Special Publication 12, 2006, pp. 221–241

Chapter 11

The Role of Geologic Mapping in Mineral Exploration

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Abstract

Geologic mapping provides many types of information essential both in exploration for new mineral deposits and during subsequent mining. Geologic mapping of outcrops is used to describe the primary lithology and morphology of rock bodies as well as age relationships between rock units. This information allows delineation of ore-bearing host rocks and postore rocks that obscure or truncate ores. Mapping gathers structural information, including attitudes of veins and postore faults that can be used to predict the geology in the subsurface or laterally under postore rocks, and improves the utility of geophysical data for refinement of subsurface targets. Mapping of the mineralogy of hydrothermal alteration zones, ore minerals, igneous rocks hosting ores, and oxidized and leached rocks that commonly occur at the surface above sulfide-bearing ores can be used in conjunction with geochemical data to produce zonation patterns to target potential ore or to define prospective corridors of exotic mineralization. Similarly, regional geologic mapping in regions with both Paleozoic-Mesozoic overthrusts and Cenozoic normal faults such as the Paleozoic and Mesozoic thrust belt of the United States Cordillera and Basin and Range Province can define prospective windows into basement where mineralization such as Carlin-type gold deposits may occur. In general, geologic mapping underpins the construction of three-dimensional geologic models or hypotheses that guide exploration and discovery and, when geologic time is considered, produces the four-dimensional space-time models necessary for understanding of primary ore formation processes and post-depositional modification by secondary surficial and tectonic processes.

Geologic mapping has been used extensively for exploration for more than 100 years and we predict it will continue to be essential although the tools for recording, compiling, and synthesizing data are evolving rapidly and improve data integration in the office and most recently in the field. Both traditional and future methods rely on field identification skills of the geologist to record salient new geologic data. This review describes the traditional paper- and pencil-based mapping system developed and used extensively by the Anaconda Company from 1900 to 1985 and, because of its versatility, adapted by many other geologists in industry and academia. This and similar systems allow geologically complex and diverse data to be recorded and plotted on a base map, including lithology, rock alteration and mineralization features, relative age relationships, and structural features such as faults and veins. Traditional paper-recorded geologic mapping data are now commonly converted to digital format in the office. We document use of mapping at different stages of the mine-life cycle from general regional-scale geologic mapping to regional- to district-scale exploration targeting, to deposit assessment and ore-reserve definition, through mine planning and production. Examples of mapping described herein include the Ann Mason porphyry copper deposit, Yerington district, Nevada; the Bajo de la Alumbrera mine; Argentina; the El Abra-Fortuna-Chuquicamata districts of Chile; and the Pioneer Mountains of Montana.

Beyond the use of traditional paper-based mapping methods, recent technological advances include global positioning systems, pen tablet computers, palm computers, and laser ranging devices that all support direct (paperless) field-based digital geologic mapping. Improvements in computation speed, memory, data storage, battery life, durability, screen visibility, and portability have made digital mapping practical in general field mapping, mine sites, and advanced projects. Portable digital-electronic instrumentation allows the field geologist rapid access to digital data bases that include geologic maps and photographic and remote-sensing imagery with automatic registration and scale independence. Another example described here, using digital mapping systems in the heavily forested portions of the Pioneer Mountains of Montana, shows how on-line GPS communicating directly to the pc tablet and digital orthophotographs made mapping sufficiently effective so as to discover a previously unknown granitic pluton with a concentric breccia zone.

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These new digital mapping tools may thus improve the efficiency of mapping and support a scientist in the field with unprecedented opportunities to map where field work has been difficult before. Visualization of geophysical or geochemical data together with geology and synoptic aerial imagery at any scale while mapping provides an integrated data base that facilitates identification of crucial geologic relationships. Digital techniques improve the potential for making conceptual leaps by exploring the available integrated data sets as a field geologist maps, and may in the future lead to more comprehensive three-dimensional geologic models for mineral deposits by effectively using information technology. The authors conclude that both paper and digital systems are powerful and each has certain advantages. However, the central challenge remains the training and nurturing of highly skilled field geologists motivated to practice their profession, welcoming both the rigors of intensive field work and the excitement of scientific discovery. It is surmised here that digital mapping technology may help attract an increasingly computer-literate cadre of new practitioners of mapping into mineral resource exploration.

Introduction

THE PROCESS of geologic mapping, either on the surface or underground, creates new geologic data and knowledge that contribute to earth information science, from which insights can be drawn now and in the future. However, exposed mineral deposits are becoming more scarce than ever. Many future targets will likely be buried under postmineral rocks, or occur at significant depth, or be in terranes with little previous geologic investigation. Hence, exploration strategies of the future must adapt to meet these challenges. Toward that end, geologic mapping provides new information in real time so that the field geologist can construct or upgrade geologic hypotheses for mineral occurrences. On a fundamental level, mapping addresses the questions, *how* do we know? and what do we *not* know? Hence, mapping is about practicing science in the field, armed with trained eyes and tools that allow us to observe, record, and interpret nature by construction of geologic maps. These maps become essential parts of the geospatial genetic models of ore formation that define and guide exploration by delineating the most prospective areas. The successful exploration geologist Harold Courtright is credited with saying, "a geologist has just two tools: boot leather and a drill" (Lowell, 1995, p. 3). Even now in the Information Age, this adage remains true. Vincent Perry, exploration geologist and vice president of Anaconda, was noted for saying that the two-dimensional rock exposures representing the earth's surface remain the best guide for exploration in the third dimension for subsurface ore deposits (V. Perry, pers. commun., 1985). There is no viable substitute for geologists observing nature up close and mapping what they see.

The purpose of this paper is hence three-fold: (1) to describe how geologic mapping provides many types of information essential both in exploration and mining, (2) to describe new digital mapping technology that is beginning to pervade field methods instruction, and (3) to possibly motivate renewed interest of a computer-literate generation in mineral resource mapping by providing powerful tools based on information technology.

Why do we need geologic mapping?

Scientific methods rely upon observations that must be recorded and organized so that they may be interpreted and explained. Geologic mapping should be designed to be the most effective method of recording and organizing geologic observations in the field, and geologic maps are used as a means of presenting the observations as well as constructing geologic hypotheses. In the so-called exact sciences, such as chemistry and physics, observations are made through experiment, and the validity of results depends upon how effectively and completely the variables that bear on the experiment are anticipated and controlled. In geology, the experiment has already taken place in nature and the task of the observer is to identify the principal variables and establish how these variables probably controlled the results. Processes that resulted in formation of geologic rock bodies such as ore deposits and zones of hydrothermal alteration were commonly controlled by a number of time-dependent variables that include temperature, pressure, and the density, viscosity, and composition of multiple fluids interacting with wall rocks of contrasting chemical reactivity over time. Later overprinting by hydrothermal, structural, or surficial processes such as oxidation, leaching, and enrichment are the norm and add to the complexity of ore-forming systems. Finally, preservation of ore deposits in the rock record depends on many factors, including paleo-climatic change and its control on erosion rates. A large number of careful observations are required to understand such diverse systems, and recording and organizing these observations requires geologic mapping methods sufficient for the task. Moreover, geologic maps represent a complex portrayal or melding of both data and interpretation. The former include observations that record data, such as the strike and dip of a bedding plane, a vein, or a fault, the relative ages of two rock types at a well-exposed contact, and the thickness of a bedded geologic unit. Given a well-trained geologist, these data may be reproduced relatively precisely. The interpretation is a more difficult task. It is based on the recorded observations and a geologist's ability to synthesize these into workable hypotheses based on the quality of the data, the geologist's training and experience, and the ability to visualize three-dimensional bodies that may have formed episodically over a great length of time and are subject to destruction over time.

Examples of important interpretations that are portrayed on maps include the location of a stratigraphic contact within a sequence of strata, the position and dip of a contact or fault that is not exposed, and the three-dimensional shapes of igneous and sedimentary rock bodies. Gathering high-quality data and making map interpretations consistent with the data that are scientifically robust represent a major challenge. Since geologic hypotheses guide all exploration, the practical and economic impacts of good geologic maps are immense. A geologic map, then, must be more than just a pattern of colors that shows what rocks are present on some part of the earth.

As noted below, geologic maps portray the shapes of three-dimensional rock bodies and structures that formed them over some length of time. The ability to predict what geology occurs at depth, i.e., the third dimension, is the key to exploration. Addition of temporal geologic data allows the geologist to construct dynamic conceptual models or hypotheses that guide concepts of ore formation and exploration. Together, the four time-space dimensions represented by geologic maps underpin earth science enquiry and exploration. Another paper in this volume (Barnett and Williams, 2006) addresses data mining, which is the process of assembling and interpreting the wealth of existing geological, geophysical, and geochemical information for use in exploration.

The Heritage of Geologic Mapping

Publication in 1815 of the first colored, hand-painted geologic map of England and Wales by William "Strata" Smith heralded the birth of modern geology (Winchester, 2001). Today, almost two centuries after this early mapping was done to locate bedrocks suitable for construction of canal systems, geologic mapping still plays an essential role in serving society, especially in exploration and mining operations. The professional standards for map production were set in the United States by colored folio sheets published by the U.S. Geological Survey (e.g., Lindgren and Turner, 1894a, b, 1895; Weed, 1897), motivated to support mining through the creation and publication of information of practical value.

Special Mapping Needs for Mineral Deposits

The geologic maps available today, either published by government surveys or in many scientific journals, are generally not well suited for special needs of mineral exploration and development, and therefore require exploration geologists to undertake specialized mapping. Whereas published maps of general geology do outline information essential to exploration, including rock units, stratigraphy, ages of rocks, and general structure, they are in most cases not sufficiently detailed to help delineate mineral deposits that are typically 1 to 2 km^2 in outcrop area even for world-class deposits. For example, areas this size are miniscule when plotted on the best maps available in the United States at scales ranging from 1:24,000 to 1:125,000. In most developing countries maps are published at 1:100,000 scale or smaller, or may not exist. Comprehensive regional mapping is typically outside the scope of mining company investment of time and funds. State and federal agencies, however, are uniquely equipped to conduct such long-term mapping projects and mining companies can benefit by providing guidance to help prioritize mapping regions. It is also imperative that exploration geologists stay abreast of the regional mapping done by these agencies. The utility of general regional mapping done by federal and state surveys in providing guidance for mineral exploration is exemplified by the 30-year record of mapping in north-central Nevada by Ralph Roberts and colleagues in the U.S. Geological Survey (Ramsey, 1973). This work, summarized in a short paper only two-and-one-half pages long (Roberts, 1960), stimulated Newmont geologists John Livermore, Alan Coope, and Bob Fulton to carry the study to a logical and useful conclusion by exploring for gold within the carbonate windows of the overthrust belt of Nevada, where some gold occurrences were known. Discovery of the Carlin gold deposits resulted from this program (Roberts, 1960, 1963; Silberling and Roberts, 1962). Thus, in similar cases, the exploration geologist's first role is, within the scientific context of available regional maps, to compile a reconnaissance geologic map of a specific region where mineralization can be anticipated reasonably. The geologist commonly records new mapping at a more detailed scale, of features essential to understanding mineral potential. These prospective corridors or zones allow for focusing of drilling in the most favorable situations so that financial resources are used to greatest possible scientific advantage and risks are minimized.

A second issue of published geologic maps is that they commonly lack many of the types of data useful to identifying mineralized rocks, although many published maps portray useful geophysical, geochemical, and remote-sensing data. Salient features associated with ores include veins and veinlets, wall-rock alteration, and evidence of sulfides or oxide ore minerals. Identification and plotting of these features are important for exploration but are not needed or plotted on standard geologic maps, in part because they lie outside the normal lithological units and structures recorded on published maps, and because many government and academic geologists lack sufficient mineral deposit training. As noted below, these special features must be recorded in addition to the common geologic data, and consequently mandate the specialized training and mapping methods that have been developed in the mineral industry and some academic programs.

A significant concern for the future is that while the need for bedrock geology maps that record relevant ore features remains strong in the mineral industry, the academic programs in the developed world have been reducing instruction and training in these areas (cf. Einaudi, 1996; Dilles and Barton, 2003; Bartos et al., 2006). Programmatic emphasis in academia has shifted away from mineral deposits toward geophysics, remote-sensing, environmental geology, geomorphology, hydrogeology, geo-microbiology, and global change; all areas of research which enjoy high enrollment pressures and are well-supported by federal funding. Given static funding in universities, investment in these growing areas of earth science necessarily reduces support for field training in the solid earth sciences relevant to mineral deposits. There is significant concern that the mineral industry lacks or will soon lack well-trained and high-quality field geologists (Sillitoe, 1999) documented by Bartos et al. (2006). Although long considered a rite of passage in the training of new geologists, field mapping no longer enjoys this prominence. Academic programs are not static and respond to both student enrollment pressure and employment opportunities (Einaudi, 1996). Short-term business cycles affecting recruitment adversely affect the interest in mining careers as well as the administrative support for field training. As new geoscience areas are added to programs, others are considered for curtailment. Field training, being relatively more costly in terms of both funds and faculty time, makes it vulnerable to such assessments except in departments where a significant number of faculty agree that systematic field training offers unique educational advantages and themselves routinely participate in instruction.

Examples of Geologic Maps for Exploration

Table 1 lists examples of geologic maps of important mineral districts that portray geologic information that helped guide exploration for similar ores worldwide. The list is by no means complete, and reflects the North American bias of the authors; many other fine geologic maps exist. In several districts or metal-bearing provinces, early studies by geologists of the U.S. Geological Survey outlined the main geologic and ore features, and subsequent geologic mapping in more detail has added new interpretations of the structure, stratigraphy, alteration mineral zonation, and intrusive history. The Comstock Lode illustrates this progression, from Becker's (1882) description of the geology, which includes a discussion of propylite, thought at that time to be a local type of volcanic rock, to the district-scale map of Thompson (1956), to the present detailed maps and cross sections of Hudson (2003) illustrating structure, volcanic stratigraphy, and hydrothermal alteration zones. Maps from Yerington, Nevada; Butte, Montana; El Salvador, Chile; the Mother Lode, California; the Carlin-type deposits of Nevada; and other localities also illustrate the evolutionary improvement of geologic mapping information. Notably, in the United States, geologic maps relevant to the mineral industry were once produced dominantly by the U.S. Geological Survey and state geological surveys, but are now mainly made by geologists with industry and academic affiliations (Table 1).

Mapping Methods

Whether a paper-based or digital mapping system is used, the goal of constructing a detailed and accurate geologic map requires that observations be plotted while the geologist is in the field, to the full extent possible. Areas of rock outcrop, ore minerals, and wall-rock alteration minerals are plotted on the map with a color or pattern, and features such as contacts, faults, and veins are located, followed, and plotted as lines. A solid line indicates a relatively precise location (e.g., ±10 m), and variety of dashed lines a less precision location. All structural measurements should also be plotted in the field to guide structural interpretation and for predicting projections of rock contacts and structures. Auxiliary notes should be taken to record information that is not practical to plot directly on the map, such as detailed lithology or fault descriptions. The practice sometimes used of plotting only field locations or noting stations while in the field and then attempting to construct a map later in the office from these locations and from the observations recorded in a notebook should be avoided. We note that regardless of the tools employed, making a good geologic map requires the best precision possible. An excellent map contains precise data that rejects many hypotheses and commonly produces a robust geologic hypothesis, whereas a map with poor data produces few constraints, multiple hypotheses, and a geologic muddle.

Paper-based mapping systems

The earliest geology mapping systems designed for recording features of mineralized rock bodies employed pencils and paper, and these remain the most widely used methods today. Scales range from reconnaissance (1:24,000 or smaller) to detailed project-scale (~1:100–1:12,000). Traditional paper-based mapping employs a topographic map, aerial photo, or gridded paper as a base, and the geologist plots features directly on the base or on clear overlays such as frosted mylar. In recent years, orthophotos and digital imagery, including remotely sensing infrared spectral images, have been added as bases in some cases. This mapping scheme is simple, flexible, and requires neither computer nor electronic devices, so it is ideal for the challenges of the field environment. It is inexpensive and robust as well. The method requires skill and neatness by the geologist to record data in a retrievable manner, but abundant data can be recorded relatively rapidly. Use of notebooks, queries, and solid-versus-dashed lines are essential to record the quality of the data mapped. Compilation of geologic, ore mineral, and wall-rock alteration maps required draftsmen as recently as 10 years ago, but it is now commonly done digitally either by the same geologist who did the mapping or by GIS-experts using computers with GIS, CAD, or drawing software. Paper maps permanently preserve the field data and interpretations, some of which are commonly not compiled on the completed maps. Occasionally there is loss of a small amount of information in translating field maps into completed maps if the compiler is not the geologist.

Anaconda mapping system: Soon after the U.S. Geological Survey folio sheets were produced in the late 1890s, industrial geologists, initially in the Anaconda Company in Butte, developed standardized mapping procedures for recording, compiling, and projecting underground vein mine structure (Linforth, 1914, 1933; Sales, 1914, 1929, 1941; McLaughlin and Sales, 1933; Peters, 1984, 1987).

Other mapping systems were developed in parallel by mine and exploration geologists with other companies, principally in the United States, Canada, Australia, western Europe and Russia, but because we are familiar with the Anaconda system and it is well documented and widely used, we describe only it in detail here. In 1890, David Brunton became a consulting geologist to the Anaconda Company in Butte where he field tested the Brunton com-

TABLE 1. Compilation of Some Historic and Recent Maps Illustrating the Evolution of Mapping Styles and Interpretive Impact on Understanding Ore Deposit Genesis

Author (affiliation[2])	Description	Scale	Significance and new concepts
Mesothermal quartz-Au veins (California, South Africa) and auriferous gravels, California			
Lindgren, 1911 (f)	The Tertiary gravels of the Sierra Nevada of California	1:750,000, 1:125,000	Auriferous river drainage systems and gradients
Lindgren and Turner, 1894 (f)	Placerville sheet (USGS Atlas Folio)	1:25,000	Crustal scale reverse fault system; rock types and veins
Evans and Bowen, 1977 (o)	Geology of the southern Mother Lode, California	1:24,000	Structure and hydrothermal alteration haloes on Au veins
Anhaeusser, 1974 (a)	The Sheba Hills area, Barberton mountain land, South Africa	1:31,680	Structural framework of Au lodes; Archean banded iron formation
Virginia City (Comstock Lode) epithermal quartz Ag-Au ores, Nevada			
Becker, 1882 (f)	Geology of the Comstock Lode and the Washoe district, Nevada	1:9,600	Long section of orebodies in Comstock fault; normal faults
Thompson, 1956 (f)	Geology of the Virginia City quadrangle, Nevada	1:62,500	District geology and Basin and Range normal faults;
Hudson, 2003 (a, i)	Geologic map of Comstock Lode	~1:48,000	Veins, multiple alteration zones, and structure of ores
Butte, Montana (porphyry Cu-Mo and lode Cu ores) and Boulder batholith			
Weed, 1897 (f)	Butte sheet (USGS Atlas Folio)	1:15,000	Boulder batholith
Weed, 1912 (f)	Geology and ore deposits of the Butte district, Montana	1:4,800	Main stage vein system, porphyries, faults; level maps
Sales, 1914 (i)	Ore deposits at Butte, Montana	1:8,800, 1:17,600	Structure; maps of alteration, leaching, secondary sulfides
Meyer et al., 1968 (a, i)	Ore deposits at Butte, Montana	~1:24,000	Maps of distribution of sulfides illustrate district metal zonation
Proffett, 1973 (i)	Structural geology of the Butte district	~1;48,000 to 1:480	Conjugate faults host Main stage veins; dikes; reopened veins
Ambler, Alaska, and Kuroko, Japan, districts (Volcanogenic massive sulfide)			
Hitzman et al., 1982 (a, i)	Bedrock geology of the Ambler district, Brooks Range, Alaska	1:63,360	Structure and stratigraphy related to deformed VMS deposits
Nakajima, 1989 (f)	Geologic map and resources, Hokuroku district, Japan	1:50,000	Marine tuffs, domes, and faults localizing VMS deposits
Yerington district (porphyry Cu-skarn), Nevada			
Knopf, 1918 (f)	Geology and ore deposits of the Yerington district, Nevada	1:24,000	Quartz monzonite porphyry dikes, faults, garnet skarn
Proffett,1977; Proffett and Dilles, 1984 (i, a)	Geologic map of the Yerington district, Nevada	1:24,000	>60° rotation of ores and host rocks due to normal faulting; batholith emplacement
Dilles and Einaudi, 1992	Wall-rock alteration and fluid flow paths, Ann-Mason porphyry Cu	~1:9,600 a	6 km vertical alteration zones around porphyry Cu deposit
Einaudi, 2000	Skarns of the Yerington district, Nevada (Ludwig area)	~1:9,600 a, i	Kilometer-scale mineral zonation in calc-silicate hornfels and Cu skarn
Carlin-type deposits, Nevada			
Roberts, 1951, 1960, 1965	Geology of the Antler Peak quadrangle	1:62,500 f,a	Recognition of Antler thrust system, its relation to ores
Moore, 2002;	Geology of the Carlin District, Nevada	1:24,000	Structure, stratigraphy, and intrusions localizing Carlin ores
Norby, 2002		1:18,000, i	El Salvador district, Chile (Porphyry Cu)
Gustafson and Hunt, 1975	The porphyry copper deposit at El Salvador, Chile	~1:10,000 i	Relative ages of veins, ores, and porphyry intrusions in map and XS
Gustafson et al., 2001	Multiple centers of ore in the Indio Muerto District, Chile	~1:40,000 i	District-scale, multiple porphyry centers, alteration and ores

This compilation is not intended to be complete, nor representative, as it reflects the authors' North American experience and bias
[1] Primary affiliation of authors: a = academic, f = federal government, i = industry, o = other

pass (Brunton, 1901). In 1890, David Brunton became a consulting geologist to the Anaconda Company in Butte, where he field-tested the Brunton compass (Brunton, 1901). As a result of Brunton's work with Horace Winchell, the rudiments of a working mapping system describing the complicated fault systems emerged (Mining Engineering, 2004). Walter Weed of the U.S. Geological Survey and Reno Sales and Anaconda coworkers at Butte developed the first system to map ore distribution in Main Stage lodes in the early 1900s, motivated by predicting ore on new mine levels (Weed, 1912; Sales, 1914; Sales and Meyer, 1948). The resultant Anaconda mapping system made use of colored pencils to record details of ore veins shown in red and faults shown in blue, typically at scales of 1:120 to

1:600. Geologic understanding of the Butte ore deposit grew, and by 1970 veins were divided into red for sulfide ore and orange for gangue (quartz). Brown, orange, and green were used for sericitic, white argillic, and green argillic wall-rock alteration, respectively (Miller, 1973; Proffett, 1973; Brimhall, 1977). Because Butte ores were found in lodes, typically 10 cm to several meters in widths, each vein orientation was noted with a strike, dip, and width. Geologists recorded data on small individual field sheets (21 × 28 cm) to facilitate working in cramped quarters in stopes and raises and then transferred information to a slightly simplified compilation sheet, typically 1 × 1 m (cf. Meyer et al., 1968).

At Butte, the mine level plan maps and serial cross sections provided the basis for three-dimensional scale models relating vein and fault structures in once-separate and competing mines. The maps and models were used by Anaconda in exploration and mine development for a century and during the early years, in resolution of vein apex mining law litigation. Beginning in the late 1950s, the earlier vein mapping system was adapted to record the small veins and higher temperature hydrothermal alteration features of porphyry Cu-Mo mineralization (Brimhall, 1973) in parallel with such mapping at El Salvador, Yerington, and Chuquicamata.

The Anaconda system was exported to Chile, where in the decade of the 1960s it was modified and improved at El Salvador to record features characteristic of porphyry Cu-Mo deposits. Descriptions and recording of vein minerals and related alteration selvages led to better understanding and classification of narrow veins (<10 cm in width). For example, many workers now use the El Salvador designation of A, B, and D type veinlets for early, discontinuous, narrow quartz and copper sulfide veins with potassic halos, younger and more continuous quartz and molybdenite veins, and late and continuous pyrite and quartz veins with sericitic selvages, respectively (Gustafson and Hunt, 1975; Table 1). The mapping schemes were first employed mainly for underground drift and crosscut mapping, but later for logging drill core. With the advent of open-pit mining, more ready access and daylight made it easier to obtain accurate field data.

The Anaconda system further evolved to the current system during mapping of the Yerington open-pit mine by Charles Meyer, John Proffett, Marco Einaudi, and others in the late 1960s and early 1970s. The Yerington mapping scheme is designed to record rock type, contacts, structures, veinlets, sulfide ore minerals, and wall-rock alteration characteristic of porphyry Cu-Mo deposits, but its flexibility allows adaptation to other types of ore deposits. Marco Einaudi instructed Stanford students at Yerington in the method for 30 years, and recently produced a detailed colored guide (Einaudi, 1997) which serves as the basis for this summary (Fig. 1). The system requires a set of 10 sharpened colored pencils; individual colors record vein types, ore minerals, and alteration minerals in both mafic and feldspar mineral sites. Although the Anaconda system described here was developed for porphyry-type mineral deposits, it can be easily modified for other deposit types such as porphyry-epithermal gold ores (Muntean and Einaudi, 2000). As many as 30 individual minerals can be plotted, and colors graphically record key data. The base map is a line that represents the mine bench or tunnel wall, which is mapped at waist or shoulder level via compass and tape or survey instrument.

Contacts, faults, and veinlets are plotted with true orientation on the "rock side" of the base line, and show via schematic or actual offset the relative ages of these planar features (Fig. 1). Vein types are recorded by plotting a color corresponding to the principal mineral in the vein. The density of veins is recorded by measuring the average width of the veinlet type and average spacing; for example, 0.5/50 cm represents 0.5-cm-wide veinlets spaced 50 cm apart with a resultant density of 1 vol percent. Parallel vein sets can be estimated individually this way and the volume percents of multiple sets of different orientations summed for a total volume percent. Sulfide minerals are represented by colors (red = chalcopyrite, yellow = pyrite, etc.) or, in the case of oxidized exposures, oxide minerals are plotted with the corresponding colors (e.g., red = glass limonite or Cu-pitch; yellow = jarosite-rich limonite). Sulfides and oxides are shown as either dots for disseminations or line segments for fracture-filling, with an estimate of total sulfide or oxide volume percent, proportions of ore minerals (out of 10 or 100 total), and ratio of disseminated to vein ore mineral (D/V) all shown in notes.

On the "air side" of the base line, wall-rock alteration is mapped as two lines parallel to the base line. The inner line records via a color one or more hydrothermal minerals that replace the primary igneous mafic mineral or minerals—for example, biotite (olive green) or chlorite (dark green) replacement of hornblende. The outer line records one or more mineral(s)—for example, sericite (brown)—that replaces primary igneous feldspars. Degree of sericite replacement of feldspar is shown with a solid line (100%), dashes (partial), or dots (scant), and may be further quantified in notes. In addition, a line showing the main alteration mineral or mineral assemblage within selvages to veinlets is shown on the air side, away from the rock face, on the projection of the veinlet. For example, typical "D" veinlets, in the usage of Gustafson and Hunt (1975), are pyrite ± quartz veinlets with sericitic selvages and may be illustrated as a yellow line for the vein on the rock side of the bench and a brown line for the selvage or halo on the air side. The connection of the veinlet filling to its corresponding selvage can also be noted by the abbreviation Py±Qz//Ser, where the "//" separates filling from selvage, following the method of Seedorff (1987) and Seedorff and Einaudi (2004).

The Anaconda and similar mapping systems are powerful because they force the geologist to make numerous observations, carefully record them in map view, and think about their implications. For example, in porphyry exploration, targets may be predicted based on an increase in the density of quartz veins, on the pattern and orientation of D-veinlets, or on an increase in proportions of chalcopyrite or other Cu-Fe sulfides to pyrite (cf. Einaudi, 1997). Compilation of detailed map observations on the prospect scale can

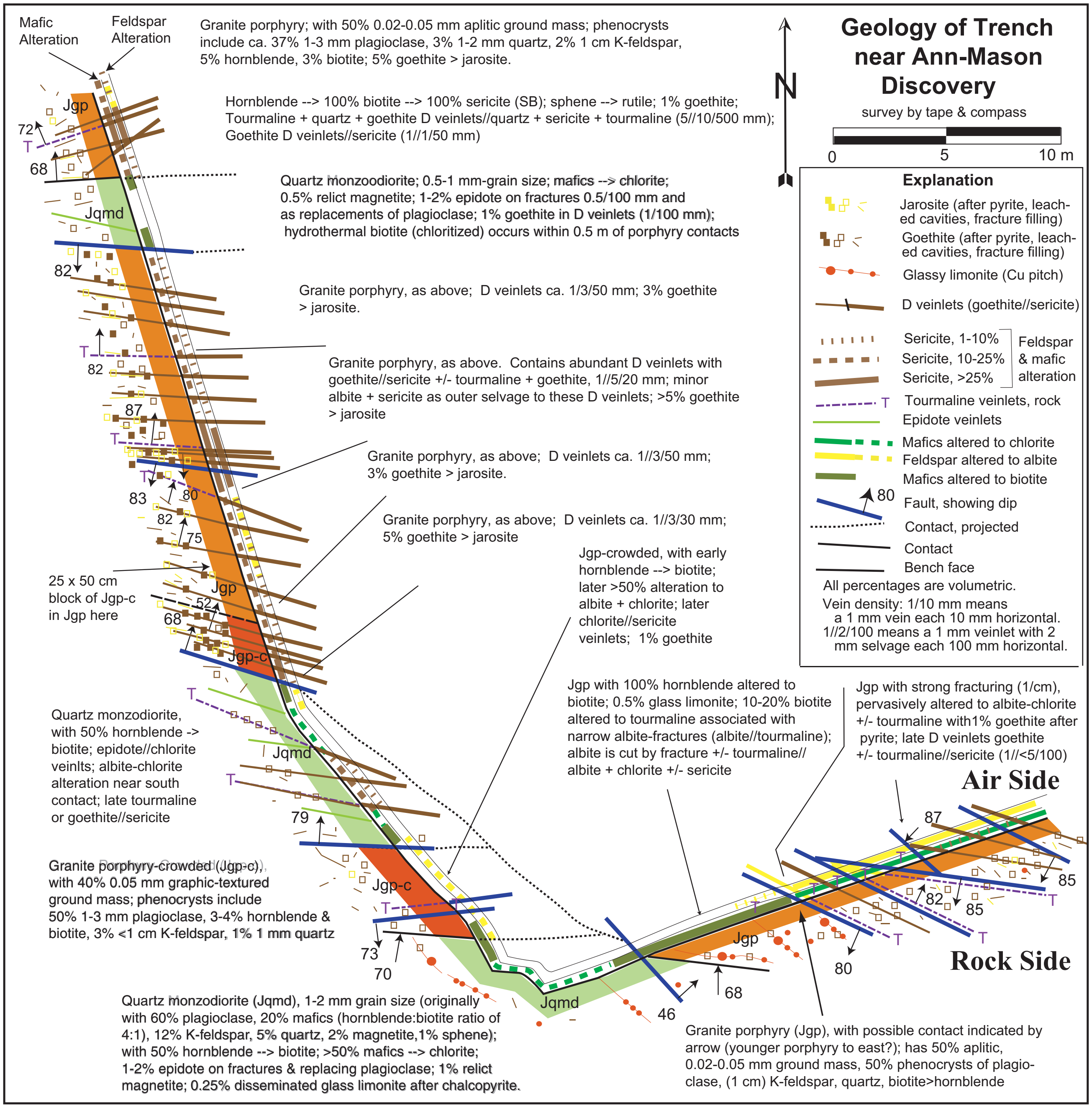

FIG. 1. Tape and compass map of the Ann-Mason discovery trench modified from Dilles et al. (2000b). This map is a simplified version of the Anaconda method of mapping in which the geologist records the following: rock type and structure; alteration mineral in primary mafic mineral and feldspar sites; vein mineralogy, density, and alteration selvage; and ore mineral (hypogene or supergene) occurrence and percentages. The method is fully described by Einaudi (1997). Abbreviations: Jgp = granite porphyry, Jgp-c = granite porphyry, crowded texture, Jqmd = McLeod Hill quartz monzodiorite.

reveal vein, sulfide, or oxide, or wall-rock alteration zoning in plan map view, and these can be used to predict the subsurface or third dimension.

A key aspect of all geologic mapping, but particularly important in mineral deposits, is establishment of the relative ages of geologic events expressing the fourth or time dimension. In porphyry and other hydrothermal environments, crosscutting relations between veins or between veins and intrusions are used to establish relative ages. An example of a diagnostic criterion is where one vein offsets or displaces another. Care must be taken with interpretation of relative ages where there is no offset. A certain type of vein may form over a significant length of time or in multiple temporally separated events (cf. Seedorff and Einaudi, 2004). In contrast, individual dike- or plug-like intrusions may usually be considered geologically short-lived events and serve as useful time lines in the life of a magmatic or hydrothermal system. In many cases, several stages of porphyry dikes can be recognized on the basis of porphyry contacts that truncate sets of veins. Recognition of late, poorly mineralized, or postmineral porphyries is essential to exploration targeting and exploitation.

Alteration assemblages, associations, or types may be further interpreted from the mapped mineral distributions and notes. In granitic rocks where only one original mafic mineral can be mapped, the geologist must decide how to record complex or multiple alteration events that may result in zones of biotite, chlorite, and sericite in mafic mineral sites (cf. Seedorff et al., 2005). Such relationships are usually recorded as notes on the map sheet. Ti-bearing minerals such as titanite, Ti-magnetite, ilmenite, and most mafic minerals are very useful, and require additional notes beyond the graphic system. Because Ti is often immobile in alteration, the Ti in these minerals remains as Ti-oxide (rutile or leucoxene) pseudomorphs, providing valuble clues to original rock mineralogy and composition, especially in intensely altered rocks.

Mapping district—scale hydrothermal alteration: The exploration geologist often examines large areas in reconnaissance (e.g., 1:24,000 or smaller scale) and records data on plan maps using topographic, aerial photo, or orthophoto bases. In addition to traditional mapping of lithology, geologic contacts, structure, and major veins recorded directly on the base map, it is also useful to show features of hydrothermal alteration and mineralization. This may be done by adding one or more overlays—for example, a transparent mylar atop the geologic map—or schemes may be devised to plot alteration and mineralization on the same sheet as rock type and structure. There are several approaches that have been developed by geologists in exploration and academia (see another example in Einaudi, 1997), and Figure 2 illustrates one technique used by Dilles (1984). A mineral that replaces the primary feldspars in the rock is recorded as a northwest-southeast–oriented diagonal colored line (100% replacement) or dashed line (partial replacement). A mineral that replaces the primary mafic minerals in the rock is recorded as a northeast-southwest–oriented diagonal colored line. The colors are coded to individual minerals (Fig. 2). In addition, sulfide and oxide ore minerals are recorded with shorthand notation. Veinlets, associated selvages, and densities can also be recorded. Individual mineral or assemblage distributions, notes, and veins are used to construct, generally in the office after supplemental geochemistry and petrography is available, a map of mineral assemblages or alteration types (e.g., Dilles and Einaudi, 1992).

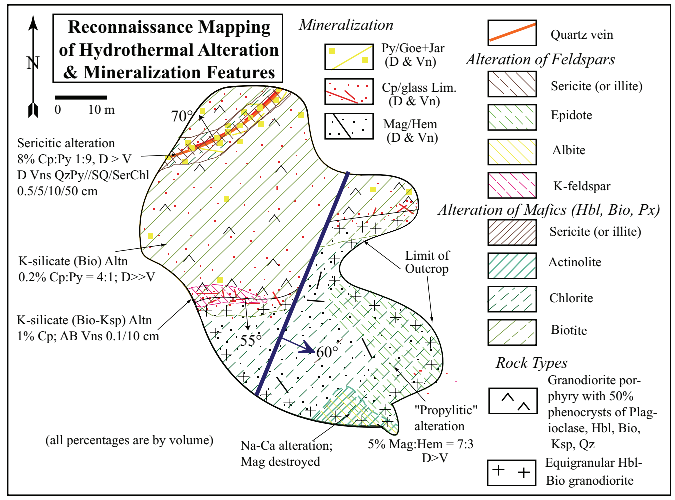

FIG. 2. Illustration of simple reconnaissance techniques, from Dilles (1984, unpub.). Outcrop, contacts, structure, veins, and lithology are plotted on a base map. Alteration minerals are plotted on an overlay: northwest-southeast sets of diagonal lines record a single mineral replacing feldspars, whereas northeast-southwest sets of diagonal lines record one or more minerals replacing mafic minerals. Ore minerals are recorded on the overlay, as either hypogene minerals (chalcopyrite, pyrite) or supergene minerals (glass limonite, goethite, jarosite), as appropriate for the area. Solid lines designate 100 percent replacement, whereas dashed lines are partial replacement. Notes record widths, percentages, and densities of veins and ore minerals. Abbreviations: Altn = alteration, Bio = biotite, Chl = chlorite, Cp = chalcopyrite, D = disseminated, Goe = goethite: Hbl = hornblende, Hem = hematite, Jar = Jarosite, Ksp = K feldspar, Lim = limonite, Mag = magnetite, Px = pyroxene, Py = pyrite, Qz = quartz, Vn = vein or veinlet.

Digital mapping on pen tablet portable computers

Digital mapping requires exactly the same geologic skills as mapping using paper-based maps but uses digital versions of base maps on portable computers and a stylus to delineate geologic features instead of paper-based maps and colored pencils. Digital base maps can be included as topography, orthophotos, or satellite images. Digital mapping systems are composed of various combinations of computer hardware, software, and analytical devices and are currently being adopted in many parts of the world (Jackson and Asch, 2002). New geologic mapping, or what is referred to as data capture, using Geographic Information System (GIS) terminology, is displayed on the screen of a portable computer often supported by a global positioning system (GPS) integrated with maps so that locations appear on the screen in relation to other graphical features. Laser range-finding devices with built-in digital tilt sensors (or accelerometer-based alternatives) and magnetic compasses can map features at distances of several hundred meters by triggering a laser as long as the geologist can discern the nature of the object being delineated remotely. Digital mapping allows the combining of graphical mapping tools, maps, GPS, and lasers into a single computer-based system. As with paper-based systems, a geologist can create and interact with evolving map patterns, but the access to other digital data is improved so that they may have a truly integrated knowledge of their local and regional surroundings in real time using information technology to advantage (Kramer, 2000; Brimhall and Vanegas, 2001; Brimhall et al., 2002). Geophysical maps are easily coordinated with geology. When geologic mapping is assisted by using a laser range-finder and/or a GPS to locate points, lines, and areas, the digital map becomes three-dimensional as each observation is recorded with (x, y, and z) coordinates. Three-dimensional data is then easily exported into a three-dimensional GIS system which is now widely used by the mining industry to compute ore reserves and construct plan maps and cross sections. Since the pen tablet computers used for mapping can be zoomed in and out at will, mapping is essentially scale independent. This feature lends a considerable flexibility to modulate detail easily via enlarging or shrinking the scale according to the size or spatial density of features to be mapped, without loss of information. Map production is thus direct and simple and may reduce the loss of information, the time, and the personnel required to produce completed maps. The disadvantages are that additional training is required for use of pen tablet computers and software, and especially the unavoidable fact that the electronic systems and mapping software are expensive and sometimes fail. Digital data formats can change as well, which puts retrieval of archived data at risk. Such issues are intrinsic to evolving computer-based systems. As more digital applications are made, a more stable configuration will emerge with time. These issues aside, the compilation step, which is also present with paper maps, is greatly reduced for digital maps, thus offsetting some of the cost of purchasing digital equipment. Nonetheless, it is still essential to rethink the validity of each contact and observation in making the compilation. Hence, digital mapping systems can speed training through visual user interfaces that are geologically intuitive and through mandatory standardization. For example, the computer will not allow a mapper to proceed until he/she assigns a number to a sample collected. Similarly, colors, line styles, and widths are easily standardized in a mapping program.

At present, there are inherent advantages and disadvantages to both paper-based and digital mapping systems. As outlined above, however, it is difficult to quantify the time and cost of each system. Paper-based systems clearly require less capital and human training and allow data to be gathered more flexibly and quickly in the field, but require additional time in the office to digitize and standardize interpretations. As a new technology coming into wider application, computer-based systems are inherently slower in the field at first, until a user gains proficiency. As with paper-based mapping, corrections need to be made and this is now easily accomplished using some digital mapping programs while still difficult with others. Computer-based mapping allows standardization and relatively rapid compilation of maps by numerous authors, and are well suited for mines and exploration with large databases in well-established mineral districts. Both systems require the same fundamental geologic knowledge of lithology, mineralogy, structural geology, and stratigraphy. In considering both paper and digital mapping methods, it is our view that the geological skills remain the greatest barrier to construction of useful geologic maps for mineral exploration, not the methodology.

Role of Mapping in Mine Life

Mapping and the closely related activity of drill-hole logging contribute to many stages in the life of a mine which, as used here, includes exploration, definition of ore reserves, mining and reserve expansion, and post-closure environmental reclamation. Mapping is done as part of regional geologic synthesis, orientation surveys, and scout or wildcat drilling, exploratory drilling, mine development, production, mine life extension, closure, and long-term environmental management.

Exploration targeting

Geologic mapping is widely used in planning exploration strategies, such as the selection of regions to explore for certain types of ore deposits. Prior to mapping campaigns, existing geologic maps are examined and may be compiled to emphasize key geologic features to assess exploration potential. Examples include the identification of belts of submarine volcanic rocks with potential for volcanogenic massive sulfide deposits and belts of shallowly eroded intermediate-to-silicic volcanic and shallow intrusive arc rocks, with potential for porphyry copper and copper-gold deposits. Geologic maps available for examination before an exploration program commences are commonly the work of government-sponsored geological surveys. Exploration geologists commonly use existing maps as the basis for preliminary examinations to assess mineral potential, frequently in conjunction with geochemical, geophysical, or remote-sensing surveys or compilation of mine and prospect data. At the stage of an exploration program when large regions are being selected, the kind of mapping activity most often undertaken is reconnaissance to help refine existing mapping, to confirm its validity, and to become familiar with the rocks as well as to examine known metal occurrences. In addition, the exploration geologist uses knowledge of mineral deposits to identify areas of hydrothermal alteration, sulfides, or veins.

With the above methodology, a minerals company generally outlines several prospective areas, acquires for some of these the rights to mineral resource extraction, and then seeks to define specific exploration targets. The geologic mapping at this stage generally is done at a more detailed and larger scale than published mapping, and key lithologic units and features of mineralization or hydrothermal alteration are mapped using the reconnaissance techniques outlined above. Trenching with attendant detailed geologic maps and rock sampling for geochemistry are commonly conducted at this stage.

The examples below illustrate the value of geologic mapping for portraying age relations that record the fourth dimension of geologic time. Understanding the nature and shapes of postmineral rock bodies is essential for targeting in covered or partly covered areas. Mapping of cover rocks can provide information on the depth of cover to be expected over potential targets.

Ann-Mason Pass porphyry copper deposit, Nevada: An example of the use of geologic mapping in exploration targeting is provided by Anaconda's discovery, in 1967, of the Ann-Mason Pass porphyry copper deposit in the Yerington district, Nevada, (Fig. 3A). Prior to 1967 surface exposures of pyritic mineralization with sericitic alteration in Jurassic porphyries had been drilled without success. Detailed mapping between 1966 and 1968 (summarized in Proffett, 1977, and Proffett and Dilles, 1984) showed that all Tertiary volcanic and older rocks in the district had been tilted steeply west, and were cut by east-dipping normal faults, the oldest of which now dip gently (Fig. 3A). This resulted in two important conclusions. First, the porphyry ore deposits in the district were tilted, and so geology in map view needs to be interpreted as pretilt cross sections. And second, the volcanic rocks bordering the Ann-Mason prospect area on the north, even though they dip steeply, are truncated at depth on a gently east-dipping normal fault (the Singatse fault: Fig. 3A), indicating that any target beneath them might be within reach.

During the period that the prospect area was being mapped, detailed mapping and interpretation of known porphyry deposits in the district (the Yerington mine, a few kilometers to the east, and the "Bear" prospect to the northeast) was also underway with guidance from Chuck Meyer and John Hunt. The studies showed that these deposits are associated with swarms of Jurassic porphyry dikes and plugs that are situated, in pretilt orientation, above the roof of a pluton of genetically related porphyritic granite (Luhr Hill Granite). They also showed that the ore was enclosed within zones in which secondary biotite had replaced hornblende and, at depth below the ore, was a zone of secondary oligoclase alteration associated with chlorite or actinolite. Late, overprinting sericite-quartz-pyrite alteration was situated around the upper sides and top of the secondary biotite zones. These patterns, though more familiar now, were largely unknown in 1967 and had been developed through detailed mapping at El Salvador, Chile (later to be published by Gustafson and Hunt, 1971, 1975), as well as by the work at Yerington.

Mapping in the Ann-Mason Pass area showed that a major swarm of granitic porphyry dikes and stocks was situated to the west or, in pre-tilt orientation, above the roof of another part of the same pluton of Luhr Hill porphyritic granite, as was the Yerington mine. Mapping defined an alteration pattern with secondary oligoclase at the east end of the porphyry swarm in the pre-tilt root zone and with sericite-quartz-pyrite alteration at the west end in the pre-tilt upper part. Small areas of secondary biotite alteration with local low-grade chalcopyrite-bornite mineralization, some of which had been drilled earlier, were exposed at the edges of the Tertiary volcanic cover. It was concluded that a porphyry deposit could be associated with the Ann-Mason Pass porphyry swarm and that it could have been preserved down the dip of the dikes (present-day orientation) beneath the Tertiary volcanic rocks. Induced polarization and magnetic surveys suggested possible sulfide and magnetite-destructive alteration beneath the Tertiary volcanic cover in support of the evidence provided by mapping. The first drill hole confirmed that the Tertiary volcanic rocks bottomed on a low-angle fault, a concept which had remained controversial. However, the hole location, which had been based partly on geophysical interpretations was north of the axis of mineralization and encountered only weak pyritic mineralization. The next two holes were located farther south and encountered more abundant sulfides in the axial part of a porphyry-style mineralized zone, with chalcopyrite to pyrite ratios increasing southeastward along the axis. Subsequent holes southeast of these drilled a half-billion-ton body of porphyry-style mineralization averaging ~0.4 wt percent Cu with a moderate Mo content (Dilles and Einaudi, 1992). The deposit has not yet been developed, partly due to the >200 m of volcanic cover but it includes some zones of higher grade.

Yerington district: Mapping such as that illustrated in Figure 3A was extended to cover the entire Yerington district, and has allowed reconstruction of the geometry of the entire Yerington batholith and related ore deposits including those discussed above (Fig. 3B; Dilles and Proffett, 1995). Porphyry Cu-Mo and skarn Cu deposits associated with granite-porphyry dike swarms focused above the top of cupolas on the cogenetic Luhr Hill granite. K silicate, sericitic, and local advanced-argillic alteration also reflect these foci of mineralization above granite cupolas. Maps of igneous rocks and hydrothermal zones thus demonstrate that multiple porphyry-related targets can occur in a single batholith. In addition, mapped zones of sodic-calcic alteration where nonmagmatic fluids leached Fe, Cu, and possibly Au have been proposed to have been related to Fe oxide–Cu-Au deposits in the contact aureole at Pumpkin Hollow and the Minnesota mines (Fig. 3B; Dilles et al., 2000a, b).

Bajo de la Alumbrera, Argentina: Geologic mapping at Bajo de la Alumbrera in Argentina (Proffett, 2003a, b) provides an illustration of some features in peripheral zones of porphyry copper deposits that could be useful in exploration and that illustrate the importance of the time dimension in geologic mapping. As noted earlier, making geologic observations is a four-dimensional problem, with three space dimensions and time, but observations are normally recorded on a two-dimensional medium, such as paper, mylar, or computer screens. An essential part of geologic mapping, therefore, is to record information about the third space dimension and time.

At Alumbrera, as in many other deposits, the potassic alteration zone which contains the orebody is surrounded by epidote-chlorite alteration commonly referred to as propylitic alteration (Fig. 4). The presence of such alteration in isolated outcrops or drill holes in covered areas could therefore indicate the presence of an orebody nearby. Parts of this propylitic zone as well as the central potassic zone are overprinted by later sericite-quartz-pyrite alteration controlled by pyritic D-veinlets (Fig. 4). As in several other porphyry deposits (for example, Gustafson and Hunt, 1975), the D-veinlets define a radial pattern centered around the center of the orebody (Fig. 4; Proffett, 2003b, Map 4). At Alumbrera, some of the porphyry dikes, of several ages, also define a radial pattern, and some of the veinlets define a conic concentric pattern. The combination of the propylitic alteration and the radial and concentric pat-

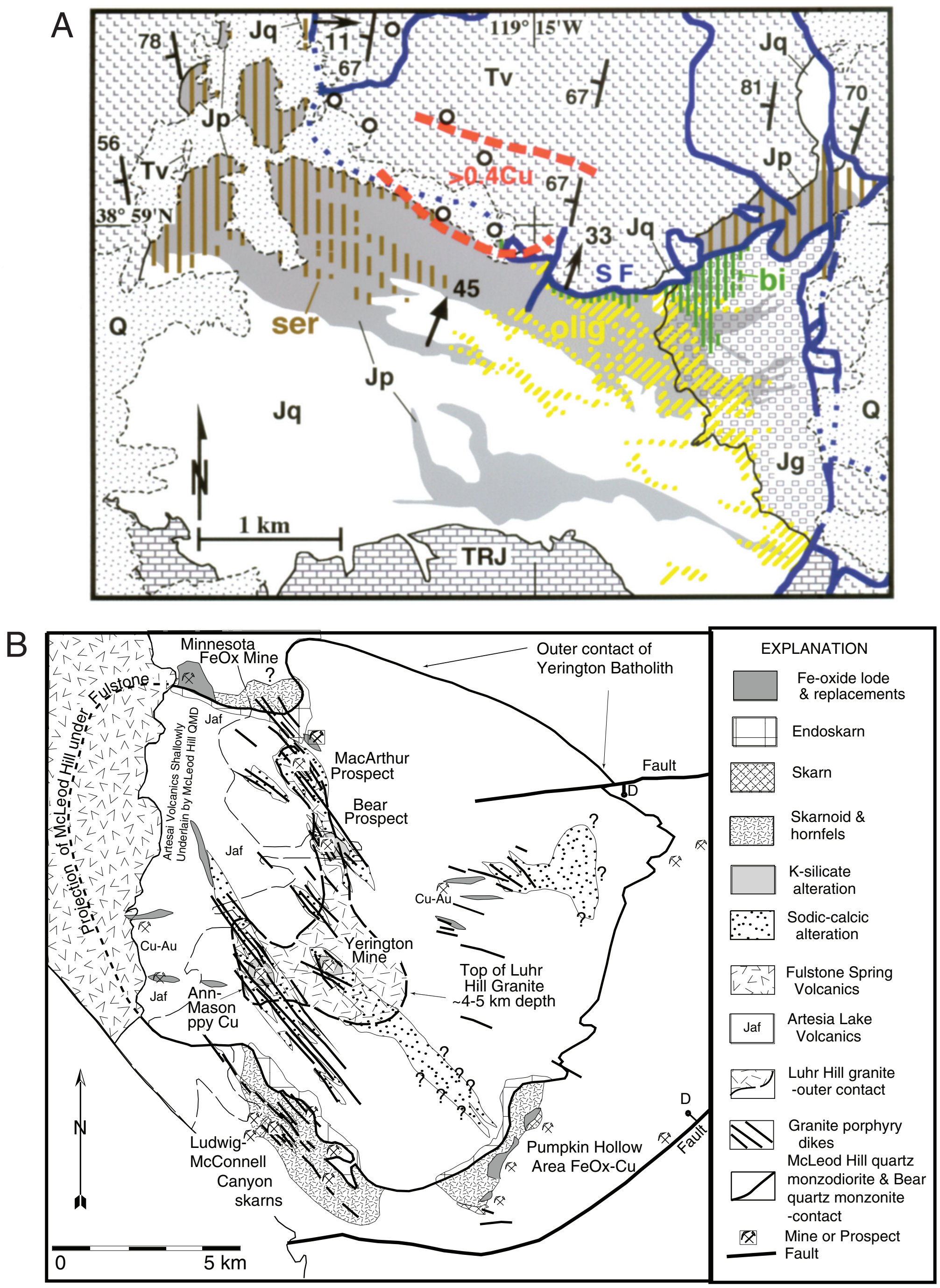

FIG. 3. A. Simplified geologic map of the Ann-Mason Pass area, Yerington district, Nevada. Jg = Jurassic Luhr Hill porphyritic granitic pluton; Jp = swarm of ~50 percent granitic porphyry dikes and small stocks, generally north dipping, in Jg or Jq; Jq = McLeod Hill equigranular quartz monzodiorite and Bear quartz monzonite; Q = Quaternary alluvium; SF = Singatse fault; Tv = Tertiary volcanic and minor sedimentary rocks; TRJ = Triassic and Jurassic sedimentary and volcanic rocks. Green vertical line pattern = secondary biotite alteration; yellow diagonal line pattern = secondary oligoclase and albite alteration; brown vertical line pattern = sericitic-pyritic alteration. All Jurassic igneous rocks are part of the Yerington batholith. Only a few of the earlier drill holes from 1967-1968 are shown (open circles); many other drill holes and body of >0.4 percent Cu are between the red dashed lines. Based on mapping by J. M. Proffett, 1966–1968, with additional information from Proffett and Dilles (1984), Dilles and Einaudi (1992) and from unpublished sections by D. L. Gustafson (1971, pers. commun.). B. Middle Jurassic Yerington batholith in plan view at estimated 1 km paleodepth, as reconstructed by removal of effects of Cenozoic normal faulting (Proffett, unpub. data; Dilles and Proffett, 1995; Dilles et al., 2000a). Porphyry Cu deposits and skarns (>5 Mt Cu) are associated with granite porphyry dikes above cupolas on the late Luhr Hill granite at the Yerington mine and Ann-Mason, whereas Fe oxide-Cu deposits fringe the batholith.

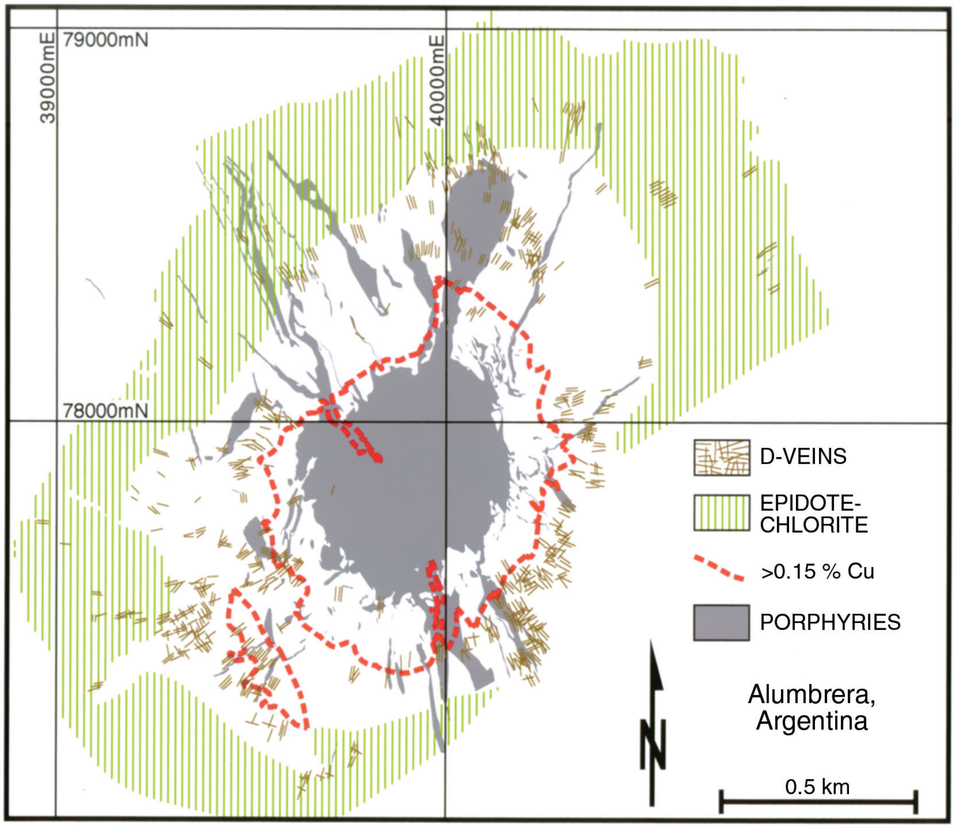

FIG. 4. Map of Bajo de la Alumbrera, showing some features in the peripheral part of the deposit that might indicate a covered target during exploration. Mapped D-veins are shown with a radial and concentric pattern. D-veins dip toward the center at moderate angles. Generalized from Proffett (2003), Map 4. Porphyries of all stages have been grouped together and comprise a central cluster surrounded by peripheral dikes in a crude radial pattern, with a preferred north-northwest orientation. The area inside the epidote-chlorite, analogous to propylitic zone is the potassic zone. Adapted from Proffett (2003b).

terns would obviously provide a powerful tool in the application of mapping to exploration.

The time dimension is important because there are at least two types of alteration and mineralization containing hydrothermal chlorite that are often referred to as propylitic in many porphyry systems, and these can be distinguished only by mapping time relationships. The type that is peripheral to the potassic zone is relatively early. At Alumbrera this type contains significant epidote and epidote veinlets but lacks sulfides. Careful observation and mapping showed that the epidote veinlets are crosscut by pyritic, sericitic D-veinlets, and by the latest porphyry dikes, but are themselves overprinted by sericite-quartz-pyrite alteration. A second type of alteration that is also referred to as propylitic is weak feldspar-destructive alteration in which mafics are altered to chlorite and feldspars are partially altered to sericite, clay minerals, calcite, or chlorite. This type of propylitic alteration is associated with disseminated pyrite and occurs as outer halos of D-veinlets. It likely constitutes a type of intermediate argillic or weak sericitic alteration. In some cases these outer halos may be quite wide and those around multiple D-veins may overlap, resulting in a pervasive zone of chloritized mafics. Such alteration could simply be an outer halo around a zone of sericitic alteration, which in turn may or may not be related to porphyry-type mineralization.

District-scale exploration targeting

The previous section emphasized the use of geologic mapping to target individual hydrothermal systems, but geologic mapping is also essential for district-scale understanding in order to predict potential ore environments within a broad mineral district, especially in areas with postore mineralization, rock deposition, and deformation. For porphyry Cu-Mo and volcanogenic massive sulfide deposits, there is a need to understand the geometries of causative igneous bodies as well as the hydrothermal mineral and ore zones, and the effect of postmineralization structural offset and tilting. Two examples follow for district-scale exploration.

El Abra-Fortuna-Chuquicamata districts: In northern Chile, large porphyry Cu-Mo deposits are spatially associated with the West Fissure and various hypotheses have been proposed for genetic links between them. Geologic mapping of late Eocene plutons, their host rocks, and the West Fissure has resulted in a hypothesis that in the Chuquicamata region the West Fissure postdates most or all ore formation

(Tomlinson and Blanco, 1997). The Fortuna granodiorite complex west of the fault (Fig. 5A) is correlated with the El Abra granodiorite complex on the east side, but offset sinistrally by 35 km of West Fissure displacement (R. Baker, unpub. report, 1978; Dilles et al., 1997). Restoration of the postmineral displacement yields a single late Eocene plutonic complex associated with at least five significant porphyry Cu-Mo deposits containing at least 30 million tonnes (Mt) of Cu as well as numerous prospects, all of which are associated with granite porphyry dikes near cupolas of the cogenetic Clara-Fiesta granodiorite. As of 1984, only the El Abra deposit had been identified but, in 1985, Cyprus-Amax identified a large porphyry Cu resource east of El Abra beneath the old Anita mine (Cu oxide) at Conchi Viejo, based on the mapping of porphyry dikes associated with strong sericitic alteration controlled by meter-wide quartz-pyrite D-veins. Beginning in the early 1990s, Codelco sponsored geologic mapping by Sernageomin of the West Fissure between Calama and Quebrada Blanca. By the late 1990s, Codelco began a program of drilling under gravel cover in the southern end of the Fortuna granodiorite complex where several small Cu prospects occur and geologic mapping at 1:50,000 by Sernageomin (Tomlinson et al., in press) had identified several small porphyry plugs as well as zones of skarn and calc-silicate hornfels. In conjunction with geophysical studies, Codelco drilled through alluvium to discovery the Toki, Genovese, and Queteña deposits (the Toki cluster; >18 Mt Cu resource; Rivera and Pardo, 2003). Geologic mapping campaigns by Codelco have been completed at 1:50,000 and are now being done at 1:25,000 and 1:5,000 to further evaluate the geology and prospects in the Fortuna and El Abra areas, and have resulted in drilling several subeconomic resources. In northern Chile, geologic mapping has helped understand both the nature of postmineral structural offset and the fact that a single large batholith with a central granitic pluton and cogenetic porphyry dikes can generate numerous mineral deposits, a relationship recognized at Yerington; Highland Valley, British Columbia; El Salvador, Chile; and Sierrita-Esperanza, Arizona (McMillan, 1985; Titley et al., 1986; Gustafson et al., 2001).

The concept that several porphyry deposits can occur in a single district, whether or not the underlying pluton is exposed, is being used to target new deposits within known

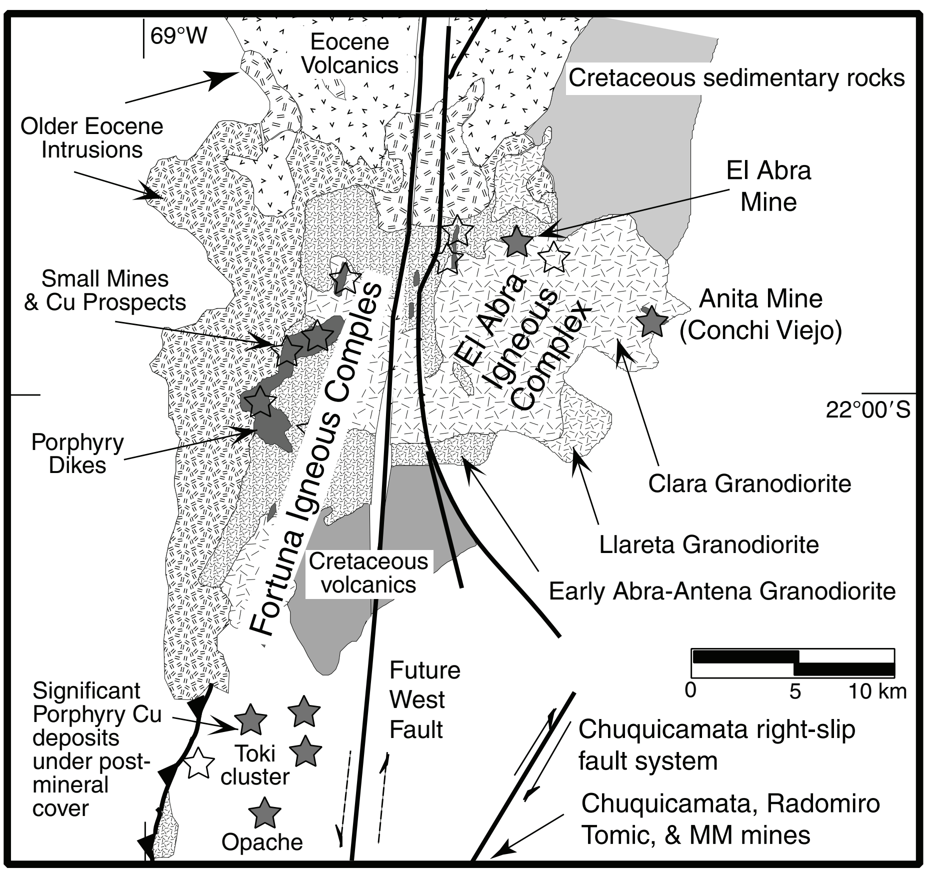

FIG. 5. The Late Eocene El Abra-Fortuna plutonic complex, Chile, as reconstructed by removal of 35 km sinistral offset by the West fault system (Dilles et al., 1997; Tomlinson and Blanco, 1997). Exposures are estimated to have been at 3 to 4 km paleodepth during the late Eocene. Porphyry Cu-Mo mines and prospects (>30 Mt Cu) are related to San Lorenzo-Abra granodiorite porphyry dikes above cupolas on the late, light-colored Clara granodiorite.

mineral districts in conjunction with geophysical data and mapping of porphyry dikes, hydrothermal alteration, and sulfides. Several recent discoveries of porphyry deposits, in addition to the Ann-Mason and Toki deposits noted above, have made use of geologic mapping and include Resolution, Arizona (Manske and Paul, 2002); Collahuasi (Rosario) and Ujina, Chile (cf. Munchmeyer et al., 1984, as shown on frontispiece, *Economic Geology*, vol. 100, no. 6, 2005; Hunt, 1985; Dick et al., 1994).

Mine planning, development, and production

There are two main reasons that mapping remains an essential part of exploration. First, mapping (and drill-hole logging) creates the geometric patterns that represent the geologic attributes of an exploration target. Second, there are scientific, engineering, and financial implications of mapping because subsequent geophysical modeling, ore-reserve estimation, financial forecasting, and economic evaluation are based on the interpretation of such work and drill-hole logging. Most critical to the economics of a project are assays that define its in situ value as well as the spatial variability of the orebody. While assaying directly supports mining, it is often impossible to interpret assay patterns without an appreciation of the geologic controls on ore, marginal ore, and waste. Increasingly, geologists are expected to map not only ore, but also to delineate other rocks such as acid-generating waste rocks, reactive limestone gangue which can serve as neutralization agents, or material for bentonite barriers to retain fluid in geochemically designed waste rock or leach impoundments.

Throughout the life of a mine, many of its features change, including the shape and size of an open pit, underground stopes, and waste-rock piles. Even those features designed to be static, such as mine shafts or haulage and ventilation networks, may be adversely affected as mining proceeds. Some changes are predictable—such as subsidence above block cave zones—and are an unavoidable consequence of extractive processes, while others—such as shaft failure—are clearly not and stem from incomplete knowledge or risk assessment not being borne out by reality. Mapping thus provides essential data for interpretation to assist operating mine engineers in conducting periodic reevaluations involving production optimization modeling and associated risk management. Mapping is also an essential part of geotechnical modeling and planning; for example, of pit-wall stability, which affects the behavior of rock masses being mined, mine installations and equipment, and safety.

Adding value through map-based decision making: Geologists apply their technical expertise in a host of ways. Schutz et al. (2004a, b) describe adding value in Newmont's Nevada gold mines in three main settings. The first setting is value creation through discovery and development of ore reserves. The single most important value-added activities of field geologists is the construction of the basic geologic and ore-grade model upon which all other work is based. The second setting is in mine support, such as ore control, selective mining, reduction of dilution of ore by waste and mixing of ore types, metallurgical support, reconciliation investigations, and strategic planning. This step includes geotechnical mapping of faults and fractures that could represent potential slope failure zones and metallurgical sampling for design of extraction processes. The third setting is opportunity recognition, by which geologists respond to changing environments developed as mining proceeds and problems arise that require geologic data and reasoning.

More broadly, effective communication is an important goal of maps and remains one of the key challenges facing the geologic community (Turner and Clague, 1999). Not only do geoscientists working in mines need maps, but the value-added information they create is essential to making decisions in planning, operations, and emergency preparedness.

Advances that Can Increase the Productivity of Geologists

The imperative of geologic mapping in discovery of orebodies and on-call problem-solving during mining places a serious challenge on geologic staff to provide accurate geospatial knowledge in a timely fashion. Advances in computer hardware, software, and digital electronic devices have evolved over the past three decades and continue to increase the productivity of geologists making maps and communicating new map information. The advantages of computerization are especially evident in advanced prospects and mines, for which vast amounts of data can be managed and portrayed more efficiently using digitally made maps and sections. Such ubiquitous application of computing in the office has advanced much faster than use of computers in the field. Perhaps this disparity has contributed to the fact that many geologists spend too little time in the field and too much time in the office.

Beginning in the 1960s, computerized ore-reserve programs ran on large main-frame computers to calculate tonnage and metal grades of ore deposits based on block models. Later, geostatistical methods using kriging of regionalized, three-dimensional variables improved ore-reserve estimation. The new field of geostatistics grew from these applications (Matheron, 1963) and provided practical methods for estimating directional variabilities in three dimensions (Variograms) from which cost effectiveness of continued drilling could be ascertained. As desktop computing became commonplace, computerized drafting programs were used in the office to digitize geologic maps made in the field on paper. This technology also reduced the size of office support staff used by geologists to maintain ore-reserve and digital-map data bases for operating mines.

GIS revolution

Although ore-reserve programs equipped with powerful geostatistics and graphics capabilities were widely used by the mining community, the revolution in geospatial science came more from the field of geography, where cartographic representation lies at the heart of spatial analysis. Geographic Information Systems (GIS) emerged as a broad tool with universal appeal (Goodchild, 1992; Worboy, 1997). GIS applications are now widespread in government, economics, medicine and health services, social sciences, political science, biological sciences, landscape architecture, and city and regional planning, among many other fields. Commercial GIS computer programs have become available to anyone with a personal computer. GIS also became the ubiquitous companion of ore-reserve utility programs. Access to public domain maps and digital data bases became much easier through an array of standard data file-type formats and import and export functions. A common standardized global coordinate system of Universal Transverse Mercator (UTM) and local reference ellipsoids such as NAD 1927, NAD 1983, or WGS 84 laid the ground work for widespread use of global positioning systems (GPS) for field location of geologic data. Considering all the digital electronic advances to date, GPS has had the greatest influence. However, it is extremely important that the specific reference ellipsoid used in determinations of locations with GPS be indicated on maps and contained in the metadata files, data bases, and reports, because there can be major differences in locations from one ellipsoid to another.

Office map production

The GIS revolution and availability of commercial software that supported map digitization, processing, and printing rapidly propelled office map production well ahead of digital field-mapping methods. Digital mapping in this sense is a process of conversion of original paper-based maps made by geologists in the field to digital record form from which identical paper maps may be printed at desired scales. Map compilation, however, still requires judicious geologic interpretation to verify that the basic constraints on map patterns and age relationships are maintained. Hence, many geological surveys in the United States, Europe, and elsewhere (Jackson and Asch, 2002), and mining and environmental companies have adopted a range of software for their map production process, including ESRI (ArcInfo, ArcView, and Arc Map) products which are the most widely used. MicroStation and MapInfo are used to a lesser extent.

Remaining challenges in office digital map production involve scientific and technical standards which reduce inconsistencies in the geologic legends and in creation of comprehensive relational digital data bases that support geologic compilation faithful to the field relationships mapped (Soller and Berg, 2001; Soller et al., 2001). Previously, paper geologic map series tolerated inconsistencies between map sheets but GIS and related digital systems demand coordination and consistency in features mapped (Jackson and Asch, 2002).

Systematic regional map production: U.S. national geologic map and data base

Whereas widespread use of GIS computer programs in map compilation provides powerful advantages over paper technology and can offer much to the mining community, digital map compilation of large regions such as entire countries also places serious demands on data uniformity, coordination, and financial support. For example, in the United States, a systematic approach was taken with leadership provided at the national level by the U.S. Geological Survey. Each state geological survey undertook its own production of a state digital map. However, so far very little new mapping was conducted, as this effort is one of digital compilation and production. The goal was to make a comprehensive national geologic map with coverage of each state at 1:24,000 scale by 2020 with complementary national geophysical and geochemical map data bases, including production of $1° \times 2°$ sheets at 1:250,000 scale. One such 2° sheet map coverage is described below for southwestern Montana. A broad objective was to support application of geologic map information to resolution of growing land-management issues. These challenges include mineral and energy exploration, water resources and quality, background geochemical concentrations in soils, industrial mineral supply near rapidly expanding urban centers of population growth, and resolution of competing land use needs of urbanization, recreation, agriculture, and conservation (Brierley et al., 2004). Throughout the 1990s federal and state agencies replaced much of their paper-based cartographic functions with GIS application-based user services. The U.S. Geological Survey and all state geological surveys acquired a stewardship service orientation and undertook a thorough transformation of their paper-based map production to digital data bases accessible from anywhere in the world though internet portals. The guiding motto became "science for a changing world," and maps and related data bases play an integral role.

Map information available from the U.S. Geological Survey with application to exploration includes the following: georectified Digital Orthophoto Quads (DOQ); Digital Raster Graphics (DRG), which are scanned images of USGS topographic maps; Digital Elevation Models (DEM) with terrain elevations; Digital Line Graphics (DLG) for roads; Land Use and Land Cover (LULC) records showing built-up land, agricultural land, rangeland, forest, wetlands, and ownership, and satellite-acquired photography as Digital Satellite Images.

Dynamic digital maps

The U.S. Geological Survey has made large strides in providing remote access to web-enabled maps through their dynamic digital map program (Condit, 1995, 1999a, b, 2004). A Dynamic Digital Map (DDM) is a stand-alone presentation manager program that displays downloads of maps, images, movies, data, and supporting text, such as map explanations and field trip guides. The downloads are stand-alone programs that run without other software. DDMs have been converted to the cross-platform Revolution (Rev) programming environment, a port that includes making DDMs WEB-enabled. This work included creating a DDM-Template (an open source Revolution program) into which anyone interested can insert maps, images, movies, text, and data to make their own DDM. DDM examples have been made for two volcanic areas (the Tatara-San Pedro volcanic complex in Chile and the Springerville volcanic field in Arizona, originally published by the Geological Society of America [GSA] on CD-ROM; Condit, 1995).

Regional stratigraphy in digital form: The AAPG COSUNA chart series

Like the U.S. Geological Survey, the American Association of Petroleum Geologists (AAPG) has made significant advances in digital map production with comprehensive regional coverage. Of particular utility to geologic mapping is the AAPG Correlation of Stratigraphic Units chart series (COSUNA). On a single CD-ROM, all known stratigraphic sections of the entire United States are available in digital format so that creating a new mapping legend of an area is straightforward (Brimhall et al., 2002). The term "correlation" is used because the charts afford an opportunity to easily visualize the stratigraphy from one column to another over an entire region (such as the western United States), and to recognize facies changes. The charts span the entire country in 20 geographic regions, including Alaska. Geologic information includes lithology, age, thickness, and formation names (Childs and Salvador, 1985) from which effective mapping legends can be readily constructed for essentially anywhere in the United States. All charts come as Adobe Acrobat pdf files and show several thousand stratigraphic columns positioned within an index plan map for the 20 regions. The sections are based both on drill-hole information and on surface geology. COSUNA charts show all stratigraphic sections in a region by their column number and geographic name with formations positioned vertically down through time with their dominant lithology color coded, including sandstone, conglomerate, shale, carbonate, chert, igneous rock, ultramafic rock, and metamorphic rock. Whereas the AAPG COSUNA database is obviously oriented toward sedimentary rocks and petroleum interests, data bases for igneous and metamorphic rocks are also being compiled (Walker et al., 2004). A continent-scale map of North America has been compiled by the AAPG using a litho-tectonic classification (Muehlberger, 1996). This AAPG map combines rock type and age of deformation with tectonic processes that have contributed to the geologic evolution of the North American continent and shows sea-floor geology as well. Like the AAPG, the GSA has now published a new geologic map of North America that also shows sea-floor geology, including subduction zones. However, the continental portion of the GSA map (Reed et al., 2005) uses conventional nomenclature and color coding. The AAPG has also published a geothermal map of North America (Blackwell and Richards, 2004) of potential use in mineral exploration for deposits related to active and recently active hydrothermal systems.

Direct paperless geologic mapping in the field

Digital map and data base production advanced far faster in the office than in the field because of the vast resources invested by the U.S. Geological Survey and AAPG, and by the fact that staff working in the office environment could utilize conventional desktop computers running commercial map production software. In the field, computing requirements are much more stringent, with changing lighting conditions, limitations in availability of electrical power and physically demanding conditions. Only in the past few years have hardware and software become available that effectively support digital mapping in the field. Important requirements include portability, transflective daylight readable screens, backlit screens for use underground in darkness, sufficient battery life for a day of work, lightweight design, small size, reasonable cost, and ruggedness and resistance to moisture, temperature, and humidity variations. Unfortunately, until there is widespread use of pen tablet computers, the costs will remain higher than for conventional indoor computers. Nevertheless, some of the advantages to direct digital or paperless mapping may outweigh higher costs to a segment of the field geology community, due to the subsequent time and cost savings in the office.

Practicing geology supported by digital technology using GIS

In addition to map production using digital methods in the office, Goodchild (1992) acknowledged the need to practice science in the field by attempting to answer, in real time, the scientific questions motivating one's field work. In practice, this means creating maps in the field using either traditional paper or digital methods. Maps have traditionally been created in the field with pencil and paper. The ability to do this digitally has now become a reality as digital electronic hardware is finally catching up to the state of development of software (Kramer, 2000; Brimhall and Vanegas, 2001; Brimhall et al., 2002). By far the most effective devices for digital mapping are portable pen tablet computers with daylight-readable color screens and sufficient memory and storage capacity to manage large complex geologic and image files.

As described above, geologic mapping has scientific traditions stemming back almost 200 years that are still relevant and that require specific types of data recordation. Aspects of mapping include strike and dip, topography, rock formations, outcrops, and vein structures. All of these features have contributed to discoveries of mineral deposits. These geologic entities must be fully supported by procedures amenable to computer programming and input by a stylus, GPS, or laser (Brimhall and Vanegas, 2001, Brimhall et al., 2002). To illustrate digital mapping capabilities and advantages in both new mapping and compilation, we describe here regional field work in Montana using a field mapping computer program called GeoMapper. Other software systems for direct digital mapping using pen-tablet computers include ArcPad (ESRI) and GVMapper (GeoVectra, Santiago, Chile).

GeoMapper computer program

A digital mapping computer program called GeoMapper was devised at the University of California, Berkeley, to implement the Anaconda mapping system using digital tools (Brimhall and Vanegas, 2001; Brimhall et al., 2002). GeoMapper uses a computer program called PenMap, which provides surveying capabilities, device drivers for GPS and lasers, raw graphics elements (points, lines, and areas), and map file handling (Kramer, 2000). It also can export mapped features in a wide variety of digital formats. GeoMapper is the front end of the system and provides the visual user interface that allows a geologist to implement the Anaconda style of mapping using intuitive, self-explanatory buttons that are touched using a stylus. A detailed description of the features and use of GeoMapper is given in Brimhall and Vanegas (2001) and Brimhall et al. (2002).

Mount Fleecer area, Wise River district, Pioneer Mountains, Montana: An illustration of regional-scale digital mapping shows its utility. Digital mapping systems were used to map a granitic pluton in the heavily forested portions of the Pioneer Mountains of southwest Montana (Fig. 6A). The granitic pluton, herein named the Parker Creek pluton, is a satellitic plug occurring 2 km immediately north of the Big Hole Canyon pluton (Zinter, 1981; Zinter et al., 1983), which is part of the Pioneer Mountains batholith (Pearson and Zen, 1985; Zen, 1988). These plutons were intruded along the axial plane of a regional-scale anticline related to the late Cretaceous overthrust belt of Montana. Some of the plutons in the Pioneer Mountains are mineralized. There is long history of mining in the region (Pearson et al., 1988), and exploration continues today. Ore deposits in the area include carbonate replacement Pb-Zn-Cu-Ag-Au deposits of the Hecla and Bryant mining districts (Karlstrom, 1948; Gignoux, 2000; McGuire, 2003), and the calc-alkaline low-fluorine Cannivan Gulch porphyry Mo deposit (Armstrong et al., 1978a, b; Rostad et al., 1978; Schmidt et al., 1979; Hammitt and Schmidt, 1984). Orthophoto imagery (Fig. 6B) was used to help locate scant outcrops efficiently. On-line autonomous GPS allowed mapping of contacts through the dense forests. These digital methods afforded an efficiency superior to traditional methods and encouraged mapping in areas previously unmapped because of remoteness and difficult access, forest cover and topography unsuitable for determining accurate locations. Mapping using GeoMapper in the Mount Fleecer area led to the recognition of a previously unknown granitic pluton with a nearly complete coaxial breccia zone (Fig. 6A) and a gabbro dike swarm.

These new digital mapping tools may improve the efficiency of mapping and support a scientist in the field with unprecedented opportunities to map where field work has been difficult or slow before. Even under fairly dense tree cover, an on-line GPS allows location where topographic control is insufficient (Fig. 6A, B). While dense forest canopies can preclude reception of GPS signals, conifer forests often permit effective GPS reception with a signal to noise ratio that is not excessively low. GeoMapper also provides a means to enter all field data into a comprehensive data base which retains the seminal scientific record of the actual outcrops mapped. Thus, later on, other geologists can easily locate these outcrops, being certain of their position, and examine and re-sample them. Digital field photos showing the location and direction of the camera view are plotted as symbols on the map. Similarly, field samples are located and a detailed description becomes part of the digital data base. Simultaneous viewing of multiple layers on the screen of the pen tablet pc allows the geologist to visualize information such as geophysical or geochemical data along with geology and synoptic aerial imagery at any scale while mapping and thus utilize a truly integrated data base.

Map scale independent integration of multiple maps and data bases in real time

In addition to working at any scale, an equally advantageous aspect of digital mapping systems is that multiple digital maps can be visualized simultaneously using the pen tablet pc on the outcrop. Digital orthophoto quadrangles and satellite images can help a person mapping find outcrops and reduce unproductive time. In addition, the geologist's new mapping may be integrated with regional or local geologic, geophysical and geochemical digital data. This data fusion, a long-standing part of traditional mapping, allows real-time interaction at any scale with existing maps and interdisciplinary digital data sets. Furthermore, with digital mapping the map image can be continually centered so that the geologist is not working at the edge of a mapping sheet. An on-line GPS unit set in "auto-scroll" mode does this centering automatically during mapping; otherwise, a mapper can scroll manually using the pen stylus. Hypothesis testing, a key part of the scientific method, is well served by mapping because an evolving map pattern motivates a prepared observer to seek key exposures. Time management is thus well served and important new geologic features can be discovered and mapped in the least amount of time. Whether or not interpretations are made using integrated geology and geophysical data bases, direct digital mapping potentially offers the ability to get field geologic data into digital format in a shorter amount of time. Nonetheless, the scientific thought process involved in geologic mapping cannot be replaced by technology.

Integration of geophysics with geology: Given the progress made in production of the National Geologic Map of the United States in digital format, geophysics now can be readily integrated with geologic mapping. An example is the Pioneer Mountains map of Montana, published as a 1° by 2°, 1:250,000 scale map with associated geophysical data (Ruppel et al., 1993). In Figure 6, aeromagnetic (6C) and Bouguer gravity anomalies corrected for terrain and isostatic-residual gravity anomalies (6D) (Hanna et al., 1993) are associated with the composite dioritic Big Hole Canyon pluton mapped in Fig. 6A. In particular, both magnetic and gravity anomalies, M38 and G38 respectively, occur in the south-central portion of the map area shown and relate to the mafic phases of the composite Big Hole River granitic pluton, especially the hornblende gabbro (Khg), quartz diorite (Kgdm), and inclusion-rich granodiorite plutons (Kgdi) through which the gorge of the Big Hole River occurs. More broadly, gravity and aeromagnetic anomalies can be interpreted in geologic terms useful in exploration. Possible interpretations include density contrasts of mapped units, depth to basement below basin-fill sediments, and the thickness of sedimentary formations resting on unconformities beneath which may be mineralized rocks. On an even larger scale, geophysical interpretation of crustal structure and its correlation with the distribution

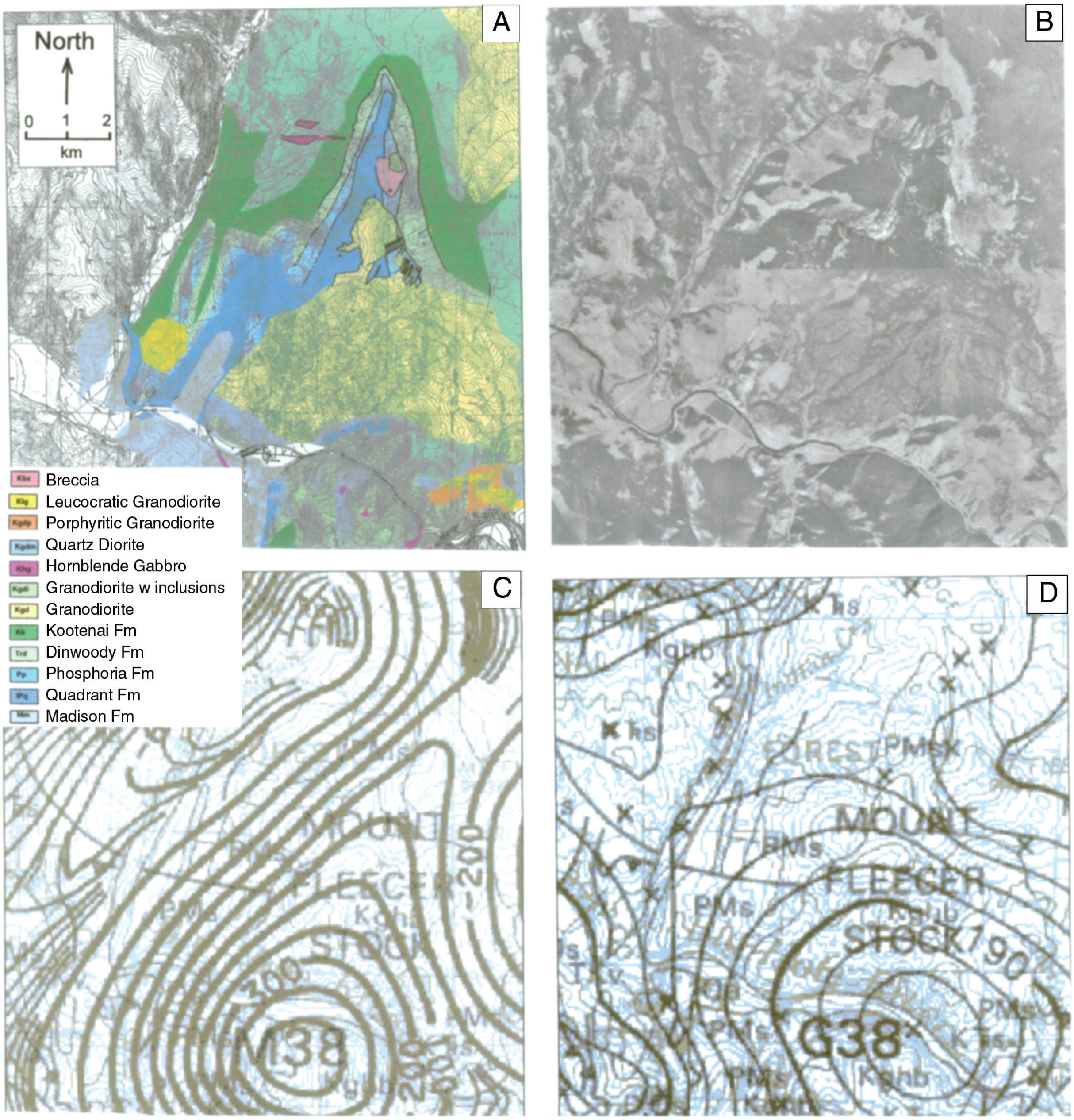

FIG. 6. A. Geologic map of the Mt. Fleecer Area, Wise River, Montana. Digital mapping by Brimhall and associates in areas where contacts are shown with black line. Other areas without black contacts were digitized using GeoMapper from earlier paper-based mapping by Zinter (1981) and Ruppel et al. (1993). B. Orthophotograph. C. Aeromagnetic map showing the geophysical expression of the composite Big Hole Canyon pluton as a magnetic high (M38). D. Gravity anomaly map showing a positive anomaly G38) near the pluton. B, C, and D at same overall area and map scale as geologic map shown in A.

of ore deposits potentially offers powerful insights to guide future exploration (Hildenbrand et al., 2000), and also to help explain in tectonic terms the sporadic occurrence of giant ore deposits.

Conclusions

Geologic mapping by geologists in the field continues to generate useful new data and understanding of geologic relationships and scientific insights difficult to gain otherwise. Mapping plays an important role throughout the mine life cycle, from regional- to district-scale exploration targeting, through drilling and ore discovery, to deposit assessment, ore-reserve estimation, preproduction mine planning to production and, ultimately, to mine closure. Traditional paper-based detailed techniques for recording data relevant to mineral deposits as developed by mining companies, such as the Anaconda system, can now be adapted to direct digital mapping systems. Digital mapping is fully feasible and allows geologic field mapping to incorporate a wealth of information in digital base maps in real time at any scale, and thus may increase efficiency and interpretive power. Furthermore, use of on-line GPS can support mapping in areas where previous work was limited by remote access or unavailability of base maps for location purposes, thus opening new opportunities for discovery. However, there are two limitations to GPS usage related to the attenuation of GPS signals by objects between the satellite transmitters overhead and the ground GPS receiver. The most common obstacles encountered while mapping are excessively dense tree cover and steep walls in valleys.

It is imperative to the continued success of mineral exploration that an investment is made to attract, train, and retain new practitioners of field geology regardless of which mapping system they choose to use. What matters is that highly skilled field geologists are motivated to practice their profession in the field, welcoming both the rigors of intensive field work and the excitement of scientific discovery. We surmise that digital mapping technology will help attract an increasingly computer-literate cadre of new practitioners of mapping into mineral resource exploration.

Acknowledgments

The authors sincerely thank Marco Einaudi and Jack Parry for thorough and thoughtful reviews which included contributing significant material to this paper, and Larry Meinert for helpful comments of a late revision. Brimhall is grateful to undergraduate students at UC Berkeley who worked with him in mapping parts of the Wise River district of Montana and to his colleagues, Paul Renne and Doug Dreger, who co-teach the summer field geology class. Brimhall also gratefully acknowledges on-going support for field camp by Berkeley alumni, including Charles Booth and Richard Nielsen, whose careers in industry were motivated by early field experiences and whose generosity now helps sustain these classes for students today. The Anaconda Company supported the Ph.D. research and also employed all three authors of this chapter early in their careers. Pen-based digital mapping instrumentation was funded by grants from the NSF Division of Undergraduate Education (DUE-9850980) to the University of California, Berkeley, and Oregon State University, with matching funds from UCB and by another grant to UCB by NASA RESAC (NAG5-6515).

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