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N98-18921 A

1992

P-18

Fault Identification Using Multidisciplinary Techniques at the Mars/Uranus Station Antenna Sites

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A fault investigation was performed at the Mars and Uranus antenna sites at the Goldstone Deep Space Communications Complex in the Mojave desert. The Mars/Uranus Station consists of two large-diameter reflector antennas used for communication and control of deep-space probes and other missions. The investigation included interpretation of Landsat thematic mapper scenes, side-looking airborne radar transparencies, and both color-infrared and black-and-white aerial photography. Four photolineaments suggestive of previously undocumented faults were identified. Three generally discrete morphostratigraphic alluvial-fan deposits were also recognized and dated using geomorphic and soil stratigraphic techniques. Fourteen trenches were excavated across the four lineaments; the trenches show that three of the photolineaments coincide with faults. The last displacement of two of the faults occurred between about 12,000 and about 35,000 years ago. The third fault was judged to be older than 12,000 years before present (ybp), although uncertainty remains. None of the surface traces of the three faults crosses under existing antennas or structures; however, their potential activity necessitates appropriate seismic retrofit designs and loss-prevention measures to mitigate potential earthquake damage to facilities and structures.

I. Introduction

The Mars/Uranus Station consists of two antennas and surrounding support buildings (Fig. 1). The DSN 70-m antennas are the largest fully steerable communications

antennas in the world. The Mars antenna at DSS 14 was constructed as a 64-m antenna in 1966 and later enlarged to 70 m in 1988. Standing more than 71 m high, this antenna is one of the more striking features of the Goldstone complex.

The Uranus antenna (DSS 15) is a 34-m, high-efficiency, precision-shaped antenna located approximately 487 m southeast of the Mars antenna (Fig. 1). Built in 1984, this

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latest antenna addition was first used in January 1986 to support the Voyager 2 spacecraft encounter with the planet Uranus, which is more than 3 billion km from Earth.

In the early 1980s, plans were developed to construct additional antennas and support buildings at the facility. Geotechnical investigations performed for the proposed expansion revealed several photolineaments within the Mars/Uranus Station valley [1]. The lineaments were thought to be associated with faulting. Refraction seismic lines run through the center of the valley were inconclusive regarding the origin of the photolineaments, and doubt remained about the possible impact of these features and the potential hazard they posed to the facilities. The late 1980s brought a renewed interest in expansion of the facility and a heightened concern among facility designers about the lineaments and the possible presence of faults within the Mars/Uranus Station valley. A multidisciplinary fault investigation was undertaken to determine the origin of the lineaments and to assess their potential impact on existing and proposed structures.

The purpose of this investigation was twofold: (1) to evaluate the Mars/Uranus Station valley for the presence of faults, including the previously identified lineaments, and (2) to determine the relative age and activity of any identified faults.

II. Location and Regional Geologic Setting

The Mars/Uranus Station is located in the northwest corner of the Goldstone Deep Space Communications Complex (DSCC) approximately 90 km north of Barstow, in San Bernardino County, California (Fig. 2). This is a remote area, about a 2- to 3-hr drive from major population centers of Southern California. Public access is restricted because the DSCC is located within the U.S. Army's Fort Irwin National Training Center and east of the China Lake Naval Weapons Center, Mojave Range B.

The Goldstone DSCC lies in the north-central Mojave Block geomorphic province. The Mojave Block is bounded on the southwest by the San Andreas Fault and Transverse Ranges; on the north and northeast by the Garlock Fault, Tehachapi Mountains, and the Basin and Ranges; and on the east by the arbitrary boundary of the Nevada state line and the Colorado River. The central portion of the block is characterized by potentially active Quaternary and locally active Holocene faults [2]. The faults trend northwest and southeast and are predominantly strike-slip faults (Fig. 3, after [3]). The faults cut Tertiary extensional basins separated by low hills of Tertiary volcanic and sedimentary

rock or pre-Tertiary intrusive rock [4]. Many basins contain Pleistocene pluvial dry lakes.

III. Technical Approach

Geologic information within the Goldstone DSCC is limited and original work was required during the course of the investigation. To cope with the remote location and lack of information in a timely and economical way, analyses were made of remote-sensing imagery and aerial photography. Results of the imagery analyses were then checked in the field with ground-truth verification, reconnaissance geologic mapping, geomorphic observations, fault trenching, and soil-stratigraphic analyses. A summary of the technical approach is presented in Fig. 4.

IV. Imagery Analysis

Remote-sensing imagery and aerial photography that encompassed 15,540 square km were reviewed for evidence of possible Quaternary faulting. The imagery included a Landsat thematic mapper scene, side-looking airborne radar (SLAR) transparencies, and both black-and-white and color-infrared aerial photography (Table 1).

The imagery was selected in accordance with the multi-approach outlined in [5]. This approach optimizes the results of an imagery analysis by reviewing multiscale, multistation, multiband, multirate, and multi-enhanced imagery. The imagery is then reviewed and interpreted by multiple observers.

Geomorphic and photographic features recognized on the imagery and considered to be evidence of faulting included:

- (1) topographic and vegetation alignments
- (2) linear breaks in slope
- (3) rectilinear closed depressions
- (4) linear or uphill facing scarps on alluvial fans
- (5) linear change in drainage or erosional texture
- (6) offset stream channels
- (7) linear change in photographic tone or color
- (8) linear spectral contrasts on Landsat imagery

A. Field Reconnaissance

After the imagery analysis, photolineaments were checked in the field. The purpose of the field reconnaissance was to differentiate fault-related geomorphic features

from those formed by man-made, natural erosional, or depositional processes. In addition, geologic mapping and geomorphic observations were made. Geomorphic observations included relative dissection of fan surfaces, relative development of desert pavement and patina (desert varnish), and fan superposition relationships. Early morning, low-angle-sun-illumination, 35mm slides were taken of photolineaments.

B. Results of Imagery Analysis

Based on the photographic evidence and observations made during the field reconnaissance, four principal lineaments were identified and suspected to be associated with Quaternary faulting (Fig. 5). Figure 6 is a composite aerial photograph showing these lineaments. The characteristics of each lineament are compiled in Table 2.

V. Exploration

Field exploration included reconnaissance geologic mapping, siting exploratory trenches, and detailed logging of the trenches, including soil-stratigraphic analyses. The trenches served two purposes: (1) to determine if the photolineaments were fault related, and (2) to expose sediments amenable to relative dating by soil stratigraphic techniques.

Fourteen trenches were excavated with a backhoe equipped with a 61-cm shovel; Fig. 7 shows the trench locations.

VI. Site Geology

The Mars/Uranus Station is in a linear interior-draining valley bounded on the south by steep volcanic ridges and on the north by low-lying alluvial fan-capped hills. Southwest of the antennas is a small dry lake. As shown in Fig. 7, the major geologic units are three different-age alluvial-fan deposits, playa deposits, and extrusive volcanic rocks.

A. Undifferentiated Volcanic Rocks

Andesite forms the steep hills south of the antennas and crops out in two isolated locations in the hills to the north. The rock is light gray to black, massive, and slightly vesicular. It is resistant to weathering and forms steep slopes.

Latitic to dacitic tuffs underlie the low hills north of the main valley where they are capped by Unit 3 alluvium. The rock is white to pink, massive to thickly bedded, lithic

tuff, and tuff breccia. It is easily eroded and exposures are limited to small stream canyons.

The volcanic rocks are probably equivalent to the Pliocene, Lane Mountain Andesite of Dibblee [6] or the lower Miocene, Lane Mountain Quartz Latite of Burke [7].

B. Alluvial-Fan Deposits

The alluvial-fan deposits were subdivided into three mapping units based mainly on geomorphic and soil-stratigraphic evidence. Diagnostic criteria included elevation above base level, superposition relationships, fan surface morphology (relative dissection, etc.), development of desert pavement and patina, and soil-profile development. These criteria and the application of soil-profile development for fault-activity assessments are summarized in [8], [9], [10], and [11]. Relative ages for site-specific surfaces and alluvial fan sediments are given in [12].

The nested geomorphic expression of the three alluvial-fan deposits and their diagnostic surface and soil-stratigraphic characteristics allow them to be mapped as generally discrete morphostratigraphic units, which were designated as Units 1 (youngest), 2, and 3, respectively (Fig. 7).

1. Unit 3 Alluvial Fans. Unit 3 fan deposits cap the low hills north of the antennas and form the highest level geomorphic surfaces flanking the Mars/Uranus Station valley. Remnant fan surfaces are heavily dissected, but locally well-developed desert pavements with dark patinas are still visible on drainage divides. The deposits are coarse gravel/cobble fanglomerates interbedded with finer grained fluvial lenses. On the undissected surfaces, these deposits support strongly developed, relict paleosols characterized by truncated argillic horizons and multiple, superimposed, stage III to IV calcic horizons (Btk).⁴ Their relative elevation, surface characteristics, and pedologic development suggest that these fans are well in excess of 100,000 years old [12].

2. Unit 2 Alluvial Fans. Unit 2 fan deposits form mid-level geomorphic surfaces surrounding the antennas on the west and east. Fan surfaces are moderately dissected with poorly to moderately developed desert pavements. Pavements display a relatively light-colored patina.

⁴ The term horizon refers to an interface indicative of a position in a stratigraphic sequence; the A horizon is the uppermost soil horizon and the B horizon is below. Bt horizon refers to an accumulation of silicate clay that has either formed in situ or is illuvial; hence, it has more clay than the assumed parent material and/or the overlying horizon. Btk indicates an accumulation of alkaline earth carbonates within the Bt horizon. See Appendix for additional definitions.

The material is finer grained than Unit 3 but still contains coarse gravel/cobble layers. The soils capping these surfaces are of moderately to strongly developed relict paleosols characterized by argillic horizons and multiple stage II to III calcic horizons. Remnants of moderately developed, near-surface buried soils are also present. Geomorphic and soil-stratigraphic evidence suggest that the Unit 2 fan complexes are at least 35,000 to 40,000 years old, but may be as old as 100,000 years before present (ybp).

3. Unit 1 Alluvial Fans. Unit 1 fans form the lowest level geomorphic surfaces in the Mars/Uranus Station valley. Fan surfaces are smooth, undissected, and represent areas of active deposition. Where desert pavement is present, it is thin and patchy. The material consists of relatively fine-grained sands and gravels. Pedogenic profiles are generally absent to weakly developed. Where present, soils are characterized by cumulic profiles with incipient argillic horizons (Btjk)⁵ containing disseminated carbonate. Geomorphic and soil-stratigraphic evidence suggests that the older portions of these fans are approximately 7,000 to 12,000 years old, but local portions may be as old as 35,000 ybp.

Recent stream channel and valley-fill sediments were also mapped as Unit 1. These deposits are inherently young, and at the scale of the mapping are difficult to separate from the older portions of the fans. These deposits are estimated to be less than about 5,000 to 7,000 years old.

C. Other Surficial Deposits

1. Playa Deposits. Playa deposits consist of unconsolidated, well-sorted clay, silt, and fine sand. This material underlies the surface of the dry lake located west of the Uranus antenna. The morphostratigraphic relationship with Unit 1 fans is not entirely clear, but the two are probably intercalated at depth.

2. Talus. Talus blankets the base of the volcanic ridges south of the main valley. It consists of loose gravel to cobble-sized clasts of volcanic rock.

3. Landslides. One small landslide was mapped on the ridge south of the Uranus antenna. The slide was mapped based solely on geomorphic evidence; hence, its age and thickness are as yet unknown.

⁵ Btjk: See preceding footnote; the "j" is used in combination with other horizon designations to denote incipient development of that particular feature or property.

VII. Fault Activity Analysis

The origin of Photolineaments 1, 2, and 3 were assessed by trenching. Faults were encountered in several trenches placed across the lineaments (Table 3).

A. Photolineament 1

The three segments that comprise Photolineament 1 were explored at trenches emplaced at 10 locations within the Mars/Uranus Station valley (Fig. 7). Nine of those trenches exposed faults that, near the surface, trend about N75E and comprise a through-going, north-stepping, en echelon system. The faults form low-angle, subdued scarps in fan Units 2 and 3, but are not surficially expressed in alluvial fan Unit 1 (Fig. 7).

The Photolineament 1 fault system is characterized by a zone of dislocation several feet wide. Movement has been typically accommodated along multiple slip surfaces and fractures. The slip surfaces generally dip steeply 60 to 90 deg to the south with the north side up. Minimum offset was in each case greater than the maximum trench depth, which varied from 1.8 to 3 m. Further, some fault-associated fractures extend into a colluvial wedge, presumably deposited on a scarp formed by an earlier faulting event (Fig. 8). This fact, combined with a minimum offset observed of least 1.8 to 3 m, suggests that the multiple movements have occurred on the Photolineament 1 fault system. However, no site-specific information is presently available from which to judge the recurrence of individual tectonic events.

In Trench 11, the fault offsets a strongly developed buried argillic horizon in fan Unit 2 (Fig. 9). Based on relative profile development, this soil required at least 35,000 to 40,000 years to form; however, it may be much older [12]. Immediately above the fault at this location is a buried cumulic soil profile within fan Unit 1. The cumulic profile is characterized by a weakly developed argillic horizon (Btjk) with disseminated carbonate filaments. This soil is an estimated 7,000 to 12,000 years old [12] and is not offset by the Photolineament 1 fault. Accordingly, while not wholly definitive, the nondisplaced Unit 1 soil horizon exposed in Trench 11, the lack of any fault-controlled geomorphic expression in Unit 1 fans, and the subdued scarps characteristic of the older fans suggest that the last fault displacement most likely occurred in pre-Holocene time.

B. Photolineament 2

Photolineament 2 was trenched at two locations near the intersection with the fault that forms Photolineament 1

(Fig. 7). Both trenches exposed faults generally coincident with lineament trend. This is exemplified in Trench 6 by a N75E fault trend and in Trench 5 where the faults trend about N80W. The Photolineament 2 fault has only minor surface expression in the Unit 3 fans and no expression in the Unit 1 fans.

In Trench 5, the fault offsets Unit 2 alluvium. These sediments were judged to be in the range of 35,000 to 100,000 years old, based on the presence of moderately developed soil profiles. Trench exposures were not sufficient to bracket the most recent offset or to determine the structural relationship between Faults 1 and 2; however, geomorphic evidence suggests that Fault 1 truncates and therefore is younger than Fault 2.

C. Photolineament 3

Three trenches were excavated across the trace of Photolineament 3 (Fig. 7). Trench 12 exposed a fault that displaces Unit 2 and Unit 3 alluvium (Fig. 10).

Trench 13, located east of Trench 12, exposed both unbroken Unit 2 alluvium and a buried paleosol estimated to be at least 35,000 to 45,000 years old. These fault-paleosol relationships suggest that the last displacement of the Photolineament 3 fault occurred between about 35,000 to 100,000 years ago.

D. Photolineament 4

Trench 3 was excavated across the trace of Photolineament 4 (Fig. 7). Unit 2 alluvium was exposed along the entire length of the trench. No faults were observed. It is possible that a fault exists below the maximum trenched depth. However, if a fault exists, the soil stratigraphic age assessments of the unbroken Unit 2 alluvium indicate that the last displacement occurred at least 35,000 years ago and probably well before that time.

VIII. Summary and Conclusions

Multidisciplinary techniques were used to determine the presence and age of faults near the Mars and Uranus antenna sites at the Goldstone DSCC. Photolineament analyses identified four linear trends suggestive of fault control. Site-specific trenching shows that Photolineaments 1, 2, and 3 are fault controlled, but that Photolineament 4 is not. The three, previously unreported, fault systems are dated mainly by geomorphic and soil-stratigraphic techniques. Based on the presence of buried and relict paleosols, with relative development of argillic and calcic horizons varying from slightly to strongly developed, three morphostratigraphic alluvial-fan units were identified: Unit 1, less than about 7,000 to 12,000 years old; Unit 2, approximately 35,000 to 40,000 years old; and Unit 3, estimated to be in excess of 100,000 years old.

The last displacement of Photolineament Faults 1 and 3 occurred between about 12,000 to about 35,000 years ago. Subsurface evidence for the existence of Fault 2, which corresponds with Photolineament 2, is less conclusive; however, when subsurface and geomorphic evidence are combined, faulting is clearly suggested. The structural relationship between Faults 1 and 2 is not known. The most recent displacement of Fault 2 is not known, but is believed to be older than Fault 1, based on geomorphic evidence. A review of Landsat and SLAR imagery indicated that Faults 2 and 3 may be the northwest and southeast extensions of the same fault.

None of the surface traces of the three faults crosses under or projects into existing Mars/Uranus Station structures. Seismic risk assessment of local and regional faults utilizing statistical analysis of earthquake data records and computer fault models based on geologic evidence indicated the maximum credible earthquake (MCE) for the site is a magnitude 7.5 event on the Garlock Fault, which is located about 19 km north of the study area. The new fault location and activity assessment will now permit design engineers to proceed with seismic retrofit designs and loss-prevention measures for mitigation of potential earthquake damage to support facilities and structures.

Acknowledgments

Valuable site geologic information, on-site liaison, and technical contributions provided by Tony Riewe of JPL are appreciated. Also appreciated are the critical reviews of this paper by Howard "Buzz" Spellman, Jr., Chief Geologist of Converse Consultants West, and Perry L. Ehlig, of California State University, Los Angeles.

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Table 1. Aerial photography, Landsat, and SLAR imagery reviewed.

Type	Date	Project	Scale	Roll/Frame	Source
Landsat TM ^a	07/28/85	-	1:155,000	50514-17515	JPL (EOSAT)
Side-looking airborne radar (SLAR)	12/85	TRPA ^b	1:250,000	1/4-7	USGS ^c
Low-altitude aerial photography					
Color infrared	06/25/83	NHAP 83 ^d	1:58,000	89/122, 123 95/136, 137	USGS
Black and white	06/25/83	NHAP 83	1:80,000	62/23, 124 66/100, 101	USGS
Black and white	10/09/87	87156 ^e	1:18,000	1/8-10 2/8-10 3/11-13	JPL
Black and white	01/14/82	-	1:6,000	-/1-8	JPL

^a Thematic mapper.

^b Trona Project Area.

^c U.S. Geological Survey.

^d National High-Altitude Photography, flown in 1983.

^e JPL photo number.

Table 2. Characteristics of photolineaments.

Photo-lineament	Length, km	Imagery in which lineament is visible	Geomorphic evidence suggestive of faulting	Projects close to existing structures	Remarks
1 (1, 1a, 1b)	>4.8	SLAR, aerial photos	Strong	Yes	Strong lineament defined by a combination of features, including obvious topographic alignments, linear scarps on alluvial fans, rectilinear depressions, and linear changes in erosional texture.
2	>16 (regional)	Landsat, SLAR, aerial photos	Moderate	Yes	Regional lineament visible on high-altitude imagery, locally defined by linear changes in drainage/ erosional texture and photographic tone.
3	>16 (regional)	Landsat, SLAR, aerial photos	Moderate	Yes	Regional lineament visible on high-altitude imagery, probably represents southeast extension of Lineament 2.
4	0.64±	Aerial photos	Weak	Yes	Local lineament (<609 m long) defined by a linear break in slope and an apparently offset stream channel.

Table 3. Summary of fault trenching.

Photo-lineament	Identified as a fault during exploration	Estimated minimum age of most recent activity, ybp	Remarks
1	Yes	~12,000	Through-going fault system dated by geomorphic and soil-stratigraphic methods. Fault trends roughly N75E and is characterized by north-stepping segments up to 2.4 km long. Minimum offset is 1.8 to 3 m, north side up. Some evidence of multiple events.
2	Yes	>12,000	Coincident with regional lineament identified on Landsat imagery. Trenching and geomorphic evidence suggest fault origin. Geomorphically it appears to be truncated by Fault 1. However, this was not demonstrated during exploration. The structural relationship with Fault 1 and the approximate age of this fault are yet unclear.
3	Yes	35,000	Fault is coincident with regional lineament identified on Landsat imagery. Dated by geomorphic and soil-stratigraphic methods. Probably forms southeast extension of Lineament 2.
4	No	-	Trenching across the trace of this lineament exposed unbroken 35,000 to 100,000-year-old deposits. Photolineament 4 is not fault related.

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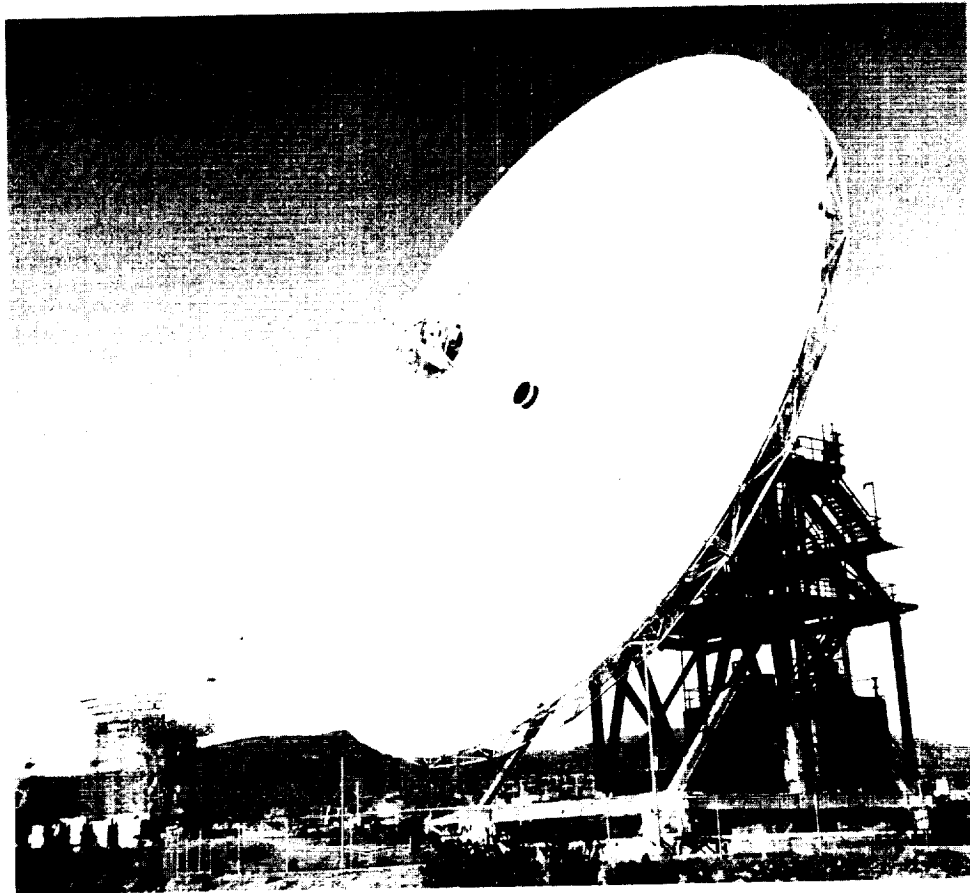


Fig. 1. The 34-m Uranus antenna (DSS 15). The 70-m Mars antenna (DSS 14) is in the background.

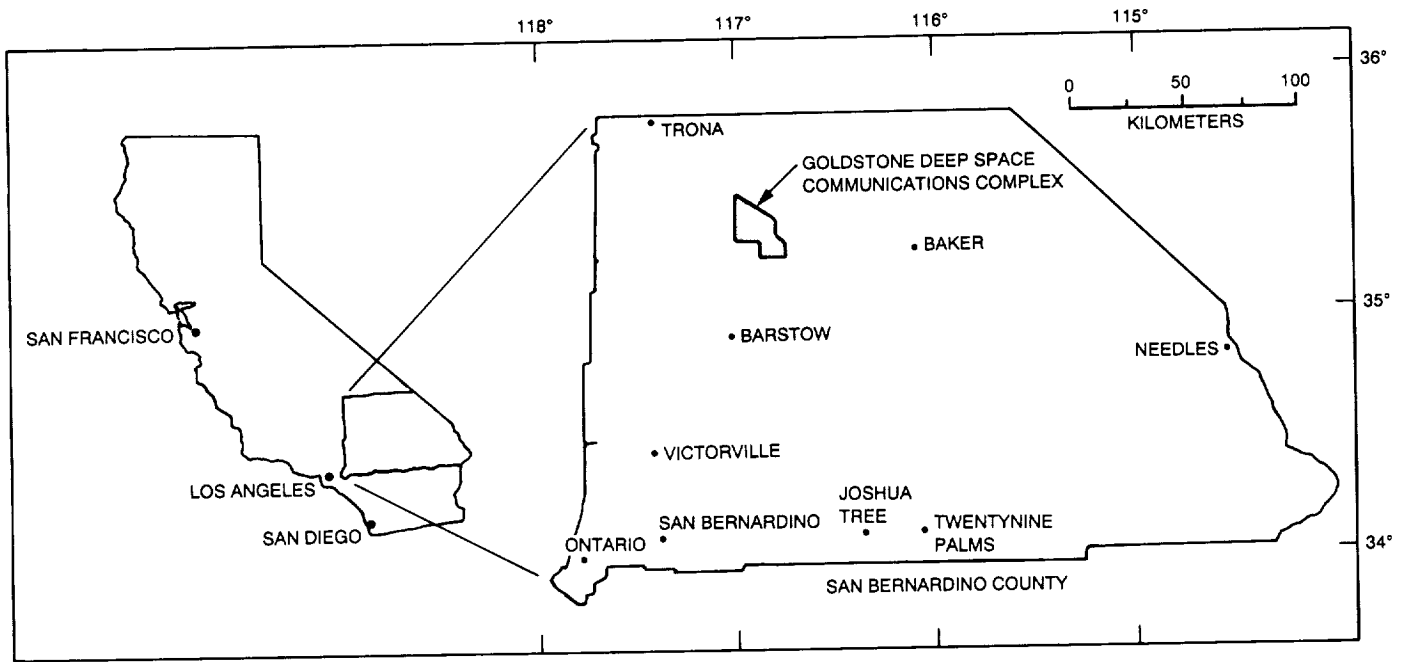


Fig. 2. Map showing the Goldstone Deep Space Communications Complex in the Mojave Desert, California.

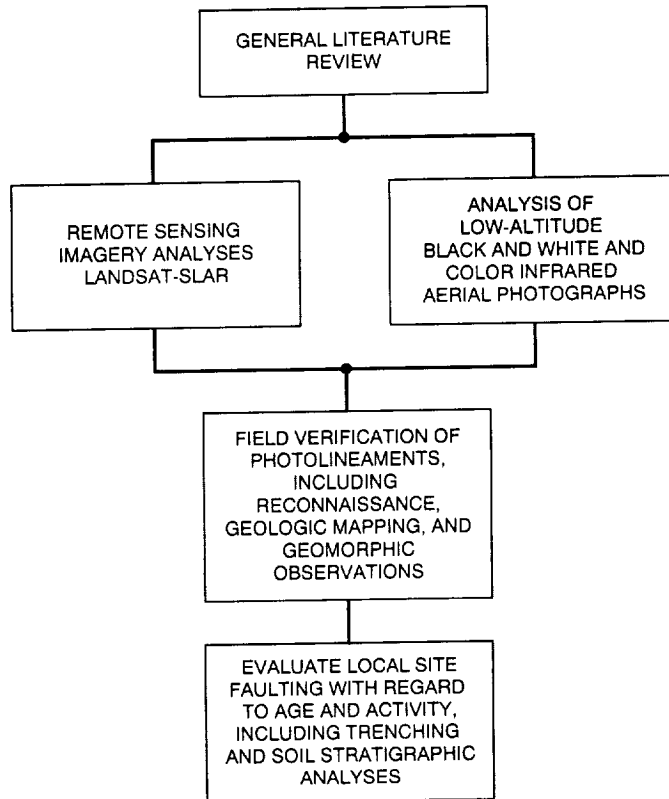


Fig. 4. Summary of technical approach.

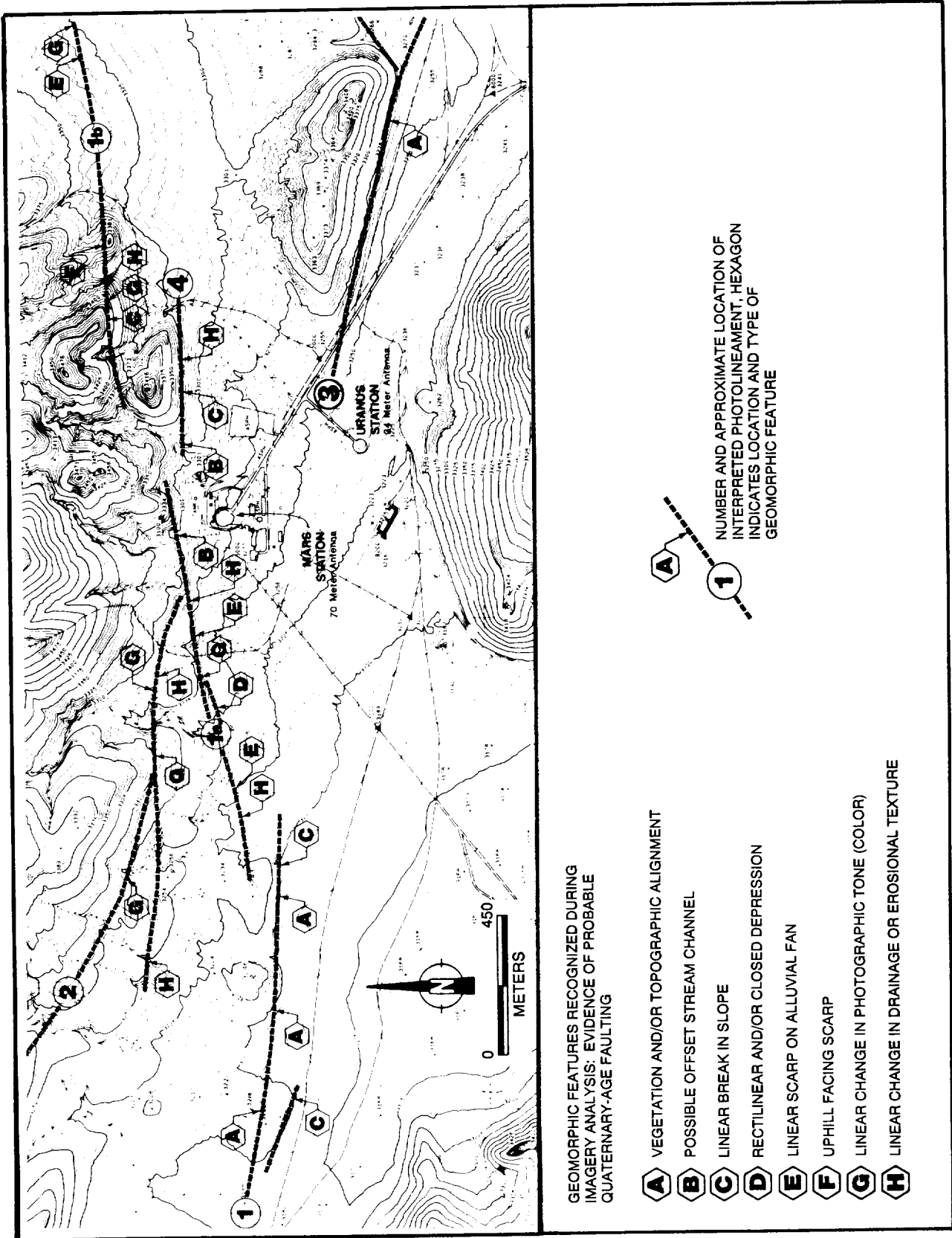


Fig. 5. Photolineament map of the Mars/Uranus Station valley.



Fig. 6. Composite serial photo of Mars/Uranus Station valley showing photographic expression of lineaments, with MA = Mars antenna and UA = Uranus antenna. Note the change in morphology and darker shade of alluvial-fan surfaces.

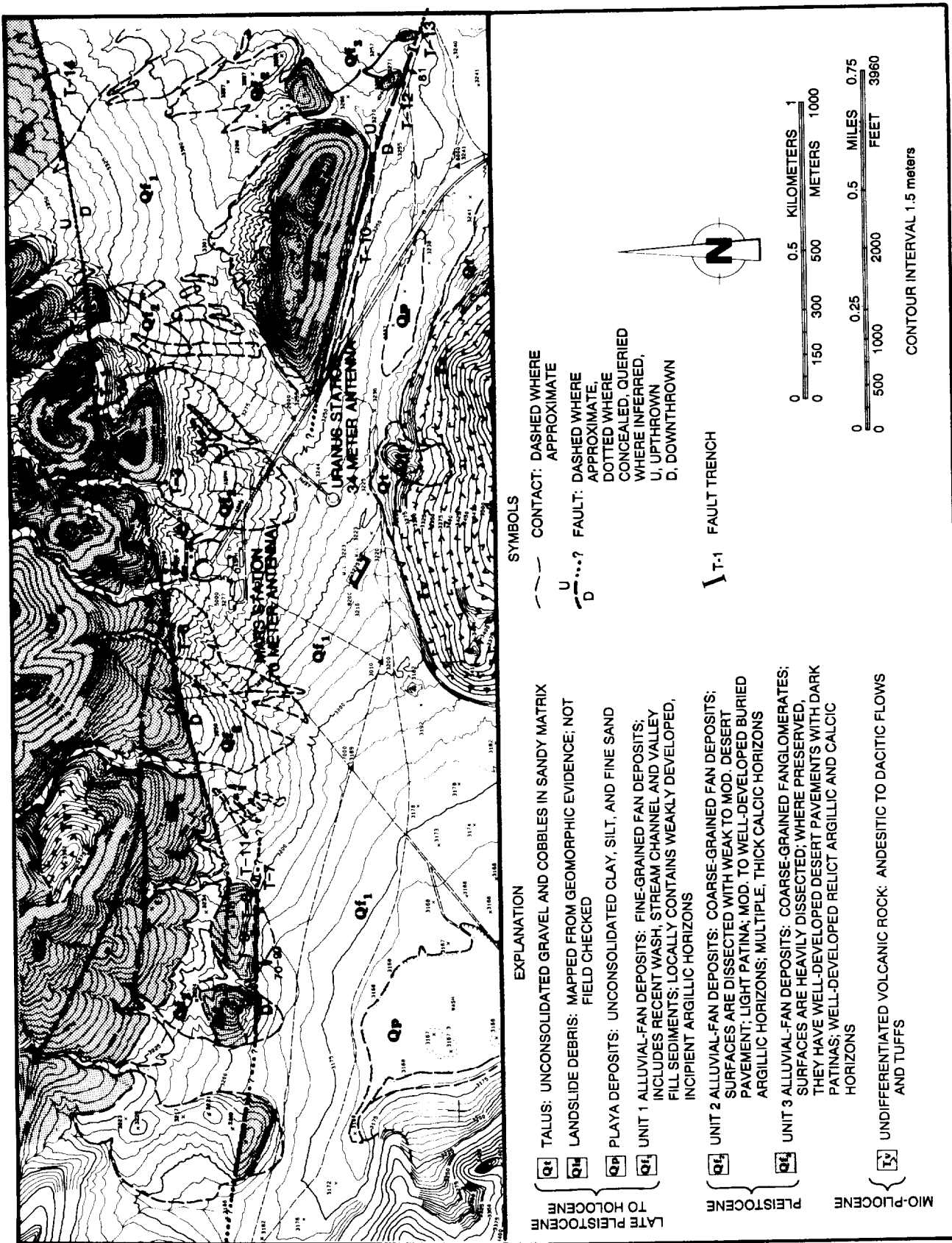


Fig. 7. Generalized geologic map of the Mars/Uranus Station valley, Goldstone DSCC.

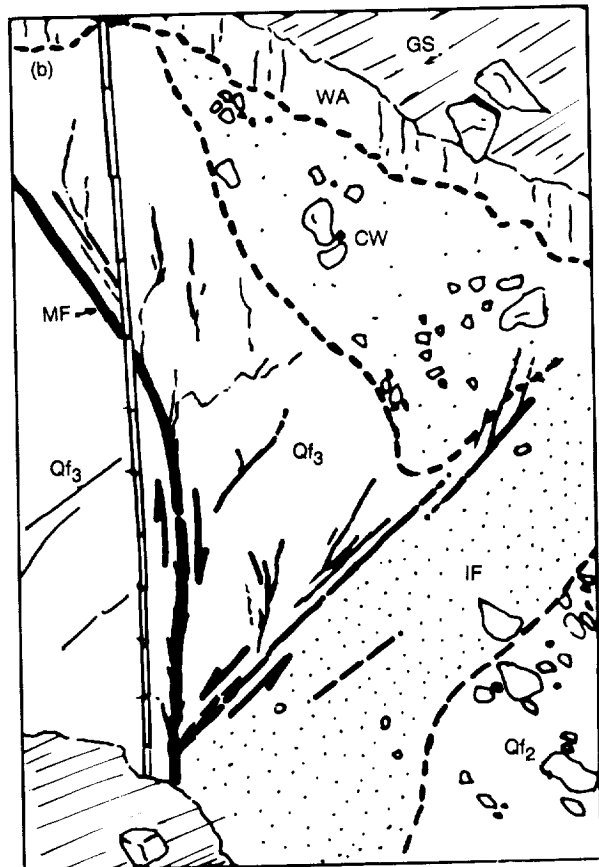
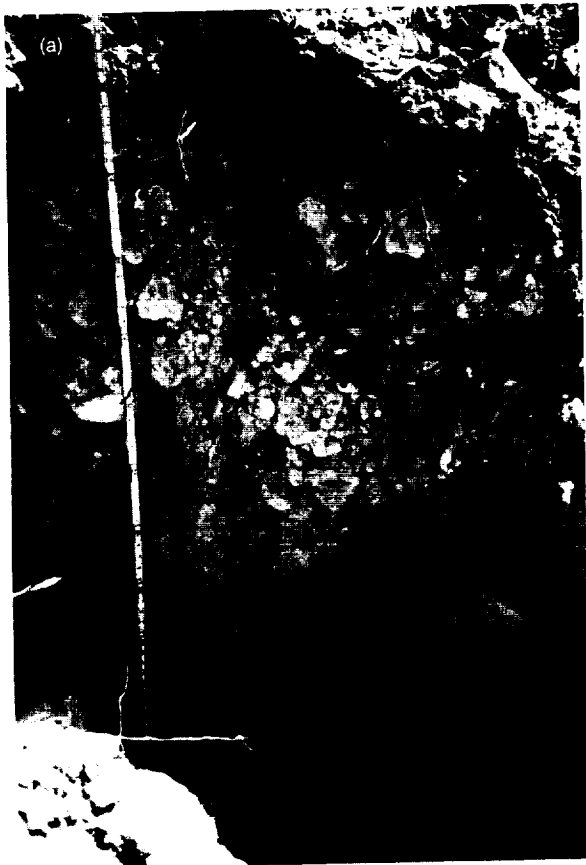


Fig. 8. Photo (a) and sketch (b) of fault observed in Trench 8 showing offset alluvial units and possible offset of scarp derived colluvial wedge. Qf_3 = Unit 3 fanglomerate, Qf_2 = Unit 2 alluvium, WA = weathered alluvium below active geomorphic surface, IF = loose, fine-grained infilling, MF = main fault splay, and GS = ground surface. The folding rule is 1.8 m long.

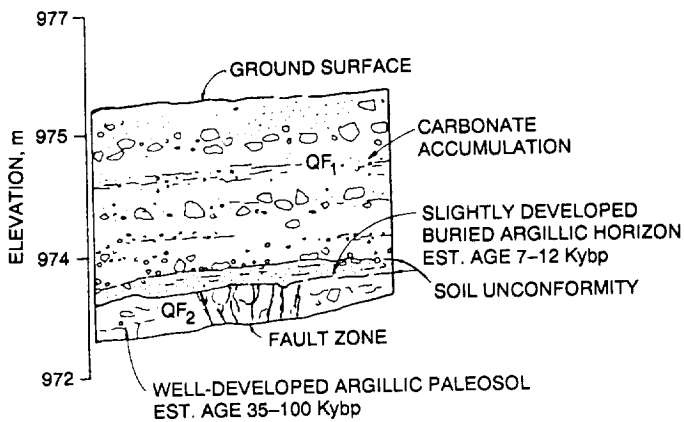


Fig. 9. Sketch of fault observed in Trench 9 showing diagnostic soil horizons used to bracket the age of most recent fault activity.



Fig. 10. Fault exposed in Trench 12 that juxtaposes Unit 2 and Unit 3 alluvium. Note color change at fault: Unit 3 is light colored, Unit 2 is dark colored.

Appendix

Glossary

A horizon: Uppermost soil horizon (loosely, topsoil); usually has roots and a mixture of organic and mineral matter.

B horizon: Below the A horizon; characterized by illuvial or in situ accumulation of clay, iron, or aluminum; residual accumulation of sesquioxides; darker, redder color due to presence of sesquioxides. Loosely: subsoil.

Alluvial: Deposited by running water.

Argillic: Pertaining to clay.

Argillic horizon: Diagnostic subsurface horizon characterized by an accumulation of clay.

Calcic horizon: Diagnostic subsurface horizon, at least 15 cm thick; enriched in secondary carbonates.

Developed: The terms weakly, moderately, and strongly developed refer to categories of paleosols described by thickness of horizons, types of materials built up in the horizons, and other criteria. (There are actually five categories altogether, including very weakly developed and very strongly developed).

Diagnostic subsurface horizon: Soil horizon that forms below the surface and is used to classify soils. Usually a B horizon (e.g., argillic, spodic, cambic) but may be A (albic) or C (calcic, duripan). B and C horizons occur at surface only if soil is truncated.

Eluviation: Downward movement of soluble or suspended material in soil from A (eluvial) to B (illuvial) horizon.

En echelon: Stepped series of parallel faults or other structures.

Fanglomerate: Conglomerate formed as part of an alluvial fan.

Fluvial lens: Buried stream or river bed deposits seen in subsurface cross section; typically lens-shaped.

Horizon: Interface indicative of a particular position in a stratigraphic sequence.

Illuviation: Accumulation in a lower soil horizon of soluble or suspended material that was exported from an upper horizon by eluviation.

Lineament: Linear topographical feature thought to reflect subsurface structure.

Paleosol: Buried, ancient (fossil) soil horizon, especially one formed during an interglacial period.

Pedogenic: Pertaining to soil formation.

Photolineament: Linear topographical feature in an aerial photograph.

Relict: Remnant of topographic feature that remains after other parts have been removed.

Stage: One of six stages, designated by roman numerals, of carbonate accumulations in paleosols that have developed in (1) gravel or (2) sand, silt, or clay.