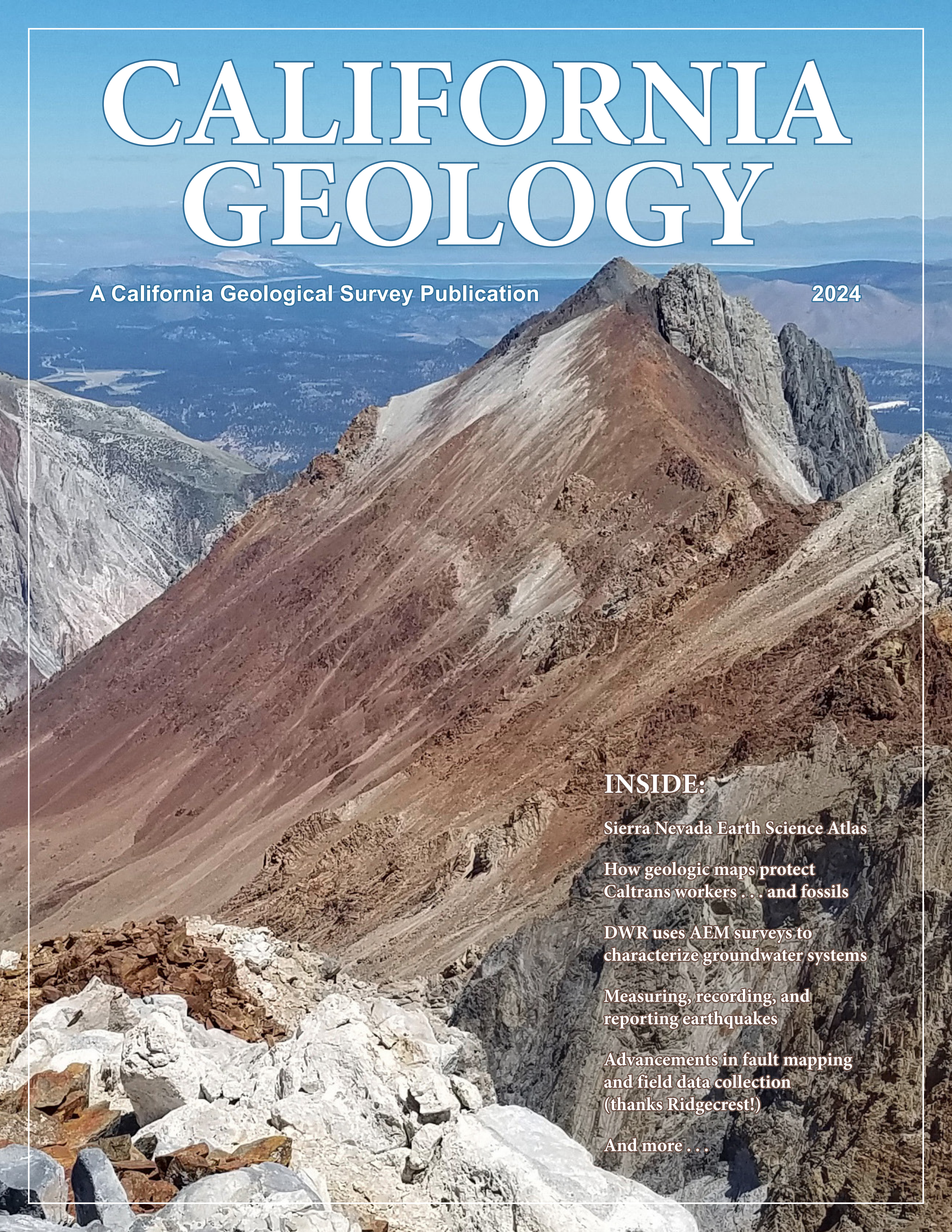
CALIFORNIA GEOLOGY

A California Geological Survey Publication

2024



INSIDE:

Sierra Nevada Earth Science Atlas

How geologic maps protect Caltrans workers . . . and fossils

DWR uses AEM surveys to characterize groundwater systems

Measuring, recording, and reporting earthquakes

Advancements in fault mapping and field data collection (thanks Ridgecrest!)

And more . . .

CALIFORNIA GEOLOGY is best viewed and printed as a booklet

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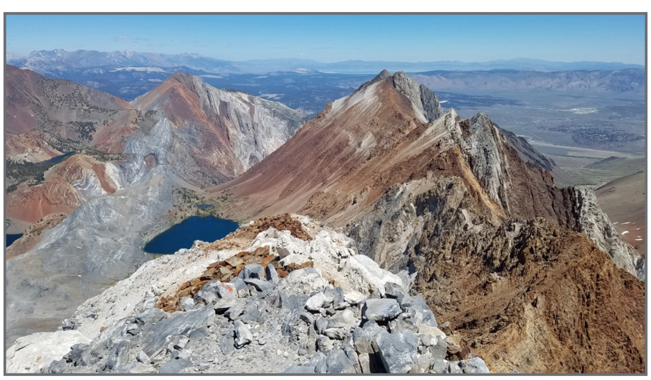
IN THIS ISSUE



On the cover: *The Mount Morrison roof pendant in the Sierra Nevada, as seen from Mount Baldwin. In the distance are the Long Valley Caldera, Mono-Inyo Craters, and Mono Lake. Photo by Brian Swanson, CGS.*

CALIFORNIA GEOLOGY™ MAGAZINE, VOL. 55

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

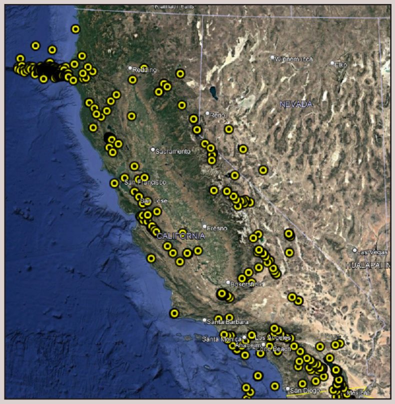
March 16, 2025

PROFESSIONAL GEOLOGIST
Jeremy Lancaster
No. 7692
STATE OF CALIFORNIA

2024 CALIFORNIA EARTHQUAKES

In 2024 California recorded 7,814 M≥1.5 earthquakes. Of those, 1,046 were M≥2.5 and 17 were M≥4.5.

The largest earthquake felt in California in 2024 was the December 5, 2024 M7.0 Offshore Cape Mendocino earthquake, located under the Pacific Ocean about 30 miles (45 km) west of Cape Mendocino. It also has the distinction of being the largest earthquake in the United States during 2024.



Source: CGS Center for Engineering Strong Motion Data; base map from Google Earth

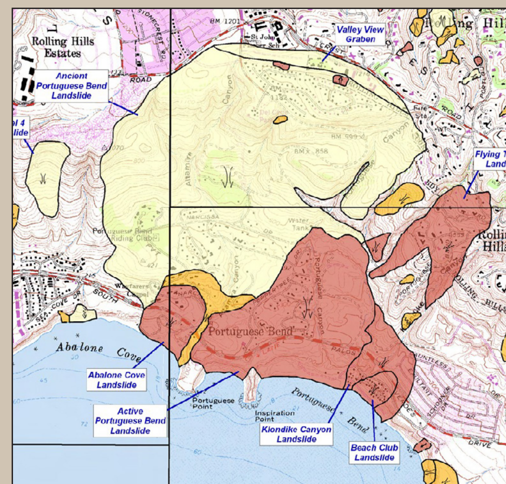
The second largest 2024 earthquake in California was the August 7, 2024 M5.2 Lamont earthquake, near Bakersfield. This was the largest onshore earthquake within California in 2024 and was felt widely in Southern California. Fortunately, it caused little damage.

In California, small earthquakes occur nearly every day. These earthquakes are reminders that California is earthquake country and that we need to be prepared for them.

DR. PERRY EHLIG'S GEOLOGIC RESEARCH COLLECTION

Dr. Perry L. Ehlig was a California-registered engineering geologist, concerned primarily with landslide, groundwater, fault, and earthquake problems. He contributed significantly to the understanding of the complex regional geology of southern California, especially of basement rocks and the displacement history of the San Andreas Fault system. You may visit the California Geological Survey's Los Angeles Office to view rock specimens and thin sections collected by Dr. Ehlig. To learn more about his life and research and to preview the collection online, go to https://www.conservation.ca.gov/cgs/education-resources.

PORTUGUESE BEND LANDSLIDE



Source: CGS Landslide Inventory Map of the Palos Verdes Peninsula, 2007, https://filerequest.conservation.ca.gov

On the southern coast of the Palos Verdes Peninsula is an infamous landslide complex that has been studied and monitored since 1946 when USGS geologist W.P. Woodring first examined it.

CGS mapping from 1998 showed three active landslides named the Portuguese Bend, the Abalone Cove, and the Klondike landslides. These were inset into a larger dormant landslide known as the ancient Portuguese Bend landslide or the ancient complex.

In 1956, the Portuguese Bend landslide began moving during the extension of Crenshaw Boulevard to Palos Verdes Drive due to placement of road fill. The Abalone Cove landslide began moving in 1974 and the Klondike Canyon slide began moving around 1980.

During a rainy period from 2022-2024, landslide activity increased, destroying properties and infrastructure. According to the City of Rancho Palos Verdes, the Portuguese Bend landslide moved approximately 4 feet per month from June to August 2024.

A NOTE FROM THE STATE GEOLOGIST

Jeremy Lancaster, PG, CEG

GREETINGS!

We live in one of the most seismically active and geologically diverse states in the country. While the state has experienced many damaging earthquakes and other natural hazard events in the past, our challenges are evolving with our changing climate, including hazards from landslides, sea level rise and coastal erosion, post-wildfire debris flows and flash flooding, demands on groundwater resources, and demands on critical minerals needed to transition toward a decarbonized economy. The California Geological Survey (CGS) has a mandate to address these challenges and to communicate actionable information to scientists, engineers, emergency workers, and planners to protect life-safety and property and to build resilient communities.

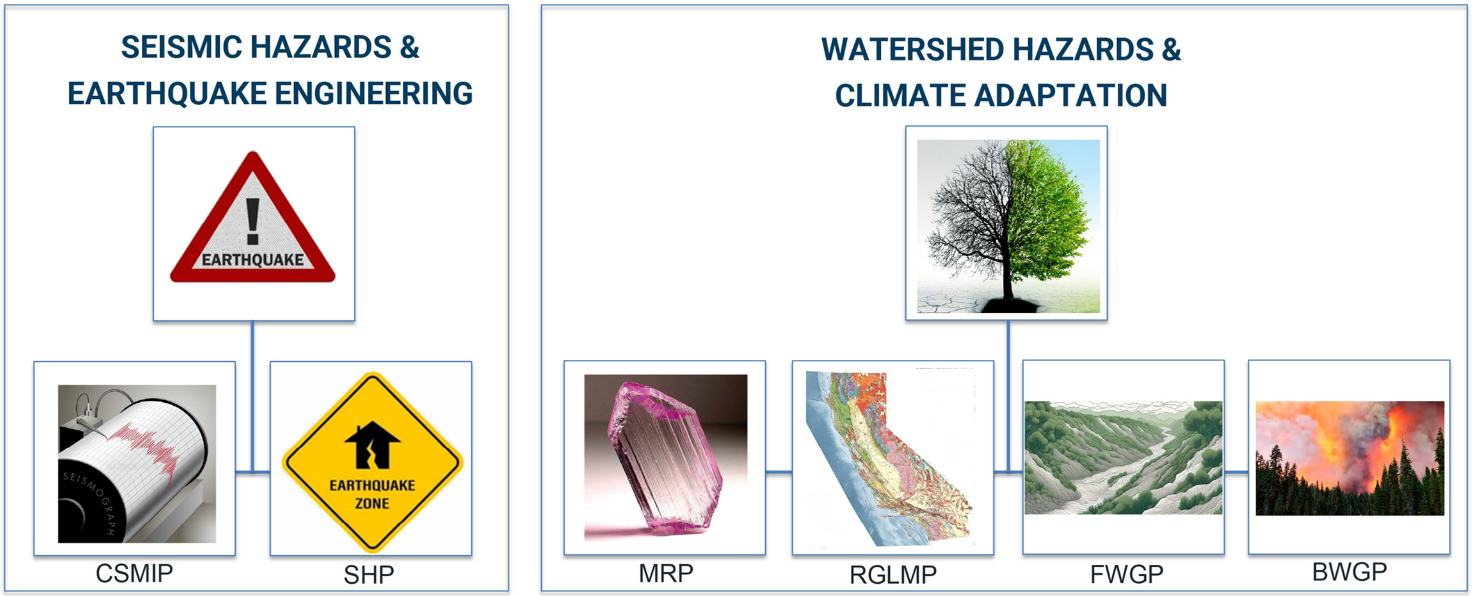
As such, I am pleased to reintroduce *California Geology* magazine. At its peak, *California Geology* had more than 10,000 subscribers, including teachers, students, professionals, and the general public. Although dormant since 2001, it has not been forgotten. Former readers of the magazine have maintained a steady, quiet chorus of requests for its return.

A NEW CGS AND A LOOK BACK AT ACCOMPLISHMENTS IN 2024

To meet the state's evolving challenges, the CGS has brought in new experts and reorganized into two principal branches, Watershed Hazards and Climate Adaptation, and Seismic Hazards and Earthquake Engineering. The CGS is revitalizing its public outreach and science communication with support from the Geographic Information Systems and Publications Program. This and future issues of *California Geology* will be an avenue for all to learn how geoscience-focused professionals benefit both the state's and the public's needs.

The watershed branch's newest group, the **Burned Watershed Geohazards Program** (BWGP), was established in 2023 with the intent to help communities prepare for debris flows and flash floods before and after wildfire. In 2024, the BWGP performed eight watershed emergency response team assessments and seven post-fire reconnaissance surveys with CAL FIRE from Tehama to Riverside counties. In addition, the BWGP performed pre-fire modeling of postfire hazards as part of a pilot project to support fuel reduction and advanced mitigation planning by providing maps, data and analyses to two tribes, three county flood control agencies, two NGOs, and the U.S. Forest Service. This work is now expanded to a statewide model that will be published in a peer-reviewed journal in 2025.

The **Regional Geologic and Landslides Mapping Program** (RGLMP) completed three Preliminary Geologic Maps: the Columbia 7.5' Quadrangle in Calaveras and Tuolumne counties, the Liebre Mountain 7.5' Quadrangle in Los Angeles County, and a revision of the Black Mountain 7.5' Quadrangle in Los Angeles and Ventura counties. A preliminary 3D model for the southern San Joaquin Valley is nearing completion by the program's Geologic Carbon Sequestration Group, which will be released as a new Subsurface Geologic Model publication by the CGS. Soon the CGS will also complete the Sierra Nevada Earth



CGS technical branches and programs. For more information see: https://www.conservation.ca.gov/cgs/about

Science Atlas. This Atlas will cover the entire Sierra Nevada range at 1:400,000 scale, and will include geology, geophysics, neotectonic features, geochronology, metallogenic belts, and carbonate deposits. Landslide inventory mapping continued in Sonoma County with nine 24,000-scale quadrangles in progress or completed, with mapping also started in the Felton 7.5' quadrangle in Santa Cruz County.

The **Mineral Resources Program** completed the 2022 Nonfuel Mineral Production Report as CGS Bulletin 232, and conducted mineral identification, classification and mapping of potential critical mineral deposits. As part of the USGS Earth Mapping Resources Initiative (Earth MRI), the program completed Preliminary Geologic Maps of the Hedges, Ogilby, and Picacho Peak 7.5' Quadrangles in Imperial County. The program also published a data release for the Nickel-Cobalt Laterite Geochemical Reconnaissance Project in Del Norte County.

To support California's economy and watershed ecosystem health, the **Forest and Watershed Geology Program** conducted geologic hazards review in areas of proposed timber harvest including office reviews of 214 timber harvesting plans, 111 field reviews of timber harvesting plans, and 347 office reviews of documents for removal of burned and drought affected timber.

"To meet the state's evolving challenges, the CGS has brought in new experts and reorganized into two principal branches"

The **California Strong Motion Instrumentation Program** (CSMIP) operates the largest number of seismometers in the state, with about 10,000 sensors and more than 1,375 stations, including 124 sensors on San Francisco's Golden Gate Bridge. These sensors detect, record, and transmit earthquake shaking information to the CGS, with 270 stations supporting earthquake early warning. To better support earthquake response and recovery, the California legislature approved the upgrade of the CSMIP network to real-time reporting stations in 2022. Since August of 2022, the CSMIP has completed 390 of 823 station upgrades.

The **Seismic Hazards Program** received funding in 2022 to complete seismic hazard zonation efforts throughout the state. The program released 22 earthquake zones of required investigation maps in November, the highest production of maps in 30 years. In addition, the Essential Facilities Review unit completed geologic and seismologic reviews for 526 K-12 schools and 40 hospitals.

We hope that the new look of *California Geology* meets your approval and we look forward to working with you in 2025.

— *Jeremy Lancaster,*
Director and State Geologist

Sierra Nevada Earth Science Atlas

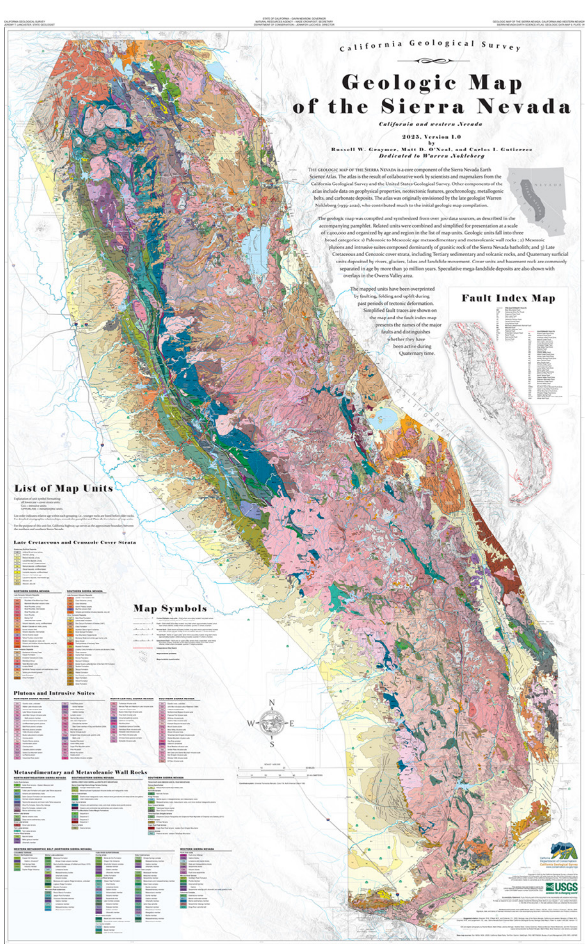
THE SIERRA NEVADA EARTH SCIENCE ATLAS (SNESA) is a collaborative project that showcases California's longest and tallest mountain range and its iconic geologic features. The project includes contributions from geoscientists of the U.S. Geological Survey and the California Geological Survey. The target audience includes researchers, applied geologists, geology students, geo-tourists, and the general public. The SNESA will include GIS data, map plates, and a pamphlet, all published by the CGS as Geologic Data Map 9.

This SNESA represents the most current, complete, and largest-scale, range-wide syntheses of geoscience data. All compilations are developed at a scale of 1:400,000 and can be grouped into five major components, summarized below.

Geologic map data were compiled and synthesized from numerous sources. Basement rocks are divided into tectonostratigraphic units, primarily terranes and plutonic complexes, many of which are subdivided into lithologic or tectonic sub-units. Younger overlapping strata are grouped into a series of sedimentary and volcanic rock and surficial units according to age, depositional environment, and (or) rock type. A separate polygon overlay depicts potential mega-landslides in the Owens Valley region.

New **gravity and aeromagnetic anomaly maps**, combined with a new compilation of rock density and magnetic susceptibility data, provide information on the depth extents of plutons and basins within and around the Sierra Nevada as well as fault continuity and cumulative offset.

A **geochronology database** was created to assist with mapping and interpretation, and to serve as a reference for others. We compiled dates from earlier published compilations and added more recent work, which helps illustrate the ages of the abundant Mesozoic intrusive rocks, the surrounding country rock, and overlapping strata.



Above: a preview of Plate 1A, Geologic Map of the Sierra Nevada. Plate size is 42 by 66 inches. The entire Atlas will be available on the CGS web site by late 2025.

Facing page: a portion of Plate 1A shown actual size.

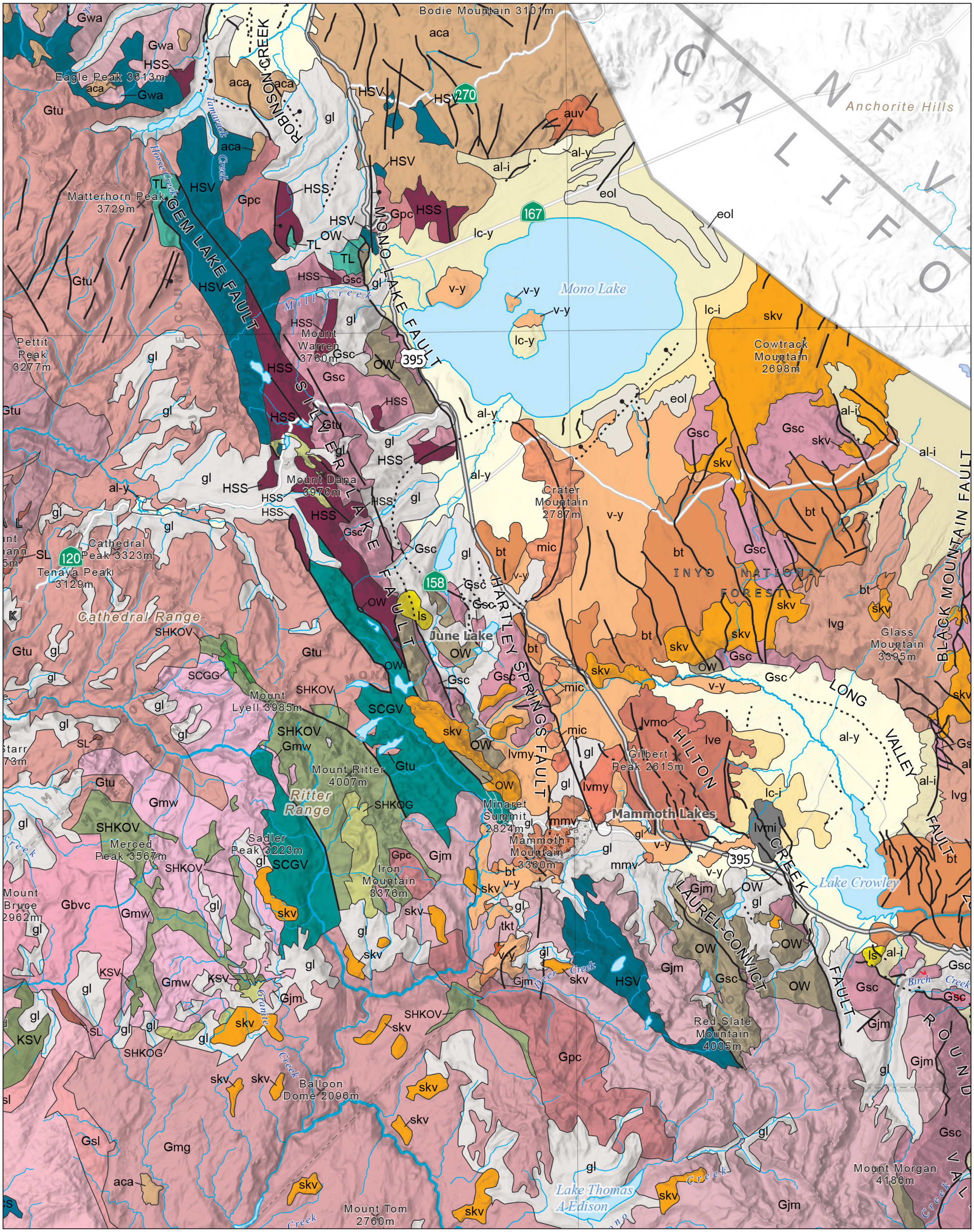
Economic geology data include metallogenic belts, carbonate deposits, and representative mines. Metallogenic belts depict areas that contain or are favorable for a group of coeval and genetically related, significant lode and/or placer deposits. The carbonate deposits database includes rock type, chemical composition, and other information.

Neotectonic features data include new map compilations of Quaternary active faults, historical earthquakes, recent volcanism, and geothermal features.

A sixth component, **Geosites**, will be released as a separate publication. Geosites are accessible sites the public can visit that illustrate and explain the broader scientific and cultural importance of geologic features representative of the Sierra Nevada.

We dedicate this work to the late Warren Nokleberg, who initiated this project and made substantial contributions before his untimely passing.

— Matt O'Neal, PG
CGS Geologic and Landslides Mapping Program



List of SNESA Contributors in alphabetical order (asterisks denote USGS staff; all others are CGS):
GEOLOGISTS – Mike Fuller, Russ Graymer*, Andrew Guglielmo, Carlos Gutierrez, Pete Holland, Erica Key, Vicki Langenheim*, Warren Nokleberg*, Matt O'Neal, Judy Zachariasen. GIS AND PUBLICATIONS – Jeremy Altringer, Rachel Beard, Heather Dean, MIlton Fonseca, Rebecca Marvail, Bob Moskovitz, Robert Wurgler

Mapping California's Mineral Hazards and Paleontological Resources on the State Highway System

by Chris Dennis, PG, CHG — *Caltrans*
and Brenda Callen, PG — *CGS Mineral Resources Program*

INTRODUCTION

WHETHER YOUR GOAL IS TO MINIMIZE EXPOSURE to mineral hazards or protect paleontological resources, geologic maps are essential to making informed decisions.

The California Geological Survey (CGS) collaborated with the California Department of Transportation (Caltrans) to conduct statewide mapping of mineral hazards and paleontological resources. The purpose of this work was to provide Caltrans with maps and data to support planning and decision making. This work required the development of new geologic mapping data for creating digital maps of paleontological resources and mineral hazards by geologic formation. The total area studied in this assessment was approximately 162,000 square miles.

Caltrans is involved in hundreds of construction projects statewide each year. These projects range from road surface rehabilitation to major highway and bridge construction and often include local city and county partners. Each project relies on the geologic maps and data.

Mineral hazards and paleontological resources along California's roadways could pose environmental or public health and safety concerns, project delays, or cost overruns. Proper handling and management of disturbed soil and rock containing mineral hazards or paleontological resources is also mandated under a variety of local, state, and federal environmental and safety laws and regulations.

"GIS screening tools enable Caltrans to quickly pinpoint issues for project design, highway maintenance, and emergency removal of geologic materials."

The ability to use digital maps and data to research and compile geologic information to determine potential mineral hazards and paleontological resources in a project area prior to construction has resulted in efficiencies that led to state cost savings of more than $200,000 annually.

MINERAL HAZARDS IN CALIFORNIA

What are mineral hazards and why does Caltrans care about them?

California is a geologically complex state with the potential for mineral hazards to occur statewide. It contains numerous types of rocks, which range from Quaternary (2.58 million years ago to present day) to Proterozoic (2.5 billion to 541 million years ago) in age (Walker and Geissman, 2022). Tectonically, it has been affected by many episodes of magmatism and metamorphism, with accompanying faulting and folding; these phenomena continue to the present. This diverse and active geologic history has resulted in a variety of potential mineral hazards throughout the state. More than 90 geologic units in the state have been identified as known or potential sources of mineral hazards.

Mineral hazards along California's roadways could pose environmental or public health and safety concerns during roadway construction and maintenance. Geographic information system (GIS) map screening tools enable Caltrans staff to quickly pinpoint issues for project design, routine highway maintenance, and emergency removal of geologic materials. With hundreds of Caltrans projects statewide each year, this results in substantial cost savings for the state.

Fibrous asbestos, Photo credit: Michael Fuller, California Geological Survey.

What are naturally occurring hazardous minerals and how do they form?

Mineral hazards are defined, in part, as minerals and elements that occur naturally in elevated, potentially harmful, concentrations in rocks, soils, and certain fluids. Mineral hazards are also features from human activities related to extraction of mineral and energy resources. Soils and rock containing mineral hazards may be harmful to the environment, the public, or construction and maintenance workers when disturbed by human activity and not handled and managed properly. Hazardous minerals and elements include, among others, naturally occurring asbestos, mercury, and arsenic.

Hazardous minerals form because of natural geologic processes such as volcanoes, geothermal springs, faults, and metamorphism. For example, the most common host rocks for asbestos mineralization are ultramafic rocks that are igneous rocks composed mainly of iron-magnesium silicate minerals, that were altered by metamorphism. Natural sources of mercury include volcanic activity and geothermal springs. Arsenic-bearing minerals may form in igneous intrusive or metamorphic rocks or in some volcanic and geothermal hot spring environments.

PALEONTOLOGY IN CALIFORNIA

What are paleontological resources and why does Caltrans care about them?

Paleontology is a natural science focused on the study of ancient life as it is preserved in the geologic record as fossils (exclusive of fossil humans). Paleontology is a sub-discipline of geology and is closely associated with evolutionary biology.

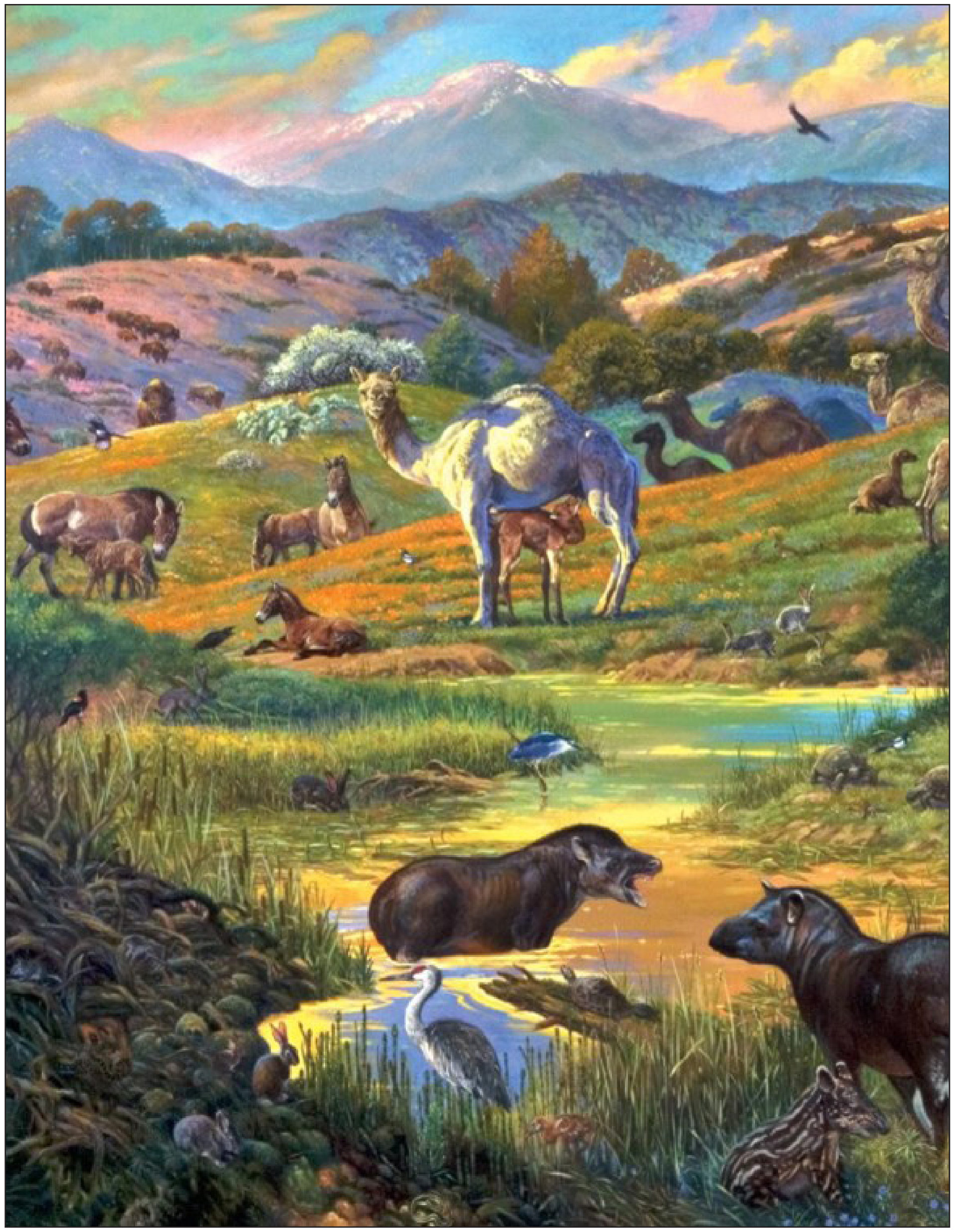
California is rich in fossil deposits that provide crucial information about the Earth's history, past climates, and ancient life forms. These fossils can offer insights into evolutionary processes, extinct species, and the environmental changes that have shaped the planet over millions of years. Fossils are non-renewable resources; once they are damaged or destroyed, they cannot be replaced. Proper protection ensures that these valuable scientific records remain intact for future research and education.

Paleontological resources include fossil remains or ichnofossils, of Pleistocene or older (>11.7 Ka) typically extinct organisms exclusive of human remains. This includes the localities where fossils originated and the rock formations in which they were preserved. When taken together, they provide evidence of past life and behavior and the environmental conditions at the time of preservation. The defining character of fossils or fossil deposits are generally regarded as older than 11,700 years, the generally accepted temporal boundary marking the end of the last Late Pleistocene glacial event and the beginning of the current period of the Holocene (~11.7 Ka years ago). Paleontological resources have educational, cultural, and scientific value and may be legally protected.

Particularly important are fossils found in situ (undisturbed) that have not been subjected to disturbance after their burial and fossilization. As such, they aid in stratigraphic correlation, particularly those offering data for the interpretation of tectonic events, geomorphological evolution, paleoclimatology, the relationships between aquatic and terrestrial species, and evolution in general.

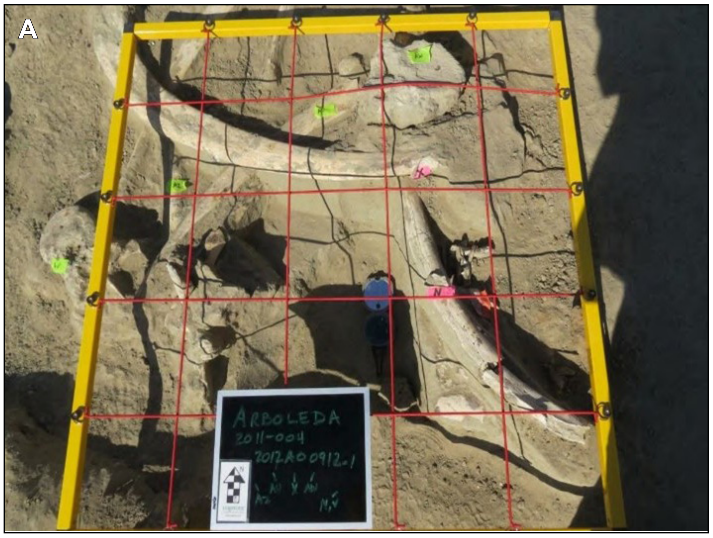
An example is the discovery of fossilized Columbian mammoth (Mammuthus columbi) bones from the Pleistocene epoch (2.58 million to 11,700 years ago) that were uncovered by Caltrans during construction work on State Route 99 (SR-99) in Merced County. The mammoth bones, including a juvenile mammoth skull and the skull, femur, and tusk of a mammoth estimated to be 49 years old at the time of death, were donated by Caltrans to the University of Merced. The mammoth bones are on permanent display on the second floor of the University library. Additionally, silhouettes of mammoths walking on the SR-99 overpasses for the 176 exit (Plainsburg Road) and 179 exit (Le Grand Road) were installed for public education and art near where the mammoth was discovered in Merced County.

Terrestrial vertebrate fossils (i.e., mammoths) are often assigned greater significance than other fossils because they are rarer than other types of fossils. This is primarily because the best conditions for fossil preservation include little or no disturbance after death and quick burial in oxygen depleted, fine-grained, sediments. These conditions are relatively rare in terrestrial settings (e.g., because of pyroclastic flows and flashflood events). This has ramifications on the amount of scientific study needed to adequately characterize an individual species and therefore affects how relative sensitivities are assigned to formations and rock units.



Camels, tapirs, horses, and early llamas roamed southern California 20,000 years ago. None of those species—not even the horses—survived there after the end of the Ice Age. Mural painted by William Stout for the permanent exhibition Fossil Mysteries at the San Diego Natural History Museum. Photo by Barret Oliver, Courtesy of the San Diego Natural History Museum.

The Society of Vertebrate Paleontology (SVP, 2010) defines scientifically significant paleontological resources as "fossils and fossiliferous deposits, here defined as consisting of identifiable vertebrate fossils, large or small, uncommon invertebrate, plant, and trace fossils, and other data that provide taphonomic, taxonomic, phylogenetic, paleoecologic, stratigraphic, and/or biochronologic information."



A. Columbian mammoth (Mammuthus columbi) field documentation, Highway 99, Madera County.

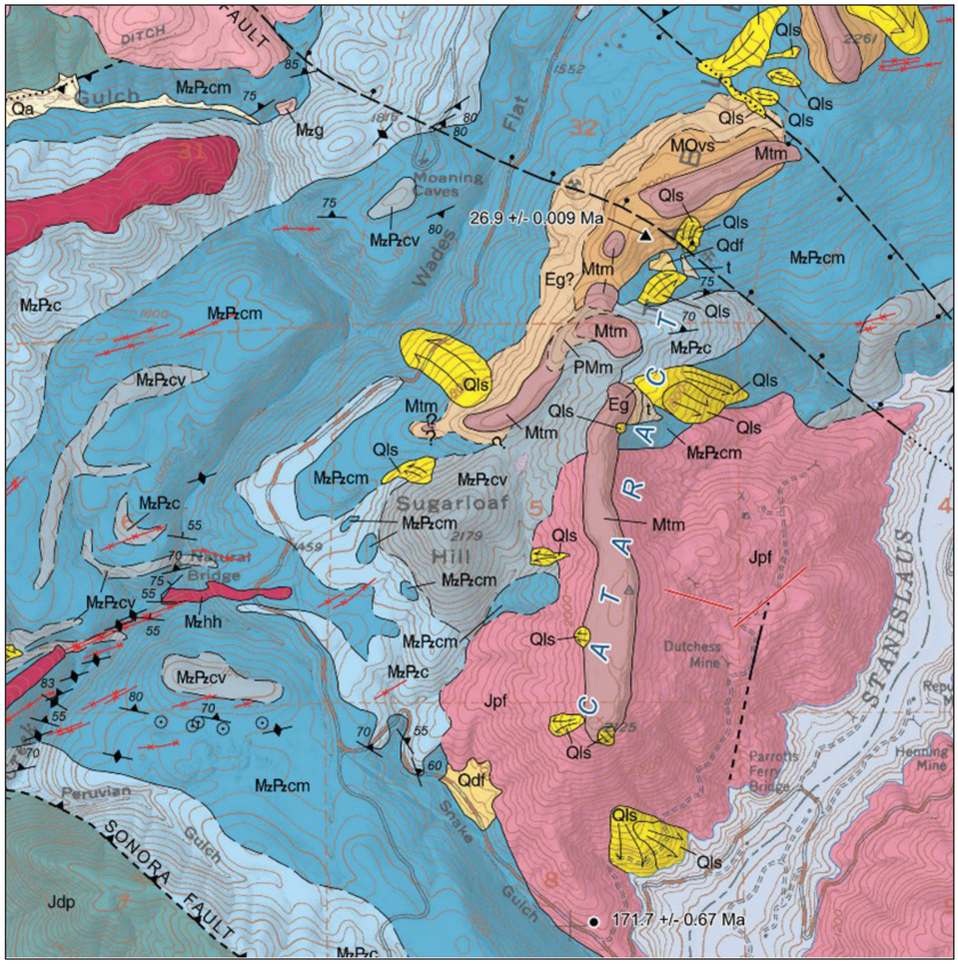
B. Caltrans construction activity in Pleistocene deposits, Madera County. White streaks seen during grading are often fossilized bones being pulverized.

C. Columbian mammoth fossils being exposed for plaster jacketing.

D. Columbian mammoth fossils jacketed and ready for transport to curation.

E. Part of the Columbian mammoth exhibit at the University of Merced library. Caltrans Photos

California's geologic record is diverse with vertebrate, invertebrate, plant, and trace fossils found throughout the state, primarily in sedimentary rocks and in some metasedimentary rocks and volcanic ash deposits. These non-renewable resources are essential to helping us understand current and past aspects of our world, such as the radiation, diversification and extinction of life, regional and local environments, climate and sea level change, plate tectonics, animal behavior and adaptation, soil characteristics, and mineral resources.



Portion of a CGS geologic map used by Caltrans (example from the Columbia 7.5-minute Quadrangle, available at https://www.conservation.ca.gov/cgs/rgm/preliminary)

Significance may also be stated for a particular rock unit, predicated on research of potential fossils suspected to occur in that unit. Such significance is often stated as "sensitivity" or "potential." In most cases, decisions about how to manage paleontological resources must be based on this potential because the actual situation cannot be known until construction excavation for a project is underway. Caltrans uses the following three-part scale (Caltrans, 2025).

- High Potential - Rock units likely to contain significant vertebrate, invertebrate, or plant fossils, including sedimentary formations known for significant paleontological resources or lithologically suitable for the preservation of fossils.
- Low Potential - Sedimentary rock units with some chance for containing fossils, generally not needing monitoring unless significant paleontological resources are found, in which case a qualified paleontologist must assess their significance.
- No Potential - Intrusive igneous rocks, most extrusive igneous rocks, and moderately to highly metamorphosed rocks, which are unlikely to contain significant paleontological resources.

APPROACH AND METHODS

Why are mapping projects undertaken and what is their scope?

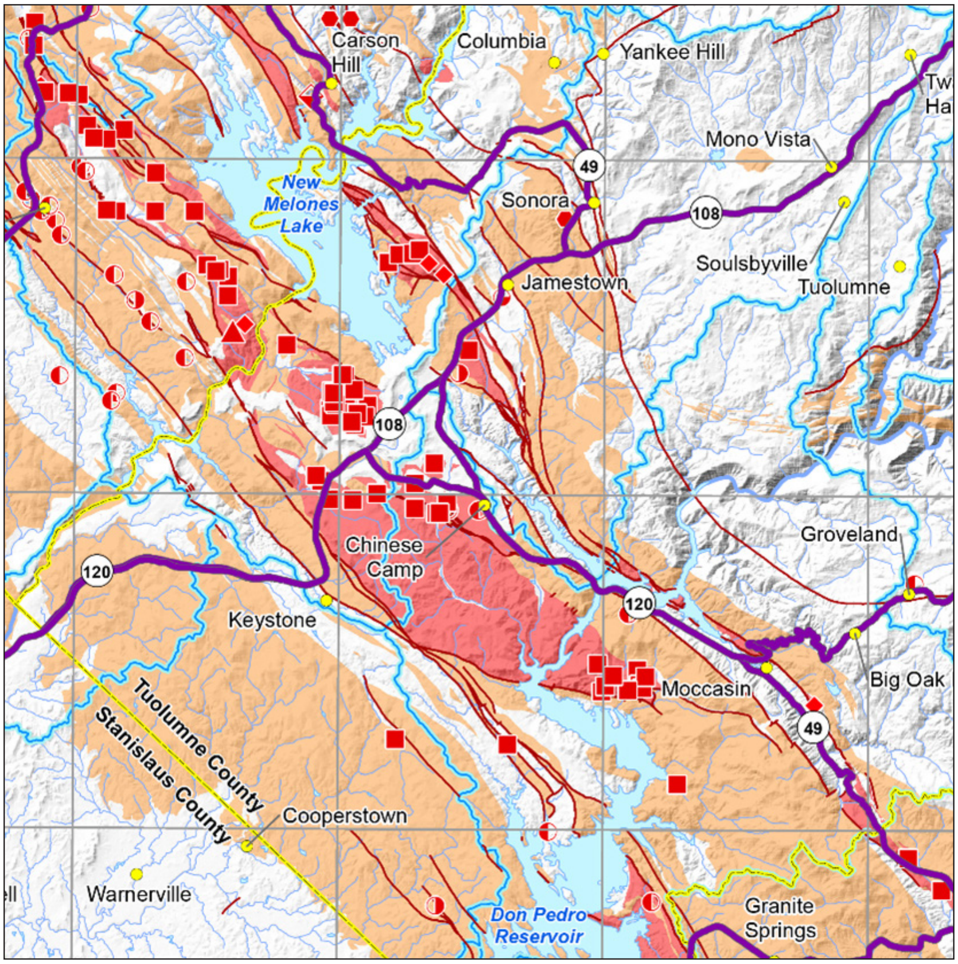
The purpose of the mineral hazards assessment and paleontological resource mapping was to assist Caltrans staff in their determination of where mineral hazards and paleontological resources may be present in each of the Caltrans 12 geographic districts; the intended audience includes engineers, geologists, planners, construction and maintenance crews, and managers, among others.

Correlating geologic formations with hazardous minerals and paleontological resources, and stitching together geologic maps from various researchers, was an immense undertaking by professional geologists, paleontologists, and university students. At times, staff conducting field investigations were required to resolve conflicts between maps.

The data and information generated during the project are used by Caltrans staff as a screening tool to improve planning of activities that involve new road projects, routine maintenance of roadways, and emergency removal of debris deposited on roads by natural processes.

Mapping of mineral hazards

The main approach of the assessment was to develop baseline information concerning the potential for mineral hazards statewide, which might adversely affect construction,



Representative mineral hazards map. Example from Caltrans District 10.

use, and maintenance of state and federal highways under Caltrans jurisdiction. The work focused on natural and man-made minerals-related features.

Geologic features investigated included geologic units (bedrock and some minor areas of unconsolidated sediments), faults, areas of highly mineralized rock, oil and natural-gas seeps, and thermal springs and fumaroles.

Geologic features investigated included: 1) geologic units that may contain naturally-occurring asbestos or elevated concentrations of regulated metals (Ag, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Tl, V, Zn) and metalloids (As, Sb, Se); 2) faults, which can serve as conduits for the movement of hazardous element-bearing fluids; and 3) areas of highly mineralized rock.

The features from human activities are related to extraction of mineral and energy resources. Specifically, these include: 1) mines and prospects, which can be sources of anomalous concentrations of metals and ore-processing chemicals; 2) oil and natural-gas seeps; 3) thermal springs and fumaroles; and 4) oil, natural-gas, and geothermal wells.

The CGS conducted fieldwork in each of the 12 Caltrans districts to directly observe and verify geologic features that were previously documented on geologic maps by other geologists. To a much lesser extent, observation and verification included mining areas, petroleum features, and geothermal features. Finally, fieldwork included observation and documentation of new localities of mineral hazards of potential interest to Caltrans. Most of the state and federal highways were driven in reconnaissance during this project. Most field observations were made along highway corridors.

What types of products did the CGS create for Caltrans?

An array of paper and digital products were prepared to accommodate the needs and background of Caltrans staff concerning mineral hazards in California that might affect Caltrans activities. These include:

› District Reports – individual reports for each of the 12 Caltrans districts. These included detailed information on the types of mineral hazards investigated, their characteristics and distribution in each district.

› District Maps – sets of 1:250,000-scale (one-inch equals approximately four miles) maps that display for each district the geologic features and features related to human activities described above.

› Geochemical Summaries – compiled tabular summaries and

DID YOU KNOW?

Medical geology is an earth science specialty that concerns how geologic materials and earth processes affect human health. Geologic materials such as rocks, soils, dusts, and volcanic emissions can contain naturally elevated levels of elements, minerals, other compounds, or microbes that harm or benefit human health. They can also contain human-related chemical, mineral, or pathogen contaminants. Medical geologists work with earth, biological, physical, and health scientists to help improve public health.

prepared maps of geochemical data from several sources.

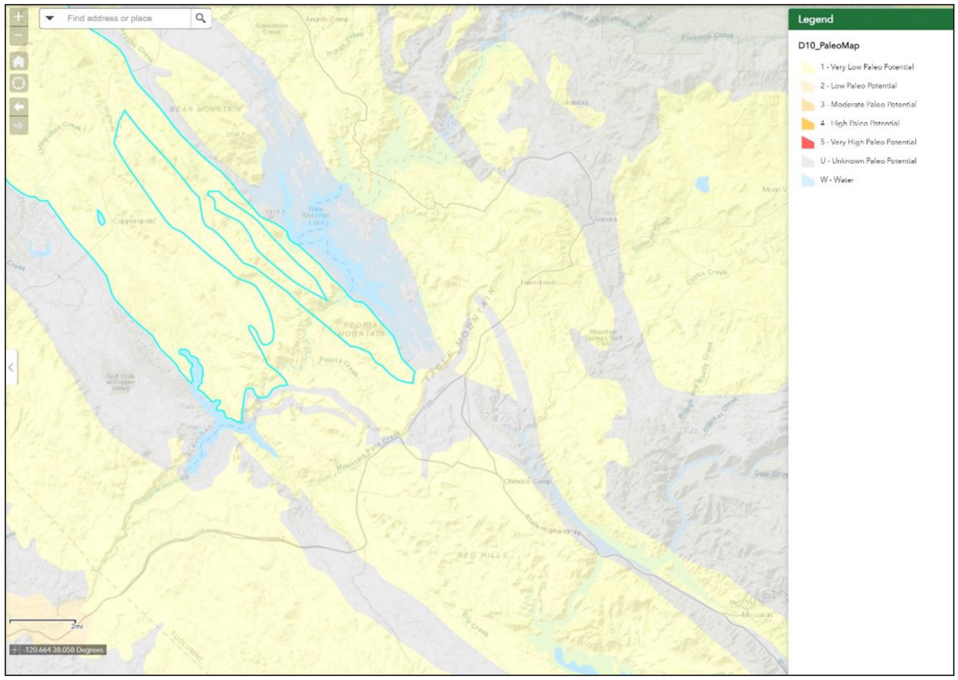
- GIS Products – many “feature classes” (digital thematic map layers) were developed during this project. The final phase of the project was integration of these into a statewide master geodatabase.

Mapping of paleontological resources

The paleontological GIS mapping utilized a group of university geology student interns with oversight by Caltrans geologists/paleontologists. The paleontological GIS mapping was beneficial for both the students and Caltrans. The students were able to work on an important project from start to finish, something they could add to their resume, and Caltrans ended up with a useful, cost-saving tool. Also, CGS geologists provided digitized geologic maps, digital mapping of formations involved in landslides, and interpretation of geologic formations.

How are paleontological resource maps and mineral hazard maps derived from geologic maps?

Geologic maps show the distribution of various geologic formations. Based on these maps and information on previously recorded fossil finds, geologic formations can be characterized as High Potential, Low Potential, or No Potential for paleontological resources. Because paleontological resources usually are irregularly dispersed throughout a geologic formation, both vertically as well as laterally, the location of fossils within a particular formation cannot be pre-determined. Comparing a Caltrans project site to a resource map showing the potential of formations to produce fossils is the first step in assessing the potential for paleontological resources to be present on a project site. More precise determinations of the potential presence of paleontological resources can be made by studying more detailed geologic maps and conducting onsite field surveys.



Representative paleontological resource map showing areas of low paleontological potential. Areas of high potential, if shown, would appear bright red or orange. Example from Caltrans District 10.

> **“California’s geologic record is diverse with vertebrate, invertebrate, plant, and trace fossils . . .”**

Occurrences of paleontological resources are known to be correlated with mapped geologic units (i.e., formations). The paleontological sensitivity or potential is a GIS layer created from geologic maps and assigns a rating to each geological unit, representing the potential abundance and significance of paleontological resources that occur in that geological unit. The rating is considered a first approximation of the potential presence of paleontological resources, subject to change based on ground verification.

The geologic units are assigned a class based on the relative abundance of significant paleontological resources and their sensitivity to adverse impacts. This classification is applied to the geologic formation, member, or other mapped unit. The classification is not intended to be applied to specific paleontological localities or small areas within units. The overall abundance of scientifically important localities is intended to be the major determinant for the assigned classification.

To complete resource identification efforts, the Caltrans project environmental staff need mapping of sufficient detail to correlate the potential project footprint with detailed geologic maps and paleontological databases. The required level of detail available may vary from project to project and will be determined by the complexity of the project and the complexity of the geology of the project area. Caltrans staff review the paleontological GIS layers to determine if there are known or reasonably anticipated paleontological resources within the project area. If so, it must be further determined if project excavation may impact the resource.

The CGS conducted fieldwork in each of the 12 Caltrans districts to directly observe and verify mapped geologic features or add refinements to the maps. The focus was on natural bedrock units as potential sources of geologic hazards. The fieldwork included observation and documentation of new localities of mineral hazards of potential interest to Caltrans.

As part of the district studies, the CGS developed a geologic map of each district at 1:750,000-scale (one-inch equals approximately twelve miles), using the Geologic Map of California as the base. Additionally, the CGS developed mineral hazard maps at 1:250,000-scale that display for each district the natural geologic features and features related to human activities.

CONCLUSION

Before Caltrans can do any soil disturbing work, potential mineral hazards and paleontological resources must be evaluated along with several other evaluations that include biological and cultural resources. These evaluations not only protect the resource through possible avoidance, but also provide for worker safety, proper soil and rock handling, management and disposal, and proper monitoring for and salvage of paleontological resources. Researching and mapping of mineral hazards and paleontological resources can be a labor and time-consuming process, even with the voluminous datasets and reports available on the internet.

Caltrans defines efficiencies as steps that may result in cost avoidance or a reduction in support or capital costs. Past practice involved review of multiple databases and site-specific history to determine if a particular project would require additional study. Now, using the GIS tool, these evaluations can be performed efficiently with geological maps and source references that can be added to evaluation memorandums and reports. Additionally, labor spent in the field verifying potential concerns can now be focused or eliminated altogether.

“. . . the improved process has resulted in efficiencies that led to state cost savings of more than $200,000 annually.”

The GIS tool provides substantial time savings for this effort. It does this by allowing the analyst to perform a comprehensive survey of the potential of paleontological resources and mineral hazards from a single GIS database, as opposed to checking multiple sources of information. Cost savings are also realized by using the internal Caltrans GIS tool rather than contracting with external consultants. Cost savings are calculated as a measure of staff hours saved per environmental document review. Using the improved process has resulted in efficiencies that led to state cost savings of more than $200,000 annually.

The value of these evaluations cannot be overstated for the protection provided from mineral hazards to the public and for worker safety; proper soil and rock handling and management; and for the preservation of non-renewable paleontological resources that provide valuable insight to our current and past world conditions and ecological processes.

The CGS has conducted studies and produced mineral hazard maps and reports at statewide and regional scales. These maps and reports are intended to educate about mineral hazards and to help in mitigation of those hazards.

For information about mineral hazards and to request published mineral hazards reports visit the CGS Mineral Resources website at: https://www.conservation.ca.gov/cgs/minerals/mineral-hazards

ACKNOWLEDGMENTS

We would like to thank Jim Allen (Caltrans), and Michael Fuller and Fred Gius (both CGS) for their critical reviews of this article.

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Mineral Production and Exploration in California

by Fred Gius, PG, CEG, and Greg Marquis, PG — *CGS Mineral Resources Program*

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 2022, there were 634 active mines producing 34 commodities in California.

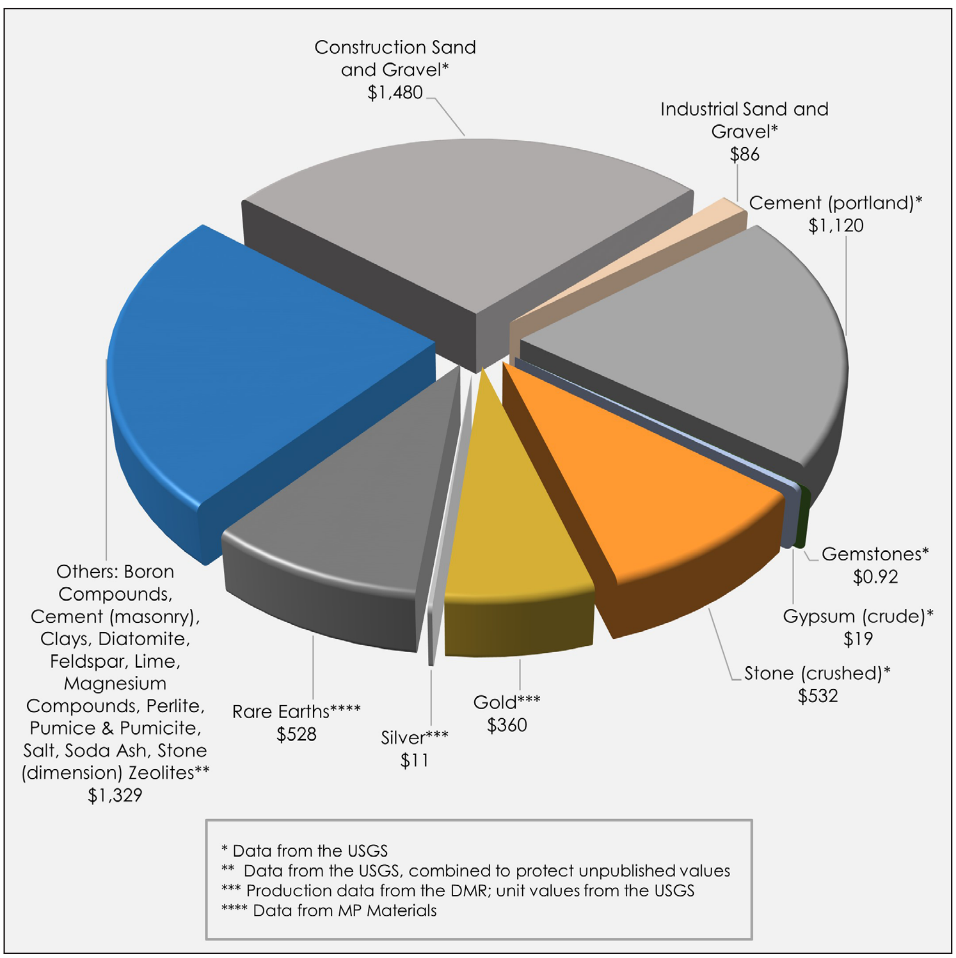
PRODUCTION

Using a combination of data from the California Division of Mine Reclamation, USGS, and MP Materials Corporation, the total estimated California non-fuel mineral production value was $5.5 billion in 2022.

Based on preliminary USGS data, California ranked fourth—behind Arizona, Nevada, and Texas—in non-fuel mineral production value, accounting for approximately 5.71 percent of the nation's total (USGS, 2023).

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

Above: California's national standing as a producer of selected non-fuel mineral commodities (Source: USGS, 2023, where production was ranked by state and California was mentioned in the commodity summary).



Left: Value (millions of dollars) of California's non-fuel mineral production in 2022. Data are available in CGS Bulletin 232. Some commodities are presented as a group to protect unpublished USGS data, as required.

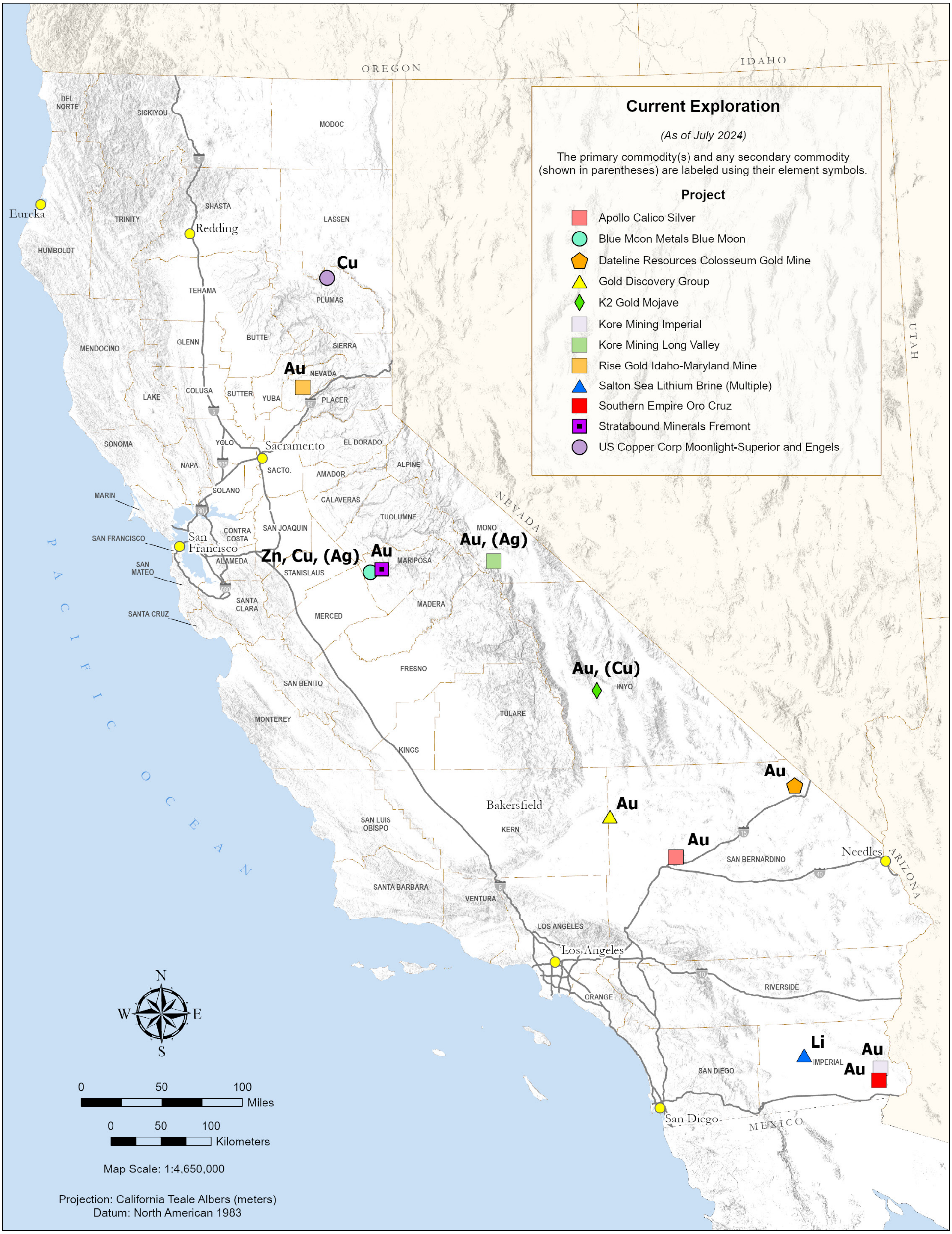
EXPLORATION

Historically, exploration has been dependent on national needs. In the 1800s, it was gold and mercury. In the 1910s and again in the 1940s it was iron and limestone for wartime steel. And in the 1970s, it was aggregate for the construction boom. Today, as the state focuses on decarbonization, mineral exploration is shifting towards resources critical for renewable energy and technology.

Currently, there are mineral exploration projects underway in California for base metals (including copper and zinc), gold and silver, and lithium. As California continues to expand its role as a leader in non-fuel mineral production, the state faces both opportunities and challenges. From advancing technological innovation in lithium extraction to balancing sustainability with economic growth, California's mining future is poised to play a critical role in shaping the nation and the world's green energy transition.

More detailed information about mineral production and exploration can be found in our annual mineral production bulletins (https://www.conservation.ca.gov/cgs/minerals/mineral-production).

Facing page: Locations of current exploration projects in California.



Information for this article comes from Bulletin 232 (Marquis, G. D., 2024, California Non-Fuel Mineral Production 2022: California Geological Survey Bulletin 232, 34 p.)

The CGS Library, Past and Present

by Amy Loseth, MLIS — *CGS Librarian*

A BRIEF HISTORY

The California Geological Survey Library was formed in 1880 by legislative mandate with the mission of developing and maintaining a collection of geoscience resources, available to staff and the public alike for research and reference.

One of its first and notable locations was in San Francisco's Ferry Building, where it lived from 1899 to 1984. The library was housed there alongside staff offices, a Geochemistry Laboratory, and a Mineral Museum that boasted a collection of more than 15,000 minerals sourced from all 58 counties of California, displayed in 50 large cases. At its height in this famed location, the museum and library reached over 10,000 visitors annually.

In 1984, due to proposed renovations of the Ferry Building, the library's collection was moved, split between offices in Pleasant Hill and Sacramento, and the expansive mineral collection was relocated to the California State Mining and Mineral Museum near the town of Mariposa in the Sierra foothills, where it remains today.

After seven years in Pleasant Hill, survey offices and the library moved back, in part, to San Francisco, in order to better meet industry and research access needs, but in 1992, when survey offices relocated within San Francisco again, the library found a home with the Survey's Headquarters offices in the Renaissance Tower in downtown Sacramento, where it has lived now for 33 years.

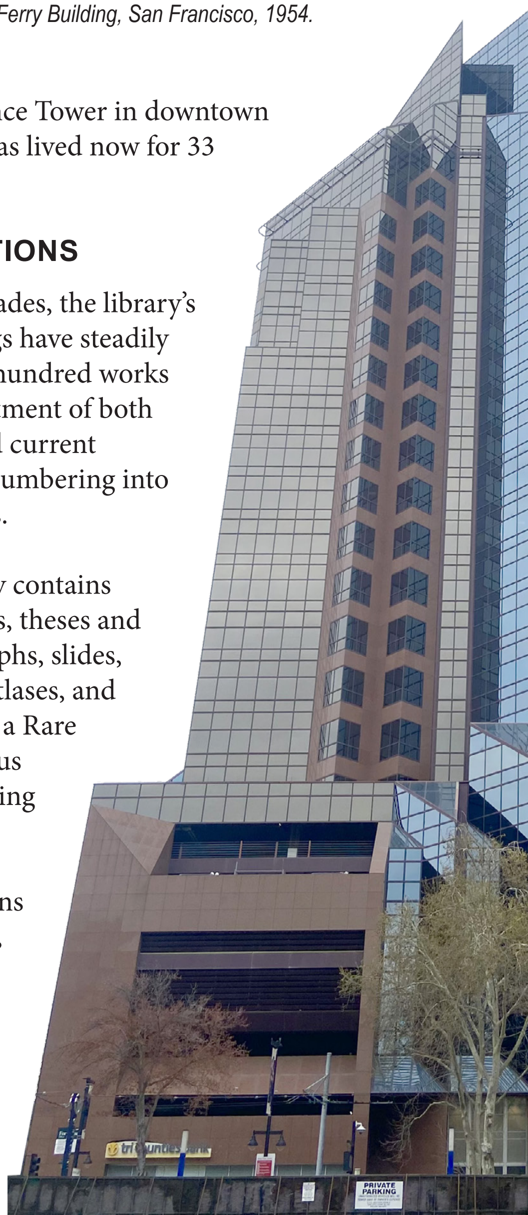
Main room of the library in the Ferry Building, San Francisco, 1954. Photo by M. R. Hill.

Mineral Museum display cases in the Ferry Building, San Francisco, 1956. Photo by M. R. Hill.

COLLECTIONS

Throughout the decades, the library's collections and holdings have steadily grown from just a few hundred works into an extensive assortment of both historical materials and current geoscience resources, numbering into well over 100,000 items.

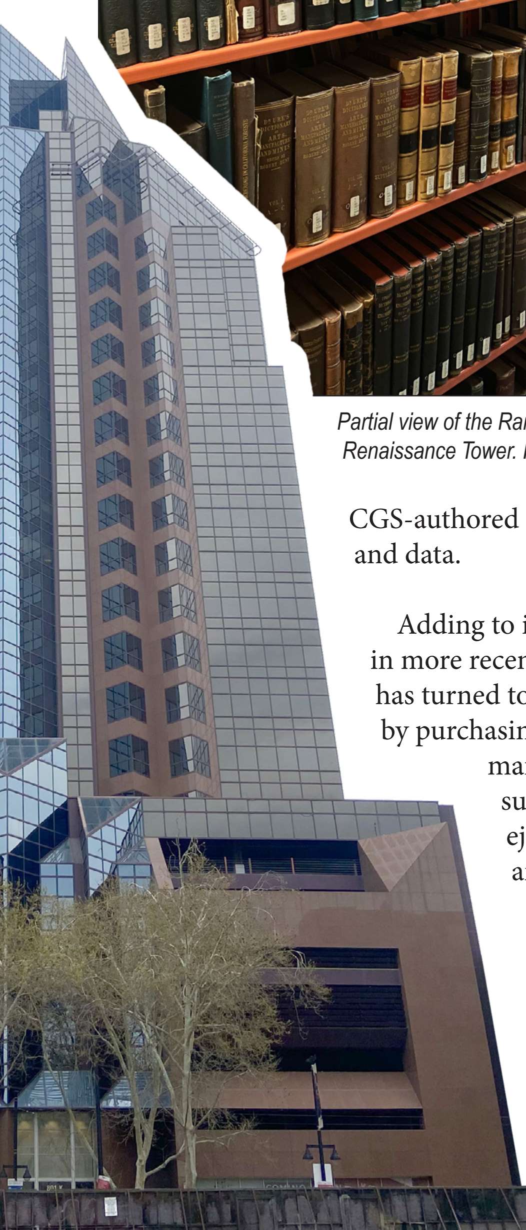
The library currently contains books, journals, reports, theses and dissertations, photographs, slides, aerial imagery, maps, atlases, and folios, and it maintains a Rare Book Room with various books and volumes dating back several centuries. The library holds a multitude of publications produced by the USGS, and it serves as a repository for its own



Partial view of the Rare Book Room shelves in the Renaissance Tower. Photo by A. Loseth.

CGS-authored publications, maps, and data.

Adding to its print collections, in more recent years, the library has turned to electronic resources by purchasing ebooks and by maintaining online subscriptions to scholarly ejournals, when available and affordable.



The Renaissance Tower in downtown Sacramento. Photo by A. Loseth.

Samples of historical photos and mine maps from the CGS Library collection. Photo by A. Loseth.

ONGOING PROJECTS

Currently, the CGS Library continues to work to digitize parts of its collection to increase research access to historical content. For several years now, library staff and students have been scanning the image collection, which largely depicts various aspects of the mining industry from the late 19th century and on. This collection is estimated to contain at least 10,000 photos, slides, and negatives, with over 6,500 of these captured as of today. Staff has also worked to scan and preserve the historic mine map collection, with just under 1,000 of these maps now digitized.

When ready, these collections will be uploaded to the library's online catalog, where all interested in the mining history of California can easily access them.

More information about the CGS Library and a link to the online catalog can be found at https://www.conservation.ca.gov/cgs/library.

Supporting information for this article was found in Bedrossian, T., 2019, The California Geological Survey: A History of California's State Geological Surveys 1850-2015*: California Geological Survey Special Publication 126, 504 p.*

California's Statewide Airborne Electromagnetic Surveys and Preliminary Hydrogeologic Interpretations

by Katherine Dlubac, Ph.D., PG, Steven Springhorn, PG, Benjamin Brezing, PE, Craig Altare, PG, and Timothy Godwin, PG, CHG
California Department of Water Resources, Sustainable Groundwater Management Office

INTRODUCTION

GROUNDWATER IS A VITAL PART OF California's water portfolio. It provides more than 40 percent of the state's total water supply during average years and nearly 60 percent in dry years when surface water is less available. Groundwater refers to water stored below the Earth's surface in aquifers, which include porous layers of soil, gravel, sand, and clay that hold water. Stacked layers of aquifers make up a groundwater basin. California's 515 groundwater basins serve as vital natural infrastructure, capable of storing and conveying significantly more water than all the state's surface reservoirs combined. These basins exhibit highly complex and diverse hydrogeologic characteristics, shaped by a range of depositional environments, structural histories, and water quality conditions, as well as intricate interactions between surface water and groundwater. As the state continues to adapt to climate change, the role of these groundwater basins will become increasingly important for ensuring water availability and resilience.

For decades, groundwater in some parts of the state has been pumped out faster than can be recharged, causing record low groundwater levels in those areas. Effective statewide groundwater management is vital to ensuring that the state's future water supply is reliable and resilient. The historic passage of California's Sustainable Groundwater Management Act (SGMA) in 2014 set forth a statewide framework to help protect groundwater resources over the long-term (Part 2.74 of Division 6 of the California Water Code). For California's high- and medium-priority groundwater basins, which are defined based on the basin's groundwater use and effects, SGMA required local agencies to form groundwater sustainability agencies (GSAs) and then develop and implement groundwater sustainability plans (GSPs) to avoid undesirable results and mitigate overdraft by the early 2040's. SGMA defines six undesirable results as: declines in groundwater levels, reductions in groundwater storage, intrusion of seawater, degradation of water quality, subsidence of land, and depletions of interconnected surface waters. The passing of SGMA has resulted in a need to better understand and characterize California's groundwater basin's complex hydrogeologic structure to support informed groundwater management decisions and avoid undesirable results.

"The [AEM] method provides information about groundwater aquifer system structure"

The California Department of Water Resources (DWR) has a long history of characterizing the state's groundwater basins as a part of *California's Groundwater* (Bulletin 118) (DWR, 2024c; California Water Code Section 12924) and through ongoing Basin Characterization Program efforts (DWR, 2024b). In 2021, DWR's Basin Characterization data collection effort expanded to include the collection of advanced geophysical data through the launch of the Statewide Airborne Electromagnetic (AEM) Survey Project (DWR, 2024e). The goal of the Project was to improve the understanding of large-scale aquifer structures across the state's groundwater basins to support the implementation of SGMA.

The Statewide AEM Survey Project data collection effort was completed in 2023, in two and a half years. The project generated 16,000 miles of AEM data collected across 95 groundwater basins. To support data accessibility, all Project data are published in a timely manner and DWR developed novel data visualization tools to allow the public to view the data online, without the use of costly software. In this paper, we examine the Statewide AEM Survey data and provide preliminary hydrogeologic interpretations for various SGMA and groundwater-related applications.

CALIFORNIA'S STATEWIDE AEM SURVEY PROJECT

The AEM method is a non-invasive, airborne geophysical technique that allows for information about the subsurface to be acquired quickly over large areas. The method provides information about groundwater aquifer system structure, including the depth and thickness of aquifer layers, aquitard layers, paleovalleys, and high salinity waters (Kirkegaard et al., 2011; Christensen et al., 2017; Gottschalk et al., 2020; Minsley et al., 2021; Kang et al., 2022; Knight et al., 2022). The AEM method has been used to support groundwater management efforts domestically in California (Knight et al., 2018), Wisconsin (Wisconsin Department of Agriculture, Trade and Consumer Protection, 2024), North Dakota (North Dakota Department of Water Resources, 2024), Nebraska (Abraham et al., 2011), Mississippi Alluvial Plains (Minsley et al., 2021), and internationally in Ireland (Geological Survey Ireland, 2024), Australia (Geoscience Australia, 2024), and Denmark (Geological Survey of Denmark and Greenland, 2024).

In 2018, California Proposition 68 was passed, which provided DWR with funding to launch the Statewide AEM Survey Project to support the implementation of SGMA (DWR, 2020). From 2018 through 2020, a set of pilot studies were conducted, led by Stanford University, to help determine the optimal workflow of AEM data collection and processing to inform the development of the Statewide AEM Survey Project (California Natural Resources Agency (CNRA), 2023).

The goal of DWR's Statewide AEM Surveys is to improve the understanding of regional groundwater systems, a critical component of California's natural infrastructure. As a part of the Project, DWR aimed to collect data in all high- and medium-priority groundwater basins, where data collection was feasible. AEM data were collected in a reconnaissance grid with a line spacing of approximately 2 by 8 miles (3 by 13 kilometers) (Figure 1). The grid was developed to allow the maximum amount of data to be collected within the defined groundwater basins while capturing the geologic heterogeneity unique to California. Additionally, DWR coordinated closely with GSAs, state, and federal agencies to plan flight lines over areas of interest.

Prior to the start of the surveys, DWR undertook a robust outreach effort to ensure the public were aware of the surveys. This included meetings with GSAs, sending notification letters to parcel owners, social media announcements, and media advisories.

Figure 1. a) Statewide AEM survey flight lines across California's high- and medium-priority groundwater basins. b) Hydrologic regions of California.

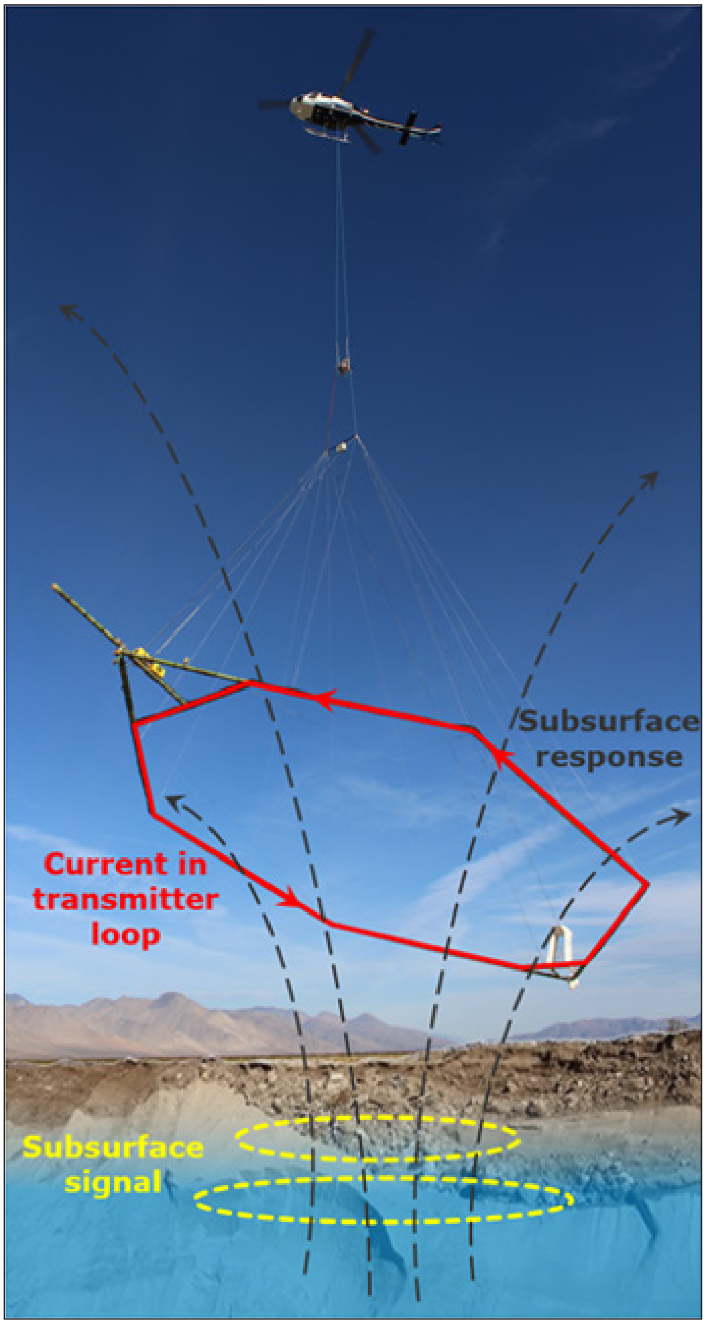


Figure 2. Schematic of the SkyTEM AEM system suspended under a helicopter.

DWR also kept the public aware of the survey schedule through an online schedule viewer (DWR, 2024a).

AEM Data Collection and Inversion

The Statewide AEM Surveys were conducted during the spring and the fall seasons of 2021 through 2023. Surveys were conducted across groups of groundwater basins that were geographically close to each other, termed Survey Areas. In total, the Statewide AEM Survey Project consisted of ten Survey Areas.

AEM data were collected using the SkyTEM 312 and SkyTEM 304 systems, depending on the groundwater basin geology and surveying goals. During the AEM surveys, a helicopter flew at a groundspeed of 50 to 60 miles per hour (80 to 100 kilometers per hour) carrying the equipment approximately 100 feet (30 meters) above the ground.

AEM data collection consists of a large loop, approximately 100 feet (30 meters) in diameter, containing geophysical equipment, mounted on a platform (Figure 2). During an AEM measurement, an electric current is generated in the transmitter loop. The current is abruptly turned off to induce electric currents (called eddy currents) in the subsurface, which in return generates a secondary electromagnetic field. The earth response is measured in a receiver coil mounted on the frame as a timeseries of induced voltages, which are referred to as the "raw" AEM data.

The raw AEM data are processed to remove electromagnetic noise and anomalies caused by metallic infrastructure, such as railroads, powerlines, cables, vineyards, and pipes. Once the data are processed, the data are inverted for a distribution of electrical resistivity values versus depth (Figure 3a). Electrical resistivity is a property that describes the ability of a material to resist an electric current. The data processing and inversion typically takes multiple iterations and quality control may be necessary before the inversion results are considered final (Viezzoli et al., 2008; Auken et al., 2009). In the Statewide AEM Surveys, data were processed and inverted using the Aarhus Workbench software package with a spatially constrained inversion. Results of the processing and inversion produced a few-layer, smooth, and sharp model showing the distribution of electrical resistivity values versus depth (Behroozmand et al., 2022).

The AEM method can measure electromagnetic properties to depths of up to about 1,000 feet (300 meters). The maximum depth that the data are considered reliable is called the depth of investigation (DOI). The DOI is dependent upon the subsurface's electromagnetic properties; typically, areas with thick very low electrical resistivity layers have a shallow DOI and areas with thick electrically resistive layers have a deeper DOI. The vertical resolution of the AEM method decreases with depth, with data generally having a resolution of about 7 feet (2 meters) in the shallow subsurface and increasing to about 100 feet (30 meters) at depth.

AEM Data Interpretation

Collection of electromagnetic data can support mapping subsurface geology and aquifer properties because a relationship exists between electrical resistivity and geologic properties (Palacky, 1987) (Figure 3c). Typically, materials that have low electrical resistivity values are interpreted for fine-grained materials, like silts and clays, or can be interpreted for high salinity waters. Materials that have high electrical resistivity values are interpreted as coarse-grained materials, like sands and gravels, or crystalline or volcanic rock. However, because there are a wide range of electrical resistivity values corresponding to a given material type, it is important to develop site-specific relationships between electrical resistivity values and lithology when interpreting AEM data.

In the Statewide AEM Surveys, electrical resistivity data were interpreted for percent coarse-grained material (also referred to as material texture) (Figure 3b). The interpretation was achieved using a modified Accumulated Clay Thickness approach (Christiansen et al., 2014; Foged, et al. 2014) where a transform was created utilizing supporting datasets, including lithology logs, electrical resistivity logs, water quality, water levels, and local geology (Behroozmand, et al., 2022). To support this process, two lithology logs and e-logs per Public Land Survey System square mile section along a survey flight line were compiled, quality controlled (for location accuracy and lithology description) and digitized. Water quality and water level data were utilized in the interpretation only when the density and quality of data were appropriate.

Interpreting AEM data for percent coarse-grained material provides information that is useful for both the development of a texture model, used in groundwater flow modeling, and hydrostratigraphic interpretations. The percent coarse-grained material ranges from 0 to 100 percent (color scale warming from blues to reds) (Figure 3b), where the percent coarse values can be loosely interpreted for the geologic material types below:

- 0 to 20 percent: clay and silt;
- 20 to 50 percent: fine sand; and
- 50 to 100 percent: sand, gravel, and cobble.

Coarse-grained dominated materials (greater than 50 percent coarse-grain material) are typically the areas within an aquifer where groundwater is stored and can more easily flow, both horizontally (e.g. water flowing into a pumping well) and vertically (e.g. water that is percolating downward during groundwater recharge). Fine-grained dominated

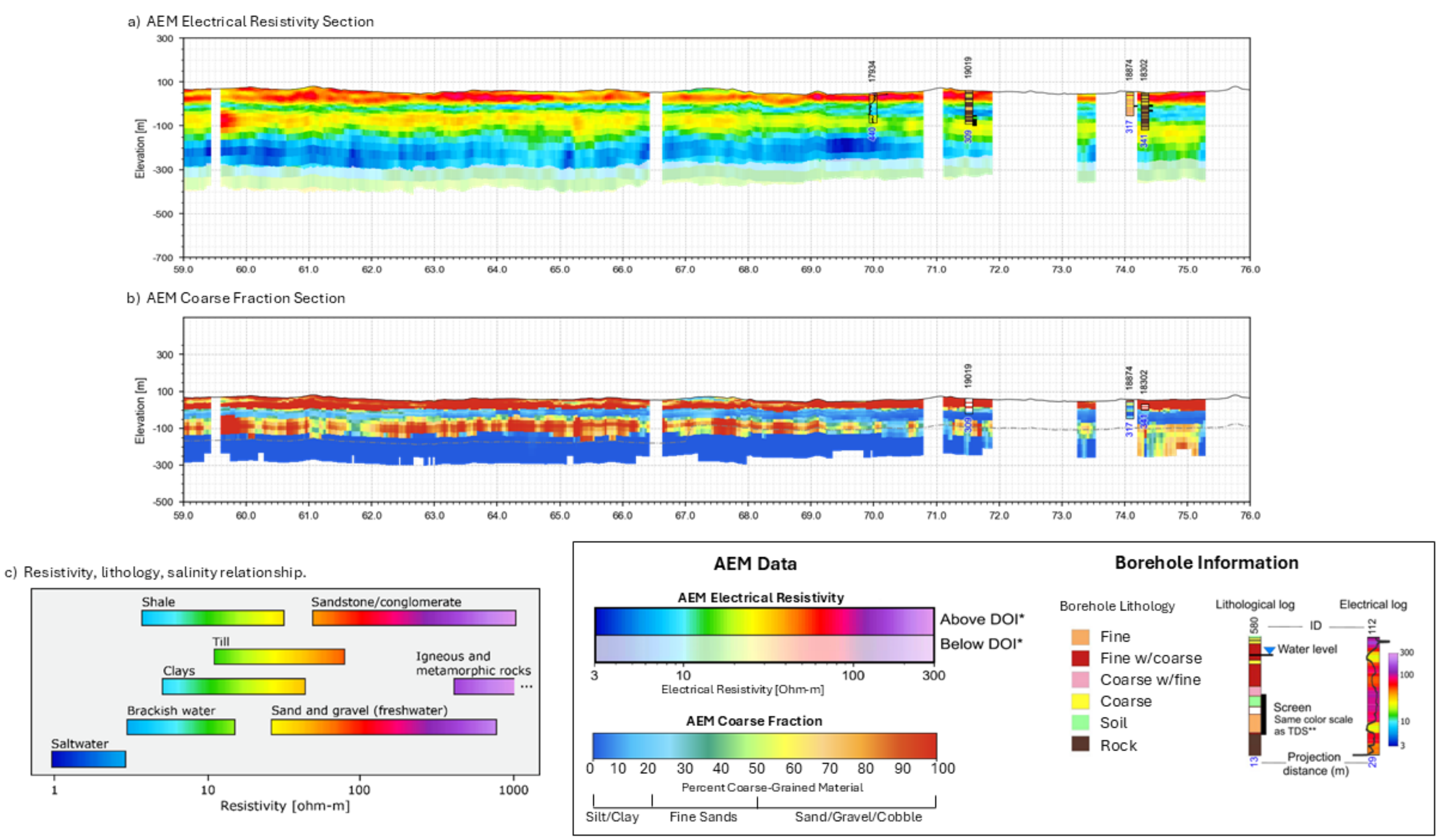


Figure 3. a) Example AEM dataset inverted for electrical resistivity. The vertical section shows low electrical resistivities in blues and greens, intermediate electrical resistivities in yellows and oranges, and high electrical resistivities in reds and purples. AEM data below the depth of investigation (DOI) are translucent. b) Example AEM data interpretation for texture/percent coarse-grained material. The vertical section shows low percent coarse-grained material (e.g. silt/clay) in blues, intermediate coarse-grained material (e.g. find sands) in light green and blue, and high percent coarse-grained material (e.g. sands and gravels) in yellows, oranges, and reds. c) Generalized relationship between electrical resistivity values and geologic material type (modified from Palacky, 1987; Behroozmand, et al., 2022).

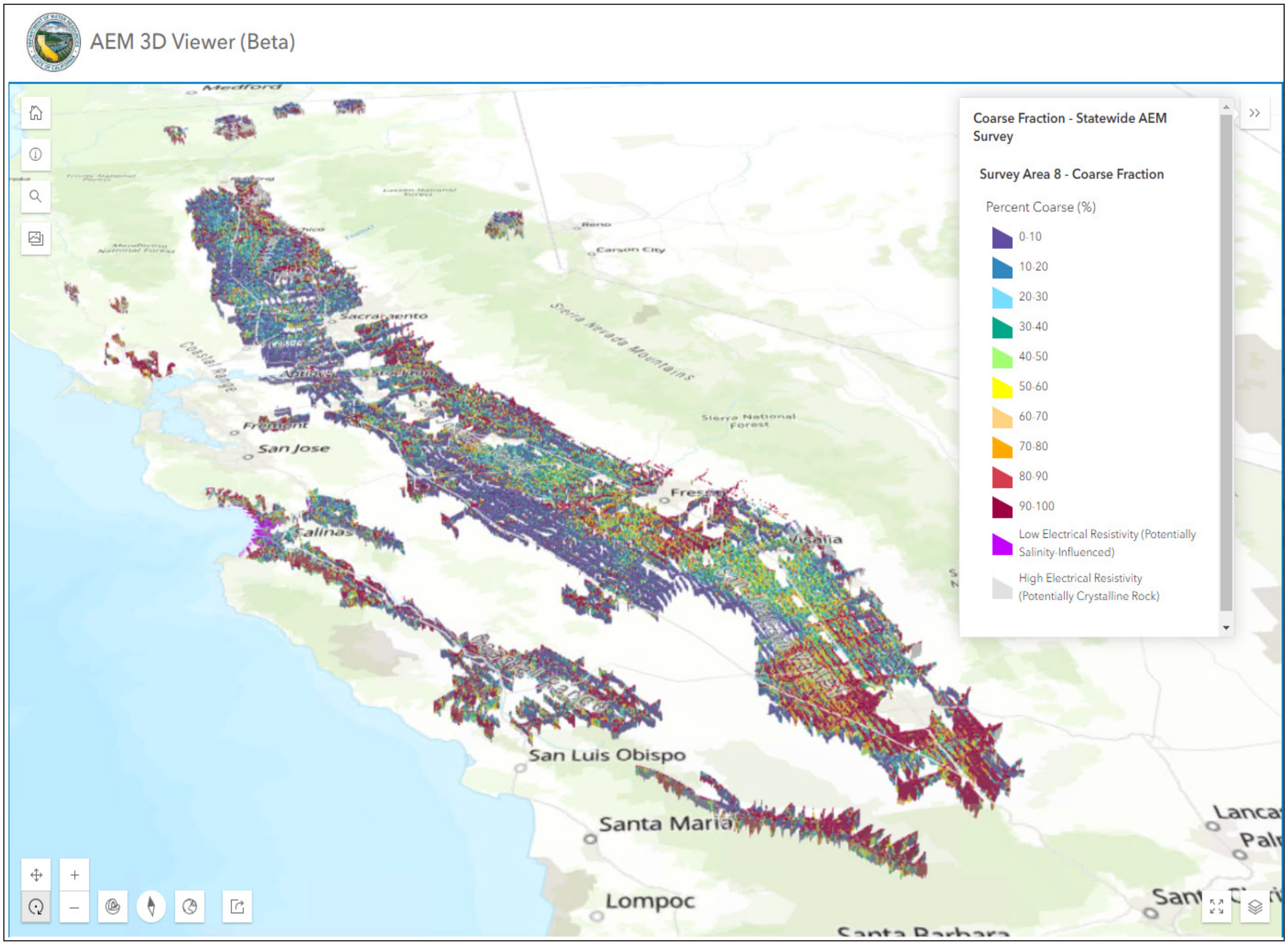


Figure 4. Screenshot of DWR's online AEM 3D Viewer. The interactive AEM 3D Viewer allows the user to zoom into the data, view it from various angles, and slice through the data at any angle. The AEM 3D Viewer shows the AEM electrical resistivity data, AEM data interpreted for percent coarse-grained material, and digitized lithology logs. The AEM electrical resistivity data and AEM data interpretations extend to depths up to 350 meters (1,150 feet) below ground surface in some parts of California.

materials (less than 20 percent coarse-grained material) are typically the areas within an aquifer that inhibit or slow water flow.

AEM Data Access and Visualization

Data access equity is a priority for the state and DWR (California Assembly Bill 1755, 2016). For the Statewide AEM Survey Project, this meant ensuring datasets could be downloaded and visualized without access to expensive data visualization software. All AEM data are publicly available on the California Natural Resources Open Data Portal (CNRA, 2024a) and all data are available to view online, through the SGMA Data Viewer (DWR, 2024d) or DWR's novel GIS-based AEM 3D Viewer (CNRA, 2024a).

DWR's SGMA Data Viewer shows the AEM data as sections along a survey line or as depth slice maps. The AEM 3D Viewer (Figure 4) allows the user to view and interact with the AEM data and lithology logs in a three-dimensional space. All digitized supporting data are also made publicly available and well locations and metadata can be viewed on DWR's Supporting Data Viewer (CNRA, 2024c).

AEM Data Limitations and Uncertainty

Although the AEM method is a unique tool that can provide continuous information about groundwater aquifers across large areas, the method also has limitations. There are areas where AEM surveys cannot be conducted due to safety and data quality considerations. Primarily for safety considerations, AEM surveys cannot be conducted over buildings and structures containing people or confined livestock, above-ground power lines, and heavily trafficked highways. Primarily for data quality considerations, it is best to avoid underground powerlines, power transformers, railroads, and vineyards. Due to these limitations, AEM data typically cannot be collected in urban and some rural areas.

In addition to data collection limitations, there are several steps within the AEM data collection, processing, inversion, and interpretation process that can introduce uncertainty into the dataset. During data processing, uncertainty can be introduced when electromagnetic noise in the data is not properly cleaned. The inversion of AEM data is a non-unique solution, meaning multiple resistivity models may fit the raw data equally well. Therefore, there is inherent uncertainty in the depth and thickness of the electrical resistivity model produced as a part of the data inversion. Additionally, because the AEM data interpretation relies on defining a relationship between existing lithology information and the electrical resistivity values, uncertainty is introduced when there is uncertainty in the lithology information. Finally, care must be taken when there is no correlation between changes in lithology and electrical resistivity, which can occur in the presence of high salinity waters.

Preliminary Hydrogeologic Interpretations of Statewide AEM Survey Data

The AEM data from the Statewide AEM Surveys has dramatically increased our ability to visualize and analyze groundwater basins. In the section below, we provide preliminary hydrogeologic interpretations of the AEM electrical resistivity data and AEM percent coarse-grained material data for various groundwater-related applications. The examples below demonstrate how the AEM datasets can be used as a standalone product to improve the understanding of aquifer structure. However, for a complete hydrogeologic interpretation, the AEM data should be incorporated and analyzed alongside other existing datasets, which will be the focus of the next phase of DWR's Basin Characterization Program.

Texture Model for the Central Valley

The AEM interpretation for coarse-grained material can be utilized to develop a texture model (which describes the distribution of coarse-grained material in the aquifer). This newly available data and continued efforts to add additional datasets and analysis tools are significantly advancing the understanding of basin characteristics and past depositional environments that controlled the distribution of fine- and coarse-grained materials and aquifers within each basin. Figure 5a shows the 3D fence diagram of the texture model for the Central Valley. The texture varies with depth and a single location may have both fine- and coarse-grained layers distributed in the subsurface. The distribution of subsurface material in the Central Valley is a result of California's geologic and climatic history which resulted in unique depositional environments.

Past climatic conditions played a significant role in shaping the composition of sediments in the Central Valley (Marchand and Allwardt, 1981; Page, 1986; Bartow, 1991; Weissmann et al., 2005). During glacial and interglacial cycles, fluctuating climate conditions influenced the types of materials deposited and their distribution. For example, during colder, glacial periods, large volumes of sediment were transported by glaciers, resulting in coarse, poorly sorted deposits in valleys and basins. In contrast, interglacial periods with warmer climates led to the deposition of finer, well-sorted sediments in floodplains and deltas.

Additionally, changes in sea levels during these periods caused the migration of shorelines, contributing to the deposition of marine and coastal sediments in areas that are now far inland of the current shoreline. These climatic shifts also influenced vegetation cover, which in turn affected the rates of erosion and sedimentation. Over time, these processes created the complex stratigraphy observed in many groundwater basins today, where layers of varying composition and permeability reflect the climatic conditions under which they were deposited.

Figure 5b shows the distribution of coarse-grained materials (50-100 percent) in the Central Valley. In the southern half of the Central Valley, both the San Joaquin River and Tulare Lake hydrologic regions (Figure 1a), contain a high presence of coarse-grained materials, especially in the eastern and southern portions of the valley.

In the northern half of the Central Valley, within the Sacramento River hydrologic region, there is an increase of coarse-grained materials along the northern and eastern portion of the valley. Generally, the source of coarse-grained materials along most of the eastern portion of the Central Valley is a combination of uplift, erosion, and glacial outwash from the Sierra Nevada and volcaniclastic sedimentation from the Cascade Mountains in the north (Marchand, 1977; Lettis, 1982; Weissmann et al., 2005; Faunt et al., 2010).

Figure 5c shows the distribution of fine-grained materials (0-20 percent) in the Central Valley. The western portions of both the San Joaquin Valley and the Sacramento Valley are dominated by fine-grained materials deposited in lacustrine and floodplain environments and derived from the Coast Range (Lettis, 1982; Sarna-Wojcicki, 1995; DWR, 2014).

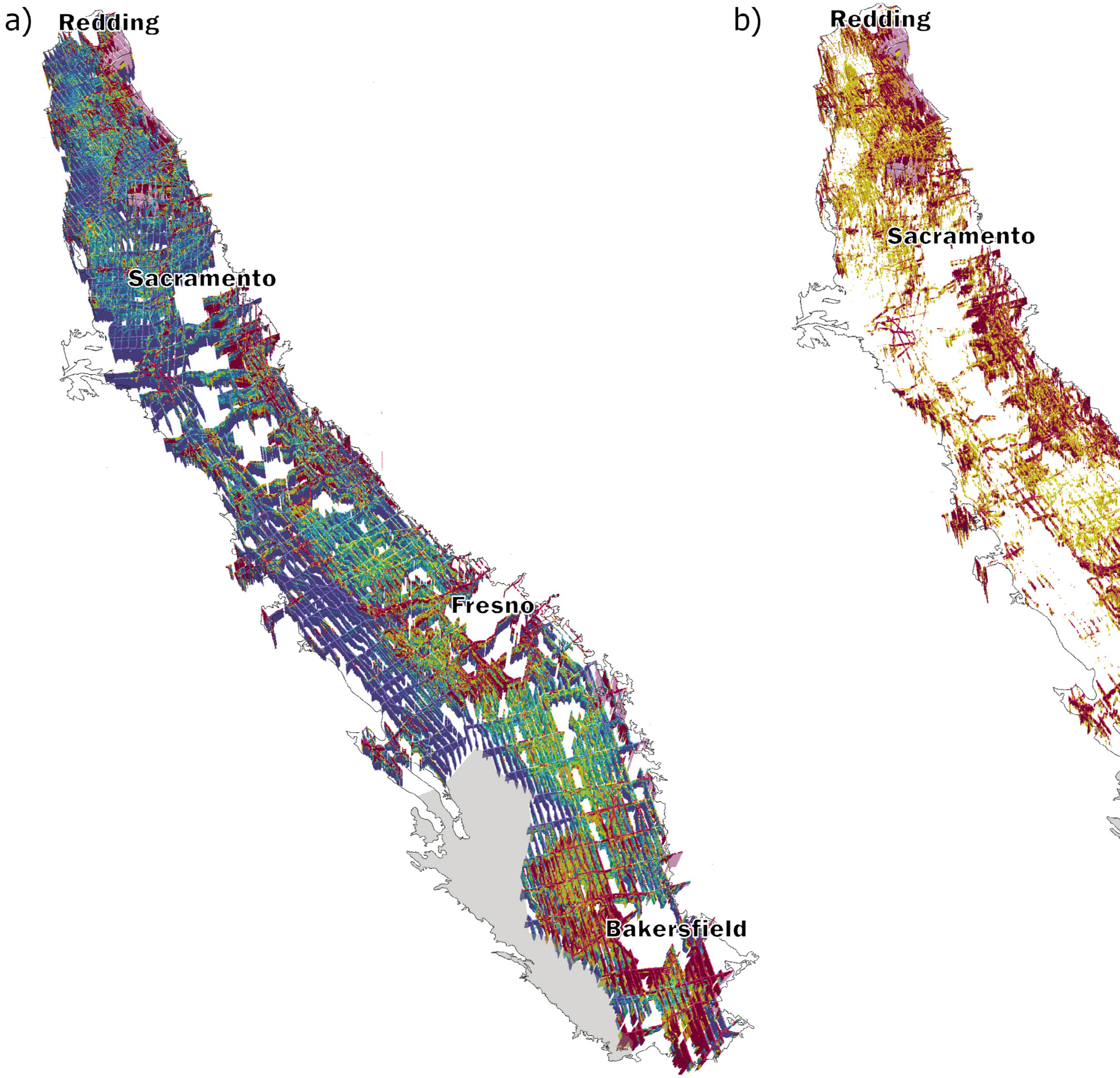
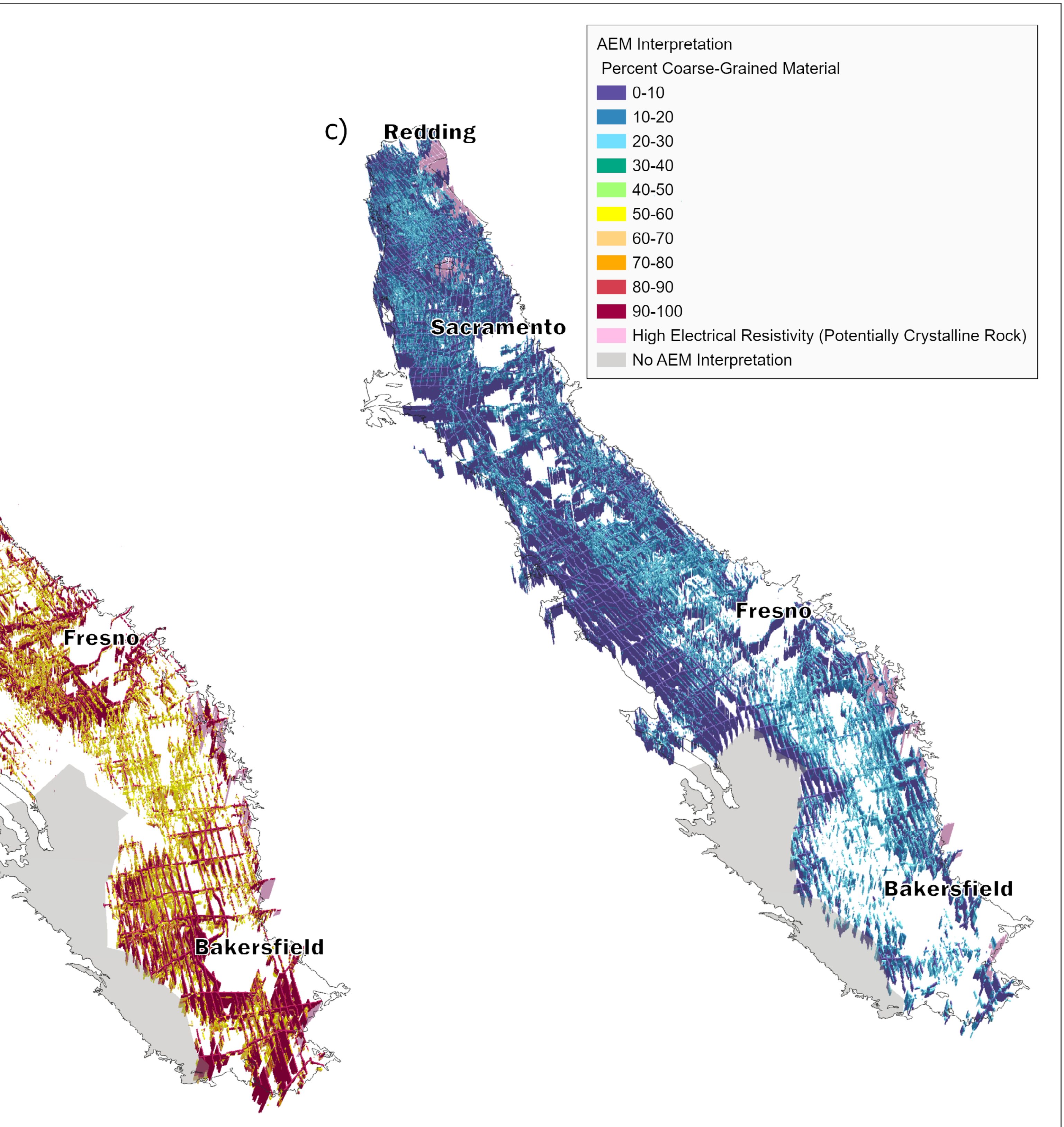


Figure 5. Fence diagrams showing the AEM data interpretations as texture for the Central Valley. The distribution of percent coarse-grained material (i.e. texture) could be interpreted to depths up to 350 meters (1,150 feet) in the Central Valley.

5a) Low percent coarse-grained material (e.g. silt/clay) are shown in blues, intermediate coarse-grained material (e.g. find sands) are shown in light green and blue, and high percent coarse-grained material (e.g. sands and gravels) are shown in yellows, oranges, and reds.

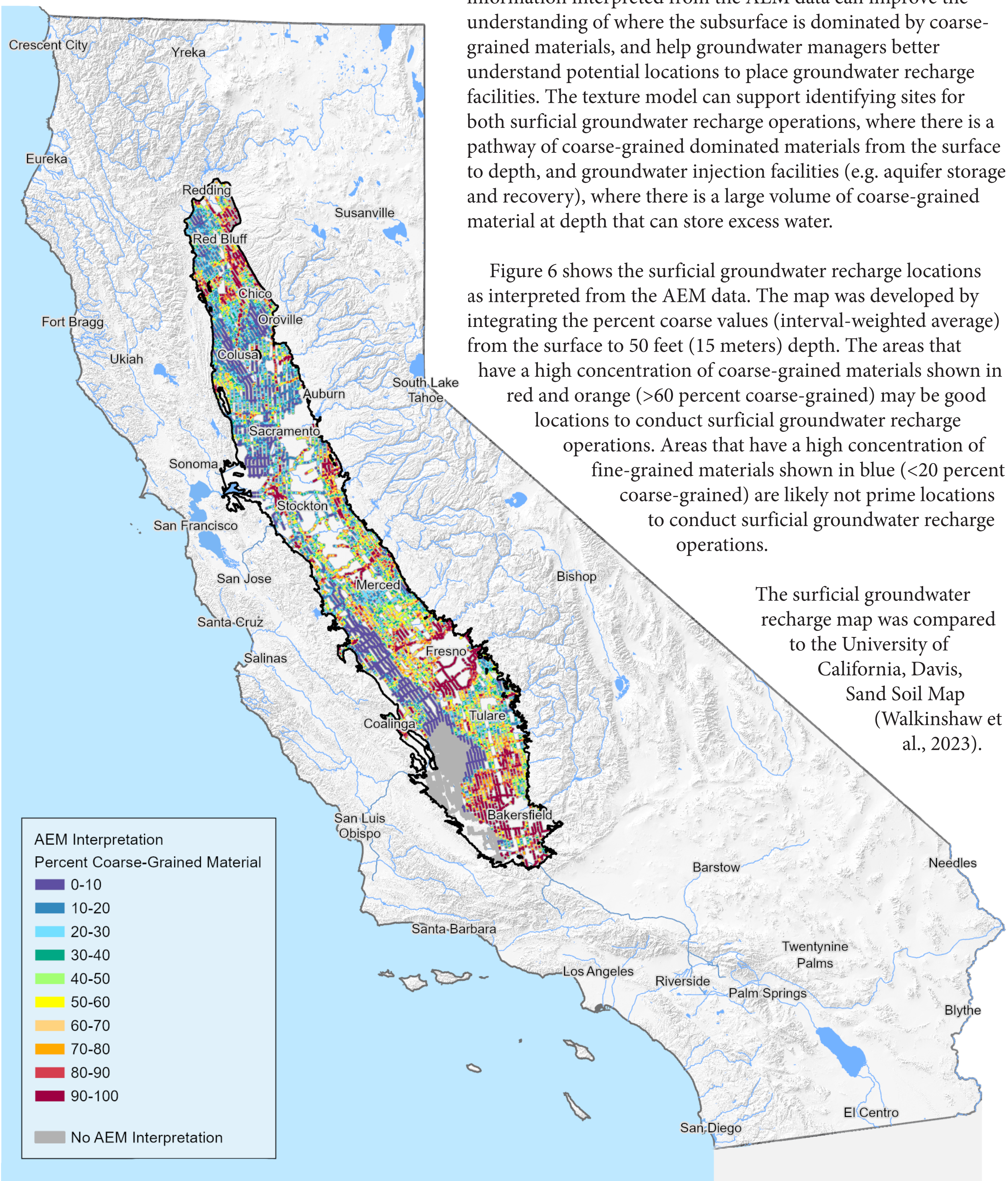


5b) Fence diagram showing the distribution of predominately coarse-grained materials (50-100 percent).

5c) Fence diagram showing the distribution of predominantly fine-grained materials (0-20 percent).

The AEM data can be further examined in detail, along with borehole lithology and texture, on the AEM 3D Viewer (CNRA, 2024a).

Figure 6. Surficial Groundwater Recharge Map (from AEM data) determined from the Statewide AEM Survey data. (a) plan view of the integrated percent coarse values from the surface to 50 feet deep. Note that this map is limited to the resolution of the AEM data; therefore, thin fine-grained layers may not be detected. Additional information (lithology logs or field-based geophysics) would be necessary to detect thin fine-grained layers.



Surficial Groundwater Recharge Map for the Central Valley

Coarse-grained materials, like sands and gravels, can serve as pathways to allow water to travel from the ground surface into an aquifer in an effective and efficient manner. The texture information interpreted from the AEM data can improve the understanding of where the subsurface is dominated by coarse-grained materials, and help groundwater managers better understand potential locations to place groundwater recharge facilities. The texture model can support identifying sites for both surficial groundwater recharge operations, where there is a pathway of coarse-grained dominated materials from the surface to depth, and groundwater injection facilities (e.g. aquifer storage and recovery), where there is a large volume of coarse-grained material at depth that can store excess water.

Figure 6 shows the surficial groundwater recharge locations as interpreted from the AEM data. The map was developed by integrating the percent coarse values (interval-weighted average) from the surface to 50 feet (15 meters) depth. The areas that have a high concentration of coarse-grained materials shown in red and orange (>60 percent coarse-grained) may be good locations to conduct surficial groundwater recharge operations. Areas that have a high concentration of fine-grained materials shown in blue (<20 percent coarse-grained) are likely not prime locations to conduct surficial groundwater recharge operations.

The surficial groundwater recharge map was compared to the University of California, Davis, Sand Soil Map (Walkinshaw et al., 2023).

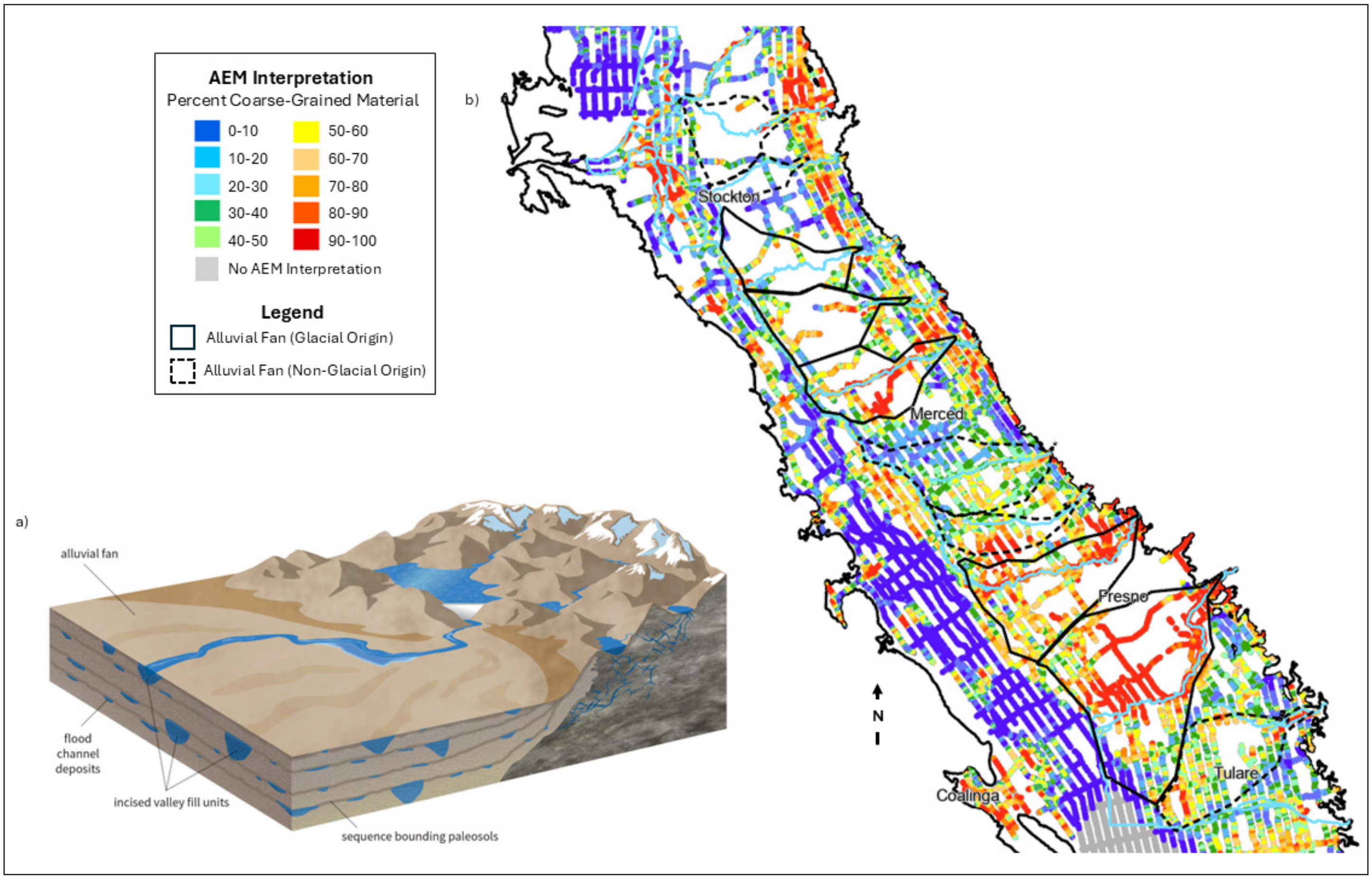


Figure 7. a) Schematic of an alluvial fan and the geologic elements, including incised valley fills. b) Plan view of the integrated percent coarse values from the surface to 50 feet deep and the location of fans having glacial and non-glacial origin (modified from Weissmann et al., 2005 and Faunt et al., 2024).

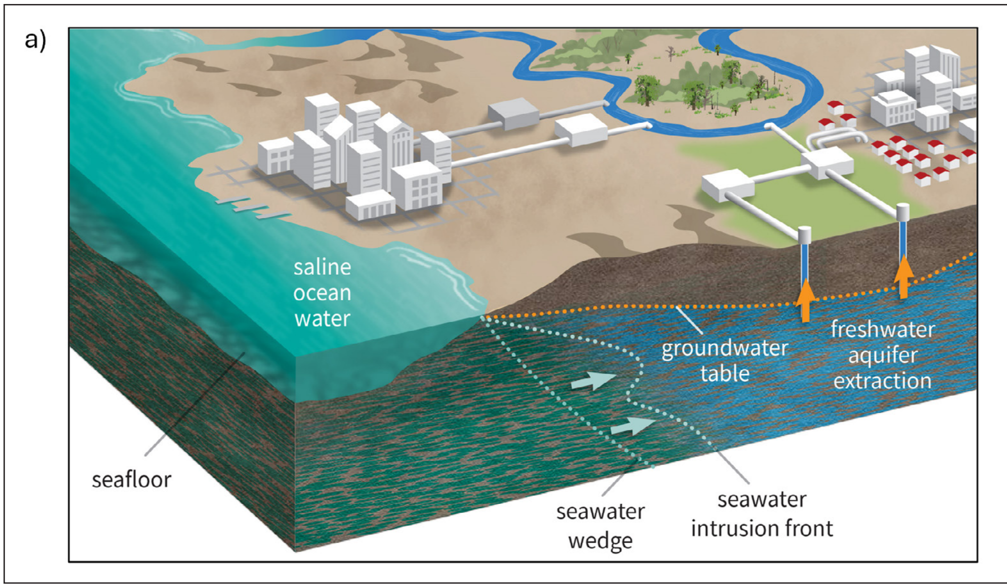
Although there was agreement between the textural classification from soil and the AEM-derived texture classification, in some areas (e.g. along river corridors and alluvial fans) there were differences in several areas. This is because the soil data only examined the top 60 centimeters of the subsurface while the surficial groundwater recharge map shows the average conditions within the top 50 feet (15 meters). In comparison to geologic maps that depict the surface expression of the underlying geology, the surficial groundwater recharge map provides a significant increase in hydrogeologic framework characterization, as the textural classification extends to a greater depth.

Comparison of Shallow Texture to Mapped Alluvial Fans

Alluvial fan development in the Central Valley has been the result of depositional and erosional conditions associated with fluvial, lacustrine, volcanic, and glacial processes (Marchand, 1977) (Figure 7a). In the southern portion of the Central Valley, alluvial fans have been described as either from a glaciated or non-glaciated (or interglacial) provenance, which significantly effects the occurrence and distribution of fine- and coarse-grained materials in the subsurface. Alluvial fans of glacial origin, such as those found on the east side of the San Joaquin Valley, typically feature coarser, poorly sorted sediments. These were the result of high-energy processes associated with glacial meltwaters from high elevation watersheds, which transported a diverse range of sediment sizes. In contrast, fans deposited during interglacial periods were the result of incision through the glacially derived fans by rivers and streams and progradation toward the valley floor (Weissmann et al., 2002). These fans exhibited finer, relatively well-sorted sediments due to the lower energy conditions. The coarser textures of fans deposited during glacial cycles generally offer higher permeability, which enhances groundwater recharge compared to the finer, less permeable sediments comprising fans of non-glacial origin. Understanding these textural differences is crucial for effective groundwater management and advancing recharge strategies in the Central Valley (Marchand and Allwardt, 1981; Page, 1986; Bartow, 1991; Weissmann et al. 2005; Faunt et al., 2024).

Figure 7b shows the percent coarse values integrated (interval weighted average) over the top 50 feet (15 meters). The coarse-grained materials (60-100 percent) show agreement with the location of the alluvial fans of glacial origin and the AEM data will likely be a useful tool

Figure 8. a) Schematic showing seawater intrusion in a coastal aquifer. b) AEM data interpreted for percent coarse-grained material (texture) in the Monterey Bay area. The area adjacent to the Monterey Bay shows very low electrical resistivity values (in purple) that may correlate to the presence of high salinity groundwater.



for mapping the extent and depth of the alluvial fans. Unfortunately, AEM data were not collected in urban areas, so the AEM data alone do not capture the full extent of the alluvial fans. Generally, the alluvial fans of glacial origin show a higher concentration of coarse-grained materials, whereas alluvial fans deposited during interglacial periods (alluvial fans of non-glaciated origin) show a higher concentration of medium- to fine-grained materials (30-60 percent).

Locations of Potentially High Salinity Groundwater

In some cases, the AEM method can be used to determine the location of high salinity groundwater because high salinity fluids have a very low electrical resistivity signature that dominates over material type (Figure 3c). For example, layers comprised of sand that are saturated with freshwater will have a different electrical resistivity signal than the same material saturated with saline water. Therefore, the AEM method can be used to support defining areas with seawater intrusion, brackish water (from oil and gas production), and the base of freshwater (Geobel et al., 2019; Ball et al., 2020; Gottschalk et al., 2020; Ball et al. 2023). It is critical to incorporate water quality information into the interpretation of AEM data for high salinity waters because silts and clays also have low electrical resistivity values and therefore may be misidentified.

Seawater intrusion may occur along coastal aquifers when seawater encroaches or replaces freshwater and typically takes the shape of a seawater wedge (Figure 8a). Accurate interpretation of AEM data for seawater intrusion requires a high density of water quality estimates in wells with known screen intervals, which were not available at the time of the Project. Therefore, AEM data were not specifically interpreted for seawater intrusion as a part of the Statewide AEM Surveys. However, preliminary interpretations can be made.

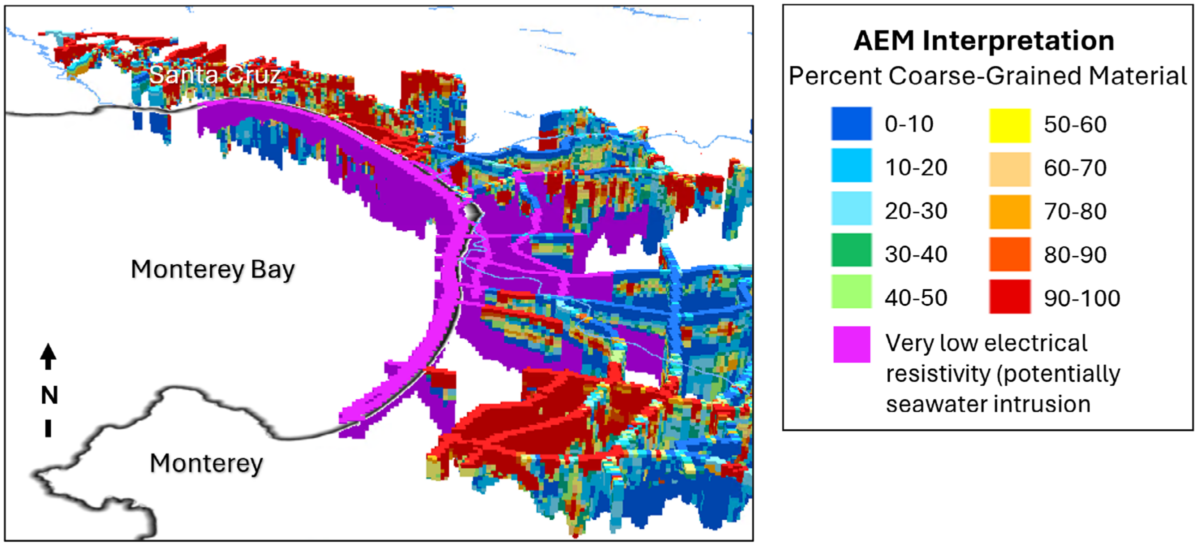
Figure 8b shows a 3D view of the AEM data from the Monterey Bay area. The area in purple shows where a resistivity-to-lithology transform could not be developed due to the presence of very low electrical resistivity values. These areas with very low electrical resistivity values show a similar wedge shape indicative of seawater intrusion (Figure 8a) and suggests this area may contain high salinity water.

CONCLUSIONS

AEM data improves the understanding of large-scale aquifer structure by providing continuous images of subsurface electromagnetic properties that are related to the distribution of fine- and coarse-grained materials in an aquifer. Improving the understanding of this important natural infrastructure and developing groundwater flow models and hydrogeologic conceptual models is a priority for DWR, as well as local GSAs, the California Geological Survey, and the United States Geological Survey. These models support multiple geologic sectors in addition to groundwater management, including energy storage in the subsurface (like compressed air, hydrogen, and geothermal), geohazard mitigation (like liquefaction, subsidence, or seismic settlement), and mineral exploration.

DWR's Statewide AEM Survey Project has delivered approximately 16,000 miles of high-quality airborne geophysical data across California's priority groundwater basins. This unique dataset provides the groundwater community with information that improves the development and implementation of management plans to achieve groundwater sustainability. DWR's preliminary analysis showed that the AEM interpretations can be used to support several hydrogeologic applications, including developing texture models, defining potential groundwater recharge locations, refining the extent of alluvial fans, and identifying high-salinity fluids that may be a result of seawater intrusion.

b)



With the data collection portion of the Statewide AEM Survey Project complete, DWR is undertaking the next phase of Basin Characterization where the AEM data will be analyzed in combination with other datasets to identify aquifer structures and subsurface conditions more thoroughly than ever before. Under the Basin Characterization Program (DWR, 2024b), new and existing geologic, hydrogeologic, and geophysical data will be collected and analyzed together to create continuous state-stewarded maps and models.

To support this effort, new data analysis tools and guidance will be developed that can generate aquifer recharge potential maps, texture models, hydrostratigraphic models (defining extent of aquifers and clays, depth to basement, and base of freshwater), and aquifer flow parameters. Continued data collection and analysis will be conducted through a series of groundwater investigations, first at a local scale and then expanding to a regional and statewide scale. The resulting maps and models will be regularly updated, as new data becomes available, ensuring that up-to-date information is accessible for groundwater management activities. Data access and data equity will continue to be provided through development of new online, GIS-based, visualization tools that will serve as a central hub for accessing and exploring groundwater related data in California.

The Basin Characterization Program's state-stewarded maps and models will provide the latest information about California's groundwater basins to help local communities better understand their aquifer systems and support local groundwater management. This information will also support the state's effort to effectively utilize groundwater aquifers, a critical component of California's natural infrastructure, to ensure that the state's future water supply is reliable and resilient.

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Burned Watershed Geohazards

2024 Program Update

by Nina Oakley, Ph.D. and Don Lindsay, PG, CEG, PE, GE — *CGS Burned Watershed Geohazards Program*

THE 2024 WILDFIRE SEASON was active in California with 7,194 wildfire incidents resulting in just over one million acres burned by the end of October. The number of incidents was slightly above, and acres burned slightly below, the five-year average.

Watershed Emergency Response Teams (WERTs), led by CAL FIRE and the California Geological Survey (CGS), are state teams deployed to identify postfire hazards that threaten life-safety, property, and infrastructure. A fundamental step in the WERT process is the identification and characterization of Values-at-Risk (VARs) using a combination of modeling and professional judgment from a wide range of disciplines including hydrology, geology, geomorphology, and meteorology.

The burned watershed geohazards (BWG) team conducted 16 postfire reconnaissance surveys in 2024. Of those, nine resulted in WERT deployments, where more than 330 VARs were identified and site-specific recommendations were made to mitigate postfire hazards. The greatest number of VARs were identified on the Bridge and Line Fires. WERT reports detailing these VARs and other findings are available online at https://www.conservation.ca.gov/cgs/bwg/recent. The other seven postfire reconnaissance surveys were documented in memoranda only, and forwarded to our partners at CAL FIRE and CalOES.

As wildfire activity wanes, the BWG team is instrumenting areas of high postfire debris flow and debris flood potential to capture data that will inform rainfall triggering thresholds as well as improve our understanding and ability to model postfire runoff-induced hazards.

To support hazard mitigation planning efforts across California, the BWG team developed a statewide pre-fire map of postfire debris-flow hazards. This map product uses terrain, soil data, simulated burn

This page: Derek Cheung conducts hillslope transects on the 2021 Dixie Fire in October 2024. These observations track changes in vegetation recovery and grain size distribution in the burn area and improve our understanding of how susceptibility to flash floods and debris flows change with time after wildfire. Photo: Rebecca Rossi

Facing page: Rebecca Rossi and Paul Richardson prepare for a helicopter flight over the 2024 Park Fire burn area. Flights over the burn area help WERT members assess areas most susceptible to postfire flood and debris flow hazards and determine areas of highest priority for site visits on the ground. Photo: Don Lindsay.

severity, and the USGS debris-flow likelihood and volume models, to estimate the potential for postfire debris flows across the state for a given rainfall intensity. The map will support communities in identifying areas that are most susceptible to debris-flow hazards and provides information they can use to plan for and mitigate postfire flood and debris-flow hazards before an area is burned. The map will be made publicly available as a GIS layer, and development of a scientific journal article describing methods and use cases is underway. BWG will work with partners to facilitate the application of this map product to their planning efforts.

From May 20-22, 2024, the BWG team attended the "Establishing Directions in Postfire Debris-Flow Science" conference in South Lake Tahoe. The conference, supported by USGS, brought together nearly 100 scientists from federal and state government agencies, university, consulting, and NGOs representing various disciplines related to postfire debris-flow science such as geomorphology, hydrology, engineering, remote sensing, ecology, and atmospheric science. The format consisted of presentations, poster sessions, and interactive breakout groups, all guided to identify and develop group consensus on establishing science directions. The three top priorities that emerged from breakout discussions and voting exercises were: (1) process-based understanding of regional postfire debris-flow hazards, which involves improved understanding of the processes driving postfire debris flows across climates and geologies; (2) a centralized data hub and standardization of data formats, which would support various efforts such as debris-flow model development and verification; (3) science communication and outreach to improve public understanding of postfire debris flow hazards and to provide support to communities where postfire hazards are emerging, as well as improve communication and collaboration between scientists and decision makers.

Learn more about burned watershed geohazards at https://www.conservation.ca.gov/cgs/bwg

The California Strong Motion Instrumentation Program

by Hamid Haddadi, Ph.D., PGP, Daniel Swensen, PE, Lijam Hagos, Ph.D., PGP, and Dave Branum, PG
CGS Strong Motion Instrumentation Program

EACH YEAR CALIFORNIA EXPERIENCES thousands of earthquakes. Although most of these earthquakes are too small to be felt by humans, the larger but less frequent events pose significant risk to both life and property. Fortunately, California boasts one of the largest and most sophisticated networks in the world for recording and disseminating earthquake shaking data.

The California Strong Motion Instrumentation Program (CSMIP) in the Department of Conservation's California Geological Survey (CGS) was established in 1972 to obtain vital earthquake data for the engineering and scientific communities through a statewide network of strong motion instruments. CSMIP is a core member of the California Integrated Seismic Network (CISN), a collaboration of organizations that monitor earthquakes in the State and collect data to support improvements to earthquake resilience.

The information gathered by CSMIP is provided to seismologists, engineers, building officials, local, state, and federal governments, and emergency response personnel. Within minutes of an earthquake, emergency operation centers can access ShakeMaps and other earthquake products. At specific sites rapid health assessments aid post-earthquake response efforts. Beyond the immediate value, the data are used to develop seismic design provisions in building codes and inform scientists and engineers internationally about how shaking affects buildings, infrastructure, and the ground.

STRONG MOTION NETWORK

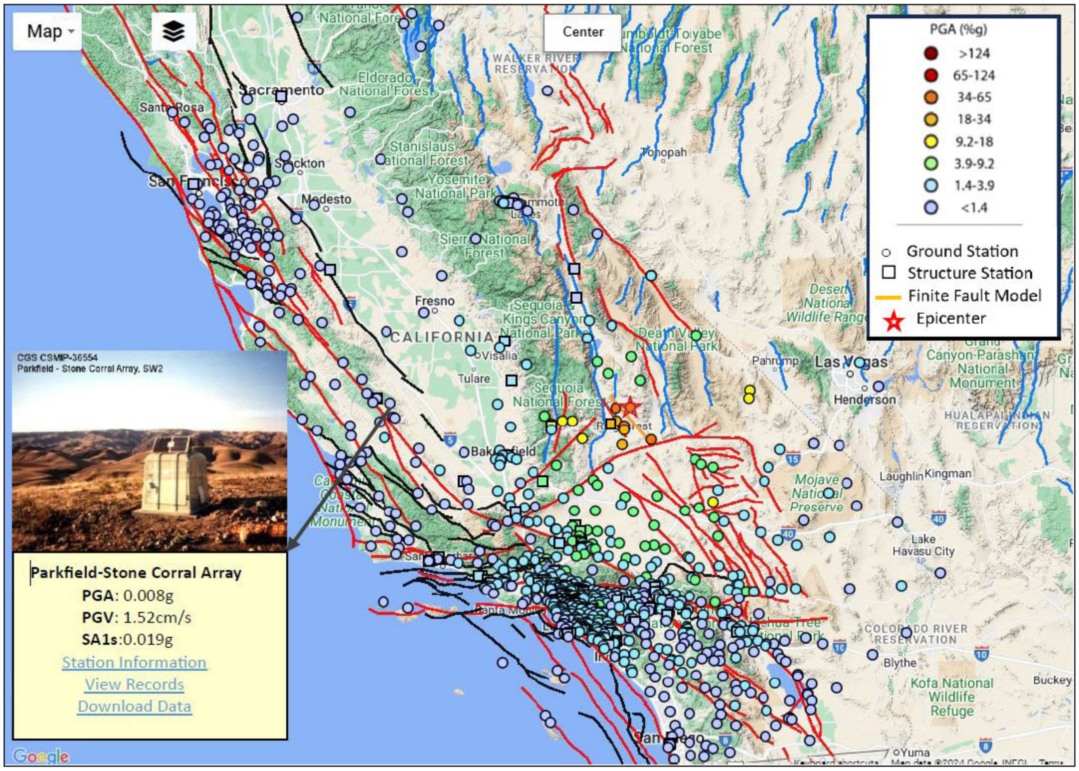
CSMIP installs state-of-the-art earthquake monitoring devices called accelerographs at various locations throughout California to measure the ground shaking (i.e., ground-response stations). Accelerographs are designed to record acceleration of ground shaking with respect to time that could cause a more sensitive seismograph to go off-scale. When activated by earthquake shaking, the devices produce a record from which important characteristics of ground and structural motion (acceleration, velocity, displacement, response spectra, and duration) can be understood and utilized.

In addition, CSMIP installs earthquake monitoring devices in structures such as buildings, hospitals, bridges, dams, utilities, and industrial facilities. These devices are predominantly accelerographs, but some stations also include sensors which directly measure the relative displacement between two points of the structure. Sites are selected by a governing committee comprised of engineers and scientists representing industry, government, and universities. These sites are chosen based on scientific significance and include factors such as population density, geology, structure type, and seismic hazard level. The program currently has more than 1,375 active stations, including 942 ground-response stations, 272 buildings, 26 dams and 82 bridges, with the total number of sensors exceeding 10,000.

DATA PRODUCTS AND APPLICATIONS

Shortly after an earthquake in California, the Strong Motion Recovery and Analysis (SARA) system receives data recorded by California Integrated Seismic System (CISN) stations. CSMIP automatically processes and disseminates the strong-motion data and the related visual products via the Center for Engineering Strong-Motion Data (CESMD) for use in post-earthquake response, and for scientific and engineering research applications. The CESMD is an internationally utilized joint center of the USGS and the CGS, providing a single access point to quality-controlled strong-motion data from CSMIP, the USGS National Strong-Motion Project (NSMP), the USGS Advanced National Seismic System (ANSS), and other affiliates.

California Geologic Data Map Series Map No. 8. February 2024. This map shows the locations of CSMIP network stations differentiated by the type of the station; Ground, Building or Bridge/Dam. Also displayed are inset photographs of ten stations.

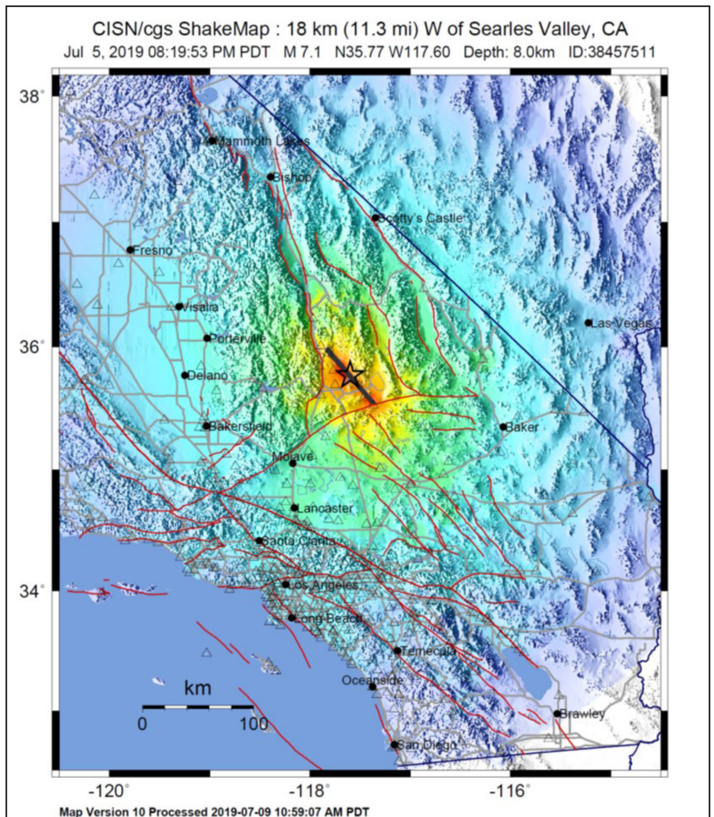


An example of the CESMD interactive map for the M7.1 Ridgecrest earthquake of July 2019 showing the spatial distribution of stations that recorded the earthquake. Ground stations are represented by circles and structural stations by square symbols. The color-codes in the stations correspond to ranges of peak ground acceleration in percent of gravity (%g) experienced at those locations. The fault overlay on the map is represented by colored lines – blue: normal fault; black: reverse fault; red: strike slip fault.

Inset: Screenshot of seismic station information popup. Such popups provide links to view station information, earthquake records, and waveform data.

The CESMD works closely with ANSS and with the Consortium of Organizations for Strong-Motion Observation Systems (COSMOS) to engage with the strong-motion networks in the U.S. and other countries. It is currently serving data from more than 40 countries via its Engineering Data Center (EDC) and the Virtual Data Center (VDC) portals. Through the VDC, the CESMD provides access to significant ground strong-motion records from data providers worldwide. In addition, the CESMD strives towards the completeness of station information such as site geology parameters, structural design characteristics, and sensor locations, all of which are critical for the analysis and interpretation of recorded data.

Strong-motion data products of engineering interest are made available to end users via the event-specific Internet Quick Report (IQR). While users can navigate the IQR to access event-specific products, the CESMD also provides a search engine and webservice data access tools to facilitate the utilization of bulk data products from a single event or multiple events. The data products provided via the IQR include raw and processed records and easily interpretable visual products such as spectral, ground and structural motion plots, the interactive station map, and a link to ShakeMap. In addition to displaying a spatial context of earthquake and recording stations, the dynamically generated interactive station map provides quick links to the station pages, record plots, and the downloadable data files. The stations on the interactive map are color-coded according to peak ground acceleration (PGA)



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)	**<0.1**	**0.5**	**2.4**	**6.7**	**13**	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	**11**	**22**	**43**	**83**	**>160**
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

ShakeMap of the M7.1 Ridgecrest earthquake of July 2019. Colors represent the range of intensities from low (light blue) to high (red). Red lines and the star icon represent active faults and the earthquake epicenter, respectively.

values matched with the intensity scale used in ShakeMap. ShakeMap displays the intensity of ground shaking due to an earthquake. ShakeMap is useful for emergency services responding to earthquakes because recorded and estimated ground motions correlate to felt effects and expected damage distributions.

CSMIP provides real-time data to the USGS west coast ShakeAlert Earthquake Early Warning System. ShakeAlert detects earthquakes quickly and alerts people and automated systems through the MyShake application to take protective action in response to earthquakes.

Also, the program annually provides grants to researchers to fund projects that will utilize strong motion records, new types of seismic recording equipment, to provide innovative approaches to improve the seismic resilience of our communities. The ultimate goal of these projects is to accelerate the process by which lessons learned from earthquake data are incorporated into seismic monitoring and structural design practice. For example, the study of CSMIP building data led to improved formulas in the building code for calculating the resonant vibration period of buildings, a key parameter in earthquake-resistant design.

GOLDEN GATE BRIDGE MONITORING

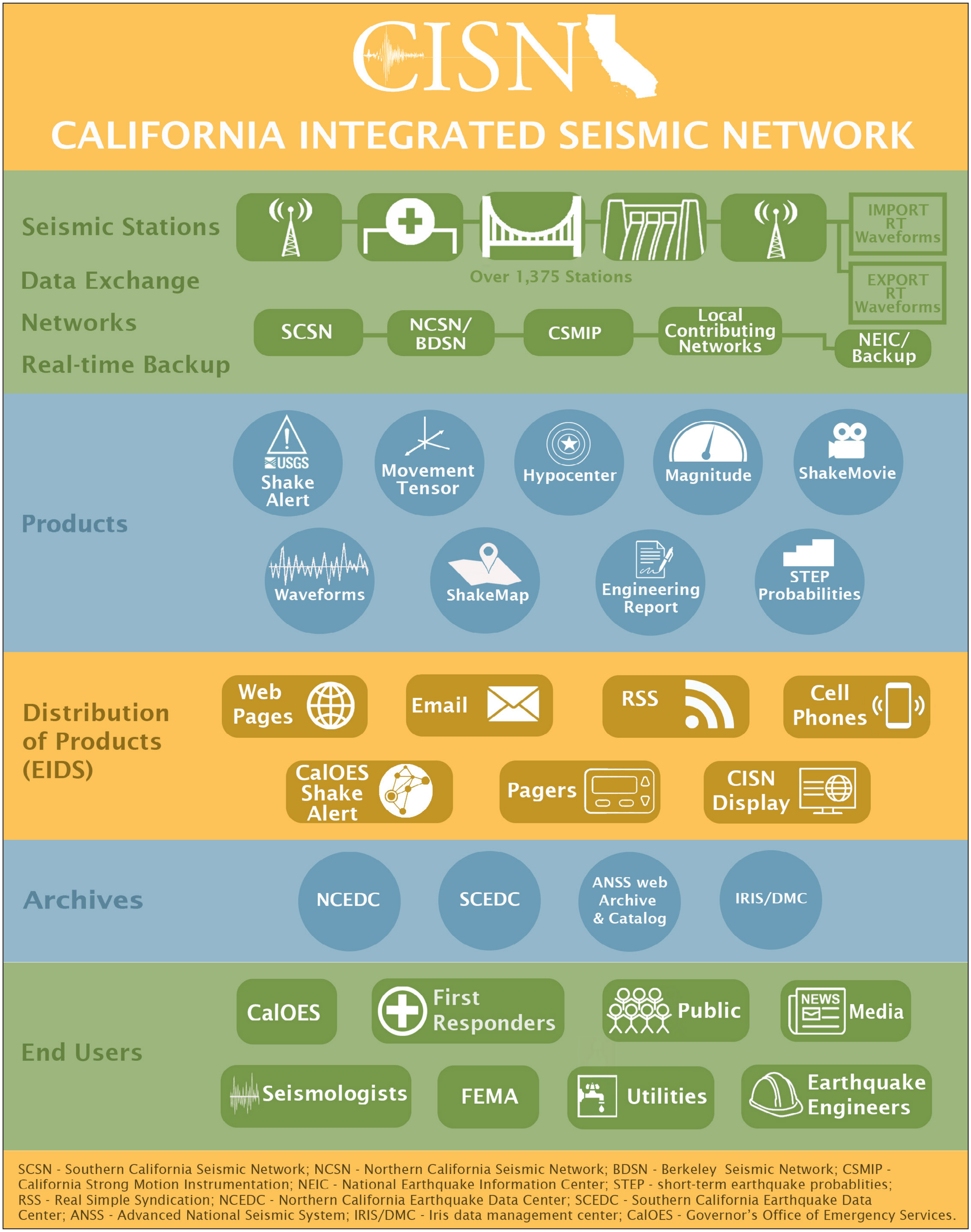
The Golden Gate Bridge (GGB) is an example of the use of data for post-earthquake response applications such as emergency mitigations. The bridge is constantly monitored by CSMIP for earthquake motions using strong-motion sensors distributed throughout the structure, all connected to data recorders by electrical cabling. The initial installation of instrumentation by CSMIP at the GGB occurred in 1995. At that time 69 accelerometers were installed on the bridge and three on the ground near the bridge. Four relative displacement sensors were also installed on the bridge at the time. As of today, the instrumentation at the GGB includes 100 accelerometers and 10 relative displacement sensors on the bridge, as well as two clusters of six accelerometers near the ends of the bridge The state-of-the-art central recorders and communication technology utilized in the seismic monitoring system at GGB allows for the rapid transfer of seismic data between the bridge and CSMIP.

To improve post-earthquake response efforts at the GGB, CSMIP recently initiated an effort to provide GGB engineers with information for their rapid structural health assessments immediately after an earthquake. Through this monitoring system, peak ground accelerations and important bridge response parameters are calculated and distributed to GGB personnel through an automated notification system. Equipped with this crucial information, on-site engineers are able to take urgent action seconds after a damaging earthquake.

For over 50 years, CSMIP has been collecting and disseminating valuable seismic data and associated products to increase public safety by enhancing rapid post-earthquake response capabilities and improving building codes for safer structures. In order to facilitate the utilization of seismic data products, the program is upgrading over 1,100 obsolete recorders with modern systems that can take advantage of faster communication methods. The upgraded equipment will allow these stations to provide data in real time and make possible advanced applications such as structural health monitoring of tall buildings, hospitals, and lifelines. The rapid delivery of earthquake information to emergency responders will ultimately help to save lives during the next damaging seismic event. For more information about the California Geological Survey's Strong Motion Instrumentation Program, visit our website https://www.conservation.ca.gov/cgs/smi/program.

CSMIP staff installing an earthquake monitoring device on the Golden Gate Bridge.

Schematic of the Golden Gate Bridge showing the locations of the sensors (red arrows) that contribute data to the bridge's automated notification system. Ground surface sensors are located near each end of the bridge. Sensors on the bridge are located at the top and bottom of each tower. The ground and bridge shaking data obtained by these sensors during an earthquake are used to produce notification messages which are rapidly distributed to Golden Gate Bridge personnel.



The CSMIP, funded by the state of California through the CGS, is one of the core members of the California Integrated Seismic Network (CISN). The CISN is California's partner to the Advanced National Seismic System.

A Field Trip to Remember

at the Geological Society of America meeting in Sacramento

Images from a past field trip.

The Cordilleran Section of the Geological Society of America will meet in Sacramento in April, and several field trips will explore Northern California's geology. One trip is unusual.

Local geologist Jim Wood and several CGS geologists will lead a fun and informative one-day field trip to the complex Sierra Nevada Metamorphic Belt in the Ione and Jackson 7.5' Quadrangles. Participants will ride speeder cars as field vehicles along the Amador Central Railroad, on a memorable transect winding through the western Sierra Nevada foothills.

From Ione eastward for approximately ten miles to Martell, participants will travel deep into geologic time, stopping along the way to examine railroad cuts that display Paleozoic to Mesozoic accretionary terranes, including mélange, tuff, pillow basalt, and slate, and Cenozoic nonmarine deposits of the Ione, Valley Springs, and Mehrten formations. Stops also include mines, past and present, in the Copper Belt and the kaolinite clay of the Ione Formation. After fourteen stops, participants will possess new knowledge and fond memories of the intriguing foothills of the Sierra Nevada.

All aboard!

Five Years Later:

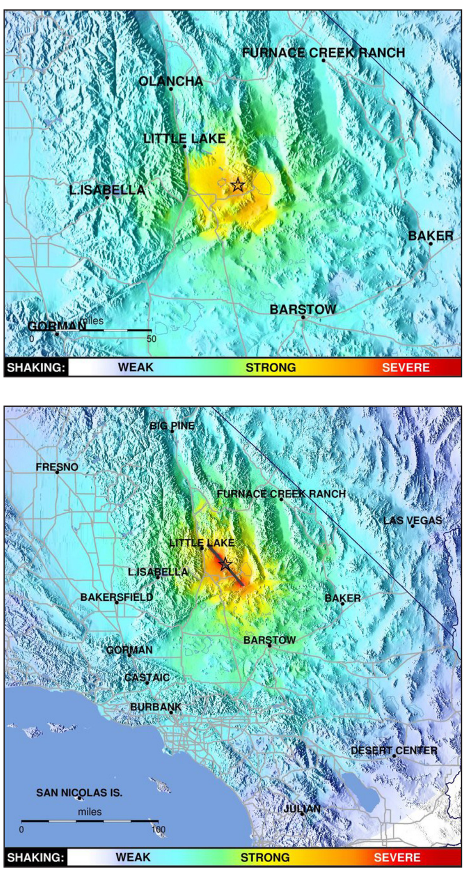
Looking Back at the 2019 Ridgecrest Earthquake Sequence

by Carla Rosa, PG, Tim Dawson, PG, CEG, Kate Thomas, and Alex Morelan, Ph.D., PG
CGS Seismic Hazards Program

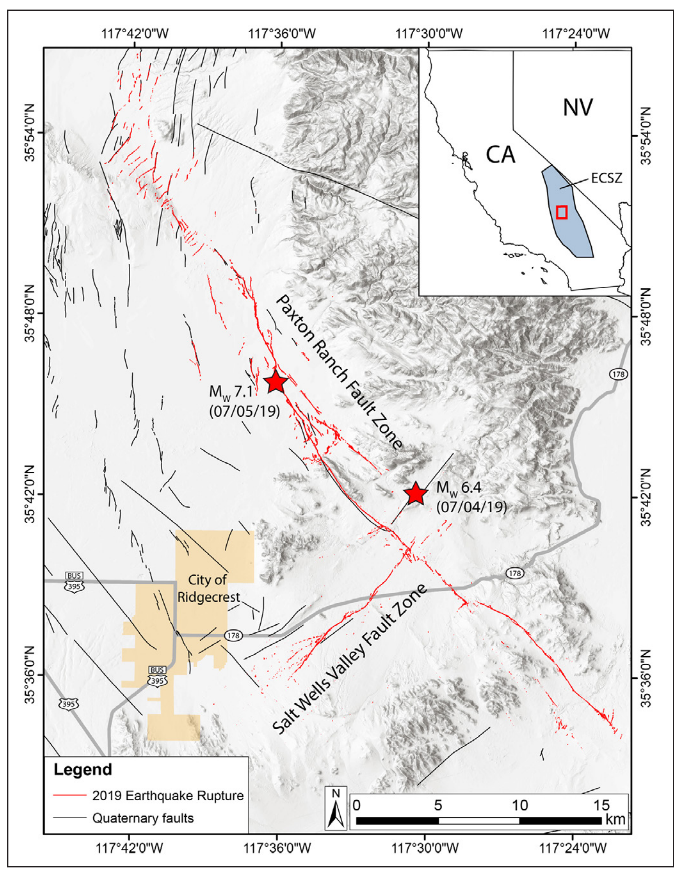
IN JULY 2019, two major earthquakes occurred near Ridgecrest, CA: a M6.4 foreshock on July 4th and a M7.1 mainshock on July 5th, known as the Ridgecrest Earthquake Sequence. The causative faults are now known as the Salt Wells Valley and Paxton Ranch fault zones, respectively, which cross each other nearly perpendicularly. The shaking produced by these two events was felt as far away as northern California and central Arizona.

Both earthquakes had widely distributed surface effects, rupturing the ground surface along numerous fault strands and displacing the ground both horizontally and vertically (Rosa et al., 2024). Liquefaction-related deformation features and sand boils also occurred across the region because of the earthquakes.

Field efforts following these two earthquakes allowed for advancements in data collection, such as methods for on-the-ground data acquisition and remote sensing and mapping techniques. Documenting perishable field data following major earthquakes is important for both immediate and long-term fault hazard assessment. This includes using earthquake mapping for swift emergency response soon after the event and to characterize deformation zones for a better understanding of fault mechanics.



Left: ShakeMaps from the Ridgecrest Earthquake Sequence foreshock on July 4th (top) and the mainshock on July 5th (bottom).



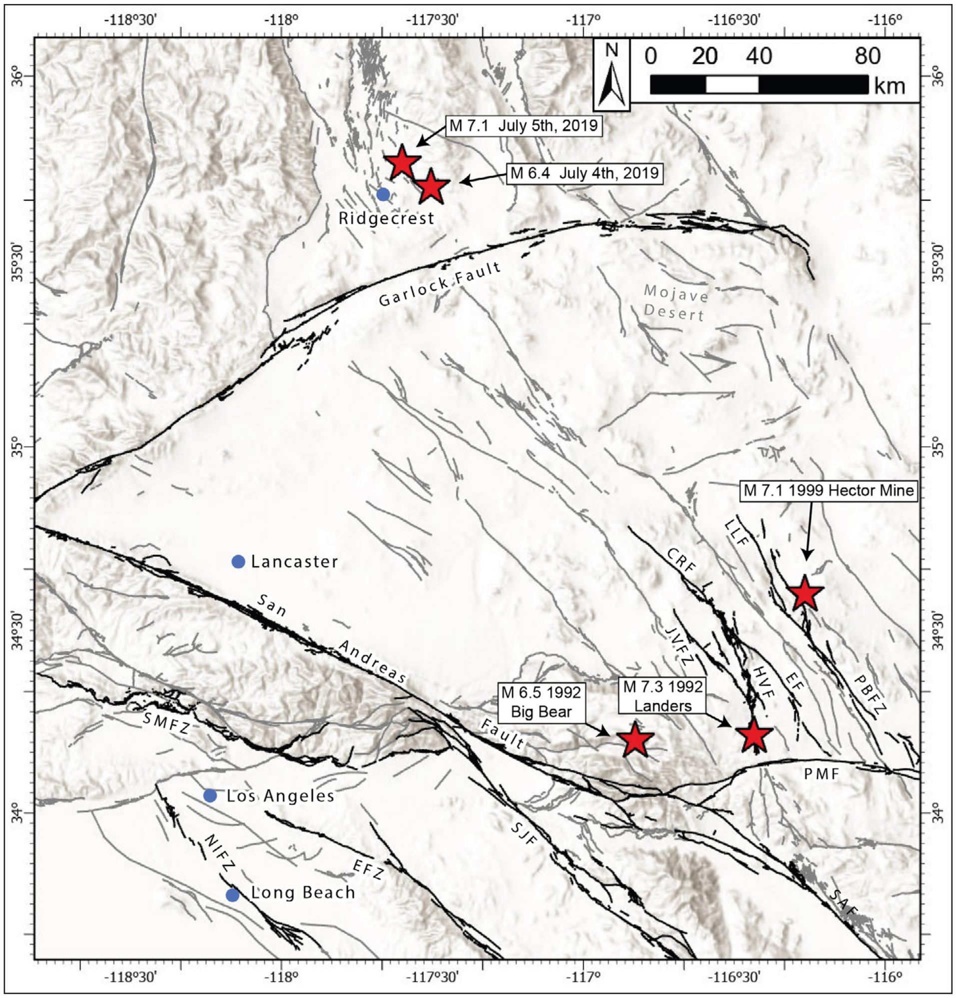
Right: The 2019 Ridgecrest earthquakes ruptured ground along the Paxton Ranch and Salt Wells Valley fault zones (red lines with epicenters marked as red stars) in a zone of known Quaternary aged faults (black lines). These faults comprise a portion of the Eastern California Shear Zone (see inset map). Base source: Airbus, USGS, NGA, NASA, CGIAR, NLS, OS, NMA, Geodatastyrelsen, GSA, GSI and the GIS User Community.

The region where these earthquakes occurred is known as the southern Walker Lane, just north of the Eastern California Shear Zone (ECSZ), both of which help accommodate deformation within the Pacific – North American plate boundary (Wesnousky, 2005). Notable prior historical earthquakes in the region include the 1992 Landers and Big Bear earthquakes, as well as the 1999 Hector Mine earthquake. All of these were located to the southeast of the Ridgecrest earthquakes. The immediate Ridgecrest area has previously experienced smaller earthquake swarms associated with minor ground cracking and displacement since the 1980s.

FIELD RECONNAISSANCE

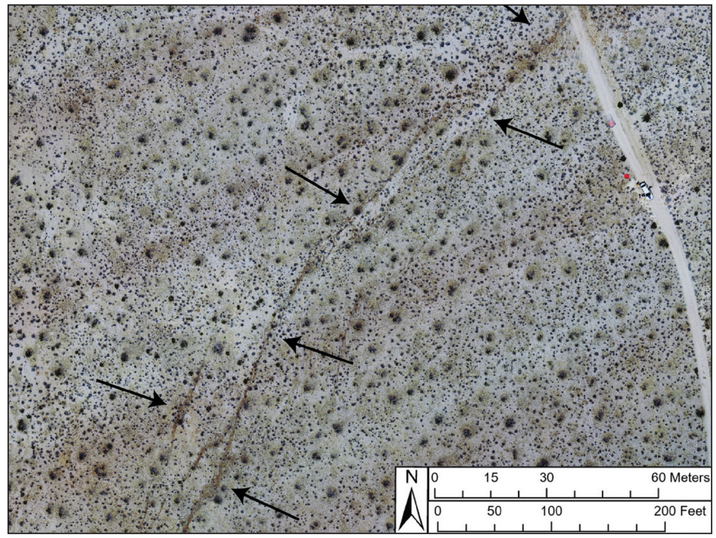
The Ridgecrest Earthquake Sequence provided a rare opportunity for geologists to observe and document the immediate effects of large earthquakes. The California Geological Survey (CGS) Seismic Hazards Program staff led the initial response to investigate the earthquakes' effects in the field, along with scientists from the United States Geological Survey (USGS) and other scientific agencies and academic institutions. Field response following the 2019 earthquakes included more than 6,000 on-the-ground site observations, of which more than 1,100 included measurements of ground offset, resulting in the mapping of over 68 km (42 miles) of surface rupture produced from both earthquakes (Ponti et al., 2020).

Field mapping and studies following the earthquakes show that the Salt Wells Valley Fault Zone is a mostly continuous, left-lateral fault zone that trends northeast-southwest for approximately 18 km. The largest offset along the Salt Wells Valley Fault Zone is almost 1.6 m of left-lateral movement, observed in the field southwest of the intersection with the Paxton Ranch Fault Zone



This map shows the 2019 Ridgecrest, the 1992 Landers and Big Bear, and the 1999 Hector Mine epicenters. Thick, black and thin grey lines depict Quaternary age faults. Lavic Lake Fault (LLF); Pisgah-Bullion Fault Zone (PBFZ); Camp Rock Fault (CRF); Emerson Fault (EF); Homestead Valley Fault (HVF); Johnson Valley Fault Zone (JVFZ); Pinto Mountain Fault (PMF); San Jacinto Fault (SJF); Sierra Madre Fault Zone (SMFZ); Newport-Inglewood Fault Zone (NIFZ); Elsinore Fault Zone (EFZ). Source: Quaternary Fault and Fold Database, version 3, USGS and CGS, 2023.

CGS geologist Tim Dawson (in green shirt at top of image) shows U.S. Navy staff surface fault rupture related to the July 5, 2019, M7.1 earthquake on the Paxton Ranch fault. Photo: Ken Hudnut, USGS



Left image shows Nathaniel Roth preparing to pilot the DJI Matrice 210 for post-earthquake field reconnaissance. Photo by Kate Thomas, CGS. Right image depicts aerial imagery acquired during post-earthquake field reconnaissance. Black arrows point to trace of surface rupture.

(DuRoss et al., 2020). The Paxton Ranch Fault Zone is characterized by right-lateral movement along a ~50 km (31 miles) long northwest trending fault zone. Right-lateral offsets observed following the M7.1 were as high as 7 m (23 ft) near its epicenter (DuRoss et al., 2020).

ADVANCES IN FAULT MAPPING

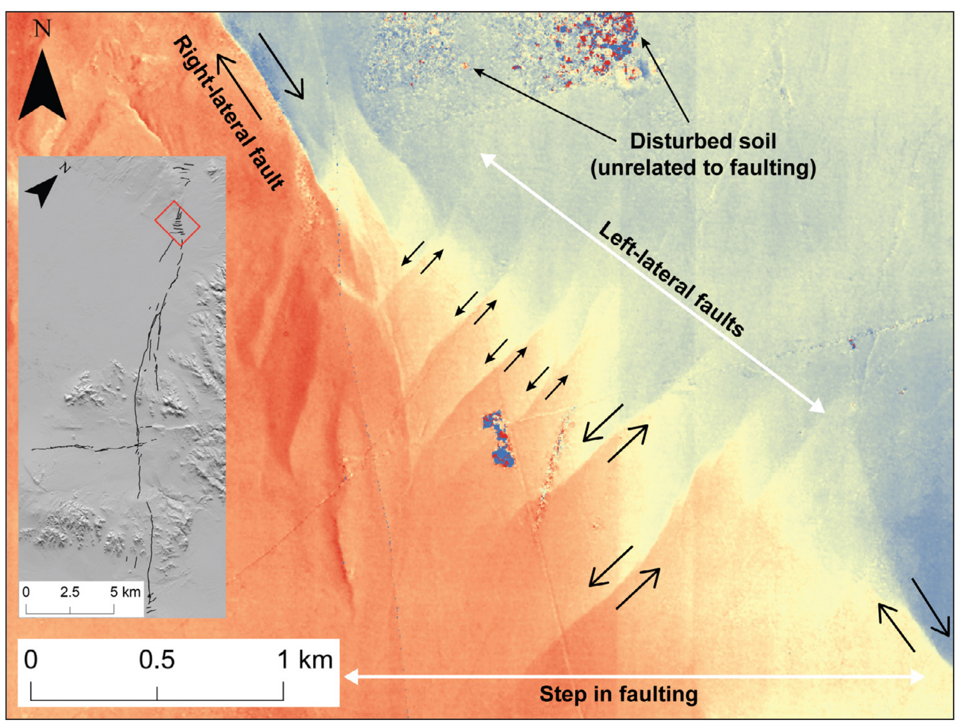
Field Reconnaissance

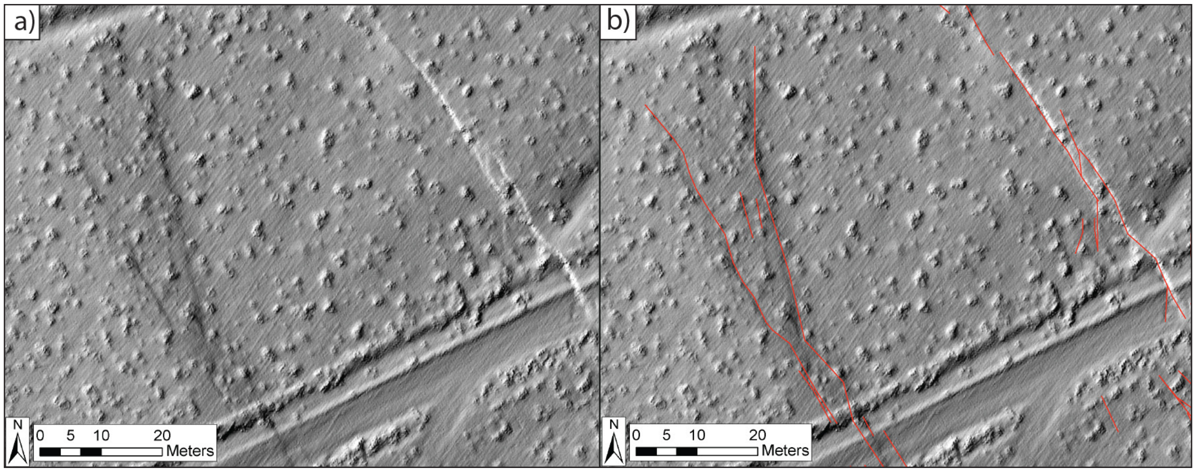
The Ridgecrest Earthquake Sequence provided the CGS with the opportunity to make advances in post-earthquake reconnaissance and fault mapping, such as implementing a digital data acquisition application (Collector for ArcGIS) which facilitated the collection of over 6,000 on-the-ground site observations. This allowed for faster data acquisition, ensured data quality, and provided seamless compilation of those data into a single database. This event also was the first post-earthquake reconnaissance where CGS flew the Da-Jiang Innovations (DJI) Matrice 210 drone to acquire video and images of the surface rupture.

In addition to field data collection advancements, remote mapping of surface rupture and ground deformation features on lidar allowed for a comprehensive and spatially accurate dataset of post-earthquake mapping at a consistent scale that captured previously unmapped features (Rosa et al., 2024). These mapped surface ruptures aided in the creation of Alquist-Priolo Earthquake Fault Zones (APEFZ), which are used for hazard disclosure under the Natural Hazard Disclosure Act and may trigger a geotechnical investigation if development is proposed within the APEFZ.

Remote Sensing Technologies

Optical image correlation is a relatively new method used to document the location and amount the ground moved during an earthquake. This technique involves using pre- and post-earthquake imagery, registered to known locations on the earth, to measure the difference between the two images. A variety of imagery can be used including satellite and aerial images collected from airplanes, helicopters, and/or drones. Following the 2019 Ridgecrest earthquakes,





Example of appearance of both east- and west-facing scarps on lidar at 1:700 scale. a) shows features without corresponding mapping; b) shows mapping of features in red. Base is the multi-directional hillshade.

optical image correlation was used to produce maps that highlight the complex patterns of surface faulting that occurred. This technique has great potential to quickly identify where surface deformation has occurred, enabling emergency responders to quickly deploy resources for infrastructure (such as roads, pipelines, buildings) repair (Morelan and Hernandez, 2020).

LEARNING FROM EARTHQUAKES

The 2019 Ridgecrest earthquakes provided an opportunity to collect a rich and unique dataset of observations that can be used to improve our understanding of earthquakes, test new technologies, and ultimately, allow us to better prepare for future earthquakes. Geologists were able to rapidly collect thousands of observations on the ground making this one of the best-documented earthquakes in California. New technologies such as lidar and the use of uncrewed aerial vehicles (UAVs, or drones) were employed to rapidly map the location of surface faulting. Recently developed techniques using satellite imagery and advanced computer processing software showed that surface deformation could be rapidly identified and measured using imagery from before and after the earthquake. These observations are essential in helping emergency managers quickly understand where earthquake damage has occurred following an earthquake and helps them rapidly deploy emergency resources where they are needed most.

Documentation of earthquake effects is also important in improving our understanding of earthquakes. This documentation leads to new and updated earthquake fault zone maps, produced by the CGS to protect the life and safety of Californians (Rosa et al., 2024; see Earthquake Hazard Zones Application (EQ ZApp)). Eventually these post-earthquake studies can lead to improvements in the engineering of buildings, pipelines, and bridges to resist damage during earthquakes.

Opposite page: This map shows displacements near the north end of the 2019 surface rupture as derived from COSI-Corr, an optical image correlation algorithm (Leprince et al., 2009) which utilized National Aerial Imagery Program (NAIP) collected from an airplane as a pre-earthquake baseline image and Pleiades satellite-based imagery as a post-earthquake image to map fault displacements. Inset depicts extent of surface rupture as mapped from COSI-Corr (black lines) and location of main image (red box). The colors in the main image show the magnitudes of movement (red shows relative northward movement and blue shows relative southward movement). Sharp discontinuities in the color ramp are surface-rupturing faults with displacement greater than around 20 cm (8 in). Black arrows show relative movement of the faults that moved during the earthquake. The complexity of faulting is illustrated by the width of deformation, steps in the faulting, and different fault orientations.

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Leprince, S., et al., 2009, Co-Registration of optically sensed images and correlation (COSI-Corr): an operational methodology for ground deformation measurements: http://www.tectonics.caltech.edu/slip_history/spot_coseis/ (accessed August 2024).

Morelan, A.E., and Hernandez, J.L., 2020, Increasing postearthquake field mapping efficiency with optical image correlation: Bulletin of the Seismological Society of America, v. 110, no. 4, p. 1419-1426, doi:10.1785/0120200034.

Ponti, D.J. et al., 2020, Documentation of surface fault rupture and ground-deformation features produced by the 4 and 5 July 2019 MW 6.4 and MW 7.1 Ridgecrest Earthquake Sequence, Seismological Research Letters, v.91, no.5, p. 2942-2959, doi:10.1785/0220190322.

Rosa, C.M., 2024, The Paxton Ranch and Salt Wells Valley Fault Zones, with modifications to the Airport Lake and Little Lake Fault Zones in the White Hills, Burro Canyon, Ridgecrest North, Lone Butte, Westend, Spangler Hills West, Spangler Hills East, and Christmas Canyon 7.5-Minute Quadrangles, Inyo, Kern, and San Bernardino Counties, California: California Geological Survey Fault Evaluation Report FER 274, 13 p.

Rosa, C. M., Dawson, T.L., and Kakaria, R., 2024, Surface rupture mapping of the 2019 M6.4 and M7.1 Ridgecrest Earthquake Sequence on Lidar and orthoimagery: California Geological Survey Special Report 257, 37 p.

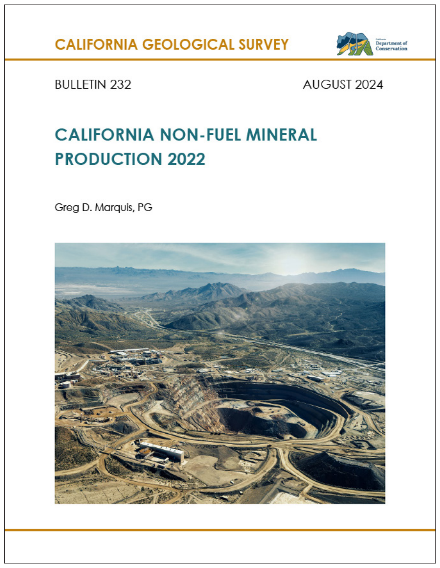
Wesnousky, S.G., 2005, Active faulting in the Walker Lane: Tectonics, v. 24, no. 3, 35 p., doi:10.1029/2004TC001645.

CGS Publications

RELEASED IN 2024

BULLETINS (B)

Bulletin 232: *California Non-Fuel Mineral Production 2022*



DATA RELEASES (DR)

DR 2024-1: *Data Release for the Del Norte Nickel-Cobalt Laterite Geochemical Reconnaissance Project*

GEOLOGIC DATA MAPS (GDM)

GDM 8: *California Strong Motion Instrumentation Program Network Stations*

FAULT EVALUATION REPORTS (FER), SEISMIC HAZARD ZONE REPORTS (SHZR)

AND RELATED EARTHQUAKE ZONES OF REQUIRED INVESTIGATION MAPS (EZRIM)*

FER 268: *The San Andreas Fault Zone in the San Mateo, Woodside, Palo Alto, and Mindego Hill 7.5' Quadrangles, San Mateo and Santa Clara Counties*

FER 270: *The Southern Rodgers Creek Fault Zone in the Sears Point, Petaluma River, Glen Ellen, Cotati, and Santa Rosa 7.5' Quadrangles, Sonoma County*

FER 273: *The San Andreas Fault Zone in the Burnt Peak, Lake Hughes, and Del Sur 7.5' Quadrangles, Los Angeles County*

FER 274: *The Paxton Ranch and Salt Wells Valley Fault Zones, with Modifications to the Airport Lake and Little Lake Fault Zones in the White Hills, Burro Canyon, Ridgecrest North, Lone Butte, Westend, Spangler Hills West, Spangler Hills East, and Christmas Canyon 7.5' Quadrangles, Inyo, Kern, and San Bernardino Counties*

SHZR 134: *Seismic Hazard Zones in the Richmond, Mare Island, and San Quentin 7.5' Quadrangles, Contra Costa County*

SHZR 135: *Seismic Hazard Zones in the Vine Hill 7.5' Quadrangle, Contra Costa County*

SHZR 136: *Seismic Hazard Zones in the Walnut Creek 7.5' Quadrangle, Contra Costa County*

SHZR 137: *Seismic Hazard Zones in the Diablo 7.5' Quadrangle, Contra Costa County*

SHZR 138: *Seismic Hazard Zones in the Benicia and Briones Valley 7.5' Quadrangles, Contra Costa County*

SHZR 139: *Seismic Hazard Zones in the Oakland East and Las Trampas Ridge 7.5' Quadrangles, Contra Costa County*

SHZR 140: *Seismic Hazard Zones in the Hayward, Dublin, and Livermore 7.5' Quadrangles, Contra Costa County*

PRELIMINARY GEOLOGIC MAPS (PGM)

PGM 21-02, v2.0: *Preliminary geologic map of the Black Mountain 7.5' Quadrangle, Los Angeles and Ventura Counties*

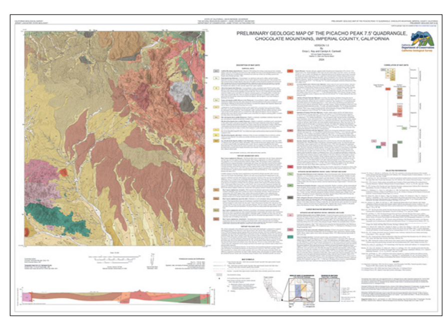
PGM 23-01: *Preliminary geologic map of the Columbia 7.5' Quadrangle, Calaveras and Tuolumne Counties*

PGM 23-02: *Preliminary geologic map of the Liebre Mountain 7.5' Quadrangle, Los Angeles County*

PGM 24-04: *Preliminary geologic map of the Hedges 7.5' Quadrangle, Chocolate Mountains, Imperial County*

PGM 24-05: *Preliminary geologic map of the Ogilby 7.5' Quadrangle, Cargo Muchacho Mountains, Imperial County*

PGM 24-06: *Preliminary geologic map of the Picacho Peak 7.5' Quadrangle, Chocolate Mountains, Imperial County*



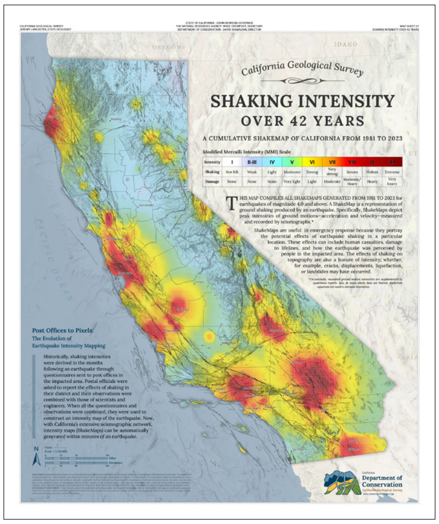
***EZRIM LISTED BY COUNTY – Contra Costa:** *Benicia, Briones Valley, Diablo, Dublin, Hayward, Las Trampas Ridge, Livermore, Mare Island, Oakland East, Richmond, San Quentin, Vine Hill, Walnut Creek;* **Inyo:** *Burro Canyon, White Hills;* **Kern:** *Lone Butte, Ridgecrest North, White Hills;* **Los Angeles:** *Burnt Peak, Del Sur, Lake Hughes;*

PUBLICATION ANNOUNCEMENTS VIA EMAIL

Be the first to know when we release new publications. Sign up at https://www.conservation.ca.gov/cgs/publications/releases

MAP SHEETS (MS)

MS 67: *Cumulative ShakeMap of California from 1981 to 2023 [Shaking Intensity Over 42 Years]*



SMIP SEMINAR PROCEEDINGS

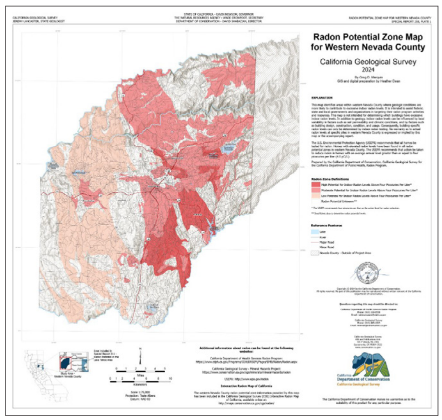
SMIP23: *Proceedings of the SMIP 2023 Seminar on Utilization of Strong-Motion Data*

SPECIAL REPORTS

SR 256: *Radon Potential in Western El Dorado County*

SR 257: *Surface Rupture Mapping of the 2019 M6.4 and M7.1 Ridgecrest Earthquake Sequence on Lidar and Orthoimagery*

SR 258: *Radon Potential in Western Nevada County*



WATERSHED EMERGENCY RESPONSE TEAM (WERT) EVALUATIONS

Airport Fire, Orange and Riverside Counties

Borel Fire, Kern County

Bridge Fire, Los Angeles and San Bernardino Counties

Franklin Fire, Los Angeles County

French Fire, Mariposa County

Lake Fire, Santa Barbara County

Line Fire, San Bernardino County

Mountain Fire, Ventura County

Park Fire, Butte and Tehama Counties

WEB APPLICATIONS

Mineral Resources Data Portal

Dr. Perry Ehlig's Geologic Research Collection (StoryMap)

Ridgecrest Earthquake Sequence - 2019 (StoryMap)

PUBLICATIONS IN THE PIPELINE FOR 2025

Note: Titles are subject to change until the day of publication.

GDM 9: *Sierra Nevada Earth Science Atlas*

MS 48: *Earthquake Shaking Potential for California (update)*

MS XX: *Geologic map of a portion of the western Cady Mountains, San Bernardino County*

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*

PGM 25-01: *Preliminary geologic map of the Rosamond 7.5' Quadrangle, Los Angeles and Kern Counties*

PGM 25-02: *Preliminary geologic map of the Colfax 7.5' Quadrangle, Placer County*

PGM 25-03: *Preliminary geologic map of the Burbeck 7.5' Quadrangle, Mendocino County*

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*

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*

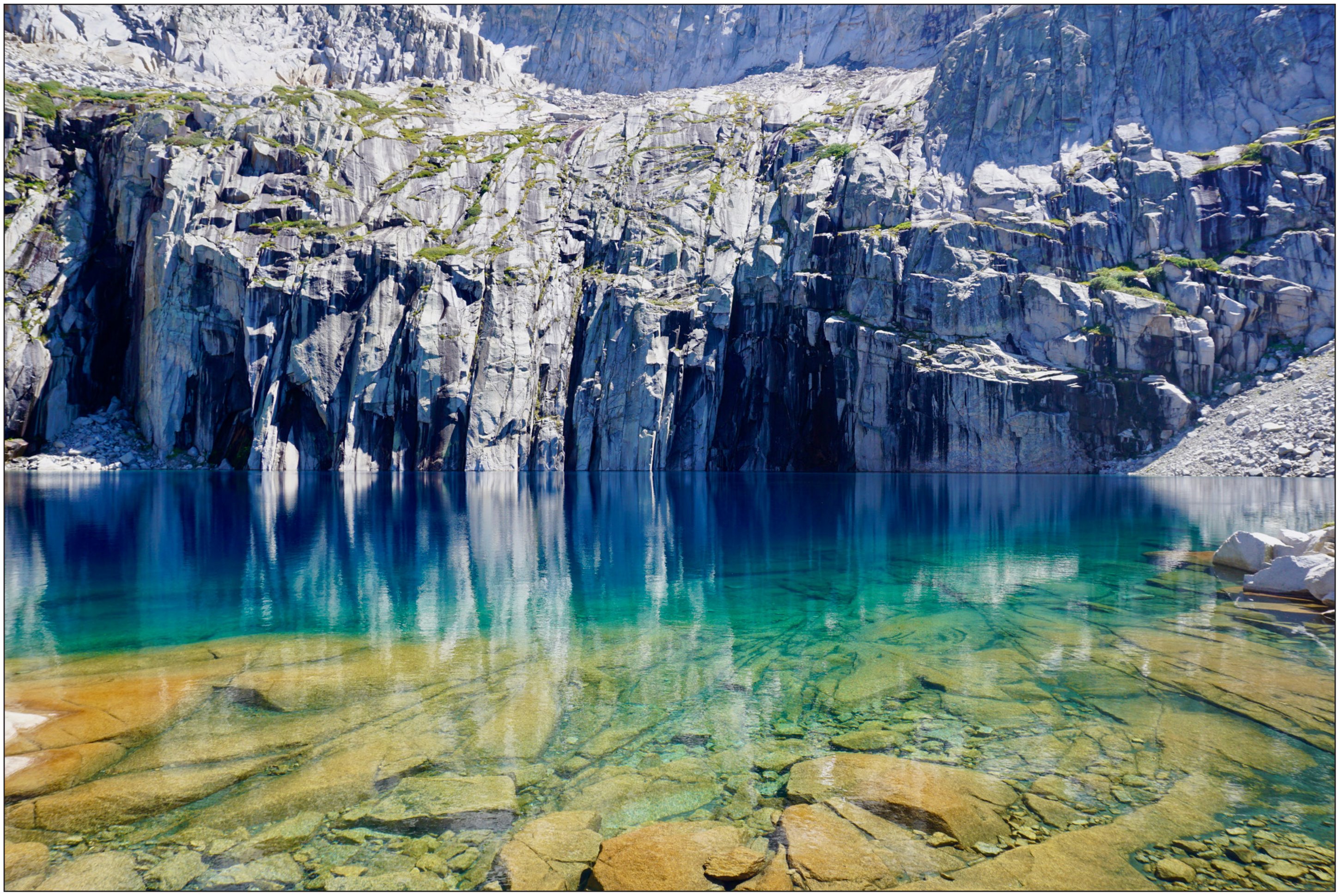
SHZR 143: *Seismic Hazard Zones in the Sebastopol 7.5' Quadrangle, Sonoma County*

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

SR 259: *Submarine Landslides Offshore California*

Web applications: Critical Minerals; Geologic Map Index; Publications Search

(EZRIM by county, continued) **San Bernardino:** *Burro Canyon, Christmas Canyon, Lone Butte, Ridgecrest North, Spangler Hills East, Spangler Hills West, Westend, White Hills;* **San Mateo:** *Palo Alto, San Mateo, Woodside;* **Santa Clara:** *Palo Alto, Mindego Hill;* **Sonoma:** *Sears Point, Petaluma River, Glen Ellen, Cotati, Santa Rosa.*



1st place: Precipice Lake, along the High Sierra trail/Big SEKI loop, Sequoia National Park. Photo by Kirk Townsend.

CGS Staff Photo Contest

IN 2024, CGS HELD AN INFORMAL PHOTO CONTEST open to staff. Many landscape images were submitted. Staff participated in blind voting where the names of the photographers were withheld; the top four vote-getters are shown here.

2nd place: Great Western Divide, view south from Elizabeth Pass trail, Sequoia National Park. Photo by Kirk Townsend.

[Above] 3rd place: Snow Creek debris flow deposits, Forest Falls, San Bernardino County. Photo by Paul Burgess.

[Left] 4th place: Mesquite Flat Sand Dunes, Death Valley National Park. Photo by Tim Dawson.

Turn the page to see more from our talented staff . . .

6. Rainbow from Monitor Pass - Bob Moskovitz

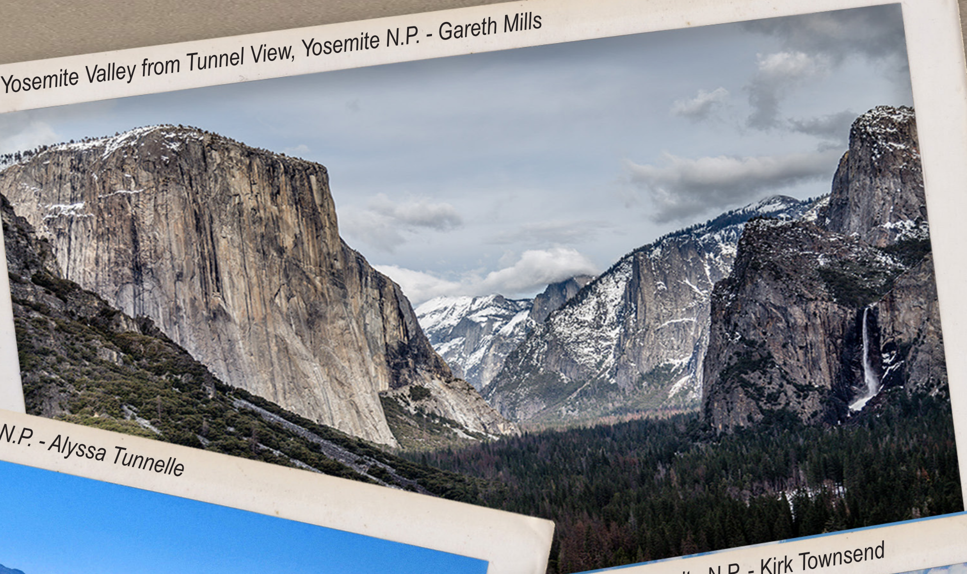
8.

11. Badlands around Manly Beacon, Death Valley

12. “Speed Racer” at Racetrack Playa, Death Valley N.P. - Tim Dawson

10. Manly Beacon from Zabriskie Point, Death Valley N.P. - Tim Dav

5. Mt. Morrison roof pendant by Brian Swanson (this issue’s cover image)



Yosemite Valley from Tunnel View, Yosemite N.P. - Gareth Mills

N.P. - Alyssa Tunnelle

9. View north from Red Peak Pass, Yosemite N.P. - Kirk Townsend

wson

7. Tulainyo Lake, highest lake in California - Brian Swanson