The Recognition of Strike-Slip Fault Systems Using Imagery, Gravity, and Topographic Data Sets*

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ABSTRACT: Remote sensing and photogeologic techniques are commonly used in the identification of high-angle faulting based on geomorphic evidence. Mapping of strike-slip fault systems can often be enhanced by use of ancillary information such as topographic and gravity data. Because most fault systems are composed of discontinuous fault traces, the deformation patterns between step-overs are consistent indicators of the sense of displacement. Once a strike-slip system is identified with the correct sense of displacement, the geometry of the fault traces can be used to predict areas of basin formation which can be targeted for exploration. The structural characteristics of two major strike-slip systems in the vicinity of Las Vegas-the left-lateral Lake Mead Fault System and the right-lateral Las Vegas Valley Shear Zone-are documented using Landsat imagery, topographic data, and gravity data. The strike-slip systems display discrete, discontinuous fault segments. Interaction of the segments regional and local deformation consistent with the kinematics of strike-slip faulting. The Echo Hills are a push-up feature located within a right-stepover of a left-lateral fault. The Overton Arm is a deep pull-apart basin formed at an extensional stepover. Three distinct basins identified by regional gravity anomaly data are aligned in a right-stepping pattern and are interpreted to have been formed by discontinuous right-stepping segments of the Las Vegas Valley Shear Zone.

INTRODUCTION

REMOTE SENSING AND PHOTOGEOLOGIC TECHNIQUES are commonly used in the identification of regional and local high-angle faulting based on geomorphic evidence. High-angle faults are expressed as an alignment of geomorphic indicators (ridges, valleys, streams, offset drainage patterns, etc.) in linear or curvilinear patterns. The traces of high-angle fault systems are usually transferred to an interpretive map. Information on the type of fault system and the associated displacement are more difficult to identify and often are omitted from the interpretive map. The type of fault system, whether strike-slip or dip-slip (normal), is important information in the tectonic analysis involved in any exploration program.

Strike-slip faults have been known and studied for a number of years. Interest in strike-slip faults has increased because they serve as the loci of earthquakes, volcanic activity, hot springs, and ore deposits; they provide sediment traps of interest to the petroleum geologists; and they are geometrically complex. They also serve as a major aspect of tectonic analyses of many regions.

STRUCTURAL RELATIONSHIPS

At the simplest level, strike-slip faults are nearly vertical faults in single sets or conjugate arrays that have subhorizontal net slips. In areas dominated by strike-slip tectonics, one set of faults usually accounts for much of the differential displacement-principal displacement zones. Between two parallel faults the country rock is subjected to a rotational stress history, and resolving the stresses within the zone gives a maximum compression orientation at 45° to the bounding faults. The ellipse marked in Figure 1A was derived from a pre-deformation circle and is designed to emphasize the extension and compression directions. With large amounts of deformation within the fault

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block, the ellipse would develop a high axial ratio and its long axis progressively becomes closer to the bounding fault. In the brittle part of the crust the main strike-slip faults accommodate much of the displacement whereas deformation within the fault blocks may be limited. Under ductile conditions, the strain will normally be more evenly distributed as a ductile shear zone.

One of the most distinctive aspects of strike-slip zones is an *en echelon* arrangement of structures, that is, parallel arrays of folds or faults oblique to the general trend of the zones (Figure 1B). In areas of low strike-slip and/or regions without well-developed principal displacement faults, the boundaries of the zones may be poorly defined. Gentle *en echelon* folds may be the only expression of incipient horizontal displacements. With increasing deformation, more and more of the associated structures develop. If a complex array is not cut by a throughgoing principal displacement fault, the pattern is as seen on Figure 1B, though disruption by a major fault can put a lot of distance



Fig. 1. (A) Strike-slip structures in a right-lateral (dextral) shear emphasizing resolved extension and shortening directions (Boulter, 1989). (B) Map of left-lateral strike-slip fault and associated folds (lines with opposed arrows), normal faults (bar and ball on downthrown side), and vertical dikes and open fractures (lines).

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Fig. 2. (A) Plan view of bends and stepovers in a right-lateral strike-slip fault (after Boulter, 1989). (B) A 3-D view of a non-planar strike-slip fault (Boulter, 1989). (C) Maps of left-stepover and right-stepover of a rightlateral strike-slip fault showing associated structures in the stepover areas. Symbols are identified in Figure 1B.

between the two halves of the array. With potential displacements of many kilometres, features that were initiated in one area at the same time on either side of the fault may eventually become far separated.

Individual strike-slip faults rarely remain planar for long. Curvature is typically localized in pronounced bends, but the faults also step sideways in a type of *en echelon* array (Figure 2A). If the sense of bending or stepping is the same sense as the net slip, then extension occurs in these releasing bends or releasing stepovers/dilational jogs (Figures 2A and 2B). Bending or stepping senses opposite to the slip sense leads to compressional zones (Figure 2C) in restraining bends or restraining stepovers/antidilational jogs. Figure 2A is a right slip fault; hence, right-stepping or right-bending produces extension; left-stepping or left-bending creates compression. In a stepover, the nature of the structure generated between the straights depends upon the separation of fault segments and the amount of overlap (if any).

Releasing bends and stepovers are ideal places to generate sedimentary basins, and many of the younger (<100 Ma) major strike-slip faults have concentrated hydrocarbon resources in such features (e.g., Los Angeles Basin). The sometimes close association of restraining and releasing structures provides both provenance and depository for sediments. Also, many strikeslip faults anastomose, and the sense of convergence or divergence of segments together with slip sense dictates which loz-



Fig. 3. USGS Landsat image mosaic of the Las Vegas 1 × 2 Quadrangle showing geographic features.



FIG. 4. Interpretation of regional pattern of major faults of the Las Vegas 1×2 Quadrangle.

enge-shaped blocks will be upthrusted to form topographic highs or downdropped to form basins.

GEOMORPHIC INDICATORS

Strike-slip faults commonly display nearly straight or smoothly curving traces on images in contrast to the zigzag traces of normal faults and the irregular traces of thrust faults (Prost, 1989). Small slivers or slices of foreign rock bodies may be caught in the strike-slip fault zone and are commonly expressed as either elongate troughs or ridges.

The lateral displacement of the crust in strike-slip faults does not produce high scarps. Fault scarps and fault-line scarps tend to face one way and then the other, depending on the lateral offset of topographic highs and lows, or of more or less resistant rock bodies. Displaced ridges can be transported so far along a strike-slip fault that they block the upper ends of valleys whose formative streams have been shifted elsewhere, thus producing shutter ridges.

The fault line is commonly marked by structural and topographic discontinuities, linear ridges and valleys, and offset drainage patterns. Small-scale tilting associated with fault movements produces depressions, often filled with water to form sag ponds. Offset drainage patterns, their terraces, and alluvial fans or strips of alluvium may indicate the direction of displacement. However, when major faults are distinctly *en echelon*, the stepover regions are marked by sunken or elevated areas that consistently indicate displacement direction.

Some of these criteria are illustrated in the following example.

SOUTHERN GREAT BASIN, NEVADA

Southeastern Nevada is an area of crustal extension accommodated by a diverse pattern of faulting. Near the southern boundary of the Great Basin, at the latitude of Las Vegas, there are two major strike-slip fault systems: a northeast trending leftlateral system (Lake Mead Fault System) and a northwest trending right-lateral system (Las Vegas Valley Shear Zone). Though these fault systems show large lateral displacements, their surface expressions are somewhat obscured by alluvial sedimentary cover. To map the regional expression of the fault systems, we have utilized Landsat imagery, aerial photography, topographic data, and geophysical field data to detect fault segments and to outline the associated basins.

A Landsat image mosaic (Figure 3) and our geologic map (Figure 4) of the area clearly show the principal strike-slip features of the two fault systems. Note that the overall pattern of the faults has a step-like arrangement of the fault segments (Figure 4). The image shows the *en echelon* arrangement of the major segments and their relationship with the surrounding terrain. The segments are easily mapped by carefully observing the displacement of ridges and alluvium in the prominent valleys associated with the major fault displacement zones.

LAKE MEAD FAULT SYSTEM

The Lake Mead Fault System was studied by Anderson (1971, 1973) and Bohannon (1979, 1983a, 1983b, 1984). They mapped the deformation along the fault system, documented various segments of the Lake Mead Fault System, and recognized the left-lateral nature of these faults. Anderson identified the Hamblin Bay and Bitter Spring Valley left-lateral strike-slip faults as the major segments of the fault system (Figure 5). Bohannon (1979) formally named the Bitter Spring Valley fault and described the Lake Mead Fault System as containing all the northeast trending left-lateral faults in the region. Furthermore, Bohannon postulated that the system probably extends further



Fig. 5. Lake Mead Fault System. Fault segments of the System are: HB, Hamblin Bay; BSV, Bitter Spring Valley; BR, Bitter Ridge; RS, Rodgers Springs.



FIG. 6. Topographic map of the Echo Hills area. Note elevated topography within the stepover of Bitter Spring Valley Fault segments.

to the east across the Overton Arm. This postulate has been verified by recent detailed mapping which documents the continuation of the Lake Mead Fault System to at least the Arizona state boundary (Campagna and Aydin, 1988).

Mapping reveals a number of local discontinuities along the strike-slip fault segments in the Lake Mead Fault System (Figure 5). The patterns of deformation within the stepover region are consistent with the kinematics of strike-slip tectonics. For example, a right step in the Bitter Spring Valley fault resulted in the formation of the Echo Hills Domain, a push-up in the general form of an asymmetric anticline. On a more regional scale, the overall geometry of the two major segments of the Lake Mead Fault System is that of a single left step. If all of the fault segments composing the two major segments of the Lake Mead Fault System are consistently dominated by left slip, a large pull-apart basin should form within the stepover region. The



FIG. 7. Perspective view of topography at Overton Arm area.



Fig. 8. Landsat image of the Overton Arm area.

following sections examine this possibility and produce evidence for the existence of the above features.

Located approximately 50 km due east of Las Vegas and 5 km west of the Overton Arm of Lake Mead, the Echo Hills are positioned along the southwestern portion of the Lake Mead Fault System. The Echo Hills are a positive topographic feature along the Bitter Spring Valley fault (Figure 6). This topographic anomaly is elliptical in map view, and the dominant structural trend is rotated as compared to the regional trend. Because the Echo Hills are an uplifted zone in a right-stepping fault, the fault must have a left-lateral displacement. Field observations by Campagna and Aydin (1991) have shown that the Echo Hills domain is a very distinctive structural feature of ENE-WSW short-

ening contained within a right-step of the Bitter Spring Valley fault.

The surficial expression of a pull-apart basin within a stepover region of the Lake Mead Fault System is marked by a topographically low area (Figure 7). This topographic anomaly is easily recognized by the outline of the Overton Arm once the lake crosses to within the stepover regions. Generally, the Overton Arm is a narrow north-south extension of Lake Mead, but once it crosses north of the southwestern strand of the Lake Mead Fault System, the lake assumes a rhomboid shape that trends to the northeast (Figure 8). The topographic low continues to the northeast beyond the lake to the Virgin Mountain front. The topographic slope to the mountain front has a significant north-south break at the caliche surface equivalent to the Mormon Mesa surface. To the southwest, the extension of the topographic low terminates at the slope marking the end of a caliche surface, which may also be equivalent to the Mormon Mesa surface. The total length of the topographic low between the caliche breaks is approximately 20 km and the width between the major segments of the Lake Mead Fault system is 8 km. Within this topographic low the rocks at the surface are young Quaternary (?) gravels that thin and pinch-out towards the caliche breaks. The sediments that fill the basin are probably of alluvial facies and should have a distinct density contrast with the Precambrian through Paleozoic rocks which frame the basin and thus could be defined by gravity data.

A regional gravity anomaly data set in the Las Vegas 1×2 degree quadrangle was compiled and in part collected by Kane et al. (1979). This data set was included in the digital gravity anomaly data for the entire state of Nevada (Saltus, 1988). A regional complete Bouguer anomaly map was contoured for a subset of these data in the region of the Lake Mead Fault System. The anomaly pattern is that of a northeast-trending rhomboid low constrained by the segments of the Lake Mead Fault System (Figure 9). A regional anomaly field was calculated by gridding only the data points acquired over pre-Cenozoic terrain. An approximate -20 mGals anomaly associated with the basin was determined after removing the regional anomaly field. Detailed gravity surveying and modeling performed resulted in an estimated basin depth of 2.5 km. Thus, the Overton Arm basin is a significant subsidence feature along the Lake Mead Fault System.

LAS VEGAS SHEAR ZONE

The existence of the Las Vegas Shear Zone was first postulated by Gianella and Callaghan (1934). Later confirmed by Longwell (1960), evidence for the right-lateral motion along the shear zone includes offset thrust exposures and large-scale folding of the mountain ranges. Estimates of the age of displacement are from 17 to 11 Ma (Fleck, 1970; Longwell, 1974). Typically, the Las Vegas Shear Zone is depicted as a northwest trending zone of right-lateral shear with an axis down the middle of the Las Vegas Valley. There is a certain amount of ambiguity in the exact location of the shear zone; for example, Longwell (1960) shows two possible locations north and south of the Frenchman block and Guth (1981) does not speculate on the extension of the zone to the Frenchman Mountain but simply shows the zone as a dashed line in the northern Las Vegas Valley. However, it is most common to continue the zone to the southwest along the northern boundary of the Frenchman Mountain (Longwell et al., 1965). In an effort to determine the structure and geometry of the fault zone, we used the patterns of pullapart basin formation and push-ups along the Lake Mead Fault System as a model. The procedure is to first identify the basins within the Las Vegas 1×2 degree sheet that are associated with the strike-slip systems using gravity data. A geometry of the strike-slip fault systems is then proposed that would be consistent with the formation of basins along the Las Vegas Valley.



Fig. 9. Bouger anomaly map of the Overton Arm area.

The gravity data for the state of Nevada compiled by Saltus (1988) were interpolated onto a 1-km grid using a program based on the minimum curvature criteria (Briggs, 1974), and a complete Bouguer anomaly map was produced (Figure 10). To isolate the gravity anomalies associated with the Cenozoic basins in the Las Vegas 1×2 quadrangle, the complete Bouguer regional field was simply subtracted from the original data set. The resulting residual map (Figure 11) shows gravity lows of up to -40 mGals. The patterns of the basin geometries can be grouped into three trends; north-northeasterly trending basins along the Lake Mead Fault System, northwesterly trending basins in salong the Las Vegas Valley Shear Zone, and narrow north-south trending basins such as the one under the California Wash.

The low gravity anomaly along the Las Vegas Shear Zone (LVSZ) is not continuous, but shows three distinct basin features that are arranged in a right-stepping en echelon pattern. Together, the basins trend approximately N45W but the gradients along the northern and southern boundaries tend to strike more east-west. Hence, the faults that mark these gradients must be discontinuous with respect to each other and are arranged in a right-stepping en echelon manner. Following the example of the Lake Mead Fault System, which was shown in a previous section to be discontinuous and producing a large pull-apart basin in the Overton Arm, the discontinuous patterns of the faults in the Las Vegas Valley are interpreted as right-stepping segments of the Las Vegas Shear Zone (Figure 4). The basins located within the step-over regions are consistent with accepted strikeslip fault kinematics in that right-steps in a right-lateral system produce a pull-apart basin (Aydin and Nur, 1985).

This new interpretation of the shear zone has several implications. First, the shear zone apparently continues to the southeast past Frenchman Mountain as indicated by the presence of the deep northwest trending basins under the cities of Henderson and Las Vegas. The fault north of the Frenchman Moun-

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FIG. 10. Bouger anomaly map (C.I.: 5 mGals) of the Las Vegas 1×2 Quadrangle.



Fig. 11. Bouger residual anomaly map (C.I.: 5 mGals) calculated by subtracting the regional field from data in Figure 10. This map shows the gravity signature of the Cenozoic Basins.

STRIKE-SLIP FAULT SYSTEMS

tain is undoubtedly a continuation of a major segment of the shear zone. The fault segment continues well past the Frenchman Mountain and may extend towards the southwestern extension of the Bitter Springs Valley segment of the Lake Mead Fault Zone. The projected intersection site is covered by alluvium. Cakir (1990) proposes three possibilities as to the configuration within the intersection area: (1) the two faults die out without intersecting; (2) the LVSZ (Las Vegas Valley Shear Zone) and the BSVF (Bitter Springs Valley) are connected to form a continuous curved fault; and (3) the BSVF cuts the LVSZ and may extend due southwest. Detailed field mapping of the intersection reveals that most of the slip associated with that segment of the LVSZ to be reverse (compressional) and thus is consistent with our new interpretation that the strike-slip deformation associated with the LVSZ continues south of Frenchman Mountain.

There may also be other forms of contractional deformation associated with the Las Vegas Valley Shear Zone. Near Indian Springs (Figures 3 and 4), the shear zone has been mapped as taking a transpressional bend. Because the nature of the shear zone is now considered to be composed of discontinuous segments, it is postulated that the shear zone makes a left step to the west of Indian Springs. Hence, the southern hills of the Spotted Range should be an area of contractional deformation. This may be evidenced by the east-west folding in the hills; however, detailed field mapping will be necessary to confirm this hypothesis.

CONCLUSIONS

Photogeologic mapping of strike-slip faults on remote sensing imagery using a variety of geomorphic criteria enables one to establish the orientation and sense of the fault movements. The synoptic view provided by the imagery enables widely separated pieces of evidence to be linked together in order to establish the pattern of various fault segments and their associated bends and stepover regions that are consistent with the accepted kinematics of strike-slip faulting. Analysis of the patterns with ancillary topographic and gravity data provide a valuable approach to determining areas of uplift and basinal development. Analysis of the Lake Mead Fault System shows that a left-step along the left lateral fault system initiated the Overton Arm basin whereas the Echo Hills formed as a pushup because of a right step along a segment of the system. A similar type of analysis controlled by the use of gravity data provided an improved mapping of the Las Vegas Shear Zone and a definition of basins along the zone. Such analysis provides a powerful means for establishing the tectonic and economic significance of any given area.

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