three-Dimensional Geological Mapping and Modelling Activities in the U.S. Geological Survey

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Introduction

The U.S. Geological Survey (USGS), created in 1879, is the national geological survey for the United States and the sole science agency within its cabinet-level bureau, the Department of the Interior. The USGS has a broad mission, including: serving the Nation by providing reliable scientific information to describe and understand the Earth; minimize loss of life and property from natural disasters; manage water, biological, energy, and mineral resources; and enhance and protect quality of life. USGS scientific activities are organized around major topics, or Mission Areas, aligned with distinct science themes; three-dimensional (3D) modelling typically supports research and project work within a specific Mission Area. The vastness, diversity, and complexity of the geological landscape of the United States has resulted in the creation of 3D geological framework models that are local or regional in scale; a National-scale 3D model is only beginning to evolve. This paper summarizes 3D geological modelling at the USGS and does not discuss 3D modelling that is conducted by other Federal agencies, state geological surveys, academia, or industry within the U.S. This paper updates and expands upon a similar status report of USGS 3D modelling activities of Jacobsen et al. (2011).

Organizational Structure and Business Model

In 2010, the USGS was organized into major topics, or Mission Areas, that were aligned with the broad science themes outlined in a 10-year Bureau-level Science Strategy (U.S. Geological Survey, 2007): Land Resources, Core Science Systems (which includes the National Cooperative Geologic Mapping Program), Ecosystems, Energy and Minerals, Environmental Health, Natural Hazards, and Water Resources. At the same time, 10-year science strategies were created for each of the USGS Mission Areas and for the programs focused on those topics (e.g., Evenson et al. 2013; Ferrero et al. 2013).

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 the Water Mission Area, and the balance of the funding supports work in the geological, biological, and geographic sciences and information delivery. The USGS workforce is approximately 9,000 distributed in three large centers (Reston, Virginia; Denver, Colorado; San Francisco Bay area, California) and in numerous smaller science centers across the 50 states (Jacobsen et al. 2011).

Scientific work is organized into "projects" run by principal investigators (PIs) who have significant latitude in planning and conducting research in accordance with Program-level guidance, including acquisition of the resources (e.g., equipment, computers, software, and data) needed to carry out their studies. USGS 3D geological mapping efforts typically occur on a project-by-project basis, and 3D modelling activities are decentralized and spread across USGS Mission Areas. The USGS uses a myriad of 3D modelling and visualization programs (Jacobsen et al. 2011) due to the variety of 3D applications, the distributed nature of scientific projects throughout USGS, and differences in scientific focus between Mission Areas. As a result, implementing a single organization-wide software platform is challenging and perhaps not even desirable.

Overview of 3D Modelling Activities

Within the Energy and Minerals Mission Area, a wide variety of 3D data management, modelling, and visualization tools are applied as part of resource assessments. In Energy, 3D geologic models are built as standalone research projects for reservoir characterization and as geologic input to 4D pressure, volume, temperature models that are used in petroleum geology assessments to understand and delineate areas that are thermally mature for oil and gas generation, evaluate timing of generation and migration relative to tectonic events and trap formation, and determine volumes of generated hydrocarbons for each modelled petroleum source rock. 3D data are released as grid files of elevation and thickness, and 3D model files with model-viewing capability (Higley et al. 2006; Higley, 2014; Hosford Schierer, 2007). Geothermal energy assessments increasingly use 3D geologic models in developing the structural framework to locate intersections of faults at geothermal prospects. In Minerals, 3D modelling includes 3D representation of geophysically derived surfaces and forward modelling of geophysical data to create 3D geologic models to support mineral-resources assessments and research. Recent emphasis on mineral commodities considered critical to the economic and national security of the United States (Schulz et al. 2017), particularly in areas buried beneath glacial or Phanerozoic cover, require extrapolating geological mapping from the surface to depths greater than 1 km over large areas where little borehole information exists. To extrapolate below ground, various geophysical datasets are integrated with surface geologic and borehole data to develop a 3D geologic model of the region (e.g., Drenth et al. 2015; Finn et al. 2015). In areas of thick cover where borehole data are sparse, much of the region's geology and mineral potential is poorly constrained and geophysical methods are a primary means of developing a 3D subsurface representation.

Within the Water Resources Mission Area, the USGS has conducted regional hydrologic studies of principal aquifer systems (Figure 1) under the Groundwater Resources Program (Reilly et al. 2008) and currently as part of the USGS National Water Availability and Use Program (Evenson et al. 2018). Regional groundwater availability studies typically include a conceptualization of the hydrogeologic system, inventory of hydrologic data sets, and construction of a numerical simulation (e.g., Faunt, 2009; Feinstein et al. 2010; Heilweil and Brooks, 2011; Brooks et al. 2014). Understanding of groundwater flow systems is enhanced through the development of 3D hydrogeologic framework models produced as part of the regional study (e.g., Burns et al. 2011; Feinstein et al. 2010) or created by the USGS National Cooperative Geologic Mapping Program or state geological surveys. These 3D framework models are produced for regional water-availability assessments and are not intended to be components of a national geological model, yet are comparable in areal size to national-scale models produced by other national geological agencies (Figure 1; Table 1). At the groundwater basin scale, 3D modelling activities focus on the thickness and extent of specific aquifers, the configuration of the basin, and the geometry of faults that affect the aquifers (Pantea et al. 2011; Sweetkind, 2017; Page et al. 2018).

Within the Hazards Mission Area, 3D geologic modelling activities include building geologically realistic fault-block models used for incorporating geology into hazard scenarios (e.g., Phelps et al. 2008) and the development of crustal-scale 3D fault surfaces to help characterize complex patterns of fault interactions and 3D deformation (e.g., Plesch et al. 2007; Nicholson et al. 2014). Crustal-scale models for seismic hazard analysis incorporate geology-based 3D seismic velocity models that are used to model the propagation of seismic energy through the upper to middle crust (e.g., McPhee et al. 2007, Aagard et al. 2010). National scale three-dimensional geophysical structure based on knowledge of surface and subsurface geologic variations will assist with earthquake hazard risk assessment by supporting estimates of ground shaking in response to an earthquake (Boyd and Shah, 2018; Shah and Boyd, 2018). For assessment of volcanic hazards, 3D models of hydrothermal alteration and water content derived from airborne geophysical data delineate zones susceptible to sector collapse of Cascade arc volcanoes and subsequent destructive lahars (Finn et al. 2007; 2018) in addition to mapping structure and volume of volcanic products (Langenheim et al. 2016) and the magmatic system beneath Mono Basin (Peacock et al. 2015).

Resources Allocated to 3D Modelling Activities

An estimated 50 to 100 people within the USGS routinely or occasionally conduct geological 3D modelling activities. These scientists are dispersed across the organization and 3D geological mapping efforts occur on a project-by-project basis. A far greater number of staff are able to visualize data in 3D, including the analysis and use of airborne and ground-based LiDAR and using animations, fly-throughs, and data-discovery tools to help researchers conduct science and communicate results.

Overview of Regional Geological Setting

The United States has a large variety of geological terranes that record more than 2 billion years of geologi-

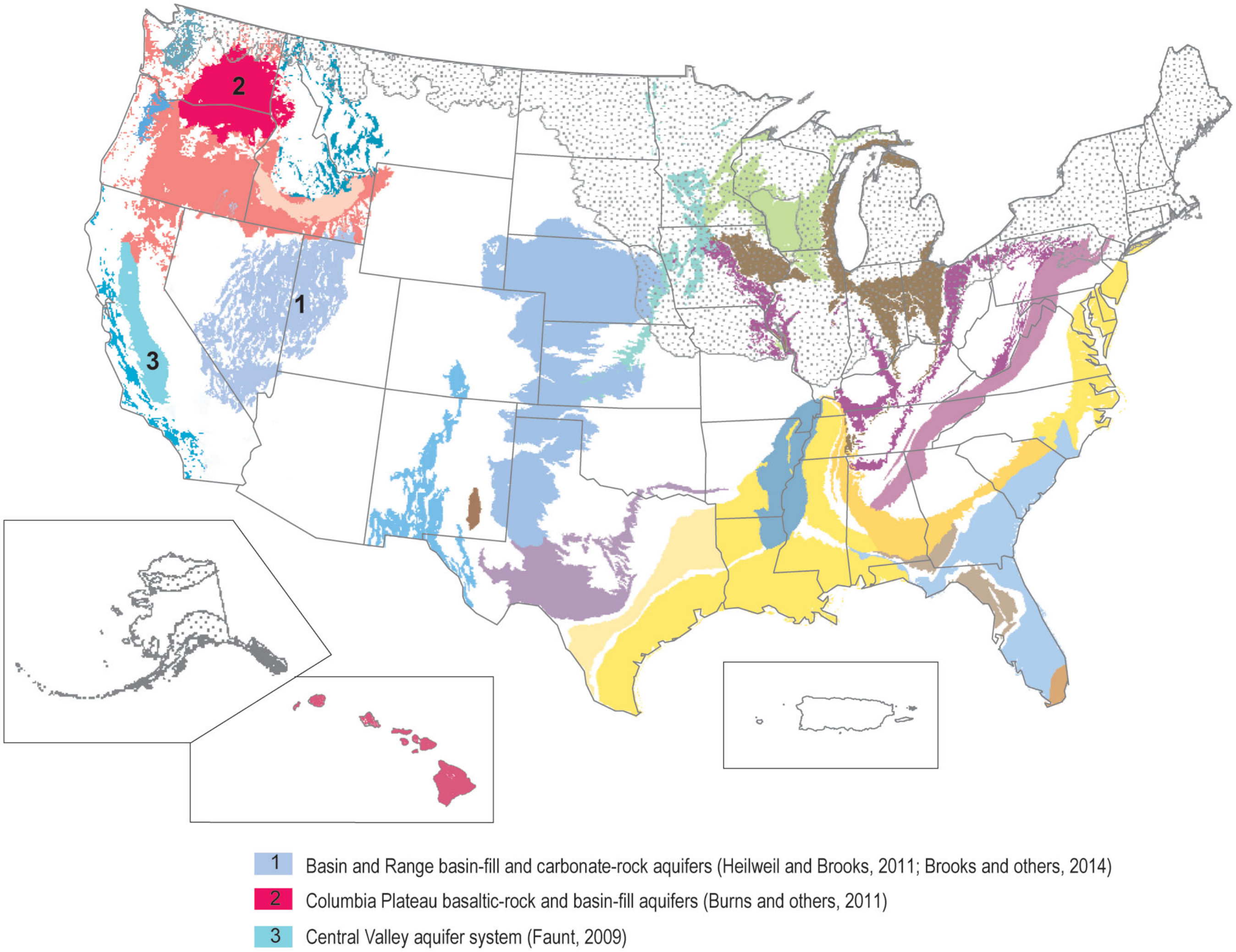

Figure 1. Principal aquifers of the United States (after Reilly et al. 2008). Colored regions represent separate regional aquifer systems as described by Reilly et al. 2008; only aquifers discussed in text are labeled.

Table 1. Area of selected 3D hydrogeologic framework models, USGS Water Mission Area compared to the area of the UK National model

3-D Model	Area, in mi^2 (km^2)	Reference
USGS California Central Valley[1]	20,000 mi^2 (52,000 km^2)	Faunt, 2009
USGS Columbia Plateau[1]	44,000 mi^2 (114,000 km^2)	Burns et al. 2011
USGS Great Basin carbonate and alluvial aquifer system[1]	110,000 mi^2 (285,000 km^2)	Heilweil and Brooks, 2011
British Geological Survey UK framework model	93,600 mi^2 (242,500 km^2)	Mathers et al. 2014

[1] Shown in Figure 1.

cal history. The complexity of U.S. geology ranges from horizontal stacking of sedimentary rocks in the Great Plains, Colorado Plateau, and Coastal Plain Physiographic Provinces to compressional orogens of the Appalachians and Rocky Mountains Provinces to the complex overprinting of compressional, extensional, and transform tectonics of the Pacific Border Province of the western United States and Alaska (King and Beikman, 1974; Schruben et al. 1994; Reed et al. 2005a, b; Horton et al. 2017). These varied geological terranes present a challenge to 3D modelling of numerous stratigraphic units in divergent, convergent, transform, and stable cratonic settings. 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 (Soller et al. 2012; Soller and Garrity, 2018).

Data Sources

Construction of 3D geologic framework models typically involves the use of data from geologic maps, cross sections, water well and oil and gas wells, and surfaces developed from geophysical data (typically a depth-to-pre-Cenozoic basement surface). Because of the expense in acquiring or obtaining data, seismic data are less typically used, except where societal need demands specific knowledge of the subsurface, such as in seismic hazard studies (e.g., Wentworth et al. 2015). Geophysical data are generally developed in-house and integrate existing datasets with collection of new data.

Challenges faced by the USGS in creating 3D models, particularly at the regional scale, include: (1) lack of seamless and consistent geologic map portrayal across different states at scales needed for model creation; (2) differences in regional naming conventions for geologic formations; and (3) differences in the digital and layout formats that are present in various State-managed collections of oil and gas and water-well drillers' records and the need for hand entry of scanned records into numerical format. More general 3D modelling challenges include how to translate physical properties into meaningful geologic units (and vice versa), how to incorporate uncertainty, and how to incorporate results of multiple realizations and alternate models.

3D Modelling Approach

Most USGS 3D geologic framework models are deterministic models of geologic surfaces (Belcher and Sweetkind, 2010; Burns et al. 2011; Sweetkind, 2017) or surfaces and bounding faults (Pantea et al. 2011; Page et al. 2018; Phelps et al. 2008). Some models use lithologic information from driller's logs or are interpreted from downhole electric logs to develop 3D textural models of grain-size variability (Faunt, 2009, Sweetkind et al. 2013; Wentworth et al. 2015). A few stochastic geologic models have been created through geostatistical modelling of geologic and geophysical data (Phelps, 2016).

USGS 3D gravity models use gravity inversion and geologic constraints from boreholes or seismic data to create a structural elevation grid that has geologic meaning (e.g., Grauch and Connell, 2013). 3D geologic framework models can be especially tightly constrained when multiple geophysical techniques (gravity, magnetic, MT) are combined with borehole and rock property measurements (e.g., Finn et al. 2015; Langenheim et al. 2016)

Clients

Because of collection of long-term monitoring data, 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. Most USGS 3D geologic framework models are used within the organization to support process and predictive models. Where models are built for outside entities, model extent and level of detail are closely coordinated to meet the needs of cooperators. The USGS takes advantage of cooperative research and development agreements to collaborate with research institutions both within and outside the United States (e.g., Berbesi et al. 2012).

Recent Jurisdictional-Scale Case Studies Showcasing Application of 3D Models

Case study 1: 3D framework in Anadarko Basin petroleum assessment

In 2010, the U.S. Geological Survey (USGS) completed an assessment of the undiscovered oil and gas resource potential of the Anadarko Basin Province of western Oklahoma and Kansas, northern Texas, and southeastern Colorado, covering an area of approximately 58,000 mi^2 (150,200 km^2) (Higley, 2014). The assessment is based on analysis and modelling of geologic elements including: hydrocarbon source rocks; reservoir rock type, distribution, and quality; types and distribution of reservoir traps and seals; and timing of petroleum generation and migration and defining migration pathways (Higley, 2014). Stratigraphic units range in age from Precambrian to present; petroleum is produced from Cambrian through Permian strata. Much of the production is reported as being commingled from numerous formations that were deposited over broad age ranges; this requires modelling at the basin scale of the full thickness of geologic formations (Higley, 2014).

To support the assessment, a 26-layer 3D geologic framework model was constructed that serves as the geometric basis for petroleum system models

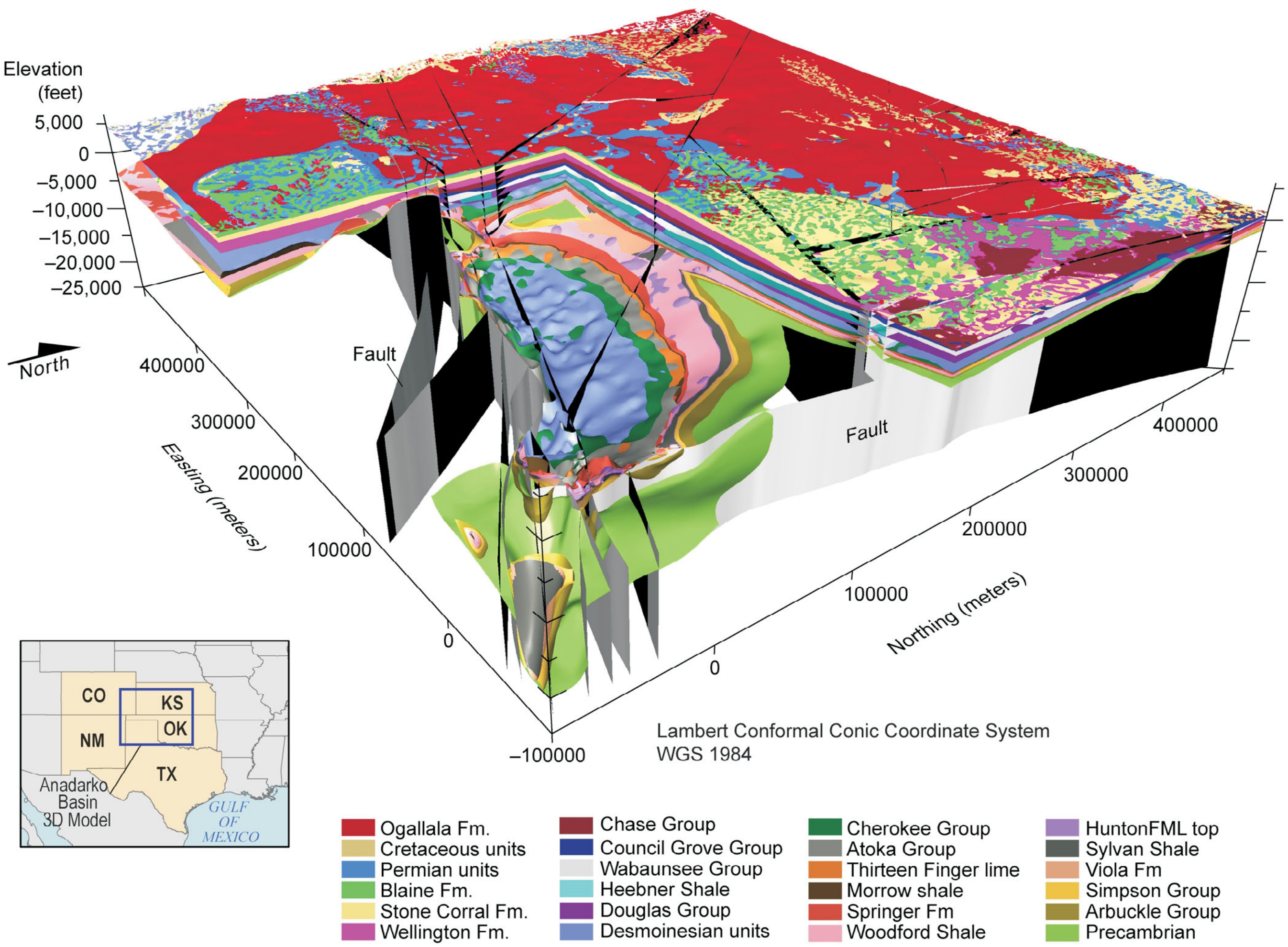

Figure 2. Perspective view from the southeast of a cutaway block model showing the 26 structural surfaces and vertical fault traces present in the 3-D geologic framework model of the Anadarko basin province (model of Higley, 2014). Fault plane colors range from light gray to black because of directional lighting of the model.

(Higley et al. 2014; Figure 2). Elevation, thickness, and fault data sources for the 2D grids and 3D model include formation tops from wells, contoured formation tops from proprietary and published sources, and outcrop/subcrop data from surface geologic maps. Data files were edited using 2-D GIS and 3D geologic modeling software to remove anomalies such as location errors and incorrect formation-top elevations. 3D grids were compared to published cross sections and maps, and anomalous surfaces were edited and regridded. A 3D geologic framework model was created by stacking the 26 stratigraphic surface grids and including Precambrian fault surfaces from the province (Figure 2; Higley et al. 2014). Model grid spacing was 1-km with 601 cells in X-dimension and 576 in Y-dimension. Volumes of units are defined and shown in Figure 2 as the space between (1) two geologic surfaces, (2) geologic surfaces and fault planes, or (3) geologic surfaces and model extents. Faults in the 3D model were subdivided based upon whether they extended from Precambrian basement to the ground surface or crossed only some of the model layers. Due to modeling and time constraints, faults were designated as vertical.

Much of the petroleum assessment-related modelling was conducted in 4D modelling software that supports analysis petroleum migration pathways, time-temperature maturation pathways in the basin, and modelling of hydrocarbon generation, migration, and accumulation through time (Higley et al. 2006; Higley, 2014). However, formation tops grids and associated data were used for other assessment purposes including 1D burial history models and 2D cross sectional models, such that it was more efficient to generate and edit layers in 2D GIS and 3D geologic modelling software and import the resulting grids or the 3D geologic framework model into the 4D modelling platform (Higley et al. 2006; Higley, 2014).

Case study 2: 3D geological models for regional groundwater availability studies

The USGS conducted a regional assessment of groundwater availability of the Great Basin carbonate and alluvial aquifer system (GBCAAS) as part of a U.S. Geological Survey National Water Census Initiative to evaluate the nation's groundwater availability (Heilweil and Brooks, 2011; Brooks et al. 2014). Located within the Basin and Range Physiographic Province, the aquifer system covers an area of approximately 110,000 mi^2 (285,000 km^2) across five states, predominantly in eastern Nevada and western Utah (Figure 1) and includes the Basin and Range carbonate-rock aquifers, the southern Nevada volcanic-rock aquifers and much of the Basin and Range basin-fill aquifers (Reilly et al. 2008). Diverse sedimentary units of the GBCAAS study area are grouped into hydrogeologic units (HGUs) that are inferred to have reasonably distinct hydrologic properties due to their physical characteristics. These HGUs are commonly disrupted by thrust, strike-slip, and normal faults with large displacement, and locally affected by caldera formation.

A three-dimensional hydrogeologic framework (3D HFM; Figure 3) was constructed that defines the physical geometry and rock types through which groundwater moves (Heilweil and Brooks, 2011). The 3D HFM consists of nine HGUs with distinct physical and hydraulic properties: three units representing Cenozoic basin-filling sedimentary and volcanic rocks and six units representing consolidated Mesozoic and Paleozoic bedrock and intrusive rocks (Figure 3). The framework was built by extracting and combining a variety of data, including:

- Land-surface elevation from seamless 1:24,000-scale National Elevation Data (NED) digital elevation models (DEM);
- Geologic data from five state geologic maps integrated into a seamless 1:500,000-scale geologic map database. Geologic contacts were sampled at regularly spaced points within a GIS and then assigned coordinate locations from the map base and elevations from a digital elevation model. The geologic map also provided location of faults and caldera boundaries.
- Stratigraphic log data from 441 wells compiled from oil and gas, mining, water-well, and other records;
- Geologic contacts digitized from 245 cross sections compiled from 99 separate sources;
- Elevation data of geologic surfaces from an existing 27-layer 3D-hydrogeologic framework for part of the study area; and
- A gridded surface defining depth to top of consolidated rock created by combining the results of five regional and subregional gravity-based surveys. The resulting surface defines both the top of pre-Cenozoic rocks and the base of the Cenozoic sedimentary basin-fill deposits and volcanic rocks.

The top elevations of the HGU surfaces were modelled from the input data using a 1 mi^2 (2.59 km^2) grid cell size. In the hydrogeologic framework, individual HGUs are represented by an interpolated gridded surface of the top altitude of each HGU. The HGU surfaces were combined and stacked, resulting in the 3D-hydrogeologic framework (Figure 3). Major fault zones and caldera margins were incorporated as vertical boundaries to define abrupt changes in unit elevation and as structural control on the hydrogeology. Interpolation of spatial data points into grids representing the HGU surfaces was processed using 3D modelling software, and further modification and interpretation of the gridded HGU surfaces was completed using geographic information system (GIS) software. The model was released as a series of GIS raster files that represent the modelled top surface altitude and extent for each of the hydrogeologic units within the study area (Heilweil and Brooks, 2011).

The 3D geologic framework was the primary geologic input into a steady-state numerical groundwater flow model of the aquifer system (Brooks et al. 2014). Explicit incorporation of a detailed three-dimensional hydrogeologic framework into the numerical simulation allowed evaluation and calibration of complex hydrogeologic and hydrologic elements, incorporated a conceptual understanding of an interconnected groundwater system throughout the region, and allowed an evaluation of inter-basin bedrock hydraulic connectivity and regional groundwater flow directions.

Case study 3: 3D models for seismic hazard analysis, from local to National scale

Starting in 2007, the USGS developed a 3D fault framework model of the San Francisco Bay area, California (Figure 4) as a part of the larger effort to develop a statewide fault model as a primary data set for the Uniform California Earthquake Rupture Forecast, version 3 (UCERF3; Field et al. 2014), which "…provides authoritative estimates of the magnitude, location, and time-averaged frequency of potentially damaging earthquakes in California." UCERF3 is used widely in California for seismic hazard analyses, including by the California Earthquake Authority in setting insurance rates to reflect localized actual risk.

The San Francisco Bay Area 3D fault model was built using the following steps:

1) The regionally most important faults were selected, and their traces were simplified from geologic maps of the region (Graymer et al. 2006a; 2006b).

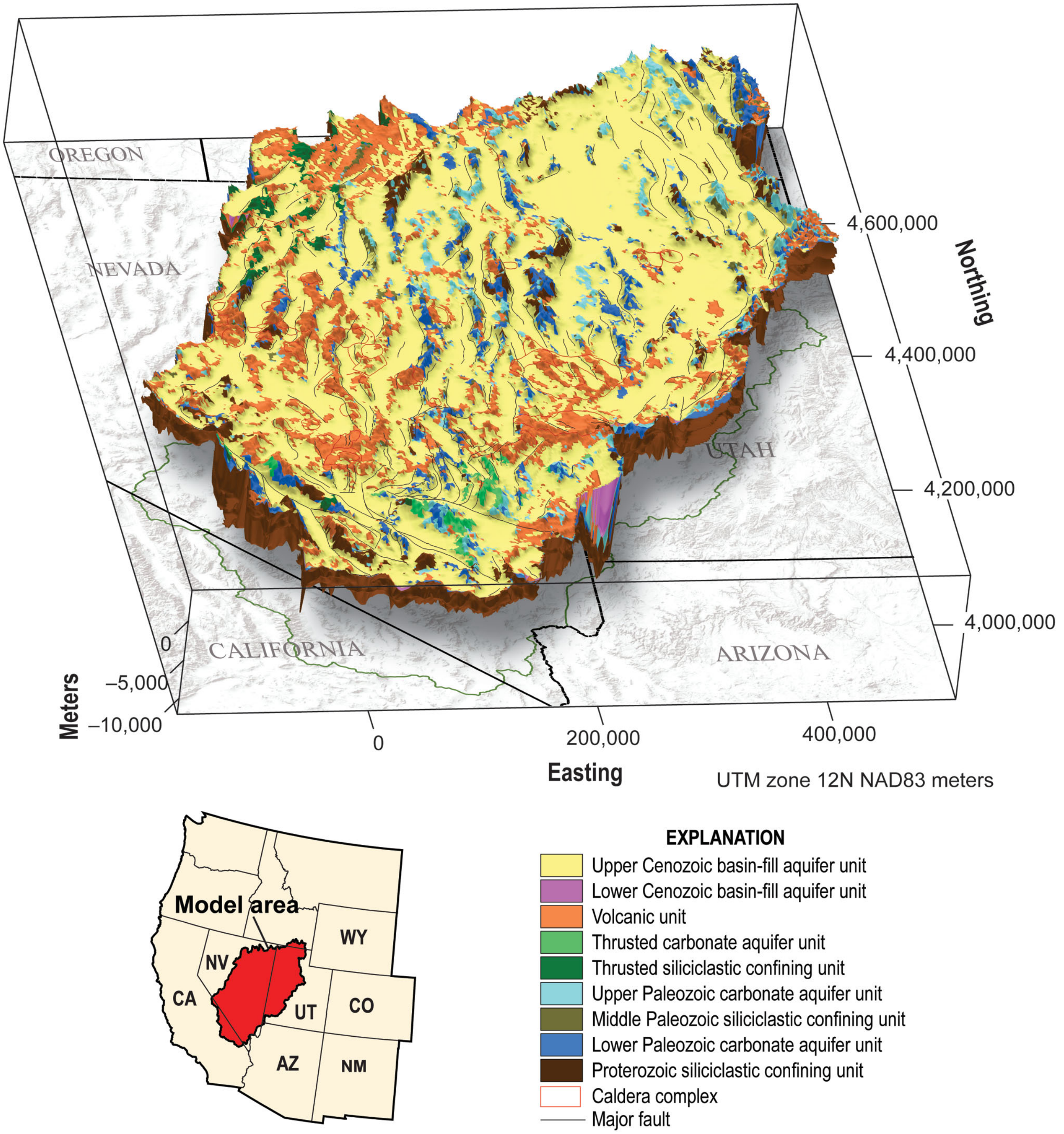

Figure 3. Perspective view of the upper surface of the 3D geologic framework model for the Great Basin carbonate and alluvial aquifer system (from Heilweil and Brooks, 2011). The colored units are nine hydrogeologic units that are stacked in 3D space.

2) Surface traces were projected onto a digital elevation model (Figure 4).
3) Subsurface projection of faults was constrained by, in order of preference: (a) double-difference relocated hypocenters; (b) gravity and aeromagnetic data; (c) fault dip as reflected by the effect of topography on the fault trace; and (d) generic fault dip assigned based on relative fault offset (e.g. pure strike-slip, vertical; pure reverse slip, 60° dip; oblique reverse slip, 75° dip).

These data sets and interpretations were converted into a suite of 3D points reflecting the surface trace and

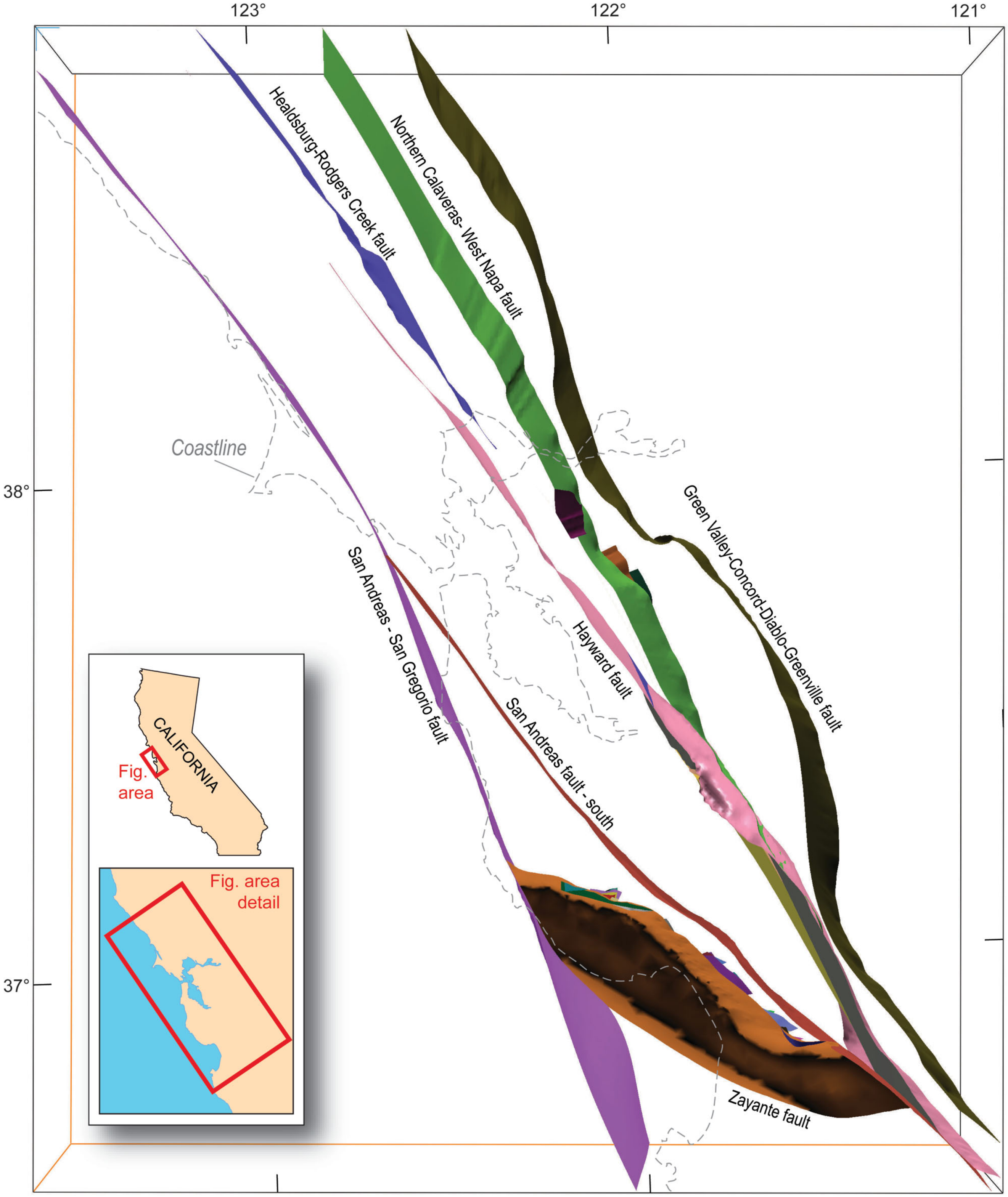

Figure 4. View from above of the San Francisco Bay region 3D fault framework. Various colors represent individual modelled fault planes, of which only the major faults are labeled.

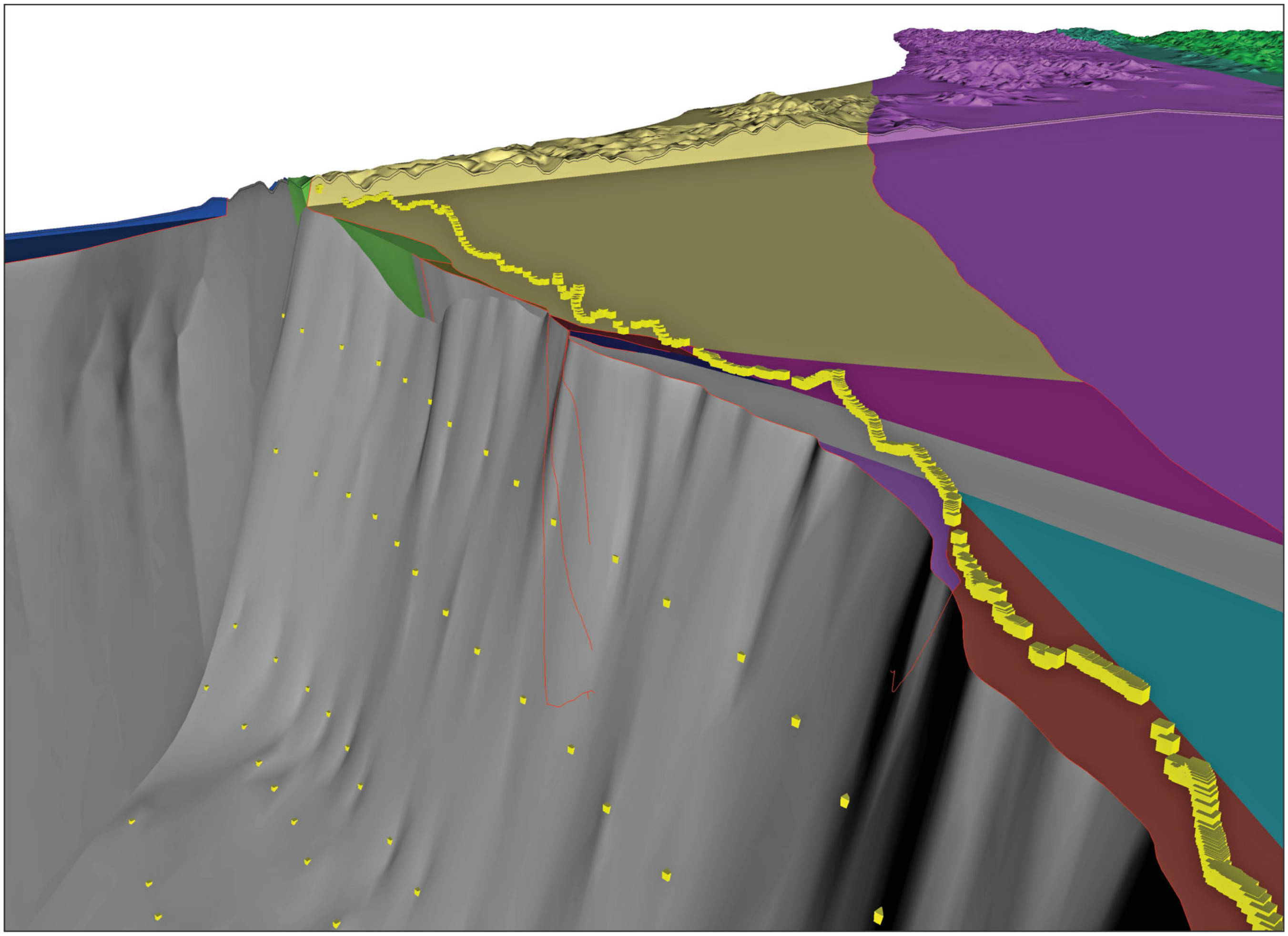

Figure 5. Perspective view from the southwest of a cutaway block model showing the 3D data points (yellow cubes) associated with the Zayante fault. The regularly spaced points are from structure contour data, the closely spaced points in the undulating trend represent the surface trace projected onto the Earth's surface, represented by a digital elevation model.

structure contours at depth (Figure 5). The 3D fault surface was generated using a least tension algorithm to fit the fault to the 3D points. A spatial hierarchy was defined to allow the various faults to be combined into a fault framework model.

A 3D fault framework is important to earthquake studies in a number of ways. In general, the 3D geometry of a fault network affects how the faults slip as a result of the regional tectonic stress, and thus the 3D geometry is incorporated into source characterization as well as geodetic models of slip rates. The 3D fault framework in the San Francisco Bay region also reveals faults without apparent surface connection that are directly connected in the subsurface, and therefore can accommodate longer fault ruptures and potentially larger earthquakes.

Seismic hazard assessments also depend on an accurate prediction of earthquake ground shaking, which in turn depends on knowledge of three-dimensional variations in density, seismic velocity, and attenuation. Examples from the San Bernardino basin in southern California (Graves and Wald, 2004) and the Santa Rosa plain in the northern San Francisco Bay area (McPhee et al. 2007) highlight the importance of 3D basin geometry in producing damaging ground motions. Local to regional 3D geologic models have been constructed as the foundation to seismic velocity models and numerical earthquake simulations (Aagaard et al, 2010; Stephenson et al, 2017). Nationally, the USGS is building a crustal-scale model that includes development of a multi-layered 3D geologic framework model, application of a physical theoretical foundation to couple geology and geophysical parameters and use of measured geophysical data for calibration (Boyd and Shah, 2018). The framework model is intended to be internally consistent and seamless on a national scale, defined on a 1-km grid, and integrate results of previous studies including maps of surficial porosity, surface and subsurface lithology (Horton et al. 2017), and the depths to bedrock (Shah and Boyd, 2018), crystalline basement or seismic equivalent, lower crust, and Moho.

A calibrated national crustal model can be used to assess and apply parameters currently used to predict earthquake ground motions including shear-wave velocity parameters that roughly correlate to the depths to bedrock and basement (Shah and Boyd, 2018). The model could also be used to develop new parameters with greater predictive power that can be applied in national seismic hazard assessments (Petersen et al. 2015).

Current Challenges

Current challenges are in part related to the broad overall mission of the USGS and the focused nature of individual Mission Areas within the organization, which lead to decentralized 3D modelling activities. Pockets of 3D modelling expertise develop on a project-by-project basis, but there may not be enough knowledge transfer between projects. Across the USGS individual researchers and teams acquire 3D technologies with little to no knowledge or bureau-level coordination of other similar efforts. Although projects and Mission Areas add 3D applications as analysis tools, there are few forums for sharing ideas, data, products, and knowledge of emerging technologies. Although cost efficiencies could perhaps be realized using a standardized, organization-wide modelling platform, the use of multiple software platforms in general supports the diverse needs of the Mission Areas and, in and of itself, is not a major challenge. The bigger challenge is in developing datasets that are accessible, transferrable and importable into multiple software platforms.

At the National level, no Bureau-level guidance or infrastructure supports the following: (1) development of regional or National-scale drill-hole databases in a standard format; (2) development of national databases of gravity, magnetic, or seismic observations that could support framework model development; (3) guidance on database standards for 3D data; (4) guidance on archiving procedures for developed 3D models; and (5) National-scale efforts to catalog and maintain already-developed 3D framework models, beyond releasing models in publications.

Lessons Learned

The USGS ScienceBase repository (https://www.sciencebase.gov/catalog/) is being used as a catalog and data store to track projects and their deliverables including publications, models, and datasets. Many of the model and data outcomes of focus area and topical studies are available directly from ScienceBase, whereas reports and data stored elsewhere are available through links cataloged in ScienceBase.

Next Steps

The continued need for national-scale research and assessment of energy, minerals, geologic hazards, and water resources will continue to drive the development of 3D geologic framework models and their link to numerical process models. Energy resource assessments will continue to develop capabilities to understand basin stratigraphic, structural, and thermal development and use developed frameworks as part of hydrocarbon maturation and stratigraphic backstripping analyses as part of basin-scale petroleum assessments. In the Minerals realm, recent emphasis on availability of critical minerals for the Nation requires the evaluation of undiscovered resources, particularly beneath Quaternary and Phanerozoic cover. Such evaluations rely on the use of geophysical methods, both to map subsurface features in 3D and to forward-model geophysical anomalies in terms of geology. In the Water Mission Area, numerical groundwater models will continue to increase in sophistication as software platforms and computing power evolve, allowing for the inclusion of increasingly complex 3D geologic frameworks in regional and local-scale numerical models of hydrologic processes. Development of 3D geologic frameworks will increasingly become needed at the energy-water nexus, both as a means of evaluating potential interactions between aquifer systems and shallow producing regions of oil and gas fields, and to evaluate possible interaction between groundwater aquifers and injection of fracking liquids and produced waters. Societal pressure for accurate and precise hazard and risk assessment in populated areas will continue to demand higher-resolution 3D framework models and closer integration with physical properties modelling.

The National Cooperative Geologic Mapping Program has recently updated its strategic vision to focus on the accelerated development of regional-scale geologic maps and the development of 3D geologic frameworks. To this end, the Program has started several new projects that are regional in scope and explicitly include 3D frameworks, for example, a planned regional mapping transect in the US Southwest and merging of multiple 3D models in central and northern California. Knowledge gained from these projects will inform strategies for resolving current challenges as various USGS science centers look to this Program and the Core System Science mission area for continued guidance.

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