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Geology and Minerals Issues

ABSTRACT

This chapter consists of maps and text describing possible undiscovered and known ore deposits, mineral-development issues, public health and safety issues such as asbestos, mercury, and open-pit mines, the role of calcium, as well as the hazards posed by volcanoes and earthquakes in the Sierra Nevada ecosystem. Maps of likely undiscovered and known deposits of gold, copper, sulfide, and others show the present distribution of such ores and are useful in metal-supply issues, water quality studies, and planning for avoiding environmental hazards. Information on exploration shows potential for development and is important to rural communities, the general economy, employment, and mineral supply. Mercury has important effects on plant communities and water systems in the Sierra Nevada ecosystem, with possible consequences for humans. Asbestos occurs naturally in the study area, though its health risk for humans is controversial. Calcium from carbonate rocks is essential for metabolic processes of aquatic life and in the buffering system of waters in the area. Volcanic activity and earthquakes have played a major role in shaping the environment of the study area.

EARTH SCIENCES OVERVIEW

Geology

As part of the U.S. Geological Survey (USGS) National Mineral Resource Assessment Program, an overview of California minerals was produced by Dellinger (1989), excerpts of which are reproduced here. The Sierra Nevada extends 644 km (400 mi) from the Modoc Plateau in the north to the Mojave Desert in the south; it varies in width from 64 to 161 km (40 to 100 mi). The range is highest and most rugged along much of its east side, and overall elevation gradually decreases to the west. The range can be divided into western and eastern belts that have different geological characteristics. The western belt, along the west edge of the north half of the range, consists of Paleozoic to Mesozoic oceanic, island-arc, and composite terranes that are intruded by Mesozoic quartz dioritic to granodioritic plutons. These three terranes form narrow bands that parallel the trend of the range; generally the oceanic terrane band is closest to the core of the range, and the island-arc terrane band lies along the west edge. The eastern belt of the Sierra Nevada is batholithic terrane, composed almost entirely of Mesozoic granodioritic to granitic plutons that enclose remnants of older Mesozoic, deep-marine volcanic and clastic rocks in its western part and Paleozoic, shallow-marine quartzose and carbonate rocks in the eastern part. The different geologic characteristics of the eastern and western belts are reflected in the different mineral deposit types found in these two regions.

The western belt is historically important as the center of the California gold rush in the middle nineteenth century. The Mother Lode is in the western belt, and about a third of California's total gold production was taken from gold-quartz veins in this region; the belt contains nearly all the large lode-gold deposits in California (Albers, 1981). Virtually the entire western belt is considered geologically permissive for mineral deposits containing gold, chromium, nickel, copper, zinc, manganese, or mercury, and about a third of the belt has numerous known deposits of one or more of these metals. The large disseminated-gold deposit at Jamestown, southwest of Sonora, lies within the western belt. Gold-quartz vein deposits are present in all three terranes of this belt, but the existence of other mineral deposit types is more restricted. Podiform chromite and laterite nickel deposits are associated with ultramafic rocks that occur typically within or at the margins of oceanic and composite terranes. Chert-associated manganese deposits occur mostly in oceanic and composite terranes, but they also occur in a small area of island-arc terrane that lies northeast of the oceanic terrane at the north end of the range. Pyrite-rich massive sulfide deposits are restricted to the island-arc band.

Sierra Nevada Ecosystem Project: Final report to Congress, vol. II, Assessments and scientific basis for management options. Davis: University of California, Centers for Water and Wildland Resources, 1996.

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Internet Access to SNEP Earth Sciences Data

The files produced by the USGS and the U.S. Bureau of Mines for the Sierra Nevada Ecosystem Project (SNEP) are on the Internet and available via anonymous file transfer protocol (FTP) from mojave.wr.usgs.gov/pub/mdiggles/snep. This area also contains a text file, `contents.txt`, that describes the files in the directory. The maps were produced by Barry C. Moring and Robert J. Miller of the USGS and Charles Bishop of the U.S. Bureau of Mines. Users may address questions to Michael F. Diggles at USGS via e-mail at mdiggles@mojave.wr.usgs or phone (650) 329-5404. A summary of U.S. Geological Survey and U.S. Bureau of Mines work for SNEP is available via the Internet's World Wide Web (WWW) in a Home Page whose Universal Resource Locator (URL) ("address") is http://caldera.wr.usgs.gov/mdiggles/SNEP-USGS.html.

MINERAL DEPOSITS IN THE SIERRA NEVADA

The major minerals issues within the SNEP study area concern metallic deposits of gold, silver, copper, lead, and zinc. Tungsten and industrial minerals such as sand and gravel are also potential issues. The assessments of undiscovered resources that are part of the USGS Mineral Resource Surveys program provide useful tools for addressing minerals issues. Some areas that are permissive for undiscovered mineral resources are areas where, were a deposit discovered and developed, an environmental impact could take place. Knowledge of where such deposits are likely to be prepares land-use managers to help minimize impacts.

For mineralized rock in a deposit to be considered "ore," it must be possible to mine it at a profit. The quantitative assessment presents numerical estimates of amounts of copper, zinc, lead, silver, and gold in undiscovered mineral deposits. It does not include additions to resources that can be made by extending known deposits. That an undiscovered deposit might exist does not mean it will be discovered or, if discovered, if it will be mined.

Quantitative Resource Assessment Technique

This resource assessment is part of a pilot project for an ongoing assessment of all mineral resources in the United States. The purpose of the assessment is to maintain a consistent, minimum level of current mineral-resource information so that such information can be considered in planning for the optimum use of public lands and for obtaining secure, long-term mineral supplies from domestic and international sources. Further details are given in McCammon and Briskey 1992. An assessment is an estimation or evaluation in this instance of undiscovered resources of base and precious metals within specific volumes of rock. This assessment is quantified in that the result is expressed in numbers. Because of the uncertainty inherent in such an assessment, the obtained results are presented probabilistically.

Methods used in this study are based on mineral deposit models. Mineral deposit models are collections of data in a convenient form that describe a group of deposits that have similar characteristics and origins. They are based on worldwide literature and observation. They contain information on the common geologic attributes of the deposits and the environments in which they are found. Grade and tonnage models consist of information on the grade and size of the individual deposits, which serve as examples for that deposit type. To begin an assessment, we review the geology of the area and select appropriate deposit models. We then delineate permissive tracts for each type of deposit. The permissive tract is defined by the environments of formation described in the deposit model. Geologic maps and maps showing location and type of mineral deposits and occurrences, if any exist, are used in outlining these permissive tracts. Geophysical and geochemical maps as well as satellite images, are also useful, and the exploration history may be important. Estimates of undiscovered resources are made to a depth of 1 km (0.6 mi) beneath the surface of the permissive tract. If an area of permissive rock is covered by more than 1 km (0.6 mi) of rock or sediment, it is excluded from the tract. Then we review the worldwide data on grade and tonnage for each model. Reasoning by analogy, the undiscovered deposits that are estimated in the area should be similar in grade and tonnage to known examples. For many deposit types, these data are available in the form of grade and tonnage models in USGS Bulletins 1693 (Cox and Singer, 1986) and 2004 (Bliss, 1992).

We review the grade and tonnage data for known deposits, if there are any, in the tract, decide whether the worldwide models are appropriate for the tract, and modify them if necessary. In well-exposed areas the largest deposits are often discovered first, and we consider how this might affect the expected tonnage of undiscovered deposits.

The Mineral Resource Data System (MRDS) of the USGS is a computerized database containing nearly 110,000 records of mines, prospects, and occurrences throughout the world. Records can contain detailed information on the name(s), location, commodities, exploration and development, deposit description, geology, references, production, and reserves and resources. Most of the data have been collected from published literature and unpublished files maintained by USGS geologists. Additionally, some data have come from the field observations of USGS geologists and, to a lesser degree, contributions from other federal agencies (such as the U.S. Bureau of Mines, U.S. Forest Service, U.S. Bureau of Land Management [BLM], U.S. Department of State), state geological surveys, mining companies, and private consultants. Plans are under way to release MRDS and its updates on CD-ROM in the near future. For access to MRDS in the meantime, contact Nancy Milton, Acting Eastern Regional Geologist, or Joseph S. Duval, Eastern Minerals Chief Scientist, at the USGS, 12201 Sunrise Valley Drive, Reston, Virginia 22092. For small requests, contact the senior author, Michael F. Diggles.

Finally, we estimate the number of undiscovered deposits of each type in the permissive areas. The estimates are subjective and are expressed in terms of percentage chance of X or more deposits. Estimates are made by teams of geoscientists who know about the deposit type or about the area, preferably both. The result of the estimation process is a probability distribution of numbers of undiscovered deposits. Details regarding the deposit estimation procedure are given in Root et al. 1992, which include a an explanation of the Mark 3 simulation program.

The deposits estimated should be consistent with the grade and tonnage model. That is, if ten deposits are estimated, five of them are visualized to be larger than the median tonnage and five of them (not necessarily the same five) are visualized to have a higher grade than the median grade. If the grade and tonnage model is based on district data, then the number of undiscovered districts is estimated.

There are many geologic, geochemical, and geophysical characteristics useful in estimating undiscovered mineral deposits. Estimates can be guided by counting mineral occurrences, geochemical anomalies, or exploration “plays” and assigning to each a probability of its being a member of the grade and tonnage distributions. Estimates can also be guided by analogy with well-explored areas that contain known numbers of deposits and that are geologically similar to the study area. Areas with geologic or morphologic structures commonly associated with mineralization are likely permissive.

The probability distribution of numbers of undiscovered deposits is then combined with probability distributions for tonnage and grades. A Monte Carlo simulation technique is used to select randomly, from each distribution, a number, a tonnage, and a grade. This procedure is done iteratively by computer many thousands of times, and a new probability distribution is generated that shows the distribution of contained metal.

Qualitative Descriptions

Quantitative assessments were made for lead, copper, zinc, gold, and silver. In addition to these assessments, treated in separate sections later, qualitative descriptions and discussion of issues for some other deposit types are included here.

Placer Gold and Recreational Prospecting

Information on placer gold and recreational prospecting is useful to rural communities and also to studies of spawning gravels in riparian habitat and in water-clarity work. Anecdotal information from the Gold Prospectors Association of America suggests that about 50,000 to 100,000 Californians a year engage in recreational prospecting in the Sierra Nevada. An additional 10,000 to 20,000 nonresidents are thought to participate as well. The average recreational prospector spends from three to ten days a year in this activity and spends perhaps $50 a day in the local areas. Under the Mining Law of 1872, placer deposits can be claimed, and the claim holder acquires the mineral rights. In 1994, to increase public access to placer deposits for recreational prospecting, the BLM has removed from Mining Law coverage the 11 km (7 mi) stretch of the Mokolumne River from Highway 49 to Electra and now issues two-week permits for prospecting in placer deposits there. The U.S. Bureau of Mines has summarized placer locations on maps elsewhere in this chapter that show areas with the greatest number of occurrences.

Tungsten Mineralization

Tungsten, with associated gold, silver, copper, and molybdenum, is found in narrow bands of highly altered rock (“tactite” or “skarn”) at contacts between granitic intrusions and metamorphosed calcareous sedimentary rocks (Einaudi and Burt 1982). Most of these deposits occur at the margins of metamorphic rock pendants generally located in the eastern part of the central Sierra Nevada.

In 1916, deposits of scheelite, a tungsten-bearing mineral, were discovered in the Pine Creek area (Bateman 1965). The Pine Creek mine began operation in 1918; it has been among the free world’s largest tungsten producer. Scheelite has also been discovered and mined in the nearby Mount Morrison area and in numerous small bodies of calcareous metamorphic rocks elsewhere in the east-central Sierra Nevada. The Pine Creek and Mount Morrison pendants contain most of the known tungsten resources in the Sierra Nevada (Newberry 1982). The Pine Creek mine and associated deposits, which lie just outside the eastern boundary of the John Muir Wilderness in the Pine Creek pendant, form the largest, most productive tungsten reserves in the United States (du Bray et al. 1982), with proven reserves of 1.5 million tons of mineralized rock as of 1995. The Pine Creek mine shut down when President Carter, in reaction to the former Soviet Union’s invasion of Afghanistan, put an embargo on such high-tech exports to the former USSR as deep-drilling technology for Siberia. As a result, Hughes Tool Company required less tungsten for the production of drill bits. By the time the embargo was lifted, United States trade relations with China—the country with the largest tungsten deposit in the world—had been normalized. Availability of low-cost Chinese tungsten and the lower demand for bomb casings since the end of the Vietnam War have kept the world price at a level too low for the Pine Creek mine to be reopened. A joint venture of Strategic Minerals Corporation of Connecticut and Avocet Ventures, Inc., of London hopes to mine Pine Creek reserves in the near future (R. Kattelmann, letter to M. Diggles, August 1995). In the long run, the world’s known tungsten reserves can do nothing but decrease. For mineralized rock to be considered “ore,” it must be possible to mine it at a profit, something that has not been done at Pine Creek recently. Because the Pine Creek mine is located on the up-thrown side of the Sierra Nevada front fault, water drains from the mine without the use of pumps. The tendency of the mine to drain naturally and the fact that the ore here falls easily into the crusher enhance the potential that operators will reopen the mine sometime in the future.

North of Lake Tahoe, the Sierra Nevada batholith contains a few roof pendants that have deposits of, and are geologically permissive for, tungsten or gold deposits. Much of the area between Lake Tahoe and Bridgeport is permissive for gold, tungsten, mercury, manganese, or uranium in skarn deposits in roof pendants and in hot-spring, vein, and other deposits in Cenozoic volcanic rocks, but known deposits are sparse (Dellinger, 1989). South of Bridgeport, the batholithic terrane contains numerous roof pendants; collectively, these bodies have numerous deposits of, and are considered to be geologically permissive for, tungsten and molybdenum in skarn deposits, gold in quartz veins, iron in epigenetic magnetite deposits, or chromium in podiform chromite deposits that occur in roof pendants of oceanic affinity along the west edge of the batholith. Batholithic rocks along the central east edge of the Sierra Nevada, from Mono Lake to Independence, contain numerous roof pendants and are considered to be geologically permissive for deposits of tungsten and gold. Deposits of tungsten, gold, or molybdenum occur locally, but known deposits are sparse or absent in most of this area. Most of the Sierra Nevada south of the thirty-sixth parallel is considered to be geologically permissive for gold, tungsten, lead, zinc, antimony, or mercury in roof-pendant skarn deposits or in gold-quartz and other vein deposits. Known deposits of gold, tungsten, antimony, or mercury occur in parts of the area, but most of the area lacks known deposits.

Sand and Gravel

Sand and gravel production in California had a total value 1.2 times as much as gold in 1994. Sand and gravel deposits are abundant in alluvium in the lower parts of drainage basins. Development of these deposits is limited by the high cost of transporting them to markets, but as sources closer to the markets are depleted and Sierra Nevada population centers grow, these resources will become more important. As the highway systems widen, expand, and need repair or replacement, the need for sand and gravel deposits will increase. A consideration in developing these deposits is the potential for a significant impact on riparian habitat and siltation of streams needed for clean water supplies. A source of sand and gravel available in some parts of southern California is closed military bases, particularly low-lying alluvial areas occupied by airfields. These areas, however, sometimes contain dump sites for fuels and solvents that have permeated the gravels (L. Darlene Batatian, conversation with Michael F. Diggles, December 1991). With these issues in mind, such deposits may be available to fill the needs in parts of the Sierra Nevada. Land-use planners need to be able to adjust from heavy-industry sand and gravel production during the life of the deposit to some other land use after the deposit is depleted (Kockelman 1990). The sites need to be reclaimed for other uses, particularly for urban buildout that is moving toward these deposit sites.

Environmental problems in the sand and gravel industry faces include damage to riparian habitat and fisheries, water quality, air emissions of small particulate matter, diesel-engine emissions, and blasting activities. Commercial and housing developments are being built ever closer to these operations, and as potential issuers of complaints against ground vibrations, their needs must be met (Clark 1992). Dust can be controlled by watering down the operation or other more sophisticated methods (Scherer, 1992). Solutions are apt to increase water-supply needs and introduce runoff considerations. Congress has been concerned with visibility around national parks and may enact new visibility regulations that could affect the industrial-mineral industry. Mining operations may be in conflict with wetlands programs in which a no-net-loss policy is common. There may be cases where industry has the opportunity to create wetlands.

LOW-SULFIDE GOLD-QUARTZ VEIN DEPOSITS

The Mother Lode held the world record for gold deposits for many decades. It still produces some gold today and has its own health and safety issues.

Descriptive Model

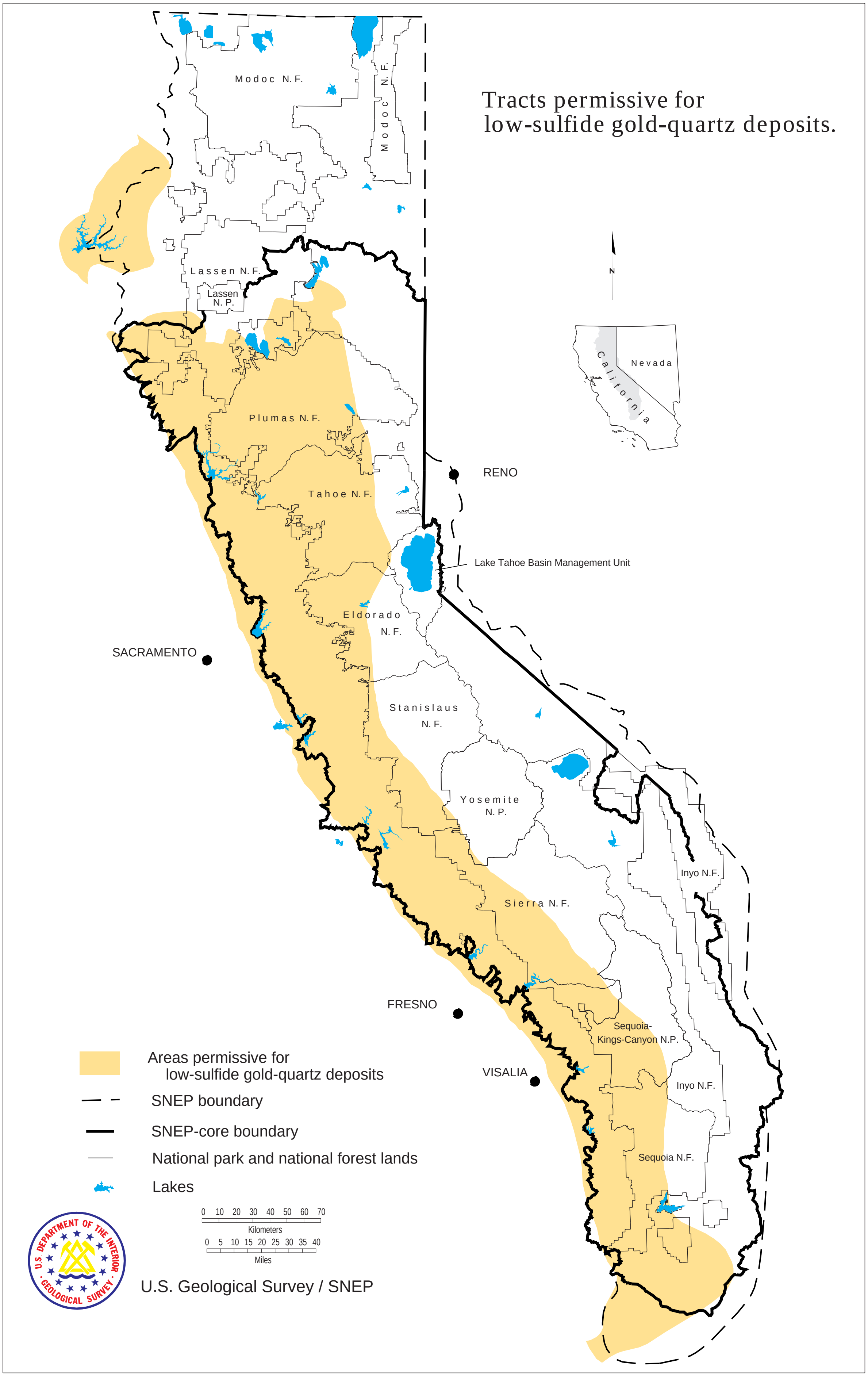
Low-sulfide gold-quarts vein deposits contain gold in massive persistent quartz veins mainly in shear zones in regionally metamorphosed volcanic rocks and volcanic sedimentary rocks (Model 36A, Berger 1986).

Rationale for Model Choice

Gold-bearing mesothermal quartz veins are localized along major deep-seated, through-going structural features in low- to moderate-grade marine metasedimentary and metavolcanic rocks. Many of the type examples used by Berger (1986) in the low-sulfide gold-quartz descriptive model (Model 36A) are in the Pacific Coast region.

Rationale for Tract Delineation

The permissive tract was defined principally by the location of low- to moderate-grade regionally metamorphosed marine sedimentary and volcanic rocks of Jurassic and older age, based on the state geologic maps for California and Oregon (Jennings 1977; Walker and MacLeod 1991) and the personal knowledge of the assessors (figure 18.1). Geophysical evidence



Tracts permissive for
low-sulfide gold-quartz deposits.
Modoc N.F.
Modoc N.F.
Lassen N.F.
Lassen N.P.
Plumas N.F.
Tahoe N.F.
Eldorado N.F.
Stanislaus N.F.
Yosemite N.P.
Sierra N.F.
Sequoia-Kings-Canyon N.P.
Inyo N.F.
Inyo N.F.
Sequoia N.F.
Lake Tahoe Basin Management Unit
RENO
SACRAMENTO
FRESNO
VISALIA
N
Nevada
California
Areas permissive for
low-sulfide gold-quartz deposits
SNEP boundary
SNEP-core boundary
National park and national forest lands
Lakes
0 10 20 30 40 50 60 70
Kilometers
0 5 10 15 20 25 30 35 40
Miles
U.S. Geological Survey / SNEP

Figure 18.1

was used to extend the tracts into areas of valley fill or thin Quaternary, Tertiary, or Cretaceous cover. In California most of the tract contains known gold deposits and includes those deposits in the famed California Mother Lode (Clark, 1976).

Potential Environmental Concerns

The following discussion was provided by Richard Goldfarb (letter to Michael F. Diggles, May 1995) of the Geochemistry Section of the Central Minerals Team at the USGS and is part of a draft mineral-environmental model book (Goldfarb et al. in preparation). The principal environmental concerns for low-sulfide gold-quartz vein deposits, also called Mother Lode deposits, are as follows:

- Potential for moderate amounts of acid mine drainage where local, relatively high sulfide concentrations occur in association with the gold ore, where broad zones of sulfide minerals characterize wall rocks, or where much of the ore is hosted by greenstones that have relatively low acid-buffering capacity.
- Oxidation of mine tailings or soils formed from unmined, yet sulfide minerals rock can convert harmless arsenopyrite to potentially harmful arsenates, arsenites, and methylarsenic species.
- Increased concentration of arsenic, antimony, and, less consistently, other trace metals downstream from occurrences. The use of cyanide for gold extraction at many active mines presents a potential additional contaminant in wastewater discharges.
- Mercury amalgamation carried out during historic operations may be a source of mercury contamination in aquatic life and in surface sediments for many tens of years post-mining. The use of mercury amalgamation and roasting for gold extraction is a direct and serious health concern.
- Disposal of tailings from deposit development can cause sedimentation problems in adjacent waterways.
- Modern open-pit mining methods, allowing for development of previously uneconomical, low-grade, low-sulfide gold deposits, provide quality-of-life concerns when mining is near population centers. These concerns include traffic, noise, and dust generation. Open-pit mining also produces significantly greater volumes of untreated waste rock.

Cyanide

Cyanide is commonly referred to as “toxic” but not “hazardous.” The distinction is that it can be harmful, but it can also be controlled with little difficulty. Cases occur, nonetheless, where it is not controlled despite the lack of difficulty. In about August 1995, there was a major breach of a cyanide-laced tailings pond in South America by a United States gold company that caused massive fish and livestock deaths. The company used helicopters to go down the river broadcasting to the local population of the oncoming cyanide-laced flood (James J. Rytuba, e-mail to Michael F. Diggles, August 1995).

Open-Pit Mines

The Jamestown mine is a former underground mine that was later mined by open-pit methods. Other underground workings may be open-pitted in the future, but the extent of such pits would be limited. The ore bodies tend to be tabular in nature, and, because they also tend to dip downward at an acute angle, accessing them by excavating a pit becomes increasingly expensive with depth (Richard M. Tosdal, conversation with Michael F. Diggles, September 1995). The pit at Jamestown is small by comparison to the pits at the large hot-springs-type deposits at McLaughlin (Coast Ranges) and Mesquite (Mojave Desert). Ore reserves the Mesquite mine are about 56 million tonnes (62 million short tons) and about 35 million tonnes (39 short tons) for the McLaughlin mine. By applying a 20% expansion factor and a density of 2.7 g/cc (grams per cubic centimeter), Mesquite’s figure converts to about 33 million cubic yards for the ore body. A stripping ratio of between 1:1 and 1:6 can be applied that will increase this volume. Nearly all the material stays on the site except for some wind-blown sediment, and dust-abatement treatment is applied to reduce this. The amount of material moved during even these large open-pit operations is small by comparison to the hydraulic mining of the 1880s. In 1880 alone, about 46 million cubic yards left the sites and entered the Sacramento and San Joaquin Rivers. Even more material left the sites but stayed in the drainages where it was mined. The amount of sediment that eventually settled in San Francisco Bay totaled more than 1.1 billion cubic yards (McPhee 1992), and that is just the fine-grained fraction.

The U.S. Geological Survey MRDS shows 106 open-pit mines in and within 10 km^2 (6.2 mi^2)of the SNEP study area (Lorre A. Moyer, e-mail to Michael F. Diggles, September 1995) (plate 18.1). Of these, forty-six are wholly within the SNEP study area. Within the SNEP study area, two deposits are listed in MRDS as “large,” the Jamestown gold mine and the Atlas asbestos mine. Three others are listed as “medium,” the B&B mercury mine and the Oasis clay mine, both in Esmeralda County, and the Tungstar tungsten mine in Inyo County. Forty are listed as “small.” Of the small open-pit mines, seven are gold, sixteen are other metals (chromium, copper, mercury, antimony, tungsten), and seventeen are nonmetallic (clay, talc, gems, mica). Sand and gravel operations constitute an open-pit mining activity that statewide is probably at least as extensive as the other minerals combined.

Arsenic Issues

The Central Eureka mine in Sutter Creek, Amador County, is one of 123 mineral deposits in a 16 km (10 mi) stretch of the Mother Lode belt that are in the USGS MRDS database. The Mesa de Oro housing project is situated on the mine lands

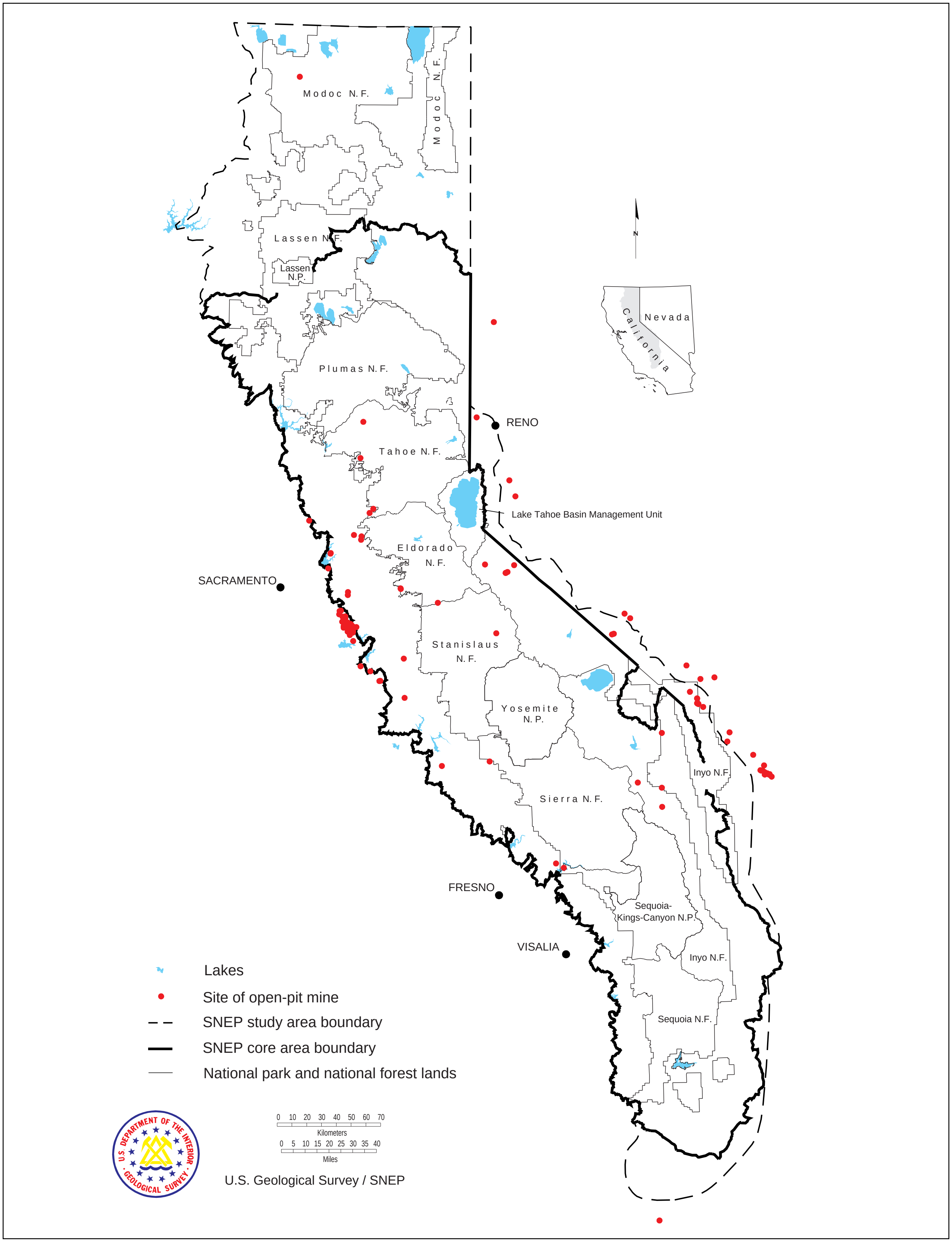


PLATE 18.1

Locations of open-pit mines within and near the SNEP study area.

and is the topic of an extensive U.S. Environmental Protection Agency (EPA) project addressing arsenic content. Other such sites may be of interest for buildout as the population of the Sierra Nevada increases and a workable, effective management strategy for dealing with arsenic in the Mother Lode becomes established.

Until arsenic-rich soils are covered, it is difficult to sell property because potential buyers cannot get mortgages. The community consists of one-third finished houses, one-third deserted houses, and one-third vacant lots. According to interviews with home owners, (M. F. Diggles, unpublished data), when two feet of topsoil are in place to cover the arsenic-rich surface that is there now, an attachment to each home owner's deed will state that the work has been done, so that banks will lend on the properties again. Work is also being done to stabilize the sides of the "mesa" because when it gets wet, the finely ground material runs off. Popular opinion is mixed, but generally it is felt that the EPA thresholds are fair. Measurements are 1,000 to 1,200 parts per million (ppm) arsenic compared to about a tenth that in Jackson. Many homes are built around Mother Lode tailings heaps in the foothills, but Mesa de Oro is the only housing project built on one.

Important Examples of Deposit Type

The low-sulfide gold-quartz grade and tonnage model is based on deposits containing 100 metric tons or more of gold (Bliss 1986). More than 50% of the deposits in the worldwide model (Bliss and Jones 1988) are located within this tract and include those of the California Mother Lode and the Grass Valley district in the Sierra Nevada foothills, as well as deposits in the Klamath, Siskiyou, and Trinity Mountains in northern California and southern Oregon. Several major mines in the tract are currently in operation or have been active recently. Most notable are the Harvard mine near Jamestown and the Royal Mountain King mine near Copperopolis, both in the California Mother Lode. Reserves at the Harvard mine are estimated to be in excess of 100 metric tons of gold (Bliss and Jones 1988).

Rationale for Numerical Estimate

The team concluded that nearly all deposits that are exposed at the surface have been discovered. The part of the tract most favorable for undiscovered deposits is that part that is covered by less than 1 km (0.6 mi) of Cretaceous sedimentary and Tertiary volcanic rocks between the Klamath Mountains and the Sierra Nevada. Estimates for this area were made using deposit density data. The shallow-covered region extending southeast from the Klamath Mountains has an area of 490 km^2 (191 mi^2). The shallow-covered region extending northwest from the Sierra is 1,700 km^2 (664 mi^2) in area. The density of distribution of low-sulfide gold-quartz vein deposits in the Klamath Mountains is four deposits per 1,000 km^2 (390 mi^2); for the Sierra Nevada, the density is 4.6 according to Bliss et al. (1987). Inasmuch as the concentration of deposits tends to drop off with distance from the zones of greatest mineralization, we expect that the density of deposits in the areas beyond the known deposits is half that given by Bliss. These densities (2 and 2.3 per 1,000 km^2 [390 mi^2]) multiplied by the areas of covered tract results in an expected value of about one deposit for the Klamath Mountains and about four for the Sierra Nevada.

The tract considered includes not only the Sierra Nevada but the Klamath Mountains, areas near Monterey, and areas in southern California . Of the 113,300 km^2 (43,745 mi^2) considered, the 51,800 km^2 (20,000 mi^2) in the SNEP study area are thought to contain nearly all the deposits. The estimates, therefore, should be treated as minimums but only slightly low. In the exposed part of the tract, the team estimated that only about one undiscovered deposit could exist giving a total expected value of about six undiscovered deposits. For the ninetieth, fiftieth, tenth, fifth, and first percentiles, the team estimated to, six, nine, twelve, and fifteen or more deposits consistent with the grade and tonnage model of Bliss (1986). The "expected value" for this set of estimates is 5.8 deposits. Deposits of this type worldwide have a mean tonnage of 0.03 million tonnes (0.033 million short tons) and a mean grade of 1.6 grams per tonne (ppm) gold and 2.5 g / t (ppm) silver. The mean amount of contained metal is 9.54 tonnes (10.54 short tons) gold and 1.22 tonnes (1.35 short tons) silver.

MASSIVE SULFIDE DEPOSITS, SIERRAN KUROKO TYPE

Base and precious metals produced from kuroko types of deposits are important to the nation's metal supply. Acid drainage is a major environmental consideration. These deposits contain copper and zinc in massive sulfide deposits in intermediate to felsic marine volcanic rocks. Triassic and Jurassic deposits have significantly lower tonnages than worldwide kuroko-type deposits (Model 28A.1, USGS Bull. 2004).

Rationale for Model Choice

Volcanogenic massive sulfide deposits are located in and near the foothills of the Sierra Nevada, in belts of intermediate to felsie marine volcanic rock. Volcanogenic massive sulfide deposits have been a historically important source of copper, zinc, silver, and gold in this region. Relatively high grades of polymetallic ores, simple metallurgy, and potential for large deposits make these deposits attractive exploration targets; exploration for, and development of, these deposits continues. Although both kuroko (Singer 1986) and Cyprus types of massive sulfide deposits are possible in this tract, the team assessed only the kuroko type because it is the only type with significant known deposits. The Sierran kuroko model, which is defined to be restricted to deposits of Triassic and Jurassic age (Model 28A.1) (Singer, 1992), was selected because the known deposits, many of which are included in the Sierran kuroko model, are in Jurassic rocks.

Potential Environmental Concerns

These types of deposits, with their high sulfide content, have been areas with acid mine-drainage problems. The Penn mine superfund cleanup site is from one such deposit. Acid-buffering maps can be made for mine-drainage and water-clarity work once a digital geologic map of the Sierra Nevada is released. A draft had been completed by July 1995. As Mount (1995) pointed out, base metals become more toxic to aquatic life in water that has a higher temperature, contains reduced, dissolved oxygen, and is acidic. Where high-carbonate-content rocks crop out downslope or downstream from kuroko-type deposits, sulfuric acidformed from the weathering of pyrite could be buffered. Conversely, where such buffering is not available, managers and mineral producers can be made aware of potential acid mine-drainage issues and take mitigating steps. A treatment of mine-drainage issues and mineral-environmental models is given by Plumlee et al. 1994.

Durkin (in press) describes techniques of mitigation in an acid mine drainage area. His paper is also available at: http://www.enviromine.com/case_hist/richmondhill/ch1.html on the World Wide Web. Action includes removing reactive rock from the dump and leach pads, backfilling, grading slopes, capping with a multimedia cover, and revegetation. The cover consists of "6 inches of onsite crushed limestone, 18 inches of compacted low-permeability manufactured soil, 4.5 feet of nonreactive crushed waste material for thermal/frost/root protection of the manufactured soil layer, and 4 to 6 inches of topsoil." The revegetation is done with "a mixture of aggressive grass species to limit the establishment of deeply rooting woody species and trees that could damage the integrity of the soil liner." The cap included a riprap-lined channel to manage runoff and control erosion. The reactive ore left on the leach pad was treated by mixing limestone with it. Postclosure monitoring is included in the plan.

Rationale for Tract Delineation

All map units in the foothills of the Sierra Nevada that contain sequences of submarine volcanic rocks have been included and define the permissive tract for volcanogenic massive sulfide deposits (figure 18.2). The tract extends westward under the Great Valley where the depth to Jurassic basement is no more than 1 km (.62 mi), based on drillhole data (Wentworth et al., in press).

Important Examples of Deposit Type

The Penn mine is one of the larger examples of volcanogenic massive sulfide deposits from the Sierra foothills metavolcanic terranes. It produced 38,000 metric tons of copper, 10,000 metric tons of zinc, 66 metric tons of silver, and 2 metric tons of gold. The Blue Moon and Western World deposits have been actively explored in recent years.

Rationale for Numerical Estimate

The tract considered includes not only the SNEP study area, but areas nearby. Of the 13,500 km^2 (5,300 mi^2) considered, the 9,240 km^2 (3,600 mi^2) in the SNEP study area are thought to contain nearly all the deposits. The estimates, therefore, should be treated as minimums but only slightly low. This region has been explored extensively in the past, focusing on easily observed surface gossans. There are seven known deposits and nineteen smaller occurrences in the area, and we judged that about a quarter of those occurrences could be deposits falling within the grade and tonage models with further exploration and development. This observation, coupled with consideration of substantial amounts of concealed potential host rocks, guided our estimate for the fiftieth percentile. The substantial concealed area also guided our estimate for the tenth percentile. For the ninetieth, fiftieth, and tenth percentiles, the team estimated two, thirteen, and twenty-five or more deposits consistent with the Sierran kuroko grade and tonnage model of Singer 1992. The "expected value" for this set of estimates is 13.2 deposits. Deposits of this type worldwide have a mean tonnage of 0.31 million tonnes (0.34 million short tons and a mean grade of 0.37% copper, 2.9% zinc, and 2.4% lead. The mean amount of contained metal is 1.51 tonnes (1.66 short tons) gold, 81.59 tonnes (89.95 short tons) silver, 25,987 tonnes (28,651 short tons) zinc, and 11,733 tonnes (12,936 short tons) lead.

PORPHYRY COPPER DEPOSITS

The generalized porphyry copper deposit model includes various subtypes, all of which contain chalcopyrite in stockwork veinlets in hydrothermally altered porphyry and adjacent country rock (Model 17, Cox 1986a).

Rationale for Model Choice

The Lights Creek porphyry copper deposit (Storey 1978) is located in the northernmost part of the Sierra Nevada, in the Plumas County copper belt of Knopf (1935). Lights Creek consists of two mineralized zones 3 km (1.9 mi) apart. It differs from typical porphyry copper systems in that magnetite is more abundant than pyrite and chlorite is the main alter-

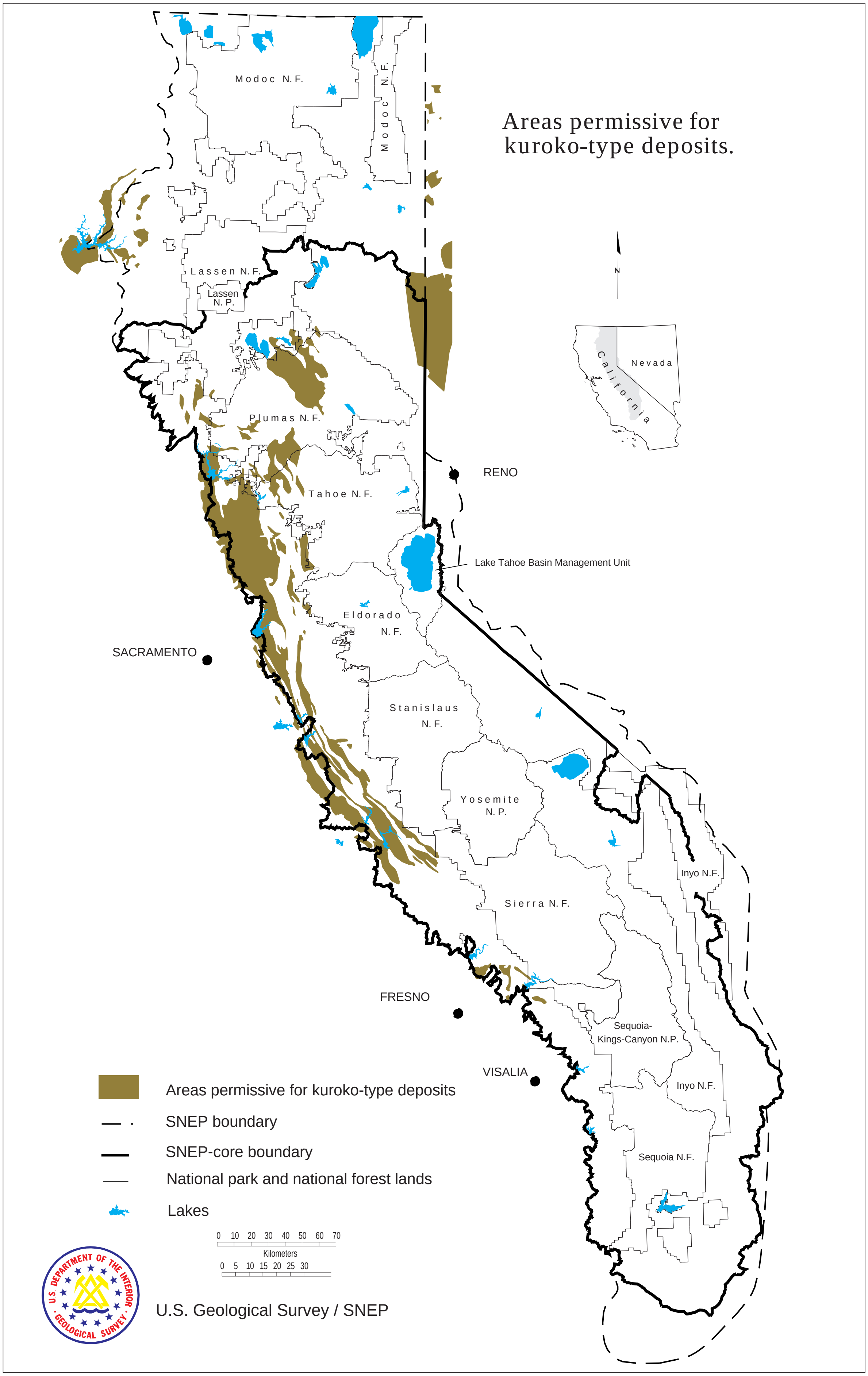

Areas permissive for
kuroko-type deposits.
Modoc N.F.
Modoc N.F.
Nevada
California
Lassen N.F.
Lassen N.P.
Plumas N.F.
Tahoe N.F.
RENO
Lake Tahoe Basin Management Unit
Eldorado N.F.
SACRAMENTO
Stanislaus N.F.
Yosemite N.P.
Inyo N.F.
Sierra N.F.
FRESNO
Sequoia-Kings-Canyon N.P.
VISALIA
Inyo N.F.
Sequoia N.F.
Areas permissive for kuroko-type deposits
SNEP boundary
SNEP-core boundary
National park and national forest lands
Lakes
0 10 20 30 40 50 60 70
Kilometers
0 5 10 15 20 25 30
U.S. Geological Survey / SNEP

Figure 18.2

ation mineral. Zoned potassic and phyllic alteration typical of porphyry copper deposits is indistinct. The copper belt includes the Engels and Superior copper vein deposits near Lights Creek (Anderson, 1931) and the Walker vein deposit 20 km (12 mi) to the southeast. The vein deposits are large compared to polymetallic vein median tonnage and contain magnetite, tourmaline, and actinolite in addition to chalcopyrite, bornite, and other sulfides. Deposits in the Plumas County copper belt are all related to stocks of gabbroic to granodioritic composition that are older than the major batholiths in the northern Sierra Nevada.

The abundance of magnetite in these deposits suggests an affinity with porphyry copper-gold systems, but no gold grades for the deposits are available. The general porphyry copper grade and tonnage model (Model 17) (Singer et al. 1986) was used in the assessment.

Rationale for Tract Delineation

The permissive tract includes all the major plutons of the Sierra Nevada, Salinian block, and Klamath Mountains (figure 18.3). Plutons permissive for porphyry copper deposits are believed to be emplaced at shallow levels in the crust, but because we have no way to distinguish this environment on a regional scale, the entire tract is considered permissive. Despite the apparent scarcity of pluton-related deposits in the Klamath Mountains, this part of the tract is considered permissive for several types of pluton-related deposits. Of these, polymetallic veins might be indicators of concealed porphyry copper systems. The only vein deposits that clearly fit the polymetallic vein model are quartz veins rich in silver and base metal sulfides in the South Fork district, located in the Shasta Bally pluton at the southern edge of the Klamath Mountains (Silberman and Danielson 1993). Some occurrences in the Gold Hill, Ashland, and Applegate districts of Oregon may also be polymetallic veins.

Important Examples of Deposit Type

The Lights Creek bodies contain 315 million metric tons of mineralized rock that average 0.34% copper. The Engels and Superior veins together produced about 4 million metric tons of ore averaging 1.79% copper (Storey 1978). In the Klamath Mountains, the most important polymetallic vein deposit is the Silver Falls–Chicago Consolidated mine in the South Fork district, which produced $1,000,000 worth of metal, mainly silver (Hotz 1971).

Rationale for Numerical Estimate

The terrane for which the estimates were made extends slightly beyond the SNEP study area. Permissive terranes within the Great Basin and the southern basin and range extend slightly into the SNEP study area. Those extensions are about as unfavorable for these types of deposits as the terrane considered. The permissive terrane for which estimates were made is 143,100 km^2 (42,749 mi^2) and the permissive terrane within the SNEP study area is 109,438 km^2 (32,693 mi^2) and includes the extensions. The estimates, therefore, should be treated as maximums.

Because of the scarcity and restricted extent of porphyry copper environments in the Sierra Nevada and Klamath Mountains, a low estimate of undiscovered deposits was made. For the ninetieth, fiftieth, tenth, fifth, and first percentiles, the team estimated zero, zero, zero, one, and one or more porphyry copper deposits consistent with the grade and tonnage model of Singer et al. (1986) (Mark 3, no. 4). Most of the undiscovered resource is believed to be in the northern Sierra Nevada. The “expected value” for this set of estimates is 0.08 deposits. Deposits of this type worldwide have a mean tonnage of 140 million tonnes (154 million short tons) and a mean grade of 0.54% copper, 2.6 g/t (ppm) silver, 0.4 g/t (ppm) gold, and 0.03% molybdenum. The mean amount of contained metal is 3.1 million tonnes (3.4 million short tons) copper, 592 tonnes (653 short tons) silver, 88,586 tonnes (97,666 short tons) molybdenum, 28.83 tonnes (64.86 short tons) gold, and 593 tonnes (654 short tons) silver.

EPITHERMAL VEIN DEPOSITS, QUARTZ-ADULARIA TYPE

The epithermal vein deposit model is a combination of grades and tonnages of Comstock and Sado types (Models 25C and 25D, USGS Bulletin 1693).

Rationale for Model Choice

Northeastern California contains intermediate to felsic Tertiary composition and bimodal Quaternary volcanic rocks and associated high-level intrusions. The region contains throughgoing fracture systems, major normal faults, and fractures related to intrusive doming (Rytuba 1988; 1989). Classification of deposits as Comstock or Sado type requires information on basement geology that is not available (Klein and Bankey 1992). Therefore, a combined Comstock-Sado model (Models 25C and 25D) was used.

Rationale for Tract Delineation

The tract encompasses all Tertiary and Quaternary volcanic rocks in northeastern California and was delineated using the geologic map of California (Jennings 1977) (figure 18.4). Volcanic sequences include andesite and rhyolite domes of Tertiary age and other manifestations of volcanic centers where magmatic events might generate ore-forming hydrothermal systems.

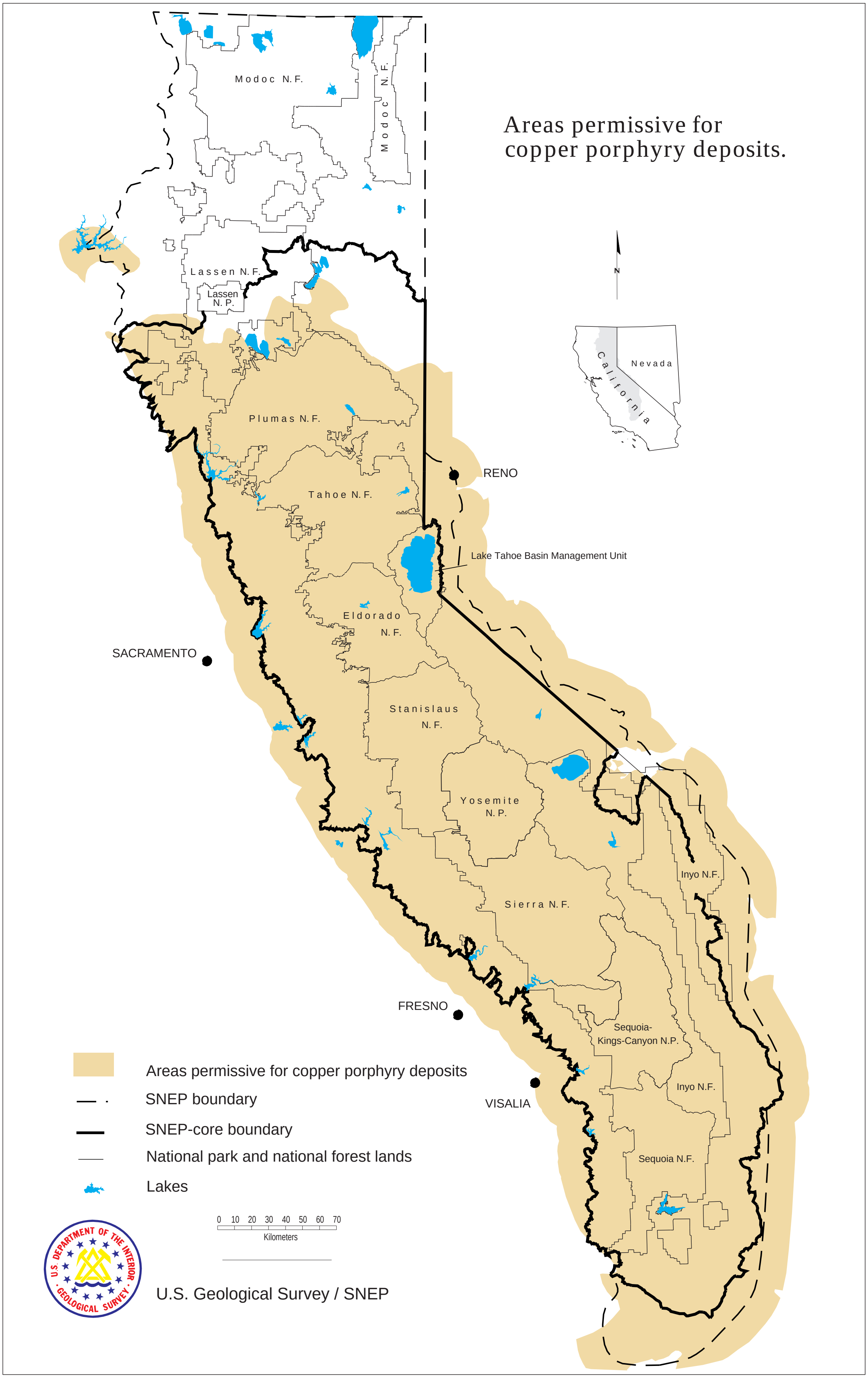
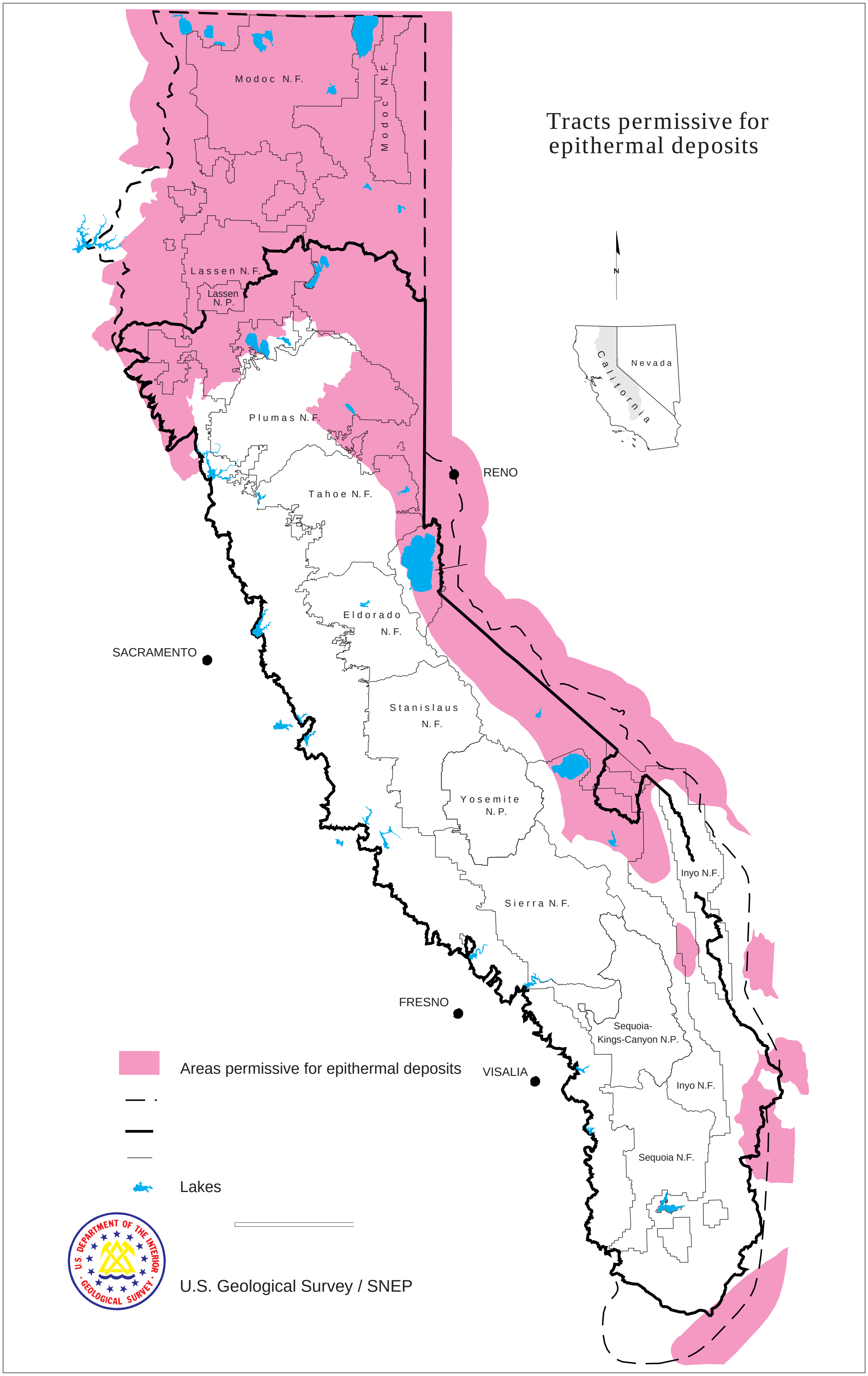

Areas permissive for
copper porphyry deposits.
Modoc N.F.
Modoc N.F.
Lassen N.F.
Lassen N. P.
Nevada
California
Plumas N.F.
RENO
Tahoe N.F.
Lake Tahoe Basin Management Unit
Eldorado N.F.
SACRAMENTO
Stanislaus N.F.
Yosemite N.P.
Inyo N.F.
Sierra N.F.
FRESNO
Sequoia-Kings-Canyon N.P.
Inyo N.F.
VISALIA
Sequoia N.F.
Areas permissive for copper porphyry deposits
SNEP boundary
SNEP-core boundary
National park and national forest lands
Lakes
0 10 20 30 40 50 60 70
Kilometers
U.S. Geological Survey / SNEP

Figure 18.3



Tracts permissive for epithermal deposits
Modoc N. F.
Modoc N. F.
Lassen N. F.
Lassen N. P.
Plumas N. F.
Tahoe N. F.
Eldorado N. F.
Stanislaus N. F.
Yosemite N. P.
Sierra N. F.
Inyo N.F.
Sequoia-Kings-Canyon N.P.
Inyo N.F.
Sequoia N.F.
RENO
SACRAMENTO
FRESNO
VISALIA
N
Nevada
California
Areas permissive for epithermal deposits
Lakes
U.S. Geological Survey / SNEP

Figure 18.4

Important Examples of Deposit Type

There are no known quartz-adularia deposits in the area. The Skedaddle Mountain Wilderness Study Area on BLM land east of Susanville had more than 280 lode claims for epithermal deposits (Diggles et al. 1988; Munts and Peters 1987).

Rationale for Numerical Estimate

The terrane for which the estimates were made does not include the entire permissive tract within the SNEP study area, but rather a large subset of it. The permissive terrane within the SNEP study area is 68,495 km^2 (26,756 mi^2) and the terrane within it for which the estimates were made is 47,760 km^2 (18,656 mi^2). The remainder is in five subsets of larger terranes that include much of the Great Basin and Oregon. The estimates, therefore, should be treated as minimums but only slightly low. The estimators thought that there was a 50% chance of one or more undiscovered districts. For the ninetieth, fiftieth, and tenth percentiles, the team estimated zero, one, and two or more quartz-adularia epithermal-vein districts. The “expected value” for this set of estimates is one deposit. Because the size of any undiscovered deposit will depend on its deposit type, more information about the target area is needed to list an expected mean tonnage and grade; Comstock-type deposits worldwide have a mean contained amount of silver of 1.6 million tonnes (1.8 million short tons) while Sado-type deposits have just over 10% as much.

COPPER SKARN

Copper-skarn deposits contain chalcopyrite in calc-silicate metasomatic rocks near contacts with weakly mineralized igneous intrusive rocks (Model 18B,Cox and Theodore 1986).

Rationale for Model Choice

Although copper skarn deposits (Model 18B) are much less common in this tract than lead-zinc dominated systems, widespread igneous intrusions into carbonate rocks represent permissive conditions for copper skarn formation. Copper skarn mineral assemblages were observed in ores from the Gold Bottom–Copper Queen mine (Dennis Cox, unpublished data).

Rationale for Tract Delineation

The permissive tract is a nearly continuous area marked by small plutons that intrude Precambrian metamorphic and Precambrian and Paleozoic sedimentary rocks in a highly faulted part of the Mesozoic continental margin (figure 18.5). There are few areas that truly lack carbonate or other reactive rocks, so the entire sedimentary section is included. Small areas of basin fill more than 1 km (0.6 mi) in depth are excluded.

Rationale for Numerical Estimate

The terrane for which the estimates were made does not include the entire permissive tract within the SNEP study area, but rather a subset of it. The permissive terrane within the SNEP study area is 63,147 km^2 (24,667 mi^2) and the terrane within it for which the estimates were made is 17,700 km^2 (6,900 mi^2). The remainder is in four subsets of larger nearby terranes. The additional terrane is thought to be mostly much less favorable for deposits of this type. The estimates, therefore, should be treated as minimums but only slightly low. For the ninetieth, fiftieth, tenth, and fifth percentiles, the team estimated zero, one, one, and two or more copper skarn deposits consistent with the grade and tonnage model of Jones and Menzie (1986) (Mark 3, no. 8). The “expected value” for this set of estimates is 0.7 deposits. Deposits of this type worldwide have a mean tonnage of 0.56 million tonnes (0.62 million short tons) and a mean grade of 1.7% copper, 2.8 g/t (ppm) gold, and 36 g/t (ppm) silver. The mean amount of contained metal is 55,496 tonnes (61,184 short tons) copper, 0.91 tonne (1.00 short ton) gold, and 8.20 tonnes (9.0 short tons) silver.

POLYMETALLIC SKARN AND REPLACEMENT DEPOSITS

Polymetallic skarn and replacement deposits are hydrothermal, epigenetic deposits that contain silver, lead, zinc, and copper minerals in massive lenses in limestone, dolomite, or other reactive rocks, with or without calc-silicate minerals, near igneous intrusive contacts (Models 19A and 18C, USGS Bulletin 1693).

Rationale for Model Choice

Mesozoic plutons on the southeast flank of the Sierra Nevada batholith show a consistent association with numerous zinc-lead skarn and polymetallic replacement districts where they intrude Paleozoic carbonate rocks (figure 18.6). These districts include Darwin, Cerro Gordo, Modoc, Santa Rosa (MacKevett 1953), and Ubehebe (McAllister 1955). Darwin, the largest, produced more than a million metric tons of ore containing about 6% lead, 6% zinc, 0.2% copper, 200 g/t (ppm) silver and recoverable gold (Hall and MacKevett 1962; Newberry et al. 1991).

The Shoshone (Tecopa) district (Carlisle et al. 1954) produced about 600,000 metric tons of lead-zinc-silver ore and is the largest of a group of similar districts that includes Queen of Sheba, Honolulu, Ashford, Paddy’s Pride, and Blackwater.

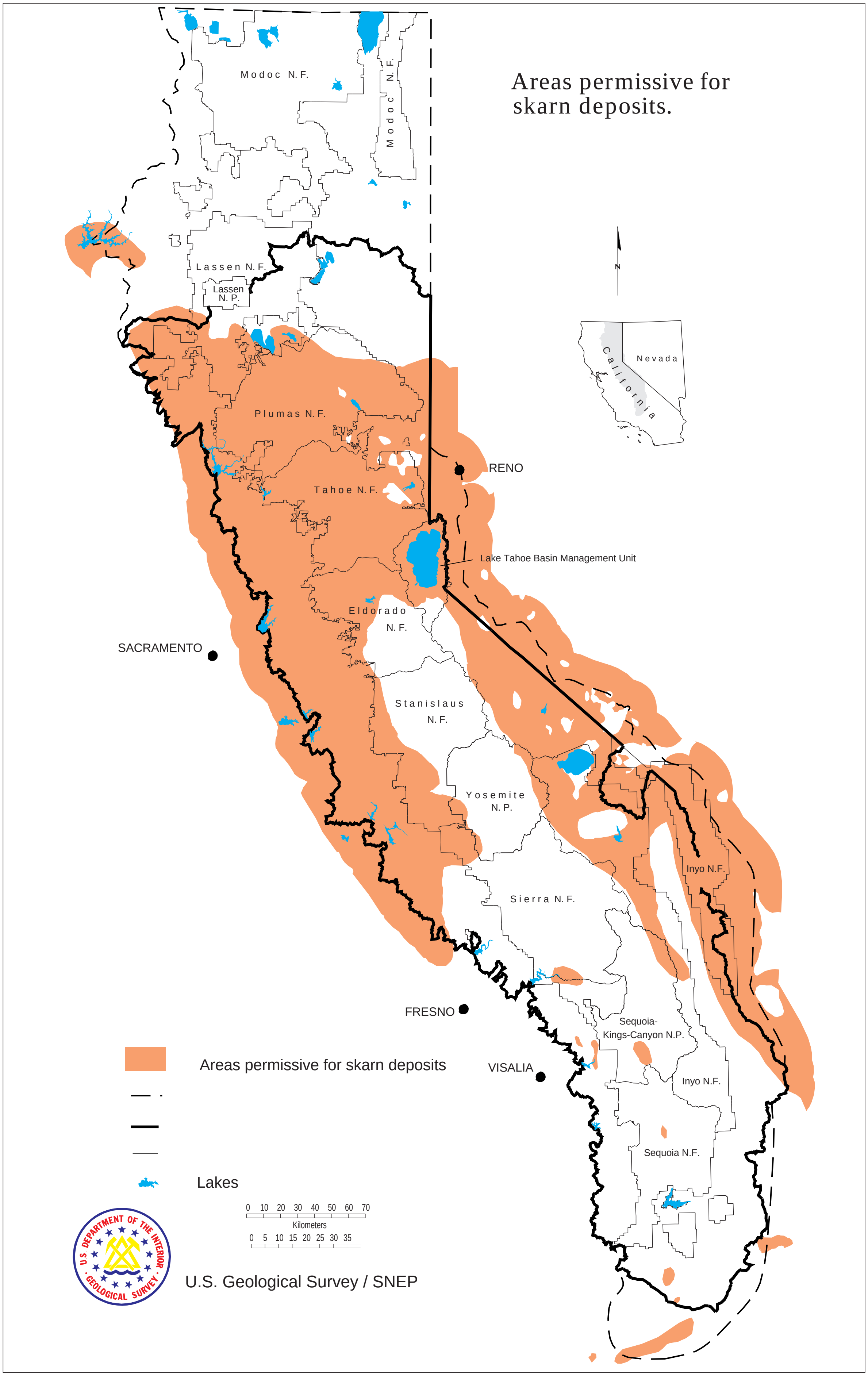

Areas permissive for skarn deposits.
Modoc N.F.
Modoc N.F.
Lassen N.F.
Lassen N.P.
Plumas N.F.
Tahoe N.F.
RENO
Lake Tahoe Basin Management Unit
Eldorado N.F.
SACRAMENTO
Stanislaus N.F.
Yosemite N.P.
Inyo N.F.
Sierra N.F.
FRESNO
Sequoia-Kings-Canyon N.P.
VISALIA
Inyo N.F.
Sequoia N.F.
Nevada
California
N
Areas permissive for skarn deposits
Lakes
0 10 20 30 40 50 60 70
Kilometers
0 5 10 15 20 25 30 35
U.S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
U.S. Geological Survey / SNEP

Figure 18.5

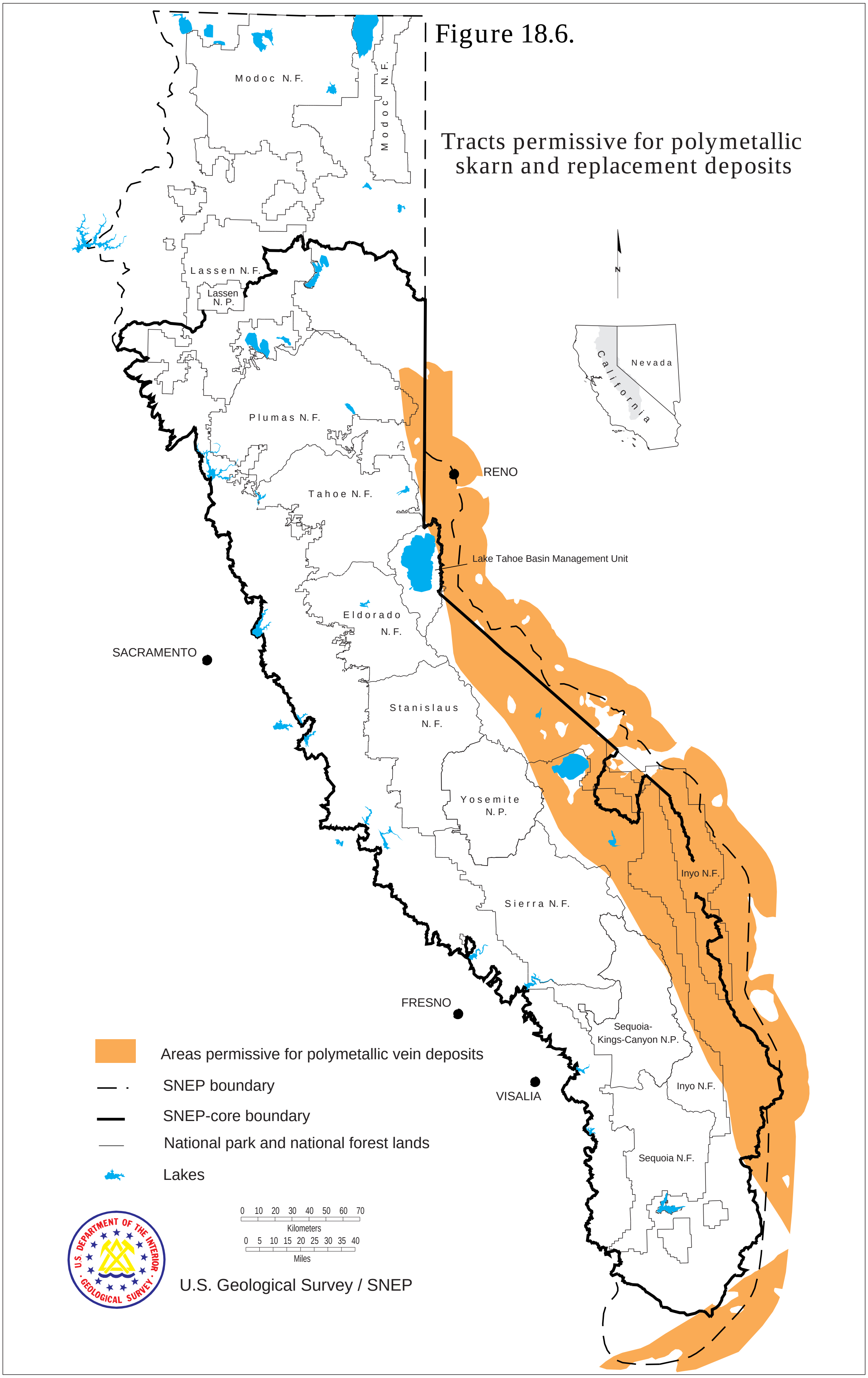


Figure 18.6.
Tracts permissive for polymetallic skarn and replacement deposits
Modoc N. F.
Modoc N. F.
Lassen N. F.
Lassen N. P.
Plumas N. F.
Tahoe N. F.
RENO
Lake Tahoe Basin Management Unit
Eldorado N. F.
SACRAMENTO
Stanislaus N. F.
Yosemite N. P.
Inyo N.F.
Sierra N. F.
FRESNO
Sequoia-Kings-Canyon N.P.
Inyo N.F.
VISALIA
Sequoia N.F.
N
California
Nevada
Areas permissive for polymetallic vein deposits
SNEP boundary
SNEP-core boundary
National park and national forest lands
Lakes
0 10 20 30 40 50 60 70
Kilometers
0 5 10 15 20 25 30 35 40
Miles
U.S. Geological Survey / SNEP

Figure 18.6

These districts are all localized within the Late Proterozoic Noonday Dolomite and have no consistent relation with igneous rocks of any specific age. They also have much lower pyrite contents compared to the ores related to Jurassic plutons. They may be incorrectly classified here as polymetallic replacement districts; however, more work needs to be done to establish their classification.

Zinc-lead skarn deposits are possible in the same environment as polymetallic replacement deposits; therefore, a new model that combines the zinc-lead skarn (Mosier 1986) and polymetallic replacement (Mosier et al. 1986) was used to represent the undiscovered districts (Models 19A and 18C) (Mark 3, no. 92).

Rationale for Tract Delineation

The permissive tract is a nearly continuous area that encompasses many small plutons that intrude Proterozoic metamorphic and Proterozoic and Paleozoic sedimentary rocks in a highly faulted part of the Mesozoic continental margin. Small areas of basin fill more than 1 km (0.6 mi) in depth are excluded.

Rationale for Numerical Estimate

The terrane for which the estimates were made does not include the entire permissive tract within the SNEP study area, but rather a large subset of it. The permissive terrane within the SNEP study area is 31,680 km^2 (12,375 mi^2) and the terrane within it for which the estimates were made is 19,505 km^2 (7,619 mi^2). The remainder is in two subsets of larger terranes, much of which is less favorable for undiscovered deposits. The estimates, therefore, should be treated as minimums but only slightly low. For the ninetieth, fiftieth, tenth, and fifth percentiles, the team estimated zero, three, five, and eight or more districts consistent with the combined grade and tonnage model for zinc-lead skarn (Cox 1986) and polymetallic replacement districts (Morris 1986) of D. A. Singer (Donald A. Singer, e-mail to David H. Root, September 1994) (Mark 3, no. 92). This estimate was based on the belief that approximately three known districts have grades and tonnages close to the median of the combined model. An equal number of undiscovered districts probably exists under cover or in old districts that are, as currently known, too small to fit the tonnage model distribution. The “expected value” for this set of estimates is 2.93 deposits. Because the size of any undiscovered deposit will depend on its deposit type, more information about the target area is needed to list an expected mean tonnage and grade; polymetallic replacement-type deposits worldwide have a mean contained amount of zinc and lead of 0.336 million and 0.344 million tonnes (0.370 million and 0.379 million short tons), respectively, whereas polymetallic skarn-type deposits have 0.113 million and 0.256 million tonnes (0.125 million and 0.282 million short tons) respectively.

KNOWN MINES, CLAIMS, AND PROSPECTS

The U.S. Bureau of Mines at the Western Field Operations Center in Spokane, Washington, has produced a series of maps for the SNEP report. The data consist of minerals availability information, mine-claim maps, and maps showing areas of development interest.

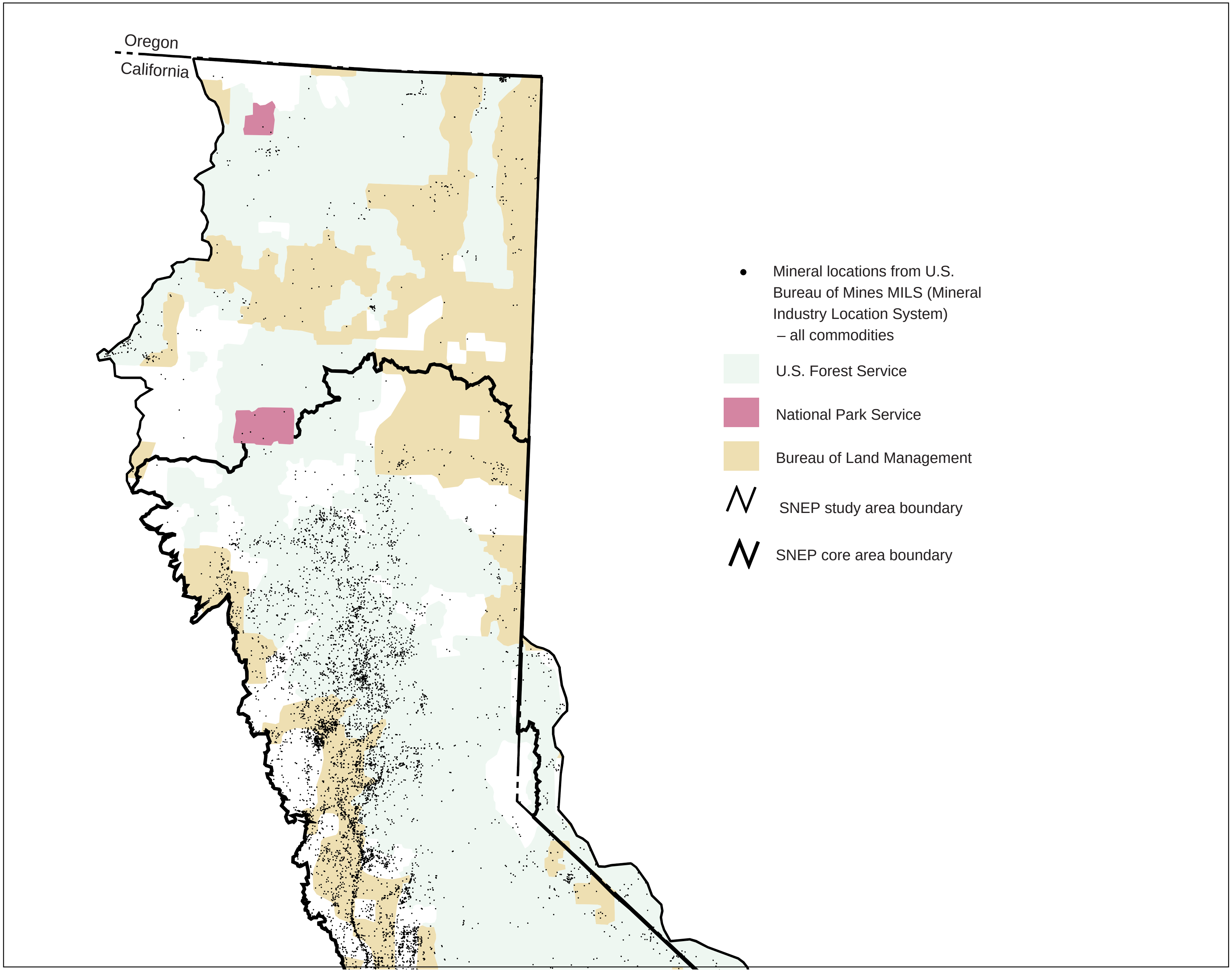
The Mineral Industry Location System (MILS) database is a subset of the Minerals Availability System (MAS) which maintains comprehensive minerals development information on significant deposits as well as less-detailed data on many additional deposits and mineralized areas worldwide. MILS emphasizes properties that have undergone exploration / prospecting or some form of past, present, or intended future development. Database fields include location, mineral commodities, production status, type of operation (for example, prospect, surface, underground, placer, processing facility), and bibliography. Where the data are not proprietary, information on reserves, tonnage, and grade may be included. Database searches can be performed on any element in the database. Additionally, data from MILS are easily combined with other data to screen on abandoned and inactive mine lands for chemical hazards. Plate 18.2 shows the total concentration of mineral deposits in the SNEP study area. A version of MILS is in preparation as a CD-ROM (Oddenino et al., 1995) and should be available by the end of 1995.

The BLM claim recordations database for both California and Nevada was used. Several maps derived from it have been placed on the anonymous FTP site mojave.wr.usgs.gov / pub / mdiggles / snep. These maps show the diversity of open lode claims per section (640 acres) (plate 18.3), density of open placer claims per section (plate 18.4), density of total claims per section, both open (active) and closed (former) and both lode and placer (plate 18.5), and density of open claims per section, both lode and placer (plate 18.6).

The mine-claim database is used to generate various maps and lists and help analyze the extent of past, present, and potential future mineral development. More sophisticated analyses were performed when elements of the claim database were combined with other mining and geological information to delineate known mineral deposit areas (plate 18.7). This map is used to analyze environmental disturbances and socioeconomic costs and benefits for potential future development.

MERCURY IN THE SIERRA NEVADA ECOSYSTEM

Both anthropogenic and natural sources of mercury affect the Sierra Nevada ecosystem. Natural sources of mercury include


Oregon
California
Mineral locations from U.S. Bureau of Mines MILS (Mineral Industry Location System) – all commodities
U.S. Forest Service
National Park Service
Bureau of Land Management
SNEP study area boundary
SNEP core area boundary

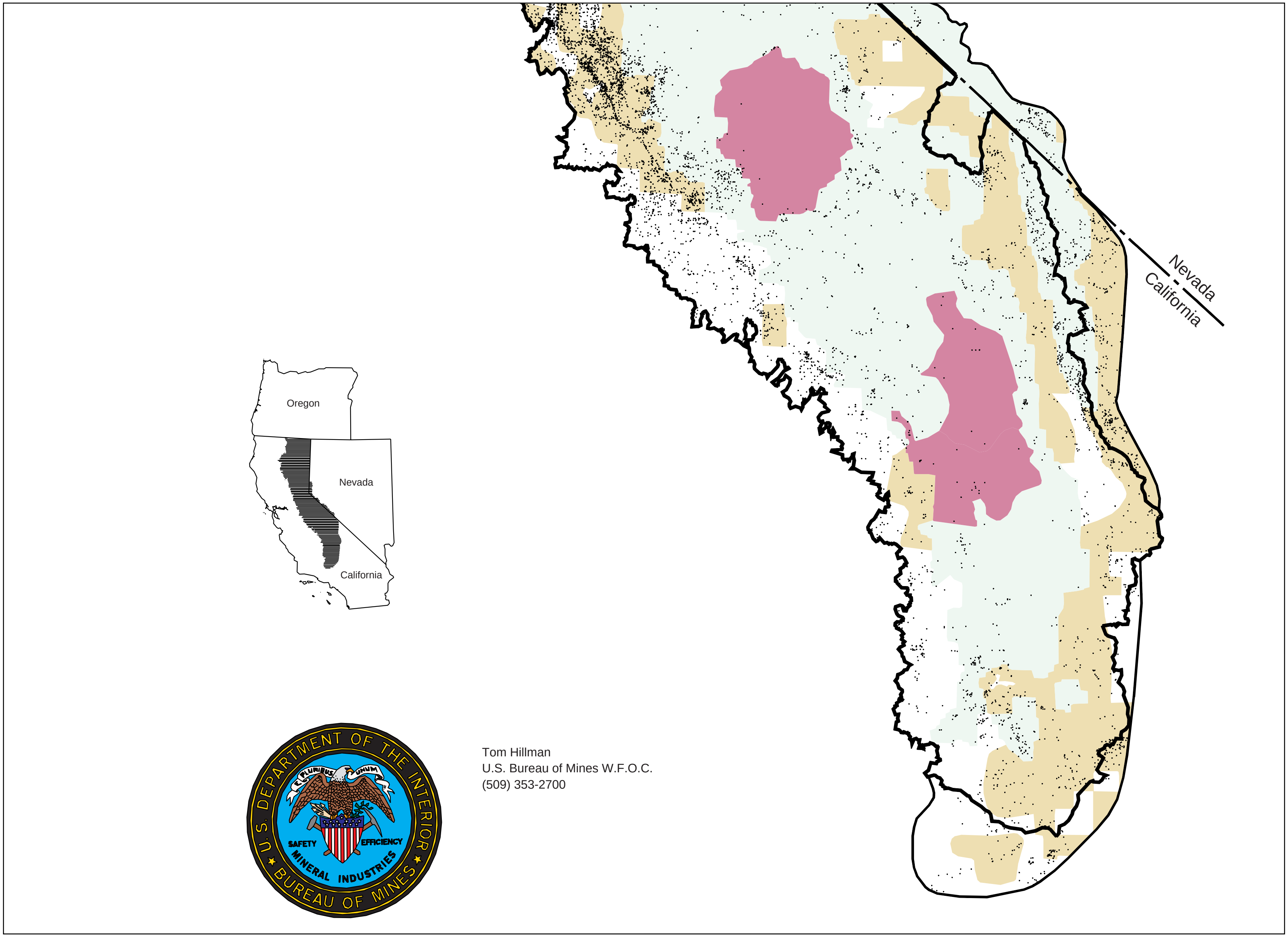


PLATE 18.2

Location of mineral deposits within the SNEP study area.

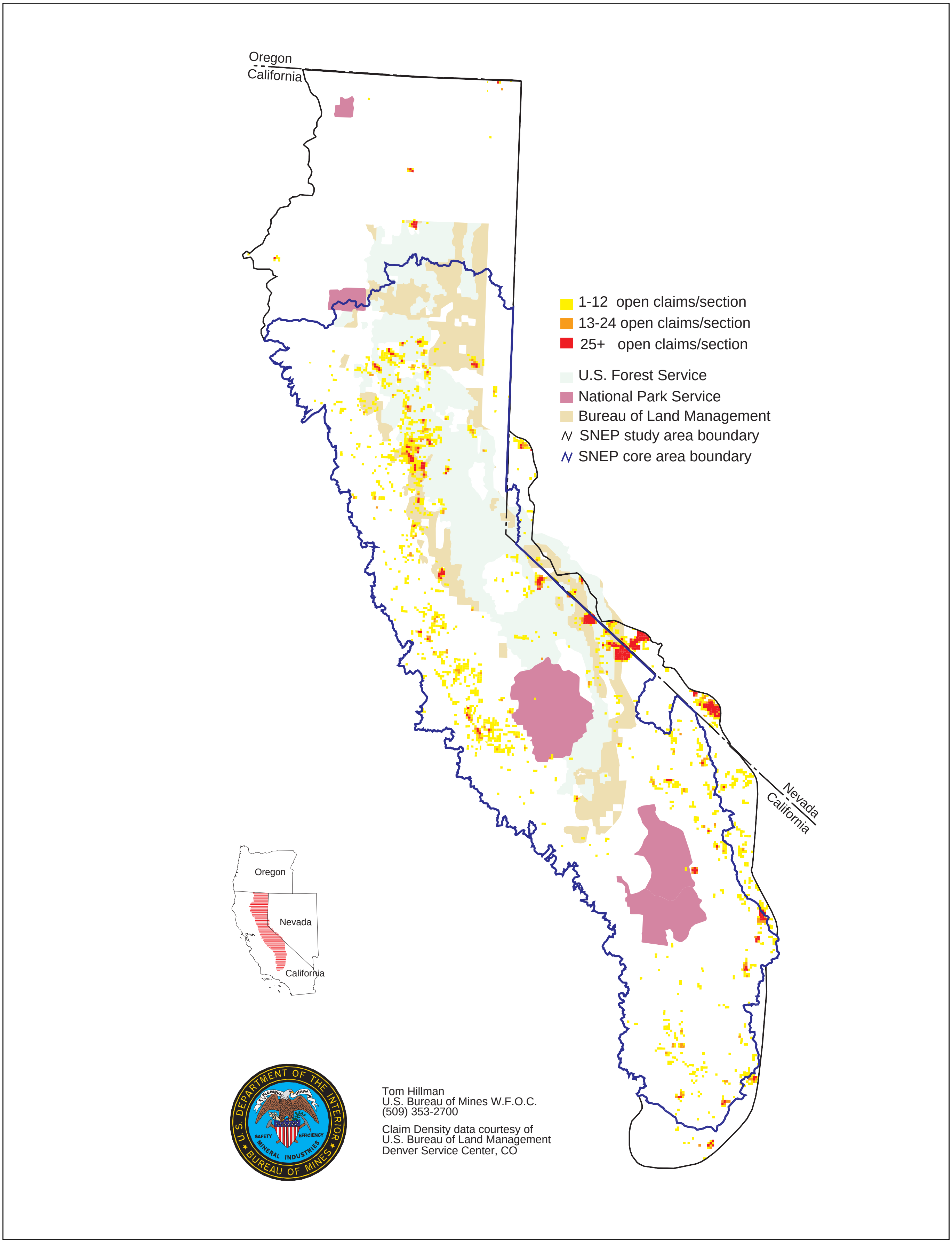


PLATE 18.3

Density of open lode claims per section in the SNEP study area.

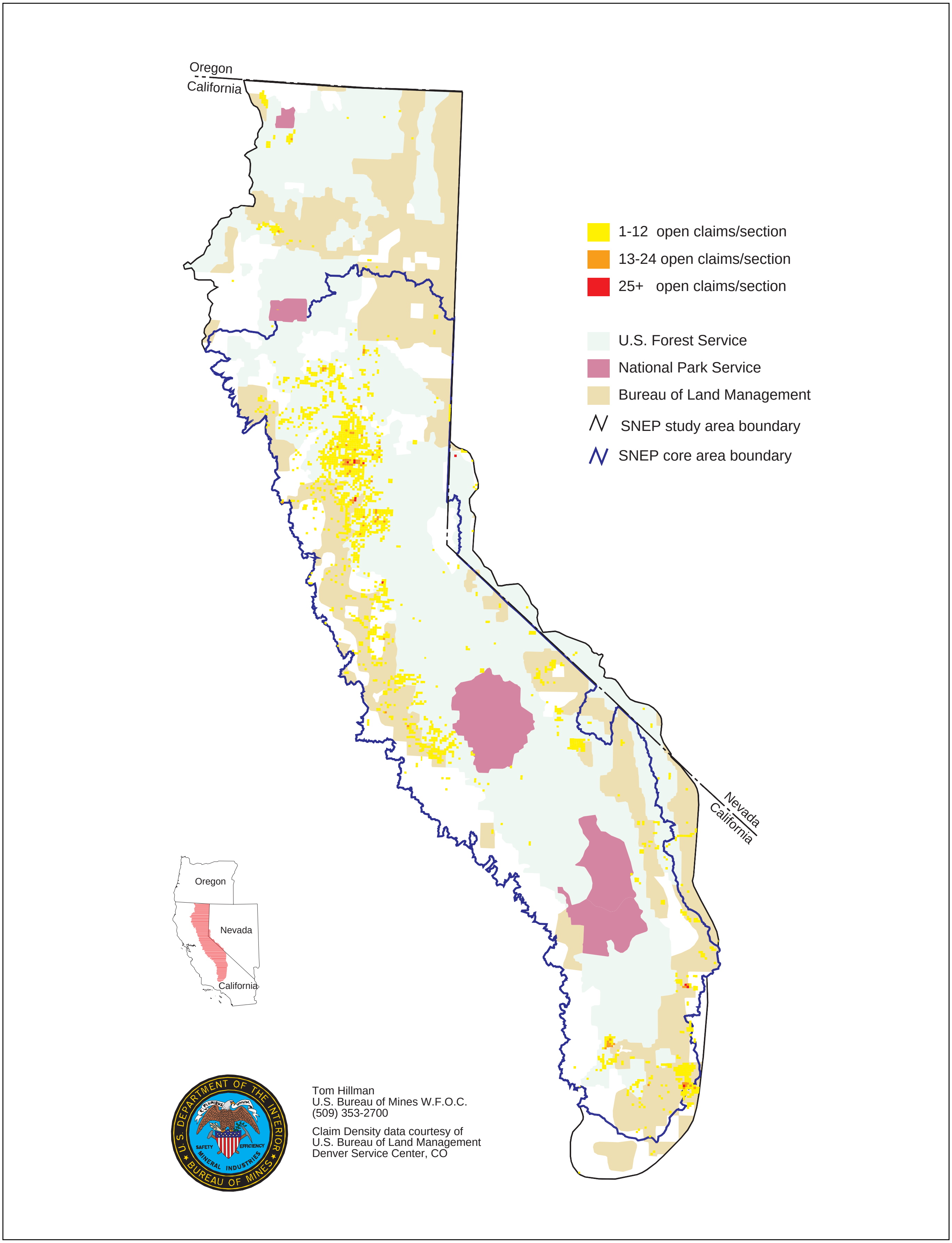


PLATE 18.4

Density of open placer claims per section in the SNEP study area.

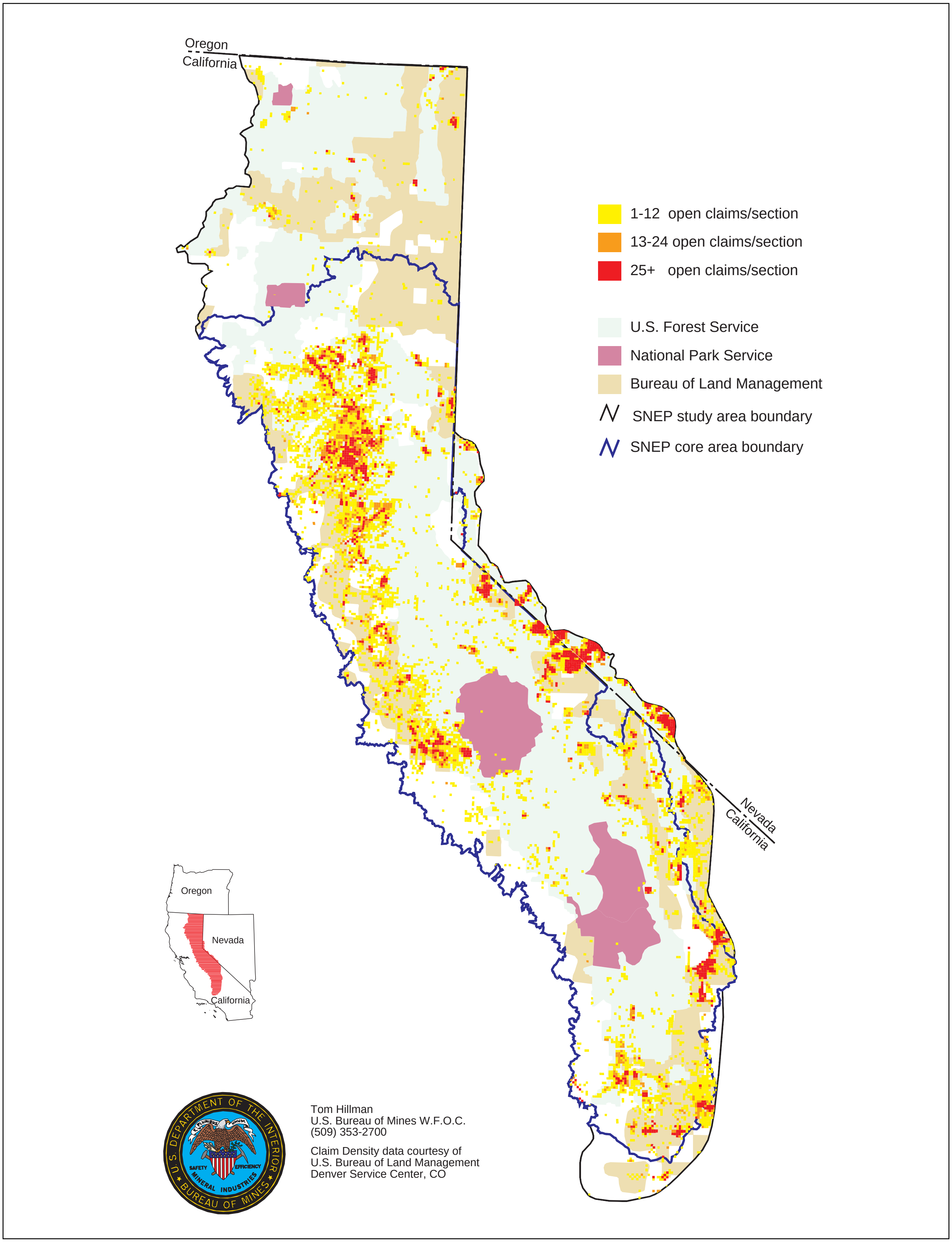


PLATE 18.5

Total claim density per section in the SNEP study area.

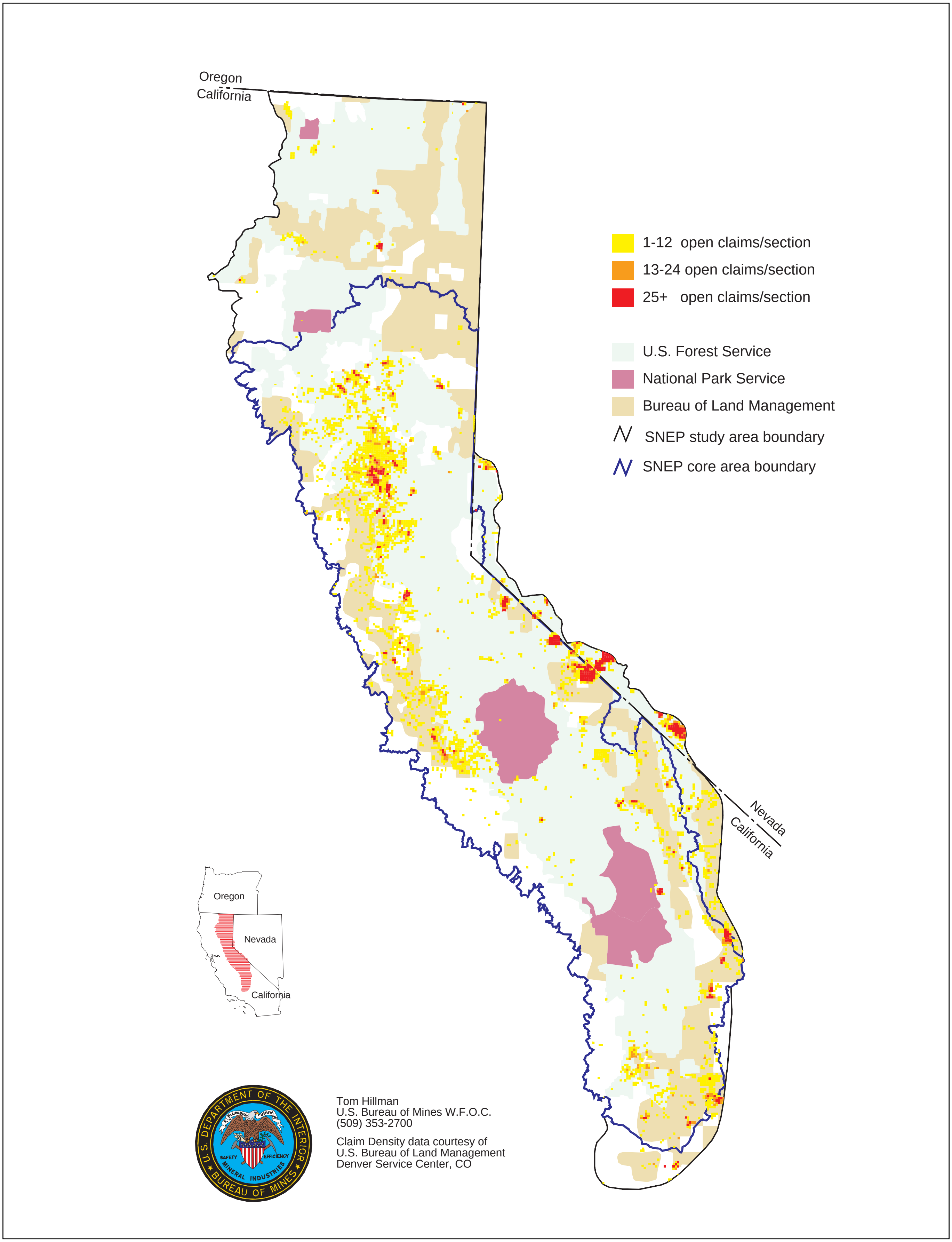


PLATE 18.6

Open claim density per section in the SNEP study area.

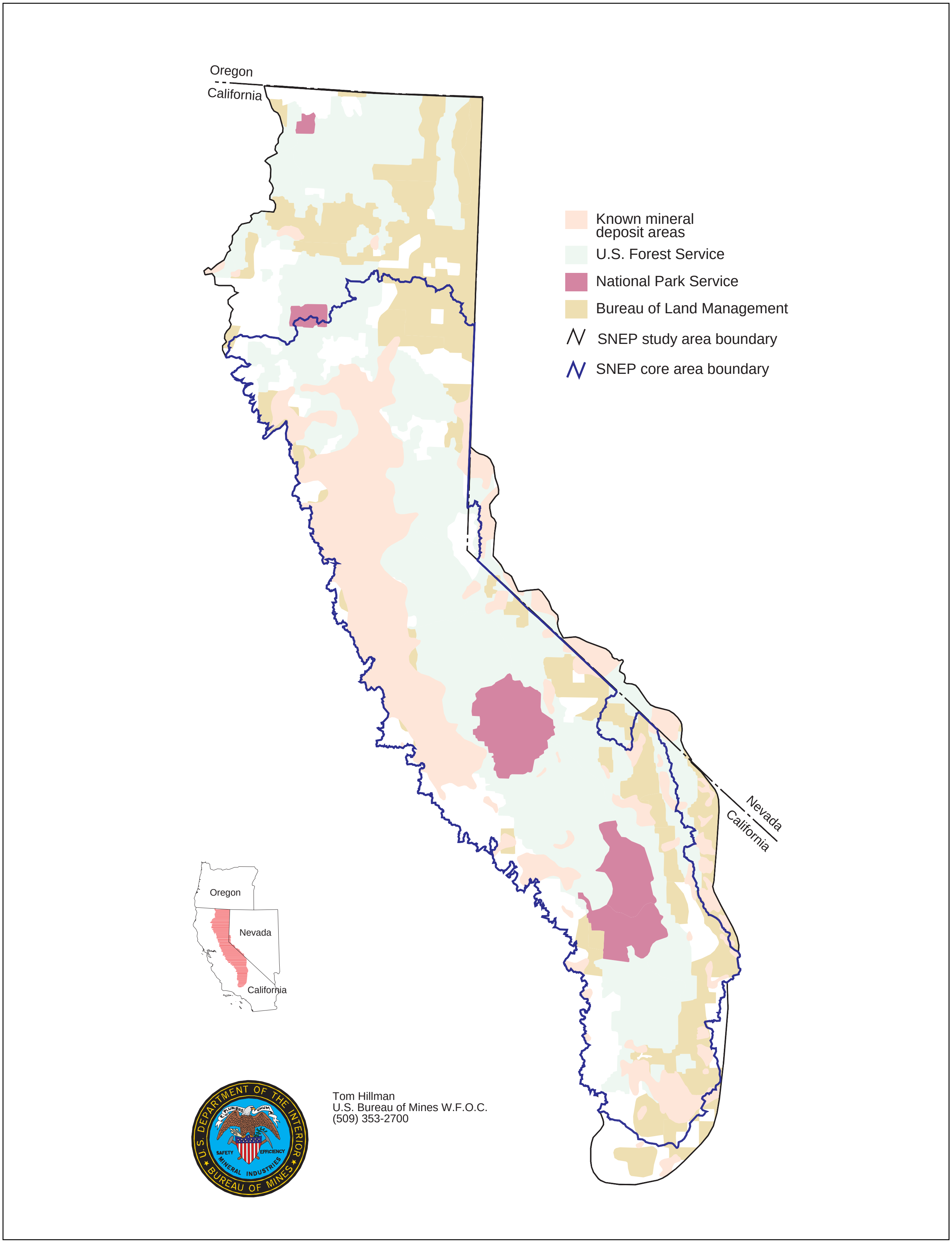


PLATE 18.7

Known mineral deposit areas in the SNEP study area.

mineral deposits containing anomalous concentrations of mercury, undeveloped hot springs and thermal gas vents, recently active faults, passively degassing volcanoes, and mercury derived from the natural global atmospheric mercury cycle and added to the ecosystem through wet and dry deposition (plate 18.8). Anthropogenic sources of mercury include mercury introduced during gold mining and processing (Lindberg et al. 1979), developed geothermal areas, and mercury, derived from the atmosphere, primarily from coal combustion (Mason et al., 1994), and added to the ecosystem by precipitation. Plant communities in the ecosystem are important in concentrating and redistributing mercury (Lindberg et al. 1995).

Mercury from the Global Atmospheric Mercury Cycle

The primary source of mercury to the Sierra Nevada ecosystem is from the global atmospheric mercury cycle. Both anthropogenic and natural sources of mercury are of equal importance to the global mercury cycle, adding about 6,000 to 7,500 metric tons of mercury to the atmosphere per year (Nriagu and Pacyna 1988). The most important natural source is from evasion of elemental mercury vapor, Hg^o, from the world's oceans; the major anthropogenic source comes from coal combustion (Fitzgerald 1989; Rasmussen 1994). Soil gas emission is the third most important source of Hg^o to the atmosphere. The atmospheric mercury flux to the terrestrial environment has increased substantially since the beginning of the industrial period (about 1850) because of anthropogenic release of mercury into the atmosphere.

In California, sources of anthropogenic mercury emission to the atmosphere include waste incineration, electric utility power plants (including coal, oil, and geothermal powered plants), coal and petroleum combustion and uses, industrial-commercial sources, paint emissions, mine roasting and smelters, mobile sources (vehicles, tractors, locomotives), fugitive emissions from mine tailings and waste, landfills, and, in the past, mercury catalysts for caustic soda (now nearly all replaced). Natural sources of mercury to the atmosphere in decreasing importance include oceans, erupting volcanoes, soil vapor flux (Lindberg et al. 1995), geothermal systems and hot springs (Janik et al. 1994; Rytuba and Miller 1994), passively degassing volcanoes (Varekamp and Buseck 1986), fumaroles, soil vapor from mineralized areas, and active faults.

Wet Deposition of Mercury

Pacific weather fronts that move through the Sierra Nevada ecosystem are the primary source of wet deposition of mercury from the atmosphere in either rain or snow. The mercury species in precipitation is primarily in the ionic, oxidized form, Hg^{++}, which is derived from photooxidation of elemental mercury vapor, Hg^o, and Hg^o aerosols, primarily by ozone (Gill and Bruland 1990). The flux of wet deposition of mercury to the Sierra Nevada ecosystem is about 13 $mg/m^2/yr$ and may vary by several micrograms near regional point sources that vent mercury to the atmosphere.

Dry Deposition of Mercury

Dry deposition of mercury is important in the terrestrial part of the atmospheric mercury cycle. Elemental mercury vapor, Hg^o, and Hg^o aerosols from the atmosphere are taken up by plant communities in the Sierra Nevada ecosystem. Dry deposition accounts for about 6 $mg/m^2/yr$ of mercury added to the ecosystem.

Effect on Plant Communities of Elevated Mercury Content

Mercury in Ambient Air

Typical mercury concentrations in ambient atmosphere in the Sierra Nevada ecosystem range from 2 to 3 mg/m^3. Ambient concentration of mercury in the atmosphere is important in determining whether plant communities in the Sierra Nevada ecosystem take up mercury into their leaves. Mercury uptake through the plant's root system is low relative to uptake through foliage. At low ambient mercury concentrations, plants give off mercury to the atmosphere through their foliage, and the foliage does not increase in mercury concentration during its growth cycle. At high ambient concentrations of mercury, plants take up mercury through their leaves directly from the air. Thus, for example, in a contaminated mine site where ambient air concentration of mercury is high, the mercury content of leaves increases throughout the growth cycle. Litter fall from plants and wash off from leaves are major components of mercury added to soils, creeks, and lakes.

Elemental mercury vapor, Hg^o, is the dominant mercury species in the atmosphere at normal ambient concentrations (Seigneur et al. 1994) as well as in geologic environments where elevated concentrations of mercury are present in air. Hg^{++} is present at low levels in the atmosphere. Particulate Hg may be a significant component in emanations from volcanoes such as Lassen Peak. In volcanic and geothermal environments and contaminated mine sites, the ambient air concentration can increase to several orders of magnitude above normal.

Natural geologic sources of mercury having the greatest potential regional impact on ambient atmospheric concentration include, in decreasing importance, active volcanoes, passively degassing volcanoes, geothermal areas, mineralized areas, and active faults. Permissive tract maps for epithermal deposits (figure 18.4), low-sulfide gold quartz (Mother Lode gold) (figure 18.1), and kuroko (figure 18.2) (listed in decreasing order of importance) delineate those areas with the potential for elevated ambient mercury concentrations in air where these deposits are exposed at the surface or covered by residual soils and alluvium. Deeply buried, these deposits will not contribute mercury to the ambient atmosphere. Elevated fluxes of soil gas emission from these areas, combined with the atmospheric mercury flux, may cause above-normal

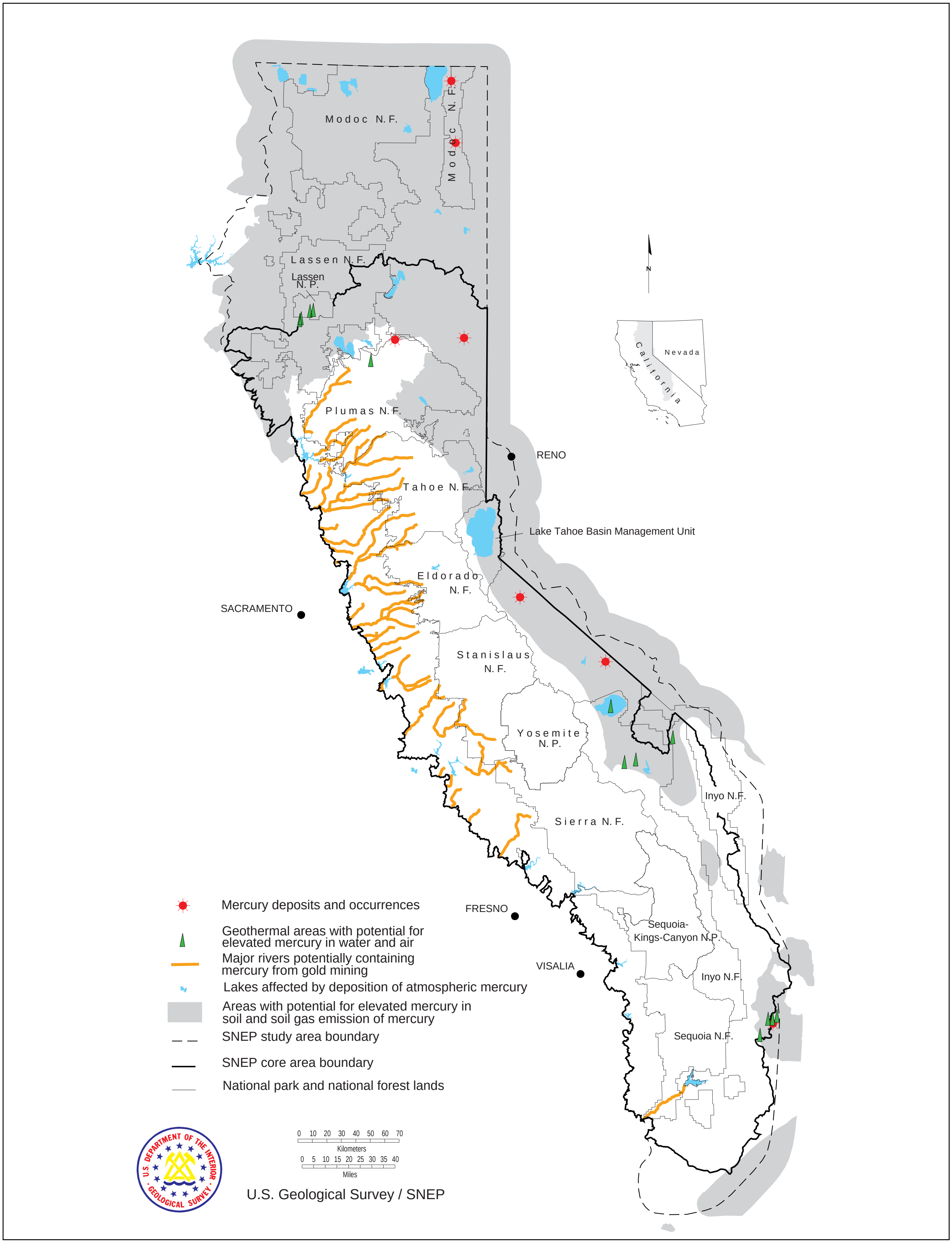


PLATE 18.8

Areas of possibly elevated mercury concentration.

concentrations of mercury in plant foliage. Plant material falling to the forest floor leads to litter-fall deposition flux of mercury exceeding the normal level of 20 mg / m^2 / yr. Plants in these tracts are an important source of mercury contamination to creeks and lakes.

Mercury Concentrations at Geothermal Sites

Natural point sources of mercury that persist over geologically long periods may have a regional impact on the ambient atmospheric concentration of mercury in the atmosphere. More importantly, these sources will affect the uptake of mercury by plant communities adjacent to these areas. Geothermal areas in the Sierra Nevada ecosystem such as the Lassen, Long Valley, and Coso volcanic centers are point sources for mercury emission into the atmosphere. Ambient mercury concentrations in air are elevated in these areas, and adjacent plant communities will take up mercury through their leaves and concentrate mercury in foliage. Mercury concentrations in wash off and litter fall from these plant communities will have elevated and will exceed the normal flux of mercury from litter fall, about 20 mg / m^2 / yr, and wash off, about 6 mg / m^2 / yr, to the soil and into drainage basins and lakes.

Mercury Concentrations at Mine Sites and Ore Deposits

In areas with kuroko, low-sulfide gold-quartz (Mother Lode gold), and epithermal ore deposits (see figures 18.1, 18.2, and 18.4), elevated mercury levels can be expected in soils above and adjacent to the deposit. In mine sites where mercury was used in the gold amalgamation process, elevated mercury levels are present in the soils and tailings. In these areas, native mercury was also released into nearby creeks.

Gas emission from soils above and adjacent to ore deposits and from contaminated soils in mine sites can be expected to exceed the natural soil gas flux of mercury of about 7 mg / m^2 / yr. Elemental mercury vapor flux from contaminated soils, soils from mineralized areas, and soils in areas with naturally elevated background mercury is controlled primarily by volatilization of Hg^o and secondarily by biotic and abiotic reduction of Hg^{++} in pore water to Hg^o. The Hg^o flux from soil increases exponentially with increases in soil temperature. Thus, during the summer, soil gas emission will be greatest, and uptake of mercury into plant leaves will be highest.

Typical Hg^o flux from contaminated soils in mine sites and measured above contaminated soils range from 10,000–22,000 mg / m^2 / h, compared to background values of 1–10 mg / m^2 / h. Mercury concentration in air over contaminated soils ranges from 3–4 mg / m^3, compared to background concentrations of 1–2 mg / m^3. The yearly soil emission flux of mercury from a contaminated soil or mine site ranges from 10–100 kg of Hg^o / km^2.

Mercury in Water and Sediment of Seepage Lakes

In seepage lakes within the Sierra Nevada ecosystem, the global increase in the mercury flux is recorded in lake sediments (Hurley et al. 1994). Before about 1850, baseline mercury concentrations in lake sediments are relatively constant and range from 10–50 mg / m^2 / yr. From about 1850 until about 1960–70, anthropogenic mercury associated with industrialization added to the atmospheric mercury cycle and increased mercury content in lake sediments. Maximum recorded mercury concentrations range from 55–2,000 mg / g. Because of restriction of mercury release to the atmosphere since the 1960–70 period, sediments deposited in lakes since that time show decreased mercury concentration. However, this mercury content is still above initial baseline concentration.

The ratio of the maximum mercury content in the sedimentary record at about 1960–70 to the baseline concentration before evidence of anthropogenic input is termed the `enrichment factor`. Enrichment factors for seepage lakes are a function of the lake's location and range from two to about six. Little is known about the exact magnitude of enrichment factors for lakes in the Sierra Nevada ecosystem or about the effect of regional point source mercury sites on these lakes.

Methylmercury concentration in lake sediments shows a similar pattern of enrichment and then decline in last two decades, but the concentrations of methylmercury are considerably lower. The enrichment factors are much higher however, ranging from twelve to fifteen. In preindustrial (pre-1850) sediments, methylmercury typically constitutes 0.15%–0.3% of the total mercury present, and, in the sediments reflecting high anthropogenic mercury input, methylmercury constitutes from 0.4%–1.4% of the total mercury present. Methylmercury concentration in sediment corese before the industrial period is about 0.2 mg / g and in modern-day sediments ranges up to 1.5 mg / g.

In the lakes, biologically mediated reduction of Hg^{++} in large part controls the Hg^o concentration and evasion rate of Hg^o from the lake to the atmosphere. Removal of mercury through sedimentation is relatively low and about equivalent to the fluvial flux of mercury into lakes. Evasion is the primary factor in removal of mercury from seepage lakes in the Sierra Nevada ecosystem. The total mercury flux added to lakes is about 50 mg / m^2 / yr.

Methylmercury in Lakes

Formation of methylmercury in lakes is an important environmental factor. Methylmercury (CH_3Hg^+) concentration increases in organisms that are higher in the food chain resulting in significant biomagnification of methylmercury in species such as fish. This high concentration results principally because methylmercury has a long biological half-life in fish. Low levels of methylmercury in lake water may result in very high levels in fish and affect the wildlife that consume fish, as well as the quality of fisheries for human consumption. This problem is the primary environmental concern with respect to methylmercury.

Formation of methylmercury in lakes and wetlands is favored by low pH of the water and high levels of dissolved organic carbon. Mercury methylation is a co-metabolic reaction, and biotic methylation accounts for nearly all the methylmercury in most lakes. Sulfate-reducing bacteria are the most important mediators in the biotic methylation process, a process inhibited by the absence of sulfate. Methylmercury from precipitation accounts for less than 1% of total mercury in a lake system.

Wetlands play a major role in forming methylmercury because of their low pH and high levels of dissolved organic carbon. In the wetland environment, abiotic methylation of Hg^{++} most likely occurs in the presence of humic acids and metal catalysts.

Demethylation is primarily mediated by enzymes in single cells in a variety of organisms within lakes. Detrital particles such as clays and organic matter absorb Hg^{++} from water, and sedimentation of these particles reduces the methylation process. Methylmercury is also partly removed from the water during sedimentation and sequestered in sediments. The sediment trap flux is typically an important factor in the methylmercury cycle.

Nearly all methylmercury is formed in the lake ecosystem. For many lakes the primary concentration of methylmercury resides in the fish population. Methylmercury in the water column is relatively low and only somewhat higher than that present in zooplankton.

SERPENTINE AND LIMESTONE AS HOSTS FOR RARE PLANTS

A preliminary digital version of the geologic map of California (Jennings 1977) is currently being revised by the USGS and the California Division of Mines and Geology. We have used this draft digital file to produce a map showing areas underlain by ultramafic rocks, such as serpentine (unit um) (Jennings 1977) (plate 18.9). This map is useful in assessing the extent of areas where rare plants are likely to be present and in assessing the completeness of the rare-plant lists, because the plants that have adapted to serpentine soils are uncommon. Plants that grow in such soils include, but are not limited to, Lewisia, pitcher plant, Indian paintbrush, Mariposa lily, and lady's slipper (Kruckeberg 1984). Soils developed on carbonate rocks also host rare plants. Therefore, we plotted those areas underlain by carbonate rocks, such as limestone and for other map units that contain carbonate rocks. The units that contain carbonate rocks are further divided into those dominated by carbonate rocks and those dominated by clastic rocks. On Jennings's (1977) map, the units are ls (limestone), Pm (Permian rocks that may contain limestone and dolomite), Tr (Triassic units that likewise may include carbonate rocks), and D (Devonian units that likewise may include carbonate rocks).

SERPENTINE-HOSTED ASBESTOS

Chrysotile (white asbestos) is found in veins in serpentinized ultramafic rocks. Protoliths include ophiolite and stratiform complexes. The veins commonly originate from fractures developed in response to stresses in shear zones, notably near changes in rock competency, as near margins of serpentinite bodies and contact aureoles of later intrusive rocks, but some deposits may result from more uniformly distributed stresses. Minor asbestos veins can be found in unaltered ultramafic rocks adjacent to serpentinite. General references on the geology of these deposits are Virta 1989; Ross 1981; Shride 1969, 1973; Chidester et al. 1978; and Anhaeusser 1986. References on the environmental geology include Coleman in press and Derkies 1985.

The following discussion is part of a draft mineral-environmental model book that is in preparation by the Minerals Teams at the USGS (Wrucke in preparation).

Economic Geology

Serpentine-hosted asbestos deposits do not show significant correlation between tonnage and grade (Orris 1992). The mean tonnage is 17 tonnes (19 short tons) with the range at one standard deviation of between 2 and 149 tonnes (2.2 and 164 short tons). The mean grade asbestos is 4.6% with the range at one standard deviation of between 1.9% and 11%. These figures are reported with no distinction between types of asbestos (cross and slip fibers).

Potential Environmental Impact

Reserves of chrysotile fiber at the asbestos deposit near Copperopolis, Calaveras County, are reported to be about 1.2 million tonnes (1.3 million short tons) (Rice 1966). The deposit, now closed, is used as an asbestos waste dump. The impact of deposits of this type consist of the following

1. Natural exposures of asbestos-bearing rock, particularly serpentinite derived from ultramafic rocks, are readily eroded by natural agents and human activities because most serpentinite is composed of incompetent, highly fractured rock. A few serpentinite bodies are highly resistant to erosion.

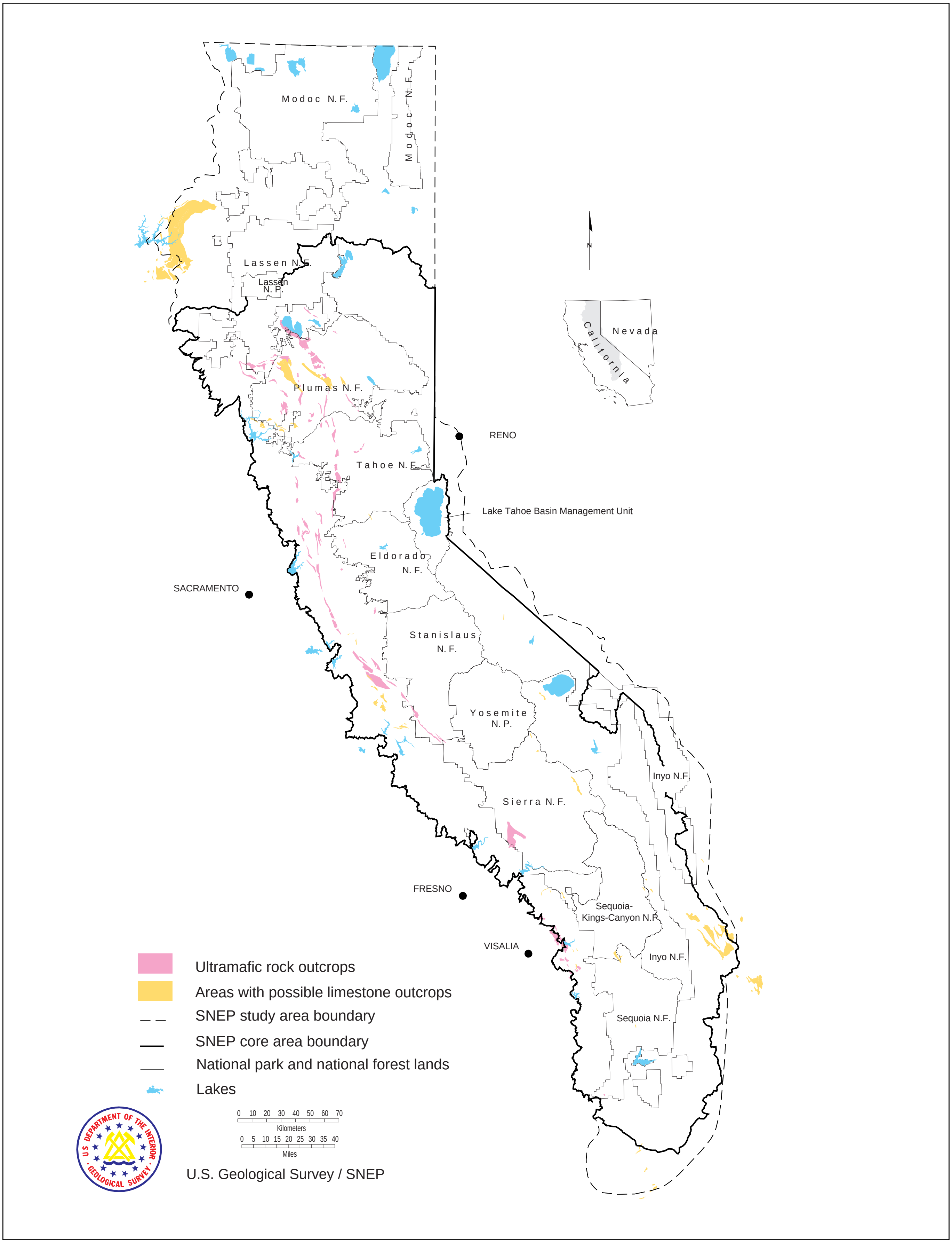


PLATE 18.9

Serpentine and carbonate-rich rocks.

2. Asbestos from sedimentary deposits and debris slides from asbestos-bearing rocks is redistributed by water and wind.

3. Vehicles driven across serpentinite and mine waste can dislodge asbestos, adding it to dust or runoff. Roads also produce channels that aid runoff. The surface area of roads in the southern half of the chrysotile-bearing New Idria serpentinite in San Benito County exceeds the area disturbed by the three largest asbestos mines (Woodward-Clyde Associates 1989).

4. Waste generated from asbestos mining and milling operations exposes asbestos to erosion by natural agents. The EPA considers mine waste containing more than 1% asbestos to be hazardous (Derkies 1985). The California Air Resources Board considers asbestos contents of mine waste greater than 5% as a potential toxic hazard (Resolution 91-27, April 1990).

5. Asbestos fibers can be picked up by surface drainage in areas of asbestos-bearing rocks and mines. In central California, water in the California aqueduct system contains asbestos (Kanarek et al. 1980; Coleman 1995). However, the EPA has concluded that there is no significant risk of cancer from the ingestion of asbestos fibers (EPA 1991).

6. Chrysotile deposits may contain small amounts of fibrous tremolite, which the EPA classifies as asbestos and a risk to human health (OSHA 1975).

7. Health risks to humans from exposure to small quantities of chrysotile asbestos in the environment are controversial. The controversy results from the EPA assumption that any amount of asbestos is potentially hazardous.

Environmental Considerations

Host Rocks and Surrounding Geologic Terrane

Serpentine-hosted deposits are present in massive serpentinite, commonly highly sheared and widely exposed, that has largely replaced the host protolith. Associated ultramafic rocks locally host asbestos veins. Most serpentine-hosted deposits have developed in ophiolite complexes, which are composed of oceanic crustal fragments consisting of a basal peridotite (that becomes serpentinized) overlain in sequence by cumulate gabbro, sheeted dikes, and pillow basalt, often capped by deep-oceanic pelagic sedimentary deposits. Accreted ophiolite often is dismembered into structurally complicated relationships.

Mineral Characteristics

Chrysotile is one of six mineral species called asbestos because of their fibrous habit (Skinner et al. 1988). Of these, chrysotile is the only fibrous serpentine mineral. The five other asbestos minerals belong to the amphibole group; these are grunerite asbestos (commonly referred to as amosite), riebeckite asbestos (commonly referred to as crocidolite), anthophyllite asbestos, tremolite asbestos, and actinolite asbestos.

Hydrology

Debris slides along the flanks of serpentinite bodies and in drainage channels can contain asbestos-bearing material available for removal and dispersion by streams (Cowan 1979). During flood stage, streams flowing into the San Joaquin Valley from the New Idria mass have introduced sediments into the California aqueduct (Coleman 1995). Asbestos fibers have been found in the water supply for San Francisco (Kanarek et al. 1980).

Asbestos Mobility from Mining Operations

Mine dumps and mill tailings at chrysotile deposits are sources of asbestos in runoff water and are more easily eroded than outcrops. The principal concerns associated with mineral processing include dust and tailings from asbestos milling operations. Asbestos fibers in tailings are available for airborne and fluvial transport.

Controversy Regarding Health Risks to Humans from Chrysotile Asbestos

The risk of asbestos to human health has been known since at least 1906 when deaths of workers in an asbestos weaving mill in France were noted (D'Agostino and Wilson 1993). In the 1920s, a death from asbestosis (fibrosis of the lung) was reported, and the disease was named (Sawyer 1987). However, not until the 1960s were the biologic effects of asbestos fibers documented in great detail and a relationship clearly established between exposure to asbestos and lung disease, including cancer. As a result of increasing concern about the health hazards of asbestos minerals, the U.S. Occupational Safety and Health Administration (OSHA) in 1971 issued regulations restricting airborne asbestos in the workplace, and in 1987 OSHA established the current standard of 0.2 fibers per cubic centimeter of air in the workplace. However, the regulations do not discriminate between fibers of the different asbestos minerals. Since the establishment of these regulations, numerous studies have supported the conclusion that significant differences exist in the health effects of the various asbestos minerals. For example, the few cases of mesotheliomas (cancer of the pleura or peritoneum) in Canadian chrysotile miners and mill workers appear to be not from chrysotile but perhaps from small amounts of tremolite asbestos, and a study of British workers manufacturing friction materials using only chrysotile showed no excess of deaths from lung diseases (Mossman et al. 1990). Chrysotile has been found to have the least health effects of any asbestos mineral in occupational exposure and to produce no excess lung cancer in people exposed to chrysotile alone in amounts more than ten times higher than recommended by the EPA (Coleman in press).

Risk Assessment

Hazards resulting from the inhalation of asbestos fibers have been documented by the EPA and have been the topic of considerable scientific inquiry (McDonald and McDonald 1995; D'Agostino and Wilson 1993; Mossman et al. 1990; Skinner et al. 1988; Ross 1981, 1987; Ross and Skinner 1994). Although asbestos as a cause of lung disease is well documented, debate continues regarding the risk from low levels of exposure to asbestos fibers. In a report prepared for the California Environmental Protection Agency, risk from asbestos was not ranked because data on low-level exposure were considered inadequate (California Comparative Risk Project 1994). Studies show that important factors to be considered in evaluating risk from the inhalation of asbestos are the type of asbestos mineral, length and diameter of the asbestos fibrils, amount of asbestos inhaled, and the duration of the exposure. Yet, despite conclusions that risks from chrysotile asbestos are almost certainly lower than for other asbestos minerals, uncertainty in the degree of risk from exposure to chrysotile remains and results in part from disagreement on the threshold below which which inhalation can be considered safe or if such a threshold level even exists (D'Agostino and Wilson 1993).

The EPA has concluded that inhalation of any amount of asbestos is potentially hazardous, that a single asbestos fiber can be lethal (Abelson 1990). This conclusion results from belief that the relationship between asbestos dose and health risk is linear, such that there is some risk even at very low levels of exposure (D'Agostino and Wilson 1993). According to this theory, there is no safe level of asbestos exposure. In a nonlinear relationsh, risk from exposure decreases rapidly at low levels, and a threshold value can be reached below which the risk is zero. Recent studies suggest that low-level exposure to chrysotile asbestos in the environment has generated unwarranted concern (D'Agostino and Wilson 1993) and that the single-fiber view is unproved (Abelson 1990). Other studies suggest that there is a threshold value below which exposure to chrysotile asbestos causes no measurable health effects (Ross 1987).

Estimates of risk to human health from numerous activities have been quantified, including everyday risks, and a few attempts have been made to quantify risk of exposure to chrysotile asbestos under different environmental conditions (D'Agostino and Wilson 1993; Coleman 1995). For example, data show that risks from inhaling asbestos during recreational activities at the chrysotile-bearing New Idria serpentinite or from exposure to asbestos in schools are low. Coleman (in press) concluded that "the apparent risk in making one trip by automobile to New Idria is 300 times greater than inhaling [chrysotile] fibers during a lifetime of recreation in this area." Risks from occupying schools containing chrysotile fibers is even lower and has been categorized as harmlessly small (Abelson 1990).

CALCIUM CONCENTRATIONS

James Shevock, a botanist with the U.S. Forest Service in San Francisco, suggested the usefulness of a calcium-concentration map for SNEP. Such a map is also being produced by Tom Frost, Gary Raines, and Lynn Decker for the Interior Columbia Basin Ecosystem Management Project. The following text is excerpted and adapted from Frost, Raines, and Decker (Thomas P. Frost, letter to Michael F. Diggles, February 1995).

Rock Types and Calcium Content

A bedrock calcium-concentration map (see plate 18.9 for simplified version) might serve as a tool for both addressing stream productivity and providing a measure of acid mine drainage and acid rain buffering capacity. We produced such a map by grouping rock types into calcium content classes. The base map from which the classes were defined is the digital version of the geologic map of California at 1:750,000 scale (Jennings 1977). Calcium carbonate, or calcite, is the dominant carbonate phase or mineral.

Rocks have different calcium contents and the easiest way to classify elemental abundances is by the weight percentage of the equivalent oxide, in this case CaO. Calcium rarely occurs as a mineral CaO, but it occurs complexed in distinct minerals. For example, the mineral calcite ($CaCO_3$) is the main component of limestone and calcic marble or calcite. Calcite is very soluble in water relative to other common minerals and is typically the dominant mineral dissolved to form hard water. Other calcium-rich minerals are less soluble under normal surficial conditions and thus may not be as readily available to the aquatic habitat under otherwise similar conditions. Plagioclase feldspar is one of the most common minerals in the earth's crust, but there are variations in the calcium and sodium contents of plagioclases found in different rock types. Calcium in basalts is localized in calcic plagioclase, clinopyroxene, and glass, which are relatively unstable under surficial conditions and readily alter to clays, calcite, and other soft minerals. The calcium, once soluble, is available for biotic uptake.

Rocks such as granites have low calcium content. In areas such as that underlain by the Sierra Nevada batholith, relatively little Ca is available. Some of the folded, faulted, and locally metamorphosed sedimentary rocks of the Sierra Nevada roof pendants are high in Ca and are included in plate 18.9 with other carbonate-rich rocks.

Carbonate rocks are soluble, but where climate is arid, as on the east side of the Sierra Nevada, carbonate rocks tend to be the rock types most resistant to erosion. In arid areas, abundant calcium may not be available to the aquatic environment because there is no mechanism to dissolve it.

Role of Calcium in Aquatic Systems

The calcium content of waters varies from region to region, reflecting both local geography and climate. Calcium is essential for metabolic processes in all living organisms. It plays an important role in its effect on pH and is essential in the main buffering system of natural waters.

Virtually all vertebrates, mollusks, and certain other invertebrates require large quantities of calcium (in the form of $CaCO_3$) as a major skeletal-strengthening material. Because animals need large amounts of calcium, their growth and, ultimately, size may be limited by the lack of it. Where calcium is plentiful, for example in what are commonly referred to as "chalk streams," one will potentially find large macroinvertebrates and large fish.

Most lakes have a pH of 6 to 9. When the pH of a lake falls below 4 or 5, the species diversity is likely to be severely restricted. Most fish species can live in waters with pH ranging from 5 to 9. In general, the higher the pH, the greater the productivity of the waters and the faster the growth rates of the fish and macroinvertebrates. The most productive waters (in general) have a pH of about 8. However, only a few fish are adapted for living in water of pH 8.5 or greater. One example of a fish adapted for life in alkaline waters is the Eagle Lake trout in Lassen County, where pH levels may reach 9.6. In general, water of pH greater than 10 or less than 4 will be fatal to fish.

There are at least two obvious difficulties with attempting to work out ratios of various minerals in solution in a drainage basin. One is the differential solubilities of minerals and the other is that the aquatic biota exert selective effects on dissolved substances.

VOLCANIC HAZARDS

The principal volcanic-hazard area in the SNEP study area is in the vicinity of Mammoth Lakes in the Long Valley caldera. Outside the SNEP core study area and within the greater SNEP study area, volcanic centers of the Cascade Range are important as well. These include Lassen Peak, Mount Shasta, and Medicine Lake Volcano.

Long Valley Caldera

Long Valley and Mono Craters have been the site of volcanic activity for millions of years. Bailey (1989) presents a geologic map of the region that shows extent, ages, and descriptions of volcanic rocks in the area. He includes a comprehensive treatment of the formation of the caldera, which was the resulted from massive eruptions more than 700,000 years ago.

Earthquake activity in the Long Valley region began to increase in 1978 and peaked in 1980. This activity was interpreted to be the result of magma movement beneath Long Valley caldera. Miller et al. (1982) show potential hazard zones in the region, taking into account common wind directions and topographic barriers.

A comprehensive response plan for volcanic hazards in the Long Valley caldera and Mono Craters area was prepared by Hill et al. (1991) of the USGS in cooperation with the California Division of Mines and Geology. In their report, Hill et al. (1991) state that recurring earthquake swarms in Long Valley caldera through the 1980s and associated inflation of the resurgent dome in the caldera emphasize that this geologically youthful volcanic system is capable of further volcanic activity. Specific response actions under their plan are keyed to a five-level status ranking of activity level. The activity levels are eruption likely within hours to days, and intense strong, moderate, or weak unrest. The USGS continuously monitors volcanic activity in Long Valley caldera and vicinity by means of a seismic network and deformation monitoring networks (dilatometers [strainmeters], tiltmeters, and magnetometers).

If activity levels indicate that an eruption is likely, the response plan states that an eruption will most likely produce small to moderate volumes of silicic lava similar to the eruptions that occurred 650 years ago at the north end of Mono Craters and 550 years ago at the Inyo Domes. In this case, we may expect to see

- phreatic eruptions as the magma interacts with the shallow ground water producing steam blasts that can throw large rocks several hundred meters from the vent (the "eruption" could stop at this point as it did with the phreatic blasts that formed the Inyo Craters)
- an explosive magmatic phase during which hot pumice and ash would be ejected thousands of feet into the air producing thick pumice accumulations near the vent, extensive deposits of fine ash hundreds of kilometers downwind, and destructive pyroclastic flows that may reach distances as great as 5 to 10 km (3–6 mi) from the vent
- a final phase that involves the slow extrusion of lava to form steep-sided flows and domes.

Like the eruptions 550 and 650 years ago, eruptions may occur from several separate vents in succession with the vents spaced over a distance of 5 to 10 km (3 to 6 mi). Individual eruptions may be separated in time by days or perhaps weeks. Larger, more destructive eruptions following the same basic pattern are possible, but less likely. Also possible, but less likely, is a small to moderate eruption of basaltic lava similar to the eruptions that produced the Red Cones several thousand years ago. This lava could travel at speeds ranging from a few meters per hour to several kilometers per hour. The resulting lava flows may extend 10 km (6 mi) or more from the vents depending on the vigor and duration of the eruption.

Miller et al. (1982) include a hazard zone for the unlikely event of an eruption as large as that which took place 700,000 years ago. Devastation within 120 km (75 mi) would be severe to total. Pyroclastic flows would move at speeds of several hundreds of kilometers per hour. Deposits of ash 15 cm (6 in) thick would fall as far away as 500 km (300 mi) with appreciable thickness deposited all across North America. Such an event has not taken place anywhere on the earth in historic times.

Cascade Volcanoes

The three volcanic centers of the Cascade Range within the SNEP study area are Medicine Lake Volcano, Lassen Peak, and Mount Shasta (USGS 1994). Information about Cascade volcanoes is available from the Cascade Volcano Observatory of the USGS on the WWW Home Page whose URL is http://vulcan.wr.usgs.gov/home.html. Lassen Peak erupted early this century, and Mount Shasta's last eruption (Miller 1980) was about two hundred years ago. Medicine Lake Volcano has not erupted in nearly a thousand years.

The following text is published on the WWW at http://vulcan.wr.usgs.gov.

Lassen Peak

This text is excerpted from Hoblitt et al. 1987. The Lassen volcanic center consists of a chain of vents aligned roughly north-south that extends about 8 km (5 mi) north from Lassen Peak. Although volcanism began between about 600,000 and 350,000 years ago, events of the last 35,000 years are the most thoroughly studied and form the basis for assessing hazards from future eruptions in the region. The stratigraphic record of late Pleistocene and Holocene eruptions in this region contains evidence of many eruptions during the last 35,000 years

> 35,000 years ago: Eruptions produced two pyroclastic flows from a vent east of Sunflower Flat near the north end of the chain. These eruptions were followed by extrusion of one or more domes at vents in the same area.
>
> 25,000–35,000 years ago: Eruptions at Hat Mountain produced andesitic lava flows that reached up to 6 km (4 mi) from their vents. About the same time, eruptions at a vent now buried by the Lassen Peak dome produced at least four pyroclastic flows and several short rhyolite lava flows.
>
> 20,000 years ago: Eruptions formed an ancestral dome, now buried by the Lassen Peak dome, which is thought to have erupted shortly before 11,000 years ago. During late Wisconsin deglaciation, lahars formed on the slopes of Lassen Peak and flowed at least several kilometers, primarily to the northeast.
>
> 1,000–1,200 years ago: The Chaos Crags eruptive episode began with eruption of a pumiceous tephra. At least two pyroclastic flows traveled west down Manzanita Creek about 4 km (2.5 mi) and a similar distance north down Lost Creek. Explosive activity generated pyroclastic flows that extended down Manzanita, Lost, and Hat Creeks. Shortly thereafter, extrusion of five dacite domes formed the Chaos Crags.
>
> 300 years ago: Three or more rockfalls from the Chaos Crags generated high-velocity avalanches of rock debris that traveled as far as 4.3 km (2.7 mi) westward from the Chaos Crags. The falls may have resulted from earthquakes, steam explosions, or intrusion of a dome into the central part of the Chaos Crags.
>
> A.D. 1914–1917: The most recent eruption at Lassen Peak took place early in this century, when a small phreatic eruption occurred on May 30, 1914, at a new vent near the summit of the peak. More than 150 explosions of various sizes occurred during the following year. A vertical eruption column resulting from the pyroclastic eruption rose to an altitude of more than 9 km (5.6 mi) above the vent and deposited a lobe of pumiceous tephra that can be traced as far as 30 km (19 mi) to the east-northeast. The fall of fine ash was reported as far away as Elko, Nevada, more than 500 km (300 mi) east of Lassen Peak. Intermittent eruptions of variable intensity continued until about the middle of 1917.

The record of late Pleistocene and Holocene eruptive activity at the Lassen volcanic center suggests that the most likely hazardous future events include pyroclastic eruptions that produce pyroclastic flows and tephra. The Lassen volcanic center is one of the principal candidates in the Cascade Range for future silicic, probably explosive, eruptions. Based on its history, pyroclastic flows could endanger areas within several tens of kilometers of an active vent. Lahars and floods could affect low-lying areas even farther from the vent, particularly if eruptions occur during periods of thick snow cover. Eruptions that produce lava flows are generally less dangerous, although both lava flows and domes can become unstable and produce pyroclastic flows and rockfall avalanches that could affect areas as far as several kilometers away. Mixing of hot debris with snow can generate lahars that could inundate valley bottoms for tens of kilometers as in 1915.

Mount Shasta

Future eruptions like those of the last ten thousand years will probably produce deposits of lithic ash, lava flows, domes, and pyroclastic flows and could endanger works of humans that lie within several tens of kilometers of the volcano. Lava flows and pyroclastic flows may affect low areas within about 15–20 km (9–13 mi) of the summit of Mount Shasta or any satellite vent that might become active. Lahars could affect valley floors and other low areas as far as several tens of kilometers from Mount Shasta. Owing to great relief and steep slopes, a part of the volcano could also fail catastrophically and generate a very large debris avalanche and lahar. Such events could affect any sector around the volcano and could reach more than 50 km (32 mi) from the summit. Explosive lateral blasts could also occur as a result of renewed eruptive activity, or they could be associated with a large debris avalanche; such events could affect broad sectors to a distance of more than 30 km (19 mi) from the volcano. On the basis of Holocene behavior, the probability is low that Mount Shasta will erupt large volumes of pumiceous ash in the future. The distribution of Holocene tephra and the prevailing wind directions suggest that areas most likely to be affected by tephra are mainly east and within about 50 km (32 mi) of the volcano's summit. However, the andesitic and dacitic composition of its products suggests that Mount Shasta could erupt considerably larger volumes of tephra in the future. Moreover, Christiansen (1982) has suggested that because it is a long-lived volcanic center and has erupted only relatively small volumes of magma for several thousand years, Mount Shasta is the Cascade Range volcano most likely to produce a very large explosive eruption (101–102 km^3 [24.7–24.9 mi^3]). Such an event could produce tephra deposits as extensive and as thick as the Mazama ash deposits and pyroclastic flows that could reach more than 50 km (32 mi) from the vent. The annual probability for such a large event may be no greater than 10^{-5}, but it is finite.

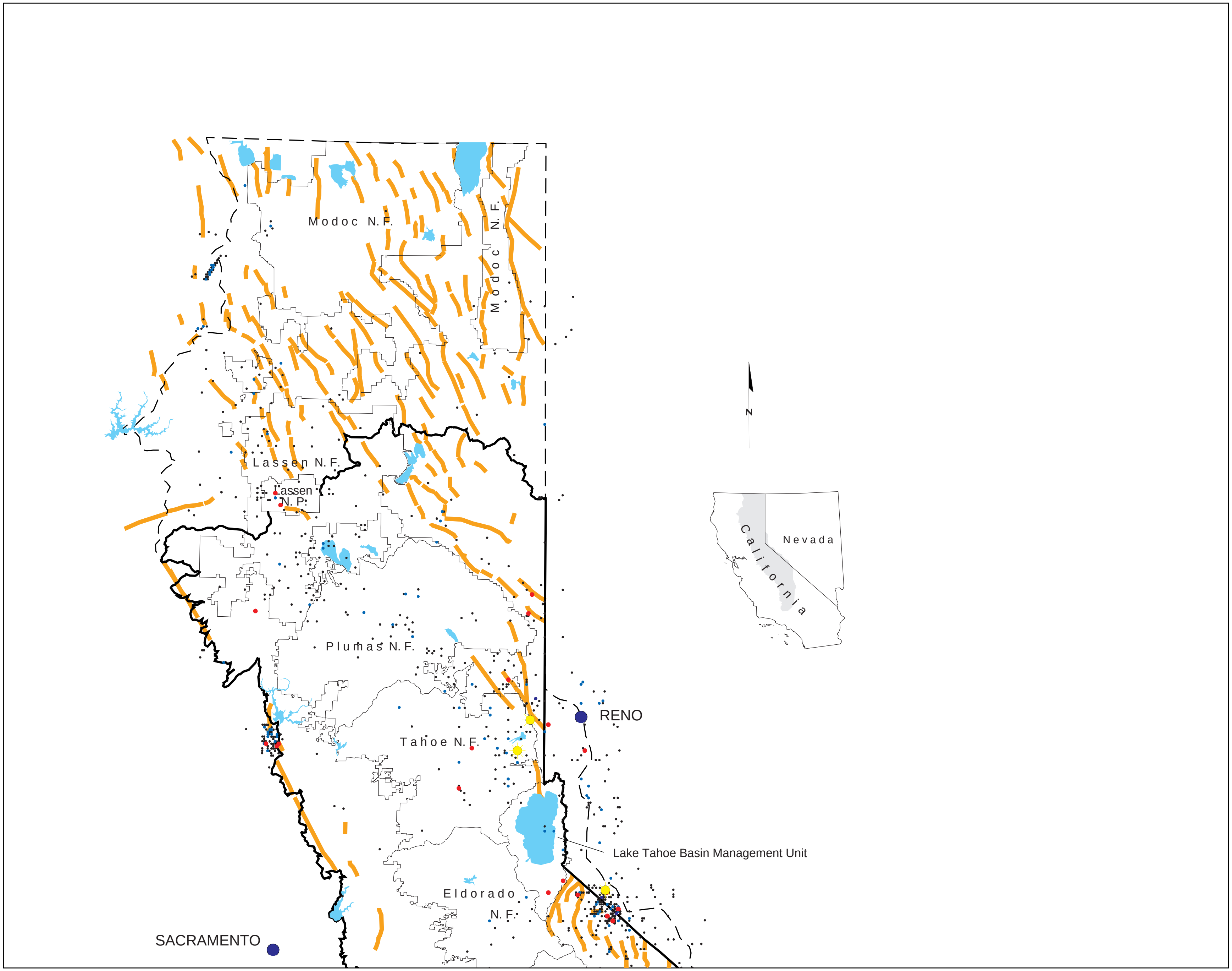
Medicine Lake Volcano

Eruptions occurring during the past ten thousand years form a reasonable basis for assessing hazards from future eruptions. Similar eruptions of silicic magma are likely from vents within and just outside the summit caldera, which is thought to be underlain by silicic magma (Heiken 1978; Eichelberger 1981), part of which could still be molten. These eruptions probably will produce tephras that could fall as much as several hundred kilometers downwind and mostly east of the volcano (Christiansen 1982; Miller, in press). Such eruptions could also produce pyroclastic flows that could endanger areas within about 10 km (6 mi) of the active vent, although such phenomena are not known to have occurred during Holocene time. Silicic eruptions are likely to culminate with eruption of dacite to rhyolite lava flows or domes that could reach as far as several kilometers from their vents. Eruptions of basalt and basaltic andesite lava may also occur from vents on the flanks of the Medicine Lake volcano (Christiansen 1982). Such eruptions may begin by forming cinder cones and dispersing mafic tephra as far as 20 km (13 mi) from the active vent and culminate with the production of lava flows that may extend for tens of kilometers downslope from their vents. Eruptions of both mafic and silicic magma may be fed by dikes. As a consequence, eruptions of basalt and rhyolite may occur simultaneously, or nearly so, from multiple, probably aligned vents. Eruptions of volumes larger than those of Holocene time are possible, including a caldera-forming eruption (Christiansen, 1982), because of the inferred existence of a large body of silicic magma beneath the Medicine Lake volcano (Heiken 1978; Christiansen 1982). Future eruptions of this type could deposit thick accumulations of tephra over wide regions and produce pyroclastic flows that could affect areas more than 50 km (32 mi) from the vent. Debris avalanches and laterally directed blasts are not known to have occurred in this region in the past. Owing to the limited relief of the Medicine Lake volcano, debris avalanches are not considered likely in the future. Because of the absence of permanent snow and ice, future eruptions are not likely to generate large-volume lahars and floods, although lahars and floods of moderate volumes are possible if eruptions occur when snow covers the ground.

EARTHQUAKE HAZARDS

The alignment of epicenter clusters along the east side of the Sierra Nevada branches northward from the south end of the San Andreas fault system in the Salton Trough and bends back toward the north terminus of the San Andreas fault system at the Mendocino triple junction in northern California (Hill et al. 1990). A dense cluster of epicenters in the Mammoth Lakes area represents an episode of intense earthquake activity in Long Valley caldera that began in 1978 (Hill et al. 1985). To make a map showing twentieth-century seismicity in the Sierra Nevada (plate 18.10), we downloaded the latest data (as of January 16, 1996) from the Northern California Earthquake Data Center at the University of California, Berkeley, using their Home Page whose URL is http://www.quake.geo.berkeley.edu/ and imported the data into Arc/Info software. A total of 3,321 earthquakes with magnitudes of at least 3.0 that occurred since 1910 are plotted on the map. From magnitude 3.0 to 3.9, there are 2,614 points; from magnitude 4.0 to 4.9, there are 616 points; from magnitude 5.0 to 5.9 there are 79 points; and from magnitude 6.0 to 6.3 there are 12 points. No earthquakes greater than magnitude 6.3 have occurred in the SNEP area during this century.

The largest historic earthquakes in the region were in Owens Valley in 1872. Between twenty-three and twenty-nine people died in the magnitude 7.6 earthquake in Lone Pine on May 26 (Sharp 1972), and the town was virtually leveled when the entire 100–110 km (63–69 mi) length of the Owens Valley fault ruptured (Ellsworth 1990). A magnitude 6.75 aftershock occurred later that same day, and another magnitude 6.75 aftershock occurred north of Bishop several days later (Goter et al. 1994). Adobe and brick buildings in Owens Valley sustained most of the damage. John Muir experienced the shaking from Yosemite Valley where he witnessed a rockfall triggered by the event. Ellsworth (1990) points out that the first long-term seismic forecast was made by G. K. Gilbert in 1883 when he noted that rebuilding Independence with wood was an extravagance because "the spot which is the focus of an earthquake . . . is thereby exempted [unlikely to have an



Modoc N.F.
Modoc N.F.
Lassen N.F.
Lassen
N.P.
Plumas N.F.
Tahoe N.F.
RENO
Lake Tahoe Basin Management Unit
Eldorado
N.F.
SACRAMENTO
N
Nevada
California

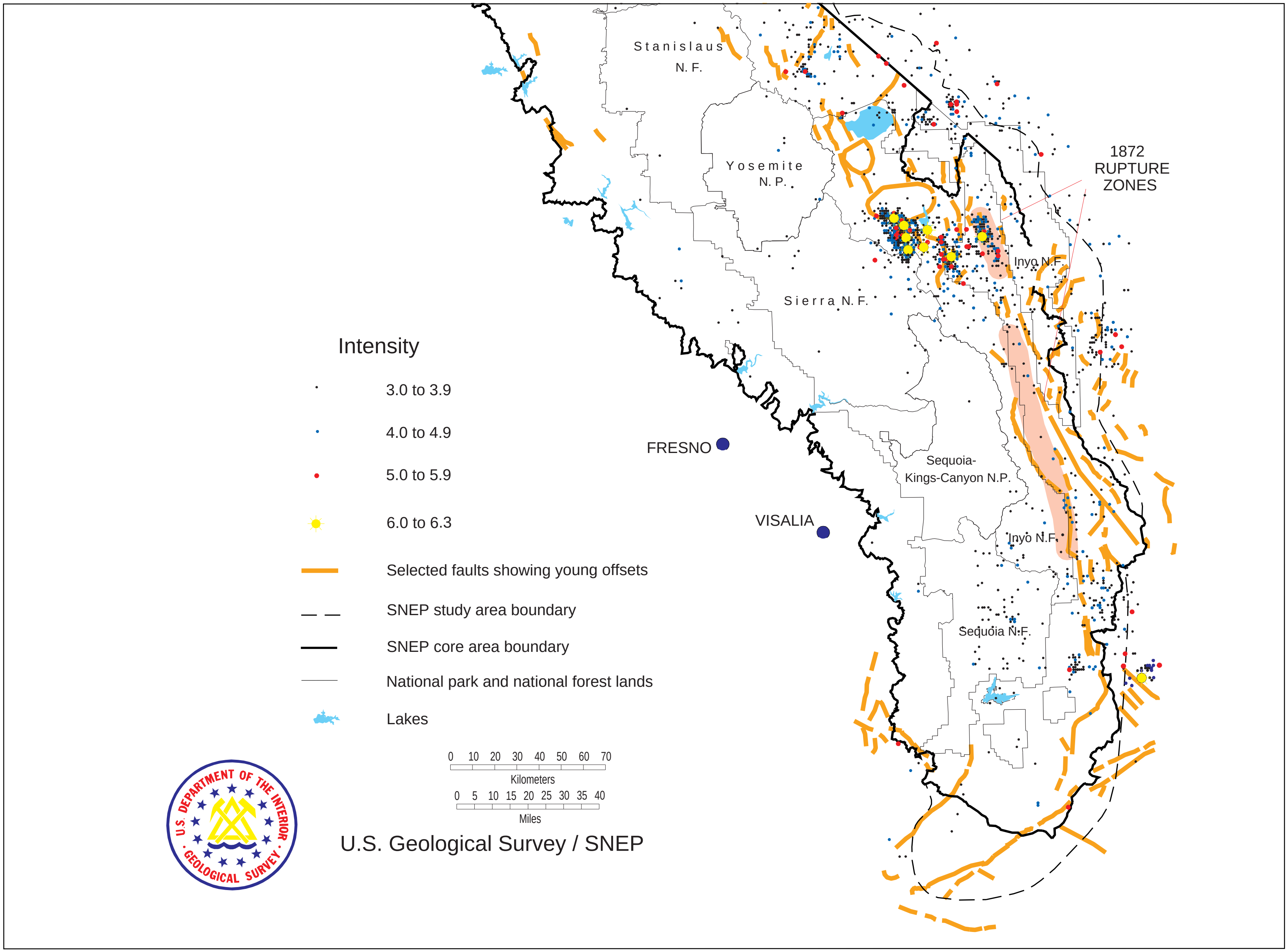
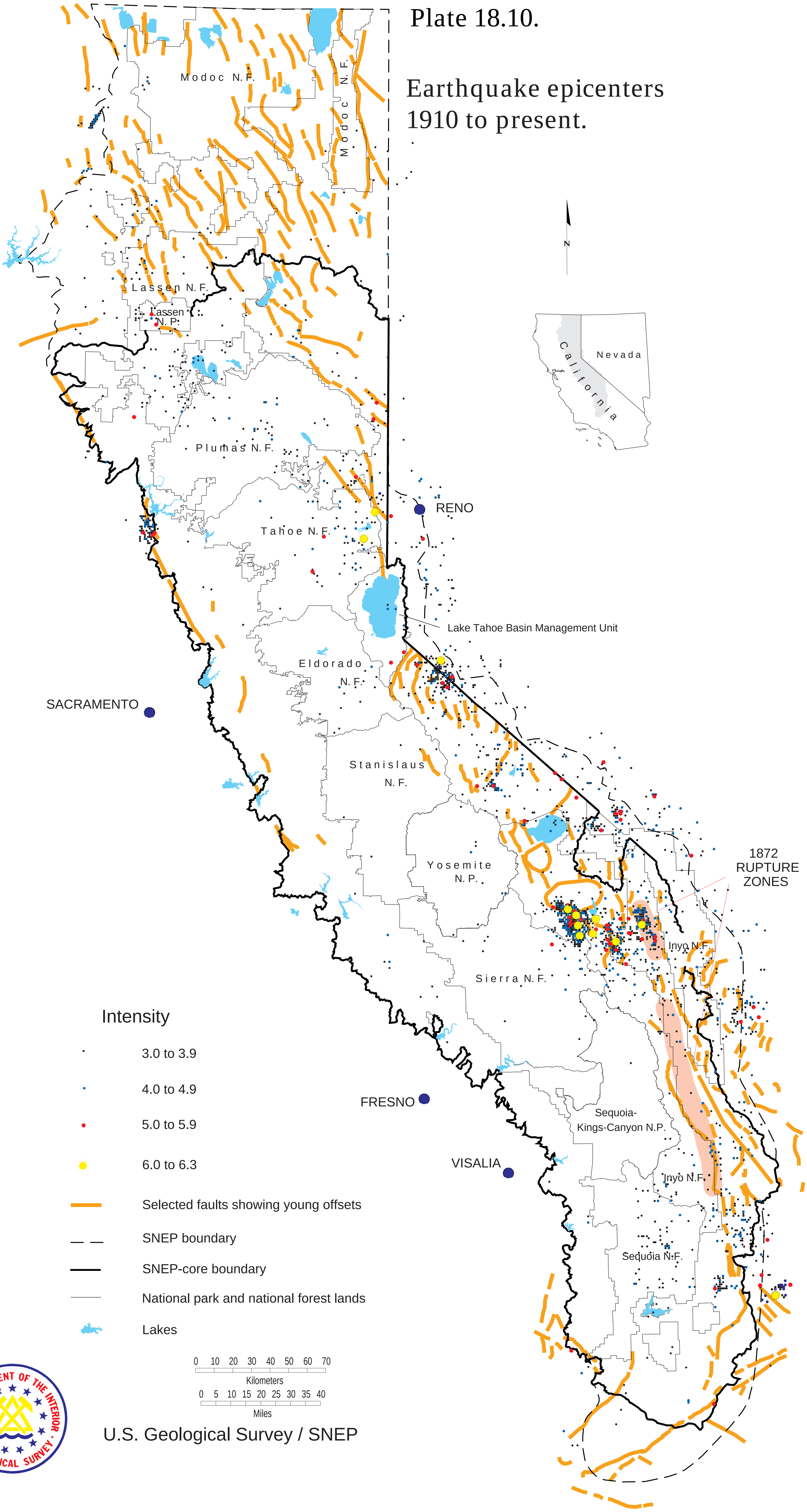


PLATE 18.10

Earthquake epicenters from 1910 to the present.

Plate 18.10.

Earthquake epicenters 1910 to present.



U.S. Geological Survey / SNEP

earthquake] for a long time" (Gilbert 1884). It has now been a long time, and attention to seismic building standards is wise and encouraged.

A more general map showing all of California and Nevada was produced by Goter et al. (1994). It covers all events up to its publication date, including those with magnitudes below 1.0 and those that occurred in the last century. In that report, the authors point out that many faults capable of producing large earthquakes are quiescent for long periods between such events. Therefore, the faults indicated by seismicity on maps do not represent all faults in the region that have seismic-hazard potential.

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