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Digital Mapping of Potential Mineral and Geochemical Hazards in California: Examples for Naturally Occurring Asbestos, Radon, and Highway Corridor Mapping Projects

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Introduction

Over the last two decades, the California Geological Survey (CGS) has increasingly received requests for environmental geology/mineralogy/geochemistry information from State and local agencies, consultants, industries, and the public. These requests have led to projects to identify and map potential mineral hazards such as naturally occurring asbestos, heavy metals, and radon. In these projects, digital mapping technology is used to compile, evaluate, and interpret data from a variety of sources and to develop associated products. The information and advice provided by the CGS are used by State and local government agencies and the public to protect the life and safety of California citizens, to protect the health of the environment, and to raise public awareness of these hazards.

This paper discusses three different types of mineral-hazard studies and the use of Geographic Information System (GIS) tools in their preparation. The complexity of these studies, both in geologic and GIS context, varies depending on the amount, type, and format of data involved as well as the intended use, audience, and format of the final products. These vary from relatively simple derivative maps based on geological information and intended for use by non-geologists to more complex maps and datasets combining data from varied sources and intended for multiple user groups with wide-ranging technical backgrounds. The reports accompanying all of these studies describe and document the study methodology, data sources, methods of analysis, interpretive conclusions, and limitations of the products.

Mapping Of Naturally Occurring Asbestos In California

Asbestos is classified as a known human carcinogen by State, Federal, and international agencies. In California, chrysotile and tremolite-actinolite asbestos are the most common types of naturally occurring asbestos (NOA) found, but occurrences of all six regulated asbestos minerals (chrysotile, tremolite, actinolite, anthophyllite, crocidolite, and amosite) have been reported. Currently, all six types of asbestos are considered hazardous and may cause lung disease and cancer. Fibrous richterite and winchite (currently unregulated) have also been reported. NOA is most commonly associated with serpentinite, serpentinized ultramafic rocks, and associated soils in California, but may also be found less commonly in other rocks or soils. It may also be more common in fault or shear zones in certain rock types or at geologic boundaries (Clinkenbeard and others, 2002; Van Gosen, 2007). Reported occurrences of asbestos minerals, fibrous amphiboles, or ultramafic rock/serpentinite are known in 53 of California's 58 counties.

Government agency and general public concerns about potential public health impacts from NOA exposure over the last two decades have resulted in State and local regulations to minimize the public's exposure to asbestos by requiring work practices that minimize dust emissions from various activities. In California, these regulations govern construction, excavation, and mining activities in areas that may contain NOA, and place restrictions on the use of aggregate materials containing NOA for surfacing applications. With these concerns and regulations, there has been a growing demand for information on where NOA is likely to be encountered in California. The CGS has been assisting various Federal, State, and local agencies by providing geologic information about NOA in the State since the late 1980s. Over the last decade, products have included a statewide map of ultramafic rocks (Churchill and Hill, 2000); guidelines for geologic investigations of naturally occurring asbestos in California (Clinkenbeard and others, 2002); county maps showing the relative likelihood for the presence of naturally occurring asbestos in western El Dorado (Churchill and others, 2000), Placer (Higgins and Clinkenbeard, 2006a), and eastern Sacramento (Higgins and Clinkenbeard, 2006b) Counties; and a collaboration with the U.S. Geological Survey (USGS) to perform a preliminary evaluation of a remote-sensing instrument, the Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS), as a potential tool for mapping the occurrence and distribution of asbestos-bearing rocks (Swayze and others, 2004; 2009).

The first county NOA study, western El Dorado County, was a pilot project prepared in response to a recommendation by a multi-agency asbestos task force formed in the late 1990s to advise government officials and the general public of the distribution, potential health risks, and possible mitigations for NOA in the county. Subsequent NOA studies in Placer and eastern Sacramento Counties were requested and funded by local Air Pollution Control Districts (APCDs). The CGS NOA maps are intended to provide information to local, State, and Federal agencies and the public about where NOA is more likely to be found in a region. The maps, while not regulatory, may be used to help determine where agencies wish to consider actions to minimize generation and exposure to dust that may contain NOA. They do not indicate whether NOA is present or absent in bedrock or soil on a particular parcel of land. Determination of the actual presence or absence of NOA at a particular site requires a site-specific examination of the property and sampling and analysis for NOA.

The NOA maps are derivative maps intended for use by non-geologists. Rather than showing conventional geologic units, they show the relative likelihood of areas to contain NOA (see figure 1). GIS tools are used for data management in compiling geologic maps, soil maps, and geologic or other information related to NOA and for aiding in the analysis of the spatial distribution of these elements as they apply to the potential occurrence of NOA.

Geology is compiled at an appropriate scale, typically 1:100,000, from a variety of sources, both electronic and hard-copy, to create a digital geologic map of the area being studied. Soil reports are reviewed to identify those soil units associated with ultramafic rock/serpentinite parent materials. Because of the characteristics of serpentine soils and their vegetation, they stand out in some types of remote-sensing imagery, potentially making such imagery useful in mapping areas of serpentinite and related soils. The boundaries of serpentine soils are added to the digital database for comparison to the geology. Information on known natural asbestos occurrences in the region is compiled, and information on the occurrence of other mineral deposits typically associated

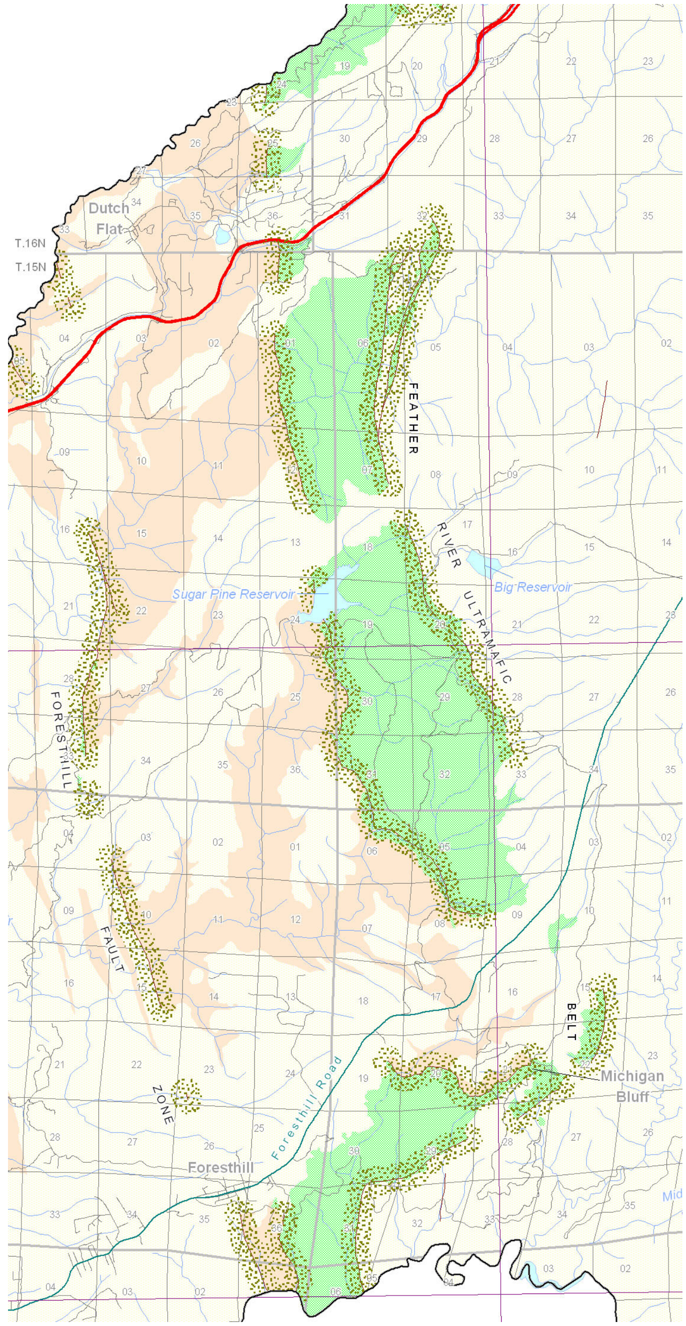

Figure 1. Part of map showing the relative likelihood for the presence of naturally occurring asbestos (NOA) in Placer County, California. Green = Areas Most Likely to contain NOA; buff = Moderately Likely; cream = Least Likely. Stippled pattern indicates areas of faulting or shearing that may locally increase the likelihood for NOA within or adjacent to areas moderately or most likely to contain NOA. Solid brown lines within stippled areas represent mapped traces of faults or shear zones. Original scale 1:100,000.

with ultramafic rock or serpentinite is also evaluated. These deposits include chromite, magnesite, mercury, nickel, and talc. Fieldwork is conducted to observe and verify the character of rocks and structures in the major rock units, evaluate the accuracy of the geologic boundaries of previously mapped areas, and collect samples for analysis.

Once the various data have been compiled, the information is interpreted and used to identify areas where NOA is most likely to occur, moderately likely to occur, and least likely to occur based on the likelihood of asbestos occurrence in different geologic environments. Areas determined most likely to contain NOA typically are underlain by ultramafic rocks, serpentinite, and associated soils. Areas identified as moderately likely to contain NOA typically are underlain by metamorphosed mafic volcanic rocks, metamorphosed igneous intrusive rocks, gabbroic rocks, and structurally complex units of mixed metamorphic rocks of different origins. Examples of rock types that underlie areas identified as least likely to have NOA include metamorphosed felsic volcanic rocks, granitic rocks, volcanic rocks, and glacial deposits.

Published California Geological Survey NOA maps and companion reports are available for viewing or downloading on the CGS NOA Web page, at *http://www.conservation.ca.gov/cgs/minerals/hazardous_minerals/asbestos/Pages/Index.aspx*.

Radon Hazard Mapping In California

Radon is a radioactive gas present in soil, rocks, water, and the atmosphere. It is produced by radioactive decay of small amounts of uranium and thorium naturally present in rocks and soil. Radon is not normally a health issue under ambient conditions. However, under certain conditions, radon may concentrate in the indoor air of homes and other buildings to the point where long-term exposure to such air significantly increases an individual's lung-cancer risk. The U.S. Environmental Protection Agency (EPA) estimates over 21,000 lung cancer deaths occur annually in the United States from radon exposure. A preliminary EPA estimate suggests about 1,700 radon-related lung-cancer deaths occur annually in California, which exceeds the State's annual number of deaths related to drunk driving.

Maps accurately predicting indoor-radon concentrations in specific buildings are not possible because of the number of variables involved, many of which vary from building to building. However, it is possible to construct maps indicating areas with higher or lower likelihood of buildings having indoor-air concentrations exceeding the 4 picocuries per liter (pCi/L) EPA recommended action level. Such "radon-potential" maps commonly are advisory, not regulatory. Government agencies and non-profit organizations can use them to target their radon public outreach and education campaigns for the greatest benefit. These maps also identify areas where radon-resistant building practices for new construction should be considered. Additionally, individuals contemplating home purchases in California are increasingly interested in obtaining information about the likelihood of indoor-radon problems in areas where they are considering purchases.

Simple radon-potential maps are constructed by displaying indoor-radon data means, medians, or percentages of data exceeding the EPA recommended action level for specific areas. Areas defined by county boundaries, Zip Code zone boundaries, and grid boundaries (for example, square kilometers or miles) can be used for radon maps. However, such maps often fail to identify the relatively small- to medium-sized radon "hot-spot" areas typical in California. Approaches using grid areas could identify small or medium-sized radon hot-spot areas, provided the grid area sizes are similar to or smaller than hot-spot areas and sufficient indoor-radon data are available for each grid cell. However, a grid cell approach is not viable at this time in California because of low indoor-radon sampling density.

Another radon mapping approach groups indoor-radon measurements and other radon related data by geologic unit. This approach has several advantages. First, because geologic units vary in physical and compositional character within relatively narrow limits by definition, occurrences of a unit without data often have radon potentials similar to occurrences of that geologic unit with data. One cannot assume the radon potential of a Zip Code area or county lacking indoor-radon data, on the basis of the radon potential of an adjoining Zip Code area or county. Second, certain lithologic types are more prone to indoor-radon problems than others. In California, organic-rich siliceous marine shale and mudstone and certain granitic and volcanic rocks, which typically have higher background uranium contents than many other rock types, are examples of units with higher radon potential. Such units deserve higher priority for indoor-radon surveys. Using a geologic-unit approach to radon potential mapping, the CGS has successfully identified a number of small- to moderate-sized high-radon potential areas in California not identified by county-wide or Zip Code area approaches.

In 1995, the CGS produced its first radon-potential maps (Santa Barbara and Ventura Counties), for the California Department of Health Services (CDPH) Radon Program. Since 2004, the CGS has had cooperative agreements with CDPH to produce radon maps. All CGS radon-potential maps have utilized GIS for data management, analysis, and cartographic design. These maps display radon-potential areas according to five categories: Very High, High, Moderate, Low, and Unknown (fig. 2). These categories correspond to the percentage of indoor measurements equal to or exceeding 4 pCi/L as follows: Very High ($\geq$ 50 percent); High (20 to 49.9 percent); Moderate (5 to 19.9 percent), Low (< 5 percent), and Unknown (insufficient data to estimate radon potential).

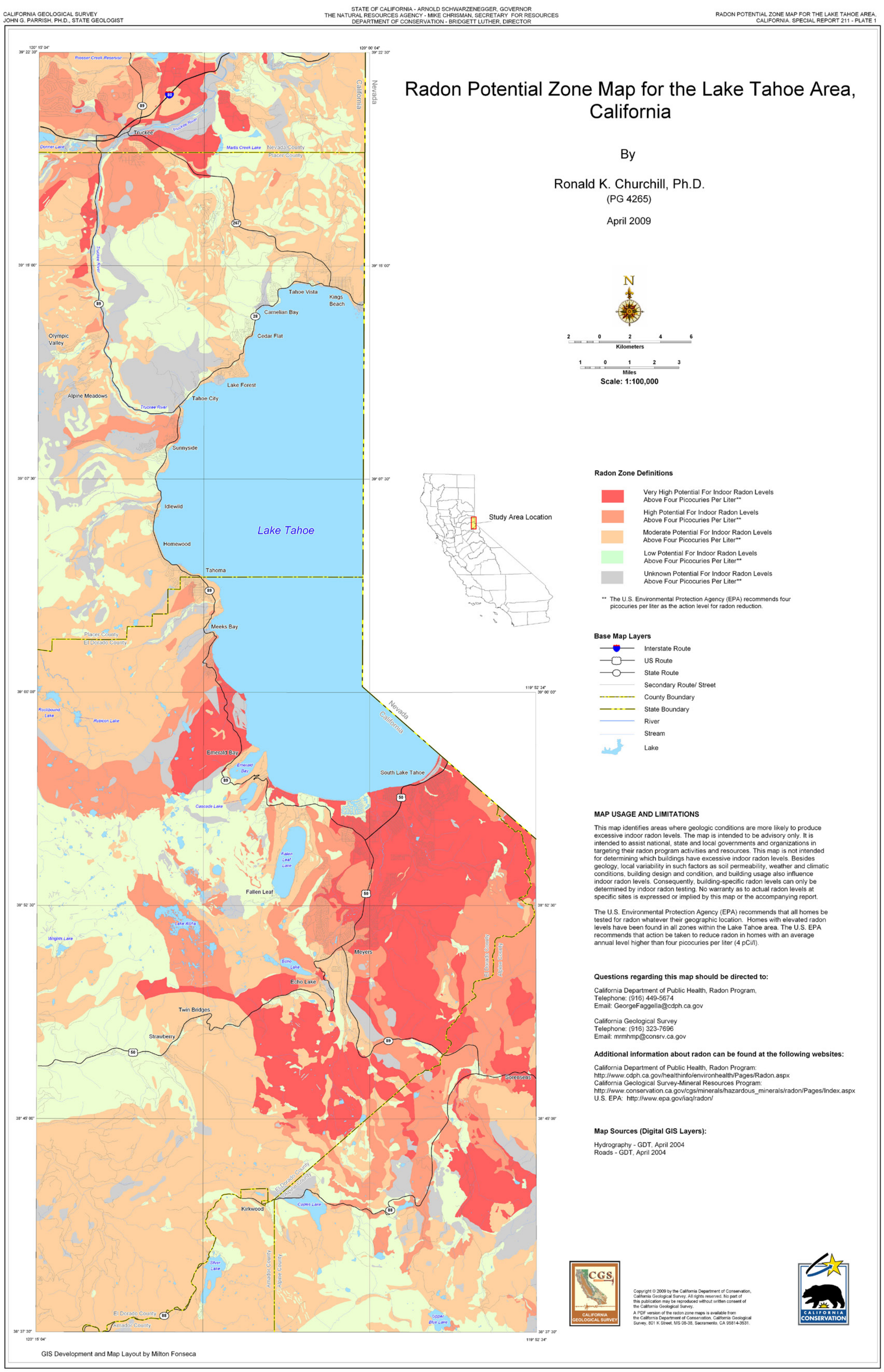

Figure 2. Radon Potential Zone Map for the Lake Tahoe Area, California. Original scale 1:100,000.

The CGS uses GIS for four principal activities to develop radon-potential maps:

1. Compilation of homeowner mailing lists for counties or areas selected by CDPH for indoor-radon surveys,
2. Preparation of a digital geologic layer,
3. Management and evaluation of indoor-radon and other data needed to classify radon potential and identify radon-potential zone areas, and
4. Design and production of the final map.

Because indoor-radon measurements are inexpensive and easy for homeowners to perform, CDPH usually can enlist some local homeowners to participate in a home survey program in support of the radon mapping process for a county or area. Using homeowner-occupied house address lists obtained by CDPH from commercial vendors or county governments, the CGS geocodes the addresses and selects a subset of homeowners to receive a CDPH letter requesting participation in the indoor-radon survey. Except in low population counties or areas, only some residents in a survey area are solicited for survey participation because the number of homeowner-occupied homes exceeds the CDPH mailing and radon-detector budgets. (Homeowner survey participation rates usually range between 3 and 8 percent of the solicitation letters mailed.) Additionally, the CGS attempts to ensure that a minimum of 20 to 25 measurements are collected from homes associated with geologic units known or suspected to have radon problems, on the basis of previous work. Experience has shown that this is the minimum number of measurements required for a high likelihood of proper radon potential categorization of a geologic unit. At this point, available 1:100,000- or 1:250,000-scale vector or raster geologic maps are used to provide geologic-unit location information. Given a worst-case survey participation rate of 3 percent, between 667 and 833 addresses are randomly selected from those associated with geologic units that have potential radon problems. If fewer than 667 addresses are available, all addresses receive a survey solicitation letter. After addresses associated with suspected high-radon geologic units have been identified, the remaining survey quota is filled by selecting homes from other parts of the survey area so that some indoor-radon measurements are obtained from as many geologic units as possible. For geologic units with high population densities, GIS queries that randomly select one of every three or four addresses have been used for mailing list development.

A digital (vector) map of geologic units at 1:100,000 scale is utilized for radon data evaluation and for final radon-zone map development. Experience has shown that 1:100,000-scale or more detailed geologic mapping is needed for radon potential mapping. At these scales geologic units tend to be more homogeneous in physical and chemical characteristics than geologic map units developed at less detailed map scales. Only some parts of California currently have digital 1:100,000-scale geologic maps available. In other areas, such maps need to be compiled from scanned paper geologic maps of more detailed scales. Once the digital geologic map layer is developed, indoor-radon measurements and additional radon data (discussed below) are compiled for each geologic unit through queries linking data from these layers with geologic unit areas on the geologic map layer. Next, the percentages of 4 pCi/L or higher measurements are calculated for each geologic unit, other available radon-related data are evaluated, and radon potentials are assigned to each geologic unit. Geologic units with similar radon potentials are grouped into the radon potential zones shown on CGS radon maps.

As mentioned, when available, additional data related to radon concentration and movement in the upper several meters of the subsurface are compiled into GIS layers and data are assigned to geologic units. These data may include:

1. Airborne gamma-ray spectral data collected during the National Uranium Resource Evaluation (NURE) project in the 1970s and 1980s,
2. NURE uranium-abundance data for soil and sediment samples,
3. Non-NURE uranium-abundance data for rock, soil, and sediment,
4. Surface gamma-ray spectral data, and
5. Near-surface soil-gas radon measurements.

The additional data sometimes support a “provisional” radon-potential ranking for geologic units with few or no indoor-radon measurements. Otherwise, units with few or no indoor data will be assigned to the “unknown” radon-potential category. Units assigned to the unknown radon-potential category become potential targets for future radon surveys if they underlie any homes.

Although not used directly in determining geologic unit radon potentials, soil permeability, soil shrink-swell characteristics and, in some cases, depth to bedrock and depth to water table data are compiled from U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) and U.S. Forest Service (USFS) soils reports and added to the attributes for indoor-radon measurements. Comparison of trends between these data and indoor-radon data, in combination with other previously listed radon and uranium data, have led to valuable insights and conceptual models for radon problem areas.

After the geologic units are classified for radon potential (Very High, High, Moderate, Low, or Unknown), all occurrences of units with the same classification are combined, forming one or more polygons. A single GIS layer is then created that contains all of the radon potential classes. All of the polygons for the geologic units in a category now represent the spatial distribution of that category. For example, if units A, B, and C met the criteria for high radon potential, and their presence in the study area is represented by 10 polygons, 4 polygons, and 7 polygons, respectively, then the high radon potential portion of the study area is represented by the 21 polygons of these units. Note that out of seven CGS radon potential maps completed to date, only one has "Very High" radon potential areas present.

The next step is to check the resulting radon potential categories for statistical validity. This check is done as follows:

1. Compile indoor radon data for each radon potential category.
2. Compare resulting data populations using the Mann-Whitney rank-sum (non-parametric) statistical test to confirm that each layer is significantly different from the others.

Typically the populations are confirmed as being different, and no further adjustments of the radon potential category polygons are made. On the rare occasion when two unit radon populations are not statistically different, then one of the following approaches should be chosen:

- The two categories may be combined into one. For example, the High category is not statistically different from the Moderate category, so all of the High category polygons will be reclassified as Moderate, and in this example the final map will not have any high radon potential areas.
- Polygon boundaries of the different categories may need to be adjusted to produce statistically different radon populations for the radon potential categories. For example, in California there are some areas where landslides have developed in portions of a high radon potential unit, and this material has moved down slope and now overlies the lower radon potential units. Because the thickness of the displaced higher radon material is at most a few tens of feet, these displaced areas were not mapped as the high radon potential unit. By adding buffer zones of 0.1 or 0.2 miles to the down-slope sides of the high radon unit polygons, these displaced high-radon unit areas can be removed from the lower radon potential group and, more properly, included with the high radon potential polygons. If a statistical comparison of the adjusted radon populations for the high and lower radon potential units now confirms that they are statistically different, then no further adjustments are needed.

Estimates of the number of individuals living in residences where indoor radon levels exceed the EPA recommended action level are made for each radon potential zone and for the entire map area. These estimates are included in the final report that accompanies the radon potential map, in order to put the significance of radon risk for a county or area into perspective. To make these estimates, radon potential zone layers are compared with U.S. Census data (TIGER) GIS layers for census tracts and census blocks. The populations for each radon potential zone are estimated by summing the tract or block populations contained within the areas of each zone. Where individual tracts or blocks include more than one radon potential zone, populations are divided between the zones proportionally by the area of the track or block within each zone. Once the total population for each radon potential zone is estimated, the total is multiplied by the percentage of indoor radon measurements for that zone that equaled or exceeded the EPA recommended action level to obtain the population at risk for radon exposure.

To complete the radon potential map, the radon potential layers are overlain on a 1:100,000-scale base map showing streets and highways, water features, and parks, which serve as points of reference. Individual city blocks can be resolved on the base map at this scale. This is usually sufficient information to allow most people to locate a point of interest on the map and determine its radon potential. Information about map use and limitations is included in the map margins. A PDF version of the final map and accompanying report is placed on the CGS Radon Web Page for viewing and downloading/printing by interested parties. Because paper copies of these maps and reports are requested by some users, a small number are available for purchase through the CGS Publications Office.

Published CGS radon potential maps and their companion reports completed to date are available for viewing or downloading on the CGS Radon Web Page at *http://www.conservation.ca.gov/cgs/minerals/hazardous_minerals/radon/Pages/Index.aspx*.

Mineral-Hazard Maps For Highway Corridors

Through a cooperative agreement with the California Department of Transportation (Caltrans) Division of Environmental Analysis, the CGS has prepared maps of potential environmental geology/mineralogy/geochemistry hazards along portions of two state-highway corridors (SH128 and SH299) in northern California. These products differ somewhat from the previously described studies in that they are intended for internal use by Caltrans and are not intended for use by the general public. These maps, reports, and digital datasets are designed to assist district staff in planning and conducting more detailed hazardous materials evaluations where regulatory compliance may be required, where frequent maintenance is needed, or where health and safety or public relations related to mineral hazards may be a concern along these highway corridors. The CGS employed standard digital mapping techniques to prepare the maps and related products for both corridors. The SH128 project was a pilot study to establish the process of mapping the potential for mineral hazards along highway corridors. The SH299 project expanded this process to a segment that is much longer and more geologically and mineralogically complex than the SH128 corridor.

All products were developed and generated using a commercial GIS and related software. The final products were designed based on two important needs of Caltrans: (1) presentation of information about potential mineral hazards in a fairly direct way that could be used by staff with a range of backgrounds (engineers, planners, maintenance workers) and (2) accommodation of users with different levels of computer experience or available computer resources. Correspondingly, the CGS provided Caltrans with products that ranged from paper maps, which can be used by Caltrans staff not familiar with GIS software or techniques, to digital products such as shapefiles and PDF files, which can be integrated into internal Caltrans GIS packages and other software for staff that routinely use such resources.

To evaluate and understand potential sources of mineral hazards that might affect these two highway corridors and associated operations along them, many base- and technical-data layers and ancillary data were needed. Geology is the essential foundation layer for interpretation of potential for mineral hazards; it was compiled for each corridor from existing digital geologic maps prepared by the CGS, USGS, USFS, and California Department of Water Resources. Gaps in the digital coverage were filled by digitizing and edge-matching of scanned paper copies of geologic maps. The geologic layer for each corridor was then reinterpreted to generate a "lithologic" layer, which established a consistent set of rock groups (polygons) that were categorized based on their geochemical and mineralogical characteristics rather than their ages or stratigraphic groupings. Interpretation of geochemical and mineralogical characteristics of each polygon is important because it gives some indication whether or not the lithology might contain particular minerals or metals in concentrations that exceed those established or proposed by governmental agencies as being hazardous to human health or the environment. Each lithologic polygon was then assigned to one of three layers of physical features: bedrock, alluvial deposits, and landslide deposits. Also from the geologic compilation, a separate layer of faults was developed for each corridor. Faults can be sites of anomalously high concentrations of different types of mineralization. Technical layers prepared for other physical features included mines and prospects, sediments along small streams (represented by a stream layer), and, along the SH299 corridor, areas of metal-sulfide mineralization. Mines and prospects are important because (1) they can indicate where anomalous concentrations of minerals or metals may be present and (2) they may be sites where contaminants were possibly produced by mining and mineral processing. They were mainly obtained from the USGS Mineral Resources Data System (MRDS), with supplemental information from CGS files. MRDS is not a "clean" database and can be locally misleading especially concerning locations of mines and prospects. For example, a given mine may be represented by two or three separate records in the database, each of which may have very different assigned locations for the mine. Consequently, we researched the records to help eliminate multiple records and improve the accuracy of locations. Stream locations also are important because they may transport harmful materials eroded from bedrock and mine sites upstream from the highway corridors and deposit them locally within the corridors.

All physical features described above are represented by points, lines, or polygons and thus were easily assigned attributes that provide Caltrans staff with information on each feature's potential for mineral hazards. Within each corridor, the physical features were evaluated and rated for their potential as sources of mineral hazards. With the exception of the areas of sulfide mineralization along SH299, each feature was rated as High (1), Medium (2), or Low (3) for its potential to contain naturally occurring asbestos (NOA) and to locally equal or exceed regulatory threshold concentrations for each of 17 metals that Caltrans routinely evaluates as possible sources of toxicity in earth materials. Referred to as the "CAM17" list, this group of metals can be hazardous to human health or the environment. Among these metals are copper, lead, zinc, cadmium, mercury, chromium, and nickel; these seven metals were the ones of most concern along the SH299 corridor, while chromium and nickel were of most concern along the SH128 corridor. The ratings for the physical features were assigned by a process that combined qualitative geological and semiquantitative geochemical evaluation with simple digital algorithms applied to the vector features. For example, because serpentinite commonly hosts naturally occurring asbestos, all bedrock polygons labeled as serpentinite in both the SH128 and SH299 corridors were digitally assigned a rating of "High" (1) for their potential to contain NOA. For evaluation of the CAM17 metals, baseline concentrations of each of the CAM17 metals were estimated for each bedrock polygon, based on the prevalent rock type of that polygon. Because there are very few available chemical analyses for CAM17 metals for rocks in the corridors, most of the baseline estimates are from generic rock types judged to be similar to those that comprise the polygons. For alluvial and landslide deposits, potential for NOA and CAM17 metals in them was based on estimates of the original upstream sources (bedrock, mining, and so on) from which the deposits are assumed to have been derived.

Finally, each physical feature along the highway corridors was ultimately assigned a single "overall" rating for its potential to contain mineral hazards. This approach was developed mainly so that the paper copies of the corridor maps would be simpler and therefore easier to use by Caltrans staff as initial screening tools for such hazards. Based on the geochemical and mineralogical characteristics of the feature, the overall rating combines the individual potential ratings for both NOA and each CAM17 metal and is shown on the final corridor maps by color coding. It represents the highest expected potential for a mineral hazard to be present in a physical feature. For example, given a specific bedrock polygon, if NOA is rated Low and the highest rating for any one of the CAM17 metals is High (for example, copper and zinc are High, but all other metals are Low), the polygon is assigned an overall rating of High and thus colored red on the corridor map. Furthermore, additional information about individual features is available to staff as attributes in the digital files that accompany the paper maps.

Mines and prospects were also evaluated as potential sources of mining chemicals. They were not rated, however, because of generally insufficient historical information about mining and processing activities at these sites as well as the additional time needed to research this information. Instead, estimates of types or degrees of ore processing are presented for most mines and prospects. Actual ore-processing operations, if any, may be determined in some cases by literature searches on individual mines and prospects. Correspondingly, on the digital layer of mines and prospects, a list of references is included as one of the attribute fields for Caltrans staff who wish to research individual mines or prospects.

To further assist Caltrans staff, several digital base-data layers that show terrain and hydrography were displayed on the paper maps to help visualize and interpret potential movement of hazardous materials related to mineralization and mining from upstream sources to the highway corridors. These layers included shaded relief from digital elevation models, topographic contour lines, watershed boundaries, and stream flowlines. As an alternative, the CGS advised Caltrans that its staff could view the various digital layers with Web-based image viewers or simple GIS freeware, which allow three-dimensional perspectives of the layers superimposed on underlying color imagery of the corridors. Examples of the mineral-hazard maps for SH128 and SH299 corridors are shown in figures 3 and 4.

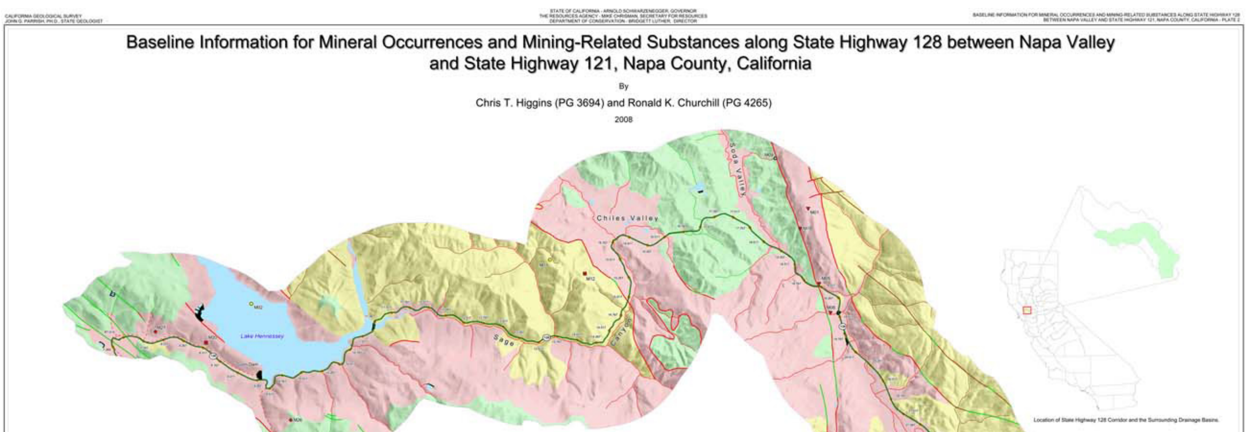

Figure 3. Derivative map that shows ratings for potential mineral hazards along the SH128 corridor. Original scale is 1:24,000. The map is available to Caltrans staff as paper copy and as a PDF file.

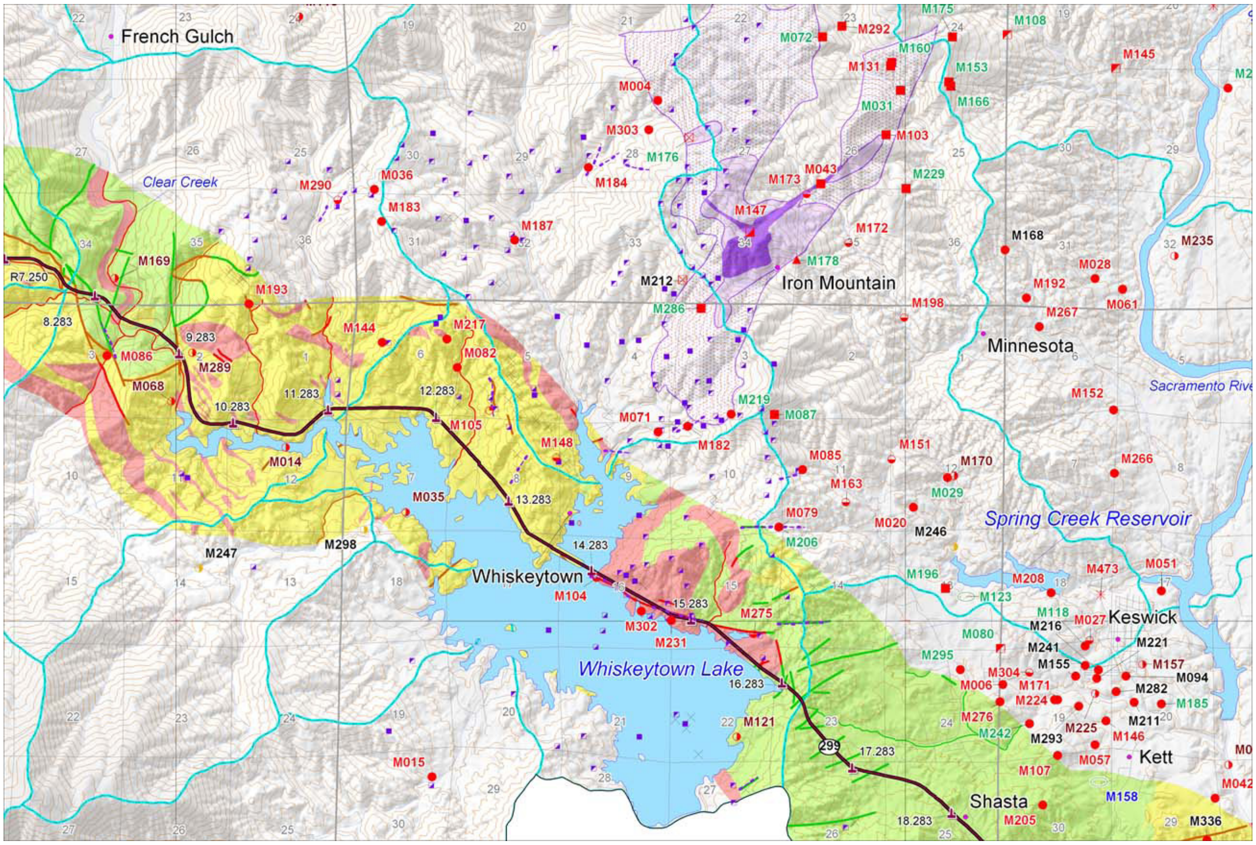

Figure 4. Part of map that shows potential for mineral hazards along the SH299 corridor. Original scale is 1:62,500. Accompanying attributed digital layers provide additional technical information for use by Caltrans staff. Colored areas in the highway corridor represent ratings for mineral occurrences in bedrock and alluvial deposits: red = high potential, yellow = medium potential, green = low potential. Colored symbols with labels represent locations of mines and prospects; color of labels indicates type of known or possible ore processing at site. Thick colored lines in corridor represent faults. Thin colored lines in corridor represent streams. Purple symbols and areas represent localities of hydrothermal alteration and mineralization. Light blue lines represent watershed boundaries.

The processes described above for mapping potential for mineral hazards along highway corridors are not necessarily in final form. Modifications and improvements to the processes will likely be made in the future as the CGS receives suggestions from Caltrans staff and researches and employs more rigorous quantitative methods to assign ratings of potential for mineral hazards. For example, a raster, rather than vector, approach could allow cell- or grid-based rankings of geochemical and mineralogical characteristics of physical features. In turn, such rankings might enable further refinement or discrimination of the potential for specific mineral hazards in certain areas. Nonetheless, any improvements in processes will be limited by the quality, consistency, and completeness of the original data used for each project.

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