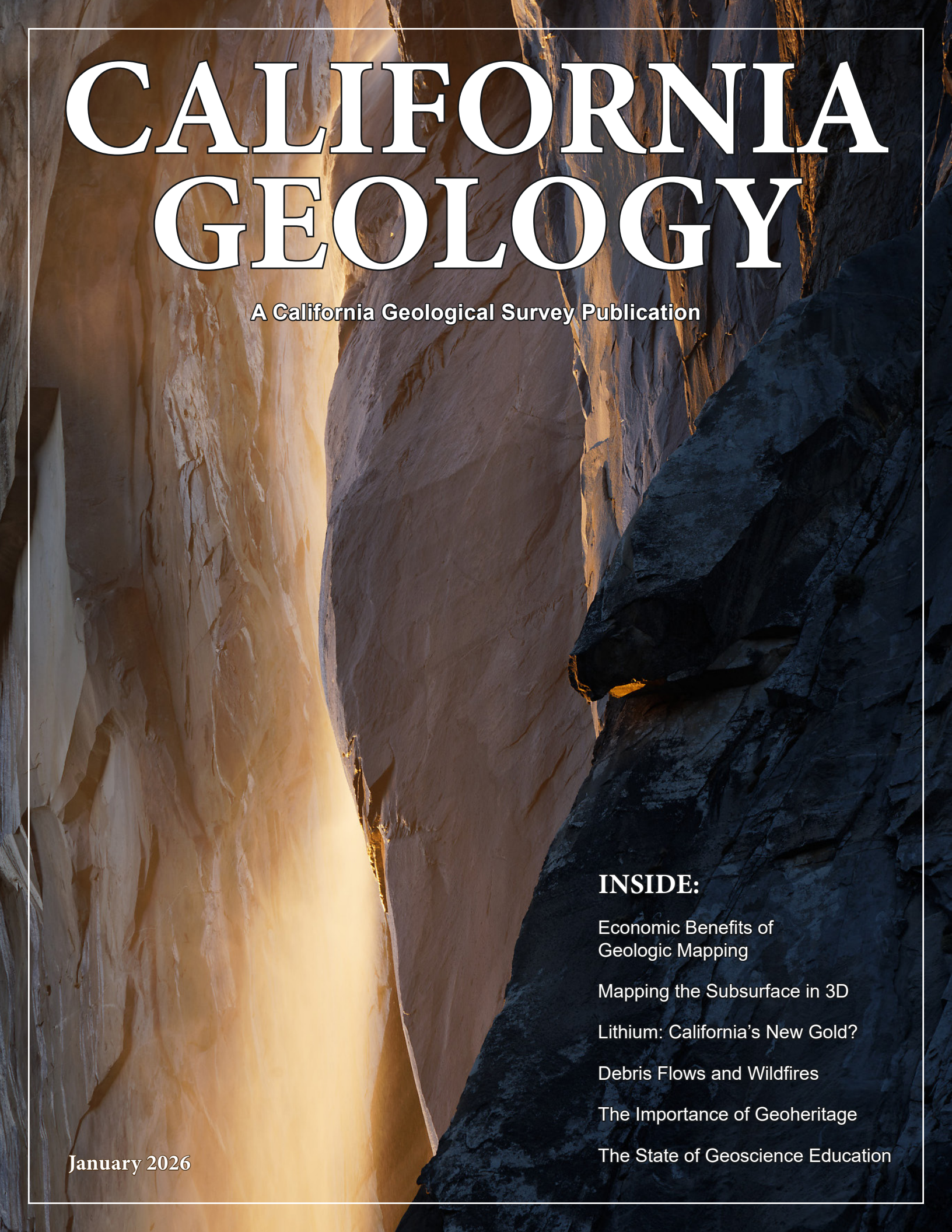
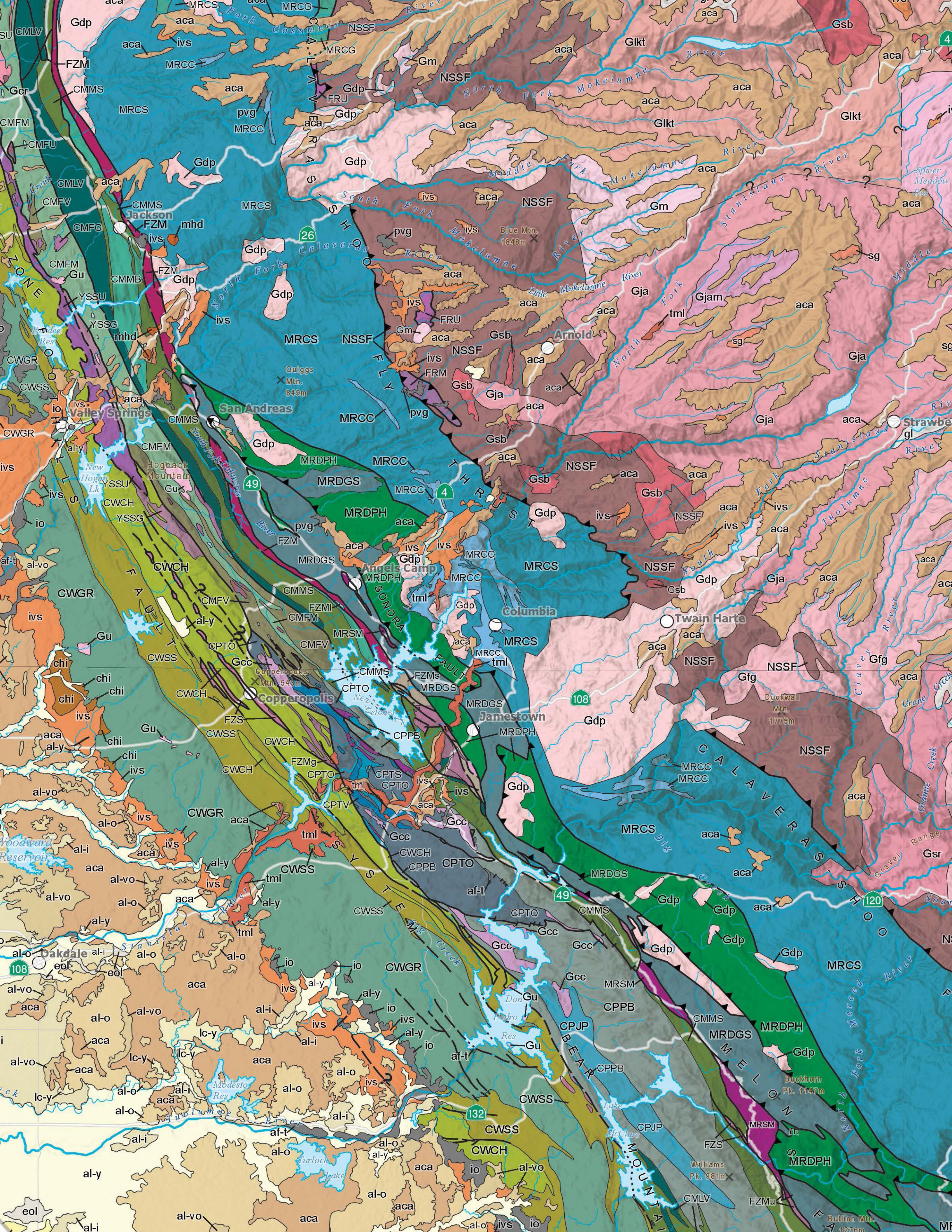
CALIFORNIA GEOLOGY

A California Geological Survey Publication



INSIDE:

January 2026



Jackson
San Andreas
Valley Springs
Angels Camp
Columbia
Twain Harte
Arnold
Copperopolis
Jamestown
Oakdale
Strawberry
Blue Mtn. 1848m
Quiggs Mtn. 849m
Copperopolis Mtn. 544m
Duckwall Mtn. 1775m
Buckhorn Pk. 1147m
Williams Pk. 981m
Bullion Mtn.
Hogback Mountain
New Hogan Lk.
Pardee Res.
Woodward Reservoir
Modesto Res.
Turlock Lake
Don Pedro Res.
Lake McClure
Spicer Meadow Res.
North Fork Mokelumne River
Middle Fork Mokelumne River
South Fork Mokelumne River
Little Mokelumne River
North Fork Calaveras River
South Fork Calaveras River
Calaveras River
North Fork Stanislaus River
Middle Fork Stanislaus River
South Fork Stanislaus River
Stanislaus River
Tuolumne River
South Fork Tuolumne River
Clavey River
North Fork Merced River
Merced River
Fork Cosumnes River
Big Creek
Moccasin Creek
Crane Creek
Grizzly Creek
Gravel Range
CALAVERAS SHOO FLY THRUST
FOOTHILLS FAULT SYSTEM
SONORA FAULT
BEAR MOUNTAINS FAULT ZONE
MELONES FAULT ZONE
26
49
4
108
120
132
Gdp
aca
ivs
MRCS
MRCC
MRCG
NSSF
FZM
CMMS
CMLV
CMFV
CMFM
CMFG
CMMB
CMFU
Gcr
Gm
FRU
FRM
pvg
mhd
Glkt
Gja
Gjam
Gsb
sg
tml
gl
Gfg
Gsr
YSSU
YSSG
SSU
CWGR
CWSS
CWCH
MRDPH
MRDGS
MRSM
FZMl
FZMs
FZMg
FZMu
FZS
CPTO
CPTS
CPTV
CPPB
CPJP
Gcc
Gu
chi
io
af-t
al-vo
al-y
al-o
al-i
lc-y
eol

CALIFORNIA GEOLOGY™ MAGAZINE, VOL. 56

CALIFORNIA GEOLOGY™ is an annual publication of the California Geological Survey, a division of the Department of Conservation.

Managing Editor ..... Elaine K. Young, PhD

Assistant Editor ..... Erik Frost, PhD, PG, CEG

Graphic Designer ..... Meerea Kang

Chief Librarian ..... Amy Loseth, MLIS

Publications Program Manager ..... Robert Wurgler

State Geologist ..... Jeremy Lancaster, PG, CEG

Contributed articles, photographs, news items, and geological meeting announcements are welcome; please email us at CalGeology@conservation.ca.gov before submitting content. The magazine is not responsible for unsolicited materials.

CGS Headquarters
715 P Street, MS 1901, Sacramento, CA 95814
(916) 445-1825
cgshq@conservation.ca.gov

Southern California Regional Office
320 West 4th St., Suite 850, Los Angeles, CA 90013
(213) 239-0894

San Francisco Bay Area Regional Office
1900 S. Norfolk St., Suite 300, San Mateo, CA 94403
(650) 350-7307

Additional offices in:
Eureka • Redding • Santa Rosa

Website
https://www.conservation.ca.gov/cgs

Social Media
@cageosurvey • @calconservation

California Department of Conservation
California Geological Survey

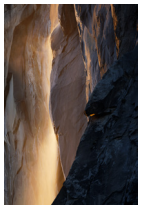
The content herein has been completed under the technical review and approval of the Director and State Geologist.

January 30, 2026

PROFESSIONAL GEOLOGIST
Jeremy Lancaster
No. 7692
STATE OF CALIFORNIA

GOVERNOR, STATE OF CALIFORNIA: GAVIN NEWSOM
SECRETARY, NATURAL RESOURCES AGENCY: WADE CROWFOOT
DIRECTOR, DEPARTMENT OF CONSERVATION: JENNIFER LUCCHESI

IN THIS ISSUE



On the cover:
Close-up of Horsetail Fall in Yosemite National Park, exhibiting its famous winter firefall effect as it cascades down the east buttress of El Capitan. See page 3 for an expanded view of the fall.
Photos by Bob Moskovitz, CGS

Previous page:
A portion of the geologic map plate from the Sierra Nevada Earth Science Atlas.

The Role of State Geological Surveys

State Geological Surveys are important sources of information and expertise about their respective geologic framework, energy, minerals, water, and geologic hazards. These are often localized phenomena and therefore require local knowledge. Federal agencies should coordinate their programs and activities with State Geological Surveys, as the State Surveys have local knowledge and a responsibility to assist local governments, serving as implementers of scientific information. State Geological Surveys work closely with other State and local agencies, including emergency management, law enforcement, natural resources, and environmental protection. The responsibilities of each State Survey vary depending upon state legislation and traditions. Most State Surveys function as an information source for government and society. Some have regulatory roles for topics such as water, oil and gas, mining, and land reclamation.

The first State Survey was established in 1823 in North Carolina, well before the establishment of the U.S. Geological Survey in 1879. By 1840, there were at least 15 State Surveys, most of which were charged with the discovery of mineral, energy, land, and water resources in their state or territory. The California Geological Survey (CGS) has its beginnings after the start of the California Gold Rush when the state legislature commissioned Dr. John Trask to report on the geology and mineral resources of the state; however, the formal authorization of the CGS was not established by the California legislature until 1860 under Josiah Whitney (See CGS Special Publication 126).

The mission of the CGS is to provide scientific products and services about the state's geology, seismology, and mineral resources, including their related hazards, that affect the health, safety, and business interests of the people of California. The CGS connects to state and local government via its geologists and engineers making local observations and studies and archiving them for the public good. In addition, the CGS has a primary role in natural hazards event response to earthquakes, landslides, tsunami, volcanic eruptions, and other phenomena. Local knowledge development and local government connection is carried out at its headquarters in Sacramento and five field offices throughout the State.

In most cases, CGS products and maps communicate the regional nature of hazards and resources and are not meant to replace the detailed, site-specific work of local government and private sector geologists and engineers. Rather, CGS maps are meant to highlight the regional framework of hazards and resources, supporting wise land use decision-making and directing geo-professionals to where more detailed studies are needed. The CGS has been consistent in this way for more than 100 years; in the words of Olaf P. Jenkins after publishing the first geologic map of the state in 1938:

"I also learned that state [geological survey] projects should not be allowed to duplicate projects of other institutions. … state investigations can be of great help to private consultants so long as the work does not take work away from them. This interference of state with private undertakings need not happen if the state work is of regional or general character and is not just focused on limited investigations for special interests."

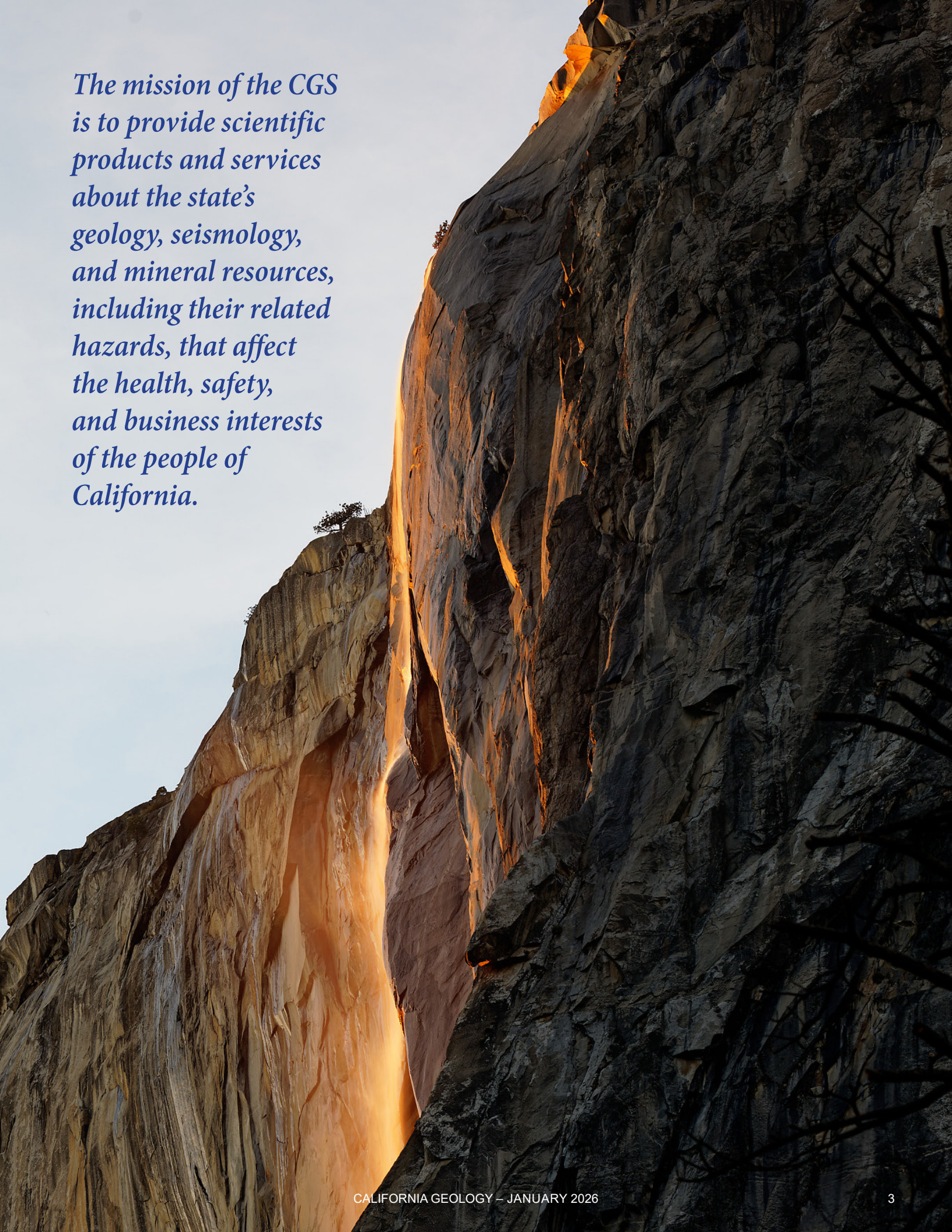
For many decades the CGS has been focused on providing regional maps and data at enough detail to support strategic decisions at all levels of government and the private sector. CGS maps support the de-risking (cost control) of both hazards and resources investigations, providing up to a 10 to 1 benefit to cost ratio (See later section on the value of framework geologic maps on page 6).

A recent example of hazard mapping completed at the regional level is the statewide prefire debris-flow hazard model that is presented in this issue. The mapping presented in that article supports community adaptation to climate change by identifying areas that are most susceptible to debris-flow hazards, so that communities can plan for and mitigate postfire flash flood and debris-flow hazards before an area is burned (See pages 24-35 for more information).

Lastly, it is my goal that the CGS be a unifying voice in the geosciences community. And, while this magazine is a step towards that, as a public servant, I'm forever open to your suggestions for improvement.

— Jeremy Lancaster,
Director and State Geologist

The mission of the CGS is to provide scientific products and services about the state's geology, seismology, and mineral resources, including their related hazards, that affect the health, safety, and business interests of the people of California.



NEWS NUGGETS 2025

M. 8.8 RUSSIA EARTHQUAKE AFFECTS CALIFORNIA

On July 29, 2025, a M8.8 earthquake occured on a shallow reverse fault in the Kuril-Kamchatka subduction zone east of Petropavlovsk-Kamchatsky, Russia. It was among the 10 largest earthquakes to occur anywhere in the world since 1900. The earthquake generated a tsunami that triggered advisories and warnings for the west coast of North America.

The CGS Tsunami Unit provided scientific support to state and local officials and harbors/ports along the California coast during the tsunami event. Fortunately, the tsunami's impact on California was minimal.

More: https://earthquake.usgs.gov/storymap/index-kamchatka2025.html

BERKELEY EARTHQUAKE PUTS GOLDEN GATE BRIDGE INSTRUMENTS TO THE TEST

During earthquakes, the CGS collects ground and structural shaking data, which are processed and disseminated to emergency responders, engineers, and partners. These data are used immediately for emergency response purposes, such as creating ShakeMaps, and as part of the Earthquake Early Warning Network. Efforts are underway to develop tools and alerts that will utilize these data to assess the structural integrity of select critical infrastructure immediately after a seismic event (structural health monitoring). A M4.3 earthquake near Berkeley in September of 2025 served as a proof of concept when the shaking triggered CGS sensors at the Golden Gate Bridge. The data were used to produce an automatic report detailing the bridge's response to the earthquake. This report was sent to the Golden Gate Bridge engineers within moments of the earthquake.

CGS HAS JOINED THE ANSS

In 2025, the CGS joined the USGS's Advanced National Seismic System (ANSS). The CGS network is the nation's largest self-supported seismic network. Membership in the ANSS allows the CGS to help steer national efforts and standards.

The ANSS is a "cooperative effort between state, regional, federal and academic partners to collect and analyze seismic and geodetic data on earthquakes, issue timely and reliable notifications of their occurrence and impacts and provide data for the hazard and risk assessments that are the foundation for creating an earthquake resilient nation." The ANSS includes a national backbone network, the National Earthquake Information Center (NEIC), the National Strong Motion Project, and 16 regional seismic networks operated by USGS and its partners.

More: https://www.conservation.ca.gov/cgs/smi

CGS CONTINUES TO ENSURE EARTHQUAKE SAFETY FOR SCHOOLS AND HOSPITALS

The CGS Essential Facility Review (EFR) Unit reviews geologic and geotechnical reports for new public school, hospital, and essential services building projects to ensure that these critical facilities are safe from geologic hazards during earthquakes. These assessments include the review of school and hospital sites for the Division of the State Architect and the Department of Healthcare Access and Information (HCAI, formerly OSHPD), and help protect Californians in earthquake-safe school buildings and hospitals. These products and services assist in the development of earthquake-safe structures, reducing both casualties and economic losses.

Between the beginning of January and the beginning of November 2025, the CGS reviewed 405 school projects and 45 hospital projects.

More: https://www.conservation.ca.gov/cgs/sh/review

EARTHQUAKE EARLY WARNING SYSTEM

The CGS continues to work closely with the California Governer's Office of Emergency Services (CalOES), the U.S. Geological Survey (USGS), and others in developing and implementing the California Earthquake Early Warning System (CEEWS). As of this writing, the CGS has completed 138 stations that contribute to the CEEWS.

SEISMOMETERS GO HEAD-TO-HEAD ON SHAKE TABLE

In June 2025, UC San Diego's Englekirk Structural Engineering Center conducted shake table tests on a full-scale, 10-story cold-formed steel building. Shake tables simulate earthquake shaking, allowing researchers to study structural performance, pinpoint weaknesses, and assess new construction techniques. The California Geological Survey's Strong Motion Instrumentation Program collaborated with UCSD, installing 33 high-resolution and 33 lower-cost, lower-resolution seismometers to compare their performance and evaluate the potential of lower-cost instruments.

More: https://nheri.ucsd.edu/projects/seismic-resiliency-repetitively-framed-mid-rise-cold-formed-steel-buildings

MONITORING INJECTION-INDUCED SEISMICITY IN CARBON RESERVOIRS

With the state's goal to reach carbon neutrality by 2045, 100 million metric tons per year of carbon dioxide will be required to be injected into the subsurface by that time. The CGS is actively working with partners to enhance seismic monitoring networks around future carbon sequestration projects to support identification of injection-induced seismicity.

NEWS NUGGETS 2025

NEW INSIGHTS INTO SHAKING

In 2025 the CGS completed self-funded instrumentation of a 13-story residential building in San Francisco. Twenty-one accelerometers were installed at six levels of the building. The data recorded by this building during earthquakes will provide valuable insight into the shaking response of concrete shear wall buildings.

WEEKLY CALIFORNIA EARTHQUAKE REPORT

CGS has launched a weekly earthquake report on social media detailing information about state-wide earthquakes of magnitude 2+ that occurred during the previous week. The goal of this effort is to improve public understanding of earthquake rates and highlight the natural variability of quakes across California. The weekly report is posted every Monday on Instagram, X, and BlueSky.

More: https://cadoc.maps.arcgis.com/apps/dashboards/73071ff159bc4214b03201fb5088e718

INSIGHTS FROM A 25-YEAR DATABASE OF POSTFIRE DEBRIS FLOWS IN CALIFORNIA

Post-wildfire debris flows (PFDFs) frequently threaten life, property and infrastructure in California. The CGS developed a database of PFDF events in California for the period 2000–2024 and analyzed the data to describe variability in location and timing of PFDFs. Most of the events occur in the Transverse Ranges and the Sierra Nevada and during the cool season (Oct. – May). Fifty-five percent of the events are associated with atmospheric rivers. About thirty-one percent of PFDFs are during the warm season (June-Sept.) and are associated with the North American monsoon, tropical cyclones, and other thunderstorms. This work supports hazard planning and mitigation efforts and allows California to track changes in a warming climate.

STATEWIDE PREFIRE DEBRIS-FLOW MODEL

The CGS developed a statewide prefire debris-flow hazard model for identifying areas of California that are most susceptible to debris-flow hazards. Communities can use the model results to plan for and mitigate postfire flash flood and debris-flow hazards before an area is burned.

More: See article on pages 24-35 of this issue.

STATEWIDE VEGETATION TREATMENT/WILDFIRE FUELS REDUCTION PLAN

The CGS is assisting the California Board of Forestry and Fire Protection in planning and implementation of wildfire fuels reduction and vegetation management projects across the state. The CGS provides technical information and advice about erosion, sedimentation, landslides, and other geologic hazards on California's forested lands and in watersheds where land use decisions may affect public safety, water quality, and fish habitat.

More: https://www.conservation.ca.gov/cgs/fwg/fr-vm

CGS "COVE" INITIATIVE

The CGS has launched a Communication, Outreach, Visibility, and Education (COVE) initiative to ensure that externally-facing efforts are coordinated, targeted, and effective. The plan centers on three interconnected areas:

- *Communication*—externally-facing discussion;
- *Outreach*—connecting people, partners, and communities; and
- *Education*—building knowledge and skills.

Together, these efforts will elevate the visibility of CGS products and information and help improve understanding of geologic hazards and risks in California.

More: See article on pages 36-37 of this issue.

MEETING THE PUBLIC AND SHOWCASING CGS VALUE

The CGS showcases its products and interacts with various communities by attending meetings, conferences and/or staffing booths at events throughout the year, including at the Geological Society of America (GSA) meeting, the Southern California Earthquake Center meeting (SCEC), ShakeOut Events in Northern and Southern California, Girl's STEM Night at the Natural History Museum of Los Angeles, Girl's STEM Day at the Aerospace Museum, the LA County Emergency Preparedness Fair, the Disaster Expo, the Disney World Preparedness event, and the Race The Wave Tsunami event in Santa Cruz.

More: See article on pages 36-37 of this issue.

CGS PUBLICATIONS AND RESEARCH

Notable publications and research completed in 2025 included:

- Four new geologic maps.
- Eleven Earthquake Zones of Required Investigation Maps (EZRIM).
- Two Fault Evaluation Reports and three Seismic Hazard Zone Reports.
- Completed a major revision of Map Sheet 48, "Earthquake Shaking Potential in California."
- Developed a "Quaternary Faults Data Upload Portal" to streamline the collection of new Quaternary fault mapping from the research community.
- Published a new issue of CALIFORNIA GEOLOGY™ magazine for the first time in 23 years.
- CGS staff appeared as co-authors on twenty separate peer-reviewed published research articles.

More: See article on pages 52-55 of this issue.

FOLLOW CGS!

The CGS maintains an active social media presence (follow us! @CaGeoSurvey) on Instagram, X, and BlueSky.

Economic Benefits of Geologic Mapping

Kirk Townsend, PhD, PG

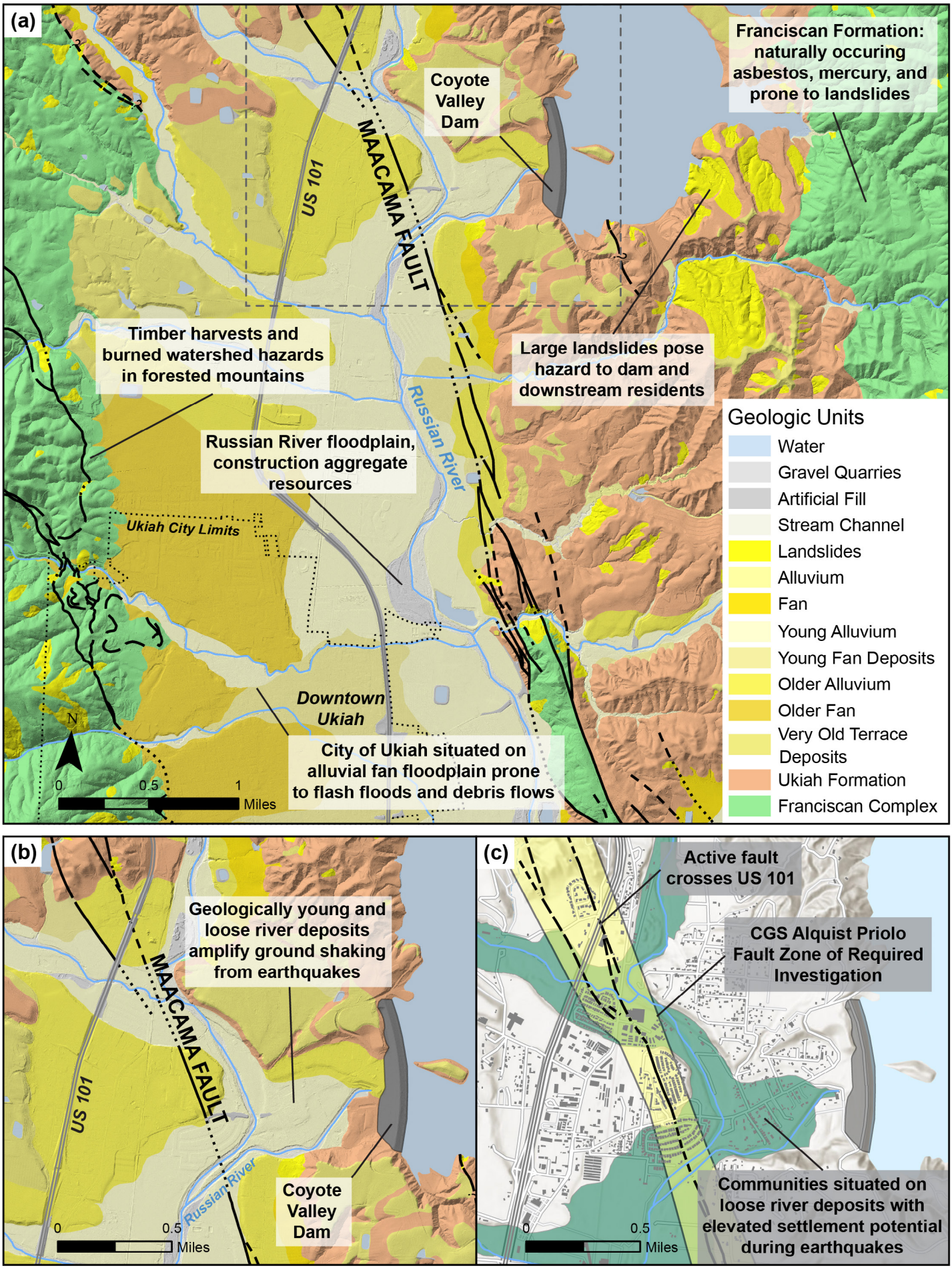
CGS geologist Kirk Townsend documenting a debris flow deposit in Snow Creek, near Forest Falls in San Bernardino County. Debris flow deposits are one of many geologic hazards that are communicated through geologic maps and derivative products. Photo by Paul Burgess, CGS

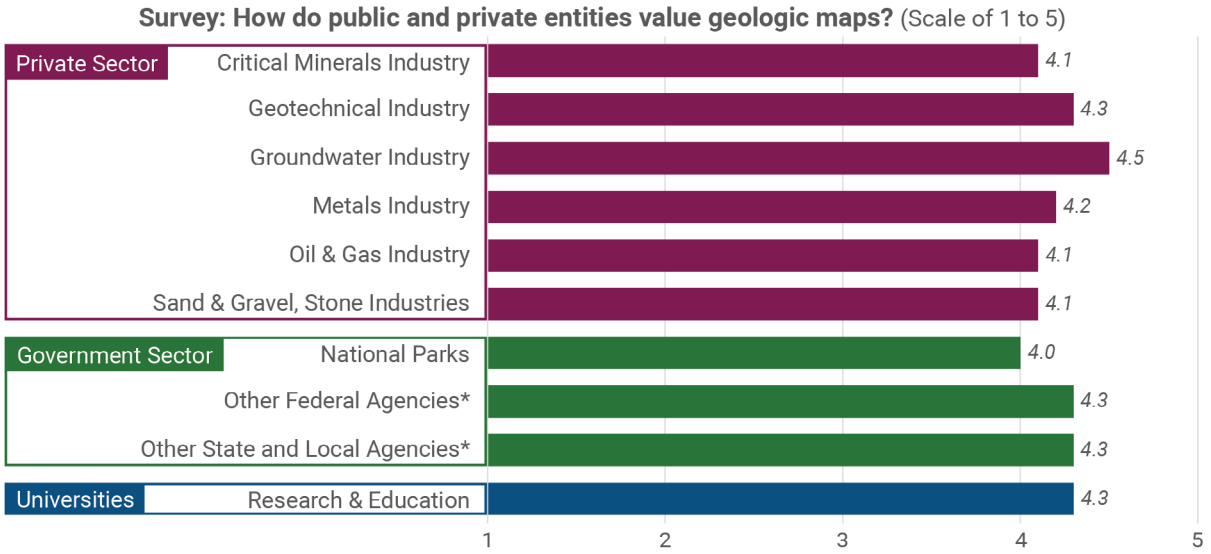
GEOLOGIC MAPPING AT THE CALIFORNIA GEOLOGICAL SURVEY

Public investment in geologic mapping at State Geological Surveys and the U.S. Geological Survey (USGS) results in economic benefits to private sector companies, all levels of government, and individuals with returns of up to 35 times the initial funding (Berg and Faulds, 2025). Geologic maps hold tremendous value through their identification and documentation of extractable materials including energy resources, construction minerals, and precious mineral deposits, and through indirect socioeconomic value associated with land-use planning, infrastructure placement, and engineering decisions. Basic framework geologic maps show the distribution, relationship, and composition of earth materials (rocks, surficial sediments) and structural features of the earth (faults and folded strata).

The California Geological Survey (CGS) conducts regional geologic mapping across California to identify and document potential impacts of geologic and seismic hazards in regions with high population growth, development pressure, significant infrastructure, and climate change hazards, and to document earth materials of direct economic value. The CGS's mapping products are significant resources for the public because they provide the most up-to-date understanding of the regional and local geology across the state by utilizing advanced geologic mapping techniques, considering changes in land use development, and including recent mapping from historical geologic events such as earthquakes and landslides. Once prepared, reviewed, and published, California geologic maps are available to the public and other stakeholders as free downloadable PDF files and data from the CGS's website. The information presented in these geologic maps provides the public with access to

Next page: *Geologic maps of a region encompassing the community of Ukiah in Mendocino County show the close relationship that communities, infrastructure, and developments have with the surrounding geology. Accurately located fault traces and geologic units significantly aid in recognition and mitigation of earthquake, hillslope, and mineral hazards posed by specific geologic formations, and identification of potential economically viable resources. (a) Geologic map of a portion of the Ukiah 7.5' Quadrangle (Delattre and Rubin, 2020). Dashed gray rectangle shows the extent of inset maps (b) and (c). (b) Geologic map of the region west of Coyote Valley Dam. (c) Seismic hazards identified from the geologic map in b. Identification of these hazards helps communities make informed development decisions and prepare for earthquakes. Note that the areas of elevated liquefaction (settlement) potential shown here in green are for illustrative purposes only; the Ukiah 7.5' Quadrangle has not been formally zoned for liquefaction hazards by the CGS.*


(a)
Franciscan Formation: naturally occuring asbestos, mercury, and prone to landslides
Coyote Valley Dam
US 101
MAACAMA FAULT
Timber harvests and burned watershed hazards in forested mountains
Large landslides pose hazard to dam and downstream residents
Russian River
Russian River floodplain, construction aggregate resources
Ukiah City Limits
Downtown Ukiah
City of Ukiah situated on alluvial fan floodplain prone to flash floods and debris flows
N
0
0.5
1
Miles
Geologic Units
Water
Gravel Quarries
Artificial Fill
Stream Channel
Landslides
Alluvium
Fan
Young Alluvium
Young Fan Deposits
Older Alluvium
Older Fan
Very Old Terrace Deposits
Ukiah Formation
Franciscan Complex
(b)
Geologically young and loose river deposits amplify ground shaking from earthquakes
MAACAMA FAULT
US 101
Russian River
Coyote Valley Dam
0
0.5
Miles
(c)
Active fault crosses US 101
CGS Alquist Priolo Fault Zone of Required Investigation
Communities situated on loose river deposits with elevated settlement potential during earthquakes
0
0.5
Miles



The value of geologic maps to national survey respondents as reported in the 2025 AGI economic analysis of the costs and benefits of geological mapping (Berg and Faulds, 2025). High ratings across the private sector, government agencies, and universities justify investments in geologic mapping.
**Other federal, state, and local agencies are those that are not geological surveys (e.g. planning commissions).*

geologic data and supports development decisions made by businesses and local municipalities.

DERIVATIVE MAPS AND PRODUCTS

Basic framework geologic maps produced by the CGS are the foundation from which critical map products are derived. California state laws mandate that the CGS identify and map areas of the state that are susceptible to earthquake-induced hazards including liquefaction, earthquake-triggered landslides, and surface fault rupture. These mapped areas are derived, in part, from basic geologic framework maps, and form the basis for map products showing hazard zones where cities, counties, and state permitting agencies may require that stronger building codes are necessary for safe development. Production of maps showing the locations and distribution of other hazards, including radon potential and inventories of existing landslides, also starts with review of basic geologic framework maps. Maps showing the locations of extractable resources, from aggregate sources supporting California's construction industry, to critical mineral resources that the state will need in its effort to decarbonize California's economy, are shown in maps derived from basic geologic framework maps. Geologic mapping is also the starting point for derivative maps and products that support legislatively mandated hazard documentation and information about the State's diverse non-fuel mineral resources. Like basic framework geologic maps, these derivative map products are freely available to the public and other stakeholders as PDF map sheets that can be downloaded from the CGS's website.

ECONOMIC RETURNS ON PUBLIC INVESTMENTS IN GEOLOGIC MAPPING

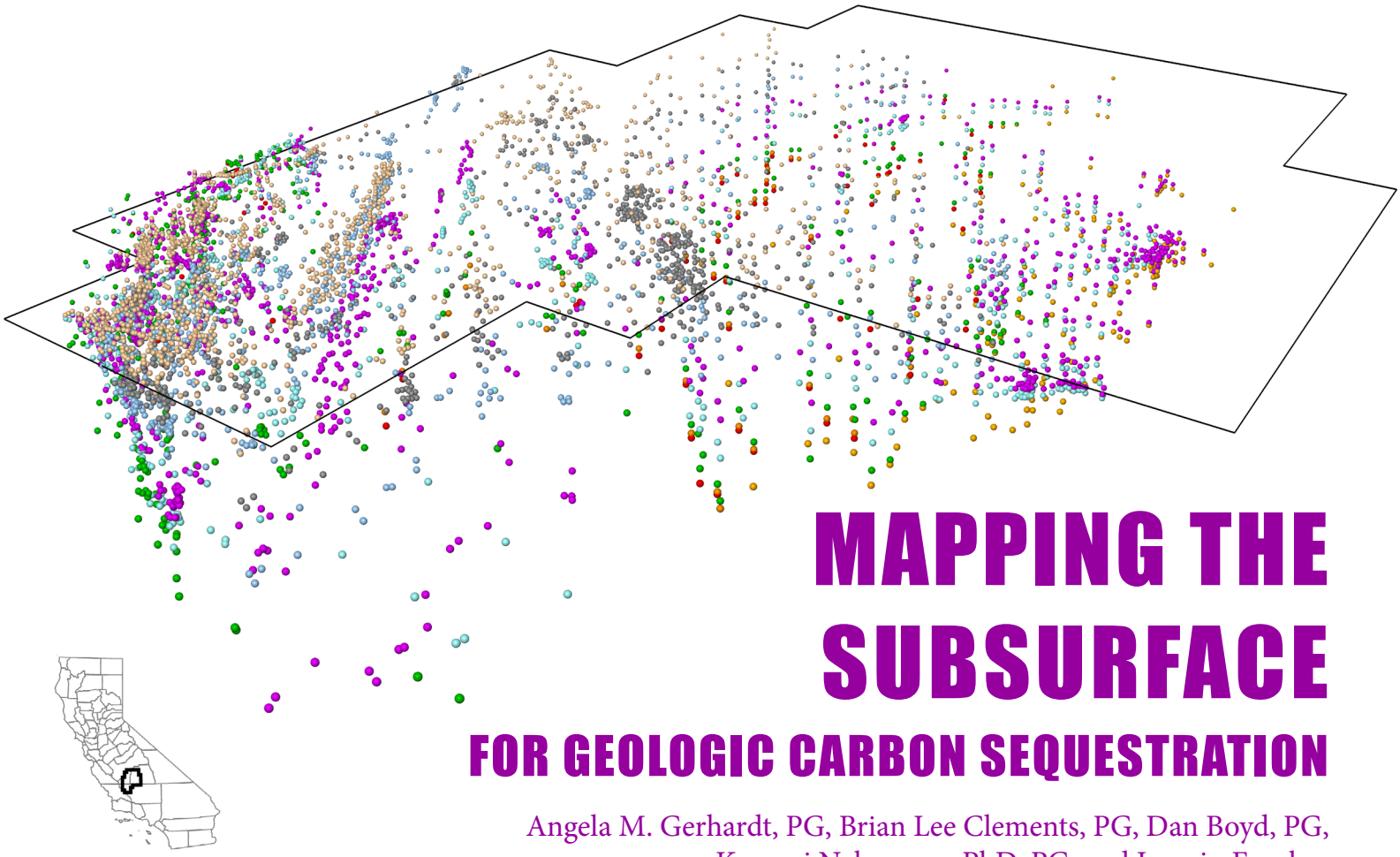
Public investment in geologic mapping at the CGS, other State Geological Surveys, and the USGS generates considerable return on investment and benefits to industry, government, and broader society at large. A recent study (Berg and Faulds, 2025) conducted by the American Geosciences Institute in collaboration with the Association of American State Geologists demonstrated that investments in geologic mapping by the federal government resulted in economic returns 7 to 10 times the initial costs in most cases, and in some cases as high as 35 times initial costs. This economic assessment found that from 1994 to 2019, the federal government invested $1.99 billion (in 2020 dollars) in geologic mapping at the USGS and State Geological Surveys, with 7.1 million geologic maps downloaded or sold nationwide in that time, resulting in a total estimate of economic benefit between $13.9 billion and $20.6 billion. Through a survey of 4,779 stakeholders, the study confirmed that geologic maps provide benefits across many sectors of the economy, including construction and real estate, mining and energy, infrastructure and transportation, environmental protection, and government and public policy. The findings make a strong case for the continued investment in geologic mapping in California and throughout the United States, with human health and safety and economic benefits that far outweigh the costs.

REFERENCES

Berg, R. C., and Faulds, J. E. (Eds.), 2025. Economic analysis of the costs and benefits of geological mapping in the United States of America from 1994 to 2019. American Geosciences Institute. https://doi.org/10.62322/wra5.gs9v.

Delattre, M. P., and Rubin, R. S., 2020, Preliminary geologic map of the Ukiah 7.5' Quadrangle, Mendocino County, California: California Geological Survey Preliminary Geologic Map Series.

Titus Canyon in Death Valley National Park. Photo by Alyssa Tunnelle-Cramer, CGS



MAPPING THE SUBSURFACE

FOR GEOLOGIC CARBON SEQUESTRATION

Angela M. Gerhardt, PG, Brian Lee Clements, PG, Dan Boyd, PG,
Kazumi Nakamura, PhD, PG, and Lennin Escobar

Each dot in this figure represents the top of a geologic formation interpreted from geophysical well log signatures. The 7,589 interpretation points were created by CGS geologists to correlate eight major geologic sequences within the project area (black outline), a 3,600 square mile area in the San Joaquin Valley.

A NEW FRONTIER IN SUBSURFACE MAPPING FOR CALIFORNIA

The California Geological Survey (CGS), with its long history of geologic mapping and hazard assessment, is advancing initiatives towards a promising carbon management strategy: geologic carbon sequestration. To reach its carbon neutrality goals, California is transitioning away from carbon-emitting technologies in the transportation, industrial, and electricity sectors. Even with these shifts, certain sectors will remain difficult to decarbonize. That's why the removal and permanent sequestration of carbon dioxide (CO_2) from industrial sources remains a critical component of the state's climate plan. Under Senate Bill 905 (SB 905), the CGS formed a new Geologic Carbon Sequestration Group (GCSG) to identify high-quality subsurface formations suitable for sequestration and to provide expertise and guidance to the California Air Resources Board to ensure safe and long-term storage of CO_2.

SB 905, signed into law in 2022, marked a pivotal moment for California's climate policy. The law establishes a plan to accelerate carbon capture and storage development, focusing on reducing greenhouse gas emissions from hard-to-decarbonize sectors such as cement production, steel manufacturing, and petroleum refining. Duties of the GCSG within this legislation include, but are not limited to:

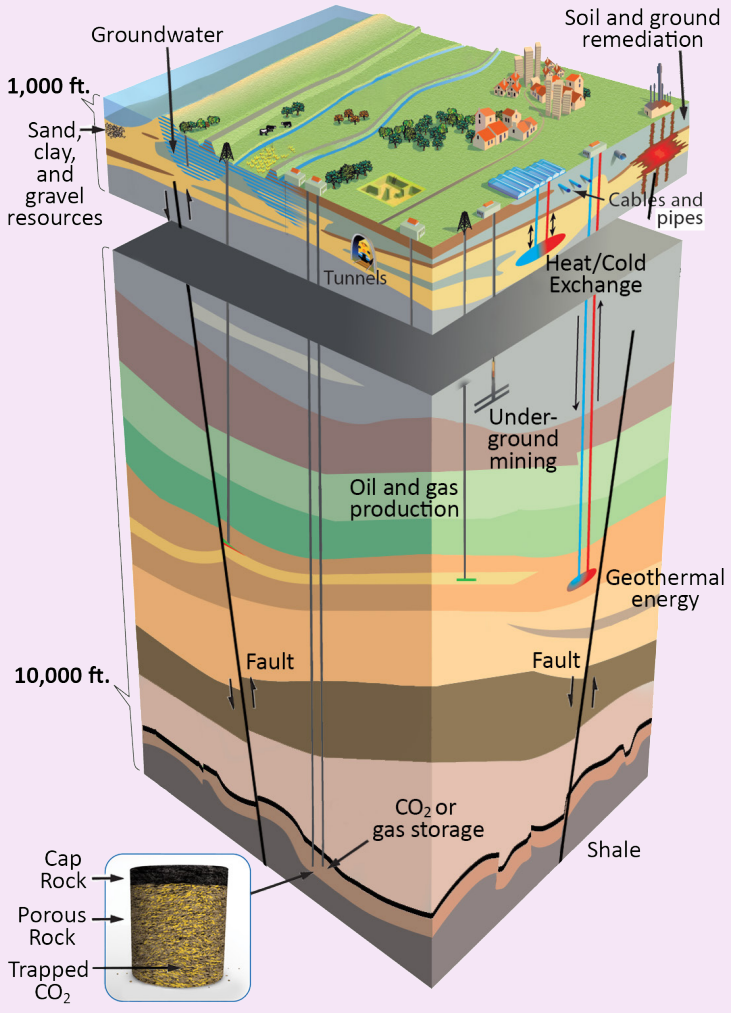
1. Identification of high-quality, suitable subsurface locations for Class VI injection wells (Class VI is the US EPA designation for wells used to inject CO_2 into deep rock formations for purposes of long-term sequestration).
2. Identification of appropriate subsurface monitoring to ensure geologic sequestration of injected carbon dioxide.
3. Identification of hazards that may require the suspension of carbon dioxide injections.

To begin this assignment, the CGS is providing geologic expertise while developing subsurface geologic maps and models for California, starting with the Central Valley. Most carbon storage projects are proprietary; however, California is investing in open data to support the public, policy makers, regulators, and project developers. Through this legislation, the State of California and the CGS are building public, science-based subsurface models for climate solutions.

WHY THE CENTRAL VALLEY?

The Central Valley is a vast sedimentary basin that stretches from Redding to Bakersfield, and is known for its deep sedimentary layers, an extensive oil and gas exploration history, and relatively low (though still present) seismic risk compared to other parts of California. These characteristics create conditions where long-term carbon storage is possible. Preliminary carbon sequestration assessments of the Central Valley by the CGS and Lawrence Livermore National Laboratory highlighted the San Joaquin and Sacramento basins as possible locations for sequestration. These specific basins are ideal because they contain several thick and laterally extensive porous formations and potential reservoirs overlain by impermeable shale and mudstone formations that provide a caprock (Downey and John, 2006).

The CGS is advancing prior work by developing a series of subsurface models within the San Joaquin and Sacramento basins to further assess the suitability of geologic formations for carbon sequestration based on



Conceptual 3D geologic diagram showing CO_2 injection and storage co-located among other uses and interests. Geologic carbon sequestration works by injecting CO_2 deep below the earth's surface into a naturally-occurring formation of porous rock for long term storage. Additional opportunities for CO_2 sequestration include carbonate mineralization of CO_2 through chemical reaction with mafic to ultramafic rocks such as basalt. Modified from TNO, Geological Survey of the Netherlands and the Global CCS Institute.

What is Geologic Carbon Sequestration?

Geologic carbon sequestration involves capturing CO_2 from industrial sources and injecting it deep into naturally-occurring formations of porous rock, called reservoirs, for long-term storage. CO_2 injection for long term storage is feasible at depths greater than 2,600 feet (800 meters), where the temperature and pressure conditions keep CO_2 in a supercritical fluid phase. For comparison, groundwater aquifers in California are typically a few hundred feet deep, and rarely deeper than 1,000 feet (305 meters). Supercritical fluids behave as both a gas and a liquid, taking up less space and dispersing through pore spaces in rock formations faster than either gases or ordinary liquids.

Formations considered for long term storage of CO_2 are: deep saline aquifers; depleted oil and natural gas reservoirs; and mafic to ultramafic rocks such as basalt, which catalyze the chemical conversion of CO_2 to a solid mineral form. A critical aspect of geologic carbon sequestration is identifying an effective confining layer: regional-scale impermeable rock layers, referred to as caprock or seal, that trap the CO_2 and prevent it from migrating to the surface and into drinking water sources. The suitability of a site for geologic carbon sequestration must be determined on a case-by-case analysis. (NETL BPM site screening 4.1.2)

key criteria such as depth, thickness, confining layer integrity, local faulting, porosity, and permeability (Figure 1). Focusing first models on the Central Valley, addresses regions with the greatest storage potential and high industrial emissions, aligning the project with California's climate goals.

SUBSURFACE MAPPING AND MODELING METHODS

Constructing subsurface geologic maps and 3D models is foundational to the GCSG's assessment. These maps and models are critical for identifying and characterizing potential carbon storage reservoirs, evaluating subsurface hazards, and creating regional geologic frameworks for future geologic studies. The workflow (Figure 2) includes:

- Compiling published literature, geologic maps, and cross sections
- Collecting data such as oil and gas well attributes; geophysical well logs; and seismic, gravity, and magnetic data
- Correlating the tops of geologic formations from geophysical well logs and producing surfaces through algorithmic interpolation
- Constructing 3D geologic models and maps
- Delivering these products in a format for public use

Compiling Published Literature and Cross Sections

As a starting point for all subsurface characterization, the CGS reviews and compiles published literature, maps, and geologic cross sections spanning decades of research into regional-, basin-, and formation-scale contexts. This compilation provides a conceptual model for an area of interest and guides our next steps delving into data analysis and well-to-well correlation.

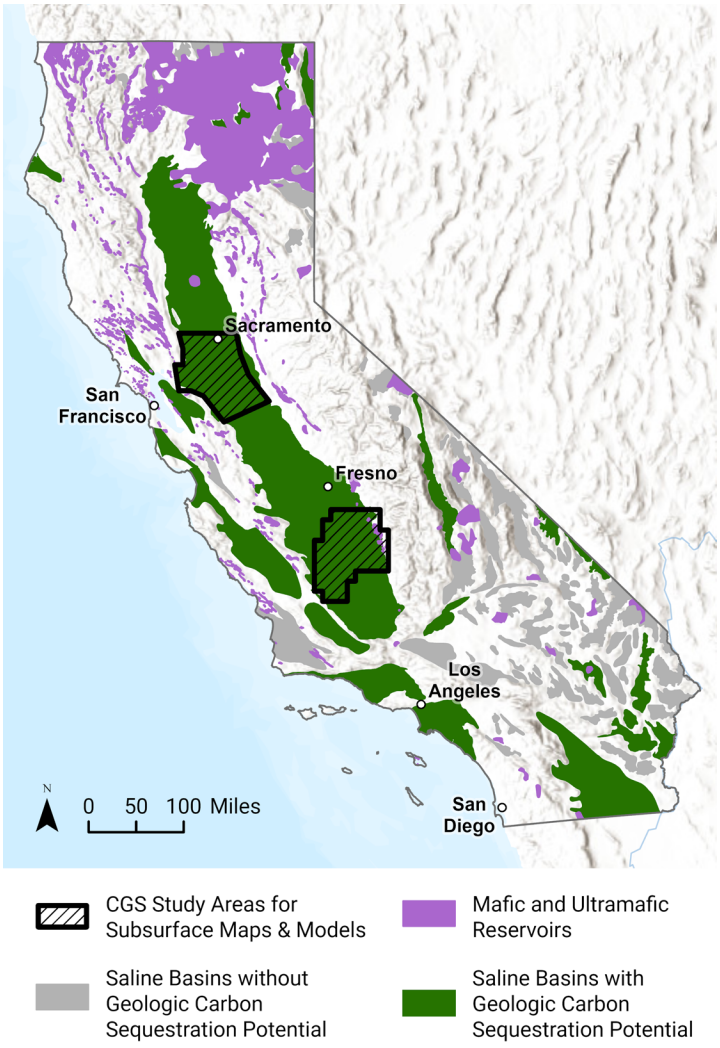


Figure 1. California basins with geologic carbon sequestration potential. This map shows basins with relative potential for geologic carbon sequestration based on basic criteria related to caprock thickness, reservoir thickness, and associated depths applied to data from CGS Special Report 183. Mafic and ultramafic rock types are also shown as potential reservoirs for carbon sequestration that need to be defined with more research. The map also highlights active subsurface model project areas at the CGS.

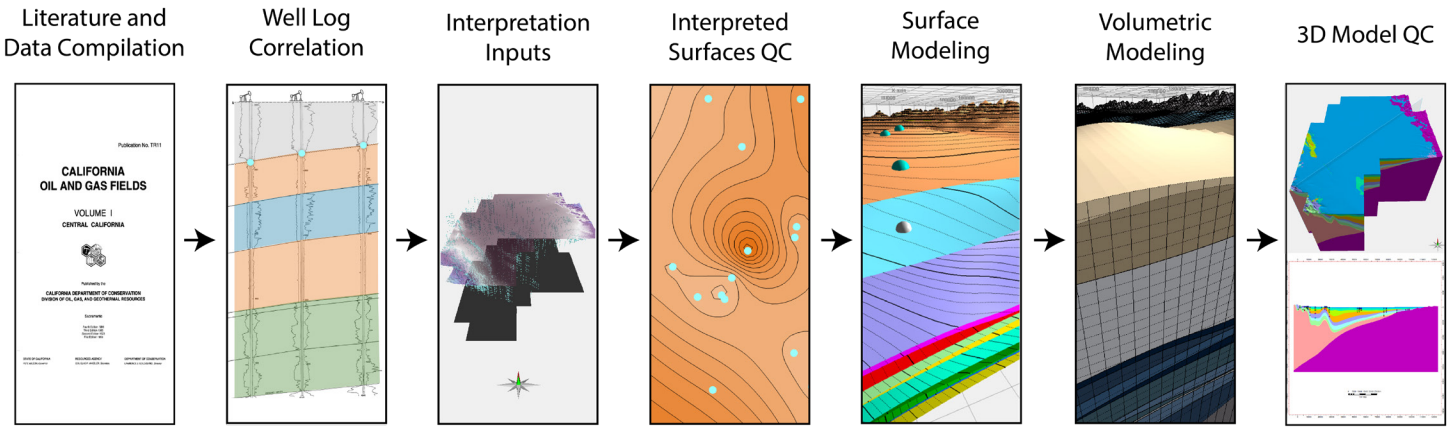


Figure 2. An example of the GCSG workflow from literature and data compilation to producing a 3D Subsurface Model. (QC = Quality Control).

Collecting Data

Many different datasets originally collected for oil and gas exploration can be reporpused to support subsurface geologic mapping and modeling. These datasets include:

- Geophysical well logs, some dating back to the 1930s, that are digitized and prepared for use in interpretation software
- Temperature data and total well depth are compiled from each well log header, which details the drilling process
- Seismic reflection data in both low-resolution and high-resolution formats
- Gravity and magnetic data from both ground and air surveys

The combination of these datasets provides valuable information about the subsurface stratigraphy, structure, and geomechanics.

Correlating Geological Surfaces and Boundaries

Modeling and mapping the subsurface geology begins by interpreting the top of formations and major sequence boundaries from the geophysical log in each well. These geological features are correlated between wells by identifying similar features and tracking changes in the depth of that feature across different wells. Correlating geological features from well-to-well is a time consuming and iterative process informed by the conceptual model developed in the literature review and compilation phase.

A typical correlation workflow begins with two steps: 1) depth registering well logs using geological interpretation software and 2) interpreting geophysical logs to identify and differentiate individual stratigraphic units. Step 3 is repeating the process in each well until formations and boundaries are identified. A stratigraphic framework is constructed by repeating these three steps for several thousand wells across a basin. Each well may be reviewed and reinterpreted several times, so that the conceptual model informs the stratigraphic framework and vice versa, reducing uncertainty with each iteration. The result is an increased understanding of stratigraphic features at each well and of how these features change from well to well.

While well-to-well correlation is used to construct a stratigraphic framework, the integration of seismic reflection data introduces a crucial technique for defining the subsurface structure. Two-dimensional (2D) seismic reflection data, where available, provide additional geological insights between wells and help the geologist interpret subtle or abrupt changes in geological features like lateral continuity, thickness, or geologic structures (faults and folds) to build the geologic framework model. Combining well-to-well correlation with 2D seismic reflection data builds a model that accurately represents the subsurface geology (Figure 3). This refinement allows the geologists to make more detailed assessments of carbon sequestration potential at the formation level, which is essential for planning any future sequestration endeavors.

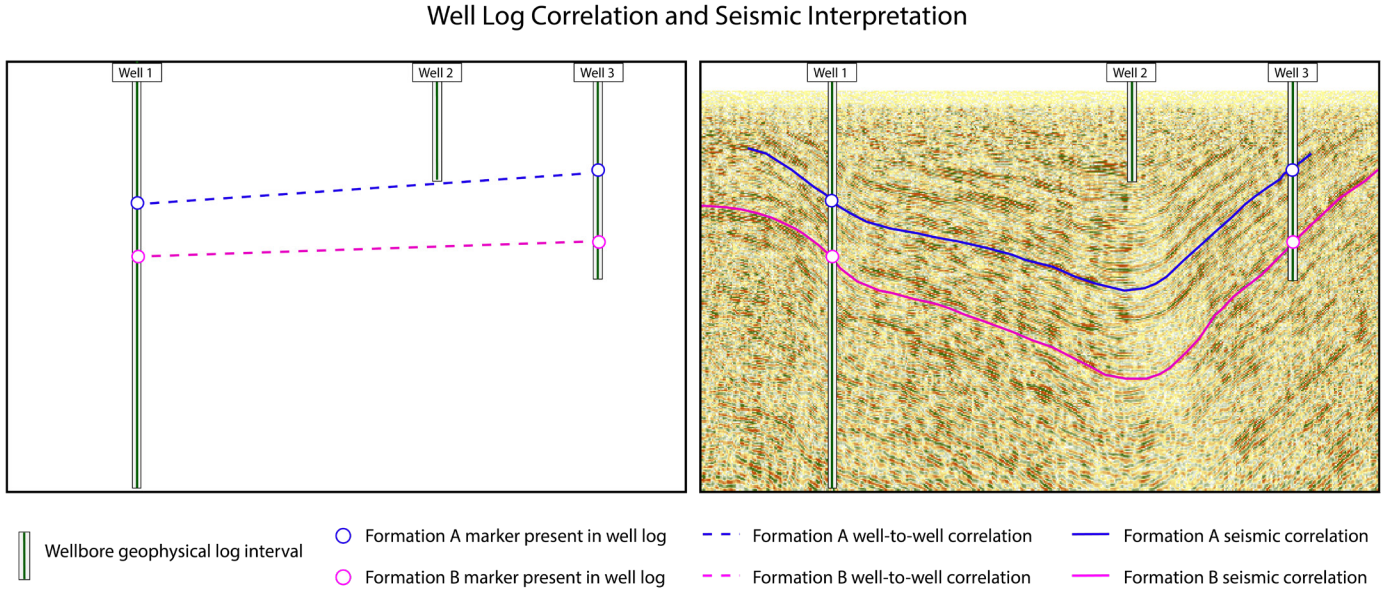


Figure 3. An example of combining well log data and seismic reflection data to understand structural and stratigraphic changes over areas with sparse borehole data. SEISCO, Inc., 1988 (reprocessed), SEISCO, Inc. Seismic Database: SEISCO, Inc. (accessed 1994).

Constructing 3D Maps and Models

Specialized software is used to construct three-dimensional (3D) geologic models. The software uses logic-based rules to interpolate diverse data across a 3D grid. This initial interpolation usually requires manual refinement by geologists to ensure the resulting model adheres to geologic principles and creates a realistic subsurface representation (Figure 4). Like well-to-well correlation, 3D model development is an iterative process, requiring careful interpretation, validation, and adjustment across multiple scales. The resulting 3D models provide essential information on the changes in porosity and permeability across and within formations as well as highlight changes in facies, key formations, sequence boundaries, and subsurface structure. These 3D models are critical for identifying suitable carbon storage reservoirs and potential geologic hazards.

Mapping the Basement with Gravity and Magnetics

Mapping the underlying basement is a crucial part of the refined assessment, as it contributes to understanding the geological history and defines the overall thickness of the sedimentary fill within a basin. The location of, or depth to, the basement can be identified in geophysical logs and correlated from well to well. However, many existing wells terminate above the basement, making defining the basement through well correlation a challenge. Seismic reflection data can also be used to define the top of the basement and to supplement well data in shallow basins, although deep basins require additional methods.

To rectify the lack of data in deep locations, changes in density and magnetization of the geologic units detected using potential field methods are used to infer the contact between sedimentary features and the basement. By combining potential field modeling with seismic interpretation and well-to-well correlation, the

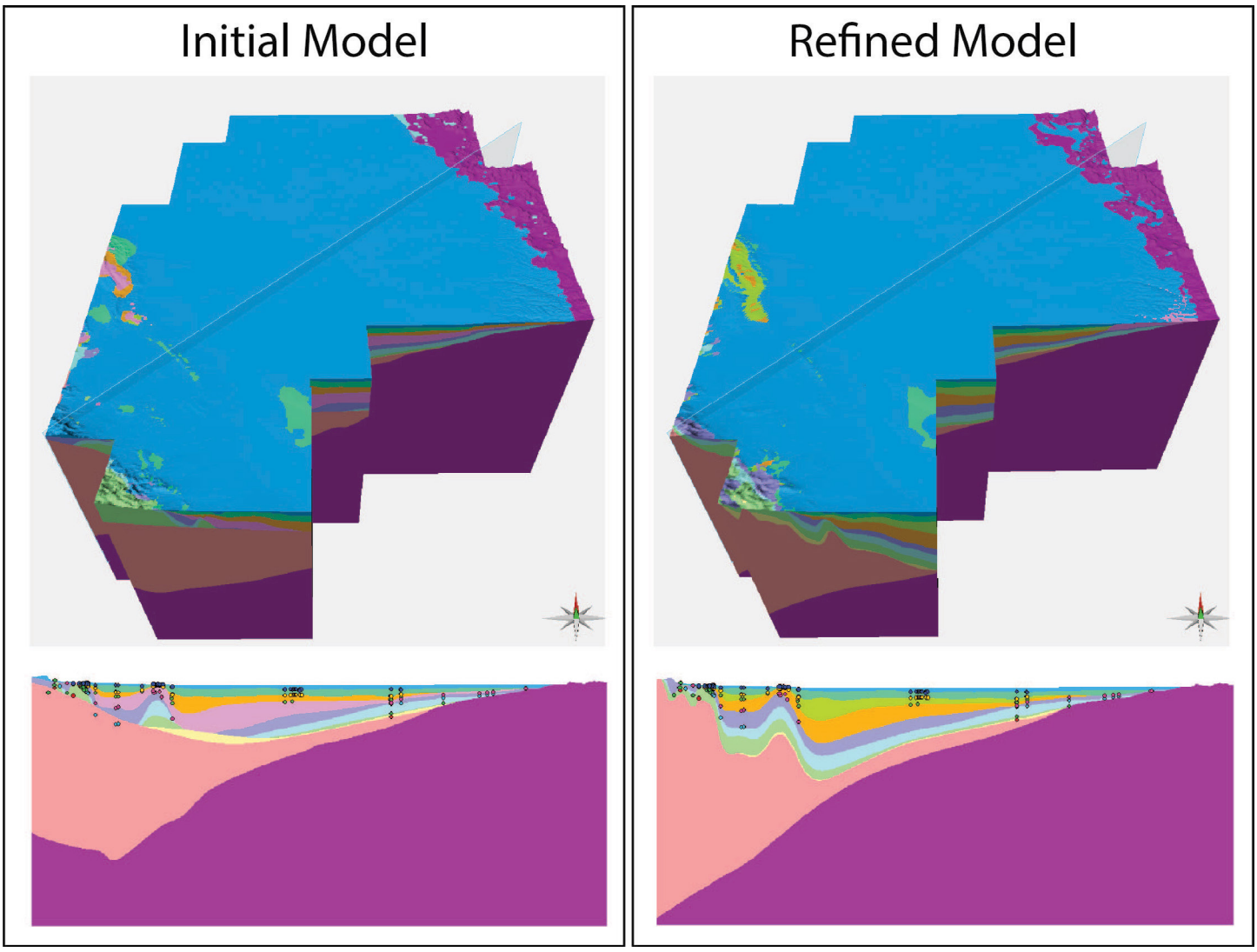


Figure 4. The model refinement process starts with an initial model generated through software logic-based rules to interpolate data points across a 3D grid. Then manual adjustments by geologists are required to ensure the resulting model adheres to geologic principles.

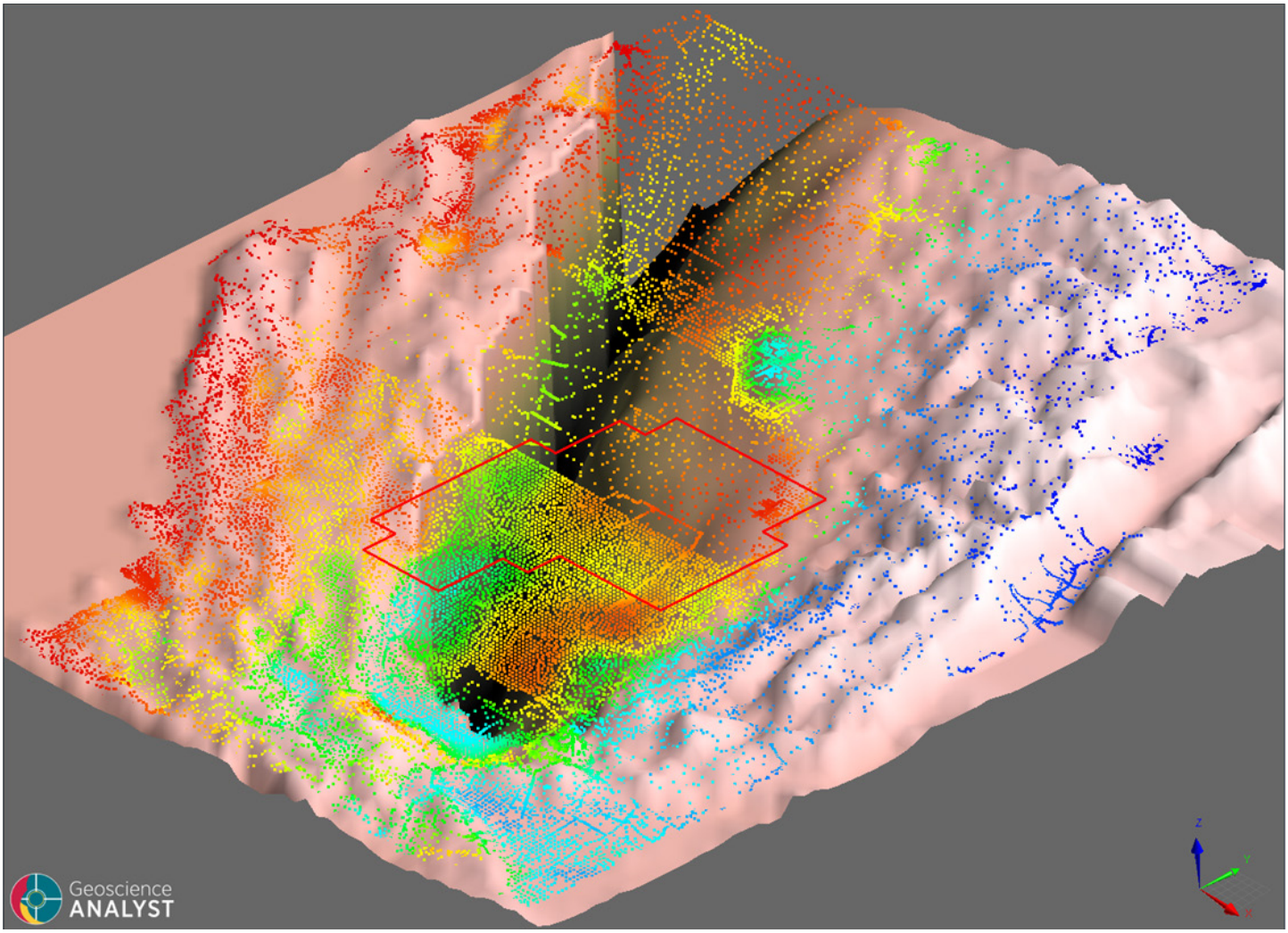


Figure 5. This is an image of GCS's preliminary San Joaquin Valley basement surface model using Geoscience ANALYST software. Points represent complete Bouguer gravity anomaly data. The model incorporates gravity and electromagnetic data, geophysical well-log basement surface picks, geophysical well-log density measurements, CGS geologic map of California, USGS digital elevation models, and previous depth-to-basement models.

basement surface can be interpreted throughout an entire basin (Figure 5). Defining and mapping the top of the basement allows us to determine the total thickness of the sedimentary fill. Knowing these thicknesses and depths is essential for characterizing the structure and tectonic history of the basin. All of this information is then incorporated into the refined assessment.

Building a 3D Temperature Model

Certain temperature conditions must be met for a reservoir to be suitable for carbon sequestration. This means understanding how the temperature changes at depth throughout the basin is an important part of evaluating the basin's potential for carbon storage. To evaluate temperature, especially temperature gradients, across the basin, borehole bottom-hole temperature measurements are collected and calibrated to equilibrium records. Those calibrated measurements are used to model the distribution of subsurface temperatures. The geological framework model accounts for lithology-specific changes that affect the propagation of temperatures from the basement to the ground surface. The resulting temperature model is used to evaluate cold, warm, and hot formations at depth.

Modeling in Higher Detail

While regional frameworks are the current focus, there is also a need for detailed reservoir characterization. The CGS anticipates collaborating with academic institutions and research partners that specialize in reservoir geomechanics and CO_2 plume migration behavior modeling to ensure that California's publicly available 3D geologic models serve as a foundation for both regulatory decision-making and cutting-edge academic research.

DELIVERING DATA

The CGS aims to provide public access to non-proprietary datasets used to develop and interpret the 3D geological framework models, as well as actual model outputs. This access will benefit and inform regulators, project developers, and the public alike. The datasets will include well lists, formation depths, cross sections, structure maps, isopach maps, carbon sequestration suitability maps, 3D models, and technical reports. These products will be hosted through an official data portal (https://maps.conservation.ca.gov/cgs/gcs/) to support decision making and project development. Making these datasets open access will provide an unprecedented resource for evaluating carbon sequestration in California.

LOOKING AHEAD: BUILDING CALIFORNIA'S SUBSURFACE KNOWLEDGE

As California charts a path towards carbon neutrality, understanding the geologic framework of potential carbon storage sites is essential. In 2026 and beyond, the CGS will continue expanding its work with the following near-term priorities:

- Release data for the Preliminary Subsurface Geologic Model of the South-Central San Joaquin Basin
- Expand modeling efforts into the southern portion of the Sacramento Basin and San Joaquin Delta
- Engage with academic institutions and industry to perform peer review and to validate models
- Coordinate with state and federal partners as advisors

California's geologic record tells a story of dynamic Earth processes and resource potential. The subsurface story is revealed through California's geologic carbon sequestration initiative and the CGS's focus on modeling the subsurface. Through the culmination of these efforts the GCSG is honoring the CGS's mission and mandate by providing scientifically based publicly accessible data that supports pore-space management and conservation and regulatory review of risks to public health and safety.

REFERENCES

Baker, Sarah E., et al., 2020. Getting to Neutral: Options for Negative Carbon Emissions in California: Lawrence Livermore NBational Laboratory, LLNL-TR-796100. https://doi.org/10.2172/159721.

California Department of Conservation, Geologic Energy Management Division, 2024, WellSTAR: California Department of Conservation, Geologic Energy Management Division, https://calgem.conservation.ca.gov/WellRecord/ (accessed April 2022).

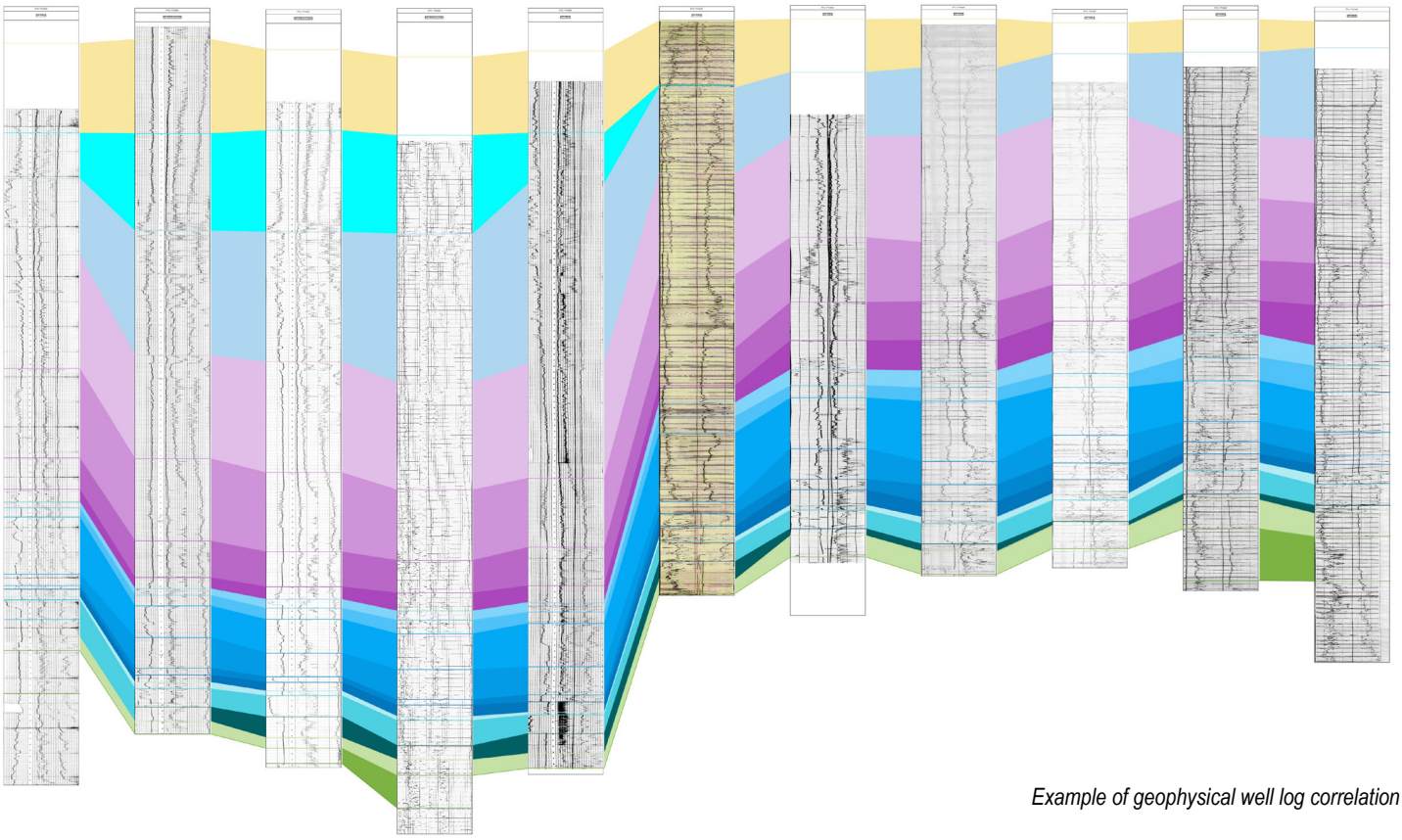
California Legislature. Senate Bill No. 905: Carbon sequestration: Carbon Capture, Removal, Utilization, and Storage Program. 2021-2022 Reg. Sess., ch. 359, 16 Sept. 2022. California Legislative Information, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220SB905.

California Oil and Gas Fields, Volume 1 – Central California, 1998, California Department of Conservation, Division of Oil, Gas and Geothermal Resources, Oil and Gas Technical Report TR10-12, 499 p.

Downey, C., and John, C., 2006, An Overview of Geologic Carbon Sequestration Potential in California: California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-088, https://doi.org/10.2172/903323

SEISCO, Inc., 1988 (reprocessed), SEISCO, Inc. Seismic Database: SEISCO, Inc. (accessed 1994).

U.S. Department of Energy, National Energy Technology Laboratory. Best Practices Manuals for Carbon Storage. Carbon Management, https://www.netl.doe.gov/carbon-management/carbon-storage/strategic-program-support/best-practices-manuals.



Example of geophysical well log correlation

Chief Scientific and Data Advisor Nate Roth holds a geologic map while CGS geologist Brian Swanson presents recent geologic mapping on a field trip with Department of Conservation leadership near the St. Francis dam site. Photo by Sarah Rubin, DOC

CGS geologist David Reioux taking notes during fieldwork in the Mojave National Preserve, San Bernardino County, using a mobile device and a digital mapping application. The app allows David to see high resolution topographic data, prior mapping and data collection, as well as his new mapping and observations. If multiple people are working together in the field, data added during the fieldwork can sync across devices to be visible to all participants. Photo by Ben Parish, CGS

California's New Gold?
Lithium for our Electric Future

Erica Key, PG

FROM THE GEOTHERMAL FIELDS OF THE SALTON SEA TO THE ANCIENT LAKEBEDS IN the Mojave Desert, the Golden State holds significant lithium potential. Discover why California's geology is well-suited to host lithium and where geologists are looking for it.

INTRODUCTION

Lithium is an essential element used in many products found in everyday life, from lubricants and pharmaceuticals to ceramics and heat-resistant glass. Accelerated development in lithium-ion battery technology over the past decade has increased demand for lithium, fueling interest in identifying and developing new lithium sources. Current global lithium production comes primarily from hard rock mines in Australia and brines in South America, but California's diverse geology also hosts a unique set of lithium resources.

LITHIUM IN HOT BRINES

The Salton Sea Geothermal Field, located on the southeastern shore of the Salton Sea, is currently the most high-profile lithium prospect in California. Here, lithium is dissolved in the superheated geothermal fluid circulating beneath the surface. These fluids, referred to as brines due to their high dissolved mineral content, contain lithium that was likely dissolved from the surrounding rocks.

The Salton Sea overlies a network of faults and basins that developed during the formation of the Gulf of California (Elders et al., 1972; Han et al., 2016). The Gulf

The 45,000-acre Bristol and Cadiz Dry Lake lithium brine project is located in the Mojave Desert, San Bernardino County, California. From Resource World Magazine Inc.

Map showing lithium occurrences and deposits discussed in this article.

of California began opening about 6 million years ago, creating a basin, and by about 4 million years ago the Colorado River had built a delta that cut off the northern part of that basin (Oskin and Stock, 2003; Dorsey et al., 2007). Over time, the river periodically flowed into the northern part of the basin, creating a large lake that repeatedly filled and evaporated over thousands of years and deposited the sequences of sediments and evaporite rocks that host the geothermal brines (McKibben, 1991; Dorsey et al., 2011).

The Salton Sea area is also characterized by volcanism; the geothermal brines are heated by rifting-related magma intrusion beneath the surface of thin continental crust (Brothers et al., 2009). Research on how geothermal activity may contribute to the formation of lithium-rich brines is in its early stages, but the co-existence of the two presents a tremendous opportunity for geothermal power producers. The hot mineral-rich brines, with subsurface temperatures above 300°C, are currently tapped for power production in geothermal plants, and are now potential targets for direct lithium extraction (DLE) technologies (Hulen and Pulka, 2001; Levin, 2025).

According to a recent study led by the Lawrence Berkeley National Laboratory, the Salton Sea Geothermal Field contains over 4 million metric tons of lithium carbonate equivalent (LCE) (Dobson et al., 2023). LCE is a standard unit that expresses lithium content as if it were all in the form of lithium carbonate (Li_2CO_3), a common form for battery manufacturing, making production and demand figures easier to compare (USGS, 2024). The amount of lithium estimated would support production of over 300 million batteries for electric vehicles (LBNL, 2023).

Exploration and development of DLE technology at Salton Sea has grown rapidly over the past several years. Companies such as Controlled Thermal Resources, EnergySource Minerals, and BHE Renewables (a subsidiary of Berkshire Hathaway) are all working in the region to develop commercial-scale DLE and geothermal production.

LITHIUM IN NOT-SO-HOT BRINES

California also hosts lithium brine prospects, unrelated to geothermal systems, in playas throughout the desert. Lithium brine deposits consist of saline groundwater that contains elevated concentrations of dissolved lithium. Producing lithium brine deposits around the world share several key traits, including an arid climate, a closed basin with a dry lake, basins created by faults, lithium-bearing source rocks, and sufficient geologic time for brines to accumulate, which can be on the order of thousands to millions of years (Bradley et al., 2013).

Closed basins that contain dry lakes and potentially host mineral-rich brines occur in the deserts of southeastern California. These basins across the state's deserts have formed through fault-driven subsidence over millions of years and many have hosted lakes during wetter climatic periods (Stewart, 1988; Dokka and Travis, 1990). For example, less than two million years ago (recent in geologic time), Searles Lake was part of an interconnected system of lakes that joined Mono, Owens, China, Searles, Panamint lakes and Death Valley (Gale, 1914; Smith, 1979). Perhaps not coincidentally, the earliest known production of lithium from brine in California was in the early 1900s in minor amounts from Searles Lake, where borax, sodium, and potash production continue today (Bradley et al., 2017).

South of Searles Lake, in the Mojave Desert, lithium brines have also been found in Bristol and Cadiz Dry Lakes (Rosen et al., 2020). Standard Lithium's Mojave lithium brine project spans over 45,000 acres across these two dry lakes, where National Chloride and Tetra Technologies are currently processing brine to produce calcium chloride (Standard Lithium, 2025).

LITHIUM CLAYS IN THE DESERT

Also in the Mojave Desert, you'll find a different kind of lithium deposit, one hosted in clay-rich sediments. These deposits, similar in type to the lithium clay deposits at

Searles Lake in the Mojave Desert of southeastern California. From NASA Earth Observatory

Rhyolite Ridge and Thacker Pass in Nevada, are attracting industry interest to California.

In these sediments, much like in brines, the lithium-rich clays may have originated from the accumulation of sediments in shallow lakes that periodically evaporated due to wet and dry climatic periods. Rivers and streams weathered minerals containing lithium from the surrounding rocks into lakes, where it precipitated into lithium-rich clays over thousands to millions of years (Bradley et al., 2017). Further lithium enrichment of these deposits may have been influenced by volcanic eruptions or circulating geothermal fluids; this is an idea that geologists are actively researching (Putzolu et al., 2025).

The existence of lithium clay deposits in California has been known since the 1950s. The mineral hectorite, an important lithium-bearing clay mineral, was first described near Hector, California and is still being produced there today for use in cosmetics, pharmaceuticals, and paint (Ames et al., 1958; Bradley et al., 2017).

We still have much to learn about California's clay-hosted lithium potential. That's why the CGS Mineral Resources Program, with support from the USGS Earth Mapping Resources Initiative, is studying lithium-bearing clays in ancient lake deposits near Barstow, California. CGS geologists are conducting new geologic mapping and collecting new geochemistry data to provide a better understanding of where and why these clay-hosted resources are found in the Mojave Desert.

MOVING FORWARD: MORE WORK TO DO

As the energy, technological, and economic needs of Californians grow, we are asking more questions about the rocks beneath our feet. Understanding where lithium is stored, how it got there, and how it moves through the subsurface is not just a matter of scientific interest, its the foundation for our state's sustainable future.

The diversity of lithium potential in California reflects the state's geologic complexity; our unique landscape holds tremendous opportunity. Close collaboration between local and state government agencies like the CGS, the USGS, academic institutions, Native American tribes, private industry, and the public will be critical to responsible access and conservation of these resources.

REFERENCES

Ames, L.L., Jr., Sand, L.B., and Goldich, S.S., 1958, A contribution on the Hector, California, bentonite deposit: Economic Geology, v. 53, p. 22–37.

Bradley, D.C., Munk, L.A., Jochens, H., Hynek, S.A., and Labay, K.A., 2013, A preliminary deposit model for lithium brines: U.S. Geological Survey Open-File Report 2013–1006, 6 p., https://pubs.usgs.gov/of/2013/1006/OF13-1006.pdf.

Bradley, D.C., Stillings, L.L., Jaskula, B.W., Munk, L.A., and McCauley, A.D., 2017, Lithium, chapter K of Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, p. K1–K21, https://doi.org/10.3133/pp1802K.

Brothers, D.S., Driscoll, N.W., Kent, G.M., Harding, A.J., Babcock, J.M., Baskin, R.L., et al., 2009, Tectonic evolution of the Salton Sea inferred from seismic reflection data: Nature Geoscience, v. 2, p. 581–584, https://doi.org/10.1038/ngeo590.

Dobson, P., Araya, N., Brounce, M., Busse, M.M., Camarillo, M.K., English, L., Humphreys, J., Kalderon-Asael, B., McKibben, M.A., Millstein, D., Nakata, N., O'Sullivan, J., Planavsky, N., Popineau, J., Renaud, T., Riffault, J., Slattery, M., Sonnenthal, E., Spycher, N., Stokes-Draut, J., Stringfellow, W.T., and White, M.C.A., 2023, Characterizing the geothermal lithium resource at the Salton Sea: LBNL Report LBNL-2001557, 350 p.

Dokka, R.K., and Travis, C.J., 1990, Late Cenozoic strike-slip faulting in the Mojave Desert, California: Tectonics, v. 9, p. 311–340, https://doi.org/10.1029/TC009i002p00311.

Dorsey, R.J., Housen, B.A., Janecke, S.U., Fanning, C.M., and Spears, A.L.F., 2011, Stratigraphic record of basin development within the San Andreas fault system: Late Cenozoic Fish Creek–Vallecito basin, southern California: Geological Society of America Bulletin, v. 123, p. 771–793.

Elders, W.A., Rex, R.W., Robinson, P.T., Biehler, S., and Meidav, T., 1972, Crustal spreading in Southern California: The Imperial Valley and the Gulf of California formed by the rifting apart of a continental plate: Science, v. 178, no. 4056, p. 15–24.

Gale, H.S., 1914, Salines in the Owens, Searles, and Panamint Valleys, Southeastern California: U.S. Geological Survey Bulletin 580-L, p. 251–323.

Han, L., Hole, J.A., Stock, J.M., et al., 2016, Seismic imaging of the metamorphism of young sediment into new crystalline crust in the actively rifting Imperial Valley, California: Geochemistry, Geophysics, Geosystems, v. 17, no. 11, p. 4566–4584.

Hulen, J.B., and Pulka, F.S., 2001, Newly-discovered, ancient extrusive rhyolite in the Salton Sea geothermal field, Imperial Valley, California: Proceedings of the Twenty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.

Lawrence Berkeley National Laboratory Media Relations, 2023, Berkeley Lab led analysis confirms California's Salton Sea region to be a rich domestic lithium resource: https://newscenter.lbl.gov/2023/12/12/berkeley-lab-led-analysis-salton-sea-region-domestic-lithium-resource/.

Levin, R.B., 2025, Powering up Lithium Valley: USC Today, March 28, https://today.usc.edu/powering-up-lithium-valley/.

McKibben, M.A., 1991, The Salton Trough rift: San Bernardino County Museum Association Special Publication 9, p. 76–80.

Oskin, M., and Stock, J., 2003, Pacific-North America plate motion and opening of the Upper Delfín basin, northern Gulf of California, Mexico: Geological Society of America Bulletin , v. 115, no. 10, p. 1173–1190.

Putzolu, F., Armstrong, R.N., Benson, T.R., Boutt, D.F., Butler, K.L., and Dolgopolova, A., 2025, Volcano-sedimentary deposits: Overview of an emerging type of lithium resource: Economic Geology, v. 120, no. 3, p. 541–573, https://doi.org/10.5382/econgeo.652887.

Rosen, M.R., Stillings, L.L., Kane, T., Campbell, K., Vitale, M., and Spanjers, R., 2020, Li and Ca enrichment in the Bristol Dry Lake brine compared to brines from Cadiz and Danby Dry Lakes, Barstow-Bristol Trough, California, USA: Minerals, v. 10, 284, https://doi.org/10.3390/min10030284.

Smith, G.I., 1979, Subsurface stratigraphy and geochemistry of late Quaternary evaporites, Searles Lake, California: U.S. Geological Survey Professional Paper 1043, 122 p., https://pubs.usgs.gov/pp/1043/report.pdf.

Standard Lithium Ltd., 2025, Mojave Project (Bristol & Cadiz dry lakes, California): Standard Lithium Ltd. project webpage, accessed July 14 2025, https://www.standardlithium.com/projects/bristol-lake.

Stewart, J.H., 1988, Tectonics of the Walker Lane belt, western Great Basin: Mesozoic and Cenozoic deformation in a zone of shear, in Ernst, W. G., Metamorphism and crustal evolution of the western United States, Rubey volume VII: Prentice Hall, Englewood Cliffs, N.J., p. 683-713.

U.S. Geological Survey, 2024, Mineral commodity summaries 2024: https://pubs.usgs.gov/periodicals/mcs2024/mcs2024.pdf.

CGS geologist Carolyn Cantwell conducting field work near Barstow, using a handheld laser-induced breakdown spectrometer to determine lithium concentrations in mudstone in the Barstow Formation. Photo by Erica Key, CGS

The CGS Library Has a New Home

Amy Loseth, MLIS, CGS Librarian

The main stacks at the new library. Photo by Amy Loseth, CGS

AFTER 34 YEARS IN THE RENAISSANCE Tower in downtown Sacramento, the CGS Library relocated in the summer of 2025 to the newly renovated Gregory Bateson Building at 1600 9th Street.

Plans to move the Library began in conjunction with the larger development project of the new California Natural Resources Agency Building, located at 715 P Street. This move brings the library within closer proximity to the Natural Resources Building and other downtown public agencies, improving access to its extensive collection of geoscience research materials.

The Bateson Building renovation discussions began prior to 2020, and plans for the inclusion of the Library into the space were finalized in 2021. A number of other options for a new library space were previously explored, including the area vacated by the California Energy Commission

The exterior façade of the Gregory Bateson building, showcasing exposed concrete, wood panels, and windows. Photo by Amy Loseth, CGS

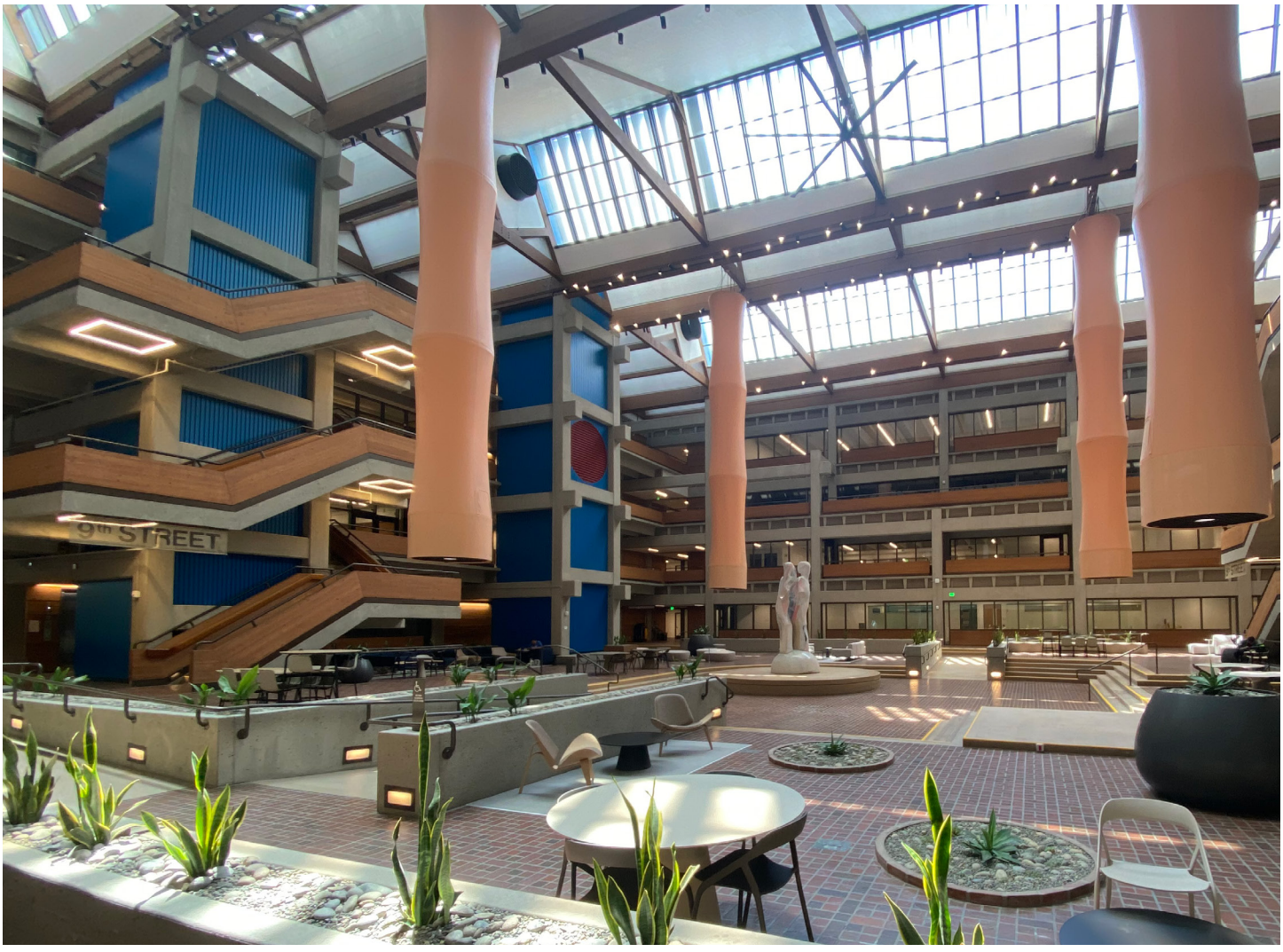
Library in the Warren-Alquist State Energy Building, and the Poppy Pavilion retail space at the new CNRA Building, but due to the limited square footage these options afforded, the Bateson Building was chosen as the most appropriate location for the library's collections and needs.

The Bateson Building, named for the anthropologist Gregory Bateson, was constructed in the late 1970s with an eye toward an energy-efficient design in response to the energy crisis of the time. Its interior features a large, open atrium and four floors of office spaces around the perimeter of the building. While the atrium remains largely unchanged from the original design, the office spaces have been updated to include lobbies, conference rooms, training rooms, and break areas. Improvements and updates have also been made to mechanical, electrical, and plumbing systems throughout, minimizing energy and water use.

The physical move was carried out by library staff and a professional moving company with specialized experience in moving library collections. Over the span of three weeks in June of 2025, the library's collections of books, reports, maps, photos, negatives, slides, oversized folios, and atlases were removed from shelves and drawers, placed on rolling carts, while rare and fragile items were carefully wrapped and secured in boxes for safe transit.

In completion, the renovated library space measures just under 7,200 square feet and is comprised of shelving, flat map filing drawers, desks and tables for public and staff workspaces, and library equipment used for digitization projects and scanning requests. The Rare Book Room features its own dedicated fire suppression system and HVAC unit to monitor and maintain temperature, air flow, and humidity, which are critical for the preservation of aging materials.

The CGS Library reopened its doors in July of 2025 and has welcomed staff, researchers, and visitors since. More information about the CGS Library, visitation, and a link to the online catalog can be found at https://www.conservation.ca.gov/cgs/library.



Natural light pouring into the atrium of the Bateson building. The large vertical canvas tubes once operated to recirculate air and, while no longer used, remain to preserve the architectural legacy. Photo by Amy Loseth, CGS

HELPING CALIFORNIA GET READY FOR *WHEN THE MUD HITS THE FAN*

Jason Kean, PhD and Jaime Kostelnik, MS, PG
U.S. Geological Survey, Geologic Hazards Science Center

With frequent wildfires, powerful rainstorms, steep terrain, and dense population, California is particularly vulnerable to postfire hazards like flooding and debris flows. Major postfire flooding and debris-flow events can be more costly than the fire itself and can result in dozens of fatalities and widespread damage on alluvial fans (Chawner, 1934; Lancaster et al., 2021). Smaller events occur nearly every year in California and can locally damage structures and roads, affect water quality and storage, and result in injury or loss of life (e.g., Dow et al., 2024; Rodriguez, 2025; Swanson et al., 2024; Figure 1). To mitigate these threats, the U.S. Geological Survey (USGS) has developed predictive models to assist local, state, and federal agencies in rapidly assessing postfire debris-flow risk across California's diverse geology and geography. This article summarizes that effort and describes ongoing work by the USGS and partners to advance these methods and help California better prepare for future wildfires.

Figure 1. Examples of recent postfire debris flows in California. (a) Washout of U.S. Highway 1 at Rat Creek, 2020 Dolan Fire (credit: Jonathan Warrick, U.S. Geological Survey), (b) Damage to home downstream of 2020 Bond Fire (credit: Paul Burgess, California Geological Survey); (c) Inundation of California Highway 70 at Murphy Creek, 2021 Dixie Fire (credit: Don Lindsay, California Geological Survey); and (d) Debris-flow scour and removal of trees in Rubio Canyon, 2025 Eaton Fire (credit: Jason Kean, U.S. Geological Survey).

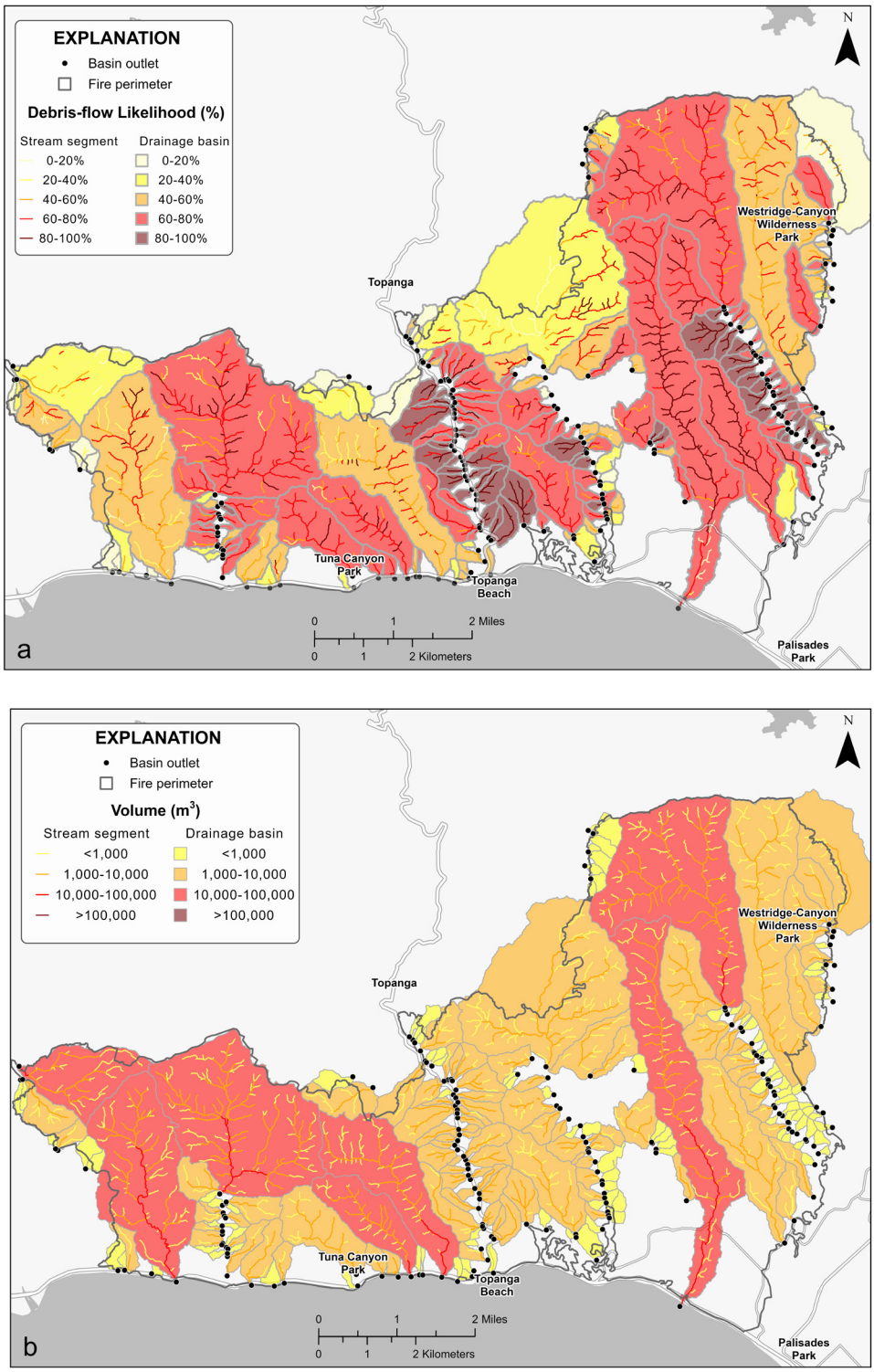


Figure 2. Example debris-flow hazard assessment from the 2025 Palisades Fire, Los Angeles County, CA (USGS, 2025). The maps depict the (a) likelihood and (b) volume of debris flow in response to a rainstorm with a 15-minute rainfall intensity of 24 mm/hr. Repeated flooding and debris flow occurred throughout the burn area in the winter of 2025.

For definitons of key terms in this article, see page 30.

WHERE, WHEN, AND HOW BIG?

Because debris flows are one of the most hazardous consequences following wildfire, land and emergency managers need to know: 1) Where in a burn area are debris flows likely? (2) When during a rainstorm will they occur? And (3) How big will the flows be? Over the last 25 years, the USGS and partners have worked to answer these questions using predictive empirical models that are primarily functions of topography, rainfall intensity, and burn severity as determined from satellite data and field observations (e.g., Cannon et al., 2003; Gartner et al., 2008; Cannon et al., 2010; Gartner et al., 2014; Staley et al., 2017). These USGS models have evolved with time as new data is collected and debris-flow processes are better understood. The current set of models answer the questions Where? and How big? by mapping the likelihood (Staley et al., 2017) and potential volume (Gartner et al., 2014) of debris flow across the burn area for different rainstorm scenarios (Figure 2). The likelihood model is also used to answer the question When? by estimating the amount of rainfall, or rainfall threshold required to trigger debris flows. These USGS models are calibrated with data from southern California (Gartner et al., 2014; Staley et al., 2017), which is where most of the state's data had been collected at the time of model development. Since that time, data collection has expanded to central and northern California (e.g., Thomas et al., 2023; Figure 3), and those new data are currently being used to develop improved models that better reflect regional differences in debris-flow susceptibility.

To date, the USGS has produced debris-flow hazard maps for 262 California wildfires since 2003 covering 54,600 km^2 (13.5 million acres) or 13% of the state (Figure 3; USGS, 2025). In general, there has

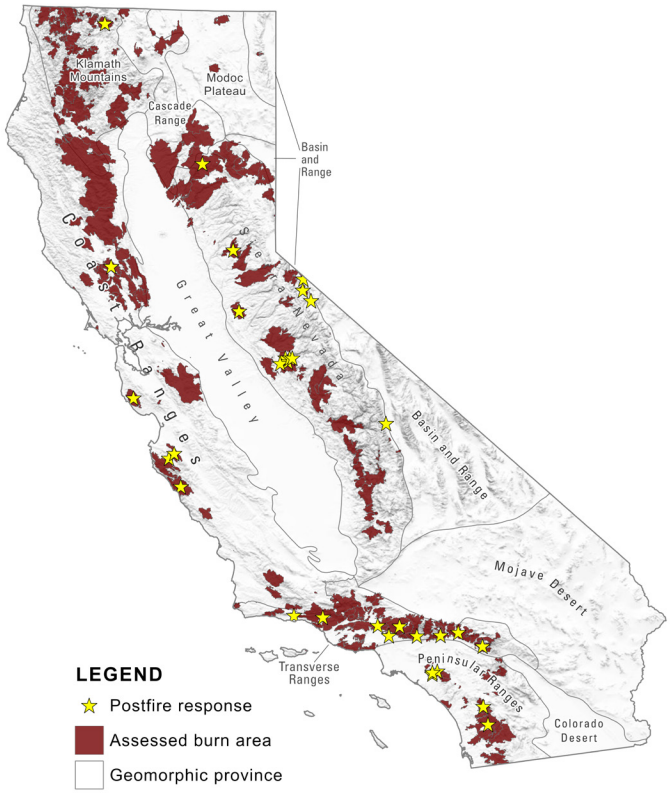


Figure 3. Map showing geomorphic provinces of California (CGS, 2018) and burn areas where postfire debris-flow hazard assessments have been completed (USGS, 2025). Yellow stars identify burn areas where hazardous postfire flooding and debris flow have been documented (Staley et al., 2017; Thomas et al. 2023; Graber, 2023 and 2024).

been an increase in the number assessments with time, as well as the area assessed (Figure 4). Part of this trend is driven by increases in wildfire activity, especially in northern California (e.g., Williams et al., 2019). Technical advances in assessment methodology have also increased the USGS's capacity to respond with additional assessments. For example, in 2014, model calculations were largely automated and product delivery switched from a written report to an interactive public web map (USGS, 2025). These developments shortened assessment completion times from a few months to about a day and importantly allowed the USGS to respond to every request for assistance rather than limit work to a few assessments per year. Recent software developments (King, 2025) have further improved efficiency, making it easier to respond with assessments for increasingly common megafires and sets of fires burning simultaneously.

A TEAM EFFORT

The USGS is part of a multi-agency team assessing postfire risk in California. The USGS's primary roles are to support postfire emergency response by applying the models described above and to conduct research to improve methods for hazard assessment, which is supported by data collected from partners.

In California, state Watershed Emergency Response Teams (WERTs) and federal Burned Area Emergency Response (BAER) teams lead on-the-ground risk assessment for individual fires. WERT focuses on state and private lands, and BAER covers federal lands. Their work begins as the fire nears containment and is typically completed in a week. A rapid schedule is important because the time available for planning between the fire and first rainfall can be short, especially for late-season California fires that burn until the start of winter rains (DeGraff et al., 2015). The teams first determine soil burn severity, a key indicator of where runoff and erosion may be enhanced after wildfire (Parsons et al., 2010). Initial estimates of soil burn severity from satellite imagery are field checked and adjusted by the teams to match ground conditions. The burn severity data are then sent to the USGS as an input to the debris-flow hazard models, and the resulting hazard maps are returned to the team as soon as possible (typically the next day or less). The local teams use the debris-flow hazard maps and additional estimates of peak flood discharge and hillslope erosion (e.g., USFS, 2025) to identify assets at risk to postfire flooding and debris flow (e.g., homes, bridges, culverts, and cultural resources). Our partners can then make recommendations to local authorities and land managers of possible mitigation to reduce potential loss. In rare cases, where a WERT or BAER team cannot be deployed to the fire, the USGS can complete a debris-flow hazard assessment using the satellite estimate of soil burn severity.

A team approach is also used to provide early warning of flash flood and debris flow following wildfires. The National Weather Service (NWS) has the statutory responsibility for issuing watches and warnings for recent burn areas. Watches and warnings are issued when weather forecasts and observations indicate the rainfall may exceed the threshold established for each burn area (NOAA-USGS Debris Flow Task Force, 2005). Initial guidance on a likely rainfall threshold is provided by the USGS using the median of modeled thresholds for all drainage basins that may source debris flows. Although USGS rainfall thresholds are estimated from a debris-flow model, data indicates they are also reasonable thresholds for hazardous postfire flash floods (Thomas et al., 2023). The WERT assessment may also recommend adjustments to the fire-wide rainfall threshold based on their field observations. Additional considerations from local authorities may also factor into the choice of the threshold, because, ultimately, the local authorities are responsible for taking actions in response to risk and warning information.

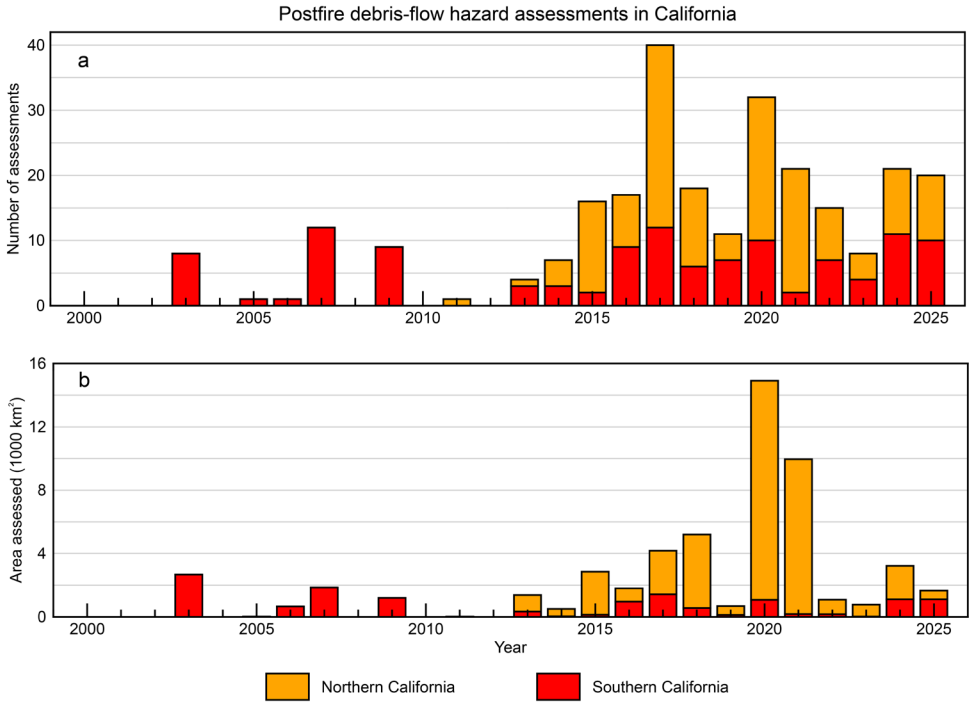


Figure 4. (a) Number and (b) annual area of U.S. Geological Survey postfire debris-flow hazard assessments in California with time (USGS, 2025). Assessments in northern and southern California (north and south of 35.75 degrees latitude) are shown in orange and red, respectively.

GEOLOGY, GEOGRAPHY, AND CLIMATOLOGY

Debris-flow hazard assessments have been completed in nearly every geomorphic province in California and intersect most of the generalized geologic units mapped by the California Geological Survey (CGS, 2018; Figure 5). Similarly, observations of hazardous postfire floods and debris flows span a wide range of geologic and geomorphic units. Plutonic, marine sedimentary, and meta sedimentary units are the most common rock types covered by USGS assessments.

The role of geology on postfire debris-flow susceptibility is not fully understood, and geology is not directly represented in debris-flow hazard models for recent burn areas. For example, the debris-flow likelihood model of Staley et al. (2017) accounts for geology indirectly through a soil erodibility term in a national soils database (Schwarz and Alexander, 1995), but the soil erodibility term has less predictive power than the other terms related to burn severity, topography, and rainfall. Arguably, the most important geologic factor for postfire debris-flow susceptibility is how much sediment is available that can

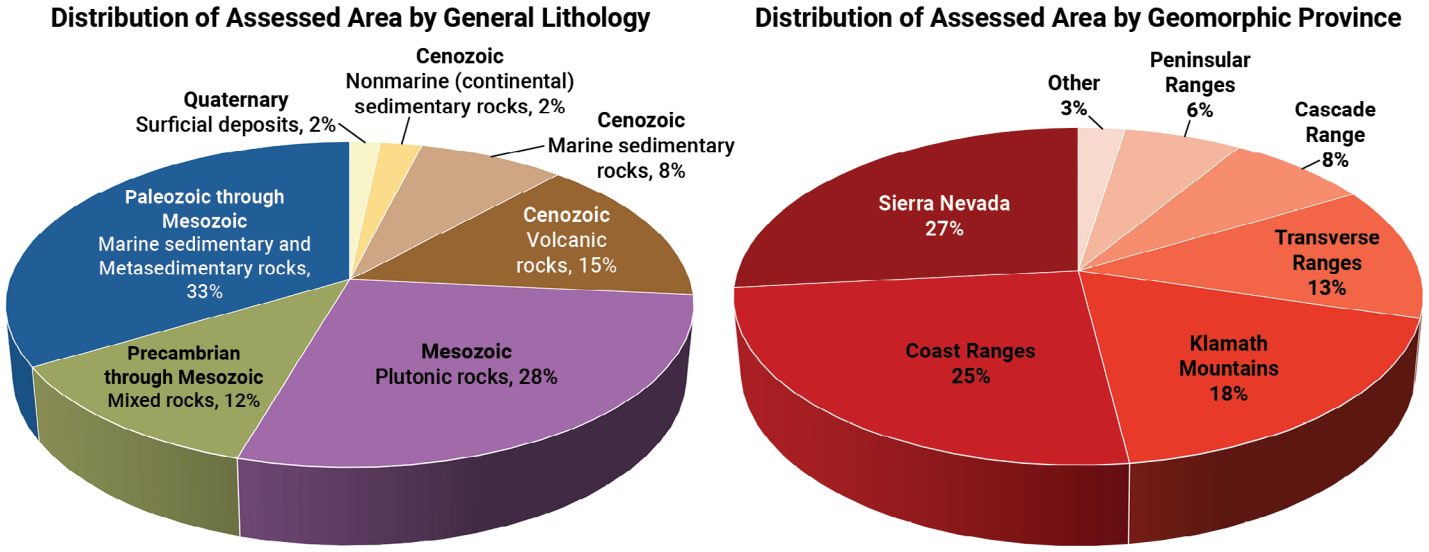


Figure 5. Representation of (a) generalized geologic units and (b) geomorphic provinces (CGS, 2018) of California burn areas where debris-flow hazard assessments have been completed (USGS, 2025).

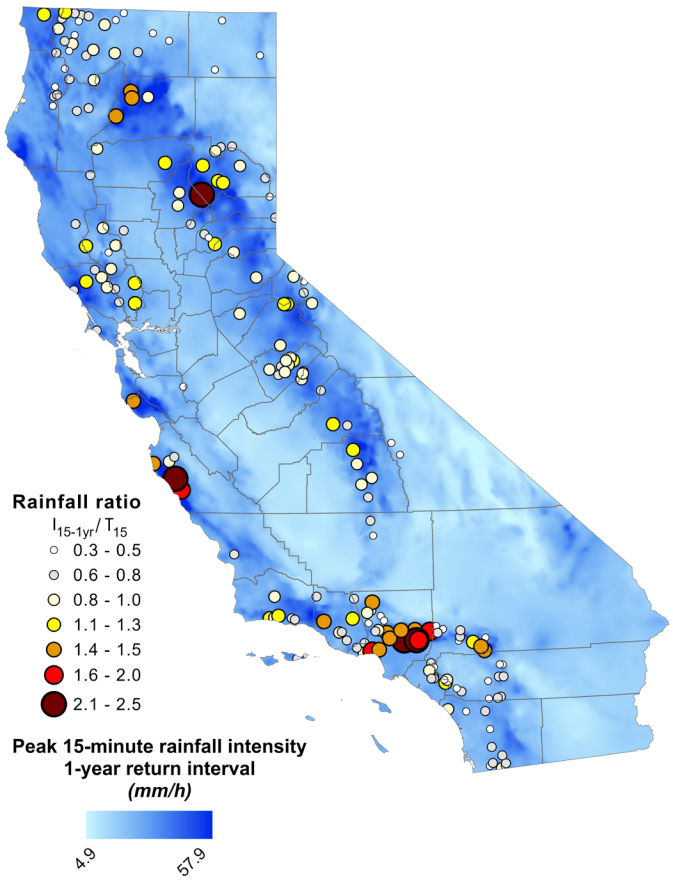


Figure 6. Distribution of 15-minute rainfall intensities with a 1-year recurrence interval ($I_{15\text{-}1yr}$) across California (NOAA, 2025) and comparison to estimated rainfall thresholds (T_{15}) for burn areas (USGS, 2025). Burn areas with ratios of $I_{15\text{-}1yr}/T_{15} > 1$ are likely to receive above-threshold rainfall in the first year after the fire.

be readily mobilized into a flow. For example, the steep, tectonically active San Gabriel Mountains are a global hotspot for postfire debris flows, and granitic units typically produce large quantities of dry ravel during or immediately after wildfire (e.g., Lamb et al., 2011). This sediment can substantially load channels with loose material before any rainfall, making it easier for debris flows to initiate and grow once intense rainfall begins. Abundant dry ravel is not a prerequisite for debris flows; however, a lack of loose material may be a factor in the absence of debris flows observed after the 2018 Carr Fire (Shasta and Trinity Counties) despite the burn area having very steep topography, high burn severity, and intense rainfall after the fire (East et al., 2021). National datasets that capture the combined effects of geology and tectonics on the abundance of easily erodible sediment are not available, so alternative indicators of basin sediment availability, such as mapped alluvial fans that indicate past sediment transport, could potentially improve rapid hazard assessment.

Precipitation frequency is another important factor in postfire hazard assessment because it indicates how likely a rainfall threshold may be met or exceeded each year. Bursts of high-intensity rainfall (such as those measured over 15-minute intervals) are the most common trigger of postfire debris flows in the first two years after a fire. For example, 6 mm (one quarter inch) of rainfall in 15 minutes has been known to trigger debris flows in some burn areas in California (Staley et al., 2017). The intensity of bursts with a one-year recurrence interval ($I_{15\text{-}1yr}$) varies greatly across the state due to variability in climate (NOAA, 2025). A comparison of $I_{15\text{-}1yr}$ to the fire-wide threshold for individual burn areas (T_{15}) shows that rainfall is likely to meet or exceed the threshold for many burn areas in the first year after the fire (Figure 6). This finding is consistent with those of Staley et al. (2020) who showed that most postfire debris flows are triggered by storms with less than a two-year recurrence interval.

Debris-flow likelihood and volume increase with increasing rainfall above threshold. Accordingly, burn areas with high values of $I_{15\text{-}1yr}/T_{15}$ may be more susceptible and more hazardous than burn areas with low values of $I_{15\text{-}1yr}/T_{15}$. Although this ratio is useful for quickly comparing the relative hazard among burn areas, a recent study by Cavagnaro et al. (2025) indicates that debris-flow susceptibility may be modulated by the rainfall climate. Specifically, they found that landscapes accustomed to receiving frequent high-intensity rainfall have higher thresholds for debris-flow initiation than landscapes that do not. Further study to include variability in climate into debris-flow hazard assessment would be beneficial.

HOW FAR AND HOW LONG?

Presently, the two biggest gaps in postfire hazard assessment are the ability to predict: 1) How far will debris flows travel or runout? And 2) How long will the burn area remain hazardous? These predictions could inform decisions about evacuation, mitigation, road safety, and reopening a burn area for public use. Several factors have challenged providing accurate and timely predictions of debris-flow runout. These factors include uncertainty in volume and mobility, topographic complexity of the built environment, and the fact that runout calculations are much more computationally complex than current predictions of debris-flow likelihood and volume. The USGS is making progress towards adding forecasts of debris-flow runout to postfire hazard assessment through extensive model testing and discussions with decision makers about what information is needed (e.g., Barnhart et al., 2023 and 2024). The goals are to model debris-flow runout for the entire fire, address uncertainty in model input parameters, and evaluate multiple rainstorm scenarios. To address how long burn areas will remain hazardous, the USGS continues to evaluate methods to update both hazard maps and

rainfall thresholds as the hazard evolves with time during vegetation and soil recovery. Initial work has shown that remotely sensed metrics of vegetation recovery can be used to evaluate when runoff-generated debris flows are no longer likely to occur in a burn area (Graber et al., 2023). The California Geological Survey is using this methodology to recommend changes to rainfall thresholds in burn areas that are two to six years old. In the future, repeat imagery may be used to make annual updates to the hazard maps and rainfall thresholds, as well as help assess the hazards from shallow landslides that occur in the late stages of recovery several years after the fire (e.g., Thomas et al., 2025).

CONCLUSIONS

Future wildfires in California are inevitable, but secondary losses from debris flows can be mitigated through coordinated risk assessment by local, state, and federal agencies. Assessment capabilities and coordination have grown substantially over the last 25 years as wildfire activity has increased and more population is exposed to resulting hazards. Continued research can help better support decision makers by providing more accurate and timely answers to the postfire questions: Where?, When?, How big?, How far? and How long? Each postfire hazard assessment represents a set of testable hypotheses for the response of a burned watershed to rainfall. The USGS and partners are working to systematically evaluate the accuracy of past assessments to determine how well the current models perform and develop improvements to model future fires before the mud hits the alluvial fan.

ACKNOWLEDGEMENTS

We thank David Cavagnaro, Corina Cerovski-Darriau, Erik Frost, and Elaine Young for their constructive reviews and help in improving the manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES

Barnhart, K.R., Romero, V., and Clifford, K.R., 2023, User needs assessment for post-fire debris flow inundation hazard products: U.S. Geological Survey Open-File Report, 2023–1025, 25 pp., https://doi.org/10.3133/ofr20231025.

Barnhart, K.R., Miller, C.R., Rengers, F.K., and Kean, J.W., 2024, Evaluation of debris-flow building damage forecast: Natural Hazards and Earth System Sciences, v. 24, p. 1459-1483, https://doi.org/10.5194/nhess-24-1459-2024.

California Geological Survey (CGS), 2018, Geology of California: Map sheet 57, scale 1:2,000,000, https://www.conservation.ca.gov/cgs/Documents/Publications/Map-Sheets/MS_057-2018-Geology-of-California.pdf.

Cannon, S.H., Gartner, J.E., Rupert, M.G., Michael, J.A., Djokic, D., and Sreedhar, S., 2003, Emergency assessment of debris-flow hazards from basins burned by the Grand Prix and Old Fires of 2003, Southern California: U.S. Geological Survey Open-File Report 03-475, https://pubs.usgs.gov/of/2003/ofr-03-475/.

Cannon, S.H., Gartner, J.E., Rupert, M.G., Michael, J.A., Rea, A.H., Parrett, C., 2010, Predicting the probability and volume of postwildfire debris flows in the intermountain western United States: Geological Society of America Bulletin, v. 122, no. 1/2, p. 127-144, https://doi.org/10.1130/B26459.1.

Cavagnaro, D.B., McCoy, S.W., Lindsay, D.N., McGuire, L.A., Kean, J.W., and Trugman, D.T., 2025, Rainfall thresholds for postfire debris-flow initiation vary with short-duration rainfall climatology: Journal of Geophysical Research: Earth Surface, v. 130, https://doi.org/10.1029/2024JF007781.

Chawner, W.D., 1934, The Montrose-La Crescenta Flood of January 1, 1934, and its sedimentary aspects [M.S. Thesis]: California Institute of Technology, Pasadena, CA, 78 p.

DeGraff, J.W., Cannon, S.H., Gartner, J.E., 2015, The timing of susceptibility to post-fire debris flows in the western United States: Environmental and Engineering Geoscience, v. 21, https://doi.org/10.2113/gseegeosci.21.4.277.

Dow, H.W., East, A.E., Sankey, J.B., Warrick, J.A., Kostelnik, J., Lindsay, D.N., and Kean, J.W., 2024, Postfire sediment mobilization and its downstream implications across California, 1984–2021: Journal of Geophysical Research: Earth Surface, v. 129, https://doi.org/10.1029/2024JF007725.

East, A.E., Logan, J.B., Dartnell, P., Lieber-Kotz, O., Cavagnaro, D.B., McCoy, S.W., and Lindsay, D.N., 2021, Watershed sediment yield following the 2018 Carr Fire, Whiskeytown National Recreation Area, northern California: Earth and Space Science, v. 8, https://doi.org/10.1029/2021EA001828.

Gartner, J.E., Cannon, S.H., Santi, P.M., and Dewolfe, V.G., 2008, Empirical models to predict the volumes of debris flows generated by recently burned basins in the western U.S.: Geomorphology, v. 96., p. 339-354, https://doi.org/10.1016/j.geomorph.2007.02.033.

Gartner, J.E., Cannon, S.H., and Santi, P.M., 2014, Empirical models for predicting volumes of sediment deposited by debris flows and sediment-laden floods in the transverse ranges of southern California: Engineering Geology, v. 176, p. 45-56, https://doi.org/10.1016/j.enggeo.2014.04.008.

Graber, A.P., 2023, Compilation of runoff-generated debris-flow inventories for 17 fires across Arizona, California, Colorado, New Mexico, and Washington, USA: U.S. Geological Survey data release, https://doi.org/10.5066/P98Q4CDH.

Graber, A.P., 2024, Compilation of runoff-generated debris-flow inventories for 18 fires across Arizona, California, Colorado, New Mexico, Utah, and Washington, USA: U.S. Geological Survey data release, https://doi.org/10.5066/P13ZFKJS.

Graber, A.P., Thomas, M.A., and Kean, J.W., 2023, How long do runoff-generated debris-flow hazards persist after wildfire?: Geophysical Research Letters, v. 50, https://doi.org/10.1029/2023GL105101.

King, J., 2025, wildcat - Command line tool to assess and map post-wildfire debris-flow hazards, version 1.1.0: U.S. Geological Survey software release, https://doi.org/10.5066/P1YN79CN.

Lamb, M.P., Scheingross, J.S., Amidon, W.H., Swanson, E., and Limaye, A., 2011, A model for fire-induced sediment yield by dry ravel in steep landscapes: Journal of Geophysical Research – Earth Surface, v. 116, https://doi.org/10.1029/2010JF001878.

Lancaster, J.T. et al., 2021, Observations and analyses of the 9 January 2018 debris-flow disaster, Santa Barbara County, California: Environmental and Engineering Geoscience, v. 27, no. 1, p. 3-27, https://doi.org/10.2113/EEG-D-20-00015.

National Oceanic and Atmospheric Administration (NOAA), 2025 Precipitation Frequency Data Server, https://hdsc.nws.noaa.gov/pfds/ (accessed September 2025).

NOAA-USGS Debris Flow Task Force, 2005, NOAA-USGS debris-flow warning system—Final report: U.S. Geological Survey Circular 1283, 47 p., https://doi.org/10.3133/cir1283.

Rodriguez, M., 2025, Topanga Canyon closed indefinitely after mudslide spills onto roadway: KCAL news, https://www.cbsnews.com/losangeles/news/topanga-canyon-closed-indefinitely-after-mudslide-spills-onto-roadway/ (accessed June 2025).

Schwarz, G.E. and Alexander, R.B., 1995, Soils data for the Conterminous United States Derived from the NRCS State Soil Geographic (STATSGO) Data Base: U.S. Geological Survey data release, https://doi.org/10.5066/P94JAULO.

Staley, D.M., Negri, J.A., Kean, J.W., Laber, J.L., Tillery, A.C., and Youberg, A.M., 2017, Prediction of spatially explicit rainfall intensity–duration thresholds for postfire debris flow generation in the western United States: Geomorphology, v. 278, p. 149–162, https://doi.org/10.1016/j.geomorph.2016.10.019.

Staley, D.M., Kean, J.W., and Rengers, F.K., 2020, The recurrence interval of post-fire debris-flow generating rainfall in the southwestern United States: Geomorphology, v. 230, https://doi.org/10.1016/j.geomorph.2020.107392.

Swanson, B.J., Lindsay, D.N., Cato, K., DiBiase, R.A., and Neely, A.B., 2024, Debris flows and sediment transport at Yucaipa Ridge and impacts to Oak Glen and Forest Falls area, southern California, following the 2020 El Dorado and Apple Fire: Geological Society of America Field Guide 70, p. 45–73, https://doi.org/10.1130/2024.0070(03).

Thomas, M.A. et al., 2023, Postfire hydrologic response along the Central California (USA) coast: insights for the emergency assessment of postfire debris-flow hazards: Landslides, v. 20, p. 2421–2436, https://doi.org/10.1007/s10346-023-02106-7.

Thomas, M.A. et al., 2025, Landsliding follows signatures of wildfire history and vegetation regrowth in a steep coastal shrubland: Geosphere, v. 21, p. 823-840, https://doi.org/10.1130/GES02856.1.

United States Forest Service (USFS), 2025, Forest Service Watershed Erosion Prediction Project (WEPP) Interfaces, https://forest.moscowfsl.wsu.edu/fswepp/ (accessed September 2025).

United States Geological Survey (USGS), 2025, Emergency Assessment of Post-Fire Debris-Flow Hazards, https://usgs.maps.arcgis.com/apps/dashboards/c09fa874362e48a9afe79432f2efe6fe (accessed September 2025).

Williams, A.P., Abatzoglou, J.T., Gershunov, A., Guzman-Morales, J., Bishop, D.A., Balch, J.K., and Lettenmaier, D.P., 2019, Observed impacts of anthropogenic climate change on wildfire in California: Earth's Future, v. 7, p. 892–910. https://doi.org/10.1029/2019EF001210.

Let us explain...

Postfire flash flood and debris flow on Oak Creek, Inyo County, CA. Photo by Ken Babione

Two of the articles in this issue discuss the hazards associated with watersheds that have recently experienced wildfire. Below are some definitions of key terms used in those articles.

A **debris flow** is a fast-moving landslide composed of water, sediment, and organic material, with a consistency like wet concrete. Unlike flash floods, debris flows transport material in suspension, leading to greater flow heights, and making them particularly hazardous to life and property. They travel downslope much faster than a person can run and have the potential to travel great distances beyond the burn area where they are triggered, posing serious risks to life and property. In the news, debris flows are often referred to as mudflows or mudslides.

A **design storm scenario** represents a specific rainfall event used to calculate the level of debris-flow hazard. Design storms are defined by characteristics such as rainfall intensity (mm/h or in/hr) or accumulation (mm or in), duration, and storm recurrence interval. The USGS evaluates debris-flow hazard for design storms with peak 15-minute rainfall intensities ranging from 16-40 mm/h in 4 mm increments.

A **flash flood** occurs when runoff from excessive rainfall causes a rapid rise in the water height (stage) of a stream or normally-dry channel. Flash floods are more common in areas with a dry climate and rocky terrain because lack of soil or vegetation allows torrential rains to flow overland rather than infiltrate into the ground.

USGS postfire debris-flow **rainfall thresholds** are the rainfall conditions that correspond to a specific probability of triggering debris flows. They represent the rainfall intensity or accumulation over a specific time period above which the likelihood of a debris flow increases significantly.

Intensity refers to how hard it is raining (e.g., mm/h), while **accumulation** refers to the total rainfall over a set duration (e.g., mm in 15 minutes). These thresholds are reported for the entire burn area as well as for individual watersheds and are expressed using both rainfall rate and rainfall accumulation — two related measures of storm intensity.

Definitions provided here by authors Jason Kean and Jaime Kostelnik and the USGS and CGS websites. See https://www.conservation.ca.gov cgs/ and https://www.usgs.gov/science/faqs/natural-hazards for more.

MEET AN EARLY CAREER GEOSCIENTIST:

DAVID CAVAGNARO

DAVID CAVAGNARO is a Research Data Specialist within the CGS GIS and Publications Program. Since January 2024, David has supported the Burned Watershed Geohazards (BWG) Program in both emergency response and postfire monitoring work.

The California Geological Survey (CGS) works under contract with the California Department of Forestry and Fire Protection (CAL FIRE) to deploy Watershed Emergency Response Teams (WERTs) to recently burned areas with a potential for postfire geohazards. David is critical for quickly developing and deploying the digital maps and applications that geologists use to collect data on potential geohazards and values at risk (like houses and infrastructure). He coordinates a team to process this data and generate analyses and map products for the WERTs to communicate their findings to state and local partners. His experience with Python and GIS has allowed him to streamline these time-sensitive workflows and to deploy new interactive map layers to assist geologists with their evaluations. His background in postfire fieldwork proves useful for this role and for his field deployment on the Eaton Fire WERT in January 2025.

Outside of the active fire season, David supports the BWG Program's postfire monitoring efforts, which seek to characterize and understand postfire geohazards across California's diverse climates and landscapes. These efforts involve installation of sensors, processing of data, and remote sensing of burned watersheds, including piloting lidar-equipped drones that can be used to map landscape change (check out the article on page 32 for an example of this work).

Prior to joining the CGS, David earned his PhD in Geology in 2023 from the University of Nevada, Reno (UNR), where he characterized postfire debris-flow triggering conditions across Northern California and Nevada and developed methods to assess flow type in post-event surveys. He came to UNR to pursue a Master's degree but eventually decided to pursue a PhD, feeling it could lead to a broader set of career opportunities. He has authored and collaborated on several publications on postfire geohazards and continues to bring a research background to the BWG Program.

David earned his Bachelor's in Earth Sciences from Dartmouth College in 2017 where he sought out opportunities to help professors with their research as an undergraduate, including two weeks as a field assistant sampling postglacial landforms in an alpine region of Uganda. After graduating, he interned for the Maine Geological Survey where he mapped coastal geomorphology and characterized storm impacts to beaches and harbors. He knew he wanted to eventually pursue a graduate degree in geomorphology but was not yet ready—instead, he worked for a year for the Friends of Northern Lake Champlain, a small Vermont-based nonprofit geared towards improving water quality and performing community outreach. The next year, while applying to graduate programs, he tuned skis in Vermont and helped build bike and ski trails in Maine before ultimately moving west in the summer of 2019.

David's diverse career path involving research, field work, data science, writing, and community outreach has helped provide a breadth of experience to serve the CGS mission to help protect Californians from geologic hazards. He is particularly excited about the unique role the CGS plays in both characterizing geohazards and actively using these new findings to help respond to the next emergency.

David performing soil measurements in the area burned by the Bridge Fire. Photo by Derek Cheung, CGS

CGS scientists Nina Oakley and Derek Cheung conducting measurements of soil hydraulic properties in a watershed burned by the Park Fire. Photo by David Cavagnaro, CGS

Can we predict postfire debris-flow hazards prior to wildfire in California?

Paul W. Richardson, PhD, PG,
Rebecca K. Rossi, PG,
David B. Cavagnaro, PhD,
Donald N. Lindsay, CEG, GE

MITIGATING POSTFIRE GEOHAZARDS IS A GROWING CHALLENGE

Since the 1980s, there has been a noticeable uptick in California wildfires. They have increased in number, size, and severity, and have negatively impacted the environment, economy, and society. Eighteen of the twenty largest wildfires in California history have occurred since 2000 and the most destructive fires have occurred in the last decade (California Department of Forestry and Fire Protection (CAL FIRE) https://www.fire.ca.gov/our-impact/statistics). The recent January 2025 Eaton and Palisades Fires in Los Angeles County will likely surpass prior records to become the most expensive wildfires in the state's history.

One of the more impactful postfire hazards in California is runoff-generated debris flows that can occur within three years following fire. They not only have the potential to cause fatalities, but also can damage infrastructure, homes, and other property. Following the Thomas Fire in 2018, deadly and highly destructive debris flows inundated portions of Montecito with rock, debris, and water, resulting in 23 fatalities, at least 167 injuries, and 800 rescues (Kean et al., 2019, Lancaster et al., 2021). More recently, multiple postfire geohazards have already followed the Eaton and Palisades Fires: vehicles and their passengers were swept away by high postfire floods, several debris retention basins were partially filled with sediment

and debris and overtopped by water, and communities downslope of the burned areas were flooded and inundated with mud and other sediment. Emergency managers, road and critical facility engineers, and flood control district officers are often challenged with little time to develop and implement postfire response and evacuation plans or construct and maintain mitigation measures between the fire and stressing rainstorms. In the case of the Palisades and Eaton fire debris-flow and flood events, there were only weeks between fire containment and the arrival of winter storms.

As a core product of the Watershed Emergency Response Team (WERT), the California Geological Survey's (CGS) Burned Watershed Geohazards (BWG) Program relies on models to make rapid assessments of postfire geohazards. The USGS postfire debris-flow models (this issue) use burn severity data collected immediately after wildfires to predict debris-flow likelihood and volume (e.g., Staley et al., 2016, Gartner et al., 2014). These postfire debris-flow hazard models require burn severity products that are only available after wildfires. Knowing the potential of postfire hazards prior to wildfire would be advantageous and could provide emergency managers and others with information to better prepare for inevitable wildfires.

Due to this need, the USGS developed an approach that predicts burn severity prior to wildfire (Staley et al., 2018) using existing vegetation type (EVT) data to predict differenced normalized burn ratio (dNBR), a satellite-derived product that quantifies the change in vegetation conditions from prefire to postfire used to create burn severity maps (Key and Benson, 2006). EVT classes that represent grasslands typically produce low dNBR values while EVT classes that represent forests produce higher dNBR values. They then used this simulated burn severity map as an input to the USGS postfire debris-flow likelihood and volume models to map potential postfire debris-flow hazards across southern California (Kean and Staley, 2021).

PREDICTING POSTFIRE GEOHAZARDS PRIOR TO WILDFIRE

Recognizing the opportunity to expand the USGS approach to the entire state of California, the CGS staff worked with other postfire scientists to create products that predict postfire debris-flow hazards prior to wildfire for the entire state of California (Rossi et al., 2025). The authors used EVT and the relations developed by the USGS to predict burn severity from EVT (Staley et al., 2018). They split the state into eight regions and calibrated the predicted burn severity for each region based on historical wildfires. The authors then used predicted burn severity to run the USGS postfire debris-flow likelihood and volume models, which estimate a rainfall-intensity threshold and debris-flow volume. However, the USGS postfire debris-flow model assumes that a site has already burned and does not account for the fact that wildfire is more likely in some parts of the state than others. The model also does not account for the fact that a given rainfall intensity may be common in a wet region of the state but rare in a dry region.

To address these limitations, CGS scientists and colleagues accounted for fire probability and rainfall intensity data. In an independent study, Vogler et al. (2021), in conjunction with the US Forest Service and CAL FIRE, produced a statewide map of California that estimates annual fire probability. By combining predicted annual probability of fire occurrence (Figure 1a) with annual probability of above-threshold rainfall based on climatological data (Figure 1b), it was possible to predict

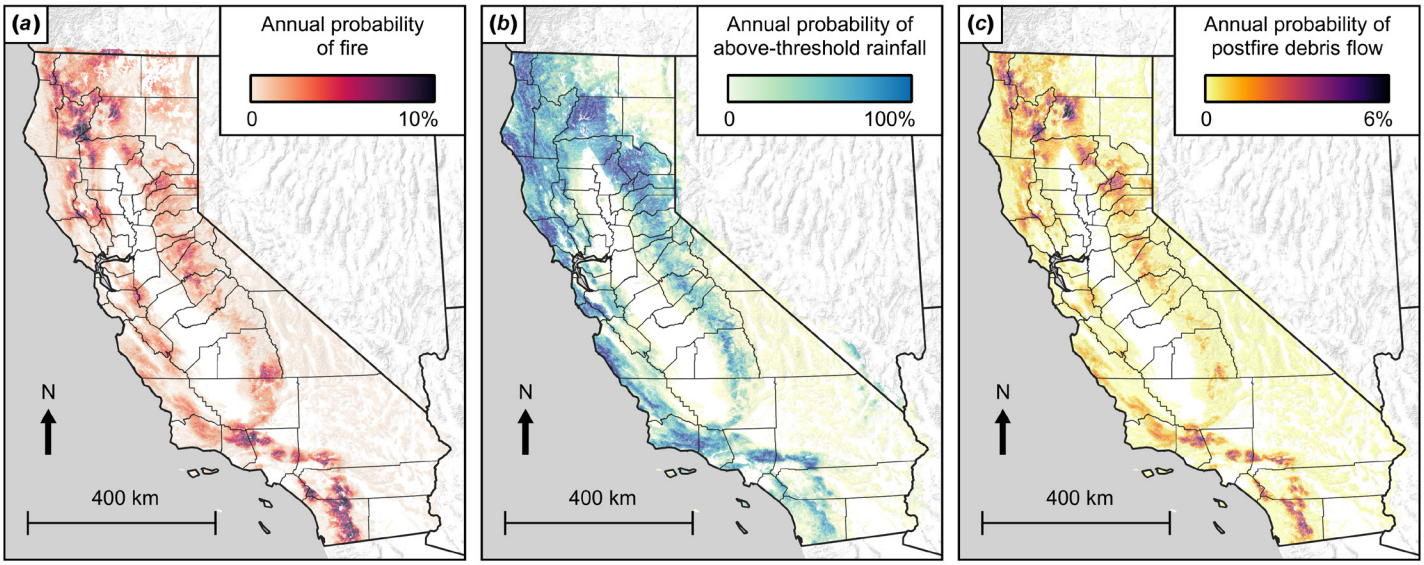


Figure 1. Maps showing annual probability of (a) fire, (b) rainfall exceeding the debris-flow threshold, and (c) postfire debris flow.

Figure 2. These photographs show sensors deployed over Pasadena Glen, which is located along the flank of the San Gabriel Mountains in southern California. The upstream area was burned by the 2025 Eaton Fire. Members of the BWG Program installed noncontact stage and velocity sensors (shown suspended above the channel) soon after the fire to quantify postfire changes to runoff and monitor debris flows and floods. These photographs were taken after a storm on 14 February 2025 that produced flooding along Pasadena Glen, transported boulders, and damaged a debris rack (visible in the larger photograph with multiple bollards bent or missing). The sensors were installed the week following the February storm and collected data during the next storm on 13 March 2025. Photographs by Paul Richardson, CGS

annual probability of postfire debris-flow occurrence. The result (Figure 1c) is a statewide map showing the annual probability that a given site experiences wildfire and then, within one year, experiences rainfall exceeding the modeled debris-flow threshold. This product and other prefire products, such as predictions of postfire debris-flow sediment volume, can be used to inform mitigation efforts prior to wildfire (Rossi et al., 2025).

OPPORTUNITIES FOR PREFIRE GEOHAZARD MITIGATION AND IMPROVING POSTFIRE GEOHAZARD MODELS

There are multiple opportunities to leverage the results from the statewide modeling and mapping effort. For example, the postfire debris-flow likelihood and volume predictions can be used to assess threats to downstream values at risk (e.g., homes, bridges, and other infrastructure), estimate sediment volumes and flow properties used to parameterize hydraulic models (Pak et al., 2023), and inform potential mitigation efforts. The results can also be used to inform active fire suppression operations and emergency response efforts during a wildfire. For long-term planning, the results can be used to prioritize fuels reduction projects across the state (such as vegetation thinning and prescribed burning) and used by local governments to inform residential development plans, zoning maps, and local hazard mitigation plans.

Often in science and engineering, one finding builds on another and the statewide modeling and mapping efforts are no exception. As techniques are improved and additional data are collected, opportunities abound to improve the prefire inputs and the postfire models. For example, EVT is useful for estimating future burn severity, but new methods are being developed that will improve our ability to predict wildfire burn severity. The CGS is currently assisting scientists at Utah State University (USU) to refine a machine learning model that uses a wide variety of data to predict wildfire burn severity. Conditions prior to wildfire such as daily fire weather (air temperature, wind speed and direction, relative humidity, etc.) and fuel moisture are critical drivers of fire behavior but are not known far in advance; these limitations hamper our ability to incorporate critical fire factors into models that predict burn severity. However, other important factors such as topography (elevation, aspect, landscape location), proximity to developed areas, road density, fuel loads, rock type, and seasonal climatic information can be considered prior to fire occurrence. The USU scientists have successfully demonstrated the value of incorporating additional factors to predict wildfire burn severity. They found that vegetation productivity, elevation, and canopy fuels were the most important predictor variables in forested land in Utah (Klimas et al., 2024). Expanding this machine learning approach to California is promising for improving burn severity predictions, a critical input to postfire debris-flow models.

Although the prefire modeling results are a promising tool for postfire geohazard mitigation, caution must also be applied when using the debris-flow likelihood and volume models in areas outside the original calibration area in southern California. For example, debris-flow sediment sourcing (dry ravel, landslide, in-channel storage, hillslope rilling), sediment characteristics (grain size, embeddedness, volume of available sediment, etc.), and storm behavior (convective, atmospheric river, etc.) vary in California. These differences are currently not accounted for in the debris-flow likelihood and volume models. An expanded database of debris-flow triggering conditions and volume measurements is required to fully validate the models for all of California or to develop new regional models. The CGS is currently collecting these data.

In 2024 and the beginning of 2025, the CGS installed instruments for monitoring postfire debris flows and floods after five wildfires: the Lake Fire (Santa Barbara County), Borel Fire (Kern County), Park Fire (Butte and Tehama Counties), Bridge Fire (Los Angeles and San Bernardino Counties) and Eaton Fire (Los Angeles County). The BWG Program also continues to maintain monitoring equipment at earlier fires, including the Dixie Fire (Shasta, Butte, Lassen, Tehama, and Plumas Counties), Mosquito Fire (Placer and El Dorado Counties), McKinney Fire (Siskiyou County), and Caldor Fire (Alpine, Amador, and El Dorado Counties). Future efforts will emphasize collecting data at sites outside of southern California. Existing postfire measurements include rainfall intensity, debris-flow timing, flow depth, flow velocity, infiltration rates, vegetation recovery, ground cover, and surface roughness. Collecting unmanned aerial system (UAS)-based lidar data and images will also help characterize terrain, identify debris-flow source areas, and quantify debris-flow volume. These data will help validate and improve future postfire debris-flow and flood models by better characterizing flow type (debris flow, debris flood, or flood), rainfall triggering thresholds, postfire runoff response, postfire recovery, and debris-flow volume.

ACKNOWLEDGEMENTS

We thank Stefani Lukashov and Mary Ellen Miller for their contributions to the work presented.

REFERENCES

Gartner, J.E., Cannon, S.H., and Santi, P.M., 2014, Empirical models for predicting volumes of sediment deposited by debris flows and sediment-laden floods in the transverse ranges of southern California: Engineering Geology, v. 176, p. 45–56, https://doi:10.1016/j.enggeo.2014.04.008.

Lancaster, J.T., Swanson, B.J., Lukashov, S.G., Oakley, N.S., Lee, J.B., Spangler, E.R., Hernandez, J.L., Olson, B.P.E., DeFrisco, M.J., Lindsay, D.N., Schwartz, Y.J., McCrea, S.E., Roffers, P.D., and Tran, C.M., 2021, Observations and Analyses of the 9 January 2018 Debris-Flow Disaster, Santa Barbara County, California: Environmental & Engineering GeoScience, v. 27, no. 1, p. 3-27, https://doi.org/10.2113/EEG-D-20-00015.

Kean, J.W., Staley, D.M., Lancaster, J.T., Rengers, F.K., Swanson, B.J., Coe, J.A., Hernandez, J.L., Sigman, A.J., Allstadt, K.E., and Lindsay, D.N., 2019, Inundation, flow dynamics, and damage in the 9 January 2018 Montecito debris-flow event, California, USA: Opportunities and challenges for post-wildfire risk assessment: Geosphere, v. 15, no. 4, p. 1140–1163, https://doi:10.1130/GES02048.1.

Kean, J.W. and Staley, D.M., 2021, Forecasting the frequency and magnitude of postfire debris flows across southern California: Earth's Future, v. 9, no. 3, p. e2020EF001735, https//doi:10.1029/2020EF001735.

Key, C.H. and Benson, N.C., 2006, Landscape Assessment (LA): Sampling and Analysis Methods, USDA Forest Service General Technical Report RMRS-GTR-164-CD, p. LA-1-5.

Klimas, K.B., Yocom, L.L., Murphy, B.P., David, S.R., Belmont, P.B., Lutz, J.A., DeRose, R.J., and Wall, S.A., 2024, A machine learning model to predict wildfire burn severity for pre-fire risk assessments, Utah, USA: Fire Ecology, v. 21, no. 8, https://doi: 10.1186/s42408-024-00346-z.

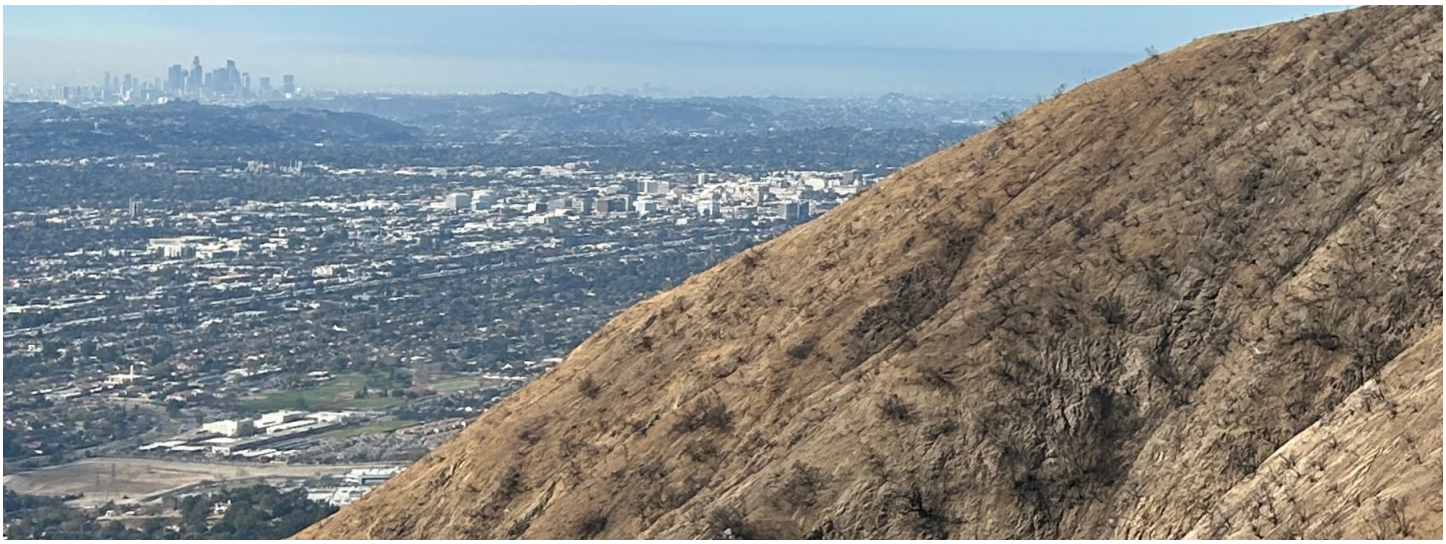
Pak, J., Pradhan, N., Floyd, I., and Fleming, M., 2023, Post-wildfire hydrology and debris flow analysis using hydrologic modeling system (HEC-HMS). SEDHYD 2023 Conference.

Rossi, R.K., Richardson, P.W., Cavagnaro, D.B., Lukashov, S.G., Miller, M.E., and Lindsay, D.N., 2025, Predicting potential postfire debris-flow hazards across California prior to wildfire: International Journal of Wildland Fire, v. 34, no. 7, https://doi.org/10.1071/WF24225.

Staley, D.M., Negri, J.A., Kean, J.W., Laber, J.L., Tillery, A.C., and Youberg, A.M., 2016, Updated logistic regression equations for the calculation of post-fire debris-flow likelihood in the western United States, US Geological Survey Open-File Report 2016–1106, https://doi.org/10.3133/ofr20161106.

Staley, D.M., 2018, Data used to characterize the historical distribution of wildfire severity in the western United States in support of pre-fire assessment of debris-flow hazards: US Geological Survey Data Release, https://doi:10.5066/P9TKYL5K.

Vogler, K.C., Brough, A., Moran, C.J., Scott, J.H., and Gilbertson-Day, J.W., 2021, Contemporary wildfire hazard across California, Pyrologix, LLC.



Altadena and Pasadena, with downtown Los Angeles in the distance, as seen from the slopes burned by the 2025 Eaton Fire. Photo by David Cavagnaro, CGS

Outreach & Education

at the California Geological Survey

Wendy Bohon, PhD

(upper image) CGS geologist and forester Annie Fehrenbach, front right, discusses how timber harvesting operations can impact unstable areas and geologically sensitive areas with students from College of the Redwoods. Photo provided by Valerie Elder, College of the Redwoods

(lower image) CGS geologists Annie Fehrenbach, left, and Sara Gallagher, right, represent CGS at McKinleyville High School's career fair. Photo provided by Sara Gallagher, CGS

(top of next page) State Geologist Jeremy Lancaster (center) participating in a Pardee Keynote Symposia panel discussion at the 2024 Geological Society of America Connects Meeting. Photo by Wendy Bohon, CGS

The mission of the California Geological Survey (CGS) is to provide scientific products and services about the state's geology, seismology, and minerals that affect the health, safety, and business interests of the people of California. We have a wide variety of audiences, partners, and end users, and we strive to ensure that we are reaching each of our audiences in ways that are meaningful, accessible, and sustainable.

LOOKING AHEAD

Building on the tireless Outreach and Education efforts of long-time employee Cindy Pridmore, the CGS continues to expand its engagement and impact through a dedicated Outreach and Education Committee, which meets biweekly to coordinate future initiatives, discuss potential opportunities, and track previous events.

To guide and enhance these efforts, we have also developed a **Communication, Outreach, Visibility, and Education (COVE) Strategy**. This framework helps us prioritize activities, assess effectiveness, and ensure efficient use of resources, enabling the CGS to meet its Outreach and Education goals and better serve the people of California.

We remain committed to making communities and our economy more resilient through strategic outreach, education, and communication. By investing in future geoscientists, developing tools for professionals, and connecting with communities across the state, the CGS is ensuring that geoscience continues to play a vital role in California's safety, resilience, and progress.

ACTIVITIES

CGS staff engage in numerous activities that highlight our products and services, promote interest in geoscience, support workforce development, and increase public awareness of geologic hazards. Below are a few key initiatives and examples from the past few years:

Workforce Development Internships

Our internship programs provide students with hands-on experience, professional connections, and practical skills for pursuing careers in geoscience. In partnership with UC Davis, we recently launched a for-credit internship program in Spring 2024 that supported five students. Interns worked on digitizing legacy maps using GIS software and converting them into a standardized digital database (USGS Geologic Map Schema, GeMS) to support ongoing geologic mapping efforts. Students from California colleges and universities are also eligible for paid internships. The CGS typically has about 10-15 paid interns across programs throughout the year!

Products for Partners

As part of the Seismic Hazards Program Essential Facilities Review, CGS staff are producing an educational video series for geotechnical consultants focused on *CGS Note 48* — a checklist of 34 geologic and geotechnical considerations required for construction projects on school properties. This series aims to clarify expectations and reduce common errors, leading to more efficient and effective project reviews.

Showcasing Our Work

The CGS showcases our products and interacts one-on-one with various communities by staffing booths at multiple events throughout the year, including at the California Association of Science Educators (CASE) Conference, the Geological Society of America (GSA) meeting, the Humboldt County Fair, ShakeOut Events in Northern and Southern California, Girl's STEM Night at the Natural History Museum of Los Angeles, Girl's STEM Day at the Aerospace Museum, the LA County Emergency Preparedness Fair, the Disaster Expo, the Disney World Preparedness event, and Earth Day.

Additional Engagement

CGS staff give talks at universities, schools, conferences, and public events; serve on expert panels; lead geoscience field trips; and mentor students. We maintain an active social media presence (@CaGeoSurvey) and have launched internal science communication training to enhance our ability to engage with diverse audiences effectively.

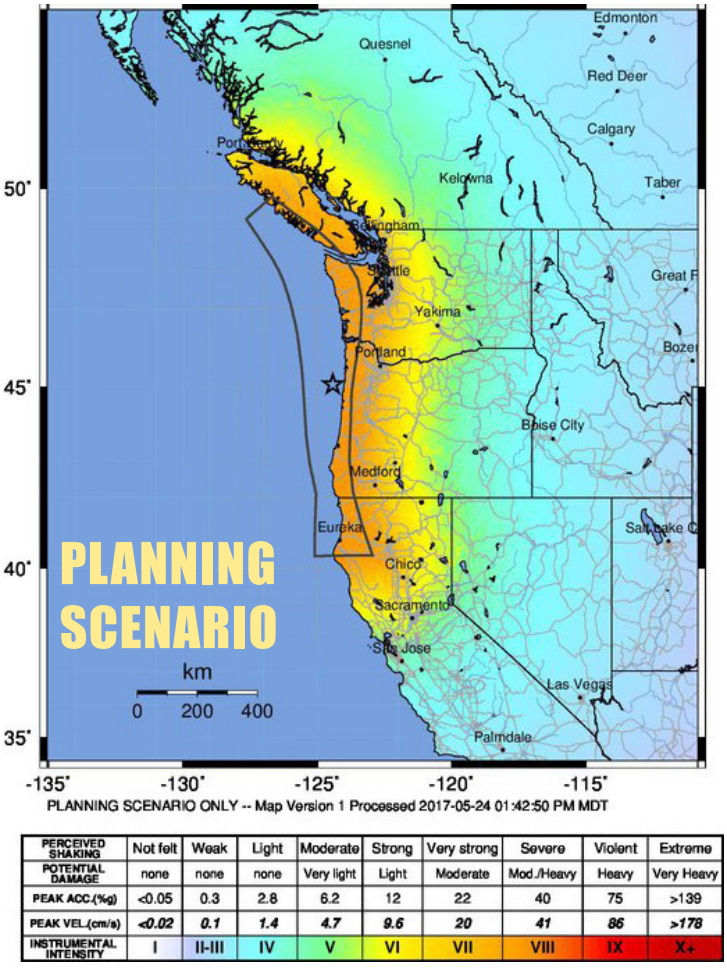
(lower image) CGS geologist Patrick Brand explaining the geological factors underlying the formation of marine terrace deposits with CGS geologist Kevin Doherty at an outing with the Professional Soil Scientists Association of California (PSSAC) and the California Forest Soils Council (CFSC) at Jug Handle State Park and Jackson Demonstration State Forest (JDSF). Discussions focused on the formation of Spodosols, nutrient poor soils underlying the pygmy forest and prescribed fuel reduction studies currently in progress at JDSF. Photo by Dave Longstreth, CGS

Interested in learning more? See the article published in CALIFORNIA GEOLOGY magazine in January 1976 (https://www.conservation.ca.gov/cgs/publications/cg-magazine), and in the 2015 Special Report "Geological Gems of California State Parks" (https://www.parks.ca.gov/?page_id=29631).

CASCADIA MEGATHRUST M 9.3

Multi-State Clearinghouse Tabletop Exercise

Kate Thomas
California Clearinghouse Chair



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

In August of 2025, the California Geological Survey (CGS) hosted a two-day Cascadia Megathrust multi-state tabletop exercise (discussion-based simulation), inviting participants from Washington, Oregon, and California. The purpose of this exercise was to foster interstate partnerships for scientific studies, communication, and collaboration among clearinghouses in Washington, Oregon, and California in the event of a large Cascadia subduction zone earthquake.

The exercise focused on the Cascadia Megathrust Scenario, which simulates a M9.3 earthquake at a depth of 21.4 km off the coast of Oregon within the Cascadia subduction zone. The earthquake rupture in this scenario is approximately 1,000 km (620 miles) in length and extends from Cape Mendocino, California to Vancouver Island, Canada (black polygon on map above). The expected effects from the earthquake are strong ground shaking lasting 4-6 minutes, subsidence and/or uplift of coastal areas, liquefaction, landslides, tsunami, and numerous large-magnitude aftershocks. This scenario represents one of the largest earthquakes that can occur in the continental United States, spanning Northern California, Oregon, and Washington. This large area covering multiple states creates unique challenges for emergency managers in all three states due to widespread impacts to buildings, lifelines, and other infrastructure along the west coast.

The Cascadia exercise consisted of three modules for discussion: 1) clearinghouse activation and communications, 2) data acquisition and data sharing, and 3) sharing resources across state lines. Working through these modules allowed us to identify opportunities for improving response and clearinghouse protocol in the event of a Cascadia subduction zone earthquake. One step to implement these improvements is planning annual exercises to help everyone involved practice and test protocols, solve problems, and document challenges for sharing data and resources across state lines. We also recognized the need to include international partners who will be impacted, like representatives from British Columbia, Canada.

Access to data and data sharing is a key component of clearinghouse and response activities. Identifying and coordinating with organizations who can assist with data acquisition, especially high-resolution topography or satellite imagery of the west coast, will be vital in helping responders assess areas that may be inaccessible due to

What is a Clearinghouse?

During major and great earthquake events, states set up a "clearinghouse" — a location, physical or virtual — where field investigators can come together to coordinate scientific investigations, share field observations and data, and streamline communication to the Governor's Office of Emergency Services' (Cal OES) State Operations Center (SOC). The SOC coordinates response efforts between scientists at the clearinghouse and local emergency managers. The CGS is mandated by Public Resources Code 2201 to set up a clearinghouse after a significant geologic hazard event. The CGS serves as the chair of the California clearinghouse, however, there are multiple co-chairs who are vital to the success of the post-earthquake clearinghouse. The co-chairs include the Earthquake Engineering Research Institute (EERI), Cal OES, the United States Geological Survey (USGS), and the Seismic Safety Commission (SSC). For more information, visit: https://CaliforniaEqClearinghouse.org and https://learningfromearthquakes.org/.

road, bridge, or other infrastructure damage during the earthquake. These data are often collected and managed by many organizations and by state and federal agencies, reinforcing the need for a clear collaboration plan.

One of the greatest successes of the 2025 Cascadia tabletop exercise was the development of partnerships between clearinghouse managers in Washington, Oregon, and California. By the end of the exercise, we realized that the formation of an inter-state, or regional, clearinghouse would help facilitate communication and coordinate logistics between the individual state clearinghouses. Future exercises will provide the opportunity to continue planning how this regional clearinghouse would operate.

Overall, the tabletop was a success and the continued communications between participants and future exercises will ensure that the Washington, Oregon, and California clearinghouses have a clear plan for collaboration when a large Cascadia earthquake occurs.

ACKNOWLEDGMENTS

This exercise was funded by the National Earthquake Hazards Reduction Program (NEHRP) subaward A241014107 through Cal OES.

PARTICIPATING ORGANIZATIONS

- California Geological Survey (CGS)
- California Office of Emergency Services (Cal OES)
- Earthquake Engineering Research Institute (EERI)
- Oregon Department of Emergency Management (OEM)
- Oregon Department of Geology and Mineral Industries (DOGAMI)
- Washington Department of Natural Resources (DNR)
- Washington Military Department - Washington Emergency Management Division
- U.S. Geological Survey (USGS)

(previous page) ShakeMap for the Cascadia Megathrust M9.3 scenario. The star is the epicenter, and the black polygon indicates the length of the rupture. For more information on the scenario, visit: https://earthquake.usgs.gov/scenarios/event page/bssc2014cascadia_sub0_m9p34_se/executive

(upper image) Kate Thomas (CGS) presenting during the Cascadia tabletop exercise. Photo by Wendy Bohon, CGS

(lower image) Working Group 1 discussing topics such as Clearinghouse communications, data acquisition and data sharing, and sharing resources for support across state lines. Photo by Kate Thomas, CGS

Castle Crags, near Castle Crags State Park, in front of a snowcapped Mount Shasta (14,162 feet elevation). Photo by Chris Mizeur

THE IMPORTANCE OF GEOHERITAGE

Mike Fuller, PG

INTRODUCTION

The California Geological Survey (CGS) and other state and federal agencies have long histories of providing the State of California with geologic information regarding diverse natural resources and hazards. This information continues to guide efforts to plan, manage, and respond to the state's needs from an economic and natural hazard resilience standpoint.

Geologic processes are dynamic, acting on multiple timescales, such as the American River eroding through the Sierra Nevada and depositing sediment in the valley below and the formation and eruption of Mount Shasta and its subsequent dormancy. These processes, whether slow or rapid, leave behind deposits that we utilize and majestic landforms that inspire. Geology provides communities with construction materials and critical resources like oil, gas, and geothermal power and, unfortunately, with earthquakes and other hazards that damage them. Just as the gold rush led to the establishment of our state, geologic processes continue to shape our future.

As science and society progress, certain geological locations gain exceptional scientific, educational, cultural, or historic significance. Through time, these geological sites become part of our geoheritage. For example, the iconic features of Yosemite Valley were formed by the processes of subduction, volcanism, and glaciation that shaped the tectonic evolution of western North America, making it an important study area for

Lime kilns in Lime Kiln State Park on the Big Sur coast. Photo by Catherine Wesoloski, CGS

geological researchers. Yosemite Valley, or "Ahwahnee," is also the ancestral homelands to Native American tribes, like the Southern Sierra Miwok who have lived in connection to these lands for millennia, and is now known as a crown jewel of the National Park Service, visited by millions of people each year.

In 2024 and 2025, prominent geological organizations pursued new efforts to make geological knowledge available and relevant to the public and researchers by establishing geoheritage sites, which are locations of both scientific and historical significance.

WHAT IS GEOHERITAGE?

Geoheritage is a term applied to features and landforms of geological significance that hold scientific, educational, cultural, economic, and aesthetic value to society (GSA, 2022). It celebrates the many, but often overlooked, ways that geological resources have been and will always be foundational to humankind's social system and its built environment. However, geoheritage is much more than society's raw materials, as evidenced by state and national parks and other public lands. Geologic landmarks, like Yosemite Valley, carry cultural and scientific meaning. Scenic landmarks and mining districts are end members on a continuum of what constitutes geoheritage.

The moniker "geoheritage" originated in Europe and Asia and achieved widespread recognition before finding its legs in the US. The concept of geoheritage has deep roots and is well established throughout human history. In California specifically, there are many geologically prominent sites that were, and still remain, culturally and spiritually important for Native American tribes; each site carrying its own history, story, and lessons. For example, the Coso Hot Springs, located in the Coso Volcanic Field, have been used by the Paiute and Shoshone peoples for healing and ceremonial purposes. The nearby Big and Little Petroglyph Canyons host one of the largest collections of Indigenous rock art in North America. These examples reflect thousands of years of cultural connection to the land.

The modern geoheritage movement is driven by geologists and geographers sharing interesting facts about everything from breathtaking landscapes to materials used in our ordinary lives. Geoheritage sites may extend for hundreds of miles or just a few acres, may be in remote regions or along busy highways, and may be

Yosemite Valley, or "Ahwahnee," Yosemite National Park. Photo by Bob Moskovitz, CGS

heavily visited or relatively unknown. They invite visitors to wonder "What about this landscape and its geology has influenced culture and society?" That variety and scope represents the significance of geoheritage to the nation (NAS, Engineering, and Technology, 2021).

For more on geoheritage, keep an eye out for the upcoming publication of the Sierra Nevada Earth Science Atlas GeoSites, check out the 2015 Geological Gems of California State Parks (Special Report 230), or any of the great resources provided by the U.S. Geological Survey and the American Geosciences Insitute. Several articles within this edition of California Geology touch on the concept of geoheritage. In future editions of California Geology, we plan to reserve space for discussion of geoheritage sites in California and around the world. If you would like to contribute to this effort, please contact the California Geology editorial team.

REFERENCES

American Geosciences Insititute, 2025, Geoheritage Site Resource Collection: AGI Opportunities for Educators. https://education.americangeosciences.org/opportunities/geoheritage-sites/ (accessed January, 2026).

Geological Society of America, 2022, GSA Position Statement: Geoheritage, https://www.geosociety.org/gsa/positions/position20.aspx, (accessed July, 2025).

Geological Society of America, 2025, https://community.geosociety.org/histphildiv/home, (accessed July, 2025).

IUGS International Commission on Geoheritage, 2025, https://iugs-geoheritage.org/eventsnews/, (accessed January, 2026).

National Academies of Sciences (NAS), Engineering, and Technology, 2021, America's Geoheritage II: Identifying, Developing, and Preserving America's Natural Legacy, Proceedings of a Workshop, https://nap.nationalacademies.org/download/26316.

United Nations Educational, Scientific and Cultural Organization (UNESCO), 2025, International Geodiversity Day October 6, https://www.geodiversityday.org/.

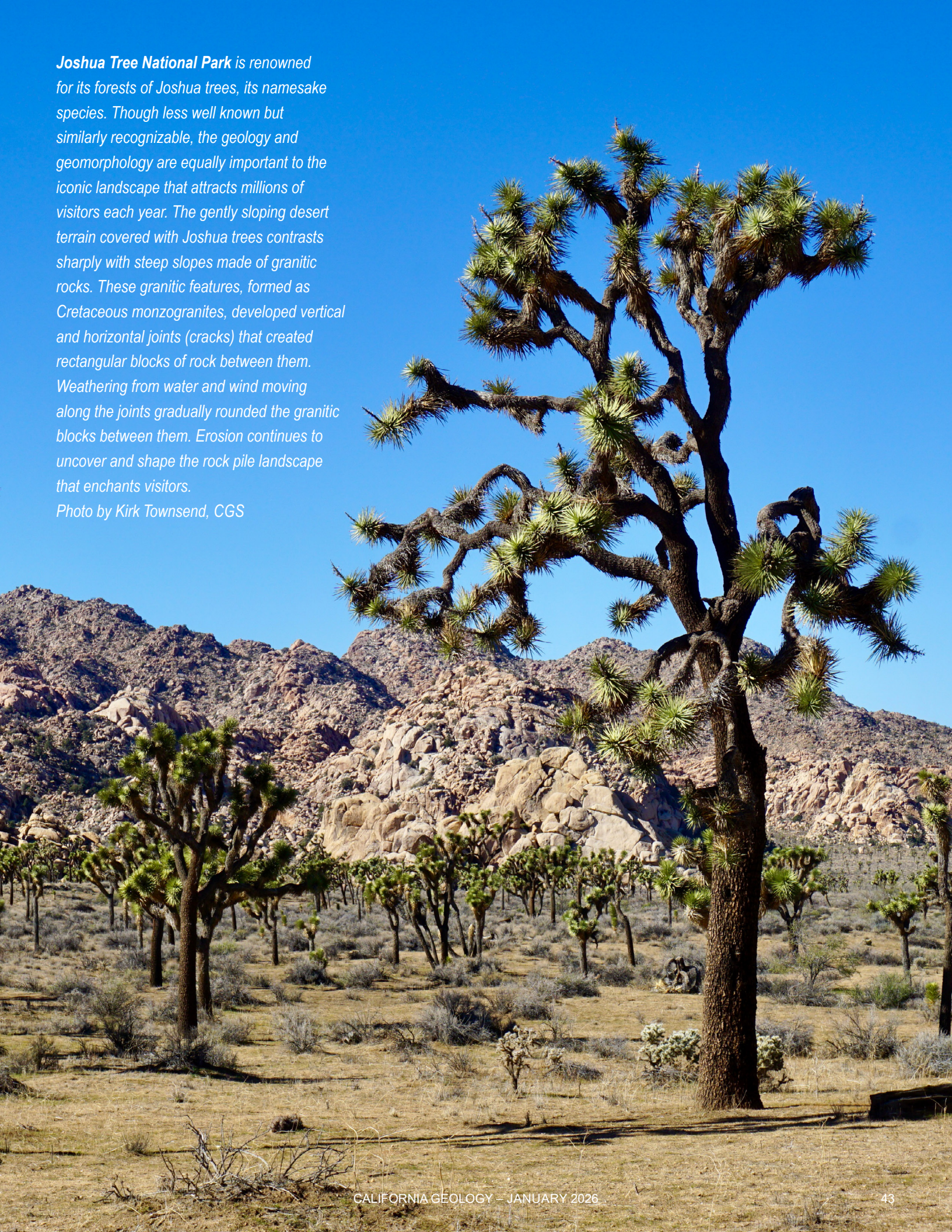
GLOBAL DEVELOPMENTS OF NOTE

› October 6th was proclaimed as International Geodiversity Day during UNESCO's 41st General Conference in 2021 and was first celebrated in 2022. The theme for the 2025 Geodiversity Day was "One Earth, Many Stories" (UNESCO, 2025).

› In July 2024, the International Commission on Geoheritage (IUGS) published a second volume of geoheritage sites across the globe titled, "The Second 100 IUGS Geological Heritage Sites" and was finishing reviews of the third 100 in 2025. This was followed by a publication titled "The First 55 IUGS Heritage Stones," which highlights how geologic materials are used in cultures through time and across the globe. Additional projects include ratifying Geo-collections (11 so far), which highlight museum collections with geological, historical, scientific, and and/or educational significance (IUGS, 2025).

› In 2025, the Geological Society of America (GSA) became the official sponsor of the U.S. Geoheritage Committee and assumed the activities of the U.S. National Committee for the International Union of Geological Sciences regarding U.S. geoheritage efforts. GSA added geoheritage to one of its divisions, now called the History, Philosophy, and Geoheritage Division (GSA, 2025).

› The AmericanGeosciences Intitute has compiled a list of USGS and other education resources on geoheritage sites within the United States (AGI, 2025)



Joshua Tree National Park *is renowned for its forests of Joshua trees, its namesake species. Though less well known but similarly recognizable, the geology and geomorphology are equally important to the iconic landscape that attracts millions of visitors each year. The gently sloping desert terrain covered with Joshua trees contrasts sharply with steep slopes made of granitic rocks. These granitic features, formed as Cretaceous monzogranites, developed vertical and horizontal joints (cracks) that created rectangular blocks of rock between them. Weathering from water and wind moving along the joints gradually rounded the granitic blocks between them. Erosion continues to uncover and shape the rock pile landscape that enchants visitors.*
Photo by Kirk Townsend, CGS

Mineral Highlight: Barite

Annalise Gay and David Reioux, PG

You are surrounded by minerals. Do you notice them?

Minerals are naturally occurring solids with a well-defined chemical composition and crystal structure. Minerals are not only the building blocks of rocks but also the key components of materials and products we use every day. The mineral barite has been mined in California since the 1880s due to its unique properties that allow it to be used for products like oil drilling mud, fireworks, radiation protection, and fillers for rubber, plastic, and paint (Fitch, 1931; Riddle, 2018; Princy, 2020). In fact, barite's high specific gravity leads to its name stemming from the Greek word "barys" meaning "heavy" (King, 2015).

BARITE BLOCKS X-RAYS!

Barite is opaque to X-rays and similar forms of radiation, a characteristic called radiopacity (United General, 2016). This has led to barite being used in the construction and medical fields. In construction, barite is added to concrete at medical imaging facilities, research labs, and nuclear plants to help contain radiation (King, 2015).

In the medical field barite is purified to make barium sulfate, which is ingested by a patient with water. This mixture temporarily coats the inside of their digestive tract (United General, 2016; Noah Chemicals, 2024). The barium sulfate absorbs the X-rays and appears light on a radiograph (the image produced by X-ray or other radiation-based imaging techniques). This allows for imaging of soft tissues, aiding in the diagnosis of tumors and diseases that affect the digestive tract.

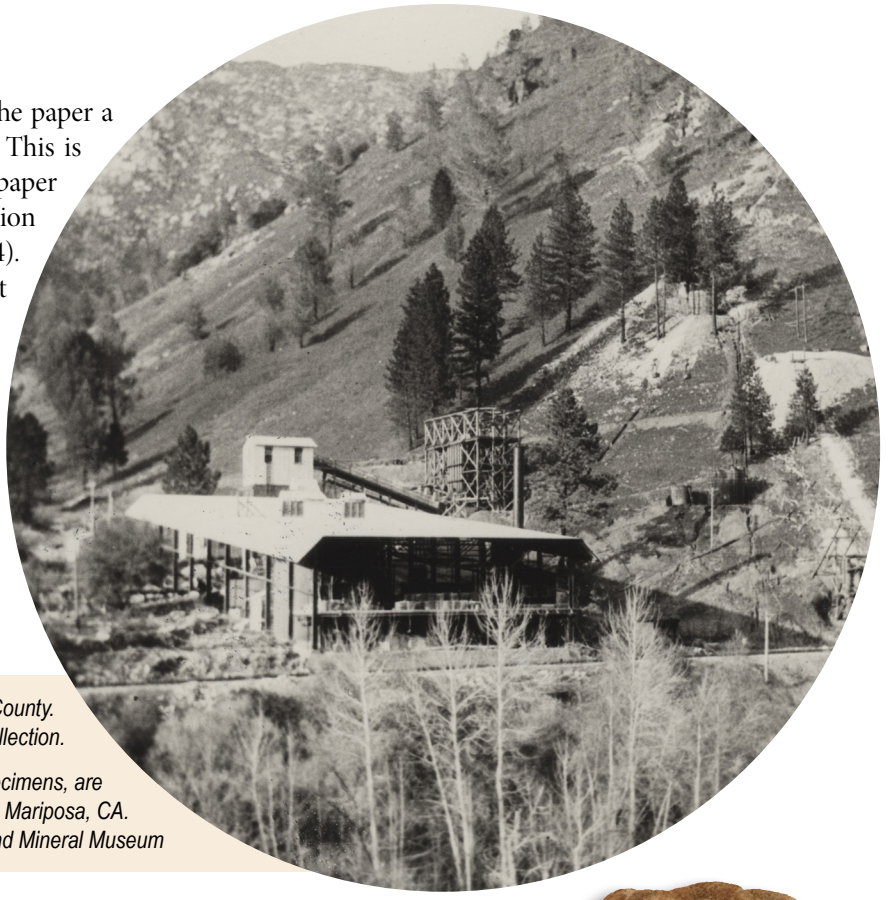
MINERAL PROPERTIES

Composition: barium sulfate, sometimes trace amounts of strontium, calcium, and lead
Chemical Formula: $BaSO_4$
Hardness: 3-3.5
Luster: vitreous or pearly
Color: translucent to transparent white, yellow, grey, brown, or light blue
Streak: bright white
Crystal Habit: usually tabular, sometimes prismatic, fibrous, and nodular
Cleavage: good to perfect
Crystal Form: orthorhombic
Specific Gravity: 4.5
Under a microscope: gray or colorless, with weak pleochroism and low to moderate birefringence (in thin section).

(Information from the Handbook of Mineralogy, 2005; Riddle, 2018).

BARITE IS BRIGHT!

Powdered barite is used in paper products, giving the paper a smoother surface and a consistent bright white color. This is especially important for creating smooth recycled paper products. The smooth surface leads to an even distribution of ink, improving print quality (Iran Minerals, 2024). Paper with barite also has a higher density, making it an important component of products such as playing cards, art paper, and posters (King, 2015).



Now that you know more about Barite, how many ways can you spot it in your everyday life?

A barite mine near El Portal, in Mariposa County.
Photo by Walter Bradley, from the CGS Library photo collection.

The samples seen on p. 21 and 44, and many other mineral specimens, are on display at the California State Mining and Mineral Museum in Mariposa, CA.
Photos by Carlos Antunez, California State Mining and Mineral Museum

Tabular barite crystals.
Photo by David Reioux, CGS

Fun Fact: Barite can form desert roses, a type of evaporite growth where a mineral crystallizes in thin blades around sand grains and the radiating crystal clusters resemble rose petals.

Photo by Elaine Young, CGS
Desert rose provided by Ben Parish, CGS

REFERENCES

Fitch, A.A., 1931, Barite and witherite from near El Portal, Mariposa County, California: American Mineralogist, v. 16, no. 10, p. 461–468.

Handbook of Minerology, 2005, Barite: Mineral Data Publishing, version 1: https://handbookofmineralogy.org/pdfs/baryte.pdf (accessed September 2025).

Iran Minerals, 2024, The Essential Role of Barite in Paper Production: https://iranmineral.net/the-essential-role-of-barite-in-paper-production/ (accessed September 2025).

King, H.M., 2015, Barite: The nonmetallic mineral with an incredible specific gravity: https://geology.com/minerals/barite.shtml (accessed September 2025).

Noah Chemicals, 2024, Why Barium Sulfate Is Essential in Medical Imaging and Diagnostics: https://www.noahchemicals.com/the-essential-role-of-barium-sulfate-in-medical-imaging/ (accessed September 2025).

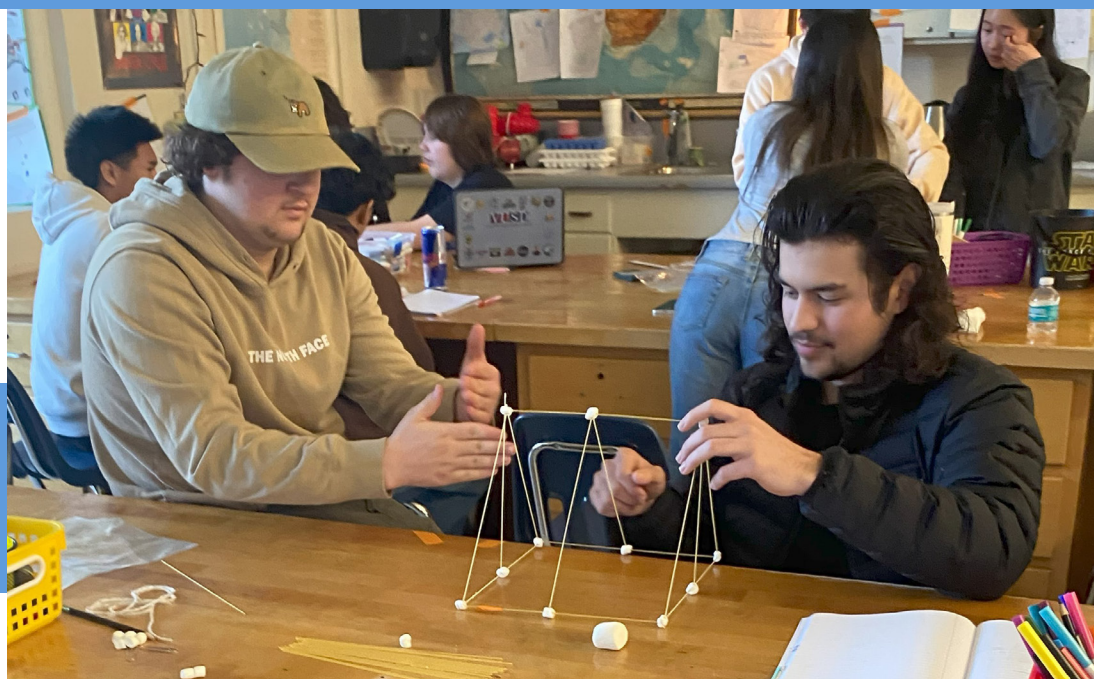
Princy, A.J., 2020, Barite: A Naturally Occurring Mineral Vitally Used in Different Industries: https://www.researchdive.com/blog/Barite-A-Naturally-Occurring-Mineral-Vitally-Used-in-Different-Industries (accessed September 2025).

Riddle, J., 2018, Baryte - Mineral Properties, Uses and Photos: https://mineralexpert.org/article/baryte-mineral (accessed September 2025).

United General, 2016, Why is barium used with X-rays?: https://unitedregional.org/wp-content/uploads/2016/01/Upper_Gastrointestinal_Series.pdf. (accessed September 2025)

The State of Geoscience Education in California

Maya Wildgoose, MS
Secondary Science Teacher



Honors Earth Science students work on designing marshmallow and spaghetti "structures" that use modern engineering principles for earthquake safety- next, they'll test their models on a shake table. Photo by Maya Wildgoose

THE LANDSCAPE

Despite being the most populous state in the U.S., California consistently ranks in the middle or lower half of the state k-12 education rankings (U.S. News, 2025; Nation's Report Card, 2024). While data specific to science performance is limited, it likely has a similar trend.

The No Child Left Behind Act-driven standards and curriculum of the early 2000s were not yielding data-supported success, so in 2013 California adopted the Next Generation Science Standards (NGSS). The NGSS framework marked a shift from overly specific content-based curriculum towards broader standards that emphasize skill development. Embedded within the standards are Science and Engineering Practices, which motivate students to develop essential scientific skills like analyzing and interpreting data, constructing explanations, developing solutions, and engaging in arguments from evidence.

WHAT ABOUT GEOSCIENCE?

Thanks to the advocacy of geoscience pillars like Eldridge Moores, earth science makes up 33% of the NGSS content, equivalent to biology and physical science (chemistry and physics). The extensive inclusion of earth science has encouraged k-12 schools to explore new, integrated pathways. Many districts in California have adopted a three-course integration model – broadly categorized as living earth, geochemistry, and geophysics. This model is attractive to science departments with teachers who are relatively unfamiliar with or potentially undertrained in geoscience, as it folds interdisciplinary topics and skills into the framework of traditional subjects. Although the curricula for these integrated courses vary, many are developed in collaboration with professional earth scientists to ensure accuracy and depth. For instance, the University of California, Davis School of Education plays a leading role in the Sacramento area by developing and implementing an integrated curriculum that authentically combines biology and earth science. The integrated approach has also helped pave the way for courses such as honors geology and honors earth science, which were rare in California 20 years ago. Currently, the state has about 20 public high schools that offer honors or advanced courses in earth science (UC Office of the President, 2023).

With a view of San Pablo Bay, Honors Earth Science students work with local geologists to map the Franciscan Formation at Ring Mountain in Tiburon, CA. Photo by Maya Wildgoose

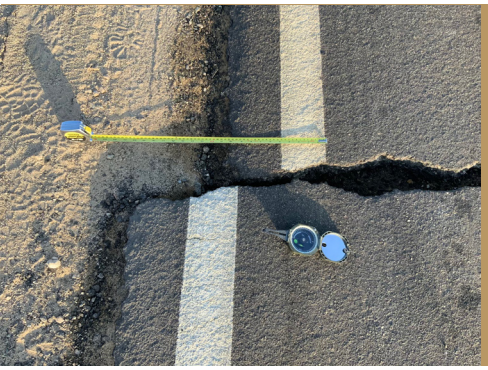
CHALLENGES AND OPPORTUNITIES

Despite the advances made in introducing additional earth science content into the curriculum at the k-12 level, many colleges and universities in the U.S. continue to face challenges in maintaining sufficient levels of enrollment in geosciences to fill job demands in the field (Keane et al., 2022; Moss et al., 2025). This is particularly concerning because the need for geoscientists is projected to grow in the coming years. The U.S. Bureau of Labor Statistics' (2025) Employment Projections expects the demand for geoscientists to increase by 3.7% between now and 2034, a gain of almost 17,000 jobs. Additionally, the American Geosciences Institute (AGI) projects that 27% of the current workforce will retire between 2019-2029 (Gonzales and Keane, 2020). This increase in demand for geoscientists coupled with an aging workforce underscores the critical importance of addressing the challenges universities face in maintaining geoscience enrollment to ensure a sufficient workforce in the years to come.

"The need for geoscientists is projected to grow in the coming years"

Part of the struggle colleges and universities face may stem from limited awareness among students and the public about college majors that can lead to lucrative and fulfilling careers in the geosciences. The adoption of the NGSS framework and the shift toward curricula that emphasize critical thinking over content memorization may eventually help turn the tide. Despite the disruptions caused by COVID-19, k-12 students have responded positively to the idea that earth science is fundamentally about inquiry, reasoning, and communication – not just memorization. Amongst the honors-level earth science students that I have taught in the past few years, I have seen a clear favorable shift in their approach to science. My junior and senior-level students come into class at the beginning of the academic year with a more skills-based "toolbox," primarily due to the science practices emphasized in NGSS, and are prepared to tackle challenging content with confidence. For example, when given a dataset with no certain answer, my students are equipped to confidently interpret and communicate data-informed conclusions. When I first started teaching earth science 15 years ago, my students struggled with problems that had no unique solutions or single best answer. This slow shift towards problem-solving and critical thinking in science classes is evident every day to me now.

Although concerns persist that undergraduate students are coming into college with low critical thinking skills, the impact of NGSS-aligned geoscience instruction is designed to facilitate slow but gradual improvement. This shift, coupled with increased opportunities to demonstrate their learning beyond traditional testing, will encourage students to hone their scientific reasoning in ways that will serve them in college and beyond.



TEST YOUR KNOWLEDGE!

In this image, we can see a fault where the pavement has cracked and separated features across the crack. Look at how the white stripe is offset.

What type of fault motion is shown in the photo?

See the next page for the answer!

At the Geological Society of America Cordillera Section meeting in April 2025, the geoscience community discussed challenges and opportunities in geoscience education across all levels. Here are some of the overarching themes:

1. Greater collaboration between schools, agencies, and professionals should yield significant benefits like expanding opportunities for students across all learning levels and providing instructional material aligned with skills that are critical for the workforce of the future. Professional guest speakers are still relatively rare in California's science classrooms, and improved partnerships between educators and professionals or agencies could offer students valuable, even inspirational, exposure to real-world science and firsthand insight into careers in the geosciences.

2. Public school teachers are often asked to teach complex topics without specialized professional development. Providing more curricular support led by professionals with deep subject matter knowledge could help bridge that gap while increasing instructional effectiveness.

3. To ensure the vitality of the geosciences, outreach must begin with young students and continue throughout their educational journey. Introducing them early to the skills and career paths available in earth science can spark curiosity and foster interest in the field. Continued interactions with and mentorship by scientists with a broad range of backgrounds and experiences throughout a student's education can help students to imagine their future selves in a similar role and to better understand the relevance and applications of science beyond academic settings.

Geoscience education in California is moving in a positive direction and can only benefit from ongoing collaboration and vertical articulation efforts. The shift from science standards that emphasized memorization to standards that emphasize applicable skills was championed by many in the geoscience community. Slowly but surely, the NGSS standards are helping prepare our students to enter the post-secondary geoscience community with confidence and ingenuity. Continued contributions from the community via innovative ideas and mentorship are a key part of inspiring our youth to pursue careers in earth science.

Solutions mixed by students are put to the density test as they try to create a 5-color stack by only varying salinity and temperature.
Photo by Joel Rosenbaum

Vertical articulation is a term used to refer to the progression of classes and curricula from level to level in such a way that the material learned follows a logical progression. In a K-12 setting, this is usually referring to the progression from elementary to middle school then to high school, which requires collaboration between teachers across grade levels. It can also be applied to the transition between secondary and post-secondary curricula, as described in this article.

REFERENCES

Gonzales, L. and Keane, C., 2020, Geoscience Workforce Projections 2019-2029: American Geosciences Institute Geoscience Currents, Data Brief 2020-025. https://www.americangeosciences.org/static/files/profession/geoscience-currents/DB_2020-025_EmploymentProjections2019-2029.pdf. (accessed August 2025).

Keane, C., Gonzales, L., and Robinson, D., 2022, Status of Recent Geoscience Graduates 2021: American Geosciences Institute. ISBN:978-0-922151-54-4. https://www.americangeosciences.org/static/files/GraduateSurvey2021.pdf (accessed August 2025).

Moss, D. K., et al., 2025, Recruiting geoscience majors: Student perceptions and a path forward: Journal of Geoscience Education, pp. 1–14. doi: 10.1080/10899995.2025.2535770.

The Nation's Report Card, 2024, State Profiles: https://www.nationsreportcard.gov/profiles/stateprofile/overview/CA?sfj=NP&chort=2&sub=MAT&sj=CA&st=MN&year=2024R3&cti=PgTab_OT (August 2025).

US Bureau of Labor Statistics, 2025, https://www.bls.gov/ooh/life-physical-and-social-science/geoscientists.htm#:~:text=3%25-,Employment%20of%20geoscientists%20is%20projected%20to%20grow%203%20percent%20from,on%20average%2C%20over%20the%20decade.(accessed August 2025)

US News, 2025, Best States, Education: U.S. News and World Report. https://www.usnews.com/news/best-states/rankings/education (accessed August 2025)

University of California Office of the President, 2023, a-g Course Approval List: https://hs-articulation.ucop.edu/agcourselistresults;searchType=1;query=honors%2earth%20science;filters=institutionTypeName%7CSchool_-_schoolGovernanceName%7CPublic_-_ (accessed August 2025).

Answer to the Test Your Knowledge question on the previous page: The fault motion shown in the photo is **right-lateral strike slip**. The photo was taken by CGS geologist Francesca Rodriguez while recording offset measurements along a surface rupture caused by the 2019 Ridgecrest earthquake. The tape measure is placed parallel to the fault to measure separation across the fault and the Brunton compass is measuring the orientation of the surface rupture at this location.

Bumpass Hell in Lassen National Park. Photo by Annalise Gay, CGS

2023 Mineral Production in California

Greg D. Marquis, PG

CALIFORNIA IS ONE OF THE LARGEST PRODUCERS OF NON-FUEL minerals in the United States. Non-fuel minerals comprise a variety of commodities but exclude fuel commodities like coal and oil shale. In 2023, production of non-fuel minerals occured at 626 mines and included 33 commodities, two of which are not produced anywhere else in the nation.

PRODUCTION

Using a combination of data from the California Division of Mine Reclamation (DMR), the U.S. Geological Survey (USGS), and MP Materials Corporation, the total estimated California non-fuel mineral production value in 2023 was $5.6 billion.

Based on USGS preliminary data, California ranked fifth—behind Arizona, Minnesota, Nevada, and Texas—in non-fuel mineral production value, accounting for approximately 4.85 percent of the nation's total (USGS, 2024).

Commodity	Rank
Boron	1
Construction sand and gravel	1
Gypsum	1
Rare earth elements	1
Cement	3
Gemstones	4
Crushed stone	9
Industrial sand and gravel	9

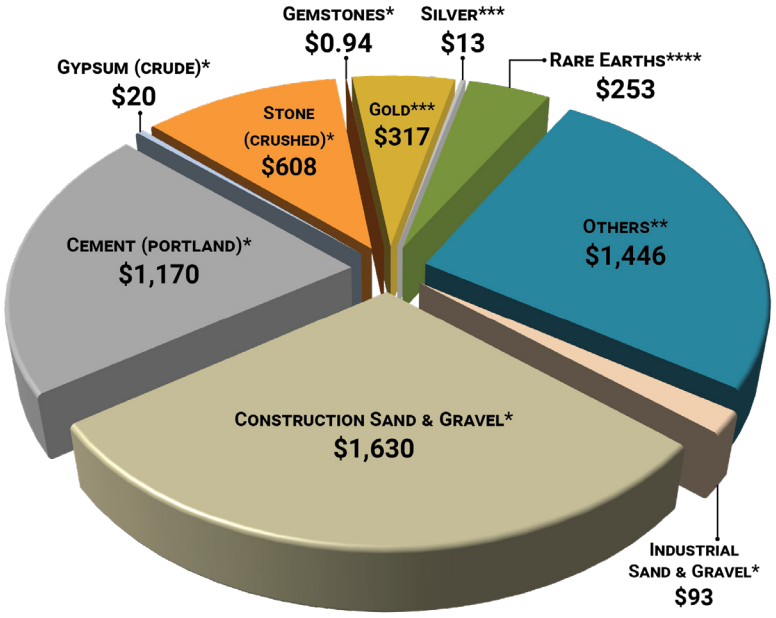
NATIONAL IMPORTANCE

California is the nation's only producer of rare earth elements (REEs) and borates. Both commodities have extensive uses, ranging from everyday products to cutting-edge technologies required for a decarbonized future.

Table: California's national standing as a producer of selected non-fuel mineral commodities. Source: USGS, 2024.

Above image: Calico Mine area in the Mojave Desert. Silver and borate were mined at Calico during the late 1800s. The nearby town, Calico, is now a preserved ghost town and tourist attraction. Photo by Catherine Wesoloski, CGS

2023 Mineral Production



Value (millions of dollars) of California's non-fuel mineral production in 2023. Data are available in CGS Bulletin 233. Some commodities are presented as a group to protect unpublished USGS data, as required.

"Others" category includes boron minerals, cement (masonry), clays (ball clay, bentonite, kaolin, montmorillonite), clays (common), diatomite, feldspar, lime, magnesium compounds, perlite (crude), pumice and pumicite, salt, soda ash, and zeolites.

** Data from the USGS.*

*** Data from the USGS, combined to protect unpublished values. Original USGS data included gold, silver, and rare earths. DMR and MP Materials values for those commodites were subtracted from the USGS values.*

**** Production data from the DMR; unit values from the USGS.*

***** Data from MP Materials.*

Rare Earth Elements

REEs are a group of metallic elements with unique properties that make them indispensable for high-tech applications. These elements comprise 15 of the 60 critical minerals on the current USGS critical minerals list (USGS, 2025). Some uses for REEs, and their related periodic table symbols, include:

- Magnets (Nd, Pr, Sm)
- Metal Alloys (La, Ce, Pr, Nd, Y)
- Ceramics and glass (Ce, La, Pr, Nd, Gd, Er, Ho)
- Catalysts (La, Ce, Pr, Nd)
- Phosphors (Eu, Y, Tb, Nd, Er, Gd, Ce, Pr)

REEs are produced by MP Materials at Mountain Pass Mine in San Bernardino County. Until recently, magnets made from its ore were produced exclusively overseas. In 2024, MP completed a neodymium-iron-boron magnet production facility in Fort Worth, Texas (MP Materials, 2025a). In July 2025, MP announced a private-public partnership with the U.S. Department of Defense, which includes heavy REE mineral refinement at Mountain Pass and investments into a second magnetics facility (site location to be determined; MP Materials, 2025b). Shortly after, MP announced a $500 million partnership with Apple Inc., which includes recycling of used rare earth magnets as feedstock (end-of-life and post-industrial magnets) at Mountain Pass, which will be used to produce magnets at its Texas facility (MP Materials, 2025c).

Borates

Borate applications are extensive and include the following:

- Thermally resistant glass
- Cleaners
- Insecticides/fungicides
- Fire retardants
- Armor (boron carbide)
- REE magnets

Borates are produced at two mines in California, including U.S. Borax's Boron Pit in Kern County, which is the largest open-pit mine in the state. Beyond its significance to the US, one-third of world's refined borates come from Boron Pit (U.S. Borax, 2025). Borates are also produced by Searles Valley Minerals in San Bernardino County, using a solution mining process to extract evaporite minerals from Searles Lake (Searles Valley Minerals, 2025).

More information related to non-fuel mineral production is available at https://www.conservation.ca.gov/cgs/minerals/mineral-production

REFERENCES

MP Materials, 2025a, MP Materials Announces Transformational Public-Private Partnership with the Department of Defense to Accelerate U.S. Rare Earth Magnet Independence https://mpmaterials.com/news/mp-materials-announces-transformational-public-private-partnership-with-the-department-of-defense-to-accelerate-u-s-rare-earth-magnet-independence (accessed August 11, 2025).

MP Materials, 2025b, Magnetics: https://mpmaterials.com/magnetics/ (accessed August 11, 2025).

MP Materials, 2025c, MP Materials and Apple Announce $500 Million Partnership to Produce Recycled Rare Earth Magnets in the United States: https://mpmaterials.com/news/mp-materials-and-apple-announce-500-million-partnership-to-produce-recycled-rare-earth-magnets-in-the-united-states/ (accessed August 11, 2025).

Searles Valley Minerals, 2025, Seales Valley Minerals. https://www.svminerals.com/ (accessed October 31, 2025).

U.S. Borax, 2025, Boron California Operations: https://www.borax.com/about/borax-operations/boron-california (accessed August 11, 2025).

U.S. Geological Survey, 2024, Mineral commodity summaries 2024: U.S. Geological Survey, 212 p., https://doi.org/10.3133/mcs2024.

U.S. Geological Survey, 2025, Interior Department releases final 2025 List of Critical Minerals: https://www.usgs.gov/news/science-snippet/interior-department-releases-final-2025-list-critical-minerals (accessed December 23, 2025).

CGS Publications and Research

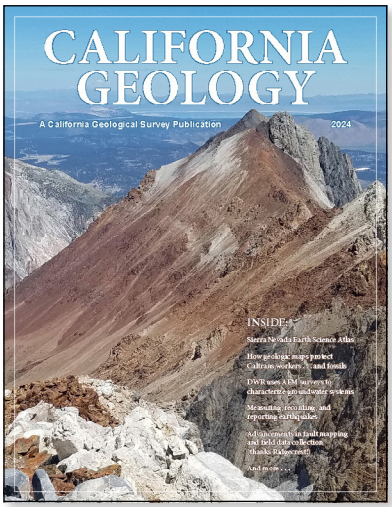
NEW AND REVISED RELEASES IN CALENDAR YEAR 2025

BULLETINS

Bulletin 233: California Non-Fuel Mineral Production 2023

CALIFORNIA GEOLOGY™ MAGAZINE

CG Volume 55 (2024-2025 annual)



CGS NOTES

CGS Note 48: Checklist for the Review of Engineering Geology and Seismology Reports for California Public Schools, Hospitals, and Essential Services Buildings (update)

EARTHQUAKE ZONES OF REQUIRED INVESTIGATION MAPS (EZRIM)

EZRIM listed by quadrangle, alphabetically

- Byron Hot Springs
- Franklin Point
- Half Moon Bay
- La Honda
- Pasadena
- Montara Mountain
- Mount Wilson
- Pigeon Point
- Point Año Nuevo
- Sacramento East
- Sacramento West
- San Gregorio
- Sebastopol

EZRIM listed by county, alphabetically

- **Alameda:** Byron Hot Springs
- **Contra Costa:** Byron Hot Springs
- **Los Angeles:** Pasadena, Mount Wilson
- **Sacramento:** Sacramento East, Sacramento West
- **San Mateo:** Franklin Point, Half Moon Bay, La Honda, Montara Mountain, Pigeon Point, Point Año Nuevo, San Gregorio
- **Santa Cruz:** Franklin Point, Point Año Nuevo
- **Sonoma:** Sebastopol
- **Yolo:** Sacramento West

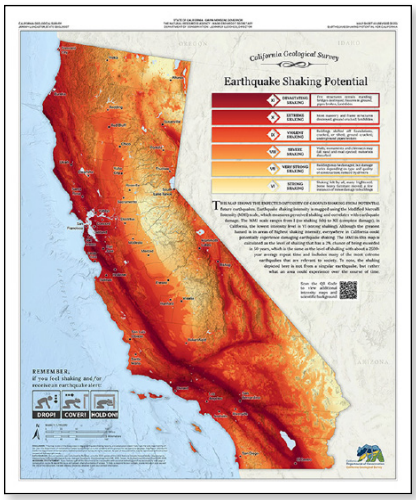
FAULT EVALUATION REPORTS

FER 263: The Sierra Madre Fault Zone in the Pasadena and Mt. Wilson 7.5' Quadrangles, Los Angeles County

FER 275: The San Gregorio Fault Zone in the Point Ano Nuevo, Franklin Point, Pigeon Point, La Honda, San Gregorio, Half Moon Bay, Montara Mountain, Montara Mountain OE W 7.5' Quadrangles, San Mateo and Santa Cruz Counties

MAP SHEETS

Map Sheet 48: Earthquake Shaking Potential for California (update)



MS 48 supplemental web maps and data

- MMI from PGV
- MMI from PGA
- MMI from PGA and disaggregated ground motion variability level
- MMI from PGA and disaggregated magnitude and distance
- 2%50 (2475-yr) ground motions (PGA, PGV, SA02, SA10, SA20)
- 10%50 (475-yr) ground motions (PGA, PGV, SA02, SA10, SA20)
- Historical Earthquakes Since 1769 in California
- Major California Faults and Their Slip Rates
- Site Condition (Vs30 data)
- Distribution of average annualized earthquake loss by state
- Distribution of average annualized earthquake loss by county in California

Map Sheet 68: Geologic map of a portion of the western Cady Mountains, San Bernardino County

MISCELLANEOUS

Web app: Quaternary Faults Data Upload Portal

REGIONAL GEOLOGIC MAPS

PGM 24-01: Preliminary geologic map of the Willits 7.5' Quadrangle, Mendocino County

PGM 24-02: Preliminary geologic map of the North Bloomfield 7.5' Quadrangle, Nevada County

PGM 24-03: Preliminary geologic map of the Warm Springs Mountain 7.5' Quadrangle, Los Angeles County

SEISMIC HAZARD ZONE REPORTS

SHZR 141: Seismic Hazard Zones in the Sacramento East and Sacramento West 7.5' Quadrangles, Sacramento and Yolo Counties

SHZR 142: Seismic Hazard Zones in the Byron Hot Springs 7.5' Quadrangle, Contra Costa and Alameda Counties

SHZR 143: Seismic Hazard Zones in the Sebastopol 7.5' Quadrangle, Sonoma County

STRONG MOTION INSTRUMENTATION

SMIP24: Proceedings of the SMIP 2024 Seminar on Utilization of Strong-Motion Data

WATERSHED EMERGENCY RESPONSE TEAM (WERT) ASSESSMENTS

WERT Post-Fire Evaluations

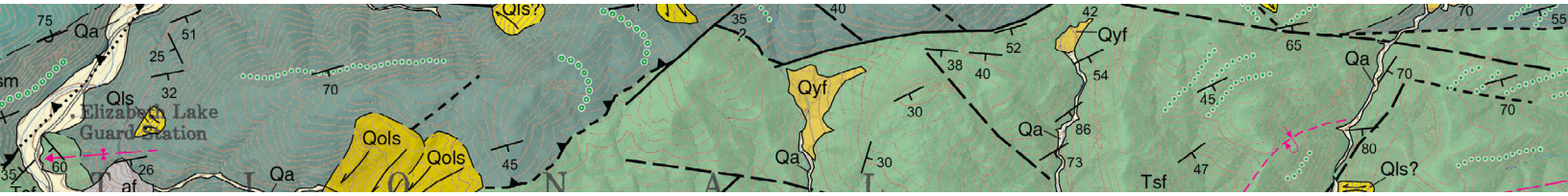
- **Eaton Fire,** Los Angeles County
- **Gifford Fire,** San Luis Obispo and Santa Barbara Counties
- **Palisades Fire,** Los Angeles County
- **Pickett Fire,** Napa County

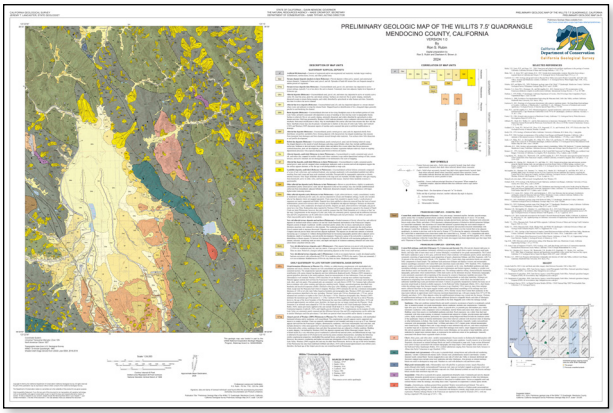
WERT Summaries of Post-Fire Field Reconnaissance

- **Border 2 Fire,** San Diego County
- **Hurst Fire,** Los Angeles County
- **Kenneth Fire,** Ventura and Los Angeles Counties
- **Wolf Fire,** Riverside County

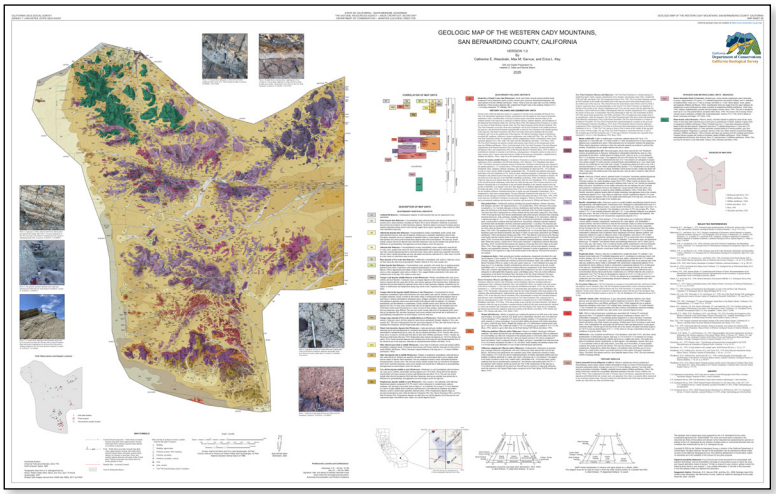
WERT Post-Event [debris flow] Response

- **Memorandum:** 9/18/2025 Storm Response, Forest Falls and Oak Glen areas, San Bernardino County

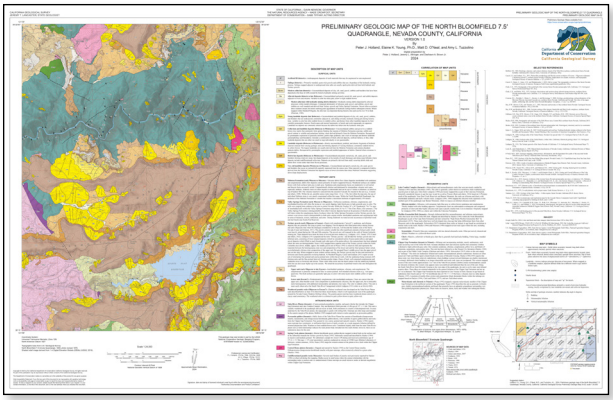




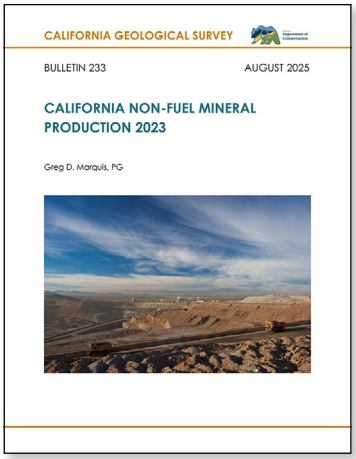
PGM 24-01: *Preliminary geologic map of the Willits 7.5' Quadrangle, Mendocino County*



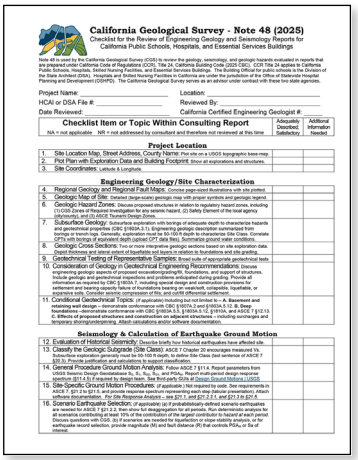
Map Sheet 68: *Geologic map of a portion of the western Cady Mountains, San Bernardino County*



PGM 24-02: *Preliminary geologic map of the North Bloomfield 7.5' Quadrangle, Nevada County*

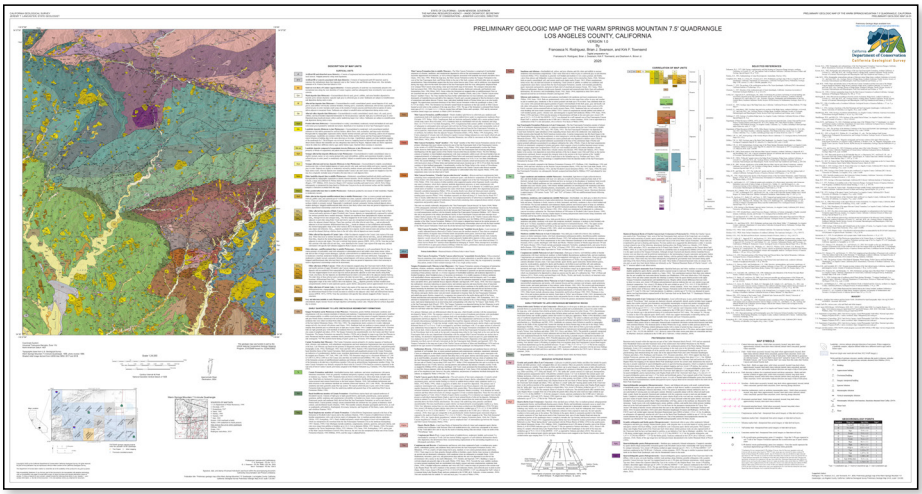


Bulletin 233: *California Non-Fuel Mineral Production 2023*



CGS Note 48: *Checklist for the Review of Engineering Geology and Seismology Reports for California Public Schools, Hospitals, and Essential Services Buildings*

PGM 24-03: *Preliminary geologic map of the Warm Springs Mountain 7.5' Quadrangle, Los Angeles County*



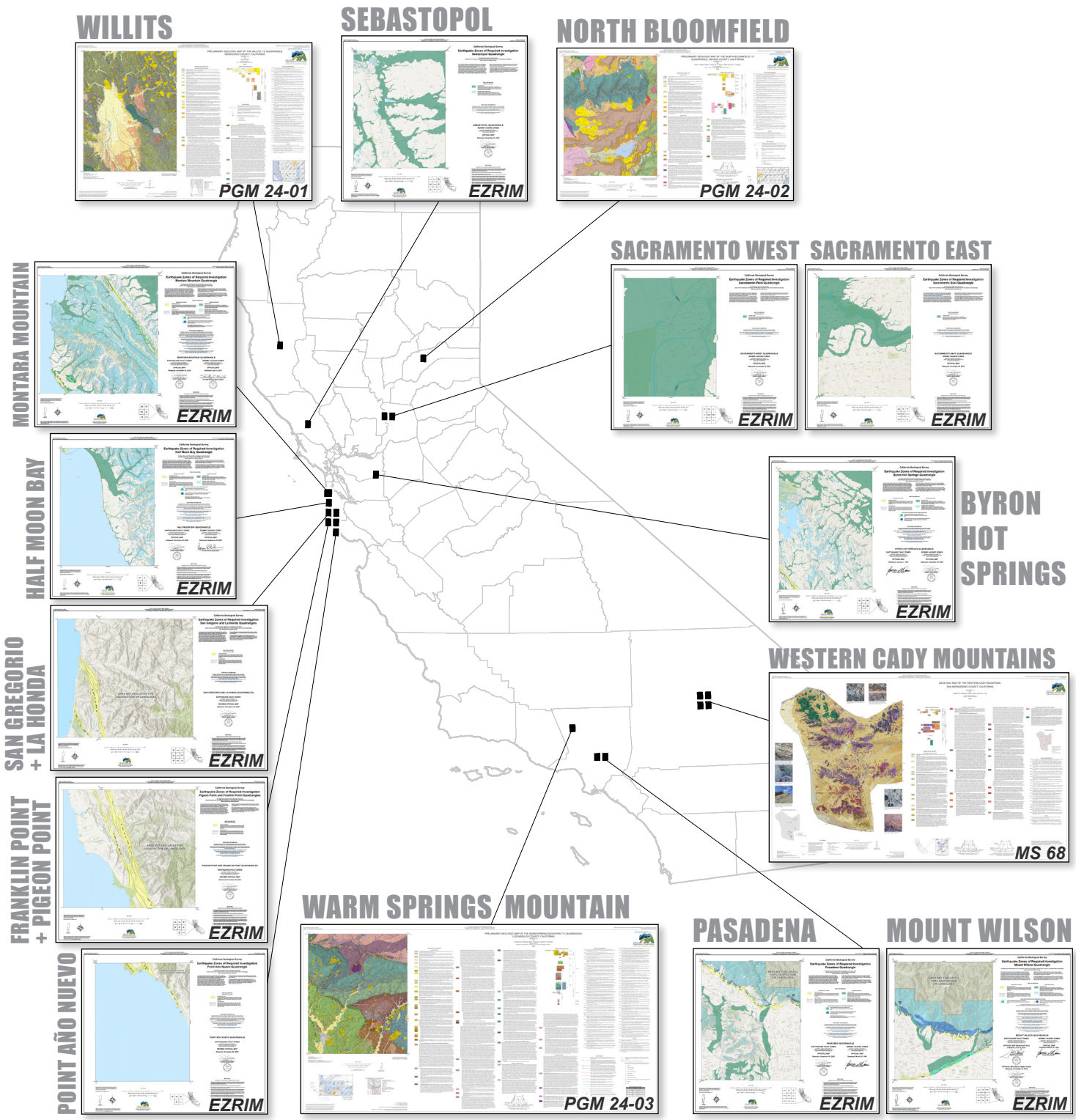
MS vs PGM, FER vs SHZR. WHAT'S THE DIFFERENCE?

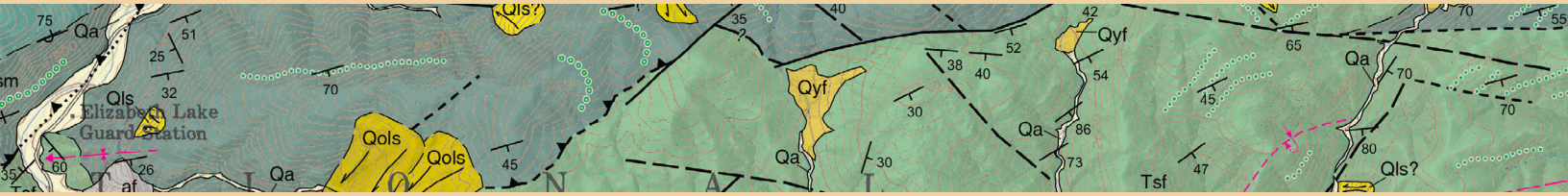
For an explanation of CGS publication types, visit the online *Glossary of CGS Publication Series* at: https://www.conservation.ca.gov/cgs/publications/series

CGS Publications and Research

NEW AND REVISED RELEASES IN CALENDAR YEAR 2025, CONTINUED

1:24,000 SCALE REGIONAL MAPS COMPLETED IN 2025





PEER-REVIEWED RESEARCH

(CGS authors in **boldface**)

Akin et al., (including **Lindsay, D.**, **Cavagnaro, D.**, **Oakley, N.**, **Cheung, D.**, and **Morelan, A.**), 2025, Reconnaissance of the Geotechnical and Infrastructure Impacts of Los Angeles Area Wildfires and Subsequent Storms: Report GEER-085, NSF-Sponsored Geotechnical Extreme Event Reconnaissance Association, doi.org/10.18118/G6X37N.

Bixler, J.D., Schwartz, J.J., **Swanson, B.J.**, Miranda, E.A., and Klepeis, K.A., 2025, Dating deformation in the Alamo Mountain and Piru Creek shear zones: Insights into Late Cretaceous tectonics in southern California, *in* Gordon, S.M., Miller, R.B., Rusmore, M.E., and Tikoff, B., eds., Jurassic–Paleogene Tectonic Evolution of the North American Cordillera: Geological Society of America Special Paper 565, 31 p., doi.org/10.1130/2025.2565(15).

Bozorgnia Y., et al., (including **Chen R.**, **Dawson, T.**, **Madugo, D.**, and **Thomas, K.**), 2025, Fault Displacement Hazard Initiative research program: Earthquake Spectra, v. 41, no. 4, p. 2679-2690, doi:10.1177/87552930251356418.

Cavagnaro, D.B., McCoy, S.W., Thomas,M.A., Kostelnik, J., and **Lindsay, D.N.**, 2025, Improved prediction of postfire debris flows through rainfall anomaly maps: Geophysical Research Letters, v. 52, e2025GL114791, doi.org/10.1029/2025GL114791.

Cavagnaro, D.B., McCoy, S.W., **Lindsay, D.N.**, McGuire, L.A., Kean, J.W., and Trugman, D.T., 2025, Rainfall thresholds for postfire debris-flow initiation vary with short-duration rainfall climatology: Journal of Geophysical Research: Earth Surface, v. 130, e2024JF007781, doi.org/10.1029/2024JF007781.

Chiou, B., **Chen, R.**, **Thomas, K.**, Milliner, C., **Dawson, T.**, Petersen, M., 2025, Fault displacement model for surface principal rupture of strike-slip faults: Earthquake Spectra, v. 41, no. 4, p. 2746-2782., doi:10.1177/87552930251337703.

East, A.E., Logan, J.B., Dartnell, P., Dow, H.W., **Lindsay, D.N.**, and **Cavagnaro, D.B.**, 2025, Post-fire sediment yield from a western Sierra Nevada watershed burned by the 2021 Caldor Fire: Earth and Space Science, v. 12, e2024EA003939, doi.org/10.1029/2024EA003939.

Ghahari, F., **Swensen, D.**, and **Haddadi, H.**, 2025, Optimal Sensor Placement in Buildings: Stationary Excitation: Sensors, v. 25, no. 24, p. 7470, doi.org/10.3390/s25247470.

Hellweg, M., et al., (including **Hagos, L.**, **Haddadi, H.**, and **Patton, J.**), 2025, Revisiting an Enigma on California's North Coast: The 6.5 Fickle Hill Earthquake of 21 December 1954: *Bulletin of the Seismological Society of America*, v. 115, no. 6, p. 2623–2639, doi.org/10.1785/0120250080.

McPherson, R.C., **Patton, J.R.**, Hellweg, M., Smith, S.W., Dengler, L., Lomax, A., and Dreger, D.S., 2025, Large Repeating Gorda Intraplate Earthquakes Occurring Along an Inherited Weak Zone near the Mendocino Triple Junction: Seismological Research Letters, v. 96, no. 5, p. 3179-3188., doi.org/10.1785/0220250005.

Melgar, D., et al., (including **Dawson, T.**), 2025, Supershear source model of the 2025 M7.8 Myanmar earthquake and paleoseismology of the Sagaing Fault: regions of significant overlap with past earthquakes: Seismica, v. 4, no. 2, doi.org/10.26443/seismica.v4i2.1771.

Oakley, N.S., **Cheung, D.J.**, **Lindsay, D.N.**, and Nash, D., 2025, Insights from a 25-year database of post-fire debris flows in California: International Journal of Wildland Fire, v. 34, no. 12, WF25136, doi.org/10.1071/WF25136.

Olsen, W., Coe, D., **Oswald, J.**, **Allison, C.**, **Fehrenbach, A.**, and Boone, M., 2025, Monitoring Results of Non-Federal Post-Fire Salvage Logging in California Forests: Report on Post-Fire §1052 Notice of Emergency Timber Operations: California. doi.org/10.13140/RG.2.2.33704.43525.

Perkins, J., **Oakley, N.S.**, Collins, B.D., Corbett, S.C., and **Burgess, W. P.**, 2025, Characterizing the scale of regional landslide triggering from storm hydrometeorology: Natural Hazards and Earth System Sciences, v. 25, no. 3, p. 1037–1056, doi.org/10.5194/nhess-25-1037-2025.

Portenga, E.W., **Townsend, K.F.**, Corbett, L.B., Bierman, P.R., Caffee, M.W., Bogoski, C., O'Neill, C., Skora, S., 2025, 10Be reproducibility in the Santa Monica Mountains, California, USA: A longitudinal study in a scorched and soaked landscape: Geomorphology, v. 478, no. 8, 109713, doi.org/10.1016/j.geomorph.2025.109713.

Rossi, R.K., **Richardson, P.W.**, **Cavagnaro, D.B.**, **Lukashov, S.G.**, **Miller, M.E.**, **and Lindsay, D.N.**, 2025, Predicting potential postfire debris-flow hazards across California prior to wildfire: International Journal of Wildland Fire, v. 34, no. 7, doi.org/10.1071/WF24225.

Sarmiento, A., et al., (including **Chen, R.**, and **Dawson, T.**), 2025, Comparisons of FDHI fault displacement models for principal and aggregate displacement: Earthquake Spectra, v. 41, no. 4, p. 2691-2720, doi:10.1177/87552930251327894.

Sarmiento, A., et al., (including **Madugo, D.** and **Dawson, T.**), 2025, Database for the Fault Displacement Hazard Initiative Project: Earthquake Spectra, v. 41, no. 4, p. 2721-2745, doi:10.1177/87552930241262766.

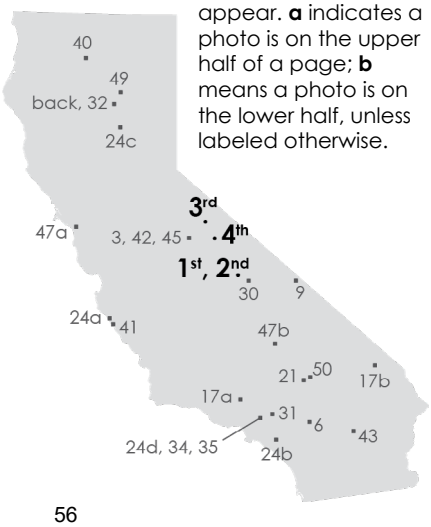
Thomas, K., Milliner, C., **Chen, R.**, Chiou, B., **Dawson, T.**, and Petersen, M., 2025, Least cost path analysis as an objective and automatic method to define the main fault trace for probabilistic fault displacement hazard analyses: Earthquake Spectra, v. 41, no. 4, p. 2938-2967, doi:10.1177/87552930231205878.

Thomas, M.A., et al., (including **Lindsay, D.N.**, **Rossi, R.K.**, **Swanson, B.J.**, **Oakley, N.S.**, **Richardson, P.W.**, and **Morelan, A.E.**), 2025, Landsliding follows signatures of wildfire history and vegetation regrowth in a steep coastal shrubland: Geosphere, v. 21, p. 1-18, doi.org/10.1130/GES02856.1.

1st place: Sierra Nevada Crest thunderstorm from Marion Peak. Photo by Brian Swanson, CGS

CGS Staff **Photo Contest** Winners

The map below shows the locations of photos throughout this issue. Contest winners are labeled **bold** while the labels for all other photos are gray. Label numbers refer to page numbers where photos appear. **a** indicates a photo is on the upper half of a page; **b** means a photo is on the lower half, unless labeled otherwise.



3rd place: North Peak and unnamed lake, Hoover Wilderness. Photo by Robert Wurgler, CGS

2nd place: Palisade Skyline from Marion Peak, Sierra Nevada. Photo by Brian Swanson, CGS

4th place: Columnar basalt, Devil's Postpile National Monument. Photo by Nicholas Graehl, CGS

Finishing a day of fieldwork in Mill Creek canyon at the Park Fire, Lassen National Forest. Photo by David Cavagnaro, CGS