NATURAL RESOURCE ASSESSMENT METHODOLOGIES FOR THE PROPOSED HIGH-LEVEL WASTE REPOSITORY AT YUCCA MOUNTAIN, NYE COUNTY, NEVADA

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ABSTRACT

Resource assessment of proposed high-level waste (HLW) repository sites and adjacent areas is mandated by Title 10 of the Code of Federal Regulations (10 CFR) Part 60. The intent of this document is threefold. First, it provides information to the U.S. Department of Energy (DOE) on accepted methods of resource assessment applicable to the proposed Yucca Mountain, Nevada HLW repository site, so DOE can demonstrate, to the U.S. Nuclear Regulatory Commission (NRC), compliance with regulations governing resource identification and evaluation. Secondly, it provides information that NRC can use in making a finding of DOE's compliance with the requirements of 10 CFR Part 60. And lastly, it will provide input to the NRC's technical position and review guide.

Methods of resource assessment, including but not limited to, geologic mapping and sampling, geochemical surveys, geophysical surveys, deposit modeling, and geomathematical studies, along with the advantages, disadvantages, and uncertainties associated with the use of the various methods, are discussed. Resource quantification, qualification, and evaluation methods and techniques are presented, as well as data sources for estimating capital and operating costs on the development and extraction of potential resources. Extraction/economic models for 5 selected deposit types are also presented.

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* Not included here as it is under development

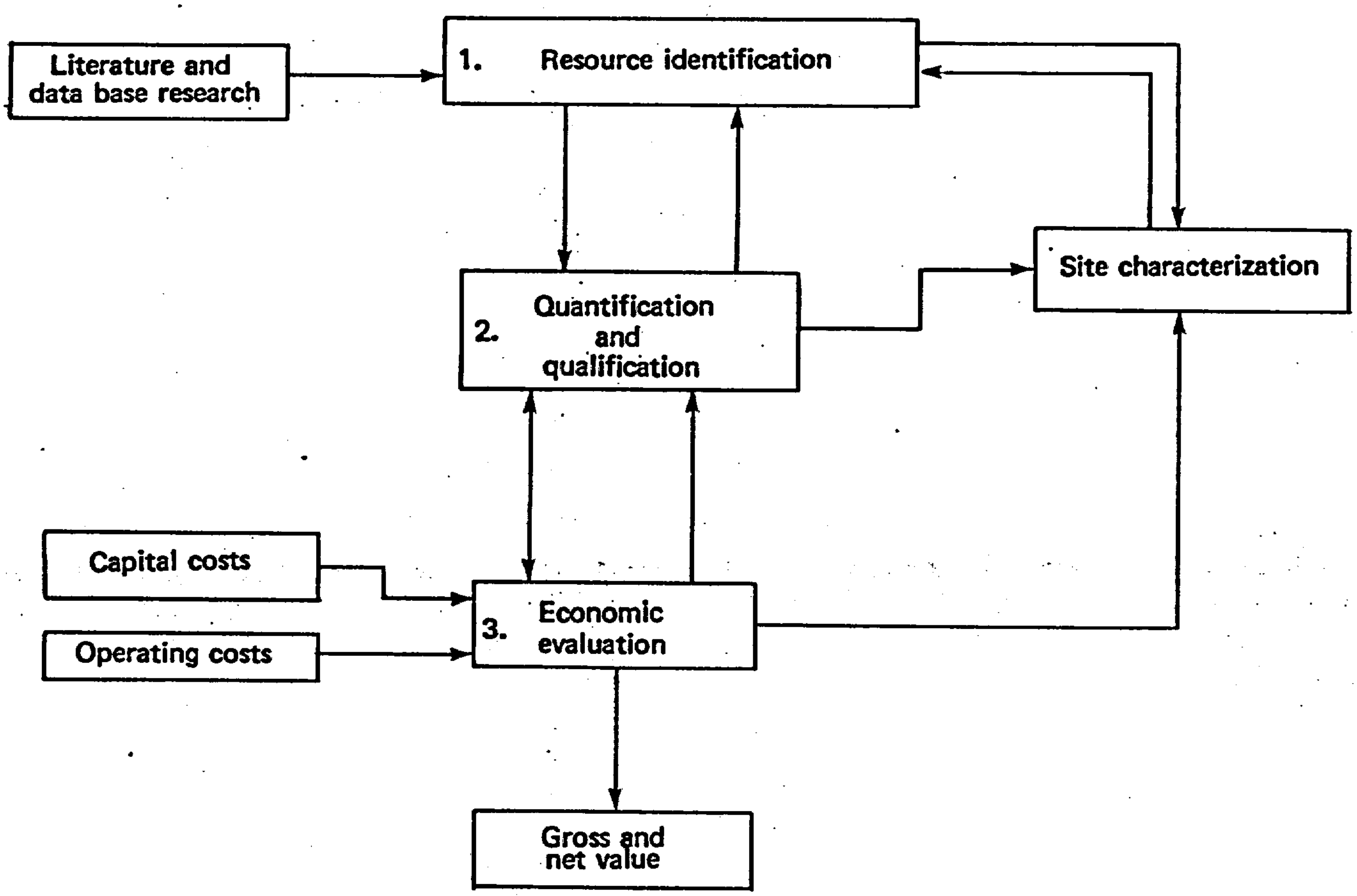


FIGURE 1. – Resource assessment process

INTRODUCTION

1. REGULATORY BASIS FOR ASSESSMENT OF NATURAL RESOURCES

1.1 Definitions

For purposes of clarity and brevity, it is necessary to define several frequently used terms. The following definitions are, for the most part, taken from NRC and Bureau of Mines (BOM) references.

"Resources" as used here is a collective term for all metallic and nonmetallic minerals and ores; fuels, including peat, lignite, and coal; or "dry heat." Ground or surface water in the usual sense (i.e., potable, agricultural, or industrial water at ambient temperature at relatively shallow depths), hydrocarbons (oil, gas, tar sands, asphalt, etc.), and geothermal occurrences are addressed in a separate report by the Center for Nuclear Waste Regulatory Analyses (CNWRA). However, ground water in the form of mineral brines (other than sodium chloride brines), or even waters of relatively low salinity, are included as resources if at depths generally below those at which potable ground water is extracted, and if they are potentially valuable for their dissolved mineral content (1) 1/. The term "natural resources" is used in the context of 10 CFR Part 60 (2) and is synonymous with "resources."

"Resource exploration or exploitation activities" as used here means " . . . any action, such as borehole drilling or sinking of shafts, in the search for mineral commodities (1)." The term "mineral commodities" is synonymous with "resources".

The term "deposit" is used in reference to the physical occurrence of a resource.

"Site characterization" as defined by 10 CFR Section 60.2 (2) is "The program of exploration and research, both in the laboratory and in the field, undertaken to establish the geologic conditions and the ranges of those parameters of a particular site relevant to the procedures in 10 CFR Part 60. Site characterization includes borings, surface excavations, excavation of exploratory shafts, limited lateral excavations and borings, and in situ testing at depth needed to determine the suitability of the site for a geologic repository, but does not include preliminary borings and geophysical testing needed to decide whether site characterization should be undertaken."

Resource assessment is not a primary goal of site characterization, and any geological, geochemical, geophysical, or engineering data acquired for other purposes, when applied to resource assessment, may be incomplete or contain significant uncertainty. This notwithstanding, integration of such data in the resource assessment program may prove to be of value in assessing the site's resource potential and, of greater importance, the potential for post-closure human interference.

1/ Numbers in parentheses refer to items in the list of references following each section.

1.2 Regulations Mandating Resource Assessment

DOE is required by 10 CFR Part 60, Subpart B (2), to apply to NRC for a license to receive and possess source, special nuclear, and byproduct material at a geologic repository operations area (GROA). License applications shall consist of general information and a Safety Analysis Report that includes provisions set forth in 10 CFR Section 60.21(c) (1-15) (2).

Resource assessment requirements as specified in 10 CFR Section 60.21(c)(13), (2) state that the Safety Analysis Report shall include:

> An identification and evaluation of the natural resources of the geological setting, including estimates as to undiscovered deposits, the exploitation of which could affect the ability of the geologic repository to isolate nuclear wastes. Undiscovered deposits of resources characteristic of the area shall be estimated by reasonable inference based on geological and geophysical evidence. This evaluation of resources, including undiscovered deposits, shall be conducted for the site and for areas of similar size that are representative of and are within the geologic setting. For natural resources with current markets the resources shall be assessed, with estimates provided of both gross and net value. The estimate of net value shall take into account current development, extraction and marketing costs. For natural resources without current markets, but which would be marketable given credible projected changes in economic or technological factors, the resources shall be described by physical factors such as tonnage or other amount, grade, and quality.

DOE is further required by 10 CFR Part 60, Subpart E (2) to identify existing or potential resources, within the controlled area, whose exploration for or exploitation of may constitute an adverse condition relating to the repository's ability to isolate radionuclides from the accessible environment. These potentially adverse conditions are specified in 10 CFR Section 60.122(c)(17-19) (2):

> (17) "The presence of naturally occurring materials, whether identified or undiscovered, within the site, in such form that: (i) Economic extraction is currently feasible or potentially feasible during the foreseeable future; or (ii) Such materials have greater gross value or net value than the average for other areas of similar size that are representative of and located within the geologic setting."
>
> (18) "Evidence of subsurface mining for resources within the site."
>
> (19) "Evidence of drilling for any purpose within the site."

1.3 Regulatory Compliance

The intent of this document is to: (1) provide information to DOE on accepted methods of resource assessment to demonstrate to NRC compliance with regulations governing resource identification and evaluation as part of site characterization at Yucca Mountain, (2) provide information that may be used by NRC in making a finding of DOE's compliance with the requirements of 10 CFR Part 60, and (3) provide input to the NRC resource assessment technical position and review guide.

1.4 Methods of Resource Assessment Available for Use as Part of Site Characterization

Geological, geochemical, geophysical, and engineering data acquired for other purposes as part of site characterization, supplemented by information from activities conducted specifically for resource assessment, may form the basis for new mineral deposit models or may be employed to augment existing models, the use of which may indicate undiscovered resources within the geologic setting. In addition to resource exploration methods, this document outlines mineral deposit models in current use that are available for a resource assessment program or that may be of value to other activities within the overall site characterization program.

1.5 References

1. Harbaugh, J. W. Resource Exploration. Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories, R. L. Hunter and C. J. Mann, eds., Sandia National Laboratories, Albuquerque, NM, 1984, NUREG/CR-3964, pp. 2-1 - 2-37.

2. U.S. Code of Federal Regulations. 10 CFR Section 60.21(c)(1-15), 10 CFR Section 60.122(c)(17-20).

2. RESOURCE ASSESSMENT METHODS

Resource assessment within or near the Yucca Mountain site is mandated by Federal regulations to minimize the risk that exploration-exploitation activities in the past, present, or future do not adversely affect the site's ability to isolate radionuclides from the accessible environment. The objective of Section 2 is to outline those methods and deposit models commonly employed in performing resource assessments, and to present methods, techniques, and models for the economic evaluation of resources.

For purposes of clarity, Section 2 presents the resource assessment process in a linear fashion with resource identification, followed by resource quantification and qualification, and finally followed by resource evaluation. It must be understood, however, that information developed in later stages of an assessment program may require modification, refinement, or abandonment of exploration methods or deposit models used, or conclusions reached, in earlier stages.

Conceptually, the resource assessment process is a three-step linear progression in which: (1) an area's resources are identified; (2) estimates are made of resource quantity and quality; and (3) studies are conducted to determine gross and net value of the resource. In practice, however, it is best described as an iterative and intricate process; inherent within the process is an infinite number of certainty levels (0-100 percent certainty range) that depend on the type and abundance of available data. For example, information developed during the course of quantification and qualification may indicate the presence of additional resource commodities not recognized in the resource identification step. Figure 1 is a simplistic diagram of the rather complex resource assessment process.

The three-step resource assessment approach is employed by the BOM in its mission to provide input for consideration in policies that affect national minerals issues (such as supply/demand analysis, wilderness area withdrawals, etc.) and by the private sector for purposes of eventual resource extraction. The basic difference between BOM and private sector assessments lies in the amount of resources (time, effort, funding, etc.) committed to the assessment. Typically, industry assessments involve greater expenditures of funds and manpower and carefully weigh the risks of committing large sums of money against the potential rewards.

Resource identification includes, but is not limited to, a host of activities and studies such as background literature research, deposit modeling, field activities, data analysis and evaluation, and geomathematical studies; methods for conducting these studies are presented in Section 2.1. Methods for deriving resource quantity and quality are discussed in Section 2.2; methods employed for estimating gross and net resource value as required by 10 CFR Part 60 (1) are outlined in Section 2.3. Economic models are discussed in Section 2.4.

Figure 1 Resource assessment process

Exploration drilling, trenching, and other piercement methods are normally employed to identify and evaluate resources. Data acquired using these techniques (in conjunction with other methods and techniques) are used to define deposit limits, determine resource quantity and quality, lithology, mineralogy, structure, and geometry, and to develop new or refine existing deposit models. However, in resource assessment of the Yucca Mountain site, the use of piercement methods is somewhat limited due to the necessity of maintaining repository integrity [10 CFR Section 60.15(d)(1-4)] (1). Accurate delineation of an ore body, for example, may require many boreholes on close centers in direct conflict with provisions of 10 CFR Section 60.15(d)(1-4). The use of test adits, raises, winzes, or deep surface pits are similarly restricted. Because of these regulatory restrictions, a significant level of uncertainty regarding the existence, extent, quantity, and quality of resources within and in proximity to Yucca Mountain is unavoidable. In view of this, non-piercement exploration and evaluation methods such as geological mapping, surface sampling, geochemical and geophysical surveys, and geomathematical techniques must be relied upon to provide much of the data necessary for resource assessment.

Resource assessment methodologies, techniques, and deposit models presented here are not all-inclusive; only the most important or widely used (with applications to Yucca Mountain) are discussed. However, the fact that a particular mineral commodity, methodology, deposit model, or technique is neither included nor discussed in detail does not preclude its use. Infrequently-used or esoteric techniques [e.g., vapor sampling using sulfide-sniffing dogs (2, p. 30)] or those that require extensive multidisciplinary knowledge (biogeochemical prospecting, geozoological prospecting, etc.) may certainly be employed if necessary or desirable.

Geologic conditions on and/or near the proposed HLW site will ultimately dictate the exploration methods employed. For example, some electrical and electromagnetic geophysical methods are decreasingly effective with increasing depth and may be of little or no practical use in assessing the mineral potential of Paleozoic and older units underlying the site; seismic reflection methods employed in past studies in the vicinity of the site have reportedly produced less than satisfactory results; the lack of standing bodies of water and perennial streams limits hydrogeochemical surveys to ground water; sparse vegetation and small faunal populations similarly limit geobotanical, biogeochemical, and geozoological surveys. And, as stated above, regulations restrict the placement of exploratory boreholes.

Detailed information on resource assessment methodologies, deposit models, and techniques is presented in references included in the References and Bibliography sections of this report.

2.1 Resource Identification

2.1.1 Background Data Collection

The body of geologic literature available to the researcher is enormous and and ranges widely in quality. Older studies and references may or may not be valid in light of more recent investigations. Therefore, care must be exercised to ensure data incorporated in the resource assessment program is of the highest quality and is as current as possible.

2.1.1.1 Literature and Database Research

Resource identification begins with comprehensive research of the literature and computerized databases maintained by a host of entities including Federal, State, and local governmental agencies, the private sector, and academic institutions. The object of the research is to amass regional and site-specific data to: (1) identify those areas that have been the object of resource exploration and/or exploitation; (2) develop preliminary deposit models; (3) define areas for geological, geochemical, and geophysical examination; (4) define areas for preliminary borehole drilling; and (5) provide data for geomathematical studies and comparisons. These applications are discussed in Section 2.1.2.1.

Sources of information include, but are not limited to, the following:

Federal Government

BOM--Results of BOM research, investigations, and studies are routinely issued as Reports of Investigations (RI), Information Circulars (IC), Bulletins, mineral commodity reports, Mineral Land Assessment (MLA) reports, Mineral Yearbooks, and other publications. The Bureau maintains extensive mineral property files that may include War Minerals Reports, Defense Minerals Exploration Administration (DMEA) reports, borehole and sample data, and other valuable information. Additionally, the BOM's computerized Minerals Industry Location System (MILS) (the nonconfidential segment of the Minerals Availability System [MAS]) contains location and identification information on over 180,000 mines, prospects, geothermal wells, and mineral locations in the United States, including Alaska and Hawaii (3).

U.S. Geological Survey (USGS)--The USGS collects, compiles, and publishes a great volume of geotechnical information in its Bulletins, Circulars, Professional Papers, Water Supply Papers, topographic, geologic, and hydrographic maps, Memoirs, Mineral Resources Data System (formerly Computerized Resource Information Bank - CRIB) database (4), reports, files, open-file reports, and miscellaneous publications. Additionally, personal journals, notes, unpublished reports, and other data sources may be available at local USGS offices.

Other Federal sources of information include reports, files, notes, memoirs, and databases maintained by the Bureau of Land Management (BLM) which maintains current mineral-interest and claim recordation files; Office of Surface Mining (OSM); Mine Safety and Health Administration

(MSHA); National Archives (NA); Library of Congress (LC), U.S. Department of Agriculture Forest Service (USFS); U.S. Department of Commerce (DOC); U.S. Department of Defense (DOD); DOE; U.S. Department of Labor (DOL); and the U.S. Internal Revenue Service (IRS).

State and Local Governments

State information sources include State geological and/or mining bureaus or agencies (e.g. Nevada Bureau of Mines and Geology, Oregon's Department of Geology and Mineral Industries, etc.); historical societies; office of mine inspectors; department of minerals or mineral resources; agencies with permitting or licensing responsibilities; State highway departments and/or commissions; utility commissions (gas, power, water, etc.); and libraries.

Local government sources include clerk and/or recorder records; city and county tax assessor's records; highway and road departments; public utilities; libraries; and agencies with permitting and/or licensing responsibilities.

Private Sector

Business and nonprofit organization sources of information include mining and/or exploration companies; historical societies and museums; industry and/or trade associations; consultants; and commercial data bases.

Educational Institutions

Sources of information may include, but are not limited to, college and university departments of geology, mining, geophysics, geochemistry, hydrology, history, economics, social science, and their associated libraries. University Microfilms International, 300 N. Zeeb Road, Ann Arbor, MI 48106, maintains a clearing house for doctoral dissertations that are available for a fee as Xerox copies or on microfiche. The Geological Society of America (GSA) periodically publishes bibliographies of theses and dissertations.

Other Sources of Information

Other sources of information, including bibliographies, indices, abstracts, translations of foreign research papers, directories, periodicals, information retrieval systems, and literature on geology and associated disciplines are presented in Section 6.1.

2.1.1.2 Personal Contacts

Valuable information is often gained through personal contacts with knowledgeable individuals. Information such as unpublished and generally unavailable geologic, mineralogical, and engineering data, personal reports, notes, memoirs, or files is often obtained by direct contact with authors, editors, compilers, and others associated with works identified over the course of literature/data base research. Other sources of information may include interviews with industry representatives (geologists, engineers, cartographers, drillers, miners, etc.); local residents (ranchers, loggers, prospectors); members of geological, mineralogical, speleological, or historical societies or associations; State or local labor unions; professional associations (Geological Society of America, American Institute of Mining, Metallurgical, and Petroleum Engineers, Northwest Mining Association, etc.); college and university professors; and former Federal, State, and local government employees.

2.1.2 Identification of Natural Resources of the Geologic Setting

2.1.2.1 Application of Background Data

Background data are compiled and analyzed to determine a number of factors to be incorporated into an assessment program. These include, but are not limited to:

1. What, if any, documented resource exploration or exploitation has ensued on or near the site;

2. Identification of specific sites for geological, geophysical, and geochemical surveys;

3. What possible resources could be reasonably inferred to exist on site or in analog areas;

4. What deposit model or models may (or may nor) apply to the site and vicinity;

5. Identification of preliminary drilling targets;

6. What boreholes are open for well logging.

2.1.3 Field Data Collection, Compilation, and Interpretation

Information and analyses developed during literature searches are subsequently supplemented and refined based on data collected through detailed geological mapping, surface and subsurface sampling, geochemical and geophysical surveys, borehole drilling, and other field investigations. The results of the field examinations may indicate the need for further site-specific studies to delineate any discovered resources, to provide data for additional deposit modeling or geomathematical analyses, or for tonnage-grade estimations.

The availability and application of methods used in field data collection and their subsequent compilation, and interpretation are presented in the following Sections.

2.1.4 Deposit Modeling and Deposit Models

This section examines resources and associated resource deposit models that could reasonably be expected to exist at and in the vicinity of Yucca Mountain and the rationale for selecting a particular deposit model for inclusion here. Geological, geochemical, geophysical, and other exploration methods applicable to the particular resource are discussed in Section 2.1.5.

As site characterization proceeds and new data are acquired, it may become necessary to consider deposit models not included here or require modifications or hybridization of a particular model or models. Further, such newly-acquired data may not support continued consideration of one or more of the models. While briefly mentioned in the following discussions, geothermal, hydrocarbon (other than coal, lignite, etc.), potable water, and brine resources (other than mineral brines) are not addressed at length. (These commodities are addressed in detail in a separate report by CNWRA).

A mineral deposit model is a concept or an analog that represents in text, tables, and diagrams the essential characteristics or attributes of a deposit type (5). The use of deposit models in resource assessment activities may alert the resource investigator to indications of a mineralized zone. Further, familiarity with deposit models developed for the area in and around Yucca Mountain may be of value in geological, geochemical, geophysical, and drilling activities conducted for site characterization purposes other than resource assessment.

Resource deposit models are the keys to any deposit identification, since valid exploration models of known mineral deposits aid the researcher to focus on critical geologic attributes of a target area. Furthermore, deposit models can conserve time and funds that might otherwise be expended to collect data not critical to identifying a resource. A comprehensive listing of references on deposit models and deposit modeling is presented in Section 6.2.

Deposit modeling terminology is somewhat confusing and often inconsistent in its application. Most terms, however, are analogous to two fundamental model types: empirical and genetic deposit models. Empirical models (also known as "occurrence" or "descriptive" models) are based solely on observation and fact. Genetic models (also known as "process," "conceptual," or "interpretive" models) incorporate empirical data and an analysis of the genetic components of the deposit and their interactions. The two fundamental models ([1] empirical and [2] genetic) are employed to identify those data compilations and field activities that may be conducted to test an area for the presence of a particular deposit type. The combined use of empirical and genetic models at Yucca Mountain and in analog areas allows the researcher to identify those geologic criteria that are most reliably related to resource occurrences. This combination of fundamental models is generally referred to as an "exploration" or "recognition criteria" model (5).

The use of deposit models facilitates extrapolation into relatively unexplored areas (6) and, when employed in one or more methods of geomathematical resource assessment, may allow reasonable estimates to be made of an area's resource potential.

Descriptive models presented in this section were modified from U. S. Geological Survey Bulletin 1693, Mineral Deposit Models, Dennis P. Cox and Donald A. Singer, editors, (7) which represents one of the most authoritative publications on this subject to date. Each descriptive model presented is duly referenced to its author by appropriate footnotes.

It is appropriate to include by way of an introduction to deposit modeling, the preface to Bulletin 1693 authored by Paul. B. Barton. The decision to include Barton's preface verbatim, rather in synopsis or abstract form, was based on: 1. an attempt on the part of the authors to minimize the confusion and inconsistencies alluded to above, 2. a presumed necessity for the reader to be aware of the background and development of the models presented here sans any unintentional editorial bias, and 3. the need for an understanding on the part of the reader of the uncertainties inherent in the formulation and application of the models. References cited by Barton are footnoted at the end of the discussion.

> Conceptual models that describe the essential characteristics of groups of similar deposits have a long and useful role in geology. The first models were undoubtedly empirical attempts to extend previous experiences into future success. An example might be the seeking of additional gold nuggets in a stream in which one nugget had already been found, and the extension of that model to include other streams as well. Emphasis within the U.S. Geological Survey on the synthesis of mineral deposit models (as contrasted with a long line of descriptive and genetic studies of specific ore deposits) began with the collation by R. L. Erickson 1/ of 48 models. The 85 descriptive deposit models and 60 grade-tonnage models presented here are the culmination of a process that began in 1983 as part of the USGS-INGEOMINAS Cooperative Mineral Resource Assessment of Colombia (2/). Effective cooperation on this project required that U.S. and Colombian geologists agree on a classification of mineral deposits, and effective resource assessment of such a broad region required that grade-tonnage models be created for a large number of mineral deposit types.
>
> A concise one-page format for descriptive models was drawn up by Dennis Cox, Donald Singer, and Byron Berger, and Singer devised a graphical way of presenting grade and tonnage data (not presented here). Sixty-five descriptive models (3/, 4/) and 37 grade-tonnage models (5/, 6/) (not included here) were applied to the Colombian project. Because interest in these models ranged far beyond the Colombian activity, it was decided to enlarge the number of models and to include other aspects of mineral deposit modeling. Our colleagues in the Geological Survey of Canada have preceded this effort by publishing a superb compilation of models of deposits important in Canada (7/). Not surprisingly, our models converge quite well, and in several cases we have drawn freely from the Canadian publication.
>
> It is a well-known axiom in industry that any excuse for drilling may find ore; that is, successful exploration can be carried out

even though it is founded upon an erroneous model. Examples include successful exploration based on supposed (but now proven erroneous) structural controls for volcanogenic massive sulfide deposits in eastern Canada and for carbonate-hosted zinc in east Tennessee. As the older ideas have been replaced, additional ore has been found with today's presumably more valid models.

Although models have been with us for centuries, until recently they have been almost universally incomplete when descriptive and unreasonably speculative when genetic. What is new today is that, although we must admit that all are incomplete in some degree, models can be put to rigorous tests that screen out many of our heretofore sacred dogmas of mineral formation. Examples are legion, but to cite a few: (1) fluid-inclusion studies have shown conclusively that the classic Mississippi Valley-type ores cannot have originated from either syngenetic processes or unmodified surface waters; (2) epithermal base-and precious-metal ores have been proved (by stable-isotope studies) to have formed through the action of meteoric waters constituting fossil geothermal systems; and (3) field and laboratory investigations clearly show that volcanogenic massive sulfides are the products of syngenetic, submarine, exhalative processes, not epigenetic replacement of sedimentary or volcanic rocks. Economic geology has evolved quietly from an "occult art" to a respectable science as the speculative models have been put to definitive tests.

Several fundamental problems that may have no immediate answers revolve around these questions: Is there a proper number of models? Must each deposit fit into one, and only one, pigeon-hole? Who decides (and when?) that a model is correct and reasonably complete? Is a model ever truly complete? How complete need a model be to be useful?

In preparing this compilation we had to decide whether to discuss only those deposits for which the data were nearly complete and the interpretations concordant, or whether to extend coverage to include many deposits of uncertain affiliation, whose characteristics were still subjects for major debate. This compilation errs on the side of scientific optimism; it includes as many deposit types as possible, even at the risk of lumping or splitting types incorrectly. Nevertheless, quite a few types of deposits have not been incorporated.

The organization of the models constitutes a classification of deposits. The arrangement used emphasizes easy access to the models by focusing on host-rock lithology and tectonic setting, the features most apparent to the geologist preparing a map. The system is nearly parallel to a genetic arrangement for syngenetic ores, but it diverges strongly for the epigenetic where it creates some strange juxtapositions of deposit types. Possible ambiguities are accommodated, at least in part, by using multiple entries in the master list (this refers to a table not included here).

In considering ways to make the model compilation as useful as possible, we have become concerned about ways to enhance the ability of the relatively inexperienced geoscientist to find the model(s) applicable to his or her observations. Therefore, we have included extensive tables of attributes in which the appropriate models are identified.

Our most important immediate goal is to provide assistance to those persons engaged in mineral resource assessment or exploration. An important secondary goal is to upgrade the quality of our model compilation by encouraging (or provoking?) input from those whose experience has not yet been captured in the existing models. Another target is to identify specific research needs whose study is particularly pertinent to the advance of the science. We have chosen to err on the side of redundancy at the expense of neatness, believing that our collective understanding is still too incomplete to rule out some alternative interpretations. Thus we almost certainly have set up as separate models some types that will ultimately be blended into one, and there surely are grouping established here that will subsequently be divided. We also recognize that significant gaps in coverage still exist. Even at this stage the model compilation is still experimental in several aspects and continues to evolve. The product in hand can be useful today. We anticipate future editions, versions, and revisions, and we encourage suggestions for future improvements.

Footnotes

1/ Erickson, R. L. (compiler). Characteristics of Mineral Deposit Occurrences. USGS Open-File Rept. 82-795, 1982.

2/ Hodges, C. A., D. P. Cox, D. A. Singer, J. E. Case, B. R. Berger, and J. P. Albers. U. S. Geological Survey-INGEOMINAS Mineral Resource Assessment of Columbia. USGS Open-File Rept. 84-345, 1984.

3/ Cox, D. P., ed. U. S. Geological Survey-INGEOMINAS Mineral Resource Assessment of Columbia; Ore Deposit Models. USGS Open-File Rept. 83-423, 1983a.

4/ Cox, D. P. U. S. Geological Survey-INGEOMINAS Mineral Resource Assessment of Columbia; Additional Ore Deposit Models. USGS Open-File Rept. 83-901, 1983b.

5/ Singer, D. A. and D. L. Mosier, eds. Mineral Deposit Tonnage-Grade Models. USGS Open-File Rept. 83-623, 1983a.

6/ ______. Mineral Deposit Tonnage-Grade Models II. USGS Open-File Rept. 83-902, 1983b.

7/ Eckstrand, O. R., ed. Canadian Mineral Deposit Types, a Geological Synopsis. Geological Survey of Canada, Economic Geology Report 36, 1984.

2.1.4.1 Model Selection Rationale

The rationale for selection of deposit models for inclusion in this document is based in most part on information, hypotheses, and postulates taken from the literature, and assumptions made in consideration of such information. The sources of reference material used in the selection include, but are not limited to the following:

1. U. S. Geological Survey Bulletins, Professional Papers, Information Circulars, Maps, Open-file Reports, etc., primarily those dealing with Yucca Mountain and vicinity;

2. Publications of the Nevada Bureau of Mines and Geology;

3. NRC and NRC contractor publications;

4. Publications by Lawrence Livermore and Los Alamos National Laboratories;

5. U. S. Bureau of Mines publications;

6. Various text and reference volumes, and;

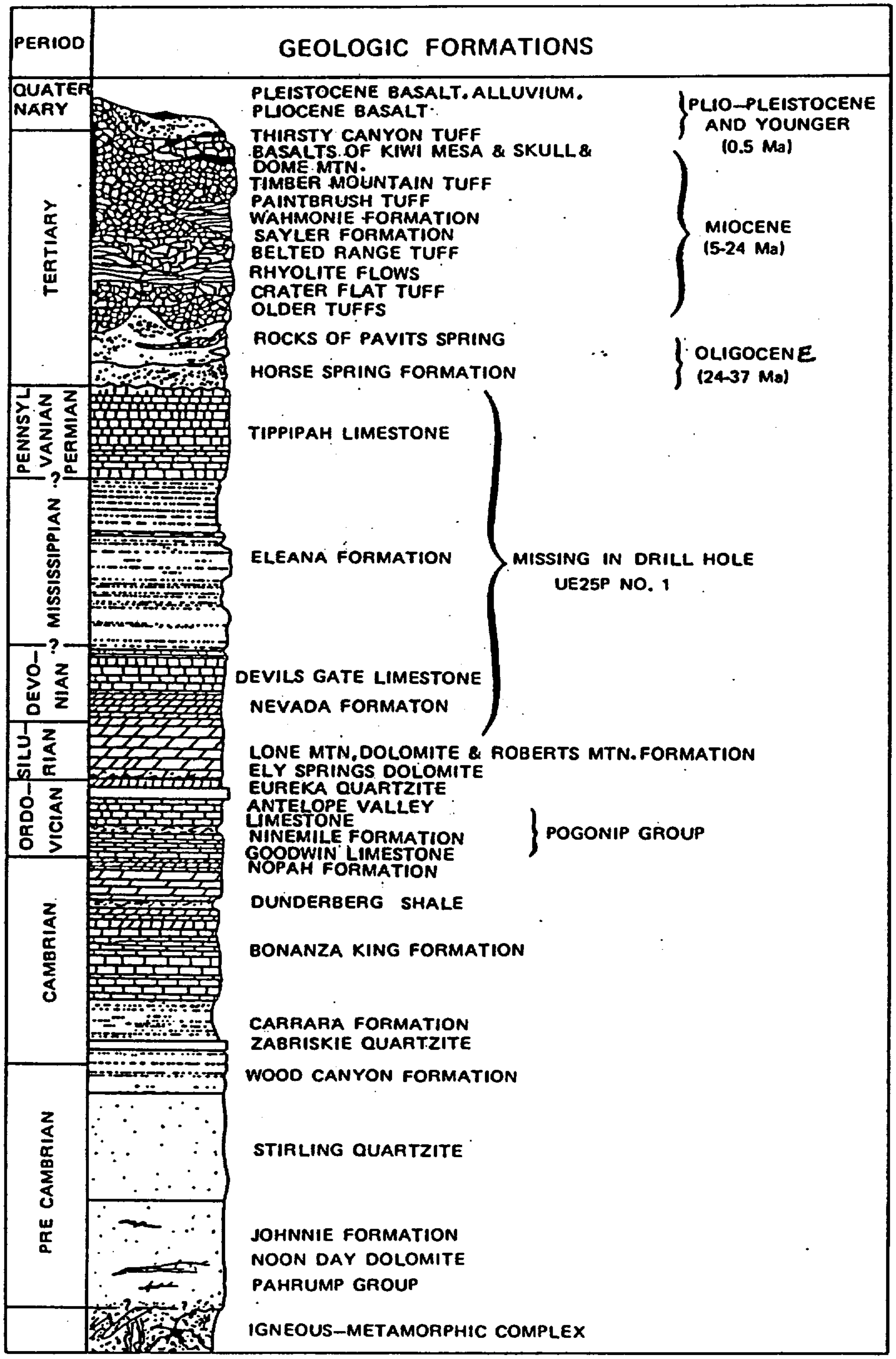
7. DOE publications including Environmental Assessment of the Yucca Mountain Site (8), Consultation Draft, Site Characterization Plan (9), and the Site Characterization Plan (10). Information on tectonic history and the regional tectonic setting was taken largely from Chapter 1 (Geology) of the Site Characterization Plan (10).

Information from the above sources was examined and a number of important points on which to base assumptions, and subsequently, the selection of deposit models, were identified; these points are listed below:

1. Yucca Mountain consists in the main of a thick sequence of calc-alkaline ash-flow tuffs (11).

2. The site is underlain by Paleozoic marine rocks of undetermined thickness (12) and at varying depths that may host resources in a wide variety of deposit types (see figure 2). Possible depositional scenarios may include but are not limited to: A. mineralization of Paleozoic and/or Tertiary rocks by hydrothermal fluids emanating from deeply buried plutons (most likely granitic, but mafic bodies but mafic cannot be ruled out) postulated to exist beneath and proximal to the site (13, 14); B. mineral deposits related to an underlying metamorphic core complex (15); C. mineralization related to possible contact metasomatism; or D. dissolution, concentration, transportation, and subsequent re-deposition of mineral material along one or more postulated underlying low-angle faults (1[illegible]) by circulating meteoric waters heated by an magma source beneath Crater Flat adjacent to Yucca Mountain. The circulating hot-water scenario has been suggested by Odt (17) as a possible genetic model for the emplacement of gold

Figure 2.-- Stratigraphic Column



Modified from Yucca Mtn Site Characterization Plan (1988)

FIGURE 2.– Generalized stratigraphic column, Yucca Mountain area

deposits in Paleozoic rocks at the Stirling Mine on the east flank of Bare Mountain.

3. Large fault/breccia zones have been identified on the flanks of Yucca Mountain (Windy Wash Fault, Solitario Canyon Fault, Bow Ridge Fault, Fran Ridge Fault, etc.). These zones, especially those on the margin of Crater Flat (Windy Wash, Solitario Canyon), may represent sites of mineral deposition.

4. Underlying Paleozoic rocks may be lithologically and structurally similar to rocks northeast of the site that are documented hydrocarbon producers (8). Further, investigations by Chamberlain (18) suggest that an overthrust belt, analogous to that in Utah/Wyoming, in which Mesozoic thrusting has placed permeable Devonian carbonates over organic-rich Mississippian rocks has been recently defined in central Nevada. Both rock types, presumably, are capped by relatively impervious Mississippian black shales.

5. Postulated heat sources (perhaps related to the Crater Flat/Prospector Pass Caldera Complex, buried pluton(s), etc.) and circulating groundwater may constitute a yet to be identified geothermal resource or may have formed mineralized areas within fossil geothermal systems. Figure 3 shows the spatial relationship of Yucca Mountain to major calderas and caldera complexes in the southwestern Nevada volcanic field.

6. The tectonic setting of Yucca Mountain is generally characterized by Proterozoic continental rifting; Paleozoic subsidence with deposition of miogeosynclinal sediments; late Cretaceous-early Tertiary east-directed faulting; widespread Tertiary extentional tectonism and volcanism (19, pp. 84-88).

For purposes of deposit model selection and, based on the above and other available information, the following assumptions have been made:

1. Paleozoic marine sediments underlie Yucca Mountain at varying depths;

2. Plutonic rocks underlie and possibly intrude the Paleozoic sediments under at least a portion of the proposed site;

3. Yucca Mountain hosts a metamorphic core complex;

4. Crater Flat represents a portion of the Crater Flat/Prospector Pass Caldera Complex as suggested by Carr and others (20).

5. A magma chamber underlies Crater Flat at an undetermined depth;

6. Extraction of resources in Paleozoic rocks beneath Yucca Mountain would most likely be carried out via long drifts or declines with terminal vertical shafts (rather than from shafts driven from the crest of the mountain); the drifts or declines would be most likely be driven from the east or west flanks (probably from the west) of the mountain; extraction of resources in tuffs would be via vertical shafts or declines on the flanks or crest of the mountain.

Figure 3. Location of Yucca Mountain in Relation to Calderas and Caldera Complexes in the Southwestern Nevada Volcanic Field.

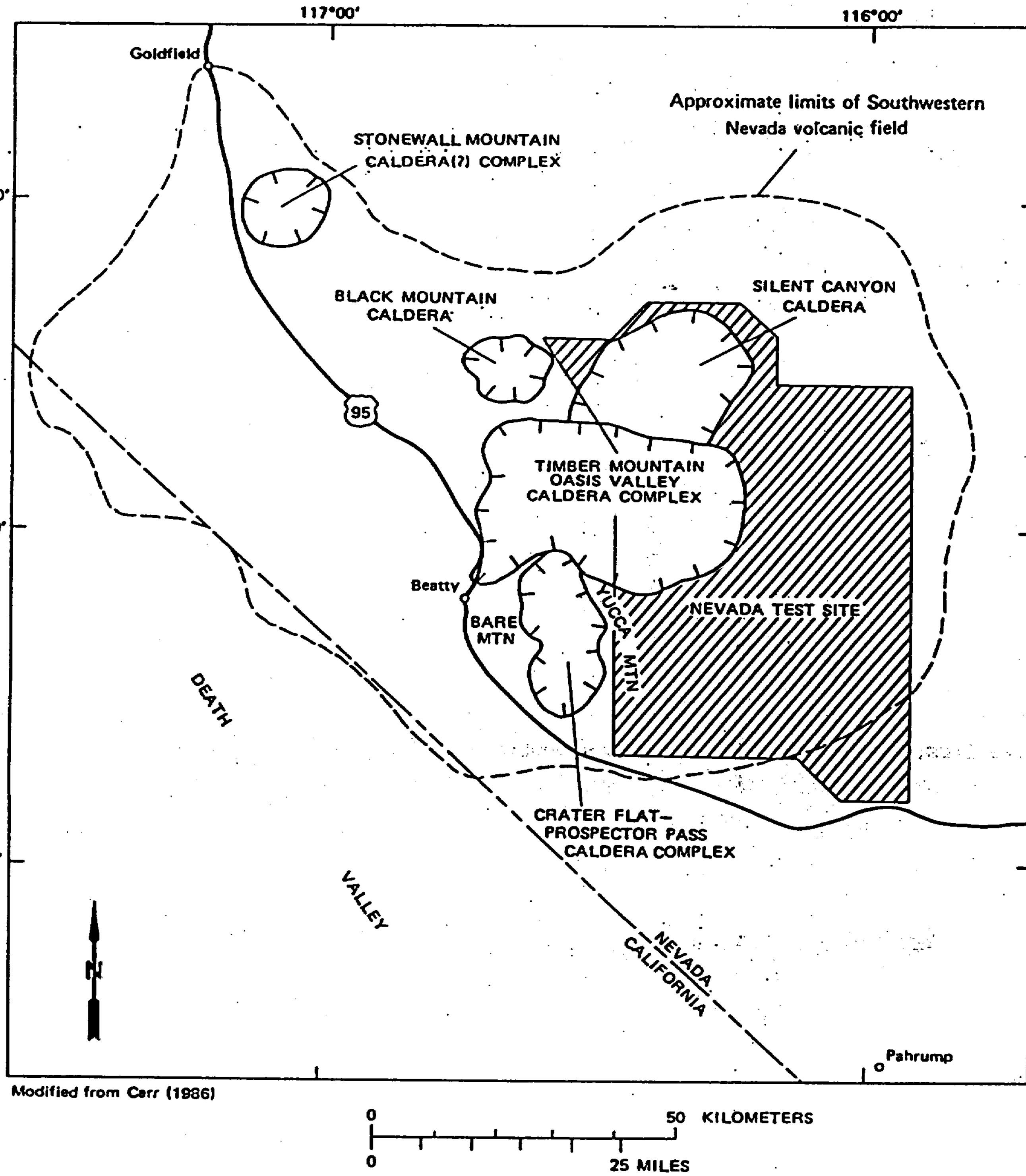


FIGURE 3.– Location of Yucca Mountain in relation to Caldrens and Caldera complexes in southwestern Nevada volcanic field

7. Technical advances over the next 10,000 years will allow economic extraction of resources at much greater depths than currently feasible;

8. Advances in drilling technology over the next 10,000 years will allow large boreholes to be drilled to much greater depths in much shorter times;

9. Depletion of near-surface resources and changes in economics over the next 10,000 years will, by necessity, force exploration/extraction at greater depths.

Information and assumptions presented above are summarized and schematically shown in figure 4 to illustrate possible environments that could engender one or more of the deposit models presented here. The diagram is not drawn to scale, bedding attitudes may not conform to map data, and specific rock types are not identified with the exception of a distinction between Paleozoic and Tertiary accumulations. Further, relative sizes of the features, attitudes of underlying low-angle normal or reverse faults, and spatial relationships are purely conjectural. Possible geothermal, hydrocarbon, or potable water resources are not included.

Figure 4. Schematic cross-section of Yucca Mountain, Crater Flat, and Bare Mountain, Showing Known and Postulated Features.

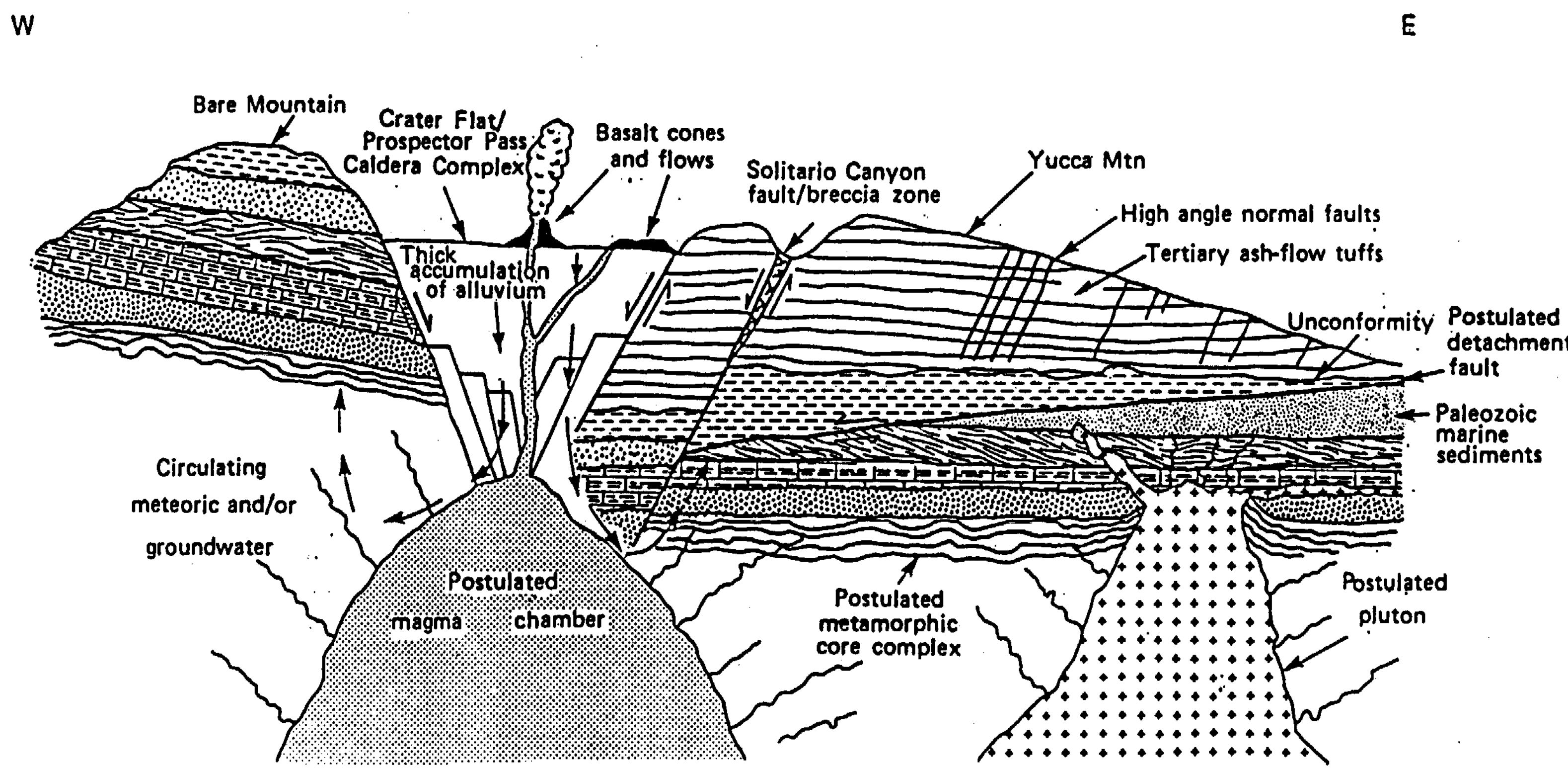


FIGURE 4.– Schematic cross-section of Yucca Mountain, Crater Flat, and Bare Mtns showing postulated subterranean features

2.1.4.2 Descriptive Models

The following descriptive models have been selected as representing possible resources that may occur on, in, beneath, or proximal to Yucca Mountain. Geochemical and geophysical exploration methods applicable to a particular model or models are presented in Sections 2.1.5.3 and 2.1.5.4, respectively. The locations of deposits used as examples for the model (country, state, or other political subdivision, etc.) are listed in Appendix A.

HOT-SPRING AU-AG 1/

(See Figure 5)

DESCRIPTION: Fine-grained silica and quartz in silicified breccia with Au, pyrite, and Sb and As sulfides.

PRIMARY REFERENCE(S): (<u>21</u>).

GEOLOGIC ENVIRONMENT:

<u>Rock Type</u>: Rhyolite.

<u>Textures</u>: Porphyritic, brecciated.

<u>Age Range</u>: Mainly Tertiary and Quaternary.

<u>Depositional Environment</u>: Subaerial rhyolitic volcanic centers, rhyolite domes, and shallow parts of related geothermal systems.

<u>Tectonic Setting</u>: Through-going fracture systems related to volcanism above a subduction zone, rifted continental margins. Leaky transform faults.

<u>Associated Deposit Types</u>: Epithermal quartz veins, hot-spring Hg, placer Au.

DEPOSIT DESCRIPTION:

<u>Mineralogy</u>: Native Au + pyrite + stibnite + realgar; or arsenopyrite ± sphalerite ± fluorite; or native Au + Ag-selenide or tellurides + pyrite.

<u>Texture/Structure</u>: Crustified banded veins, stockworks, breccias (cemented with silica or uncemented). Sulfides may be very fine grained and disseminated in silicified rock.

<u>Alteration</u>: Top to bottom of system: chalcedonic sinter, massive silicification, stockworks of quartz + adularia and breccia cemented with quartz, quartz + chlorite. Veins generally chalcedonic, some opal. Some deposits have alunite and pyrophyllite. Ammonium feldspar (buddingtonite) may be present.

<u>Ore Controls</u>: Through-going fracture systems, brecciated cores of intrusive domes; cemented breccias important carrier of ore.

<u>Weathering</u>: Bleached country rock, yellow limonites with jarosite and fine-grained alunite, hematite, goethite.

<u>Geochemical Signature</u>: Au + As + Sb + Hg + Tl higher in system, increasing Ag with depth, decreasing As + Sb + Tl + Hg with depth. Locally, NH_4, W.

1/ Modified from Berger, B. R. <u>Descriptive Model of Hot-Spring Au-Ag</u>. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 143.

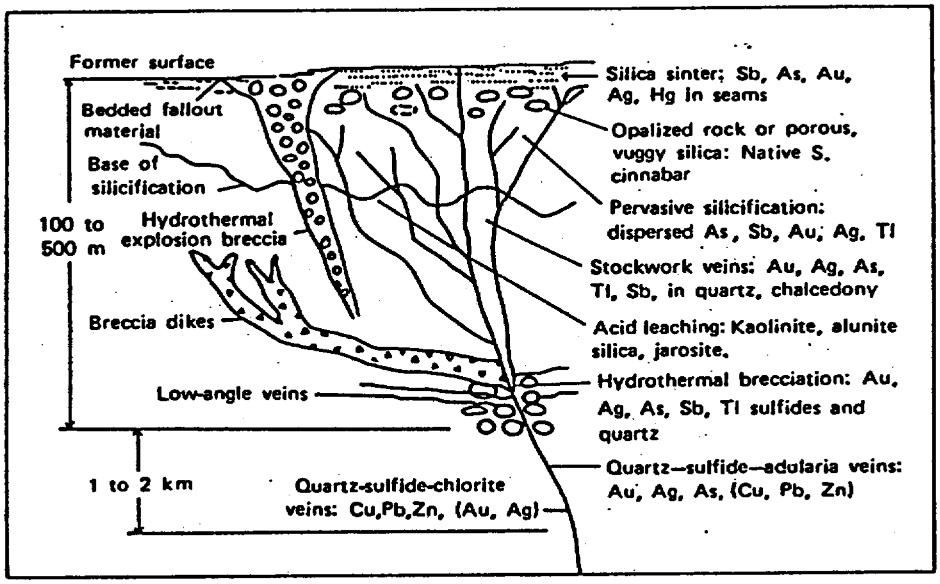
Examples:

McLaughlin, USCA 2/, (22,23) *.
Round Mountain, USNV, (24) **.
Delamar, USID, (25) *.

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

** Additional information available in Lowe, Raney, and Norberg, BOM IC 9035, pp. 162.

Figure 5. Schematic Cross-Section of Hot-Spring Au-Ag Deposit.



Redrawn from Cox and Singer (1986)

FIGURE 5.– Schematic cross-section of hot-spring Au-Ag deposit

Hot-Spring Hg 1/

APPROXIMATE SYNONYM: Sulfur Bank type of White (26) or sulfurous type of Bailey and Phoenix (27).

DESCRIPTION: Cinnabar and pyrite disseminated in siliceous sinter superjacent to graywacke, shale, andesite, and basalt flows and diabase dikes.

PRIMARY REFERENCE(S): (26),(28).

GEOLOGIC ENVIRONMENT

Rock Types: Siliceous sinter, andesite-basalt flows, diabase dikes, andesitic tuffs, and tuff breccias.

Age Range: Tertiary.

Depositional Environment: Near paleo ground-water table in areas of fossil hot-spring system.

Te nic Setting(s): Continental margin rifting associated with small vo me mafic to intermediate volcanism.

Associated Deposit Types: Hot-spring Au.

DEPOSIT DESCRIPTION

Mineralogy: Cinnabar + native Hg + minor marcasite.

Texture/Structure: Disseminated and coatings on fractures in hot-spring sinter.

Alteration: Above paleo ground-water table, kaolinite-alunite-Fe oxides, native sulfur; below paleo ground-water table, pyrite, zeolites, potassium feldspar, chlorite, and quartz. Opal deposited at the paleo water table.

Ore Controls: Paleo ground-water table within hot-spring systems developed along high-angle faults.

Geochemical Signature: Hg + As + Sb ± Au.

Examples: Sulfur Bank, USCA (28).

1/ Modified from White, D. E. Descriptive Model--Hot-Spring Hg. Paper in Mi al Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 19 p. 178.

CREEDE EPITHERMAL VEINS 1/

(See Figure 6)

APPROXIMATE SYNONYM: Epithermal gold (quartz-adularia) alkali-chloride-type, polymetallic veins.

DESCRIPTION: Galena, sphalerite, chalcopyrite, sulfosalts, ± tellurides, ± gold in quartz-carbonate veins hosted by felsic to intermediate volcanics. Older miogeosynclinal evaporites or rocks with trapped seawater are associated with these deposits.

GENERAL REFERENCES: (29), (30).

GEOLOGICAL ENVIRONMENT

Rock Types: Host rocks are andesite, dacite, quartz latite, rhyodacite, rhyolite, and associated sedimentary rocks. Mineralization related to calc-alkaline or bimodal volcanism.

Textures: Porphyritic.

Age Range: Mainly Tertiary (most are 29-4 m.y.).

Depositional Environment: Bimodal and calc-alkaline volcanism. Deposits related to sources of saline fluids in prevolcanic basement such as evaporites or rocks with entrapped seawater.

Tectonic Setting: Through-going fracture systems; major normal faults, fractures related to doming, ring fracture zones, joints associated with calderas. Underlying or nearby older rocks of continental shelf with evaporite basins, or island arcs that are rapidly uplifted.

Associated Deposit Types: Placer gold, epithermal quartz-alunite, Au, polymetallic replacement.

DEPOSIT DESCRIPTION

Mineralogy: Galena + sphalerite + chalcopyrite + copper sulfosalts + silver sulfosalts ± gold ± tellurides ± bornite ± arsenopyrite. Gangue minerals are quartz + chlorite ± calcite + pyrite + rhodochrosite + barite ± fluorite ± siderite ± ankerite ± sericite ± adularia ± kaolinite. Specularite and alunite may be present.

Texture/Structure: Banded veins, open space filling, lamellar quartz, stockworks, colloform textures.

1/ Modified from Mosier, D. L., T. Sato, N. J. Page, D. A. Singer, and B. R. Berger. Descriptive Model of Creede Epithermal Veins. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 145.

Alteration: Top to bottom: quartz ± kaolinite + montmorillonite ± zeolites ± barite ± calcite; quartz + illite; quartz + adularia ± illite; quartz + chlorite; presence of adularia is variable.

Ore Controls: Through-going or anastomosing fracture systems. High-grade shoots where vein changes strike or dip and at intersections of veins. Hanging-wall fractures are particularly favorable.

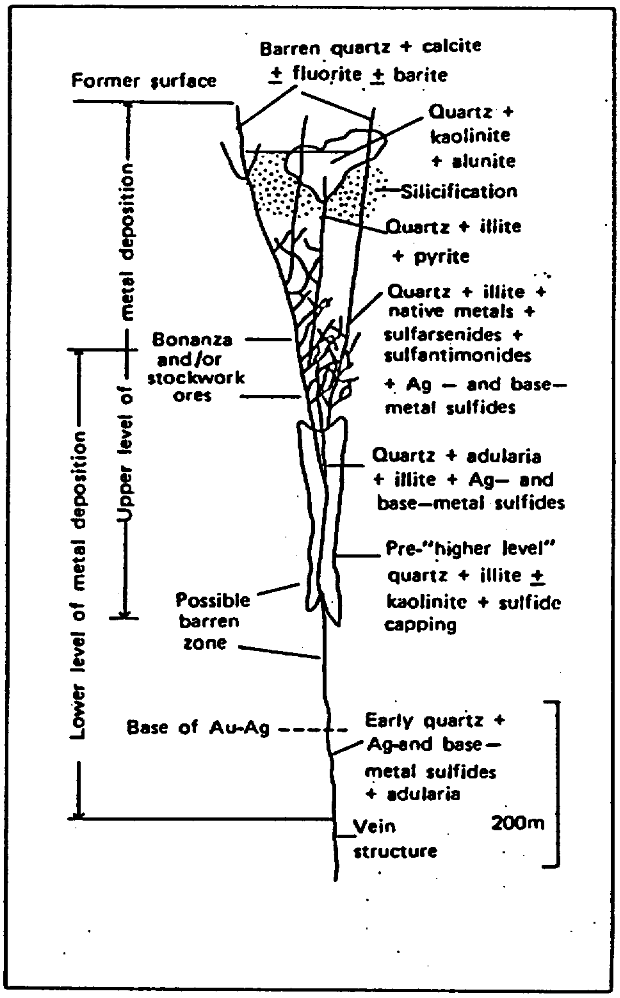
Weathering: Bleached country rock, goethite, jarosite, alunite--supergene processes often important factor in increasing grade of deposit.

Geochemical Signature: Higher in system Au + As + sb + Hg; au + ag + Pb + Zn + Cu; Ag + Pb+ Zn, Cu + Pb + Zn. Base metals generally higher grade in deposits with Ag. W + Bi may be present.

Examples: Creede, CO (31),(32) *
Pachuca, MXCO (33)
Toyoha, JAPN (34)

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

Figure 6. Schematic Cross-Section of Typical Creede-Type Epithermal Vein Deposit.



Redrawn from Cox and Singer (1986)

FIGURE 6.— Schematic cross-section of typical Creede-type epithermal vein deposit

REPLACEMENT SN 1/

APPROXIMATE SYNONYM: Exhalative Sn (35),(36).

DESCRIPTION: Stratabound cassiterite-sulfide (chiefly pyrrhotite) replacement of carbonate rocks and associated fissure lodes related to underlying granitoid complexes.

PRIMARY REFERENCE(S): (37).

GEOLOGIC ENVIRONMENT:

Rock Type: Carbonate rocks (limestone or dolomite); granite, monzogranite, quartz porphyry dikes generally present; quartz-tourmaline rock; chert, pelitic and Fe-rich sediments, and volcanic rocks may ne present.

Textures: Plutonic (equigranular, seriate, porphyritic).

Age Range: Paleozoic and Mesozoic most common; other ages possible.

Depositional Environment: Epizonal granitic complexes in terranes containing carbonate rocks. NOTE: The genetic replacement classification for these deposits has been questioned and an alternative exhalative synsedimentary origin followed by postdepositional metamorphic reworking hypothesis proposed (35), (36), (38).

Tectonic Setting(s): Late orogenic to post orogenic passive emplacement of high-level granitoids in foldbelts containing carbonate rocks; alternatively, Sn and associated metals were derived from submarine exhalative processes with subsequent reequilibration of sulfide and silicate minerals.

Associated Deposit Types: Greisen-style mineralization, quartz-tourmaline-cassiterite veins, Sn-W-Mo stockworks, Sn-W skarn deposits close to intrusions.

DEPOSIT DESCRIPTION:

Mineralogy: Pyrrhotite + arsenopyrite + cassiterite + chalcopyrite (may be major) + ilmenite + fluorite; minor: pyrite, sphalerite, stannite, tetrahedrite, magnetite; late veins: sphalerite + galena + chalcopyrite + pyrite + fluorite.

Texture/Structure: Vein stockwork ores, and massive ores with laminations following bedding in host rock, locally cut by stockwork veins, pyrrhotite may be recrystallized.

1/ Modified from Reed, B. L. Descriptive Model of Replacement Sn. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 61.

Alteration: Griesenization ($\pm$ cassiterite) near granite margins; sideritic alteration of dolomite near sulfide bodies;tourmalinization of clastic sediments; proximity to intrusions may produce contact aureoles in host rocks.

Ore Controls: Replacement of favorable carbonate units; fault-controlled fissure lodes common. Isolated replacement orebodies may lie above granitoid cupolas; faults provide channels for mineralizing fluids.

Geochemical Signature: Sn, As, Cu, B, W, F, Li, Pb, Zn, Rb.

Examples: Renison Bell, AUTS (37).
Cleveland, AUTS (39).
Mt. Bischoff, AUTS (40).
Changpo-Tongkeng, CINA (41).

EPITHERMAL QUARTZ-ALUNITE Au 1/

APPROXIMATE SYNONYM: Acid-sulfate, or enargite gold (42).

DESCRIPTION: Gold, pyrite, and enargite in vuggy veins and breccias in zones of high-alumina alteration related to felsic volcanism.

PRIMARY REFERENCE(S): (42).

GEOLOGIC ENVIRONMENT

Rock Types: Volcanic: dacite, quartz latite, rhyodacite, rhyolite. Hypabyssal intrusions or domes.

Textures: Porphyritic.

Age Range: Generally Tertiary, but can be any age.

Depositional Environment: Within the volcanic edifice, ring fracture zones of calderas, or areas of igneous activity with sedimentary evaporites in basement.

Tectonic Setting(s): Through-going fracture systems: keystone graben structures, ring-fracture zones, normal faults, fractures related to doming, joint sets.

Associated Deposit Types: Porphyry copper, polymetallic replacement, volcanic hosted Cu-As-Sb. Pyrophyllite, hydrothermal clay, and alunite deposits.

DEPOSIT DESCRIPTION

Mineralogy: Native gold + enargite + pyrite + silver-bearing sulfosalts ± chalcopyrite ± bornite ± precious-metal tellurides ± galena ± sphalerite ± huebnerite. May have hypogene oxidation phase with chalcocite ± covellite ± luzonite with late-stage native sulfur.

Alteration: Highest temperature assemblage: quartz + alunite + pyrophyllite may be early stage with pervasive alteration of host rock and veins of these minerals; this zone may contain corundum, diaspore, andalusite, or zunyite. Zoned around quartz-alunite is quartz + alunite + kaolinite + montmorillonite; pervasive propylitic alteration (chlorite + calcite) depends on extent of early alunitization. Ammonium-bearing clays may be present.

Ore Controls: Through-going fractures, centers of intrusive activity. Upper and peripheral parts of porphyry copper systems.

1/Modified from Berger, B. R. Descriptive Model of Epithermal Quartz--Alunite Au. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 158.

Weathering: Abundant yellow limonite, jarosite, goethite, white argillization with kaolinite, fine-grained white alunite veins, hematite.

Geochemical Signature: Higher in system: Au + As + Cu; increasing base metals at depth. Also Te and (at El Indio) W.

Examples: Goldfield, USNV (43) *, **.
Kasuga mine, JAPN (44).
El Indio, CILE (45).
Summitville, USCO (46) *.
Iwato, JAPN (47).

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

** Additional information available in Lowe, Raney, and Norberg, BOM IC 9035. pp. 115.

PORPHYRY MO, LOW-F 1/

APPROXIMATE SYNONYM: Calc-alkaline Mo stockwork (48).

DESCRIPTION: Stockwork of quartz-molybdenite veinlets in felsic porphyry and in its nearby country rock.

PRIMARY REFERENCE(S): (48).

GEOLOGIC ENVIRONMENT

Rock Types: Tonalite, granodiorite, and monzogranite.

Textures: Porphyry, fine aplitic groundmass.

Age Range: Mesozoic and Tertiary.

Depositional Environment: Orogenic belt with calcalkaline intrusive rocks.

Tectonic Setting(s): Numerous faults.

As[illegible]iated Deposit Types: Porphyry Cu-Mo, Cu skarn, volcanic hosted Cu-As-Sb.

DEPOSIT DESCRIPTION

Mineralogy: Molybdenite + pyrite ± scheelite ± chalcopyrite ± argentian tetrahedrite. Quartz ± K-feldspar ± biotite ± calcite ± white mica and clays.

Texture/Structure: Disseminated and in veinlets and fractures.

Alteration: Potassic outward to propylitic. Phyllic and argillic overprint.

Ore Controls: Stockwork in felsic porphyry and in surrounding country rock.

Weathering: Yellow ferrimolybdite after molybdenite. Secondary copper enrichment may form copper ores in some deposits.

Geochemical Signature: Zoning outward and upward from Mo + Cu ± W to Cu + Au to Zn + Pb, + Au, + Ag. F may be present but in amounts less than 1,000 ppm.

1/Modified from Theodore, T. G. Description of Porphyry Mo, Low-F. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 120.

Examples: Buckingham, USNV (<u>49</u>) *, **.
USSR deposits (<u>50</u>).

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

** Additional information available in Lowe, Raney, and Norberg, BOM IC 9035. pp. 90.

REPLACEMENT SN 1/

APPROXIMATE SYNONYM: Exhalative Sn (35), (36).

DESCRIPTION: Stratabound cassiterite-sulfide (chiefly pyrrhotite) replacement of carbonate rocks and associated fissure lodes related to underlying granitoid complexes.

PRIMARY REFERENCE(S): (37).

GEOLOGIC ENVIRONMENT:

Rock Type: Carbonate rocks (limestone or dolomite); granite, monzogranite, quartz porphyry dikes generally present; quartz-tourmaline rock; chert, pelitic and Fe-rich sediments, and volcanic rocks may ne present.

Textures: Plutonic (equigranular, seriate, porphyritic).

Age Range: Paleozoic and Mesozoic most common; other ages possible.

Depositional Environment: Epizonal granitic complexes in terranes c[illegible]ining carbonate rocks. NOTE: The genetic replacement classification f[illegible]these deposits has been questioned and an alternative exhalative synsedimentary origin followed by postdepositional metamorphic reworking hypothesis proposed (35), (36), (38).

Tectonic Setting(s): Late orogenic to post orogenic passive emplacement of high-level granitoids in foldbelts containing carbonate rocks; alternatively, Sn and associated metals were derived from submarine exhalative processes with subsequent reequilibration of sulfide and silicate minerals.

Associated Deposit Types: Greisen-style mineralization, quartz-tourmaline-cassiterite veins, Sn-W-Mo stockworks, Sn-W skarn deposits close to intrusions.

DEPOSIT DESCRIPTION:

Mineralogy: Pyrrhotite + arsenopyrite + cassiterite + chalcopyrite (may be major) + ilmenite + fluorite; minor: pyrite, sphalerite, stannite, tetrahedrite, magnetite; late veins: sphalerite + galena + chalcopyrite + pyrite + fluorite.

Texture/Structure: Vein stockwork ores, and massive ores with laminations following bedding in host rock, locally cut by stockwork veins, pyrrhotite may be recrystallized.

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Alteration: Griesenization (± cassiterite) near granite margins; sideritic alteration of dolomite near sulfide bodies;tourmalinization of clastic sediments; proximity to intrusions may produce contact aureoles in host rocks.

Ore Controls: Replacement of favorable carbonate units; fault-controlled fissure lodes common. Isolated replacement orebodies may lie above granitoid cupolas; faults provide channels for mineralizing fluids.

Geochemical Signature: Sn, As, Cu, B, W, F, Li, Pb, Zn, Rb.

Examples: Renison Bell, AUTS (37).
Cleveland, AUTS (39).
Mt. Bischoff, AUTS (40).
Changpo-Tongkeng, CINA (41).

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APPROXIMATE SYNONYM: Acid-sulfate, or enargite gold (42).

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GEOLOGIC ENVIRONMENT

Rock Types: Volcanic: dacite, quartz latite, rhyodacite, rhyolite. Hypabyssal intrusions or domes.

Textures: Porphyritic.

Age Range: Generally Tertiary, but can be any age.

Depositional Environment: Within the volcanic edifice, ring fracture zones of calderas, or areas of igneous activity with sedimentary evaporites in basement.

Tectonic Setting(s): Through-going fracture systems: keystone graben structures, ring fracture zones, normal faults, fractures related to doming, joint sets.

Associated Deposit Types: Porphyry copper, polymetallic replacement, volcanic hosted Cu-As-Sb. Pyrophyllite, hydrothermal clay, and alunite deposits.

DEPOSIT DESCRIPTION

Mineralogy: Native gold + enargite + pyrite + silver-bearing sulfosalts ± chalcopyrite ± bornite ± precious-metal tellurides ± galena ± sphalerite ± huebnerite. May have hypogene oxidation phase with chalcocite ± covellite ± luzonite with late-stage native sulfur.

Alteration: Highest temperature assemblage: quartz + alunite + pyrophyllite may be early stage with pervasive alteration of host rock and veins of these minerals; this zone may contain corundum, diaspore, andalusite, or zunyite. Zoned around quartz-alunite is quartz + alunite + kaolinite + montmorillonite; pervasive propylitic alteration (chlorite + calcite) depends on extent of early alunitization. Ammonium-bearing clays may be present.

Ore Controls: Through-going fractures, centers of intrusive activity. Upper and peripheral parts of porphyry copper systems.

1/Modified from Berger, B. R. Descriptive Model of Epithermal Quartz--Alunite Au. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 158.

Weathering: Abundant yellow limonite, jarosite, goethite, white argillization with kaolinite, fine-grained white alunite veins, hematite.

Geochemical Signature: Higher in system: Au + As + Cu; increasing base metals at depth. Also Te and (at El Indio) W.

Examples: Goldfield, USNV (43) *, **.
Kasuga mine, JAPN (44).
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PORPHYRY MO, LOW-F 1/

APPROXIMATE SYNONYM: Calc-alkaline Mo stockwork (48).

DESCRIPTION: Stockwork of quartz-molybdenite veinlets in felsic porphyry and in its nearby country rock.

PRIMARY REFERENCE(S): (48).

GEOLOGIC ENVIRONMENT

Rock Types: Tonalite, granodiorite, and monzogranite.

Textures: Porphyry, fine aplitic groundmass.

Age Range: Mesozoic and Tertiary.

Depositional Environment: Orogenic belt with calcalkaline intrusive rocks.

Tectonic Setting(s): Numerous faults.

Associated Deposit Types: Porphyry Cu-Mo, Cu skarn, volcanic hosted Cu-As-Sb.

DEPOSIT DESCRIPTION

Mineralogy: Molybdenite + pyrite ± scheelite ± chalcopyrite ± argentian tetrahedrite. Quartz ± K-feldspar ± biotite ± calcite ± white mica and clays.

Texture/Structure: Disseminated and in veinlets and fractures.

Alteration: Potassic outward to propylitic. Phyllic and argillic overprint.

Ore Controls: Stockwork in felsic porphyry and in surrounding country rock.

Weathering: Yellow ferrimolybdite after molybdenite. Secondary copper enrichment may form copper ores in some deposits.

Geochemical Signature: Zoning outward and upward from Mo + Cu ± W to Cu + Au to Zn + Pb, + Au, + Ag. F may be present but in amounts less than 1,000 ppm.

1/Modified from Theodore, T. G. Description of Porphyry Mo, Low-F. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 120.

Examples: Buckingham, USNV (49) *, **.
USSR deposits (50).

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

** Additional information available in Lowe, Raney, and Norberg, BOM IC 9035. pp. 90.

EPITHERMAL MN 1/

DESCRIPTION: Manganese mineralization in epithermal veins fillings fault and fractures in subaerial volcanic rocks.

GEOLOGIC ENVIRONMENT

Rock Types: Flows, tuffs, breccias, and agglomerates of rhyolitic, dacitic, andesitic or basaltic composition.

Age Range: Tertiary.

Depositional Environment: Volcanic centers.

Tectonic Setting(s): Through-going fracture systems.

Associated Deposit Types: Epithermal gold-silver.

DEPOSIT DESCRIPTION

Mineralogy: Rhodochrosite, manganocalcite, calcite, quartz, chalcedony, b[illegible]e, zeolites.

Texture/Structure: Veins, bunches, stringers, nodular masses, disseminations.

Alteration: Kaolinitization.

Ore Controls: Through-going faults and fractures; brecciated volcanic rocks.

Weathering: Oxidization zone contains abundant manganese oxides, psilomelane, pyrolusite, braunite, wad, manganite, cryptomelane, hollandite, coronadite, and Fe oxides.

Geochemical Signature: Mn, Fe, P (Pb, Ag, Au, Cu). At Talamantes, W is important.

Examples: Talamantes, MXCO (51).
Gloryana, USNM (52) *.
Sardegna, ITLY (53).

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

1/Modified from Mosier, D. L. Descriptive Model of Epithermal Mn. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 165.

CARBONATE-HOSTED AU-AG 1/

APPROXIMATE SYNONYM: Carlin-type or invisible gold.

DESCRIPTION: Very fine grained gold and sulfides disseminated in carbonaceous calcareous rocks and associated jasperoids.

PRIMARY REFERENCE(S): (54).

GEOLOGIC ENVIRONMENT

Rock Types: Host rocks: thin-bedded silty or argillaceous carbonaceous limestone or dolomite, commonly with carbonaceous shale. Intrusive rocks: felsic dikes.

Textures: Dikes are generally porphyritic.

Age Range: Mainly Tertiary, but can be any age.

Depositional Environment: Best host rocks formed as carbonate turbidites in somewhat anoxic environments. Deposits formed where these are intruded by igneous rocks under nonmarine conditions.

Tectonic Setting(s): High-angle normal fault zones related to continental margin rifting.

Associated Deposit Types: W-Mo skarn, porphyry Mo, placer Au, stibnite-barite veins.

DEPOSIT DESCRIPTION

Mineralogy: Native gold (very fine grained) + pyrite + realgar + orpiment ± arsenopyrite ± cinnabar ± fluorite ± barite ± stibnite. Quartz, calcite, carbonaceous matter.

Texture/Structure: Silica replacement of carbonate. Generally less than 1 percent fine-grained sulfides.

Alteration: Unoxidized ore: jasperoid + quartz + illite + kaolinite + calcite. Abundant amorphous carbon locally appears to be introduced. Hypogene oxidized ore: kaolinite + montmorillonite + illite + jarosite + alunite. Ammonium clays may be present.

Ore Controls: Selective replacement of carbonaceous carbonate rocks adjacent to and along high-angle faults, or regional thrust faults or bedding.

1/Modified from Berger, B. R. Descriptive Model of Carbonate-Hosted Au-Ag. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 175.

Weathering: Light-red, gray, and (or) tan oxides, light-brown to reddish-brown iron-oxide-stained jasperoid.

Geochemical Signature: Au + As + Hg + W ± Mo; As + Hg + Sb + Tl ± F (this stage superimposed on preceding); NH_3 important in some deposits.

Examples: Carlin, USNV (55) *, **.
Getchell, USNV (56) *, **.
Mercur, USUT (57) *.

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

** Additional information available in Lowe, Raney, and Norberg, BOM IC 9035, pp. 96, 112, respectively.

SIMPLE SB DEPOSITS 1/

APPROXIMATE SYNONYM: Deposits of quartz-stibnite ore (58).

DESCRIPTION: Stibnite veins, pods, and disseminations in or adjacent to brecciated or sheared fault zones.

PRIMARY REFERENCE(S): (59, 60).

GEOLOGIC ENVIRONMENT

Rock Types: One or more of the following lithologies is found associated with over half of the deposits: limestone, shale (commonly calcareous), sandstone, and quartzite. Deposits are also found with a wide variety of other lithologies including slate, rhyolitic flows and tuffs, argillite, granodiorite, granite, phyllite, siltstone, quartz mica and chloritic schists, gneiss, quartz porphyry, chert, diabase, conglomerate, andesite, gabbro, diorite, and basalt.

Textures: Not diagnostic.

Age Range: Known deposits are Paleozoic to Tertiary.

Depositional Environment: Faults and shear zones.

Tectonic Setting(s): Any orogenic area.

Associated Deposit Types: Stibnite-bearing veins, pods, and disseminations containing base metal sulfides ± cinnabar ± silver ± gold ± scheelite that are mined primarily for lead, gold, silver, zinc, or tungsten; low-sulfide Au-quartz veins; epithermal gold and gold-silver deposits; hot-springs gold; carbonate-hosted gold; tin-tungsten veins; hot-springs and disseminated mercury, gold-silver placers; infrequently with polymetallic veins and tungsten skarns.

1/Modified from Bliss, J. D. and G. J. Orris. Description Model of Simple Sb Deposits. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 183.

DEPOSIT DESCRIPTION

Mineralogy: Stibnite + quartz ± pyrite ± calcite; minor other sulfides frequently less than 1 percent of deposit and included ± arsenopyrite ± sphalerite ± tetrahedrite ± chalcopyrite ± scheelite ± free gold; minor minerals only occasionally found include native antimony, marcasite, calaverite, berthierite, argentite, pyrargyrite, chalcocite, wolframite, richardite, galena, jamesonite; at least a third (and possibly more) of the deposits contain gold or silver. Uncommon gangue minerals include chalcedony, opal (usually identified to be christobalite by X-ray), siderite, fluorite, barite, and graphite.

Texture/Structure: Vein deposits contain stibnite in pods, lenses, kidney forms, pockets (locally); may be massive or occur as streaks, grains, and bladed aggregates in sheared or brecciated zones with quartz and calcite. Disseminated deposits contain streaks or grains of stibnite in host rock with or without stibnite vein deposits.

Alteration: Silicification, sericitization, and argillization; minor chloritization; serpentinization when deposit in mafic, ultramafic rocks.

Ore Controls: Fissures and shear zones with breccia usually associated with fault; some replacement in surrounding lithologies; infrequent open-space filling in porous sediments and replacement in limestone. Deposition occurs at shallow to intermediate depth.

Weathering: Yellow to reddish kermesite and white cerrantite or stibiconite (Sb oxides) may be useful in exploration; residual soils directly above deposits are enriched in antimony.

Geochemical Signature: Sb ± Fe ± As ± Au ± Ag; Hg ± W ± Pb ± Zn may be useful in specific cases.

Examples: Amphoe Phra Saeng, THLD (61).
Caracota, BLVA (62).

GOLD ON FLAT AND ASSOCIATED HIGH-ANGLE FAULTS 1/

DESCRIPTION: Disseminated gold in breccia along low-angle faults.

PRIMARY REFERENCE(S): (63).

GEOLOGIC ENVIRONMENT

Rock Types: Breccia derived from granitic rocks, gneiss, schist, mylonite and unmetamorphosed sedimentary and volcanic rocks. Rhyolitic dikes and plugs.

Textures: Chaotic jumble of rock and vein material.

Age Range: Unknown. Examples in southern California and southwestern Arizona are mainly Mesozoic and Tertiary.

Depositional Environment: Permeable zones: source of heat and fluids unknown.

Tectonic Setting(s): Low-angle faults in crystalline and volcanic terrane. Includes detachment faults related to some metamorphic core complexes and thrust faults related to earlier compressive regimes.

Associated Deposit Types: Epithermal quartz adularia veins in hanging-wall rocks of some districts.

DEPOSIT DESCRIPTION

Mineralogy: Gold, hematite, chalcopyrite, minor bornite, barite, and fluorite.

Texture/Structure: Micrometer-size gold and specular hematite in stockwork veining and brecciated rock.

Alteration: Hematite, quartz, and chlorite. Silicification. Carbonate minerals.

Ore Controls: Intensely brecciated zones along low-angle faults. Steep normal faults in hanging wall. Sheeted veins.

Weathering: Most ore is in oxidized zone because of lower cost of recovery. Mn oxides.

Geochemical Signature: Au, Cu, Fe, F, Ba. Very low level anomalies in Ag, As, Hg, and W.

1/Modified from Bouley, B. A. Descriptive Model of Gold on Flat Faults. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, pp. 251.

Examples: Picacho, USCA (64) *.
Copper Penny and Swansea, USAZ (65) *.

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

BEDDED BARITE 1/

APPROXIMATE SYNONYM: Stratiform barite.

DESCRIPTION: Stratiform deposits of barite interbedded with dark-colored cherty and calcareous sedimentary rocks.

GEOLOGIC ENVIRONMENT

Rock Types: Generally dark-colored chert, shale, mudstone, limestone or dolostone. Also with quartzite, argillite, and greenstone.

Age Range: Proterozoic and Paleozoic.

Depositional Environment: Epicratonic marine basins or embayments (often with smaller local restricted basins).

Tectonic Setting(s): Some deposits associated with hinge zones controlled by synsedimentary faults.

Associated Deposit Types: Sedimentary exhalative Zn-Pb.

DEPOSIT DESCRIPTION

Mineralogy: Barite ± minor witherite ± minor pyrite, galena, or sphalerite. Barite typically contains several percent organic matter plus some H_2S in fluid inclusions.

Texture/Structure: Stratiform, commonly lensoid to poddy; ore laminated to massive with associated layers of barite nodules or rosettes; barite may exhibit primary sedimentary features. Small country rock inclusions may show partial replacement by barite.

Alteration: Secondary barite veining; weak to moderate sericitization has been reported in or near some deposits in Nevada.

Ore Controls: Deposits are localized in second- and third-order basins.

Weathering: Indistinct, generally resembling limestone or dolostone; occasionally weather-out rosettes or nodules.

Geochemical Signature: Ba; where peripheral to sediment-hosted Zn-Pb, may have lateral (Cu)-Pb-Zn-Ba zoning or regional manganese haloes. High organic C content.

1/Modified from Orris, G. J. Descriptive Model of Bedded Barite. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 216.

Examples: Meggen, GRMY (66).
Magnet Cove, USAR (67) *.
Northumberland, USNV (68) **.

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

** Additional information available in Lowe, Raney, and Norberg, BOM IC 9035, pp. 143.

REPLACEMENT MN 1/

DESCRIPTION: Manganese oxide minerals occur in epigenetic veins or cavity fillings in limestone, dolomite, or marble, which may be associated with intrusive complexes.

GEOLOGIC ENVIRONMENT

Rock Types: Limestone, dolomite, marble, and associated sedimentary rocks; granite and granodiorite plutons.

Age Range: Mainly Paleozoic to Tertiary, but may be any age.

Depositional Environment: Miogeosynclinal sequences intruded by small plutons.

Tectonic Setting(s): Orogenic belts, late orogenic magmatism.

Associated Deposit Types: Polymetallic vein, polymetallic replacement, skarn Cu, skarn Zn, porphyry copper.

DEPOSIT DESCRIPTION

Mineralogy: Rhodochrosite ± rhodonite + calcite + quartz ± barite ± fluorite ± jasper ± manganocalcite ± pyrite ± chalcopyrite ± galena ± sphalerite.

Texture/Structure: Tabular veins, irregular open space fillings, lenticular pods, pipes, chimneys.

Ore Controls: Fracture permeability in carbonate rocks. May be near intrusive contact.

Weathering: Mn oxide minerals: psilomelane, pyrolusite, and wad form in the weathered zone and make up the richest parts of most deposits. Limonite and kaolinite.

Geochemical Signature: Mn, Fe, P, Cu, Ag, Au, Pb, Zn.

Examples: Lake Valley, USNM (69 *.
Philipsburg, USMT (70) *.
Lammereck, ASTR (71).

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

1/Modified from Mosier, D. L. Descriptive Model for Replacement Mn. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 105.

POLYMETALLIC REPLACEMENT DEPOSITS 1/
(See Figure 7)

APPROXIMATE SYNONYM: Manto deposits, many authors.

DESCRIPTION: Hydrothermal, epigenetic, Ag, Pb, Zn, Cu minerals in massive lenses, pipes and veins in limestone, dolomite, or other soluble rock near igneous intrusions.

PRIMARY REFERENCE(S): (72).

GEOLOGIC ENVIRONMENT

Rock Types: Sedimentary rocks, chiefly limestone, dolomite, and shale, commonly overlain by volcanic rocks and intruded by porphyritic, calc-alkaline plutons.

Textures: The textures of the replaced sedimentary rocks are not important; associated plutons typically are porphyritic.

Age Range: Not important, but many are late Mesozoic to early Cenozoic.

Depositional Environment: Carbonate host rocks that commonly occur in broad sedimentary basins, such as epicratonic miogeosynclines. Replacement by solutions emanating from volcanic centers and epizonal plutons. Calderas may be favorable.

Tectonic Setting(s): Most deposits occur in mobile belts that have undergone moderate deformation and have been intruded by small plutons.

Associated Deposit Types: Base metal skarns, and porphyry copper deposits.

DEPOSIT DESCRIPTION

Mineralogy: Zonal sequence outward: enargite + sphalerite + argentite + tetrahedrite + digenite ± chalcopyrite, rare bismuthinite; galena + sphalerite + argentite ± tetrahedrite ± proustite ± pyrargyrite, rare jamesonite, jordanite, bournonite, stephanite, and polybasite; outermost sphalerite + rhodochrosite. Widespread quartz, pyrite, marcasite, barite. Locally, rare gold, sylvanite, and calaverite.

Texture/Structure: Ranges from massive to highly vuggy and porous.

Alteration: Limestone wallrocks are dolomitized and silicified (to form jasperoid); shale and igneous rocks are chloritized and commonly are argillized; where syngenetic iron oxide minerals are present, rocks are pyritized. Jasperoid near ore is coarser grained and contains traces of barite and pyrite.

1/Modified from Morris, H. T. Descriptive Model of Polymetallic Replacement Deposits. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 99.

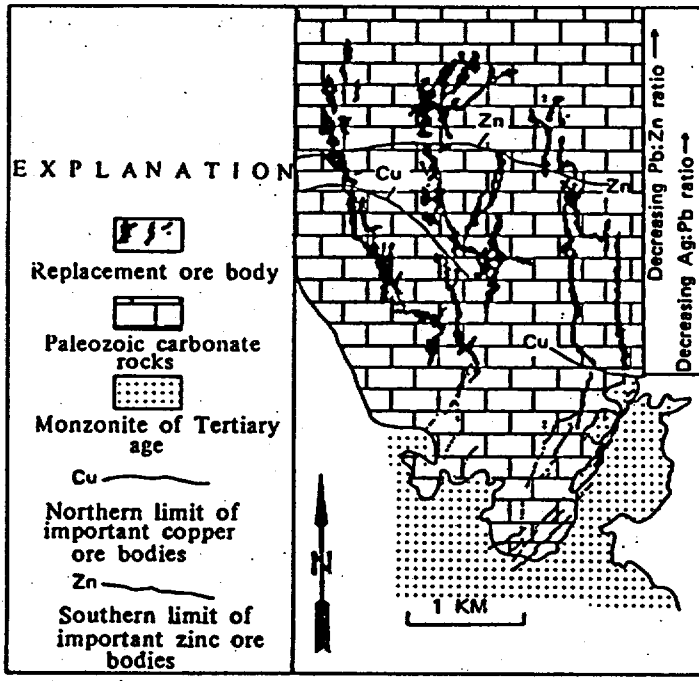
Ore Controls: Tabular, podlike and pipelike ore bodies are localized by faults or vertical beds; ribbonlike or blanketlike ore bodies are localized by bedding-plane faults, by susceptible beds, or by preexisting solution channels, caverns, or cave rubble.

Weathering: Commonly oxidized to ochreous masses containing cerrusite, anglesite, hemimorphite, and cerargyrite.

Geochemical Signature: On a district-wide basis ore deposits commonly are zoned outward from a copper-rich central area through a wide lead-silver zone, to a zinc- and manganese-rich fringe. Locally Au, As, Sb, and Bi. Jasperoid related to ore can often be recognized by high Ba and trace Ag content.

Examples: East Tintic district, USUT (73) *.
Eureka district, USNV (74) *.
Manto deposit, MXCO (75)

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).



Metals	Dominant mineralogy Ore	Gangue
Zn-Mn	Sphalerite + rhodochrosite	Fine-grained pyritic jasperoid
Pb-Ag	Galena + sphalerite + argentite + Ag sulfosalts ± tetrahedrite	Fine-grained jasperoid with barite crystals and quartz-lined vugs
Cu-Au	Enargite—famatinite + tennantite—tetrahedrite + sphalerite + argentite + digenite	Medium-grained jas-period and coarse crystals of quartz and barite

Modified from Cox and Singer (1986)

FIGURE 7.— Generalized map, metal and mineral zoning in polymetallic replacement deposits in the main Tintic district, Utah

upper case

Figure 7. Generalized Map, Metal and Mineral Zoning in Polymetallic Replacement Deposits in the Main Tintic District, Utah

FE SKARN DEPOSITS 1/

DESCRIPTION: Magnetite in calc-silicate contact metasomatic rocks.

PRIMARY REFERENCE(S): (76, 77).

GEOLOGIC ENVIRONMENT

Rock Types: Gabbro, diorite, diabase, syenite, tonalite, granodiorite, granite, and coeval volcanic rocks. Limestone and calcareous sedimentary rocks.

Textures: Granitic texture in intrusive rocks; granoblastic to hornfelsic textures in sedimentary rocks.

Age Range: Mainly Mesozoic and Tertiary, but may be any age.

Depositional Environment: Contacts of intrusion and carbonate rocks or calcareous clastic rocks.

Tectonic Setting(s): Miogeosynclinal sequences intruded by felsic to mafic plutons. Oceanic island arc, Andean volcanic arc, and rifted continental margin.

DEPOSIT DESCRIPTION

Mineralogy: Magnetite ± chalcopyrite ± Co-pyrite ± pyrite ± pyrrhotite. Rarely cassiterite in Fe skarns in Sn-granite terranes.

Texture/Structure: Granoblastic with interstitial ore minerals.

Alteration: Diopside-hedenbergite + grossular-andradite + epidote. Late stage amphibole ± chlorite ± ilvaite.

Ore Controls: Carbonate rocks, calcareous rocks, igneous contacts and fracture zones near contacts. Fe skarn ores can also form in gabbroic host rocks near felsic plutons.

Weathering: Magnetite generally crops out or forms abundant float.

Geochemical and Geophysical Signature: Fe, Cu, Co, Au, possibly Sn. Strong magnetic anomaly.

1/Modified from Cox, D. P. Descriptive Model of Fe Skarn Deposits. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 94.

Examples: Shinyama, JAPN (78)
Cornwall, USPA (79) *.
Iron Springs, USUT (80) *.

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

ZN-PB SKARN DEPOSITS 1/

DESCRIPTION: Sphalerite and galena in calc-silicate rocks.

PRIMARY REFERENCE(S): (81, 82).

GEOLOGIC ENVIRONMENT

Rock Types: Granodiorite to granite, diorite to syenite. Carbonate rocks, calcareous clastic rocks.

Textures: Granitic to porphyritic; granoblastic to hornfelsic.

Age Range: Mainly Mesozoic, but may be any age.

Depositional Environment: Miogeoclinal sequences intruded by generally small bodies of igneous rock.

Tectonic Setting(s): Continental margin, late-orogenic magmatism.

As ciated Deposit Types: Copper skarn.

DEPOSIT DESCRIPTION

Mineralogy: Sphalerite + galena ± pyrrhotite ± pyrite ± magnetite ± chalcopyrite ± bornite ± arsenopyrite ± scheelite ± bismuthinite ± stannite ± fluorite. Gold and silver do not form minerals.

Texture/Structure: Granoblastic, sulfides massive to interstitial.

Alteration: Mn-hedenbergite ± andradite ± grossularite ± spessartine ± bustamite ± rhodonite. Late stage Mn-actinolite ± ilvaite ± chlorite ± dannemorite ± rhodochrosite.

Ore Controls: Carbonate rocks especially at shale-limestone contacts. Deposit may be hundreds of meters from intrusive.

Weathering: Gossan with strong Mn oxide stains.

Geochemical Signature: Zn, Pb, Mn, Cu, Co, Au, Ag, As, W, Sn, F, possibly Be. Magnetic anomalies.

Examples: Ban Ban, AUQU (83)
Hanover-Fierro district, USNM (84).

* itional non-proprietary information available through BOM Mineral Industry Location System (MILS).

1/Modified from Cox, D. P. Descriptive Model of Zn-Pb Skarn Deposits. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 90.

CU SKARN DEPOSITS 1/
(See Figure 8)

DESCRIPTION: Chalcopyrite in calc-silicate contact metasomatic rocks.

PRIMARY REFERENCE(S): (85, 86).

GEOLOGIC ENVIRONMENT

Rock Types: Tonalite to monzogranite intruding carbonate rocks or calcareous clastic rocks.

Textures: Granitic texture, porphyry, granoblastic to hornfelsic in sedimentary rocks.

Age Range: Mainly Mesozoic, but may be any age.

Depositional Environment: Miogeosynclinal sequences intruded by felsic plutons.

Tectonic Setting(s): Continental margin late orogenic magmatism.

Associated Deposit Types: Porphyry Cu, zinc skarn, polymetallic replacement, Fe skarn.

DEPOSIT DESCRIPTION

Mineralogy: Chalcopyrite + pyrite ± hematite ± magnetite ± bornite ± pyrrhotite. Also molybdenite, bismuthinite, sphalerite, galena, cosalite, arsenopyrite, enargite, tennantite, loellingite, cobaltite, and tetrahedrite may be present. Au and Ag may be important products.

Texture/Structure: Coarse granoblastic with interstitial sulfides. Bladed pyroxenes are common.

Alteration: Diopside + andradite center; wollastonite ± tremolite outer zone; marble peripheral zone. Igneous rocks may be altered to epidote + pyroxene + garnet (endoskarn). Retrograde alteration to actinolite, chlorite, and clays may be present.

Ore Controls: Irregular or tabular ore bodies in carbonate rocks and calcareous rocks near igneous contacts or in xenoliths in igneous stocks. Breccia pipe, cutting skarn at Victoria, is host for ore. Associated igneous rocks are commonly barren.

Weathering: Cu carbonates, silicates, Fe-rich gossan. Calc-silicate minerals in stream pebbles are a good guide to covered deposits.

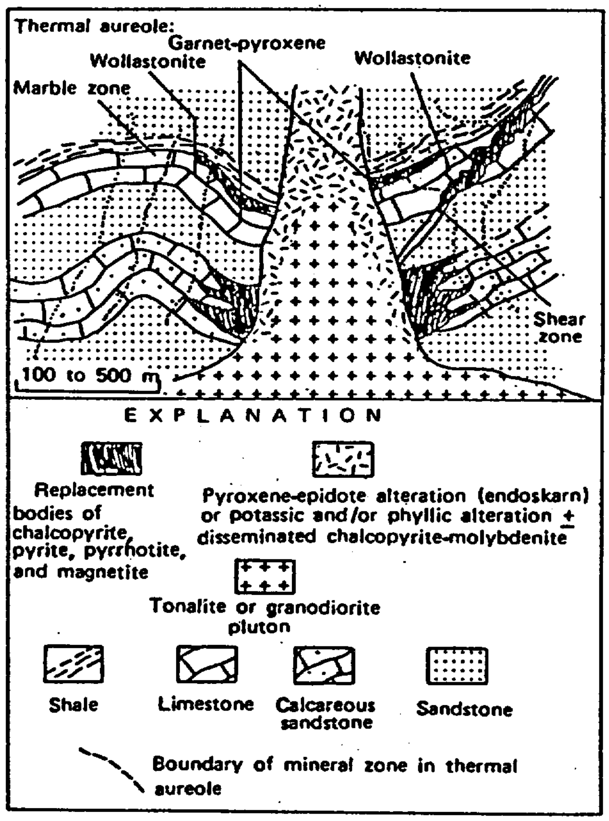
1/Modified from Cox, D. P. Descriptive Model of Cu Skarn Deposits. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 86.

Geochemical Signature: Rock analyses may show Cu-Au-Ag-rich inner zones grading outward to Au-Ag zones with high Au:Ag ratio and outer Pb-Zn-Ag zone. Co-As-Sb-Bi may form anomalies in some skarn deposits. Magnetic anomalies.

Examples: Mason Valley, USNV (87) *.
Victoria, USNV (88) *, **.
Copper Canyon, USNV (89) *, **
Carr Fork, USUT (90) *

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

** Additional information available in Lowe, Raney, and Norberg, BOM IC 9035. pp. 178, 78, respectively.



Redrawn from Cox and Singer (1986)

FIGURE 8.– Schematic cross-section of Cu skarn deposit

Figure 8. Schematic Cross-Section of Cu Skarn Deposit

W-MO SKARN DEPOSITS 1/

DESCRIPTION: Scheelite in calc-silicate contact metasomatic rocks.

PRIMARY REFERENCE(S): (91), (92).

GEOLOGIC ENVIRONMENT

Rock Type: Tonalite, granodiorite, quartz monzonite; limestone.

Textures: Granitic, granoblastic.

Age Range: Mainly Mesozoic but may be any age.

Depositional Environment: Contacts and roof pendants of batholith and thermal aureoles of apical zones of stocks that intrude carbonate rocks.

Tectonic Setting(s): Orogenic belts. Syn-late orogenic.

Associated Deposit Types: Sn-W skarns, Zn skarns.

DE IT DESCRIPTION

Mineralogy: Scheelite ± molybdenite ± pyrrhotite ± sphalerite ± chalcopyrite ± bornite ± arsenopyrite ± magnetite ± traces of wolframite, fluorite, cassiterite, and native Bi.

Alteration: Diopside-hedenbergite ± grossular-andradite. Late stage spessartine + almandine. Outer barren wollastonite zone. Inner zone of massive quartz may be present.

Ore Controls: Carbonate rocks in thermal aureoles of intrusions.

Geochemical Signature: W, Mo, Zn, Cu, Sn, Bi, Be, As.

Examples: Pine Creek, USCA, (93) *.
MacTung, CNBC, (94)
Strawberry, USCA, (95) *.

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

1/Modified from Cox, D. P. Descriptive Model of W Skarn Deposits. Paper in Mineral Deposit Models, D. P. Cox and D. A. Singer, eds. USGS Bull. 1693, 1986, p. 55.

FLUORIDE-RELATED BERYLLIUM DEPOSITS 1/

DESCRIPTION: Beryllium minerals in non-pegmatitic rocks.

PRIMARY REFERENCE(S): (96).

GEOLOGIC ENVIRONMENT

Rock Types: Carbonate rocks or calcareous clastic or volcano-clastic rocks most favorable. Silicic volcanic rocks, especially rhyolite rich in Be, K, Si, and F. Also in hypothermal veins in ordinary (non-carbonate) schist, gneiss, and amphibolite at highly-productive Boomer mine in Colorado.

Depositional Environment: Hypothermal and epithermal veins; replacement deposits; contact metamorphic deposits (beryllian tactites).

Tectonic Setting(s): Regions characterized by high-angle faults--most commonly block-faulted areas like Basin and Range; caldera ring fractures.

DEPOSIT DESCRIPTION

Mineralogy: Primary minerals; beryl, bertrandite, phenakite, chrysoberyl, helvite, barylite. Associated minerals; fluorite, topaz, quartz, magnetite, hematite, maghemite, siderite, minor pyrite, bismuthinite, wolframite, scheelite, cassiterite, rare base metal sulfides.

Alteration: Beryllian tactites; Ca, Fe, and Mg silicates, fluorite common, less common magnetite. Hypothermal and epithermal veins; K-feldspar, quartz-white mica greisen, bertrandite-mica aggregates, euclase widespread in hypothermal deposits, kaolinite and smectite in epithermal deposits.

Weathering: Beryllium minerals resistant to weathering, sometimes Be mineral crystals found loose in disaggregated vein material.

Geochemical Signature: Be, F, Fe, W, Sn, topaz common.

Examples: Boomer, USCO, (97) *
York Mountains Deposits, USAK, (98) *

Additional Reference: (99)

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

1/ Modified from Griffitts, W. R. Characteristics of Mineral Deposits. R. L. Erickson, ed. USGS Open-file Rep. 82-795, 1982, pp. 62-66.

SPOR MOUNTAIN BE-F-U 1/

DESCRIPTION: Be-F-U minerals in tuffs, tuffaceous breccias, and associated fault breccias. The Be-F-U deposits at Spor Mountain are the only ones of this type of economical value, but the existence of numerous minor occurrences elsewhere indicates that there is a class of ore deposits that resembles those at Spor Mountain and that additional economic deposits will be found (100).

PRIMARY REFERENCE(S): (100)

GEOLOGIC ENVIRONMENT

Rock Types: Tuffs, tuffaceous breccias, and associated fault breccias interlayered with volcanic dome-and-flow complexes of high-silica, high-fluorine, commonly topaz-bearing rhyolite; carbonate rocks are present in basement beneath the rhyolite.

Tectonic Setting(s): Regions characterized by high-angle faults--most commonly block-faulted areas like Basin and Range; caldera ring fractures.

D IT DESCRIPTION

Mineralogy: Bertrandite, fluorite, secondary yellow uranium minerals, Mn oxides, topaz.

Alteration: Extensive argillic (smectite) alteration displaying distinctive "popcorn" texture.

Geochemical Signature: Be, F, Li, Cs, Mn, Nb, Y, U, Th, topaz common. Mo, Sn, and W may be anomalous.

Examples: Spor Mountain, USUT, (100) *.

Additional References: (101), (102), (103), (104), (105).

* Additional non-proprietary information available through BOM Mineral Industry Location System (MILS).

1/ Modified from Lindsey, D. A. and D. R. Shawe. Characteristics of Mineral Deposits, R. L. Erickson, ed. USGS Open-file Rep. 82-795, 1982, pp. 67-69.

2.1.5 Exploration Methods

Section 2.1.5 discusses generally accepted methods and practices for locating and assessing natural resources at Yucca Mountain by describing standard assessment methodologies employed in the minerals industry and in government. It also addresses the rationale for selecting a particular methodology or hybrid methodology and includes a description of uncertainties associated with those methodologies.

Geologic/geochemical/geophysical activities planned for purposes other than resource assessment may provide valuable information. Every effort should be made to integrate data gained through these investigations, along with pre-existing data, into the resource assessment program.

2.1.5.1 Geological Mapping

The site at Yucca Mountain and analog areas should be the object of a program of detailed geologic mapping on as large a scale as is practical using photogrammetry [air photos, environmental resource technology satellite (ERTS) imagery, Thematic Mapper, SPOT (Systeme Probatoire d'Observation de la Terre) imagery and simulation data, etc.], topographic and geological maps, cross sections, and other data acquired in background research or provided by other site characterization activities. Field and background data will be employed to produce detailed composite geological maps on which rock formations, geologic structure, faults, mineral trends, bed or formation attitudes, and other germane data are plotted. Mapping results are analyzed and interpreted to produce structural analyses, cross sections, stratigraphic columns, and other map-related products for further study, and to identify target areas for subsequent sampling, drilling, or geochemical/geophysical surveys.

2.1.5.2 Sampling Methods

Sampling is a systematic process of obtaining a representative unit of ore, rock, soil, gas, fluid, faunal or floral parts, or other material for the purpose of analysis. Sampling is conducted as part of an exploration program to locate and determine the quantity and/or quality of a potential resource. An important use of sample analyses is in the construction of suites of elements for the various rock types that occur or postulated to occur at the site. Suites of elements should be constructed for silicic tuffs, skarns, carbonate and other sedimentary rocks, and for plutonic rocks.

Samples may be obtained from rock outcrops; stream or wash sediments; fan, playa, or other deposits; stream, spring, geothermal, mine, or well waters; soil; air; drill cores, cuttings, or sludges; flora; fauna; mines; mine dumps, tailings, or ore piles; processing plant dumps, tailings, or slag; and exploration pits, trenches, and adits, among others. Each sample should be suitably containerized and clearly marked with sampler's name and project, sample location, date, type of analysis desired, and other pertinent information.

The most important or widely used sample types include, but are not limited to those presented in table 1. Methodologies employed in obtaining representative samples are discussed in detail in references listed in Section 6.3.

The nature, composition, and percentage of special constituents of samples collected in the field may be determined by various physical, atomic, or chemical means that include, but are not limited to, those methods presented in table 2.

TABLE 1. Common Surface and Subsurface Sample Types - Advantages, Disadvantages, and Applications

Sample type	Advantages	Disadvantages	Applications
Channel	Provides reliable information for tonnage and grade calculations	Difficult to collect in hard rock; costly in terms of time required; bulky	In mineral exploration employed to determine tonnage and grade; limited applications in hydrocarbon exploration
Chip	May be considered quantitative for tonnage and grade calculations; random samples may be considered qualitative for homogeneous bodies; less bulk than channel samples	Less reliable than channel samples	Employed in sampling hard rocks in mineral exploration; limited use in hydrocarbon exploration
Grab	Provides information pertaining to presence of economic minerals; overall composition, maximum grades possible for mineralized zones	Cannot be used for tonnage/grade calculations	Used in mineralogic, petrographic, or chemical analysis; character samples
Bulk	Provides metallurgical information from large volume of material	Costly; large volumes (up to several tons) required	Used to determine metallurgical properties of material; information gathered used to design beneficiation plant
Soil	Provides geochemical data pertaining to minerals or elements that may occur anomalously in the underlying rock	Requires large number of samples taken on a grid or lines; time-consuming	Normally employed as a follow-up survey when geochemical or geophysical anomaly encountered; limited applications in hydrocarbon exploration
Sediment	Provides information pertaining to minerals, elements, hydrocarbons within a drainage or catchment area; useful in placer deposit identification	Requires large number of samples; time-consuming	May be employed to calculate tonnage and grade of placer deposits; to gather mineralogical or chemical data in a drainage or catchment area
Drill	Depending on type of drilling method employed, provides information pertaining to subsurface lithology, mineralogy, structure, etc.	Costly, time consuming; may be unable to drill in rough terrain	Employed to gather subsurface data in mineral and hydrocarbon exploration; normally used after one or more of the above methods has shown positive results

TABLE 1 Sampling methods

TABLE 2. Comparison of Commonly Used Analytical Methods

2.1.5.3 Geochemical Exploration Methods

"Exploration geochemistry", according to Levinson (2), "also called geochemical prospecting, is the practical application of theoretical geochemical principles to mineral exploration. Its specific aim is to find new deposits of metals, nonmetals, or accumulations of crude oil and natural gas, and to locate extensions of existing deposits, by employing chemical methods. The methods used involve the systematic measurement of one or more chemical elements or compounds, which usually occur in small amounts. The measurements are made on any of several naturally occurring, easily sampled substances such as rocks, stream sediments, soils, waters, vegetation, glacial debris, or air."

Geochemical exploration is accomplished by the employment of various methods in a geochemical survey of the area under consideration. The objective of a geochemical survey is to identify anomalous concentrations of elements or compounds that may indicate the presence of a mineral deposit or hydrocarbon accumulation.

Exploration geochemical surveys are classified in two general categories: reconnaissance surveys and detailed surveys. Each classification may employ any or all of the various survey methods.

Reconnaissance surveys are conducted to evaluate a large area (from hundreds to tens of thousands of square kilometers) with the purpose of delineating possible mineralized (or hydrocarbon) areas for followup studies, and to eliminate (from future consideration) barren ground. Typically, reconnaissance surveys incorporate a low sample density, perhaps one sample per square kilometer or one sample per 100 square kilometers.

Detailed surveys are carried out on a local, much smaller scale from a few square kilometers to tens of square kilometers with an objective of locating as exactly as possible individual resource occurrences or indications of structures favorable for resource occurrence. Sample intervals in a detailed survey may be as small as 3 meters or less, especially where veins or small targets are sought.

The most widely used exploration geochemical survey methods, or types, include, but are not limited to, soil, rock, stream sediment, water, vegetation, and vapor (including soil gases and air). Samples collected may be analyzed using one or more of the procedures listed in table 2 or other procedures such as petrographic analysis and microprobe, as needed.

Soil surveys entail sampling of soil and other residual deposits to test for anomalous concentrations of elements or compounds released from the host rock by the processes of weathering and leaching.

Rock surveys (lithogeochemical or bedrock surveys) are based on the analysis of a whole rock sample (which may include, but is not limited to, petrographic, stable isotope, instrumental neutron activation analysis (INAA), and hydrothermal alteration studies) or of contained minerals or fluid inclusions 2/ within a rock sample. This type of survey has great potential for outlining favorable geochemical or metallogenic provinces and for identifying favorable host rocks. Rock surveys are almost universally incorporated in well-conceived geochemical exploration programs.

Stream sediment surveys are employed almost exclusively for reconnaissance studies in drainage basins, and if properly collected, the samples represent the best composite of materials from the catchment area upstream from the sampling site (2). Other sediments that may be present in the Yucca Mountain vicinity (terraces, fans, playas, etc.) may also be sampled.

Water or hydrogeochemical surveys are based on the collection of samples of ground or surface water for qualitative and quantitative analysis of dissolved elements or compounds. The technique is useful in the identification of dispersal trains and haloes that may be indicators of the presence of a mineral or hydrocarbon occurrence. Water surveys are particularly useful in areas where it is difficult to obtain rock, soil, or sediment samples.

Vegetation surveys fall into two general categories: (1) Geobotanical surveys that involve a visual survey of vegetation, and (2) biogeochemical surveys that consist of the collection and chemical analyses of whole plants, selected plant tissues, or humus 3/.

Geobotanical studies include the recognition of the presence or absence of particular plant species or communities that may be indicative of certain elements or compounds, or the recognition of deformed or oddly-colored plants whose characteristics are the result of deleterious or toxic effects caused by an excess of certain trace elements (2). Table 3 presents a description of visual changes in plants that may result from elevated concentrations of some trace elements in soils.

Biogeochemical exploration methods involve chemical analyses of plants or parts of plants that may have incorporated certain elements or compounds in their tissues. Trees and phreatophytes, with their deep root systems, are particularly amenable to biogeochemical analysis. Recent studies by the USGS suggest that Artemisis tridentata Nutt., a sagebrush common to the western U. S., uptakes gold and may be useful as a tool in exploration (106).

The use of vegetation surveys as a guide to mineral resources is more complex than any other geochemical method, and may require special skills in execution and interpretation. In spite of the drawbacks, this geochemical exploration method has been successfully employed in unglaciated terranes in Canada and desert terranes in the southern United States and northern Mexico (2) 4/.

2/ See Roedder (107) for detailed information pertaining to fluid inclusion studies.
3/ Biogeochemical techniques may also be applied to animal tissues.
4/ See Cannon (1952, 1960a, 1960b) in Section 6.4.

Vapor (soil gas and air) surveys have been successfully used for more than 30 years in the Soviet Union and were recently investigated by the USGS with encouraging results (see reference 13 in appendix B). The method involves collecting samples of the air or soil gases in the vicinity of suspected resource occurrences. The most common elements or compounds associated with vapor surveys are presented in table 4. Vapor surveys are complex, require skilled collection and analytical personnel, and most often the results are very difficult to reproduce.

Other methods include heavy mineral surveys, surveys of bog and muskeg materials, chemical analysis of tissues from fish or other fauna, isotope surveys, geozoological techniques (use of animals or insects in mineral prospecting) 5/, and overburden surveys.

5/ See Brooks, 1983, pp. 85-108--"Geozoology in Mineral Exploration" (Section 6.5) for a detailed discussion of the use of animals and insects in mineral exploration.

TABLE 3. Changes in Plants due to Increased Concentration of some Trace Elements

TABLE 2. Comparison of Commonly Used Analytical Methods

Name	Lower detection limit	Advantages	Disadvantages
Atomic Absorption	Generally less than 10 ppm; some elements in ppb range	Rapid, sensitive, specific, accurate, and relatively inexpensive Several elements may be determined from same solution About 40 elements applicable to exploration geochemistry Partial or total analyses possible	Accuracy suffers with high abundances Not satisfactory for some important elements such as Th, U, Nb, Ta, and W Destructive
Colorimetry	Generally less than 10 ppm for elements commonly analyzed	Inexpensive, simple, sensitive, specific, accurate, and portable Partial or total analyses possible	Only one element (or a small group) determined at one time Not suitable for high abundances Some reagents unstable Tests not available for some important metals Destructive
Emission Spectrography	a. Usually only major and minor elements detected (visual detection) b. Generally from 1-100 ppm for most elements of interest (photograph detection) c. Generally from 1-100 ppm for most elements of interest (electronic-direct reader)	Multi-element capabilities (for all instruments) Only small sample required (for all instruments)	Complex spectra Requires highly trained personnel Generally slow (except for direct reader) Sample preparation very critical and time-consuming Destructive
X-ray Fluorescence	50-200 ppm on routine basis; more sensitive with special procedures	Simple spectra Good for high abundances of elements Uses relatively large sample All elements from fluorine to uranium are practical on modern equipment Certain liquids (e.g., brines) can be analyzed directly Excellent for rapid qualitative checks Non-destructive	Sensitivities not as good as other methods for many elements Analyses slower than some other methods Analyses are relatively expensive
Chemical Analysis	100 ppm	Precise, accurate Can be used with instrumental techniques	Less sensitive and more time-consuming than instrumental analysis Usually not suitable for determination of noble metals
Fire Assay	Less than 0.005 oz/ton Au; 0.001 oz/ton platinum group metals when used in fire assay-spectrographic procedure	Can be used for all ores, concentrates, or alloys if properly performed	Normally applied to noble metals (Au, Ag, platinum group metals); time-consuming; requires special laboratory equipment

TABLE 3. Changes in Plants due to Increased Concentration of some Trace Elements [1]

Element	Character of changes
U, Th, Ra	When present in small amounts, causes acceleration of growth in plants; high concentrations lead to the appearance of deformities in vegetative shoots, dwarfism, dark-colored or blanched leaves
Fluorine (topaz greisens)	Premature yellowing and falling of leaves
B	Slow growth and ripening of seeds, dwarfism, procumbent forms; dark green leaves, deustate at edges; high concentration in the soil causes total or partial disappearance of vegetation
Mg	Reddening of stems and leaf stalks, coiling and drying of leaf edges
Cr	Yellowing of leaves, in some cases thinning of vegetation until its total disappearance
Cu	Blanching of leaves, necrosis in leaf tips, reddening of stems, appearance of procumbent, degenerating forms; in some cases, total disappearance of vegetation
Ni	Degeneration and disappearance of some forms, appearance of white spots on leaves, deformities, reduction of corrolar petals
Co	Appearance of white spots on leaves
Pb	Thinning of vegetation, appearance of suppressed forms, development of abnormal forms in flowers
Zn	Chlorosis of leaves and drying of their tips. Appearance of blanched, underdeveloped, dwarfed forms
Nb	Appearance of white deposits on the blades or leaves of some types of plants.
Be	Deformed shoots in young individuals of pines
Rare earths	Sharp increase in the size of leaves in some wood species

1/ Source: Beus and Grigorian (1975)--see Section 6.4.

TABLE 4. Vapor Indicators of Mineralized Zones

TABLE 4. Vapor Indicators of Mineralized Zones ~~or Hydrocarbon Accumulations~~

Vapor	Type of Deposit
Mercury (Hg)	Ag-Pb-Zn sulfides; U, Au, Sn-Mo ores; polymetallic (Hg-As-Sb-Bi-Cu) ores; pyrites
Sulfur dioxide (SO_2)	All sulfide deposits ~~; hydrocarbons~~
Hydrogen sulfide (H_2S)	All sulfide deposits ~~; hydrocarbons~~
Carbon dioxide, oxygen (CO_2, O_2)	All sulfide ores; Au ores ~~or hydrocarbons~~
Halogens and halides (F, Br, I)	Pb-Zn sulfides; porphyry copper deposits
Noble gases (He, Ne, Ar, Kr, Xe, Rn)	U-Ra ores; Hg sulfides; potash deposits ~~, hydrocarbons~~
Organometallics such as $(CH_3)_2HgAsH_3$ and compounds of Pb, Cu, Ag, Ni, Co, etc.	Possibly all sulfides; Au-As deposits ~~; hydrocarbons~~
~~Nitrogen compounds (N_2O, NO_2)~~	~~Nitrate deposits~~

Source: Levinson ~~(1980)~~ 1974 (2).

TABLE 5. Mean values for some important elements in major igneous and sedimentary rock types.

TABLE 5.

Mean values (ppm) for some important elements in major igneous and sedimentary rock types.

	Igneous rocks				Sedimentary rocks			
Element	Ultrabasic	Basic	Acid	Alkaline	Sandstone	Limestone	Shale	Black shale
Antimony	0·1	0·2	0·2	-	1	-	1-3	-
Arsenic	1-2·8	2	1·5	-	-	2·5	4-15	75-225
Barium	2-15	250-270	600-830	-	100-500	20-200	300-800	450-700
Beryllium	0·2	0·1-1·5	3-5	2-12	1	<1-1	1-7	1
Bismuth	0·02	0·15	0·1	-	0·3	-	0·2-1	-
Boron	5	5-10	15	9	-	9-10	10-100	-
Cadmium	0·1	0·2	0·1-0·2	0·1	-	0·1	0·2-0·3	-
Chromium	2000-3400	200-340	2-4	1	10-100	5-10	100-160	10-500
Cobalt	150-240	25-75	1-8	8	1-10	0·2-4	10-50	5-50
Copper	10-80	100-150	10-30	-	10-40	5-20	20-150	20-300
Fluorine	100	340-500	480-810	570-1000	180-200	220-330	500-940	-
Gold	0·1	0·035	0·01	-	-	-	-	-
Lanthanum	3·3	10-27	25-46	-	-	6	20-40	25-100
Lead	0·1	5-9	10-30	-	10-40	5-10	16-20	20-400
Lithium	2	10-15	30-70	28	7-29	2-20	50-60	17
Manganese	1100-1300	2200	600-965	-	-	385	670-890	-
Mercury	-	0·08-0·09	0·04-0·08	-	0·03-0·1	0·03-0·05	0·4-0·5	-
Molybdenum	0·3-0·4	1-1·4	2	-	0·1-1	0·1-1	1-3	10-300
Nickel	800-3000	50-160	2-8	2-4	2-10	3-12	20-100	20-300
Niobium	15	20	20	30-900	-	-	20	-
Silver	0·3	0·3	0·15	-	0·4	0·2	0·9	-
Tantalum	<1-1	0·5-1	3-4	1-2	-	-	2-3·5	-
Tin	0·5	1	3	-	-	-	-	-
Titanium	3000	9000	2300	-	4400	-	4300-4500	-
Tungsten	0·5	1	2	-	-	0·5	2	-
Uranium	0·001-0·03	0·6-0·8	3·5-4·8	-	-	2	3·2-4	-
Vanadium	50-140	200-250	20-25	34	10-60	2-20	50-300	50-2000
Zinc	50	90-130	40-60	-	5-20	4-25	50-300	100-1000
Zirconium	20-70	100-150	170-200	300-680	-	20	120-200	10-20

Source: Reedman (1979).

TABLE 6. Summary of the dispersion of various elements in the secondary environment and applications in geochemical exploration

TABLE 6. - Summary of the dispersion of various elements in the secondary environment and applications in exploration

ANTIMONY	
Soils:	5 ppm.
Waters:	1 ppb.
Mobility:	Low.
Uses:	Geochemical prospecting for Sb has been undertaken, but is not very important. It has been used as a pathfinder for gold and may produce coincident anomalies over some base metal deposits.
ARSENIC	
Stream sediments:	1-50 ppm.
Soils:	1-50 ppm.
Waters:	1-30 ppb.
Plant ash:	1-2 ppm, >10 ppm may indicate mineralization. Concentrations up to 1% observed in certain plants growing over mineralized zones.
Mobility:	Fairly low, readily scavenged by iron oxides.
Uses:	Has been mainly used as a pathfinder for Au and Ag vein-type deposits.
BARIUM	
Soils:	100-3000 ppm. Anomalous concentrations over barite mineralization >5000 ppm. Peaks at many percent.
Waters:	10 ppb.
Mobility:	Low.
Uses:	Has been used in geochemical prospecting for barite, but dispersion limited by low mobility.
BERYLLIUM	
Stream sediments:	<2 ppm. Values >2 ppm may delineate areas of beryl mineralization.
Soils:	<2-6 ppm. Values >10 ppm may define beryl-bearing pegmatites. Peak values >100 ppm over rich zones.
Mobility:	Low to moderate.
Uses:	Be has been used in geochemical exploration for beryl deposits. Similar anomalous values may occur over unmineralized alkaline rocks.
BISMUTH	
Soils:	<1 ppm. Values >10 ppm may define Bi mineralization.
Mobility:	Low.
Uses:	Little work has been done with geochemical prospecting for Bi. Most Bi is produced as a by-product of other ores and there are only a few very small deposits that have been worked for Bi alone. Surveys in Zambia show peak values of 200 ppm over Bi-bearing vein deposits. May also have value as a pathfinder for certain vein Au deposits.

TABLE 6. - Continued

CADMIUM

Soils: <1-1 ppm. Values over a few ppm are anomalous and may be due to mineralization containing traces of Cd.

Mobility: High--closely follows Zn.

Uses: As in the case of Bi, Cd is produced as a by-product of other ores (lead-zinc) so that there has been little work done on prospecting for Cd. It has been used as an aid in lead-zinc prospecting to distinguish between anomalies likely to be due to mineralization (Zn + Cd) from those unlikely to be due to mineralization (Zn only). Surveys in Ireland have shown that this can be misleading since very high Cd values (>200 ppm) have been found with a Zn anomaly apparently unrelated to mineralization and low Cd values (a few ppm) are associated with a strong Zn anomaly related to good mineralization.

COBALT

Stream sediments: 5-50 ppm.

Soils: 5-40 ppm. Anomalous concentrations over mineralization >100-500 ppm.

Waters: 0·2 ppb.

Plant ash: 9 ppm.

Mobility: Moderately high, but readily scavenged and held by Fe-Mn oxides.

Uses: Has been used for Co prospecting, but, since Co is generally produced as a by-product of other metals, surveys are rarely conducted for Co alone. Useful as an ancillary element in surveys for other base metals which may be accompanied by Co mineralization.

COPPER

Stream sediments: 5-80 ppm. >80 ppm may be anomalous.

Soils: 5-100 ppm. Anomalies >150 ppm may indicate mineralization. High background basic rocks can give rise to values of many hundreds of ppm.

Waters: 8 ppb. >20 ppb may be anomalous, but hydrogeochemistry rarely used for Cu owing to limited mobility.

Plant ash: 90 ppm. Values >140 ppm may be anomalous.

Mobility: High at pH's below 5·5, low at neutral or alkaline pH. Also may be adsorbed by organic matter and coprecipitated with Fe-Mn oxides, but Cu is less readily scavenged by Fe-Mn oxides than other base metals (e.g. Co, Zn, Ni).

Uses: Stream sediment and soil sampling surveys have been widely used in all parts of the world in Cu prospecting and there is a large literature on the subject. Biogeochemical methods have also been used with some success. To help distinguish anomalies due to unmineralized basic rocks from anomalies likely to result from mineralization the Co/Ni ratio has been used in soil surveys. A high Co/Ni ratio (>1) indicates that anomalous Cu values are more likely to be due to mineralization than Cu anomalies accompanied by low Co/Ni ratios.

TABLE 6. - Continued

	FLUORINE
Soils:	200-300 ppm. Anomalies over mineralization >1000 ppm with peaks at many thousands of ppm.
Waters:	50-500 ppb. Values >1000 ppb in river waters may be due to mineralization.
Mobility:	Fairly low.
Uses:	Geochemical surveys have been undertaken for fluorite in various parts of the world using soils, groundwaters and river waters as sampling media. F now commonly used as a direct indicator, but Pb and/or Zn generally used as pathfinders before advent of specific-ion electrode analytical technique.
	GOLD
Soils:	<10-50 ppb. Values >100 ppb may indicate mineralization.
Waters:	0·002 ppb.
Mobility:	Generally extremely low under neutral, alkaline and reducing conditions, but may be moderately high with formation of complex ions under oxidizing conditions in both acid and alkaline environments.
Uses:	A number of soil surveys using Au as a direct indicator of Au mineralization have been conducted in various parts of the world with considerable success. Before cheap and sensitive AAS analytical method for Au was available, the use of pathfinders such as As and Sb was common, but not used so widely nowadays.
	HELIUM
Atmosphere:	5·2 ppm by volume.
Waters:	$4{\cdot}76 \times 10^{-8}$ cm^3 STP/g.
Mobility:	Extremely high as an inert gas dissolved in waters and diffusing through overburden and fractures in rock.
Uses:	Pathfinder for U and hydrocarbons using both soil gas and He dissolved in groundwaters.
	LEAD
Stream sediments:	5-50 ppm.
Soils:	5-80 ppm. Values >100 ppm may indicate Pb mineralization.
Waters:	3 ppb.
Plant ash:	70 ppm.
Mobility:	Low.
Uses:	Geochemical surveys for Pb using soils and stream sediments have been successfully employed all over the world. Biogeochemical and hydrogeochemical surveys have also been used with a certain amount of success. Owing to the low mobility of Pb, Zn is often a better indicator of Pb or Pb-Zn mineralization. Pb has been used as a pathfinder for barite and fluorite mineralization.

TABLE 6. - Continued

LITHIUM	
Stream sediments:	10-40 ppm.
Soils:	5-200 ppm.
Waters:	3 ppb.
Mobility:	Moderate to high.
Uses:	Stream sediment and soil surveys have been used in regional reconnaissance prospecting for various pegmatite deposits since complex Li-bearing pegmatites generally contain minerals of interest such as beryl, cassiterite, pollucite, columbite, in addition to the Li minerals which are of potential economic value. Rarely used.
MANGANESE	
Stream sediments:	100-5000 ppm.
Soils:	200-3000 ppm.
Waters:	<1-300 ppb.
Plant ash:	4800 ppm.
Mobility:	Usually very low, may become mobile under acid, reducing conditions as divalent ion.
Uses:	Soil and vegetation surveys have been conducted in prospecting for Mn ores, but Mn is more commonly used as an ancillary element in geochemical surveys to aid interpretation.
MERCURY	
Stream sediments:	<10-100 ppb.
Soils:	<10-300 ppb. Values >50 ppb may indicate mineralization such as Pb-Zn-Ag ores.
Soil gas:	10-100 ng/m^3, >200 ng/m^3 over base metal ores.
Waters:	0·01-0·05 ppb. Values >0·1 ppb may be due to Hg mineralization. Hg in waters readily adsorbed by solids, so waters are not good prospecting medium.
Mobility:	Generally low, but high as vapor phase.
Uses:	Has been used successfully in prospecting for Hg ores using stream sediments and waters and soils. Also used as a pathfinder of base metal ores. The vapor phase which can be detected in very small amounts in soil gas or the atmosphere has potential as a pathfinder of many ores. However, this is only true if Hg is present in elemental state. Many ores which contain Hg in sulphides may not release any Hg vapor unless undergoing weathering.

TABLE 6. - Continued

MOLYBDENUM

Stream sediments:	<1-5 ppm. >10 ppm may indicate Mo mineralization.
Soils:	<1-5 ppm. >10 ppm may indicate Mo mineralization.
Waters:	<1-3 ppb.
Plant ash:	13 ppm. Very high Mo concentrations (>1%) have been found in the ash of certain plants growing over Mo deposits.
Mobility:	Generally high, but is low under acid and reducing conditions when it is readily adsorbed by iron oxides and clay minerals.
Uses:	Stream sediment, soil and vegetation surveys have all been successfully employed in prospecting for Mo deposits. Mo is also used as a pathfinder for porphyry Cu deposits.

NIOBIUM

Stream sediments:	5-200 ppm. Values >200 ppm may indicate Nb-bearing minerals.
Soils:	5-200 ppm. Values >200 ppm may indicate Nb-bearing minerals.
Mobility:	Low.
Uses:	Both stream sediment and soil surveys have been successfully employed to locate pyrochlore-bearing carbonatites and columbite-bearing pegmatites. Unmineralized or poorly mineralized alkaline rocks may give high values in stream sediments and soils.

PHOSPHORUS

Stream sediments:	100-3000 ppm.
Soils:	100-3000 ppm. Values >5000 ppm may indicate phosphate-rich rocks.
Mobility:	Despite the fact that P is essential to life and is taken up by plants from soils, P generally occurs only in sparingly soluble compounds and overall mobility is low.
Uses:	Geochemical prospecting for P has only been used rarely, but it works extremely well in locating phosphate-rich rocks.

RADIUM

Stream sediments:	Measured in terms of radioactivity, usually picocuries/gram (pCi/g). 0·2 pCi/g. Values >1·0 pCi/g may indicate U mineralization.
Mobility:	Fairly low, adsorbed by organic matter.
Uses:	Can be used as a pathfinder for U in stream sediments and soils.

TABLE 6. - Continued

RADON	
Soil gas:	Measured by α counts. Over U mineralization values may be several hundred α counts/min with short measuring time of radon emanometer.
Waters:	Measured in terms of radioactivity, usually picocuries/litre (pCi/litre). 10-30 pCi/litre. Values >100 pCi/litre may be due to U mineralization.
Mobility:	Extremely high as an inert gas dissolved in waters and diffusing through overburden and fractures in rock.
Uses:	Rn in soil gas and waters is widely used as a pathfinder for U mineralization. Extensive dispersion haloes cannot form owing to the short half-life.

RARE EARTHS

Of the rare earths (RE) Ce, La and Y have been used in geochemistry most commonly and some figures for La (pathfinder of cerian sub-group) and Y (representative of yttrium sub-group) are given.

Stream sediments:	20-500 ppm La.
Soils:	20-1000 ppm La. Values several thousand ppm+ may indicate RE mineralization. <10-100 ppm Y.
Plant ash:	16 ppm (total RE).
Mobility:	Moderately low.
Uses:	La has been used successfully in stream sediment and soil surveys for locating carbonatites with which RE minerals may be associated. RE elements may also occur replacing Ca in minerals such as apatite and perovskite and may result in soil values similar to those due to the presence of discrete RE minerals such as monazite.

SILVER	
Soils:	<0·1-1 ppm. Values >0·5 ppm may indicate mineralization.
Waters:	0·01-0·7 ppb.
Mobility:	Fairly low.
Uses:	Has been used in prospecting for Ag and Ag-Au deposits. Sometimes also a useful ancillary element for surveys for complex ores which are accompanied by significant Ag contents.

TIN	
Stream sediments:	<5-10 ppm. Values >20 ppm may indicate mineralized areas.
Soils:	<5-20 ppm. Values >50 ppm may indicate mineralization.
Mobility:	Low.
Uses:	Stream sediment and soil surveys have been successfully employed in Sn prospecting in various parts of the world. Owing to the ease of identifying cassiterite in heavy mineral concentrates, however, traditional prospecting methods are often better than geochemical methods if Sn is present in the coarser size fractions.

TABLE 6. - Continued

	TITANIUM
Stream sediments:	500-10,000 ppm.
Soils:	500-10,000 ppm.
Waters:	3 ppb.
Mobility:	Low.
Uses:	Owing to ease of identifying ilmenite and rutile in heavy mineral concentrates, geochemical prospecting for Ti has hardly ever been undertaken. Often used as an ancillary element in regional surveys where it often has considerable value for delineating different rock types.
	TUNGSTEN
Stream sediments:	<2-10 ppm. Values >10 ppm may indicate mineralized areas.
Soils:	<2-20 ppm. Values >20 ppm may indicate mineralization and values >200 ppm observed over main ore zones.
Mobility:	Low to moderate.
Uses:	Stream sediment and soil surveys have been successfully employed in various parts of the world in prospecting for tungsten deposits.
	URANIUM
Stream sediments:	<1-5 ppm. Values >5 ppm may be due to mineralization.
Soils:	<1-10 ppm. Values >10 ppm may be due to mineralization.
Waters:	<1-1 ppb. Values >2 ppb may indicate mineralization.
Plant ash:	0·6 ppm.
Mobility:	Extremely high, though readily held by organic matter.
Uses:	Stream sediment, soil, vegetation and water surveys have been successfully employed in uranium prospecting.
	VANADIUM
Soils:	20-500 ppm.
Waters:	<1 ppb.
Plant ash:	22 ppm.
Mobility:	Low.
Uses:	Little use has been made of V in geochemical prospecting, though it is sometimes used as an ancillary element in regional surveys. Can be used to indicate V-rich sulphide deposits.
	ZINC
Stream sediments:	10-200 ppm. Values >200 ppm may indicate mineralization.
Soils:	10-300 ppm. Values >300 ppm may indicate mineralization, but residual anomalies over good mineralization generally >1000 ppm.
Waters:	1-20 ppb. Values >20 ppb may indicate mineralization.
Plant ash:	1400 ppm.
Mobility:	High, but adsorbed by organic matter and readily scavenged by Mn oxides.
Uses:	Zn has been widely employed in stream sediment, soil, vegetation and water surveys all over the world with considerable success in prospecting for zinc, lead-zinc and complex base metal ores.

TABLE 6. - Continued

	ZIRCONIUM
Soils:	50-600 ppm. Values >1000 ppm indicate possible interesting concentrations of zirconiferous minerals.
Mobility:	Extremely low.
Uses:	Zr has been little used in geochemical prospecting. Owing to irregular and widespread distribution of zircon in igneous rocks and as a detrital mineral, soil values often show wide fluctuations.

Source: Modified from Reedman (1979.)

TABLE 7. Commonly-used pathfinder elements.

TABLE 7. - Examples of pathfinder elements used to detect mineralization.

Pathfinder Element(s)	Type of Deposit
As	Au, Ag; vein-type
As	Au-Ag-Cu-Co-Zn; complex sulfide ores
B	W-Be-Zn-Mo-Cu-Pb; skarns
B	Sn-W-Be; veins or greisens
Hg	Pb-Zn-Ag; complex sulfide deposits
Mo	W-Sn; contact metamorphic deposits
Mn	Ba-Ag; vein deposits; porphyry copper
Se, V, Mo	U; sandstone-type
Cu, Bi, As, Co, Mo, Ni	U; vein-type
Mo, Te, Au	porphyry copper
Pd, Cr, Cu, Ni, Co	platinum in ultramafic rocks
Zn	Ag-Pb-Zn; sulfide deposits in general
Zn, Cu	Cu-Pb-Zn; sulfide deposits in general
Rn	U; all types of occurrences
SO_4	sulfide deposits of all types

Note: In most cases, several types of material (e.g., rock, soil, sediment, water and vegetation) can be sampled. In some cases, such as radon, only water and soil gas are practical. In the case of sulfate, only water is practical.

Source: Modified from Levinson (~~1974~~ ~~1980~~, (2).
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Table 8 summarizes the most important or widely used exploration geochemical survey types and advantages, disadvantages, and applications associated with their use. The selection of a particular geochemical exploration type (and associated executionary method or methods) may include, but is not limited to, those listed in table 8. Detailed discussions of these and other methods are presented in cited references listed in Section 2.5; additional references are presented in Section 6.4.

Table 9 presents the types of geochemical exploration methods that may be of value in assessing the resource potential of Yucca Mountain in which each method is keyed to one or more of the descriptive deposit models presented in the preceding section.

The success of geochemical methods in mineral exploration is often difficult to evaluate. In most cases, more than one geochemical method has been employed to locate a particular mineral deposit, and it is not always possible to assign credit to a single method. Further, the techniques or methods employed in a successful exploration program are not always reported by the company or institution sponsoring the program, although numerous discoveries can be credited to geochemical exploration.

Le· ·son (2), for example, cites the following deposits that were di· ·vered primarily through the use of geochemical exploration methods: Ca··in-type gold deposits, Nevada; the auriferous Muruntau deposit in Uzbec, U.S.S.R.; the Beltana and Aroona willemite deposits, South Australia; the McArthur River and Lady Loretta lead-zinc deposits, Australia; the Husky lead-zinc-silver deposit, Keno Hill, Yukon; the Island Copper porphyry deposit, British Columbia; and the Sam Goosley copper-silver-molybdenum deposit in British Columbia.

An overview of case histories and papers pertaining to successful geochemical exploration programs was published in 1971 by the Canadian Institute of Mining and Metallurgy (109, pp. 53-285). The case histories and papers present detailed accounts of the geochemical exploration methods, analytical techniques, and other germane information on the discovery of a wide range of metallic and nonmetallic ore bodies worldwide. References to case histories and papers from the above report and other sources are presented in appendix B.

Basically, exploration geochemistry is a simple technique, but interpretation may not be so easy as there are numerous variables and few rules that can be applied universally (108). Therefore, the selection of particular methods or combination of methods, and the uncertainties associated with their use, is largely a function of personnel expertise (application of method(s), interpretation, analysis, etc.), site and regional geology, resource commodity sought, topography, climate, and time an· ·unding constraints.

TABLE 8. Comparison of Major Geochemical Methods

(8)

TABLE 6. Comparison of Major Geochemical Exploration Methods (Surveys)

Survey Type	Advantages	Disadvantages	Applications	Scope of survey	Sampling Method(s)	Analysis Types
Soil	Highly reliable, fewer variables and limitations than most methods	Large pct of nonsignificant anomalies encountered	Important in mineral exploration; ~~limited use for hydrocarbons~~	Local, detailed; some limited use in reconnaissance surveys; generally used as follow-up to drainage basin survey	Taken on grid system; 15-61 m spacing for detail surveys, 301-1500 m for reconnaissance surveys	Primarily chemical or instrumental
Rock (whole rock; mineral and/or fluid inclusions)	High potential for outlining favorable metallogenic provinces and host rocks	Requires numerous rock outcrops; interpretation often difficult due to large number of rock types and changes in rock texture over short distances	Widely used in mineral exploration; ~~limited hydrocarbon applications~~	Local, detailed; limited regional application	Chip, channel, core, bulk, grab, and other methods; may be obtained from surface or subsurface	Petrographic, whole rock, mineral or fluid inclusions, fire assay, chemical, instrumental
Stream sediment	Samples may represent best composite of materials from catchment area upstream from sampling site	Best results from streams, lakes, and swamps; not applicable to some regions; not site specific	Important in mineral exploration; ~~limited application for shallow hydrocarbon exploration~~	Reconnaissance or detailed surveys	50 g samples of 80 mesh usually preferred for clay, silt, black sands; larger fractions may be required, however	Primarily chemical or instrumental
Water	Very useful in wooded or mountain areas; accurate field determinations possible with equipment	Metal concentration varies with rainfall; ranges of concentration low (ppb); relatively large samples required; not site specific	Applied to mineral and geothermal exploration; ~~limited hydrocarbon applications~~	Reconnaissance or detailed surveys	100 ml samples in well-cleaned, hard polyethylene bottles; sampling methods variable, depends on location, type sample required	Primarily chemical or instrumental
Vegetation	Useful in areas with few outcrops and light to heavy vegetation; humus provides a more uniform sampling media	Highly complex, requires considerable skill in execution and interpretation	Applied to mineral exploration; ~~limited hydrocarbon applications~~	Reconnaissance or detailed surveys	Various, depends on type vegetation, areal extent of survey, expertise of personnel	Primarily chemical or instrumental
Vapor (air or soil)	May be conducted from aircraft; sensitive to many elements and compounds	Soil or air contamination from nearby industrial urban environment requires special systems for collection and interpretation	Applied to mineral exploration; ~~minor use in hydrocarbon exploration~~	Reconnaissance or detailed surveys	Methods depend on type survey (air or soil gas), taken on ground or from aircraft, type of gas or vapor involved, expertise of personnel	Primarily chemical or instrumental
Other 1/						

1/ Includes heavy mineral, bog material, fish and other fauna, isotopic, and overburden surveys.

Source: Levinson (1980) (2).

TABLE 9. Geochemical Exploration Methods Applied to Selected Deposit Models

TABLE 9. - Geochemical exploration methods applied to selected deposit models.

Deposit type	Soil[1]	Rock[2]	Stream sed.[3]	Veg.[4]	Geochemical Signature[5]
Creede epithermal veins	X	X	X	X	High in system Au + As + Sb + Hg, Au + Ag + Pb + Zn + Cu, Ag + Pb + Zn, Cu + Pb + Zn. Base metals generally higher in deposits with Ag. W + Bi may be present.
Hot-spring Au-Ag	X	X	X	X	Au + As + Sb + Hg + Tl higher in system, increasing Ag with depth, decreasing As + Sb + Tl + Hg with depth. Locally, NH_4, W.
Hot-spring Hg	X	X	X	X	Hg + As + Sb ± Au.
Replacement Sn	X	X			Sn, As, Cu, B, W, F, Li, Pb, Zn, Rb.
Epithermal quartz-alunite-Au	X	X		X	Higher in system Au + As + Cu, increasing base metals at depth. Also Te and (at El Indio) W.
Porphyry Mo, low-F	X	X			Zoning outward and upward from Mo + Cu ± W to Cu + Au to Zn + Pb, + Au + Ag. F may be present but in amounts less than 1,000 ppm.
Epithermal Mn	X	X			Mn, Fe, P (Pb, Ag, Au, Cu). At Talamantes, W.
Carbonate-hosted Au-Ag	X	X		X	Au + As + Hg + W ± Mo, As + Hg + Sb + Tl ± F (this stage superimposed on preceding). NH_3 important in some deposits.

TABLE 9. - Continued

Deposit type	Soil[1]	Rock[2]	Stream sed.[3]	Veg.[4]	Geochemical Signature[5]
Simple Sb	X	X			Sb $\pm$ Fe $\pm$ As $\pm$ Au $\pm$ Ag, Hg $\pm$ W $\pm$ Pb $\pm$ Zn may be useful in specific cases.
Gold on flat faults	X	X		X	Au, Cu, Fe, F, Ba. Very low-level anomalies in Ag, As, Hg, and W.
Bedded barite	X	X			Ba, where peripheral to sediment-hosted Zn-Pb, may have lateral (Cu), Pb, Zn, Ba zoning or regional Mn haloes. High organic C content.
Replacement Mn	X	X			Mn, Fe, P, Cu, Ag, Au, Pb, Zn.
Polymetallic replacement	X	X		X	On a district-wide basis, ore deposits commonly are zoned outward from a Cu-rich central area through a wide Pb-Ag zone, to a Zn and Mn-rich fringe. Locally Au, As, Sb, and Bi. Jasperoid related to ore can often be recognized by high Ba and trace Ag content.
Fe skarn	X	X		X	Fe, Cu, Co, Au, possibly Sn. Strong mag. anomaly.
Zn-Pb skarn	X	X		X	Zn, Pb, Mn, Cu, Co, Au, Ag, As, W, Sn, F, possibly Be. Mag. anomalies.

TABLE __. - Continued

Deposit type	Soil[1]	Rock[2]	Stream sed.[3]	Veg.[4]	Geochemical Signature[5]
Cu skarn	X	X		X	Rock analysis may show Cu-Au-Ag-rich inner zones grading outward to Au-Ag zones with high Au:Ag ratio and outer Pb-Zn-Ag zone. Co-As-Sb-Bi may form anomalies in some skarn deposits. Magnetic anomalies.
W-Mo skarn	X	X		X	W, Mo, Zn, Sn, Bi, Be, As.

~~Source:~~ Cox and Singer (1986).
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~~FOOTNOTES FOR GEOCHEMICAL TABLE~~

1. May not be particularly effective for deeply-buried deposits. Pathfinder elements may be detected.

2. Includes whole rock, mineral inclusions, fluid inclusions, etc. on rock outcrops, and core, chips, etc. from drilling.

3. No perennial streams on site; samples from washes and canyons may be barren of fine fractions.

4. Water sampling restricted to groundwater. Samples may detect anomalous concentrations of elements but may be difficult to determine source.

5. Could be useful in Au exploration, especially if Artemesis tridentata Nutt. (a species of sagebrush that absorbs Au) is present on or around site. See Erdman, et. al. USGS OFR 88-236, 1988.

Radiometric methods may be employed to detect radioactive elements in tuffs or ground water. Also, vapor surveys for radioactive elements and Hg may be useful.

2.1.5.4 Geophysical Exploration Methods

Geophysical exploration methods involve the application of geophysical principles to the search for mineral deposits (as well as hydrocarbon accumulations and geothermal occurrences), and may be divided into the following general methods:

1. Seismic
2. Gravity
3. Magnetic
4. Electrical and electromagnetic
5. Radiometric
6. Well logging (borehole geophysical methods)
7. Miscellaneous chemical, thermal, and other methods.

<u>Seismic Methods</u>

Seismic exploration methods (<u>110</u>) consist of generating seismic waves and measuring the time required for the waves to travel from the source to a series of receivers, usually disposed along a line directed towards the source. From a knowledge of traveltimes to the various receivers and the velocity of the waves, one attempts to reconstruct the paths of the seismic waves. Structural information is derived principally from paths which fall into two main categories: head-wave or refracted (seismic refraction) paths in which the principal portion of the path is along the interface between two rock layers, and reflected paths (seismic reflection) in which the wave travels downward initially and at some point is reflected back to the surface. For both types of path, the traveltimes depend upon the physical properties of the rock and the attitudes of the beds. The objective of seismic exploration is to deduce information about the physical properties of the rocks, especially about the thickness and attitudes of the beds, from the observed arrival times and (to a limited extent) from variations in amplitude and frequency.

Jones and others (<u>111</u>) report that seismic reflection profiling at Yucca Mountain has been less than satisfactory and provide possible explanations for the poor record. For a discussion of the problems pertaining to reflection profiling at the site, see Jones, et. al. (<u>111</u>, pp. 112-116). Catchings and Mooney (<u>112</u>), however, report successful seismic penetration of 5 to 12 km of Columbia River Basalt and underlying sediments to obtain the first detailed look at the structure beneath the central Columbia Plateau. The technique used by Catchings and Mooney, "high-resolution full-wavefield seismic profiling", may be useful in determining structure, depth-to-basement, and other factors on and around the Yucca Mountain site.

<u>Gravity methods</u>

Gravity exploration methods (gravity prospecting) involve the measurement of variations in the gravitational field of the earth by ground, airborne, and underground surveys. Gravity surveys, like magnetics, radioactivity, and a few of the minor electrical techniques, are a natural source method <u>6</u>/ in which local variations in the density of rocks near the surface cause changes in the main gravity field. While primarily employed as a reconnaissance tool for hydrocarbon exploration, gravity exploration methods have recently become more popular for detailed followup of magnetic and electromagnetic anomalies detected in integrated base-metal surveys in mineral exploration.

Magnetic methods

Magnetic exploration methods have much in common with gravitation methods in that they both seek anomalies caused by changes in the physical properties of subsurface rocks, require fundamentally similar interpretation techniques (although interpretation of magnetic data is more complex), and are used mainly for reconnaissance (110, 113).

Whereas gravity methods attempt to locate mineral deposits by the measurement of small changes in the earth's gravitational field, magnetic methods measure variations in the earth's magnetic field caused by the presence of magnetic constituents in an ore body. Further, where maps produced on the basis of gravitational data show mainly regional effects, the magnetic map appears to be a multitude of residual anomalies which are the result of large variations in the fraction of magnetic minerals contained in the near-surface rocks (110, 113).

Electrical and electromagnetic methods

Electrical exploration methods (electrical or geoelectrical prospecting) involve the detection of surface effects produced by electric current flow in the ground (110) and represent a greater variety of techniques available than other geophysical methods. It is the enormous variation in electrical conductivity found in different rocks and minerals that makes these methods important exploration tools. Electrical methods are almost entirely confined to mineral exploration as they proved effective only for shallow exploration and seldom provide data on subsurface features deeper than 305 to 460 meters (113, PP. 339). Telluric and magnetotelluric methods, however, are routinely used in hydrocarbon exploration as the associated fields and currents are able to penetrate to the depths where oil and gas are normally found (113). These methods may of value in mineral exploration of the Paleozoic rocks underlying Yucca Mountain.

Radiometric method

The radiometric method is used to locate mineral deposits that contain radioactive elements or compounds. Of the 20 or more naturally occurring elements known to be radioactive, only uranium, thorium, and an isotope of

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Natural source methods do not require the introduction of artificial energy sources such as explosions or vibrations as in seismic methods, or currents, potentials, and fields as in several of the electrical methods. Major electrical exploration methods include self-potential, telluric currents and magnetotellurics (MT), audio-frequency magnetic fields (AFMAG), resistivity, equipotential point and line and mise-a-la-masse, electromagnetic (EM), and induced polarization (IP).

potassium are of importance in exploration (110). One other element, rubidium, is useful for determining the age of rocks. The radiometric method is not as widely used as other geophysical techniques.

These and other geophysical exploration methods (and applications) are discussed in detail in Telford and others (110), Dobrin (113), Parasnis (114), Eve and Keys (115), and Sheriff (116); additional references are presented in Section 6.4. Case histories and papers pertaining to mineral deposits discovered primarily by the use of geophysical exploration methods are presented in appendix B. The most important or widely used methods and some of the advantages and disadvantages associated with their use are summarized in table 10.

Surveys using aircraft carrying magnetic, electromagnetic, and other devices are the most rapid method of finding geophysical anomalies. Such areal surveys are also the most inexpensive methods of covering large areas and hence are frequently used for reconnaissance surveys; any anomalies of interest are later investigated using more detailed aerial surveys and/or ground surveys. Seismic exploration is another technique which has been used to explore large areas, both on land and offshore, however, at considerably greater cost, both in time and money.

T 11 presents the types of geophysical exploration methods that may be of value in assessing the resource potential of Yucca Mountain. Each method is keyed to one or more of the deposit models discussed in Section 2.1.4.2. The selection of a particular method or methods of geophysical exploration may include, but is not limited to, those listed above or in table 11.

Deciding which method or methods to use on a particular area is extremely important. An effective but costly and time-consuming procedure involves trying every method imaginable and subsequently focusing on the method(s) that produce results. This "shotgun approach" may be necessary at Yucca Mountain where the total geological picture is far from clear.

According to Telford (110), "The choice of a geophysical technique or techniques to locate a certain mineral deposit depends on the nature of the mineral and the surrounding rocks. Sometimes a method may give a direct indication of the presence of the mineral being sought, for example, the magnetic method when used to find magnetic ores of iron or nickel; at other times, the method may only indicate whether the conditions are favorable to the occurrence of the mineral sought." A good example of indirect detection is in the use of seismic techniques in hydrocarbon exploration. The techniques themselves do not generally locate oil but are used as an aid to identify favorable stratigraphy and traps that may be productive of oil. Sphalerite exploration is another good example of indirect detection. Th mineral has little or no response to IP, but there can be a c lation between sphalerite and associated pyrite or galena, both of which have good IP responses. If a positive correlation exists between sphalerite and pyrite and/or galena, then IP could be a valuable tool in detecting sphalerite zones.

TABLE 10. Comparison of Major Geophysical Exploration Methods

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TABLE 6. Comparison of Major Geophysical Exploration Methods

	Seismic refraction	Seismic reflection	Gravity	Magnetic	Electrical	Radiometric
Principal applications	Reconnaissance exploration for oil Engineering geology Regional geologic studies Geothermal exploration	Detailed exploration for oil Geothermal exploration	Reconnaissance exploration for oil and minerals Regional geologic studies	Exploration for magnetic minerals Reconnaissance exploration for oil Regional geologic studies Geothermal exploration	Exploration for minerals Engineering geology Geothermal exploration	Exploration for radioactive minerals
Quantity actually measured	Time for explosion wave to return to surface after refraction by subsurface formations	Time for explosion wave to return to surface after reflection by subsurface formations	Variations in earth's gravitational field attributable to geologic structures	Variation in magnetic elements attributable to geologic structures	Natural potentials Current transmitted between electrodes, resulting potential drop Induced electric field	Natural radioactivity of earth materials
Quantity computed from measurements	Depths to refracting horizons, horizontal speeds of seismic waves	Depths to reflecting horizons, dips	Density contrasts of rocks, depths to zones of anomalous density	Susceptibility contrasts of rocks, approximate depths to zones of anomalous magnetization	Resistivities of beds, approximate depths of interfaces between beds of contrasting resistivity	Uranium content of rocks
Geologic or economic features sought by method	Folded structures	Structural oil traps of all kinds, reefs	Salt domes, structural axes, buried ridges	Basement topography, deposits of magnetic ores, dikes, and similar igneous features	Ore deposits having anomalous electrical properties, depth to bedrock, depth to ground water surface	Uranium deposits
Corrections applied to data	Weathering, elevation, "onset-to-trough" interval	Weathering, elevation, filter shift	Latitude, free-air, Bouguer, terrain	Diurnal variation, normal	NA	Background radioactivity
Size of crew (no. of men)	15 or more	11-20	5	3 (ground)	2 or 3 (ground)	1-4 (ground)
Can measurements be made from aircraft?	No	No	No	Yes	Yes	Yes
Is method used offshore?	Yes	Yes	Yes	Yes	Yes	No
Advantages	Provides data useful to identify beds and to infer bed lithology	Provides large amount of structural data	Useful in oil and mineral exploration; highly sensitive equipment	Simplicity of execution; useful in both hydrocarbon and mineral exploration; rapid, economic, and convenient 1/	Useful in mineral exploration. Can be used from aircraft or offshore	Provides information on radioactive elements
Disadvantages	Provides lower volume and less precise data than reflection; limited application in mineral exploration	Slower and more expensive than most methods; limited applications in mineral exploration	Interpretation complex; requires independent controls; data often ambiguous	Interpretation complex; magnetic effects from rocks may be influenced by small amounts of certain contained minerals; requires independent controls such as drill logs and seismic data	Limited applications in hydrocarbon exploration	Limited applications in hydrocarbon exploration

1/Allows depth to basement estimates to be made; useful in lineament studies.

TABLE 11. Geophysical Exploration Methods Applied to Selected Deposit Models

TABLE 11 IS CURRENTLY UNDER DEVELOPMENT. INFORMATION PRESENTED ON TABLE 11 WILL INCLUDE, BUT IS NOT LIMITED TO THE METHOD, CHARACTERISTIC PHYSICAL PROPERTY, MAIN CAUSES OF ANAMOLIES, DIRECT DETECTION INFORMATION, INDIRECT DETECTION INFORMATION, AND THE PARTICULAR DEPOSIT MODEL(S) TO WHICH THE METHODS APPLY. 12 GEOPHYSICAL METHODS ARE TABULATED AND APPLIED TO 19 DEPOSIT MODELS.

~~APPENDIX G NOT INCLUDED AS IT IS UNDER DEVELOPMENT.~~

able 11, in keying geophysical methods to a particular deposit type, is ntended as a guide to what methods or combination of methods may be pplicable in the Yucca Mountain area. Entries under the heading "Applications-Investigations" includes the materials (minerals, ores, etc.) nd/or information that may be directly or indirectly gained by the use of he associated method. For example, telluric methods are useful in tructural studies, and are especially useful in Basin and Range studies. ravity methods may directly detect heavy ores such as chromite, pyrite, halcopyrite, and lead, and provide indirect information on placer onfiguration, karstic cavities, basement topography, or structure.

eposit models shown on table 11 that are followed by a question mark ithin parentheses (?) indicate that the associated method is only pplicable under certain conditions (e.g., the use of IP in a suspected ot-spring gold environment may be inconclusive unless sulfides are resent). Deposit models followed by double question marks (??) indicate hat a wide range of conditions or certain rare conditions must be met if he method is to be successfully employed. Because not all geologic onditions are known for Yucca Mountain, the inclusion of these conditional ethods for a particular deposit type was deemed necessary.

eo ysical exploration methods are relatively complex (when compared to ge ical and geochemical methods) and require highly skilled personnel in he application, execution, interpretation, and analysis. Uncertainties ssociated with their use are largely a function of personnel expertise, as ell as depth-to-target, geology, lithology, mineralogy, bedding, oliation, physical properties of the rocks, resource commodity sought, opography, and time and funding constraints.

.1.5.5 Exploration Drilling

ndications of mineralization gained through the application of the xploration methods discussed above are just that--indications--unless, of ourse, the deposit is on the surface. Such indications must be confirmed y drilling; by far, the most definitive (and expensive) exploration ethod. It is normally employed to provide subsurface geological, eochemical, and geophysical information through the recovery of core, hips, and sludge that cannot be obtained through the application of any of he exploration methods discussed so far. Furthermore, boreholes provide hannels for geophysical logging and, in the event of a discovery, data for etermining a third dimension necessary for calculating deposit volumes and onnages.

reas identified in literature research and field investigations as otential drill targets may become foci of a drilling program, the extent f which is a function of several factors that include type and volume of nfc mation required, time and funding constraints, and borehole i tions as stated in 10 CFR Section 60.15(d)(1-4). Assessment of the al oic rocks underlying Yucca Mountain, because of their depth, must ely heavily on drill-hole data supplemented by other exploration methods. s many as 15-20 deep (> 6,100 meters) boreholes (including the re-entry nd deepening of UE25p#1) may be required to adequately test these rocks. y judicious borehole placement and use of inclined drilling techniques especially useful in testing for vertical features such as high-angle faults), testing of the Paleozoic and perhaps lower sections could be effected without conflict with the provisions of 10 CFR Section 60.15(d)(1-4). Boreholes drilled over the past few years on and around Yucca Mountain may still be open for deepening or for geophysical logging. Further, drill core from past activities may be available for inspection, authentication, and relogging.

Drillholes completed for site characterization studies other than resource assessment may not uniformly cover the controlled area and may not be directed at or intersect features favorable to mineralization such as high-angle fault zones, detachment zones, or veins. Further, such drillholes may not be favorably placed or extend to the depths necessary to provide sufficient information to assess the resource potential of pre-Cenozoic rocks and volcanic rocks underlying the site. A large degree of uncertainty exists that vertical drillholes would intersect vertical to near vertical faults or mineralized zones. This notwithstanding, holes drilled for other purposes may provide valuable resource information; efforts should be made to integrate any germane data into the assessment program.

In some cases, holes drilled for resource assessment may serve multiple purposes that may require the use of dry-drilling methods if the use of drilling fluids could compromise the proposed tests or interfere with other tests proposed in the site characterization program.

The most frequently used methods of exploratory drilling are diamond core, rotary, and percussion drilling. Table 12 presents the principal features of these and other drilling methods. Acker (117), Campbell (118), Cumming and Wicklund (119), and McGregor (120) provide detailed drilling methodologies, descriptions, rationales, applications, and associated costs. Additional references are presented in Section 6.3.

TABLE 12. Exploration Drilling Methods and Normal Characteristics

TABLE 12. Exploration Drilling Methods and Normal Characteristics

	Diamond drill (core)	Rotary (cuttings)	Continuous core	Downhole rotary	Downhole hammer	Percussion	Churn
Geologic information	good	poor	fair	(------------poor-------------)			
Sample volume	small	large	small	(----large---)		small	large
Minimum hole diameter	30 mm	50 mm	120 mm	300 mm	300 mm	100 mm	1500mm
Depth limit	3000 m	3000 m	100 m	3000m	300 m	100 m	1500 m
Speed	low	(-------------high----------------)					low
Wall contamination	(--variable--)		low	(-----------variable---------)			
Penetration- broken or irregular ground	poor	(-------fair--)		(-----------good-----------)			
Site; Surface or Underground	S,U	S	S	S,U	S,U	S,U	S
Collar inclination; range from vertical and down	180°	30°	0°	30°	180°	180°	0°
Deflection capability	(--moderate-)		none	high	(--------none--------)		
Deviation from course	(---high----)		(--------low--------)			high	low
Drilling medium: Liquid or Air	L	L,A	L	L,A	A	L,A	L
Cost per unit depth	high	low	mod	(-------low---------)			high
Mobilization cost	low	(---------variable---------)				low	variable
Site preparation cost	low	(---------variable---------)				low	high

2.1.5.6 Borehole Geophysical Methods

Well logging (borehole geophysical logging surveys) is a widely used geophysical technique that involves probing the earth with instruments lowered into boreholes, with their readings being recorded on the surface. Borehole surveys provide direct and indirect lithologic, stratigraphic and structural information, indications of the mineralogy and grade of ore zones, and index measurements for surface geophysical studies. The many boreholes drilled (or planned) on and around Yucca Mountain could provide channels for a number borehole geophysical studies.

Well logging has long been employed in hydrocarbon exploration. However, as Telford (<u>110</u>, p. 771) points out, well logging has not been used extensively in the search for metallic minerals for several reasons: 1. Smaller hole sizes in diamond drilling impose some limitations on equipment, 2. identification and correlation is more difficult in the complex geologic structure often associated with mineralized areas, and 3. complete recovery of core eliminates the need for logging. Telford goes on to say, however, that it is unfortunate that well logging is generally underutilized in the mineral industry in that . . . "Well logging is cheap compared to drilling", and, "A variety of geophysical logging techniques would be valuable aids to correlation and identification of mineral-associated anomalies, particularly where core is lost or difficult to identify."

Some of the geophysical exploration methods that have been applied to well logging include resistivity, induction, self-potential, induced-polarization and occasionally other electrical methods; detection of gamma-rays and neutrons in radioactivity methods; acoustic logging; and measurement of magnetic and thermal properties. Logging methods and techniques applied to metal and nonmetal deposits are discussed in detail in Dyck (<u>121</u>), Scott and Tibbets (<u>122</u>), Threadgold (<u>123</u>), Baltosser and Lawrence (<u>124</u>), and Tixier (<u>125</u>). Other germane references are listed in Section 6.4.

2.1.5.7 Geomathematical Methods

Most analytical tools used in geomathematical resource assessment have been developed as an aid to exploration with the ultimate objective of locating and ultimately extracting minerals and fuels. Low resolution techniques, such as the use of analogs and/or subjective assessment, are meant as <u>initial</u> guides for the application of other, finer techniques (such as geochemistry and geophysics). Only within the past few decades have such issues as wilderness areas and the need to determine the National mineral position created the demand for large scale, "stand alone" resource assessment methods.

Singer and Mosier in "A Review of Regional Mineral Resource Assessment Methods" (<u>126</u>) examined over 100 research papers on regional mineral resource assessment and describe 15 methods in common use. These methods, with the possible exception of the subjective techniques, are best applied to large tracts of land that consist of hundreds of thousands or millions of hectares (the Yucca Mountain site encompasses 800 hectares or less), or require a specific quantity and type of data that may not be available for the site at Yucca Mountain (e. g., production records, tonnage and grade estimates, borehole data, etc.).

Resource assessment at Yucca Mountain presents a number of problems not normally encountered in a typical regional assessment. These include: (1) relatively small target area; (2) applicability over extremely long timeframes (10,000 or more years); and (3) regulatory constraints on additional data gathering (primarily drilling). Notwithstanding their widespread development for and application to large tracts of land, and because of time and funding constraints and limited opportunities for gathering additional resource-related data, subjective probability techniques may (or may not) represent the only reasonable alternative (to an adequate, integrated, well-conceived drilling program) for evaluating the resource potential of Yucca Mountain.

Subjective methods of resource assessment allow estimates (typically expressed as a probability) to be made of an area's resource potential in a relatively short period of time. They are inexpensive (when compared to the cost of drilling, geophysical and geochemical surveys, etc.), and can be applied in many cases where physical data are limited. However, these methods rely in large part on informed judgments of an expert or group of experts and may contain an unacceptably high degree of uncertainty.

Two general categories of subjective assessment methods are in common use: simple subjective and complex subjective methods (126).

Simple subjective methods are the most widely employed by industry and government (126) and produce estimates made directly by one or more persons, based on their individual experience and knowledge. This may involve individuals separately or in concert, and one or more iterations such as those employed by Delphi or Monte Carlo methods. Shawe (127) employed simple subjective methods to assess the mineral potential of the Round Mountain, Nevada 1:24,000 quadrangle.

Complex subjective methods employ a collection of rules (inference networks) based on expert opinion on the nature and importance of geologic relationships associated with mineral deposit types. Harris (128) discusses how an inference network representing geologic processes might be used to estimate uranium endowment.

Subjective resource assessment (either simple or complex) of Yucca Mountain's resource potential may be enhanced by the use of analogs, geographic areas within the geologic setting that are analogous to the controlled area in terms of origin, size, lithology, postdepositional or postorigin history (e. g., Bare Mountain). Analogs are often identified through information gained during background research supplemented by field data. Factors to be considered in the selection of areas to be used as analogs for resource assessment and comparison to the candidate site include (129) 8/:

(1) Analogs should be within the same or similar geologic setting and should contain similar host rocks or associated lithologies as those of the

candidate area;

(2) Genesis of rocks in both analog and candidate areas should be similar;

(3) Whereas it may be advantageous for postdepositional (or postorigin, if other than sedimentary rocks) history of both analog and candidate areas to be similar (including depth of burial), it is not mandatory; and

(4) Analogs must be extensively explored.

Furthermore, each analog must be thoroughly studied through examination of existing literature supplemented by laboratory analysis or field tests as deemed necessary noting the status of relevant criteria and one or more measures of mineral density (number of deposits in area, areal extent, quantity and/or quality of mineralized material). These and other relevant data (e.g., deposit size, average grades, mineral assemblages) are compiled, and geological, geochemical, and geophysical differences and similarities, deposit numbers and sizes, and grades across the analog are noted.

Bare Mountain, west of Yucca Mountain on the western margin of the Crater Fl 'Prospector Pass Caldera Complex, fits the criteria outlined above and sh d be considered when selecting analogs.

In summary, all geomathematical resource assessment methods are, at least initially, probabilistic and subjective in nature, whether the assessment parameters are treated explicitly or implicitly. Uncertainties associated with the application of these methods can be reduced through information gathering (including borehole drilling), statistical analysis, and exploration or production, but never totally eliminated, even in extensively explored areas. Selection of one or more methods to assess Yucca Mountain's resource potential is constrained by the amount and quality of information currently available, the tools that may be used to gather additional information, and the decisions that are affected by the assessment.

Geomathematical resource assessment methods are widely used for estimating mineral potential on a regional, national, or worldwide scale. However, it may be that none of the current methods (including subjective methods) can adequately address the unique resource assessment problems encountered at Yucca Mountain.

8/ See Harbaugh, (129--NUREG/CR-3964) for a detailed discussion of analog criteria.

2.1.5.8 Map Data Compilation and Correlation of Sample Data

Data acquired in literature research and field investigations are compiled, interpreted, and subsequently employed to produce preliminary detailed geologic maps of the candidate site, controlled area, and analogs. These maps should be drafted at the largest practical scale and should include, but not be limited to, major rock units present; lithologic contacts; faults, folds, and other structural features; attitudes (strike and dip) of formations, bedding planes, and folia; and sample locations and other pertinent data. It is important that all locations at which samples were taken, or geochemical/geophysical surveys were made, are accurately plotted. Locations of boreholes, trenches, and pits should be similarly noted.

The maps should be accompanied by as many geologic cross sections as is necessary to clearly demonstrate the structure and structural relationships of the map area. Also, stratigraphic columns and other graphic representations of the data should be drafted.

Analysis of the maps and concomitant data may disclose areas that require additional field studies as well as targets for exploratory drilling.

Compton (130), Berkman (131), and Blackader (132) discuss at length the data required for inclusion on a geologic map; additional references are presented in Section 6.3. Map symbols, terms, and data collection techniques are similarly addressed.

2.1.5.9 Data Analysis

Data acquired through background research, field investigations, and the integration of germane data from other site characterization programs are compiled and analyzed to determine what, if any, resource(s) may be present at Yucca Mountain. In the event a resource is identified, additional studies would be become necessary to collect data for an economic evaluation of the resource's gross and net value as required by 10 CFR Section 60.21(c)(13). These studies include, but are not limited to:

1. Additional drill holes to delineate the orebody;

2. Additional surface/subsurface samples for tonnage and grade; calculations;

3. Additional large-scale geological mapping;

4. Geotechnical studies;

5. Studies related to siting mine, and ancillary/infrastructural facilities.

In the event that a resource is not identified, but the data suggest the existence of undiscovered resources, additional data must be gathered in order to make an estimate of resource tonnage and grade in accordance with 10 CFR Section 60.21(c)(13).

As in the course of any resource assessment, it can never be proven that Yucca Mountain does not host mineral or energy resources. It can be said, however, that . . . "No resources have been identified within the area to the depths tested." Conversely, interception of gold-bearing material is proof that some resource exists regardless of whether the resource is economic or uneconomic given current market conditions.

The following sections (2.2, 2.3, and 2.4) presents methods, techniques, and economic models that are available for evaluating identified and unidentified resources that may be extant at Yucca Mountain (and analog areas) to fulfill the requirements of 10 CFR Section 60.21(c)(13).

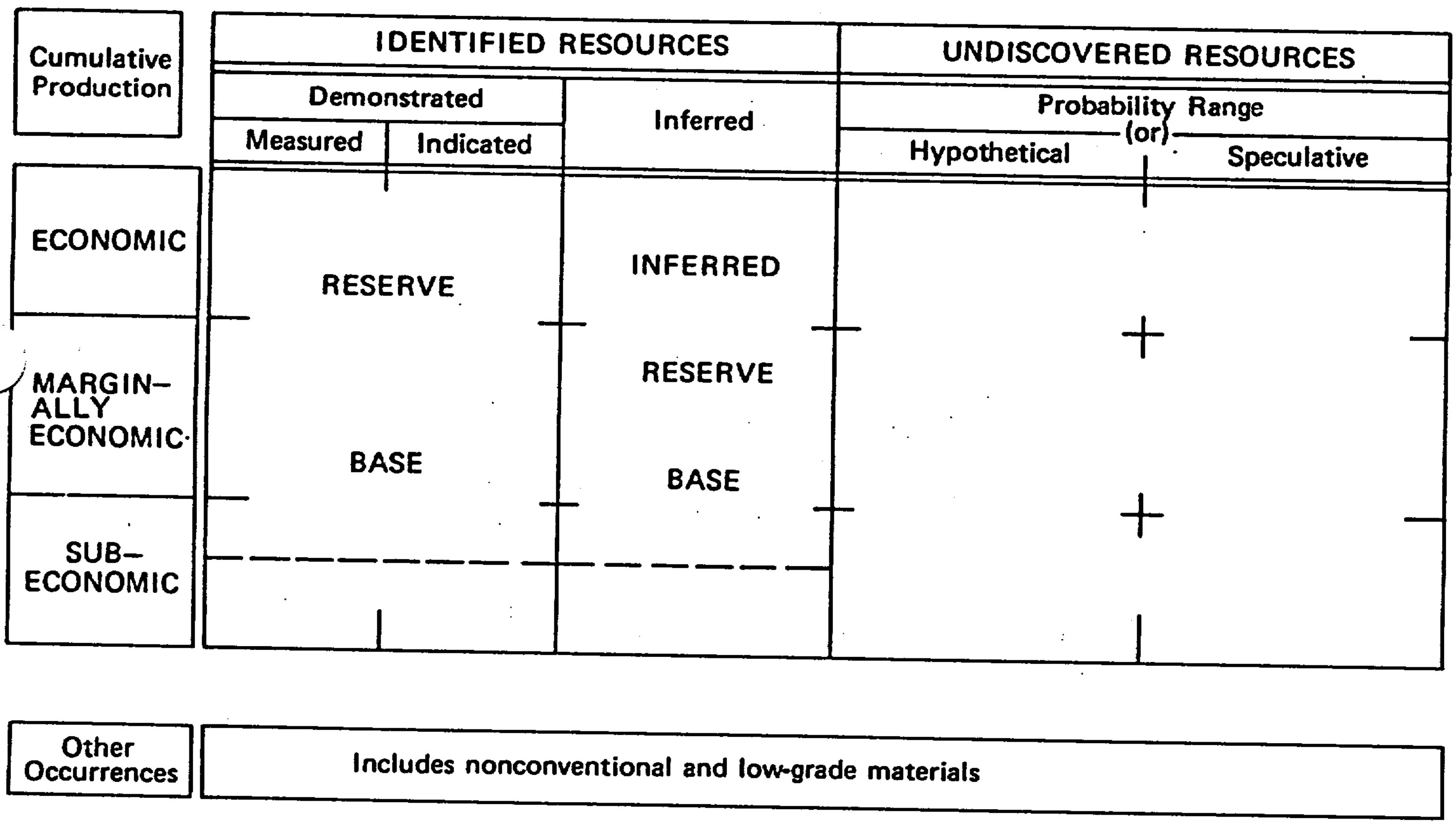
2.2 Resource Estimation

Section 2.2 discusses methods used to estimate the quantity and quality and to classify mineral or hydrocarbon resources; methods used to estimate discovered and undiscovered resources are described separately. Classification of resources use definitions and guidelines presented in USGS Circular 831 (133). Guidelines for specific resources are also available, such as USGS Circular 882 (134), which classifies phosphate resources, and USGS Bulletin 1450-B (135), which classifies coal resources.

A variety of resource-reserve classification schemes or systems has been developed. Although these schemes or systems vary in terminology, structure, and purpose, they share a commonality in attempting to provide a consistent method for defining, codifying, and reporting mineral resource quantities. USGS Circular 831 describes the resource classification system developed and employed by the Federal Government's principal mineral resource agencies, the BOM and the USGS. This classification system, and associated terminology, is used in this report. Essential components of the system are graphically illustrated in figures 9 and 10; definitions pertaining to figures 9 and 10 are presented in Section 5.

Figure 9

Figure 10



Adapted from USGS Circ. 831

Fig. 10

– *Reserve base* and *inferred reserve base* classification categories

2.2.1 Discovered Resources

Resource estimation is a technical task designed to determine resource quantity and quality. It involves integration of collected data and selection of appropriate methods for computations.

2.2.1.1. Mineral Resources

Methods for resource estimation can be classified into four broad groups: (1) Average factors and area methods, (2) cross section methods, (3) analytical methods, and (4) mining block methods (136). General applications, advantages, and disadvantages for these methods are described in table 13.

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TABLE 4. General Applications, Advantages, and Disadvantages of Standard Mineral Resource Estimation Methods.

Method	Applications	Advantages	Disadvantages
Average Factor and Area Methods	Particularly suited to tabular, bedded, and large placer deposits.	Adaptable to most deposit types. Procedures are flexible and require no complex formulas. Allows for rapid and continuous evaluation of factual data.	Accuracy may depend on personal interpretation rather than objective geologic observations and sampling.
Cross-Section Methods	Applicable to most uniform deposits. The isoline variation of the cross-section method is also used in oil and gas resource estimation.	Methods graphically portray the geology of the mineral deposit. Computations are relatively simple and, depending on spacing of sections, can yield accurate results.	Use would be impractical for small deposits or structurally disrupted deposits.
Analytical Methods	Applicable to tabular deposits such as coal, phosphate rock, oil-shale, large lenses, and thick veins.	In conjunction with an adequately designed exploration drilling and sampling program, thickness, grade, and volume are accurately determined.	Morphology of the deposit will not be revealed.
Mining Blocks Methods	Applicable to most mineral deposits with existing underground workings and drill holes.	Computations are relatively simple and yield accurate resource estimates.	Primarily designed for operating underground mines or well-delineated deposits.

Average Factors and Area Methods

These methods use analogous or geologic blocks within areas delineated by geologic data where the basic elements (thickness, grade, and weight) are determined directly, computed, or inferred from the same or similar deposits. Specific examples of these methods have been described as arithmetic average (137), weighted average (138), average depth and area (138), statistical (139), analogous (140), and geologic block (140) or general outline (141). These methods are typically employed when there is a lack of extensive exploration data (e.g., drilling); therefore, resources calculated by these methods would normally fall into the "Inferred Resources" category (Figures 9 and 10).

Cross-Section Methods

These methods involve the delineation of and subsequent resource estimate for a deposit, using engineering drawings constructed from drill intercept and other collected data. Variations include the standard, linear, and isoline methods (136). Accuracy of the final resource estimate, using one or more of these methods, depends on the extent of the data and frequency of ·ctions used to define the resource (e.g. the more sections, the sm r the individual blocks, and the greater the confidence). Thus, resources calculated using the cross-section methods can be classified as either "Indicated" or "Inferred."

Analytical Methods

Analytical methods divide a deposit graphically into blocks of simple geometric forms such as triangles or polygonal prisms. The factors for each block can be determined directly, or averaged mathematically. The polygon method is the most common variation of the analytical methods and is employed in conjunction with a diamond drilling program. Similarly, as with the cross-section method, the level of confidence is directly related to the detail of the exploration program (e.g., the closer the drill holes, the greater the confidence). Thus, as with cross-section methods, resources calculated using analytical methods can be classified as either "Indicated" or "Inferred."

Mining Blocks Methods

These methods are typically used to delineate block areas in underground mines and are used mainly for extraction. Examples of mining block methods include longitudinal sections (142), mine extraction (138), and mine exploitation (143). These methods are normally employed in operating underground mines, and resource quantities estimated are typically cla ified as "Measured."

2.2.2 Undiscovered Resources

Because of restrictions on the use of piercement methods (drilling, trenching, drifting, etc.) and because of time constraints during site characterization, the use of geomathematical methods appear to be required in estimating the quantity and quality of undiscovered natural resources. For example, tonnages and average grades of well-explored deposits can be employed as quantitative and qualitative resource models for tonnage-grade estimates of undiscovered deposits in geologically similar settings (126). Unfortunately, no subjective/geomathematical discovery model currently exists that could be applied directly in assessing the natural resources of small geographic areas such as HLW repository sites. However, if suitable methods are developed, they would probably incorporate considerations similar to those techniques discussed in PROSPECTOR (144-148), developed by the Stanford Research Institute, and ROCKVAL (149), currently under development by BOM. Detailed references on PROSPECTOR are presented in Section 6.3; because little information has been published on ROCKVAL, a detailed discussion of this method is presented in the text.

PROSPECTOR

PROSPECTOR is a computer software system that was initially employed to use and imitate the decision process an expert geologist would use to determine the favorability of a resource prospect.

The program employs techniques of artificial intelligence (AI) to represent empirical judgment knowledge in a formal way and to use that knowledge to perform plausible reasoning. The system represents inference nets and computes probabilities in ways that permit the building and use of larger and more intricate inference nets. As opposed to requiring the geologist to identify all combinations at each level and to rank them, PROSPECTOR methodology requires the geologist to provide only the odds and likelihood ratios for each rule.

Due to the complex methodology of PROSPECTOR, the following references from the Stanford Research Institute should be consulted:

- Duda, R. O., P. E. Hart, N. J. Nilsson, R. Reboh, J. Slocum, and G. L. Sutherland. Development of a Computerbased Consultant for Mineral Exploration. Annual Report, SRI Projects 5821 and 6415, Stanford Research Institute International, Menlo Park, CA, 1977 (147).

- Duda, R. O., P. E. Hart, P. Barrett, J. G. Gaschnig, K. Konolige, R. Reboh, and J. Slocum. Development of the Prospector Consultation System for Mineral Exploration. Final Report, SRI Projects 5821 and 6415, Stanford Research Institute International, Menlo Park, CA, 1978 (145).

- Gaschnig, J. Development of Uranium Exploration Models for the Prospector Consultant System. Final Report, SRI Project 7856, Stanford Research Institute International, Menlo Park, CA, 1980 (148).

ROCKVAL

ROCKVAL (149) is under constant development to improve one or more aspects, but has been used in more than test modes. For areas in which the use of traditional assessment techniques is limited, ROCKVAL and similar methods may represent the only available options. It must be noted, however, that ROCKVAL was designed for application to large areas (hundreds of thousands of hectares and larger), and some aspects of the methodology depend on the equivalent of the law of large numbers. Thus, ROCKVAL and similar approaches are not, in their current form, appropriate tools for assessing HLW repository sites; however, they could be modified, if it were deemed necessary, to make the resource estimates required by 10 CFR Part 60.

The ROCKVAL approach to natural resource assessment uses data analysis derived using methods described in Section 2.1, including background data collection, field observation, and geochemical and geophysical analysis. Subjective probability judgments are applied to the collected data to estimate the likelihood of prospects, tonnages, grades, etc. The overall approach is illustrated in figure 11.

Cumulative Production	IDENTIFIED RESOURCES			UNDISCOVERED RESOURCES	
	Demonstrated		Inferred	Probability Range (or)	
	Measured	Indicated		Hypothetical	Speculative
ECONOMIC	Reserves		Inferred Reserves		
MARGINALLY ECONOMIC	Marginal Reserves		Inferred Marginal Reserves		
SUB-ECONOMIC	Demonstrated Subeconomic Resources		Inferred Subeconomic Resources		
Other Occurrences	Includes nonconventional and low-grade materials				

Adapted from USGS Circ. 831

Fig 9

— Major elements of mineral-resources classification, excluding *reserve base* and *inferred reserve base*

105

FIGURE N. Mu~~st assign new fig. no.~~

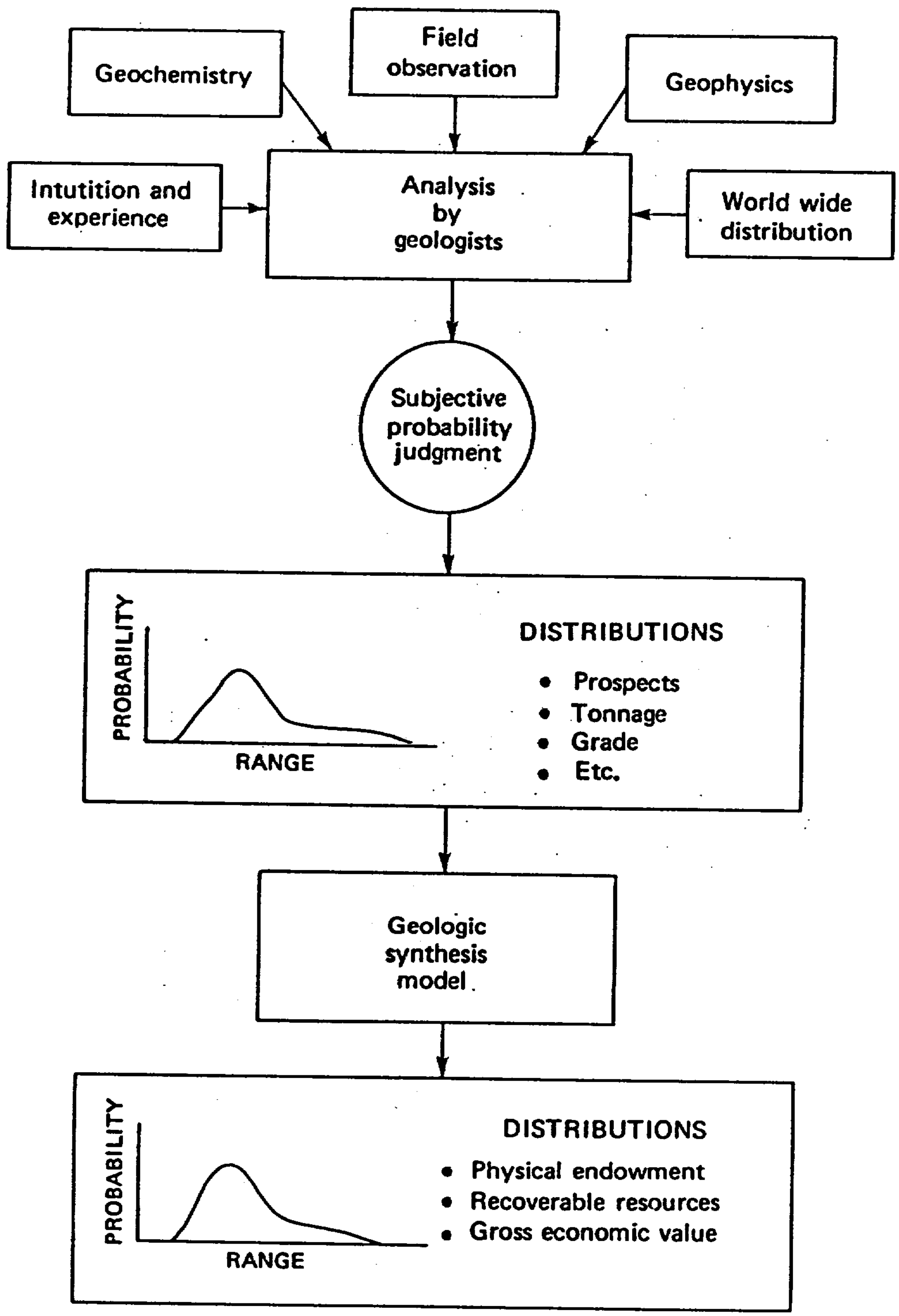

Fig. 11

.— Rockval approach to mineral resource assessment

The conceptual framework for the assessment of undiscovered but potentially valuable mineral deposit types predicted to exist within a region consists of four components: (1) A geologic model of endowment (that quantity of resource in deposits meeting specified physical characteristics such as quality, size, and depth); (2) a set of engineering screens (constraints); (3) a set of economic constraints; and (4) a statistical process to express the major geologic and economic results as probability distributions.

The geologic model of endowment divides the geologic characteristics of a particular deposit type into the following physical factors: endowment thresholds, regional parameters, deposit parameters, and commodity parameters. These are described in table 14.

Two engineering screens are employed to incorporate current technological limitations on the proportion of the mineral endowment that may be reasonably exploited. The first is a recovery factor estimated as the percent of a contained commodity in a deposit that may be efficiently recovered from the ore, and the second is a recoverable depth cutoff, below which current mining technology is unfeasible.

Two economic screens are employed to directly incorporate current (or projected) economic limitations on the proportion of the mineral endowment that may be reasonably exploited. The first is an economic cutoff on the gross value of the ore in a deposit, and the second is an economic cutoff on the unit value of ore in a deposit. The economic cutoff considers the variable costs and rate of return necessary to produce a unit of the resource. For the resources in a deposit to be considered potentially economically recoverable, rather than just part of the endowment, both the gross and the unit cutoff values for the deposit must be equaled or exceeded.

The final step in the application of ROCKVAL is to use the geologic factors and the engineering and economic screens by synthesizing them into a Monte Carlo simulation model to provide probabilistic estimates of mineral endowment and recoverable resources in terms of both physical quantities and values measured in dollars.

The model simulates one possible state of geologic nature by sampling from the probabilities assessed for each of the basic geologic factors and uses the resulting values to compute an amount of ore and contained commodities for deposits of a particular type.

The characteristics of each simulated deposit are then compared against the engineering and economic screens to determine if this deposit's resources may be considered economically recoverable. This process of simulating a particular state of nature (a Monte Carlo "pass") is repeated many times and the results stored, aggregated, and used to build a probability distribution for each of the desired products. The model also aggregates the results across all deposit types being assessed in a region, to provide total estimates for each commodity possible in the region.

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TABLE 9 ROCKVAL - Geologic Parameter Definitions

Endowment Thresholds

Cutoff Tonnage: A threshold tonnage level arbitrarily set to distinguish between anomalies and deposits to be included in estimates of resource endowment. This threshold should be set well below the current economic cutoff level.

Cutoff Depth: A threshold depth level arbitrarily set to distinguish between deposits to be included in estimates of resource endowment. This threshold should be set well below the current engineering cutoff level.

Cutoff Grade: A threshold grade level associated with each mineral contained in a deposit arbitrarily set to distinguish between anomalies and deposits to be included in estimates of resource endowment. This threshold should be set well below the current economic cutoff level.

Regional Parameters

Regional Favorability: A point estimate of the likelihood that all the geologic controls necessary for the formation of deposits of a specific type are regionally present.

Significant Prospect: A prospect, occurrence, or anomaly of sufficient interest to cause a prudent exploration geologist to commit to a drilling program.

Deposit Parameters

Deposit: A mineral prospect exceeding a specified (cutoff) ore tonnage, grade and depth.

Deposit Likelihood: A point probability estimate of the likelihood that a randomly selected prospect will contain ore in excess of the cutoff tonnage, grade, and depth.

Deposit Size: The estimated range in deposit sizes for the terrane.

Commodity Parameters

Commodity: A mineral of potential economic interest that may be present in a deposit.

Occurrence Probability: A point probability estimate of the likelihood that the particular commodity is present in a deposit above the cutoff grade level.

Average Grade: The estimated range in average grade for each commodity present in a deposit, above its cutoff grade.

2.3. Resource Evaluation

Pursuant to 10 CFR Section 60.21(c)(13), resources with current markets require estimation of gross and net value. Gross value is merely the total dollar value of the commodity (at current prices) in the ground. Net value, on the other hand, is gross value less the cost of producing a marketable product; thus, it requires estimates of capital and operating costs necessary for recovery of the commodity. The process used to estimate resource net values uses many of the methodologies that would be employed by industry in making the decision to exploit or abandon a resource. By using these methods, sufficient data can be obtained to estimate the costs involved in extracting and marketing the resource, thus determining net value.

2.3.1 Capital and Operating Costs

Capital and operating cost estimates are necessary in order to determine the net value of a mineral resource. Capital costs represent those expenditures required to bring a resource into production; operating costs, on the other hand, represent those costs required to sustain production. Major components of capital and operating costs are described in the following section.

2.3.2 Cost Components

Estimating capital and operating costs requires careful examination of the general cost categories shown below:

Capital Costs

- o Acquisition - cost of any surface and/or mineral rights.
- o Exploration - costs involved in defining the resource (costs related to methods discussed in Sec. 2.1).
- o Development - costs required to prepare a mine for production (e.g., driving drifts, sinking shafts, preparing stopes, preproduction stripping, etc.).
- o Extraction system equipment and plant facilities - costs such as those expended for mining equipment and mine communications, water, or electrical systems.
- o Processing system - costs associated with purchase and installation of process equipment.
- o Ancillary requirements - costs of associated infrastructure.
- o Engineering, design, and management costs - costs associated with the design and construction of a mine.
- o Environmental costs - costs associated with measures to mitigate environmental damage.

Operating Costs

o Labor requirements - cost of labor needed to sustain production (e.g., miners, truck drivers, drillers, plant operators, mechanics, electricians, etc.)
o Supplies - cost of supplies needed to sustain production (e.g., fuel, electricity, explosives, reagents, water, etc.)
o Equipment operations - cost to maintain extraction and processing equipment (e.g., repair parts, tires, lube, etc.)
o Administration - cost associated with management and administrative functions (e.g., administrative personnel such as plant manager, security guards, purchasing agent, etc.)

Detailed information on cost estimation and cost components may be found in the following references:

Base Line Studies, Environmental Assessment/Environmental Impact Statement (EA/EIS) Preparation, and Permitting

o Bureau of Mines Cost Estimating Handbook (150)

Underground Mines

o Cummins and Given, 1973 (151).
o [illegible]bach and Souders, 1975 (152).
o Hustrulid (ed.), 1982 (153).
o Peele and Church, 1941 (154).

Surface Mines

o Cummins and Given, 1973 (151).
o Caterpillar Tractor Co., 1984 (155).
o Pfleider, 1973 (156).
o Church, 1981 (157).
o Crawford and Hustrulid, 1979 (158).

Placer Mines

o Griffith, 1960 (159).
o Stebbins, 1986 (160).

Plant Design and Cost Estimating

o Currie, 1973 (161).
o Gilchrist, 1969 (162).
o Heady and K. G. Broadhead, 1976 (163).
o Pickett, 1978 (164).
o Pryor, 1965 (165).
o Richardson Engineering Services, 1984 (166).
o Taggart, 1945 (167).

2. Systems for Cost Estimating and Cost Data Sources

The following section discusses applications, advantages, and disadvantages of available systems used for estimating capital and operating costs.

BOM Cost Estimating System (CES) (150)

CES was first developed in 1975 to assist in the preparation of prefeasibility type (± 25 percent) estimates for capital and operating costs. The system is applicable to mining and beneficiation of various types of mineral occurrences using current technology. It has been updated to reflect the changes in costs of technologies and is current as of January 1984. The Handbook consists of a series of sections, each corresponding to a specific mining or mineral processing unit process. Within each section are methods to estimate either capital or operating cost for that unit process; costs are typically presented on a logarithmic scale of cost versus capacity.

Canadian Institute of Mining and Metallurgy (CIM) Mining and Mineral Processing and Equipment Cost and Preliminary Capital Cost Estimations (168)

The CIM estimating Handbook is useful in determining capital costs for many types of mining and processing equipment. The Handbook contains data in the form of graphs, tables, and equations to rapidly estimate the cost of individual equipment items. The Handbook cannot be used to estimate mining or processing operating costs.

BO' ost Estimation Handbook for Small Placer Mines (160)

This Handbook was written specifically to aid in estimating capital and operating costs of placer mining operations and in designing placer mines and plants. It consists of a series of costing sections corresponding to specific components of a placer operation: exploration, mining, processing, supplemental systems, and environmental considerations. Each section contains the methodology to design a unit process or to estimate associated capital or operating cost. Costs are typically presented on a logarithmic scale of cost versus capacity. The system is designed to produce prefeasibility estimates in July 1985 dollars accurate to within 25 percent. The Handbook contains methods for updating base costs derived from the equations (July 1985 dollars) to current dollars.

Mining Cost Service (169)

Mining Cost Service is a subscription service published by Western Mine Engineering, Spokane, WA. The Handbook provides sections on electric power and natural gas rates, transportation routes and rates, labor rates, cost indices, supplies, equipment, smelting, taxes, and cost models. Data contained in the various sections allow the user to estimate capital and operating costs for most mining and processing systems. Sections are periodically updated (about once a year) negating the need to escalate costs to current dollars. The service provides information pertaining to mo infrastructure requirements applicable to mining systems.

Green Guide (170)

The Green Guide, published by Dataquest, Inc., is a handbook that lists costs for new and used construction equipment. The Guide is a subscription service that provides detailed descriptions and costs for nearly all major construction equipment, including trucks, excavators, crushing equipment, air equipment, loaders, graders, pumps, generators, etc. The various sections are updated periodically (every few years); however, generally some escalation of dollar values is required to achieve current costs. The service is limited to capital cost estimates only.

Cost Reference Guide for Construction Equipment (171)

The Cost Reference Guide is a subscription service published by Equipment Guide-Book Co., Palo Alto, CA. The Handbook provides operational costs for nearly all the equipment contained in the Green Guides and is used to estimate operating costs for specific pieces of equipment. Costs are broken down into operating and overhaul labor, repair and overhaul parts, fuel, electricity, lubrication, tires, ground engaging components, etc. This service, like the Green Guide, is updated on a periodic basis (every few years) and requires some escalation of values to current dollars. The service is limited to operating costs for specific construction equipment only.

2.3.4 Economic Analysis

The purpose of economic analysis is to determine net resource value. This is accomplished by using cost estimates of the proposed extraction and processing systems in addition to other costs deemed necessary to achieve production (e.g., environmental and infrastructure costs). Economics are normally measured in terms of net cash flow, on an annual basis. Cash flow has two components; positive cash flow (sales revenue, royalty income, interest income, tax credits, etc.) and negative cash flow (purchase of assets, purchase of materials, labor, supplies, royalty payments, interest expenses, debt repayment, local and Federal taxes, etc.).

Economic analyses can be accomplished using the BOM MINSIM4 computer program for determining discounted cash flow rate of return (DCFROR) and price determinations. A complete description of the MINSIM4 package is available in Bureau of Mines IC 8820, 1980, "Supply Analyses Model (SAM): A Minerals Availability System Methodology" by R. L. Davidoff (172).

Other software is available for conducting economic analyses. A reliable system, SEE (Software for Economic Evaluation), is available from Investment Evaluations Corp., 23715 Waynes Way, Golden, CO 80401 (173).

As opposed to using computer software, the always reliable "hand calculation" methods are available. The methodologies for calculating present worth, annual worth, future worth, rate of return, and breakeven analysis are described in detail in Economic Evaluation and Investment Decision Methods by F. J. Stermole (174).

2.4 Economic models.

This Section is currently under development. Included for illustrative purposes is an example of the models slated for inclusion. Costing backup data pertaining to the individual models will be included in appendix C.

ECONOMIC MODEL

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NOTE: The following wollastonite economic model was included <u>for illustrative purposes only</u>. Its inclusion is intended to demonstrate the format, content, and level of detail of the economic models to be included in the final document. It is a prototype model developed for another BuMines project and may contain minor technical, format or grammatical errors. Models for eventual inclusion have yet to be selected or developed.

The authors feel that NRC could get a better picture of what the models will entail if an example (notwithstanding its apparent inapplicability) were included rather than presenting the model in outline form.

It is envisioned economic models will be developed for W/Mo/Au skarns, detachment and associated high-angle fault gold deposits, Carlin (GEXA or Bullfrog type) gold, epithermal gold, and one yet to be selected.
****

ECONOMIC MODEL--NON-METALLIFEROUS
SKARN DEPOSIT
COMMODITY--WOLLASTONITE

Wollastonite

Wollastonite deposits in the United States are typically produced by contact metamorphism between Paleozoic and Precambrian limestones and igneous rocks. They are directly associated with skarn deposits. Depending on the original composition of the surrounding rocks, wollastonite deposits are usually associated with varying amounts of calcite, quartz, garnet, epidote and diopside.

U.S. wollastonite production currently exceeds 135,000 tons/year and is derived from deposits in New York State and California. California production has come from deposits in the Little and Big Maria Mountains, 20 miles northwest of Blythe, a large deposit in the Paniment Range, 6 miles southeast of Ubehebe Peak, and deposits near Code Siding about midway between Randsburg and Ridgecrest. Other deposits are found in Warm Springs canyon on the east slope of the Panimint Range, on Hunter Mountain near Darwin, near Sh[illegible] Creek in the Avawatz Mountains, in the western foothills of the Shadow Mountains 22 miles northeast of Victorville, and in the Cargo Muchacho Mountains of Imperial County.

Typically, deposits being exploited today contain in excess of 10 million tons grading from 50 to 70 percent wollastonite. The wollastonite is usually banded with thicknesses from 10 to 30 feet for the higher grade material, however, often layers contain more siliceous or calcareous material with varying components of quartz, calcite, garnet, epidote, and diopside.

Impurities in the deposit greatly affect the processing of wollastonite. Where nearly pure wollastonite is mined, generally processing is restricted to crushing and sizing to make various products in a dry circuit. As impurities such as garnet, diopside, and epidote increase, a high-intensity magnetic separation circuit would be used to remove these weakly magnetic gangue materials from the wollastonite. However, when excessive calcite or silica are present, a flotation step would normally be required.

For modeling purposes, the deposit is assumed to contain 60% wollastonite, 30% calcite, 5% quartz, and 5% weak magnetics (garnet and diopside). For the small, medium, and large operation, tonnages required would be 1, 2, and 5 million tons, respectively. The deposit would be amenable to open pit mining and assumes a 3:1 waste-to-ore stripping ratio. Because of impurities, processing would require both wet and dry circuits. Dry circuits would include size reduction, high intensity magnetic separation, and size classification; wet processing would include selective flotation to remove calcite and quartz.

Open Pit Mining

The proposed mining of wollastonite assumes a deposit of sufficient size and width to permit an open pit mining system. Assumptions made to define the model are as follows:

1) A skarn deposit composed of wollastonite, calcite, quartz, garnet, and diopside.
2) A 3:1 waste-to-ore stripping ratio.
3) Medium to hard drilling.
4) A 1,640 ft waste haul.
5) A 4,920 ft ore haul to the mill.

The proposed open pit mine would operate one - ten hour shift per day, 5 days per week, 260 days per year. Three separate mining rates have been evaluated: 1) 220 short tons (st) per day ore and 660 st per day waste; 2) 440 st per day ore and 1,323 st per day waste; and 3) 1,100 st per day ore and 3,300 st per day waste.

Mining will utilize "down-the-hole" percussion drills equipped with 2.75 in. tungsten carbide bits. Holes will be 16 ft deep to maintain 12 ft benches. Drilling is accomplished at a rate of 69 ft per hour. Each hole is loaded with 21 pounds of ANFO; blasting occurs once a day. After blasting, broken ore and waste is selectively loaded into 35-ton rear dump trucks using 7 1/2 yard front end loaders. Waste haulage requires a 6.5 minute cycle time; ore haulage requires a 12 minute cycle time.

In addition to drills, trucks and loaders, other mine equipment required for open pit operations include a motor grader for road and pit maintenance, a water truck for dust control, explosives truck, mechanic's truck, and a diesel generator to supply power to mine buildings (office, maintenance shop, and warehouse).

Processing

Proposed processing of wollastonite varies considerably depending on amount and type of gangue components in the ore. Generally, processing of wollastonite ores consists of dry crushing, screening, and sizing to produce various-sized products. Impurities, such as garnet and diopside, are typically removed using high-intensity dry magnetic separators. If excessive calcite or quartz is present in the ore, flotation is used to remove the unwanted material. The evaluation model assumes the following components; wollastonite, 60 percent by volume; calcite as the major gangue mineral; and to a lesser degree, in order of abundance, quartz, garnet, and diopside.

Run-of-mine ore is delivered by dump truck from the mine to a surge bin which feeds the primary jaw crusher. Primary crushing reduces the ore to 75 percent minus 5 in. Secondary crushing further reduces the ore to 100 percent minus 0.63 in. Discharge from the secondary crusher is delivered to an impact crusher then conveyed to a series of high-intensity dry magnetic separators for removal of garnet and diopside.

The weakly magnetic fraction is then conveyed to waste and the nonmagnetic fraction would be conveyed to a series of vibrating screens set at 1/16 in. The plus 1/16 in. oversize is nearly pure wollastonite and is delivered to a pebble mill for further size reduction. Pebble mill discharge is then sized in cyclone air separators wherein various fractions from minus 100 to minus 325 mesh is separated and delivered to sackers for packaging.

The minus 1/16 in. undersize from the vibrating screens, composed of wollastonite, calcite and quartz, is wet ground in a ball mill then delivered to flotation cells. In the float cells, calcite and quartz is suppressed; the ultimate froth contains a low-grade wollastonite-calcite product. The product is thickened, filtered, and dried then delivered to a second pebble mill and cyclone air separators for product sizing and packaging. Dust collection from both product sizing and packaging facilities is combined and packaged as an intermediate grade product.

Products from this mill are assumed to be a high-grade wollastonite (99 percent $CaSiO_3$) of various sizes (80 percent of production), a low-grade wollastonite (66 percent $CaSiO_3$) of various sizes (15 percent of production), and a dust product (93 percent $CaSiO_3$) will remain un-sized (5 percent of production). The percentages of high- and low-grade production will vary with the amount of impurities in the ore.

Under the given assumptions, total daily mill production would be 139 st, 96 st, and 697 st respectively, for the small, medium and large mill. A generalized flowsheet illustrating wollastonite processing is shown in figure 1 (not included here). A material balance is shown in table 1 (not included he

Costs

Estimated mine capital and operating costs for the three proposed production levels are described in table 2 and processing capital and operating costs are described in table 3.

TABLE 2.-- Wollastonite - Estimated capital and operating costs, open pit mining model

CAPITAL COSTS

Item	220 st/day	440 st/day	1100 st/day
Capital Costs ($ x 1000)			
Exploration	$ 84	$ 168	$ 280
Infrastructure (roads)	116	174	290
Permitting	202	250	429
Development	200	200	282
Mine Equipment	1,189	1,371	2,564
Installation/facilities	959	1,231	1,993
Working capital	165	243	485
Mine Capital total	$ 2,915	$ 3,637	$ 6,323

OPERATING COSTS

Item	220 st/day	440 st/day	1100 st/day
Operating costs ($/day)			
Labor	$ 1,375	$ 1,787	$ 3,334
Steel (drill bits/rods)	243	431	631
Fuel	241	344	751
Explosives	247	463	1,086
Equipment repair parts	137	227	536
Lube	104	129	316
Miscellaneous	116	194	412
Mine Operating total	$ 2,543	$ 3,744	$ 7,456

TABLE 3.-- Wollastonite
Estimated capital and operating costs, processing model

CAPITAL COSTS

Item	220 st/day	440 st/day	1100 st/day
Capital Costs ($ x 1000)			
Permitting	$ 151	$ 195	$ 394
Water system	273	352	709
Equipment	1,515	1,954	3,941
Installation, facilities	1,968	2,540	5,125
Working capital	204	307	564
Mill Capital Total	$ 4,111	$ 5,348	$10,733

OPERATING COSTS

Item	220 st/day	440 st/day	1100 st/day
Operating costs ($/day)			
Labor	$ 1,841	$ 2,338	$ 3,793
[illegible]er	140	280	700
[illegible]er	366	522	992
Reagents	80	159	397
Steel	67	135	336
Fuel, natural gas, lube	87	151	321
Multipurpose bags	139	279	697
Equipment parts	988	1,512	2,796
Mill Operating Total	$ 3,708	$ 5,376	$10,032
Product transport to Barstow	1,759	3,518	8,974
Total mill and transport	$ 5,467	$ 8,894	$19,006

2.5 References

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3. SUMMARY

This report was prepared to help the NRC provide guidance to DOE on accepted methodologies for assessing natural resources, as required by 10 CFR Part 60. It is generally applicable to the area on and around Yucca Mountain, Nye County, Nevada and applies to all metals, nonmetals and mineral brines currently recoverable or that may become recoverable in the future as the result of likely advances in technology.

Resource assessments are mandated by 10 CFR Section 60.21(c)(13) to accompany repository license applications submitted to NRC. The goal of resource assessment at Yucca Mountain is to ensure that the likelihood of mineral extraction is considered when evaluating post-closure human activity that may compromise the ability of the proposed high-level waste repository to isolate radionuclides from the accessible environment. This goal is partially achieved by identifying and evaluating those locations within the geologic repository operations area or adjacent controlled area that may have resource potential.

The resource assessment process is a three-step, logical sequence of events in which potential resources are identified, quantified and qualified (tonnage and grade estimates), and evaluated (gross and net value estimates).

Resource identification involves extensive literature and database research, resource identification, deposit modeling, field investigations, and geomathematical studies. Information gained through such research may identify areas that in the past have been the objects of exploratory drilling or resource extraction, as required by 10 CFR Section 60.122(c). Further, deposit modeling and geomathematical studies may alert researchers involved in site characterization activities other than resource assessment to possible resource indicators.

Accepted geological, geochemical, and geophysical resource identification methods that may be employed during site characterization include (but are not limited to): geological mapping and sampling, soil and water analyses, and seismic, magnetic, electrical, and gravity surveys.

Geomathematical methods of resource assessment allow estimates to be made of an area's resource potential at varying levels of certainty, without extensive exploratory drilling and concomitant expenditure of time, effort, and funds. Two methods, simple subjective and complex subjective, and the advantages, disadvantages, and uncertainties associated with their use, are considered. It may be that none of the current methodologies (including subjective methods) can adequately address the unique resource assessment problems encountered at Yucca Mountain.
It will be necessary to expend the time and funds necessary to develop a resource assessment program that specifically addresses the requirements of 10 CFR Section 60.21(c)(13).

Quantification and qualification of existing resources encountered during site characterization, as well as of undiscovered resources thought to exist in or near the proposed HLW repository, are required. Tonnage and grade estimates may be made by the employment of one or more geomathematical resource assessment methods. These methods, by nature, contain significant uncertainties. The use of geomathematical resource assessment methods largely stems from the regulatory restrictions that have been placed on more reliable (and verifiable) methods that involve borehole drilling or other piercement procedures.

Gross and net resource value estimates (resource evaluation), as required by 10 CFR Section 60.21(c)(13), are accomplished by using one or more of the many methods, systems, models, and procedures in common use by BOM and the private sector. In addition to gross and net value, these methodologies provide for estimating capital and operating costs, extraction systems design, and environmental, ancillary and infrastructural requirements.

The primary purpose of resource assessment at Yucca Mountain is to identify those potentially adverse conditions listed in 10 CFR Section 60.122(c)(17-19). This can be accomplished by application of methods discussed and/or referenced here.

4. ACRONYMS AND INITIALISMS

AI	artificial intelligence
AIME	American Institute of Mining, Metallurgical, and Petroleum Engineers
BLM	Bureau of Land Management
BOM	Bureau of Mines
CES	Bureau of Mines' Cost Estimation System
CIM	Canadian Institute of Mining and Metallurgy
CNWRA	Center for Nuclear Waste Regulatory Analyses
CRIB	Computerized Resource Information Bank
DCFROR	discounted cash flow rate of return
DMEA	Defense Minerals Exploration Administration
DOC	(U.S.) Department of Commerce
DOD	(U.S.) Department of Defense
DOE	(U.S.) Department of Energy
DOL	(U.S.) Department of Labor
DST	drill stem test
EA	Environmental Assessment
EIS	Environmental Impact Statement
ERTS	environmental resources technology satellite
GROA	geological repository operations area
GSA	Geological Society of America
HLW	high-level waste
IRS	(U.S.) Internal Revenue Service
LC	Library of Congress
MAS	Minerals Availability System
MILS	Mineral Industry Location System
MLA	Mineral Land Assessment
MDRS	Mineral Resources Data System
MSHA	Mine Safety and Health Administration
NA	National Archives
NRC	(U.S.) Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
OSM	Office of Surface Mining
SEE	Software for Economic Evaluation
SPOT	Systeme Probatoire d'Observation de la Terre
USFS	U.S. Forest Service
USGS	U.S. Geological Survey

Incomplete

5. GLOSSARY

accessible environment -- includes the atmosphere, land surfaces, surface waters, oceans, and parts of the lithosphere containing ground water that are more than 10 kilometers (6.7 miles) in any direction from the edge of the original location of the radioactive wastes in a disposal system .

adit -- a horizontal or nearly horizontal passage driven from the surface for the purpose of resource exploration, working, or dewatering of a mine.

aeromagnetic survey (aeromagnetic prospecting) -- a technique of resource exploration using an aerial magnetometer.

agglomerate -- contemporaneous pyroclastic rock containing a predominance of rounded or subangular fragments greater than 32 mm in diameter.

alteration -- change in the mineralogical composition of a rock, typically brought about by the action of hydrothermal solutions. Also applies to secondary (supergene) changes in rocks or minerals.

am ous -- having no form; applied to rocks and minerals having no de ite crystalline structure.

analogy -- inference that if two or more aspects agree with another in some respects, they will probably agree in others.

anastomosing -- having a netlike or braided appearance, as in an anastomosing stream.

andesitic tuff -- a rock composed of andesite fragments, generally smaller than 4 mm in diameter.

anomaly -- a deviation from uniformity; a local feature distinguishable in a geophysical, geochemical, or geobotanical measurement over a larger area; a feature considered capable of being associated with economically valuable hydrocarbon or mineral resources.

anoxic -- containing no oxygen.

apical zone -- zone surrounding the apex of a mineral deposit, intrusion, etc.

argentian tetrahedrite -- a silver-bearing, copper-antimony sulfide mineral.

arg lic alteration -- alteration characterized by the presence of clay mi ls.

ash-flow tuffs -- a pyroclastic volcanic rock composed of welded or non-welded shards of glass and rock formed as the result of a nuee ardente ("glowing avalanche").

beryllian tactites --

biogeochemical prospecting -- the chemical analysis of plants or animals as a resource exploration method.

bimodal volcanism --

bulk sample -- large samples of a few hundredweight or more taken at regular but widely spaced intervals.

caldera --

caldera complexes --

channel sample -- material from a level groove cut across an exposure in order to obtain a true cross-section of mineralized material exposed.

chip sample -- a regular series of ore chips or rock chips taken either in a continuous line across an exposure or at uniformly spaced intervals.

collar -- (1) the mouth or opening of a borehole or shaft. (2) Surface area at the top of a shaft; the area is usually reinforced with concrete.

controlled area (as used by NRC) -- a surface location extending horizontally no more than 10 kilometers (6.7 miles) in any direction from the edge of the disturbed rock zone and the underlying subsurface, which area has been committed to use as a geologic repository and from which incompatible activities would be restricted following permanent closure (NRC, 1981). The outer edge of the controlled area marks the inner edge of the accessible environment.

core drill -- a mechanism designed to rotate and cause an annular-shaped rock cutting bit to penetrate rock formations, produce cylindrical cores of the formations penetrated, and lift such cores to the surface, where they may be collected and examined.

cross-section -- a profile portraying an interpretation of a vertical section of the earth explored by geophysical and/or geological methods.

crystalline rock -- an inexact but convenient term designating an igneous or metamorphic rock, as opposed to a sedimentary rock. Such rock consists almost wholly of mineral crystals or fragments of crystals.

demonstrated resource -- a term for the sum of measured plus indicated.

density log -- a gamma-gamma log used to indicate the varying bulk densities of rocks penetrated in drilling by recording the amount of back-scattering of gamma rays.

deposit -- used in reference to the physical occurrence of a resource and includes metallic and nonmetallic ore bodies, peat bogs, and coal beds.

deposit model -- a concept or an analog that represents in text, tables, and diagrams the essential characteristics or attributes of a deposit.

economic (as pertains to resources) -- this term implies that profitable extraction or production under defined investment assumptions has been established, analytically demonstrated, or assumed with reasonable certainty.

electromagnetic methods -- a group of electrical exploration methods in which one determines the magnetic field that is associated with the electrical current through the ground.

empirical deposit model -- a geologic deposit model based on known resource deposits or occurrences, containing data but no interpretation.

exploitation -- the process of winning or producing from the earth the oil, gas, minerals, or rocks that have been found as the result of exploration; the extraction and utilization of ore.

exploration -- the search for naturally occurring solid, liquid, or gaseous material on or in the earth's crust; also called "prospecting."

fuel resource -- oil, gas, coal (including lignite and peat), or uranium resources.

genetic deposit model --an explanation of an analysis that divides an ore der -it or other resource occurrence into its primary genetic components and ex ns their interactions; an expansion of the straight line data listing of the empirical model.

geochemical survey -- a survey involving the chemical analysis of systematically collected samples of rock, soil, plants, fish, or water.

geophysical log -- a graphic record of measured or computed geophysical data. Types of geophysical logs include, among others, sonic, density, natural gamma, neutron, and porosity logs.

geophysical survey -- the use of one or more geophysical techniques such as earth currents, electrical, gravity, magnetic, and seismic methods to gather information on subsurface geology.

geotechnics -- the engineering behavior of all cuttings and slopes in the ground; term is gradually replacing "soil mechanics."

gravity survey -- the systematic measurement of the earth's gravitational field in a specified area.

ground magnetic survey -- a determination of the magnetic field at the surface of the earth by means of ground-based instruments.

host rock -- (1) the medium within which radioactive waste is emplaced for dis sal. (2) Sometimes used as the particular horizon in which the waste is laced in a repository. (3) Major constituent geologic formation in mine.

hypothetical resources -- undiscovered resources that are similar to known mineral bodies and that may be reasonably expected to exist in the same producing district or region under analogous geologic conditions. If exploration confirms their existence and reveals enough information about their quality, grade, and quantity, they will be reclassified as identified resources.

identified resources -- resources whose location, grade, quality, and quantity are known or estimated from specific geologic evidence. Identified resources include economic, marginally economic, and subeconomic components. To reflect varying degrees of geologic certainty, these economic divisions can be subdivided into measured, indicated, and inferred.

indicated resources -- quantity and grade and/or quality are computed from information similar to that used for measured resources, but the sites for inspection, sampling, and measurement are farther apart or are otherwise less adequately spaced. The degree of assurance, although lower than that for measured resources, is high enough to assume continuity between points of observation.

inferred reserve base -- the in-place part of an identified resource from which inferred reserves are estimated. Quantitative estimates are based largely on knowledge of the geologic character of a deposit for which there may be no samples or measurements. The estimates are based on an assumed continuity beyond the reserve base, for which there is geologic evidence.

inferred resources -- estimates are based on an assumed continuity beyond measured and/or indicated resources, for which there is geologic evidence. Inferred resources may or may not be supported by samples or measurements.

marginal reserve -- that part of the reserve base which, at the time of determination, borders on being economically producible. Its essential characteristic is economic uncertainty. Included are resources that would be producible, given postulated changes in economic or technologic factors.

measured resource -- quantity is computed from dimensions revealed in outcrops, trenches, workings, or drill holes; grade and/or quality are computed from the results of detailed sampling. The sites for inspection, sampling, and measurements are spaced so closely and the geologic character is so well defined that size, shape, depth, and mineral content of the resource are well established.

methodology -- a body of methods, rules, and postulates employed by a discipline; a particular procedure or set of procedures.

ore -- a mineral of sufficient value as to quantity and quality that can be mined at a profit.

ore controls -- mechanism(s) that determines or controls the physical deposition or emplacement of ore bodies.

original resource -- the quantity of a resource before production.

piercement methods (exploration geology) -- (1) resource exploration methods including borehole drilling, deep pits or trenches, shaft sinking, or driving test adits, declines, etc. (2) any subsurface exploration method that may compromise the integrity of a geologic HLW repository.

ppm -- parts per million (grams per metric ton).

resources (as used here)-- a collective term for all metallic and nonmetallic minerals and ores; fuels, including peat, lignite, and coal. Ground or surface water in the usual sense (i.e., potable, agricultural, or industrial water at ambient temperature at relatively shallow depths), is excluded as a resource. However, ground water in the form of mineral brines, or even waters of relatively low salinity, are included as resources if at depths generally below those at which potable ground water is extracted, and if they are potentially valuable for their dissolved mineral content. "Natural resources" is used in the context of 10 CFR Part 60 and is synonymous with "resources."

reserve base -- that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the in-place demonstrated (measured plus indicated) resource from which reserves are estimated. It may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources). The term "geologic reserve" has been applied by others generally to the reserve-base category, but it also may include the inferred-reserve base category; it is not a part of this classification system.

reserves -- that part of the reserve base that could be economically extracted or produced at the time of determination. The term "reserves" need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials; thus, terms such as "extractable reserves" and "recoverable reserves" are redundant and are not a part of this classification system.

restricted resources/reserves -- that part of any resource/reserve category that is restricted from extraction by laws or regulations. For example, restricted reserves meet all the requirements of reserves except that they are restricted from extraction by laws or regulations.

site characterization (as defined by 10 CFR Section 60.2) -- the program of exploration and research, both in the laboratory and in the field, undertaken to establish the geologic conditions and the ranges of those parameters of a particular site relevant to the procedures in 10 CFR Part 60. Site characterization includes borings, surface excavations, excavation of exploratory shafts, limited lateral excavations and borings, and in situ testing at depth needed to determine the suitability of the site for a geologic repository, but does not include preliminary borings and geophysical testing needed to decide whether site characterization should be undertaken.

speculative resources -- undiscovered resources that may occur either in known types of deposits in favorable geologic settings where mineral discoveries have not been made, or in types of deposits as yet unrecognized for their economic potential. If exploration confirms their existence and reveals enough information about their quality, grade, and quantity, they will be reclassified as identified resources.

subeconomic resources -- the part of identified resources that does not meet the economic criteria of reserves and marginal reserves.

undiscovered resources -- resources, the existence of which are only postulated, comprising deposits that are separate from identified resources. Undiscovered resources may be postulated in deposits of such grade and physical location as to render them economic, marginally economic, or subeconomic. To reflect varying degrees of geologic certainty, undiscovered resources may be divided into two parts: hypothetical and speculative.

Location abbreviations of deposits referenced in Section 2.1.4.2

Appendix A. Locality Abbreviations

ASTR	Austria
AUQL	Australia, Queensland
AUTS	Australia, Tasmania
BLVA	Bolivia
CILE	Chile
CINA	China
CNBC	Canada, British Columbia
GRMY	West Germany
ITLY	Italy
JAPN	Japan
MXCO	Mexico
THLD	Thailand
USAR	US, Arkansas
USAZ	US, Arizona
USCA	US, California
USCO	US, Colorado
USID	US, Idaho
USMT	US, Montana
USNM	US, New Mexico
USNV	US, Nevada
USPA	US, Pennsylvania
USUT	US, Utah

APPENDIX B

ANNOTATED BIBLIOGRAPHY--CASE HISTORIES AND PAPERS PERTAINING TO RESOURCE DISCOVERIES IN WHICH GEOCHEMICAL AND/OR GEOPHYSICAL EXPLORATION METHODS PLAYED A MAJOR ROLE

References listed below cite instances in which geochemical and/or geophysical methods were extensively employed in the discovery of a mineral deposit. The level of detail in the references ranges from complete prospecting case histories to a passing statement of fact.

Geochemical methods

1. Archer, A. R. and C. A. Mann. Casino, Yukon--A Geochemical Discovery of an Unglaciated Arizona-Type Porphyry. Canada. Inst. Min. and Metall. Spec. v. 11, 1971, pp. 67-77. **** Cu-Mo porphyry deposit discovered primarily by the use of stream-sediment and soil geochemical techniques.

2. Brooks, R. R. Geobotany and Biogeochemistry. New York: Harper and Ro' 1972, pp. 190-206. **** Cu-Mo deposit in New Zealand delineated by ge emistry and extended by biogeochemistry.

3. _____. Biological Methods of Prospecting for Minerals. New York: John Wiley and Sons, 1983, pp. 93-97. **** Geologists in Finland use dogs to locate Cu-Ni ore bodies. References to other geochemical successes are found throughout the text and in the bibliography.

4. Diehl, P., and H. Kern. Geology, Mineralogy, and Geochemistry of Some Carbonate-Hosted Lead-Zinc Deposits in Kanchanabari Province, Western Thailand. Econ. Geol. and Bull. Soc. Econ. Geol., v. 76, No. 8, 1981, pp. 2128-2146. **** Geochemical soil sampling, geological mapping, and drilling delineate exploration targets. One target, Song Tho North, commenced underground operations in the fall of 1976.

5. Economic Geology. Ore Deposits in Finland, Norway, and Sweden--A Review. Econ. Geol. and Bull. Soc. Econ. Geol., v. 74, No. 5, 1979, p. 976, fig. 1. **** Vuones Copper Mine (Finland) discovered by lithogeochemical (bedrock) surveys.

6. Mining Magazine (London). Viscaria--A New Copper Mine in Northern Sweden. Min. Mag., October, 1983, pp. 226-233. **** Although details are lacking, it appears that the Viscaria Cu-Zn ore body was first identified on the basis of the existence of a plant, Viscaria Alpina, that has a high affinity for copper. See Brooks (1983, No. 3 above, pp. 41 and 251) for fur er discussions on Viscaria Alpina as a nickel as well as a copper in tor plant.

Geochemical methods, Cont.

7. Muller, D. W., and P. R. Donovan. Stream-Sediment Reconnaissance for Zinc Silicate (Willemite) in the Flinders Ranges, Southern Australia. Canada. Inst. Min. and Metall. Spec. v. 11, 1971, pp. 31-234. ****

Stream-sediment sampling led to the discovery of two willemite ore bodies.

8. Rodriguez, S. E. Geochemical Investigations for Base Metals and Silver in the Coast Geosyncline, Venezuela. Canada. Inst. Min. and Metall. Spec. v. 11, 1971, pp. 237-246. **** Stream-sediment sampling program led to the discovery of two base metal/silver zones.

9. Rugman, G. M. Perseverance Mine--A Prospecting Case History. Mining Magazine (London), May, 1982, pp. 381-391. **** The Perseverance Mine (Zimbabwe) was discovered exclusively by geochemical exploration methods.

10. Shannon, S. S., Jr. Evaluation of Copper and Molybdenum Geochemical Anomalies at the Cumo Prospect, Boise County, Idaho. Canada. Inst. Min. and Metall. Spec. v. 11, 1971, pp. 247-250. **** Limonitic discoloration found during air reconnaissance was explored using soil sampling methods; anomalous Cu-Mo led to discovery of Cumo Prospect.

11. Sinclair, W. D., R. J. Cathro, and E. M. Jansen. The Cash Porphyry Copper-Molybdenum Deposit, Dawson Range, Yukon Territory. CIM Bull., v. 74, No. 833, 1981, pp. 67-76. **** One of the largest Cu-Mo porphyries in the Yukon was discovered using a combination of soil sampling and analysis of ro fragments collected from small test pits.

12. Skillings Mining Review. MicroMin Announces Highlights of 1987 Exploration Program. Skillings Min. Rev., Feb. 20, 1988, p. 13. **** Stream-sediment and bedrock sampling led to discovery of strong, consistent gold anomaly on the Pacific island of Yap (Micronesia).

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Geophysical methods, Cont.

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22. Mining Magazine (London). Rautuvaara and Hannukainen Mines. Min. Mag., Aug., 1982, pp. 101-111. **** The Rautuvaara ore body (magnetite) was located by airborne magnetic surveys and examined in detail by surface magnetic methods and diamond drilling.

23. _____. Polaris Mine. Min. Mag., Sept., 1982, pp. 180-193. **** Ore body discovered in 1970 by gravity survey followed by diamond drilling.

24. _____. Malanjkhand Copper Project. Min. Mag., Nov., 1983, pp. 234-253. **** Resistivity surveys followed up by unspecified geophysical methods and diamond drilling led to the discovery of the deposit.

Geophysical methods, Cont.

25. Mining Magazine (London). The Elura Mine, New South Wales. Min. Mag., Dec., 1983, pp. 436-443. **** Airborne magnetics followed up by unspecified ground work and diamond drilling is credited for the discovery of the Elura Zn-Pb-Ag deposit.

26. Orajaka, I. P., B. C. E. Egboka, and E. A. Emenike. Geoelectric Exploration for Lead-Zinc Sulphide Deposits in Nigeria. Mining Magazine (London), Jan. 1988, pp. 38-41. **** Use of self-potential (SP) method to outline Pb/Zn sulfide ore bodies.

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Combined geochemical and geophysical methods

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29. Huhtala, T. The Geology and Zinc-Copper Deposits of the Pyhasalmi-Piela vesi District, Finland. Econ. Geol. and Bull. Soc. Econ. Geol., v. 74, No. 5, 1979, pp. 1069-1083. **** Several deposits are described in which airborne and ground geophysical methods and various geochemical methods were used in discovery.

30. Lowe, N. T., R. G. Raney, and J. R. Norberg. Principal Deposits of Strategic and Critical Minerals in Nevada. U.S. BuMines IC 9035, 1985, pp. 66-184. **** The following deposits were discovered by use of geochemical and/or geophysical methods and subsequent drilling:

1. Ann Mason--Cu, p. 68
2. B & C Springs--Mo, p. 74
3. Bald Mt.--Au, p. 75
4. Battle Mt. Copper Canyon--Au, p. 78
5. Bootstrap--Au, p. 85
6. Borealis--Au, p. 86
7. Calico Hills--Fe, p. 94
8. Carlin--Au, p. 96
9. Dee--Au, p. 101
10. Enfield Bell--Au, p. 107
11. Manhattan--Au, p. 131
12. Mt. Hope--Mo, p. 138
13. Northumberland--Au, p. 143
14. Piute--Fe, p. 150
15. Preble--Au, p. 151
16. Pumpkin Hollow--Fe, p. 153
17. Rain--Au, p. 155
18. Relief Canyon--Au, p. 157
19. Tonkin Springs--Au, p. 174
20. Windfall--Au, p. 183

31. Hawkes, H. E. and J. S. Webb. "Case Histories of Integrated Exploration Programs." Chapter in Geochemistry in Mineral Exploration. New York: Harper and Row, 1962, pp. 331-347. **** Three case histories in which geochemical, geophysical, and geological methods were integrated leading to the discovery and delineation of mineral deposits.

Combined geochemical and geophysical methods, Cont.

32. Reid, K. O., and M. D. Meares. Exploration for Volcanic-Hosted Sulfide Deposits in Western Tasmania. Econ. Geol. and Bull. Soc. Econ. Geol., v. 76, No. 2, 1981, pp. 350-364. **** Application of geophysical and geochemical exploration methods led to the discovery of the Que River massive sulfide deposit.

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In many cases, the subject matter has been cross-indexed for the reader's convenience. For example, the reference "Elliott, I. L. and W. K. Fletcher (eds.). Geochemical Exploration. New York: Elsevier North-Holland, 1975." can be found under the headings Geochemistry and Geophysics (Sec. 6.4) and Exploration and Economic Geology (Sec. 6.5).

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