Fault Surface Maps: Three-dimensional Structural Reconstructions and Their Utility in Exploration and Mining

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ABSTRACT

Mineral deposits that have been dismembered and tilted by syn- or post-mineral faults can be structurally reconstructed to achieve scientific and practical objectives. Fault surface maps are plan-view projections of the geology of the footwall and hanging-wall surfaces of a fault, showing rock units, faults, and other features. Here, we describe how to construct fault surface maps, how to present them efficiently in publications, and how to use them to make three-dimensional, stepwise structural reconstructions, restoring the hanging-wall map against the footwall map. Areas of complex geology containing multiple generations of faults with differing slip directions especially benefit from the use of fault surface maps for three-dimensional reconstructions. Where there are adequate geologic markers and three-dimensional control, the restoration results in numerous slip vectors across the fault surface from which the magnitude of slip in the plane of the fault can be calculated for each vector. Additional geologic constraints are required to assess the amount of tilting that occurred concurrent with slip on each generation of faults. To achieve a three-dimensional structural reconstruction of an area, the restoration process is repeated from youngest to oldest faults, working backward in time.

Older faults appear as single lines, commonly known as cutoff lines, on both the footwall and hanging wall surfaces of younger faults. Faults that moved synchronously with the fault surface being mapped (e.g., splays of the same fault) appear as a single branch-line trace in the same position in both footwall and hanging wall maps. Younger, crosscutting faults appear as gaps in the fault surfaces of older faults that are identically positioned on footwall and hanging wall maps, and the gaps widen in the direction of increasing displacement or decreasing dip of the younger fault. Examples from normal faults in the Robinson and Yerington mining districts, Nevada, illustrate the differing appearances of fault surface maps of early generations of faults versus later generations of faults. The types of movement that achieve a restoration differ depending on whether the portion of a normal fault being restored is near or far from either tip where the displacement diminishes to zero. Near-tip regions commonly display an important rotational component pinned near the tip, whereas mid-fault regions are dominated by a down-dip translational component.

Fault surface maps provide an efficient method for portraying the locations and types of three-dimensional geologic controls, thereby allowing readers to see more clearly where geologic interpretations are well constrained versus loosely constrained by the available data. This allows users to evaluate the validity of a proposed reconstruction better, to develop and evaluate alternative hypotheses more easily, and to dispense with unviably alternatives more readily. Structural reconstructions historically have led to discoveries of offset continuations of known orebodies and of new orebodies. Use of fault surface maps for reconstructions facilitates a more three-dimensional approach to mineral exploration in complexly faulted regions, such as certain parts of the Basin and Range province.

Key Words: Fault surface map, Structural reconstruction, Yerington district, Robinson district, Basin and Range province

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INTRODUCTION

Structural reconstructions attempt to undo the effects of secondary deformations that distort the primary geometry of rock units. In shallow continental extension, the principal deformations are normal faulting and to a much lesser degree distributed strains between faults. Structural reconstructions play a significant role in addressing certain scientific and practical objectives. Reconstructions can reveal something of scientific interest, such as tectonic and structural processes that lead to extension of the crust (e.g., Gans and Miller, 1983; Colgan et al., 2010), the original geometry of calderas (e.g., Colgan et al., 2008), and the original geometry and scale of ore-forming systems and the processes that formed them (e.g., Shaver and McWilliams, 1987; Seedorff, 1991; Dilles and Proffett, 1995; Stavast et al., 2008). Likewise, reconstructions can have implications for exploration and production (e.g., Maher, 2008; Nickerson et al., 2010).

Important challenges in achieving an actual structural reconstruction of deformation, however, are the completeness of subsurface geological constraints available to delimit fault geometry and displacement. Moreover, faults in three dimensions can be non-planar, and displacements can show gradients along strike. Challenges also lie in conveying and applying the results of reconstructions such as to reveal the extent of the geologic constraints available, to test the validity of the reconstruction itself, and to move toward three-dimensional reconstructions, in the face of what can seem to be blurry distinctions between the geologic facts and interpretations that underlie reconstructions.

Two-dimensional structural reconstructions for cross sections oriented parallel to the slip direction are the principal means used to test geometric validity, which is also known as balance and derives from conservation of volume (Dahlstrom, 1969). A balanced cross section purports to maintain material balance between the deformed state and the restored (initial) state. With restrictive assumptions, then area balance and line-length balance can substitute for material balance. These tests can be applied to interpretations of specific areas (e.g., Bally et al., 1966; Dahlstrom, 1969; Elliott, 1983; Groshong, 1989; Nunnis, 1991; Buchanan, 1996), but they also can be used to test geometric validity of kinematic models of deformation, such as those that have been presented for metamorphic core complexes and other products of continental extension in the Basin and Range province (e.g., Proffett, 1977; Davis and Coney, 1979; Wernicke, 1981; Davis, 1983; Miller et al., 1983; Buck, 1988; Lister and Davis, 1989). In principle, only geometrically balanced cross sections are retained as possibly valid interpretations, whereas cross sections that fail to balance must be revised or rejected because they could not possibly be correct (Dahlstrom, 1969). In practice, however, site-specific interpretations and kinematic models commonly are employed before their geometries are tested adequately for balance.

Syn- and post-mineral normal faults have dismembered and tilted ore-forming systems in certain geologic terrains such as the Basin and Range province (e.g., Proffett, 1977; Wilkins and Heidrick, 1995; Maher, 2008; Seedorff et al., 2008), and this deformation provides the opportunity to explore for structurally offset targets. Balanced structural reconstructions test the feasibility of subsurface interpretations of structural geometry (e.g., Proffett, 1977; Nickerson et al., 2010). This approach has led to the discovery of displaced extensions of veins during underground drift advance, such as in the Wright-Hargreaves mine (Hopkins, 1940). Likewise, district-scale exploration programs have discovered tilted and fault-bound fragments of large porphyry copper systems, such as Kalamazoo, Arizona (Lowell, 1968; Lowell, 1991) and the Ann-Mason deposit, Yerington district, Nevada (Proffett, 1977; Proffett and Dilles, 1984; Hunt, 2004). Similar approaches have been applied successfully in the petroleum industry, particularly to establish hydrocarbon migrations pathways across faults (Allan, 1989).

Our purpose is to offer one way in which the traditional two-dimensional, cross-sectional approach to structural reconstructions can be adapted to more of a three-dimensional approach by utilizing plan-view projections of fault surfaces. We restrict our attention to normal faults formed in areas of continental extension (e.g., Roberts and Yielding, 1994). Fault surface maps consist of information plotted on layers, which can be either physical or digital, with restoration of a geometric map of the hanging wall surface against a geologic map of the footwall surface. Fault surface maps are particularly useful for structural reconstructions where multiple, crosscutting sets of normal faults have differing slip directions. We claim that fault surface maps also provide an efficient means of portraying the locations and types of three-dimensional data available, which permit users to understand the nature of the constraints better. In turn, this allows users to evaluate better the validity of a proposed reconstruction hypothesis, to develop and evaluate alternative hypotheses more easily, and to dispense more readily with new but unviable proposals.

We begin by briefly reviewing historical approaches to structural reconstructions and then describe a multi-layer approach to constructing fault surface maps. We illustrate selected characteristics of fault surface maps in areas of complex extensional deformation with examples of normal faults in the Robinson and Yerington mining districts of Nevada. These examples also illustrate the application of fault surface maps to (1) district-scale exploration for structurally offset pieces of ore bodies and untested new ore bodies, and (2) operational issues such as ore control, geometallurgy, and slope stability in complexly faulted settings where faults juxtapose variably mineralized and altered rocks.

HISTORICAL APPROACHES TO STRUCTURAL RECONSTRUCTIONS

Structural reconstructions undo the effects of fault offsets and any distributed strains (commonly folds) in blocks between faults. By convention, the footwall block is usually assumed to
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be fixed and the hanging-wall block is moved so as to eliminate fault offset. The most common form of structural reconstruction is a two-dimensional cross-sectional reconstruction; with limited exceptions, they are accurate and viable when oriented parallel to the slip direction (e.g., Dahlstrom, 1969). In areas of complex geology containing multiple generations of faults with widely differing slip directions, the cross-sectional technique cannot be used in a straightforward manner for reconstructions, nor can it be used to display continuous changes in magnitude and direction of slip of a fault along strike. These situations warrant a three-dimensional approach.

Fault-surface map reconstructions, in contrast, are a three-dimensional restoration technique, described below, that utilizes plan-view projections of a three-dimensional fault surface. Although structure contours are widely used throughout geology, the addition of geologic maps of the footwall and hanging wall surfaces to make fault surface maps generally have not been addressed in structural geology textbooks and laboratory manuals of the last century, nor in books on applied structural geology for exploration geologists (e.g., Badgley, 1959). The usage of fault surface maps in the mineral industry, at least locally, dates back more than a half century to determine fault offsets of major veins (e.g., Hopkins, 1940), and McKinstry (1948, p. 347) alludes to them briefly in a textbook on mining geology.

Nonetheless, few economic geologists have been exposed to fault surface maps, and the latter are without mention in the current economic geology literature aside from some recent applications (e.g., Keeler, 2010; Schottenfeld, 2012; Richardson, 2014). Fault surface maps are in more routine use today in the petroleum industry (Tearpock and Bischke, 2003, Chapter 7.6), where they are known as fault cutoff maps (e.g., Needham et al., 1996). Superimposed maps of the hanging wall and footwall surfaces are known as Allan diagrams (after Allan, 1989; Groshong, 2006, p. 229). Nonetheless, fault surface maps also are uncommonly used in the petroleum geology literature.

CONSTRUCTION OF FAULT SURFACE MAPS

Definitions and data inputs

Faults are discontinuities where there is offset by shear displacement. The focus here is on faults that have a major normal component of slip, but the principles apply to all types of faults. The presence or absence of a fault on a map is in part a function of the scale of observation and documentation. The maps presented here ignore faults with offsets of less than ~10 m.

Faults typically consist of a zone of deformation (e.g., Davis et al., 2004, Figure 4; Berg and Skar, 2005, Figure 2; Wibberley et al., 2008), commonly consisting of a fault core where most of the displacement is accommodated and an enclosing damage zone of deformed rock (e.g., Caine et al., 1996; Kim et al., 2004; Micklethwaite, 2011). The entire fault zone may be tens of meters or more in true width. The fault surface is defined here, for the purpose of making fault-surface maps, by an abrupt change in lithology or alteration within the fault core. In the authors’ experience in the Basin and Range province, mixing of lithologic or alteration types—even where faults have a wide breccia zone—tends to be limited to true widths of centimeters to a few meters. The position of the fault surface is placed at the midpoint of the zone with mixed characteristics. The use of the more general term fault surface, rather than fault plane, is a recognition that the geometry of many faults is somewhat irregular, commonly curviplanar. In our view, the presence or absence of normal drag or reverse drag in the damage zone around faults is irrelevant to making of the fault surface maps, although it might be important for constructing cross sections across faults or interpreting the total amount of extension in the region.

Mineral deposits and mining districts offer the advantage of potentially offering an abundance of three-dimensional data collected across and along faults (e.g., Kloppenburg et al., 2010). The two principal means of acquiring such data are geologic mapping and drill logging, although other sources (e.g., seismic reflection images) also may offer useful information.

Geologic maps can be made of exposures at the present-day or pre-mining topographic surface, of man-made exposures along major infrastructure routes such as haul roads and underground haulage ways, and of underground drift faces and shovel advances in open-pit mines (e.g., Brimhall et al., 2006). Maps can show the trace of the fault, the elevation along its trace, and the characteristics of the immediate footwall and hanging wall. Drill holes offer comparable information at points where the holes pierce the fault surface, though the confidence in correlating data between holes and with other exposures generally decreases with distance from the drill hole collar and with increasing distance between holes. Whether the data from drill hole piercements represent different observations along a single fault—rather than miscorrelation of potentially unrelated faults—is an interpretation that must be repeatedly tested, such as by various means of structural analysis, by stratigraphic thickness criteria, or with new exposures of the fault.

A wide variety of geologic data from maps and drill holes can be displayed on layers of fault surface maps. The data can include the elevation of the fault, stratigraphic and intrusive units, lithologic and textural variations within the units, structural features, characteristics of the fault zone (e.g., tectonic breccias and gouge), and hydrothermal features. Structural features include older, synchronous, and younger faults. Older faults will show as single traces in different (offset) positions in the footwall and hanging wall surfaces of younger faults. Faults that moved synchronous with the fault surface being mapped (e.g., splays of the same fault) will show as a single branch-line trace in the same position in both footwall and hanging wall maps (e.g., Walsh et al., 1999). Younger, crosscutting faults will show as paired traces that constitute an offset. For normal separation faults, offsets create gaps in the fault surfaces of older faults that must be closed (restored) before restoring the older fault. Those gaps are identically positioned on footwall and
hanging wall maps and widen in the direction of increasing displacement or decreasing dip of the younger fault. Hydrothermal features include alteration minerals or types, ore and gangue minerals, mineralogic assemblages and associations, as well as assays for ore, by-product, and deleterious elements.

Over the life of a mine, the volume of rock that is well defined by drill holes also tends to migrate downward and outward as exploration and ore definition continue. In large deposits, this can result in as much as 2–3 km of vertical exposure (Seedorff et al., 2005). The spatial distribution of the data on a fault surface map reveals the abundance, or paucity, of geologic control on the position and characteristics of the fault.

**Preliminary structural analysis of faults and fault sets**

An analysis of the structure of a region, district, deposit, or prospect precedes construction of fault surface maps, because the latter requires at least a hypothesis about where faults are present, how many faults might have sufficient slip to warrant more detailed work, and how earlier faults may have been offset by younger faults.

The first step for this analysis is to compile a map or set of maps that contains the best available information on the geology of the area of interest, with particular attention to continuity of faults along strike and crosscutting relationships between different faults (i.e., relative ages). Second, the observed fault segments should be assigned to individual faults, with each seemingly distinct fault assigned a different name and color. Faults of similar strikes, dips, and relative crosscutting relationships might also be grouped into sets of faults (e.g., Proffett, 1977; Westaway, 1991), in which case faults in the same set may be assigned similar colors (e.g., varying shades of blue for different faults of one set, varying shades of green for faults of a second set, etc.). When there is considerable evidence that faults assigned to the same fault set—a descriptive term—were active more or less contemporaneously, sets of faults then may be regarded as constituting sequential fault generations—a temporal and potentially genetic assignment (e.g., Maher, 2008; Nickerson et al., 2010; Richardson and Seedorff, this volume).

The aforementioned exercise effectively creates a physical or digital overlay of the geologic map, showing the various faults or sets of faults highlighted in different colors. The resulting assignments of fault segments to individual, named faults then become the basis for generating fault surface maps. In practice, these assignments are part of a long, iterative process, as assignments are refined over time as the structural analysis continues, as new data are generated (e.g., from new mapping or drill holes), and as hypotheses are tested. The more complex the structure in the area of interest and the less certain the understanding of it, then the more extensive the subsequent modifications are likely to be. The assignments are particularly tentative for faults that have gentle dips and that crop out only locally and are laterally extensive beneath the surface or have been eroded overhead. For the preserved parts of such faults, it may be useful also to make a preliminary structure contour map of the features that seem to define the fault. In our experience, the surface contour maps at this stage of investigation tend to be undulatory. Later work commonly reveals that the actual fault surface consists of both a gently dipping fault and smaller, crosscutting faults that were unrecognized during the preliminary analysis. After distinguishing between the gently dipping fault and the later, smaller-offset faults, the seemingly undulatory fault surface of the gently dipping fault may be much more planar than it appeared initially.

**Construction of layers for fault surface maps**

After completion of the preliminary structural analysis of faults and fault sets, maps of individual fault surfaces can be constructed. More detailed map scales permit representation of finer geologic details and resolution of smaller offsets on faults. Nonetheless, use of numerous overlapping or quilt-like, stitched together maps can be unwieldy and may impede understanding of the overall area. Alternatively, maps of multiple scales can be utilized for different purposes. If only one scale is employed, as a rule of thumb for physical restoration exercises we recommend selecting a map scale such that the area of interest will approximate the size of a standard drafting table, as compilation may need to use mylar of similar dimensions, and presentation of final results may require plotting on paper of standardized widths.

It is useful to assemble universal base maps that apply to all faults, such as topography of the pre-mining surface, current topography, generations of pit topography, and drill hole collar maps with total depth elevations. Other information is most easily attributed on a fault-by-fault basis using multiple layers. A geologically defensible strategy for beginning to construct fault surface maps is to begin with the seemingly youngest faults and work backward in time to the oldest faults, which may minimize erasure and modification. In our experience, however, the process is highly iterative regardless of approach. Alternatively, one may choose instead to begin with faults for which there are the best, most numerous, or most widespread data, and then gradually address faults for which there is greater uncertainty regarding their location, relative age, etc.

Fault surface maps consist of information plotted on four (or more) layers: (1) data, (2) structure contours, (3) footwall geology; and (4) hanging wall geology. Separation of information onto layers, either physical or digital, keeps the observational constraints and interpretations separated and distinguishable and eases the task of modification or erasure. All layers can be reproduced to display the final results, or the information on layers 1 and 2 can be superimposed on modified versions of layers 3 and 4 to save space, as is done in this paper. Layers or sheets preferably are uniform in size and have a consistent survey grid, so that geologic maps and the various layers for each fault and for different faults can be easily compared. It is useful not to place more than one fault on each layer, for each layer to
cover the same map area at the same scale, and for layers to be labeled consistently, including the name of the fault, the type of layer, the date created, the names of the geologists who made the map, and the dates modified, as well as a key to colors and symbols.

The first layer constructed of any given fault is the data layer, which contains the observations. The surface traces of the fault over its mapped extent are shown, with measurements on the strike and dip of the fault and kinematic indicators (e.g., slickenlines), if available. Additional information can be added as desired, such as characteristics of the damage zones on either side of the fault. Along the fault trace, points are marked and labeled where major elevation contours cross the fault. Locations where each drill hole pierces the fault also are marked (e.g., with a black dot) and typically are labeled with four pieces of information for each hole: (1) the number of the drill hole (e.g., D117), (2) the elevation of the fault in that drill hole, (3) the lithology or map unit in the immediate footwall of the fault, and (4) the lithology or map unit in the immediate hanging wall of the fault. Data from drill holes that nearly pierced the fault may also be included, as they also constrain the position of the fault to be beyond the end of the drill hole. Where a fault has subsequently been intruded by a dike, then both the dike and the lithologies or map units on either side of the dike (and fault) are noted, as well as the estimated position of the fault zone prior to intrusion by the dike.

The second layer constructed is the structure contour layer. Data relevant to the elevation of the fault from drill holes and surface traces of the fault are transferred from the data layer, and an interpretation of the structure contours is drawn using sound geologic reasoning for interpolations and extrapolations. Structure contours generated solely by machines run the danger of being geologically unreasonable where data are sparse, which commonly include the edges of the map. Attempting to make the faults as simple and as close to planar as the data points will allow tends to be a good strategy. The line type used (e.g., solid, dashed, dotted) should convey the level of confidence in the interpreted position of the contours, whether interpolated on the basis of numerous, closely spaced constraints, extrapolated beyond the limit of constraints, or projected beneath or through younger rocks, respectively. Gaps and offsets in the contours result if the fault was cut and offset by a younger fault, creating gaps in the fault surface. Consequently, generation of a structure contour map for a fault generally is an iterative process, and new fault interpretations from one fault are reconciled with those of other faults nearby.

The third layer is the footwall geologic map. Boundaries between rock units (depositional, faulted, or intrusive) will appear on the footwall geologic map as traces that are called cutoffs. There will be a matching cutoff (in some form) present on the hanging wall geologic map in a displaced down-dip position for normal-separation faults that have not rotated past horizontal. Unconformity, fault, and intrusive cutoffs may show other cutoffs terminating against them, and these intersections create piercing points on the footwall and hanging wall maps that can be used to define net slip vectors on the fault surface (see below). By overlaying the footwall layer on the data layer, the subset of data that are relevant to the geology of the footwall can be transferred to the third layer using standard colors assigned to the various lithologies. The data include the geology of the rocks in the immediate footwall of the mapped surface traces of the fault and data from drill holes that pierce the fault, with some consideration given to holes that nearly reach the fault surface. The contacts between different lithologies (unconformities, depositional, intrusive, or related to other faults) then are interpolated or extrapolated, marked with the appropriate symbols (e.g., wavy lines for unconformities), ideally with means to convey the confidence in their interpreted positions (see above). The interpretations also are guided by other geologic constraints that may exist (e.g., well documented thicknesses of stratigraphic units).

The fourth layer is the hanging wall geologic map, constructed using the same methodology as the footwall geological map but using data relevant to the geology of the immediate hanging wall of the fault.

If data are available regarding alteration types, ore and gangue minerals, and assays for ore, by-product, and deleterious elements, then the approach to developing the third and fourth layers can be repeated numerous times to generate pairs of footwall and hanging wall layers for each of these types of information. These data commonly create crude, i.e., larger diameter piercing points, although metal zoning patterns in some cases produce fine-scale patterns that make excellent piercing points. All of these data potentially can be used for restoration, and in principle each should be consistent with restorations based on lithology and structure. Patterns made of hydrothermal features are particularly valuable for restorations where there are large volumes of uniform host rocks (e.g., hypidiomorphic granular granitoid). Nonetheless, reconstructions may not use data that has changed during or after fault movement. For example, Cu assays may be used for reconstruction, but only those assays in rocks where Cu was not redistributed by supergene processes during or after fault movement.

Reconstructions

Methodology

The methodology of constructing fault surface maps for a short segment of a simple normal fault is illustrated in Figure 1. Figure 1a shows a block diagram of the fault cutting three stratigraphic units and a crosscutting igneous body. Figures 1b and 1c show conventional map and cross sectional views, respectively. Figures 1d and 1e show surface projections of the footwall and hanging wall geology, respectively, i.e., fault surface map.

The amount and direction of slip is determined by restoring the hanging-wall block relative to the footwall block in the direction opposite to the slip direction, pinning geologic markers
Figure 1. Construction of a geologic fault surface map. (a) Perspective view of block diagram; (b) map view of surface of blocks and exposed fault surface; (c) cross section oriented normal to strike of fault, showing vertical projection of footwall and hanging-wall traces onto horizontal map surface; (d) surface projection of the footwall geology, showing piercing points in footwall; (e) surface projection of the hanging wall geology; piercing points are shown for hanging wall (solid) and footwall (dashed) sides of the fault surface. Vectors pointing toward hanging wall show horizontal projection of slip, i.e., heave component, indicated by offset of piercing points. Reconstruction vectors would be same length but would point in the opposite direction as slip vector, i.e., toward footwall. Elevation difference between head and tail of heave gives throw component. Total slip = sqrt(heave^2 + throw^2).
or cutoffs in the hanging wall to offset equivalents of the same markers or cutoffs in the footwall (Figure 1e). For most normal faults, the hanging wall is restored up the direction of dip (Figure 1); however, for normal faults that have been rotated through horizontal (“overturned” normal faults), the hanging-wall block will be restored down the current dip, but nonetheless opposite the slip direction (e.g., Nickerson et al., 2010). Analogous relationships exist for tilted reverse and strike-slip faults.) Depending on the geometry of the geologic units and the data available to constrain the positions of contacts in the hanging wall and footwall, the reconstruction may be non-unique, permitting a range of solutions. Ideally, the reconstruction yields a unique slip vector or a unique family of slip vectors. Multiple slip vectors are necessary to characterize a fault if the amount and direction of slip varies along strike because the hanging wall has not only translated relative to the footwall, but also rotated relative to the footwall. The fault surface method, in principle, permits display of an infinite number of slip vectors on the plane of the fault.

The amount and direction of slip can be measured or calculated from the reconstruction. The x-y component of slip, the heave, can be measured from the length of the horizontal component of the slip vector, i.e., its length on the fault surface maps, which are horizontal projections. The z component of slip is the difference in elevations of the piercing points on the hanging-wall and footwall fault surfaces, which can be determined from the structure contours. The geologic constraints in a given segment of the fault may be insufficient to determine whether or by how much the direction and magnitude of slip vary along strike; indeed, the rotational component of slip may be undetectable without geologic markers that offer detailed spatial resolution, coupled with closely spaced three-dimensional observational constraints.

Unique restorations generally involve one or more piercing points, which are geologically defined points in the hanging wall that must have a corresponding, unique point in the footwall (Figure 1e). Such points generally result from two intersecting geologic surfaces (i.e., intersecting geologic contacts) in space, thereby defining a line. Where a third surface, the fault, cuts the line, two corresponding points on either side of the fault (the piercing points) are produced. Nonetheless, the geology of the hanging wall may be uniquely matched to the geology of the footwall without involving piercing points if rock units have distinctive shapes. Note that the reconstructions are not driven by kinematic models of faults; this procedure uses the geology of the fault surfaces, which are based on interpretations constrained by observations, such as geologic maps and drill hole logs.

The geologic markers used to achieve the reconstruction commonly are supracrustal strata that are part of a known stratigraphic sequence, but there are no restrictions on the types of geologic features involved. For instance, these can include crystalline rocks such as plutons and metamorphic rocks or hydrothermal features, even though structural reconstruction software commonly is not designed to deal with them. Crystalline rocks also may contain numerous, though potentially subtle, geologic features that provide markers for constraining slip (e.g., Maher, 2008), including opportunities for generating piercing points. Examples of such markers, including some that are not routinely recorded on many quadrangle-scale geologic maps, include: (1) sills and their feeder dikes; (2) mappable, compositional or textural variants of plutons; (3) pegmatite and aplite dikes and distinctive hydrothermal veins that may be associated with a pluton; and (4) distinctive textural or compositional variants within metamorphic rock units.

The geometries of faults, which are largely inherited from their nucleation, growth, and linkage (e.g., Martel, 1999), have consequences for developing a three-dimensional approach to reconstruction. Over their full lengths, normal faults tend to have characteristic geometries, although an area of interest (e.g., a mining district) may cover only a small fraction of the entire length of a given fault. For the case of an isolated normal fault (Figure 2), its geometry is characteristic and simple, with the opposite ends of the fault having tips where the displacement diminishes to zero (e.g., Murooka and Kamata, 1983; Barnett et al., 1987; Walsh and Watterson, 1991; Schlische and Anders, 1996). The hanging wall has a gently synclinal geometry between the tips, with the axis of the syncline oriented perpendicular to the fault and plunging toward it (Figure 2). The footwall has an even more subtly antclinal geometry, with the axis of the anticline oriented perpendicular to the fault and plunging away from the fault. Real normal faults generally have more irregular, sinuous traces at the surface than is shown in Figure 2. Recesses and salients in the surface trace correspond to the troughs and ridges of fault-surface corrugations, respectively, that plunge for many kilometers down dip.

The amount of displacement increases along the fault away from each tip toward the point of maximum displacement (Figure 2); theoretically, the change in displacement with length is non-linear, and maximum displacement occurs at the midpoint between the tips for isolated faults (Walsh and Watterson, 1989). For real normal faults, maximum displacement nonetheless tends to occur near the midpoint, and the maximum tilt of both the hanging wall and footwall strata also occurs near the midpoint (Figure 3), with both the displacement and tilt tapering to zero at the tips (Anders and Schlische, 1994). Moreover, longer faults have greater displacements (e.g., Walsh and Watterson, 1987; Dawers and Anders, 1995), with a scaling relationship between displacement (D) and length (L) given by $D \propto L^n$, where n is a small number likely to be 1 (Cowie and Scholz, 1992; Dawers et al., 1993). In practice, faults may have more complex geometries and be segmented; moreover, nearby faults commonly interact with one another and join over time (e.g., Childs et al., 1995; Hodgkinson et al., 1996; Cartwright et al., 1996; Crider and Pollard, 1998; Peacock, 2002).

**Implications for accuracy**

The characteristic geometry of normal faults (Figure 2) has...
multiple implications for how normal faults are restored and for the accuracy of a reconstruction.

First, a purely rigid, up-dip translation of the hanging wall surface relative to the footwall surface in principle is likely to be in error. A purely translational reconstruction may be an exceptionally good approximation for any relatively short segment of a fault (Figure 1e), especially if the region of interest is far from a tip of the fault. This is expected because rotations about horizontal axes that result in tilting of fault blocks are clearly the dominant deformation in areas characterized by domino-style extension. Nonetheless, an increase in displacement along the strike of a normal fault implies at least a minor component of relative vertical-axis rotation between hanging wall and footwall blocks (Figure 2). This effect is expected to be most significant near a tip of a normal fault, and the net effect might be most significant regionally within accommodation zones, where many faults typically are tipping out (e.g., Faulds and Varga, 1998).

Second, the direction of rotation of the hanging wall relative to the footwall must reverse as one crosses the point of maximum displacement. Consequently, the accuracy of rigid-body approximations that employ both translational and rotational components will be increased if conducted separately on opposite ends of the point of maximum displacement.

Third, additional assumptions may be required when reconstructing displacements near the tips of faults, especially in the absence of closely spaced observational control. Strain extends beyond the tip in the form of fractures and small folds (e.g., McGrath and Davison, 1995; Schlische, 1995; Walsh et al., 1999; Crider and Peacock, 2004; d’Alessio and Martel, 2004), but the amount of slip at the tip is zero (Figure 1). Figure 3 shows two versions of near-tip behavior of a normal fault. Though omitting effects of strain beyond the tip, Figure 3a depicts non-rigid behavior of the hanging-wall block, with a distinctly non-linear increase in displacement as a function of distance from the tip. Obviously, any rigid reconstruction—whether or not it involves rotation—will be only an approximation if the change in slip along strike is nonlinear. Alternatively, an assumption of linear change in displacement along strike may be an acceptable approximation. The assumption of a linear decrease in displacement toward the tip and zero displacement beyond it implies components of both translation and rotation of the hanging wall relative to the footwall, with rotation of the hanging wall as a rigid block about a pole of rotation located at the tip and ignoring effects of strain beyond the tip (Figure 3b).

Fourth, a rigid-body reconstruction also will be only an approximation if penetrative deformation of either the hanging wall or footwall blocks occurs concurrent with slip. Penetrative deformation of both hanging wall and footwall are inherent in the flexural cantilever-type deformation (e.g., Figure 1) that seems to characterize continental extension (e.g., Kusznir and Egan, 1990; Kusznir and Ziegler, 1992; Roberts and Yielding, 1994). A perfect palinspastic reconstruction must not only restore the slip but also remove the monoclinal flexuring that accompanied slip. Theoretical calculations suggest that reconstructions assuming rigid domino-type behavior will overestimate the amount of extension if flexural cantilever-type deformation is involved (Westaway and Kusznir, 1993).

Fifth, the restoration process only backs out the movement on the fault; even if the direction and amount of slip have been determined quite rigorously (notwithstanding second-order
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characteristics of normal faults, noted above), it does not generally return the fault surface to its original orientation prior to the onset of faulting because normal faults commonly rotate or tilt as they move (Thompson, 1960; Morton and Black, 1975; Wernicke and Burchfiel, 1982; Gans et al., 1985; Jackson, 1987). Additional geologic constraints typically are required to determine the original dip of the fault. For example, bedding-to-fault angles of syntectonic sedimentary strata (Gawthorpe and Leeder, 2000) and orientations of flattened pumice in pre-tectonic ignimbrites (ash-flow tuffs)—with appropriate regard for the likelihood of unreliable measurements due to differential compaction in paleovalleys with steep walls (e.g., Henry, 2008; Henry and Faulds, 2010)—can be used to determine how each fault surface should be restored to its original dip (Proffett, 1977; Gonsior and Dilles, 2008; John et al., 2008). The original dip of the fault is of significant interest, because the angle of initiation of normal faults in continental extensional tectonics is a persistent controversy (e.g., Gans et al., 1985; Jackson and White, 1989; Lister and Davis, 1989; Roberts and Yielding, 1994; Wong and Gans, 2008), and structural reconstruction is an important method for constraining initial dips of faults. For many faults, the direction and amount of slip are well constrained, yet the constraints on the initial dips are nonetheless poor.

To obtain a three-dimensional structural reconstruction of an area, the reconstruction process proceeds backward in time, i.e., from youngest to oldest faults. Significant errors in determining crosscutting relationships generally preclude achieving a reconstruction that will balance. Hence, continual testing of hypotheses regarding the relative ages of faults is essential.

When restoring older faults, the gaps created by younger crosscutting normal faults first must be closed. Small errors in the amount and direction of slip will be introduced if the geometry of the older fault was deformed by offset on the younger fault. Errors in the amount and direction of slip also will be introduced if there was differential tilting of the older fault surface across the hanging wall and footwall blocks of the younger fault, because tilting of the fault surface changes the dimensions and geology of its surface projection. If the shape of the fault surface, as illustrated by the structure contours, changes markedly on either side of the gaps created by offsets by younger, crosscutting faults are closed, then care is required in calculating the direction and magnitude of slip.

It is unlikely that any palinspastic restoration mimics nature perfectly, because all methods make simplifying assumptions. Nonetheless, even imperfect restorations can lead to greater geologic understanding. As the models become more three-dimensional, however, the overall importance of the 3-D effects in the natural processes becomes more apparent. Indeed, a restoration cannot be achieved in some geologic settings without a satisfactory accounting of the 3-D effects.

Figure 3. Perspective view of simplified block diagrams showing movement that might occur near the tip of a normal fault. (a) Example showing non-rigid (non-linear) behavior of the hanging wall block relative to the footwall block, which resembles the case in Figure 1. (b) For comparison, an example with a simplifying assumption that might be employed in a restoration in which the hanging-wall block is assumed to move rigidly with a linear displacement-length behavior. In reality, such movement also would produce additional deformation beyond the tip of the fault (not shown). These two examples involve both translation and rotation of the hanging wall relative to the footwall.
EXAMPLES AND APPLICATIONS: TOPOLOGY AND RECONSTRUCTION OF SUPERIMPOSED FAULT GENERATIONS

The Robinson and Yerington districts, Nevada, provide examples of some of the diversity in topologies and characteristics of fault surface maps and applications of structural reconstructions to exploration and mining operations.

Overview of Robinson district geology

The Robinson district, also known as the Ely porphyry copper system, contains porphyry, skarn, carbonate replacement, and distal Au-Ag ores in the central Egan Range near the town of Ely in east-central Nevada. The Robinson district seemingly constitutes one, mid-Cretaceous porphyry copper center with early sills and several later mineralizing stocks (Seedorf et al., 1996). The system was dismembered and variably tilted by late Eocene normal faults that formed within a narrow absolute time interval between ~37.60 and 36.68 Ma.

Robinson is a monzonitic porphyry Cu-(Mo-Au) system in the classification scheme of Seedorf et al. (2005). The host rocks are carbonate and clastic units of the miogeoclone of western North America (e.g., Stewart, 1980), and those that crop out in the district range in age from Devonian to Permian (Bauer et al., 1966; Maher, 1996; Shaver and Jeanne, 1996). A batholith intrusion that is the source of the stocks and sills in the district, the Weary Flat pluton, has a U-Pb zircon LA-ICP-MS date of 109.3±1.5 Ma (Seedorf et al., this volume). From west to east, the copper occurs principally in the Veteran, Tripp, Liberty, Ruth, and Kimbley pits (e.g., Bauer et al., 1966).

Paleozoic and Tertiary strata in the northern Egan Range strike northerly and dip to the west because of tilting associated with slip on several sets of east-dipping normal faults, whereas strata in the southern Egan Range strike northerly but dip to the east, associated with slip on several sets of west-dipping normal faults. The Robinson district is located in the central Egan Range, where faults typical of the northern Egan Range are tipping out to the south and faults typical of the southern Egan Range are tipping out to the north. Thus the Robinson district occurs within a regional-scale extensional accommodation zone that persists for tens of km north-south within the central Egan Range (Seedorf et al., 1996; Gans et al., 2001; Seedorf and Maher, 2002).

The alignments of intrusions and mineralization across the district are the net result of slip on the numerous sets of post-mineral faults. The large open pits are bounded by relatively late, post-mineral normal faults (e.g., Bauer et al., 1966; Westra, 1982; Seedorf et al., 1996; Gans et al., 2001), but each big fault block internally contains numerous other, mostly older faults. Some of the older faults, including the Alpha fault described below, are gently dipping, do not crop out at the surface within any one large fault block, and in some cases have greater magnitudes of slip than the younger faults that bound the major blocks.

Selected post-mineral normal faults in the Liberty pit of the Robinson district illustrate some of the diversity in topologies of fault surface maps, even though a reconstruction of the post-mineral faulting of the district is still incomplete, so the results shown are preliminary. For geologic context and location of the faults described below, Figure 4 shows an east-west cross section from Maher and Seedorf (2000) through the middle of the Liberty pit with overlays showing rock types, alteration, and structure.

The horizontal projection of the rock/alteration types and structure of the footwall and hanging-wall surfaces is illustrated for the Dexter, Alpha, and Liberty faults in Figures 5 through 7. Grid lines are labeled in the mine grid coordinates in feet (virtually no rotation from true north), but a metric scale bar is included. The rocks in certain areas are so intensely altered that the determination of the protolith can be problematic; in such rocks, reliable bedding attitudes generally were never mapped. In some cases, bedding attitudes were measured at the surface and can be projected down to the fault surface (dips shown in parentheses). Stratigraphic and intrusive contacts are shown in thin black lines; faults contacts are shown in thick colored lines. Various lithologic/alteration types each have distinct colors, but so, too, do the various faults, their associated dip symbols, and labels. The distribution of alteration has been simplified, and certain alteration boundaries have been omitted unless they illustrate structural aspects that are the focus of this contribution. The geometry of faults is indicated by structure contour lines in feet that are identical on the footwall and hanging wall geologic maps. The locations of reliable geologic control for these maps are shown by intensely colored dots (drill hole piercing locations) and by very thick colored lines (the geology in the immediate footwall and hanging wall along the mapped trace of the fault). Interpretations of lithologic/alteration types are shown in fainter colors. Circles show reference points for restoration of slip. Black vectors show the direction and magnitude of slip, measured in the plane of the fault. Red arcs with exaggerated curvature emphasize the sense of rotation for faults with an important rotational component of slip (Figures 5b, 7b).

Fault surfaces of relatively young faults

Figure 5 illustrates the horizontal projection of the geology of the footwall and hanging-wall surfaces of the Dexter fault. This fault illustrates characteristics of fault surface maps of relatively young faults, i.e., faults from late generations of faults: the fault surface tends to contain many rock types and alteration types in complex patterns, a wide range in bedding attitudes with locally abrupt changes at boundaries between faults, a paucity of younger faults, and an abundance of older faults.

The Dexter fault is a relatively young, east-dipping normal fault that cuts across the western end of the Liberty area in the Robinson district. This fault is cut off at depth by the still
younger Footwall East fault (Figure 4b); therefore, the northward and down-dip continuation of the Dexter fault must be present somewhere in the footwall of the Footwall East fault (not shown). As indicated by the structure contours, the Dexter fault dips ~40–45°E and strikes nearly due north in the middle of the Liberty pit but swings eastward further south (Figure 5), whereas the Footwall East fault beneath it dips ~30°SE. The Dexter fault everywhere places younger rocks on older rocks, confirming that it is a normal fault.

Relatively young faults generally cut and offset numerous older faults. The older faults that are cut by the Dexter fault (Alpha, Beehive, Copper Flat, Sulfide East, Eldorado, Champion, and High Grade Hanging Wall Splay faults) occur as single, curving lines on both the footwall and hanging-wall surface geologic maps, but their positions are offset between the footwall and hanging wall (Figure 5). Among other geologic features, the older faults serve as geologic markers to constrain the direction and magnitude of slip on the younger fault. The Footwall East fault cuts off the Dexter fault to the north and at depth. The Dexter fault in the field of view of Figure 5 also is cut by two younger faults (Humbug and Josie faults), which also cut the Footwall East fault at depth. In any fault surface map, younger faults occur in the same place in the footwall and hanging-wall surfaces and create gaps in both
Figure 5. Preliminary fault surface maps for the Dexter fault in the Liberty pit, Robinson district. The Dexter fault is relatively young and its subsurface geometry is well sampled by drill holes. (a) Footwall map. (b) Hanging wall map. Structure contours (gray) on both maps show that Dexter fault is corrugated and indicate that overall it has a northerly strike and a moderate easterly dip of ~40–45°, extending from surface (green) to its down-dip truncation by the Footwall East fault (pink), except to the south where the location of the Footwall East fault is unconstrained. Geologic maps of sufficient quality and detail did not exist in this area, so only locations of reliable geologic control are intensely colored dots for drill hole piercements; interpretations of lithologic/alteration types around the drill holes are shown in fainter colors. Older faults individually colored and labeled are shown as colored lines; the locations of older faults are offset between the hanging wall and footwall fault surface maps. Therefore, the older faults constrain the direction and magnitude of slip on the fault, as do other geologic markers. The overturned dip symbol is used where the dip directions of the Alpha and Beehive faults are opposite to their interpreted slip directions. Two younger faults (Humbug and Josie) crosscut the Dexter fault on these maps, and a third younger fault, the Footwall East fault, cuts off the Dexter to the north and dips under these fault surfaces (see Figure 4). Younger faults occur in the same place in the hanging wall and footwall fault surface maps, illustrating the subsequent extension. Although the geologic interpretations require further refinement, the approximate slip is shown by circular reference points in the hanging wall and footwall blocks. Geologic reference points are shown as circles. At southern end of map the slip measured in the plane of the fault is ~95 ft (~29 m) N53E and increases to ~240 ft (~73 m) in a N66E direction at the northern end, producing a horizontal component of clockwise rotation of the hanging wall by ~2° relative to the footwall. Source of information; E. Seedorff et al. (unpub. data).
the footwall and hanging-wall fault surface maps. These gaps illustrate the extension that was produced by subsequent faulting, and the gaps must be closed before determining the slip on the older fault.

Regardless of relative age, faults with large magnitudes of slip are most likely to create large discontinuities in metal grade and metallurgical behavior, but late, small-offset faults such as the Dexter also can create large discontinuities in places where they cut and offset older, large-offset faults (e.g., Figure 4d). Because late faults tend to be more continuous along strike and down dip, they are especially critical for rock mechanics issues (e.g., pit slope stability and block caving behavior), even if they have only small amounts of slip. Of course, it is not only the characteristics of the faults (e.g., strike and dip, presence of gouge, thickness of breccia), but also the characteristics of the rocks (e.g., attitudes of bedding planes and joints, strength, friability) that affect rock mechanics, as well as the angles of intersection of the various faults and other features (e.g., whether they form wedges or buttresses).

Some of the contacts (fault, stratigraphic, intrusive, alteration) shown on the fault surface maps of the Dexter fault (Figure 5) are approximately planar, but many are highly irregular. A few of the irregularities in contacts are the product of remaining imperfections in the three-dimensional geologic interpretations. A second factor leading to irregularities is that deformation associated with movement on younger faults (e.g., flexure of the hanging wall and footwall blocks near the fault surface) can deform preexisting features, including older faults (seen best for later example of the Alpha fault). Most irregularities, however, result from a third factor: lines on these maps result from intersection of two, irregular, curviplanar features (i.e., the Dexter fault and the contact of interest), and that intersection—and its horizontal projection—can be much more irregular than the irregularities in either of the two surfaces that intersect. The structure contours on the fault surface maps help remind users of these geometric consequences.

The dip directions of older faults, which are taken from dip measurements and structure contour maps of the older faults, generally are far from perpendicular to the trace of the older faults. This effect is produced on fault surface maps by the intersection of older fault surfaces with the surface of younger faults, such as the Dexter. The effect is analogous to dip measurements on faults not being perpendicular to the trace of a fault if the fault trace is changing elevation across a topographic surface.

These preliminary footwall and hanging-wall fault surface maps do not match perfectly because of remaining imperfections in the three-dimensional geologic interpretations, but slip on the Dexter fault nonetheless can be estimated to a precision of ~10 m. The magnitude of slip on the Dexter fault at the southern end of the map is ~95 ft (~29 m), and the magnitude of slip increases to ~240 ft (~73 m) at the northern end (Figure 5), resulting in a horizontal component of clockwise rotation of the hanging wall relative to the footwall of ~2°.

Fault surfaces of relatively old faults

Figure 6 shows preliminary fault surface maps for the Alpha fault in the Liberty pit east of the Kaboony fault and west of the Sulfide East fault, exemplifying characteristics of faults from relatively early fault generations: few rock types and alteration types present, generally regular changes in bedding dips and typically of a limited range, abundance of younger faults, and paucity of older faults.

The Alpha fault in the Liberty pit is a relatively old, gently dipping fault that crops out on the western side of the Liberty pit both north and south of the younger White Hill Rhyolite (Figure 6), and it continues into other parts of the Robinson district. The Alpha fault is cut off to the north by the younger Footwall East fault (Figure 6); therefore, the Alpha fault must continue in the footwall of the Footwall East fault (not shown). Between the younger Kaboony and Sulfide East faults, the Alpha fault has a narrow range in elevation, mostly between 7000 and 7250 ft, and dips in variable directions at moderate to shallow angles, as indicated by the morphology of structure contours (Figure 6). The Alpha fault must be normal because it everywhere omits stratigraphic section (e.g., a common relationship for the Alpha fault in the Liberty pit is variably silicified Permian Rib Hill Sandstone in the hanging wall, resting on Pennsylvanian Ely Limestone altered to silica-pyrite and ore-related porphyry with intense sericitic alteration in the footwall). For some time, the slip direction of the Alpha fault was not firmly known, but the fault surface maps here (Figure 6) demonstrate that the Alpha fault is a top-to-the-east normal fault which may have originated as a steep, down-to-the-east normal fault.

Within the area shown by Figure 6, the Alpha does not cut any older faults. The Alpha fault, however, is highly dismembered by numerous younger, crosscutting faults that displace the Alpha fault (Kaboony, West Dexter, Dexter, Watson West, Watson, Watson East, Sulfide East, Humbug, and Josie faults, plus the Footwall East fault that cuts it off to the north). Each younger, crosscutting fault creates a gap in both the footwall and hanging-wall fault surface maps for the Alpha fault (Figure 6), which must be closed to assess the amount and direction of slip on the Alpha fault precisely. In the northern part of the Liberty pit, each of the small fragments of the Alpha fault dips back to the west. At the southern end of the area, the Alpha fault assumes a more consistent southerly dip. The Alpha fault also appears to be less planar than many younger faults, and structure contours suggest that this may have been caused by footwall uplift and hanging wall subsidence related to movement on the younger faults (Figure 6). Such deformation varies in magnitude along the strikes of the younger faults, causing warps and wrinkles in the surface of the older, Alpha fault. Such deformation also passively rotates the Alpha fault surface. Where the Alpha fault has been rotated through horizontal, the originally east-dipping Alpha fault becomes an “overturned,” gently west-dipping normal fault (Figures 4b and 6).

Bedding attitudes measured at the pre-mining surface in the
Figure 6A. Preliminary fault surface maps for the Alpha fault in the Liberty pit east of the Kaboony fault and west of the Sulfide fault, Robinson district, exemplifying characteristics of faults from relatively early fault generations. (A) Footwall; (B) hanging wall. The locations of good geologic control are shown by intensely colored dots (drill hole piercements). Other attributes are as described for Figure 6 and in the text. There are no older faults cut by the Alpha in the area shown, but there are numerous crosscutting younger faults that create gaps in both the hanging wall and footwall fault surface maps that must be closed before determining the slip on the Alpha fault. There is no overlap in the geology of the hanging wall and footwall fault surfaces, so the amount of slip exceeds the length of a line in the slip direction across the illustrated view, but a preliminary indication of the slip is ~3–4 km in an easterly direction. Source of information: E. Seedorff et al. (unpub. data).
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Figure 6B. Preliminary fault surface maps for the Alpha fault in the Liberty pit east of the Kaboony fault and west of the Sulfide fault, Robinson district, exemplifying characteristics of faults from relatively early fault generations. (A) Footwall; (B) hanging wall. The locations of good geologic control are shown by intensely colored dots (drill hole piercements). Other attributes are as described for Figure 6 and in the text. There are no older faults cut by the Alpha in the area shown, but there are numerous crosscutting younger faults that create gaps in both the hanging wall and footwall fault surface maps that must be closed before determining the slip on the Alpha fault. There is no overlap in the geology of the hanging wall and footwall fault surfaces, so the amount of slip exceeds the length of a line in the slip direction across the illustrated view, but a preliminary indication of the slip is ~3–4 km in an easterly direction. Source of information: E. Seedorff et al. (unpub. data).
hanging wall of the Alpha fault define a small syncline (Figure 6b). The fold is likely a synextensional Tertiary fold formed by subsidence of the hanging wall of the concave west Sulphide East fault because the syncline roughly corresponds to a trough in the fault surface and plunges toward the Sulphide East fault.

Single stratigraphic units are widespread in both the footwall and hanging-wall fault surface maps of the Alpha fault (Figure 6). Bedding in the footwall dips ~20–30°SW (Figure 6a), and bedding in the hanging wall dips ~35°NE to ~35°SE (Figure 6b). The dip of the Alpha fault is moderate to subhorizontal; hence, the angle between bedding and the fault is a small to moderate angle. The following three geologic scenarios conceivably are consistent with small to moderate bedding-to-fault angles. (1) The Alpha fault formed initially as a Tertiary, high-angle normal fault but cut bedding in Paleozoic rocks at a low angle because bedding was rotated to moderate or high angles by Mesozoic contractional folding. The strike of the later fault also would have been subparallel to the trend of the fold axis, and the limb of the fold was steep enough such that the fault was subparallel to bedding over distances comparable to the area of Figure 6. (2) The Alpha fault formed initially as a high-angle normal fault but cut bedding at low to moderate angles because bedding was tilted to high angles by movement on one or more earlier normal faults. (3) The Alpha fault formed initially as a low-angle normal fault but Paleozoic rocks were gently dipping because Mesozoic contractional deformation produced open folds; thus the Alpha fault cut bedding in Paleozoic rocks at low to moderate angles. This question remains unresolved pending completion of a compelling three-dimensional structural reconstruction of the district, but district and regional-scale geologic considerations suggest that hypothesis (2) is most likely and that hypothesis (3) is least likely.

The distribution of rock/alteration units coupled with bedding orientations in the footwall and hanging-wall maps for the Alpha fault indicates that there is no overlap between the two fault surface maps. Note that the hanging wall map contains mostly Permian Rib Hill Sandstone (variably altered to silica-pyrite) and virtually no porphyry (Figure 6b), whereas the footwall consists of an east-west trending band of sericitically altered porphyry, > 300 m wide, bordered both to the north and south by ~300-m wide zones of silica-pyrite alteration of Pennsylvanian Ely Limestone, grading outward to weaker alteration south by ~300-m wide zones of silica-pyrite alteration of Pennsylvanian Ely Limestone, grading outward to weaker alteration. (Figure 6). Bedding in the footwall dips ~20–30°SW (Figure 6a), whereas the footwall consists of an east-west trending band of sericitically altered porphyry, > 300 m wide, bordered both to the north and south by ~300-m wide zones of silica-pyrite alteration of Pennsylvanian Ely Limestone, grading outward to weaker alteration and eventually into other rock units (Figure 6a). Therefore, the Alpha fault has moved a volume of rock that formed somewhat outside the porphyry system and translated it down on the intensely altered, centrally located but high-level part of the porphyry copper system. The magnitude of slip on the Alpha fault must exceed the length of a line in the slip direction across the illustrated view, i.e., the magnitude of slip exceeds one km. Alignment of the southwesternly dipping stratigraphic contact between the Rib Hill Sandstone and Riepe Spring Limestone in the footwall with the same contact in the hanging wall suggests that there is ~3–4 km of slip in an easterly direction on the Alpha fault.

Fault surfaces in a near-tip setting

Figure 7 shows preliminary fault surface maps for the Liberty fault. The Liberty fault illustrates characteristics of fault surface maps in the near-tip environment, including a major rotational component of the hanging wall relative to the footwall. Like the Dexter fault, the Liberty fault is also relatively young—indeed even younger than the Dexter—so it also shows characteristics of other young faults.

The Liberty fault is a northeast-striking, southeast-dipping normal fault that is exposed for ~1000 m of strike length on the eastern end of the Liberty pit (Figures 4 and 7). Two vintages of reliable geologic maps are available for this region of the pit, one spatially offset from the other by mining progress; very thick colored lines show the rock/alteration types along the two mapped traces of the fault (Figure 7). Intensely colored dots show the logged geology of drill hole piercements, which are relatively few because the fault is relatively steep (requiring a deep hole to penetrate it) and the copper grade drops quickly with depth (obviating the need to drill many holes for ore delineation in this area). Because of the presence of a block cave mine nearby, the Liberty fault was crossed by underground drifts on the 6560 ft level south of 104,000N, in which the location of the Liberty fault was mapped (locations not shown because of lack of corresponding data on rock/alteration types). Fault locations at that elevation improve the control on structure contours along most of the illustrated portion of the fault, which must continue further to the northeast.

The southwestern tip of the Liberty fault was mapped (unpublished 1958 Liberty pit map, Geology Department, Nevada Mines Division, Kennecott Copper Corporation), with the fault ending in a horsetail of small faults. Continuations of the Liberty fault to the southwest of the tip are shown on some maps (e.g., Spencer, 1917), but careful attempts to trace the fault southwestward in the field and to document compelling offsets in geologic markers (after accounting for other faults in the area) in drill holes confirm that the fault terminates within the pit as originally mapped and shown on Figure 7. The Liberty fault picks up displacement northeastward, cutting and offsetting the Eureka fault immediately northeast of the northern rim of the Liberty pit (Figure 7).

Measurements on the dip of the Liberty fault range from 45° to 70°SE (Figure 7). The steepest dips are near the southwestern termination of the fault, whereas to the northeast, over the rest of its exposed length, typical dips are about 50° (Figure 7). The main Liberty fault has a nearly linear trace, but it has a concave southeast footwall splay and a north-striking, concave southeast, scooped-shaped hanging wall splay within ~600 m of its southwestern tip. The Liberty Footwall Splay fault is subparallel to the main fault but is more irregular in strike and dips 65° to the southeast (not shown); the branch-line with the main Liberty fault (i.e., where the Footwall Splay joins with the main fault) is shown on the footwall geologic map (Figure 7a). The Liberty Hanging Wall Splay fault, in contrast, swings abruptly
Figure 7A. Preliminary fault surface maps for the Liberty fault on the eastern end of the Liberty pit, Robinson district, illustrating characteristics of fault surface maps in the near-tip environment, including a major rotational component of the hanging wall relative to the footwall. (A) Footwall; (B) hanging wall. The locations of reliable geologic control for these maps are shown by intensely colored dots (drill hole piercements) and by very thick colored lines (the mapped trace of the fault on two vintages of geologic maps during mining). Other attributes are as described for Figure 6 and in the text. The southwestern end of the Liberty fault was mapped within the Liberty pit. The measured dips indicate that the fault dips to the southeast at moderate to steep angles; some of the dip orientations near the southwestern tip of the Liberty fault are measured on small horsetails (not shown) off the main fault. Branch lines show how hanging-wall and footwall splays joint with the main Liberty fault. There is no slip at the tip at the southwestern end of the fault; farther to the northeast, geologic interpretations require further modification to refine the amount and direction of slip of various piercing points along the fault surface. Nonetheless, offsets in the circular reference points at the northeastern end of the map indicate that the hanging wall point moved 227 m in the plane of the fault in a S40E direction relative to the footwall, producing a horizontal component of clockwise rotation of the hanging wall by ~7° relative to the footwall. Restoring this movement causes the position of the Eureka fault and other geologic markers in the hanging wall to match closely with corresponding markers in the footwall. Source of information; E. Seedorff et al. (unpub. data).
Figure 7B. Preliminary fault surface maps for the Liberty fault on the eastern end of the Liberty pit, Robinson district, illustrating characteristics of fault surface maps in the near-tip environment, including a major rotational component of the hanging wall relative to the footwall. (A) Footwall; (B) hanging wall. The locations of reliable geologic control for these maps are shown by intensely colored dots (drill hole piercements) and by very thick colored lines (the mapped trace of the fault on two vintages of geologic maps during mining). Other attributes are as described for Figure 6 and in the text. The southwestern end of the Liberty fault was mapped within the Liberty pit. The measured dips indicate that the fault dips to the southeast at moderate to steep angles; some of the dip orientations near the southwestern tip of the Liberty fault are measured on small horsetails (not shown) off the main fault. Branch lines show how hanging-wall and footwall splays joint with the main Liberty fault. There is no slip at the tip at the southwestern end of the fault; farther to the northeast, geologic interpretations require further modification to refine the amount and direction of slip of various piercing points along the fault surface. Nonetheless, offsets in the circular reference points at the northeastern end of the map indicate that the hanging wall point moved 227 m in the plane of the fault in a S40E direction relative to the footwall, producing a horizontal component of clockwise rotation of the hanging wall by ~7° relative to the footwall. Restoring this movement causes the position of the Eureka fault and other geologic markers in the hanging wall to match closely with corresponding markers in the footwall. Source of information; E. Seedorff et al. (unpub. data).
southward from the main Liberty fault, forming an easterly fac-
ing scoop that dips ~40° east and terminates to the south (not shown); the branch line with the main Liberty is shown on the hanging-wall geologic map (Figure 7b).

The offset segments of the older Eureka fault, which occur as a curving line on both the footwall and hanging wall Lib-

erty fault surface geologic maps (Figure 7), provide a geologic marker to restore slip on the southwestern end of the younger Liberty fault. The restoration can be accomplished by rotation of the hanging wall relative to the footwall about a rotation axis near the tip, such that any point in the hanging wall makes an arc relative to the footwall. The slip direction is defined by a vector that joins the ends of the arc, which is oriented at ~S40°E, and the length of the vector as measured in the plane of the fault, which is the magnitude of slip on the Liberty fault, is ~745 ft (~230 m). The horizontal component of clockwise rotation of the hanging wall relative to the footwall is ~7° (Figure 7), or more than three times the amount observed for the Dexter fault (Figure 5).

Overview of Yerington district geology

The Yerington district, located near the town of Yering-
ton in western Nevada, contains porphyry copper, skarn, and iron-oxide-copper-gold (IOCG) mineralization related to the Middle Jurassic Yerington batholith. Mineralization is hosted in the Yerington batholith and its Triassic to Jurassic wall rocks (Dilles and Wright, 1988; Dilles et al., 2000). The district con-
tains multiple porphyry copper centers, which are classified as quartz monzodioritic-granitic porphyry Cu-(Mo) systems in the scheme of Seedorff et al. (2005). The Yerington district has been structurally dismembered and rotated 60 to 90°, primarily by three temporally distinct sets of east-dipping normal faults since ~14 Ma (Proffett, 1977, 1979; Einaudi, 1977; Harris and Einaudi, 1982; Dilles, 1987; Dilles and Einaudi, 1992; Dilles and Gans, 1995; Barton and Johnson, 2000; Dilles et al., 2000). Rocks of the Yerington batholith crop out over an east-west dis-

traction of the Ann-Mason deposit would have had a strike of ~N35°W and dipped ~90° (Dilles, 1987; Dilles and Proffett, 1995; Dilles et al., 2000). The flanks, top, and bottom of the hydrothermal system are exposed in the Ann-Mason fault block in the Singatse Range (Dilles and Einaudi, 1992), as well as in the Buckskin Range to the west (Lipske and Dilles, 2000; Dilles et al., 2000). The main part of the Ann-Mason deposit is bound by two gently east-dipping faults: the deposit is located in the footwall of the Singatse fault and in the hanging wall of the Blue Hill fault (Figure 8). In ad-

dition, the deposit is cut by other, more steeply dipping faults. Exploration opportunities exist in each place where the deposit potentially is truncated by post-mineral faults.

Lateral continuations across fault blocks

As described above, the Ann-Mason ore body is truncated above the Singatse fault (Figure 8). The Singatse fault has 3.6 km of slip along its northern exposure and increases to 3.8 km of slip along its southern exposure directly above the Ann-Mason deposit (Figure 9) over a distance of 3.8 km (Richardson and Seedorff, this volume). The minimal increase in slip along strike is further constrained by the scoop-like geometry of the Singatse fault, which limits the viable structural interpretations, as large rotations involving north-south components would re-

quire much larger strains on the wall rocks (e.g., Needham et al., 1996). The outermost limits of the Ann-Mason ore body are projected to the footwall surface of the Singatse fault (Figure 9), and the outline of the Ann-Mason ore body in the hanging wall of the Singatse fault represents a potential exploration target. The two generations of faults that postdate the Singatse fault complicate the exercise, as these create gaps in the fault surface maps (Figure 9) that have to be closed before reconstructing the Singatse fault. These younger faults also dismember the outline of the Ann-Mason ore body and generate a smaller target on the eastern flanks of the Singatse Range in the hanging walls of the Singatse fault and a younger, crosscutting fault, such that the bulk of the hanging-wall projection is located directly beneath the abandoned pit of the Yerington mine (Figure 9). The pres-

ence of the hanging-wall fragment of the Ann-Mason deposit beneath the Yerington mine is somewhat coincidental and does not indicate that the Ann-Mason deposit is related to the Yer-

ington system; instead, each deposit is associated with separate, narrow dike swarms (each ~2 km in thickness) that dip 45° N. The northern-most limit of the Ann-Mason fragment in the hanging wall of the Singatse fault projects ~1.8 km SSW of the Yerington pit at the modern surface.
Figure 8. Bent cross section through the Yerington district, oriented approximately east-west, looking north. Adapted from cross section A-A of Proffett and Dilles (1984).
Fault surface maps: Three-dimensional structural reconstructions and their utility in exploration and mining

Figure 9. Geologic fault surface map for the hanging wall of the Singatse fault, showing closure of gaps created by younger faults. The Singatse fault is cut by faults of two younger generations of faults. (a) Map prior to closure of gaps created by younger faults. (b) Map after closure of gaps. Arrows show displacement directions based on restoration of hanging wall map on top of footwall map (not shown). From Richardson and Seedorf, this volume.
Likewise, the Ann-Mason ore body is truncated at depth by the Blue Hill fault (Figure 8), and there is mineralized rock that crops out on the footwall side of the Blue Hill fault, known as the Blue Hill deposit. Although Dilles and Proffett (1995, Figure 1) present a reconstruction that suggests that both deposits originated in the same porphyry dike swarm, most of the data that were used to generate the figure is unpublished. Richardson and Seedorff (this volume) test that hypothesis using fault surface maps, with the benefit of data derived from holes drilled by Entrée Gold more recently, and confirm that the projection of the Ann-Mason dike swarm down to the Blue Hill fault does indeed restore directly over the Blue Hill deposit and its associated dikes (Richardson and Seedorff, this volume). Thus, the Blue Hill and the Ann-Mason deposits are genetically linked, and Blue Hill indeed can be thought of, in pre-tilt position, as the lateral continuation of the Ann-Mason porphyry system (Dilles and Proffett, 1995).

Another swarm of porphyry dikes is present south of the Ann-Mason dike swarm, and it could be associated with another center of porphyry mineralization, for which a few exploration holes have been drilled. This target is known variously as Yerington West and Roulette (see Richardson and Seedorff, this volume). The viability of this center as an exploration target will be advanced by further delineation of the geology of the Blue Hill fault surface.

As the Yerington district example demonstrates, fault surface maps provide an opportunity to generate exploration targets by transferring tightly constrained interpretations of the geology across faults to where there may be little or no known information, thereby making better informed decisions about brownfields exploration for fault-offset fragments.

**DISCUSSION**

**Contrasting perspectives between 2-D and 3-D structural reconstructions**

Over the last half-century, rules and guides have been developed that govern 2-D, cross-sectional reconstructions to test interpretations, either validating or dismissing them. This work was developed in contractual settings and have been widely used in fold and thrust belts (e.g., Bally et al., 1966; Dahlstrom, 1969; Mitra, 1992; Wilkerson and Dicken, 2001), but cross-sectional reconstructions also have been applied in settings of continental extension (e.g., Proffett, 1977; Gibbs, 1983, 1984; Wernicke et al., 1988; Smith et al., 1991; Seedorff, 1991; Colgan et al., 2008; Nickerson et al., 2010). In the petroleum industry, the intent of performing this tedious process is first to test targets conceptually before spending money, in an attempt to avoid drilling dry holes. Faults can affect not only the formation of the trap, but also the migration path of hydrocarbons (Buchanan, 1996).

Cross sections are typically constructed parallel to the principal slip direction, preferably nearest to the point of maximum displacement along strike (Elliott, 1983). The slip vector at the point of maximum displacement represents the bisector between the two fault tips, also known as Elliott’s (1976) “bow and arrow” rule. Structural features plotted should be observable in the field, in seismic reflections, and/or in drill core, with structural styles shown on the section matching those observed on the ground, e.g., chevron and box folds not plotted as concentric folds (Woodward et al., 1989). Where data are sparse, data from out of the cross section can be projected down plunge (Mackin, 1950) into the cross section to provide additional constraints. Reconstructions should aim to conserve volume, which, with various simplifying assumptions, in 2-D translates to conserving bed length and unit thickness (Dahlstrom, 1969; Groshong, 1994; Judge and Allmendinger, 2011), as well as be strain-compatible, geometrically valid, and internally consistent (Woodward et al., 1986; Buchanan, 1996). In sets of serial cross sections, where one is attempting to assess changes along strike, the amount of slip on any one fault between two closely neighboring cross sections should not differ greatly nor should there be changes in structural style; whereas, over longer distances across the fault system, displacement is transferred from one fault to another (Dahlstrom, 1969).

These 2-D reconstructions show an amount of slip that is determined by the choice of a line of cross section. Faults have points of zero displacement at the tips and a point of maximum displacement between them; between the point of maximum displacement and the tips, the hanging wall should be rotating about a vertical axis relative to the footwall. Additionally, the line of section may cross multiple, superimposed fault generations with differing slip directions, where material will be moving in and out of the one, chosen line of section, making it unrestorable. The necessity for a more 3-D approach to structural reconstruction becomes apparent in the Robinson district. Strata dip moderately west in the western part of the Robinson district, but strata dip more steeply east in the central and eastern parts of the district. Thus rigid-body 2-D cross-sectional structural reconstructions cannot untilt strata on one side of the district without increasing the degree of tilting on the opposite side of the district. A restoration of the tilting of beds cannot be achieved solely by rotations about horizontal axes. Although horizontal-axis rotations characterize normal faults, an important component of vertical-axis rotation occurs near tips. The abundant 3-D geologic data available in the Robinson district, as depicted in the fault surface maps shown here, requires significant components of vertical axis rotation for the Liberty fault and non-trivial components for other faults. The importance of vertical-axis rotations in the Robinson district is consistent with the fact that strata within the central Egan Range commonly strike 20–50° from due north, which contrasts with strikes observed north and south of the accommodation zone where typical strikes are northerly.

The technique described here, though not a volumetric restoration, restores a 2-D image of the hanging wall against a 2-D image of its footwall and captures the third dimension via...
structure contours of the fault surface. The examples offered here demonstrate that fault surface maps are a useful technique for reconstruction. Nonetheless, even this type of 3-D reconstruction may not result in a substantially improved structural interpretation over a 2-D, cross-sectional reconstruction without considerable 3-D geologic control.

**Asymmetry in amount and familiarity with geologic data used in reconstructions**

The advancement of science and its practical application depend on making and presenting observations, constructing hypotheses—ideally multiple working hypotheses, and using geological reasoning to test the hypotheses to advance understanding (Chamberlin, 1890; Frodeman, 1995). Although some workers view geologic maps as anachronistic (House et al., 2013), the geologic map remains a fundamental means of presenting geologic observations (Compton, 1985; Barnes and Lisle, 2004), and cross sections and three-dimensional block models are the principal means of presenting geologic interpretations of the map area, especially in the disciplines of structural and economic geology (e.g., Stevens, 2010; Davis et al., 2012). Nonetheless, the basis for these interpretations—the geologic map—contains an underlying element of interpretation (e.g., Coe et al., 2010). A map represents the modern, irregular, two-dimensional surface through a region that evolved both in time and in three-dimensional space. The preserved geology may lack any evidence for certain time intervals; the degree of exposure in the map area may be imperfect; and critical contacts may be poorly exposed at the surface or may exist only at depth. Thus a geologic map constitutes only a working, testable hypothesis, so the impact on structural reconstructions of data derived from maps and other inputs should be displayed explicitly.

Many users of structural reconstructions, be they readers of a journal article or managers in an exploration company, may have neither the time nor the interest in evaluating the validity of the interpretation. However, the small fraction of users who have the most interest or have the most at stake in the success or failure in using the reconstruction may want to perform “due diligence” on the reconstruction. These consumers of geologic interpretations in both science and industry, however, are at a distinct disadvantage relative to the geologists who initially offer the structural reconstruction because the users typically have access to only a small fraction of the available data, or the data are in a form that make it difficult for the users to assess their quality and to consider and test alternative interpretations.

The use of fault surface maps decreases this asymmetry in knowledge because fault surface maps are an efficient means of presenting more of the data that constrain the structural reconstructions, as shown in the illustrations above. This has several important scientific consequences. First, it helps permit the reader (and earlier reviewers and editors) to evaluate better whether the reconstruction is potentially valid geologically and geometrically. Second, it makes it easier for the less informed user to generate alternative hypotheses with the same data set, including competing reconstructions. Finally, it is more difficult for geologists who are less disposed to accept the interpretation resulting from a compelling reconstruction to reject the interpretation, because it is apparent to readers that the interpretation is indeed well supported by a rich body of data. Hence it becomes incumbent on the skeptics to develop an alternative that is at least as viable. As a result, the improved transparency in reconstructions is a feature of fault surface maps that makes them an appealing alternative to 2-D reconstructions even where 3-D data are sparse.

**Exploration in 3-D**

The areas where the concepts of palinspastic structural reconstruction have been applied to district-scale exploration programs, such as San Manuel-Kalamazoo, Arizona (Lowell, 1968; Lowell, 1991) and the Yerington district, Nevada (Proffett, 1977; Proffett and Dilles, 1984), are locales where the faults with major displacement tend to have similar strike directions. Hence, 2-D reconstructions using cross sections are accurate and effective means of structural reconstruction, and the Ann-Mason examples shown here are a by-product of exploration that benefited from 2-D structural reconstructions. In areas with more complicated extensional faulting, however, a 3-D approach is especially valuable, both to aid visualization of the structure and to calculate the amounts and directions of slip more rigorously.

The Robinson district is one of those regions with complex geometries of crosscutting normal faults (Seedorff et al., 1996) that benefits most from 3-D reconstructions. Indeed, the reason that a 3-D structural reconstruction of normal faulting in the Robinson district became a long-term goal for the Robinson project was to assess whether the district had any remaining exploration potential. So many holes had been drilled in the Robinson district (>10,000) that its potential for growth in ore reserves appeared to have been exhausted, save for favorable changes in metal prices and production costs. Without a rigorous, geologically defensible 3-D reconstruction, however, it would be difficult to assess the possibility that material at minable grades and depths remains to be located. A 3-D model could show the preserved and eroded portions of fault blocks and the volumes of ore-grade material that was known (mined out or in place) or that could reasonably be inferred. Restoration of a fault or faults that identifies the projection of preserved, ore-grade material within an undrilled fault block would signify an area that would be especially prospective for mine-site exploration.

Thus, 3-D reconstructions are valuable both in grass roots exploration and in brownfields exploration when addressing the potential of regions that exhibit complex extensional faulting, and fault surface maps are useful for achieving these 3-D reconstructions.
Future developments

Many characteristics of faults described here cannot be readily incorporated into reconstructions without use of computer software; however, these characteristics are currently not well accommodated in the algorithms of commercially available structural reconstruction software programs. For example, neither non-rigid, synkinematic deformation related either to flexural collapse of the hanging wall and rebound of the footwall (Kuszniir and Ziegler, 1992) nor along-strike changes in the displacement profile (Walsh and Watterson, 1991) are incorporated easily. Indeed, the use of fault surface maps as inputs for restoration into computer software also is not readily incorporated. In the meantime, structural reconstructions of fault surface maps with adequate accuracy can be achieved manually or with standard drafting software.

CONCLUSIONS

Three-dimensional reconstructions of faults can be made with fault surface maps, which are plan-view projections of the geology of the footwall and hanging-wall surfaces of a fault. A four-layer strategy is used to develop fault surface maps. The results can be presented efficiently, however, in two panels that display interpretations of the geology of the hanging wall and footwall overlain on structure contours, as well as the sources of geologic data for each panel—usually lines from geologic maps and points from drill hole piercements. Older faults will show as lines on fault surface maps of younger faults. In contrast, younger normal faults produce gaps in the fault surfaces of older faults, and the gaps widen in the direction of increasing displacement or decreasing dip of the crosscutting fault.

The movement of a fault is restored by matching the geologic map of the hanging wall with the geologic map of the footwall. Where there are adequate geologic markers and three-dimensional control, numerous slip vectors across the fault surface result from the restoration, from which the magnitude of slip in the plane of the fault can be calculated for each vector. In a given area, the type of movement exhibited by the fault depends in part on whether the portion of a normal fault being restored is near or far from either tip of the fault; near-tip regions commonly display an important rotational component of movement, but mid-fault regions are dominated by downdip translation. Additional geologic constraints are required to determine the amount of tilting that occurred concurrent with slip. Three-dimensional structural reconstructions of areas are achieved by stepwise repetition of the process from youngest to oldest faults.

Areas of complex geology containing multiple generations of faults with differing slip directions especially benefit from the use of fault surface maps for three-dimensional reconstructions. Nonetheless, fault surface maps are effective even in areas of less complex faulting at portraying the locations and types of three-dimensional geologic controls, which aids in assessing whether the reconstruction is valid and robust. Reconstructions can play an important role in exploration for and exploitation of ore deposits, and the use of fault surface maps can facilitate a more three-dimensional approach to mineral exploration, especially in complexly faulted regions such as certain parts of the Basin and Range province.

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