Digital Method for Regional Mapping of Surficial Basin Deposits in Arid Regions, Example from Central Death Valley, Inyo County, California

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DIGITAL METHOD FOR REGIONAL MAPPING
OF SURFICIAL BASIN DEPOSITS IN ARID REGIONS,
EXAMPLE FROM CENTRAL DEATH VALLEY, CALIFORNIA

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Abstract

   Derivative maps generated from DEM's and panchromatic remote sensing data (TM Landsat 7 or SPOT) can be used to characterize surficial basin deposits in arid regions dominated by basin and range topography. Results indicate the technique is useful for rapid digital mapping of surficial deposits where a first order, systematic subdivision of bedrock, alluvial fan units, and playas is unavailable at regional scales. Digital mapping can provide information about relative age and material properties of units that in part can be derived from the position of units within the basin. This automated mapping, implemented in a GIS system, involves an iterative process applied to a combination of digital elevation models (DEM) and satellite image data, such as SPOT or the high-resolution panchromatic Band 8 of Landsat 7 scenes.

   The method first discriminates the region into first-order terrains consisting of bedrock mountain highlands, basin piedmonts, and playa-basin interiors based on user-defined slope cutoffs applied to DEM data. The basin areas are subsequently classified into surficial map units such as active channels, ground-water discharge zones, and multiple age alluvial-fan piedmont units based on reflective properties of the associated surfaces in the satellite imagery. The surficial units are differentiated through systematic classification based on specific user-defined ranges of spectral values for each unit. The spectral ranges used in the classification are largely dependent on the composite effects of surface characteristics and material properties, including depositional morphology and texture, pavement development, degree of surface clast varnishing, and (or) properties of exposed soils of the alluvial fan units. We have used the slope-curvature properties derived from the DEM data to discriminate the bajada areas that exhibit non-unique spectral characteristics. Slope curvature is particularly effective at differentiating young undissected surfaces from older dissected piedmont units.

Available geologic maps and field observations may be used both to iteratively calibrate the spectral classification scheme and to provide additional verification of the digital map output. Digital mapping combined with detailed field studies in selected areas provides useful regional maps of surficial units until time and funding is available for more field intensive studies. In addition, anomalous areas on the thematic maps indicate where more detailed field or air photo work is warranted. The technique successfully distinguishes between bedrock, alluvial fans (generally multiple fan units), active washes, playas, playa rimming marshes and seeps and other active and inactive discharge zones in arid basin and mountain regions. Limitations occur in the subdivision of some fan units where the dominant detrital clast lithologies are not susceptible to varnish development.

Introduction

There is an important need for providing regional scale maps that show the distribution of surficial units in alluvial basins from arid regions, especially at 1:1,000,000 to 1:250,000 scales, but extending usefully to 1:100,000 scale. Until systematic field and air photo mapping can be completed, interpretation of remote sensing and digital terrain data can provide a preliminary framework for discriminating surficial units. The ability to digitally characterize basin deposits and geomorphic features has broad applications to planning as well as modeling of groundwater, ecological and climate change impacts.

Death Valley has often been used for pilot studies to demonstrate the capability of remote sensing techniques to differentiate Quaternary as well as bedrock map units (Fox et al 1990, Gillespie, 1999; Gillespie et al, 1984; Kruse, F.A. et al, 1993) which makes it a useful region to further explore application of digital mapping techniques. The antiquity of the alluvial fan deposits has been digitally estimated from the maturity or degradation of desert pavement that forms on the fan surfaces (c.f. Gillespie et al, 1984; Farr and Gillespie, 1984).

Previous work combining remote sensing with digital terrain elevation data to map surficial units has focused on mapping alluvial fans and determining relative tectonic activity along active range fronts (Farr and Chadwick, 1996) and to local examination of alluvial fans (Thiessen and Farr, 1996) which resulted in a subdivision of fan units into young, intermediate and old based on reflectance characteristics. Miliaresis and Argialas (2000) used a 2 to 7 degree slope range from the USGS 90 m DEM to extract the area underlain by the head and intermediate part of alluvial fans

along the east side of Death Valley adjacent to the Black Mountain Range front; and used TM Band 1 data to capture the toe, or distal part of the fan these discreet conical fans. Miliaresis (2001) also used a block majority filtering of the drainage network in the 2-11 degrees slope range to select for the non-bedrock area underlain by fan or pediment.

In addition, remote sensing has been used to differentiate and identify evaporite deposits on playa surfaces (Crowley, 1993; Crowley and Hook, 1996; Stearns et al, 1999). Detailed field mapping of the salt deposits in Death Valley by Hunt and Mabey (1966) was based on a scheme of systematic sampling and field traverses in addition to standard air photo interpretation. Thus, they are able to show salt units that cannot be differentiated on the monochromatic imagery, but that can be mapped by using the increased spectral content of the TM data as demonstrated by Crowley and Hook (1996).

Remote sensing images of desert regions show stunning detail of bedrock and basin features (Figure 1), but study of the images has not, to date, resulted in systematic regional mapping or classification schemes that are actively used to derive surficial deposits maps from the image data. This study builds on previous work by digitally subdividing the entire arid basin system into alluvial units and subdivides the fan complexes into the alluvial (Q_{1-4}) system established by Bull (1991)

There are few currently available geologic maps of the Quaternary basins or valley floors that show subdivisions of the non-bedrock units for large regions. The objective of the effort described in this paper was to develop a digital method to produce regionally consistent surficial basin-deposit maps that differentiate surfaces underlain by playa, marsh and seepage areas, stream channels, alluvial fans, and where possible, to subdivide the fan units based on the intensity of varnish development, surface smoothness, and degree of dissection (Gillespie et al, 1984; Farr and Gillespie, 1984; Jayko and Pritchett, 1999; Jayko and Menges, 2001). The approach was to develop systematic steps to generate the map from a combination of digital elevation data (DEMs), satellite imagery using a GIS platform and digital processing techniques to discriminate surficial basin units. The product is a map similar to one produced over a much longer time period by conventional mapping techniques using air photo interpretation. The method has been developed and tested in a portion of Death Valley containing suitable landscape and deposits that have been independently mapped by methods that permits testing verification of results. However, the method can be applied to other desert regions with low vegetation and similar landscape properties.

Surficial basin units

Early work in delineating the surficial deposits in the Death Valley area of Figure 1 was undertaken by Hunt and Mabey (1966), who mapped the central Death Valley basin and adjacent bedrock at 1:96,000 and by Denny (1965), who mapped several alluvial fan complexes in this basin as well as areas to the east. Wright and Troxel (1993) and Slate and Berry (1999) added a complete suite of surficial deposits to bedrock mapping in north-central Death Valley at intermediate to regional scales of 1:48:000 to 1:100,000. General geomorphic and stratigraphic descriptions of Quaternary and basin units, with localized detailed mapping, have been completed in various parts of Death Valley generally as part of topical studies of neotectonic deformation or paleolake stratigraphy (e.g., Hooke ,1972; Brogan et al., 1991; Klinger and Piety, 2000; Knott, 1998; Machette et al., 2001). All of these studies used conventional mapping techniques applied to conventional aerial photography. A smaller number of maps with surficial mapping exists in basins to the east of central Death Valley (Denny and Drewes, 1965; McKittrick, 1988). More recently Menges et al (2001) and Workman et al (2002) produced a regional geologic map at 1:250,000-scale of the entire Death Valley region and areas to the north and east, including the entire region of Figure 1, that includes a complete suite of surficial deposits (Table 1). These surficial units were identified and mapped on specially processed Landsat 5 TM images in conjunction with standard aerial photography and selected field transects.

Many surficial basin units have primary geomorphic and geochemical characteristics that form in response to processes associated with aggradation, degradation, exposure and groundwater discharge. These characteristics can be recognized from digital analysis of their morphology, as represented in DEMs, and (or) by their spectral properties recorded in remotely sensed data such as satellite imagery (SPOT or Landsat TM). Through digital analysis, we can readily discriminate actively modifying basin landscape with features including alluvial fans, dunes, ground water discharge, and playas, as well as paleo features such as incised alluvial surface, shorelines, paleochannels, and paleo-groundwater discharge areas. The surficial basin units can be broadly grouped based on their relatively distinct geomorphic expression, without requiring additional analysis of their spectral characteristics (Table 1).

We follow common practice in developing the stratigraphic nomenclature of surficial basin deposits that is portrayed in the digital maps and summarized in Table 1. In particular, we reference two studies, Hunt and Mabey, (1966) and Workman et al (2002), that produced maps of surficial deposits in the Death Valley-Amargosa region (Figure 1) at differing scales and level of detail. Both studies emphasized a time-dependent sequence of alluvial deposits that are commonly associated with alluvial fans on flanking piedmont slopes of basins, but that also can be identified along major axial channel systems in the interior of basins. The relative ages of the sequences can be identified in the field and interpreted on aerial photography or satellite imagery by a number of age-dependent features based in part on surface morphology, degree of varnish on surface clasts, degree of soil development, presence of clay, and relative degree of internal dissection (Table 1). The alluvial sequences from both studies cited above can be correlated with a regional chronosequence of climate-controlled deposits described by Bull (1991) in the lower Colorado region, and thus we use his nomenclature (Q_1 to Q_4) in subsequent discussion.

The map stratigraphy from both studies also included a number of non-alluvial deposits not specifically addressed in the sequence of Bull (1991) (Table 1). For example, Hunt and Mabey (1966) described a detailed subdivision of fine-grained basin-interior sediments that particularly focused on various facies of salt-pan deposits widely exposed on the floor of central Death Valley, but also included some fine-grained alluvium, eolian deposits, and local lacustrine deposits associated with ancestral Pleistocene lakes. The stratigraphy of Workman et al (2002) and Menges et al (2001) depicts a more diverse set of deposits across a wide range of basins with varying source terrains and geomorphic characteristics. This stratigraphy includes not only fine-grained basin-floor alluvium, salt-pans, eolian deposits, and lacustrine deposits, but also includes fine-grained, commonly light-toned, sediments associated with non-salt playas and active and inactive ground-water discharge zones (e.g., the Ash Meadows area of the Amargosa Desert). Both studies also contain units representing locally extensive, commonly highly dissected, zones of basin-fill deposits ranging from late Tertiary to Quaternary age. These variably cemented and locally deformed sediments record basin deposition predating the younger set of surficial deposits in the basins that are morphologically associated with recognizable geomorphic elements within the present basin floor (e.g., alluvial fans, channels, basin floors and playas, or spring-paleospring discharge zones).

Characteristics of surficial basin units

The alluvial fan units digitally mapped in this study approximately correlate with units defined and mapped by Hunt and Mabey (1966) for Death Valley (Table 1 and 2). Most workers, including Hunt and Mabey (1966), have divided alluvial fan deposits into at least 4 to 5 units. Herein we follow the nomenclature (Q_{1-4} designations) established by Bull (1991) to identify the fan units in the American southwest deserts. The panchromatic TM Landsat 7 Band 8 and SPOT imagery can be used to discriminate at least three fan units based on the relative amounts of varnish and clay which tend to vary inversely with time. The intensity of varnish development is commonly associated with increasing maturity of smooth desert pavement on fan deposits and can be used to estimate relative age (Gillespie et al, 1984; Farr and Gillespie, 1984). The surface distribution of clay and silt are useful in discriminating various playa and active stream channel deposits. The varnish is expressed as areas of low reflectance, whereas the clay content is expressed as high reflectance in the panchromatic imagery.

The surface weathering characteristics of these units that enables the digital differentiation from spectral characteristics as follows: the active or 'Holocene' wash (Q_4); a late Holocene deposit with no pavement and at most weak varnish (Q_3c); two intermediate deposits defined primarily by the absence or incipient degree of pavement development, also partly expressed by the rock-varnish development (Q_3a & Q_3b); well developed smooth pavement and strongly varnished surfaces (Q_2); and dissected, weakly to moderately varnished deposits commonly littered on the surface with secondary, light colored chips of secondary pedogenic carbonate (Q_1). The middle and late Quaternary alluvial fan deposits (Q_2 and Q_3) can be differentiated based primarily on reflectance, which is generally controlled by varnish development. The late Quaternary active wash Q_4 unit can be distinguished primarily based on the high clay content and little or no varnish.

Accurate differentiation into the various age-related categories can be complicated by the sensitivity of varnish development to the dominant lithology of surface rock clasts. Certain rock types preferentially develop strong varnish (for example, mafic or intermediate volcanic rocks, metamorphic rocks and quartz-rich sedimentary rocks) relative to other lithologies such as carbonate and granitic rock that inhibit varnish development, thus creates problems in

differentiating Q_{2-4} units by reflectance alone as noted earlier. However, this was not a significant problem in the Death Valley and Amargosa area and can be addressed by calibration with existing geologic maps or field data.

Active marsh and seep deposits forming wet vegetated areas that have very low reflectivity occur in central Death Valley where the distal fan deposits reach the playa or mudflats in the basin interior. The discharge areas at the fan margins generally have higher carbonate and fine sand relative to the salt and silt that dominates the greater playa surfaces (Hunt and Mabey, 1966). This interface between the distal fan and playa deposits coincides with a subtle slope break. Thus, seep and marsh deposits typically occur where extremely low reflectance coincides with extremely low slopes. Marsh and seep areas can be classified as low reflectance areas on that part of the imagery selected from the 0-1 degree DEM slope domain. In contrast, the playas and mudflats have high reflectance and low slopes. In steeper areas, discharge zones cannot be easily distinguished because the reflectance values on monochromatic imagery overlap with the reflectance of heavily varnished surfaces on the older alluvial fan pavements, although discharge zones area rare in the more steeply sloping part of the study area. Although not used in this study, other TM spectral bands can be used if its necessary to isolate the vegetated areas associated with active discharge. To the east of Death Valley in the Amargosa area, low-reflectance areas of dense vegetation coincide with local zones of active spring discharge and ground-water seepage in areas such as Ash Meadows. Most of the Ash Meadows area, however, is underlain by light-toned, highly reflective paleodischarge deposits, consisting mostly of sparsely vegetated to barren areas of fine-grained sand and silt that correspond to currently inactive zones of past ground-water discharge during the wet intervals of the Pleistocene (Quade and others, 1995). Thus, the geomorphic context and understanding of desert geomorphic environments is important in interpretation of the results.

Methods

We use a GIS system to map surficial units by processing and combining elevation and satellite image data (Figure 2). We used U.S.G.S. 30 m Digital Elevation Models (DEM's) and Landsat7 15 m TM imagery (panchromatic Band 8) acquired Oct., 15th, 1999, scene ID LE7040035009928850. Although SPOT 15 panchromatic data was tested successfully (Jayko and Pritchett, 1999; Jayko and Menges, 2001) it requires edge matching of scenes for large study areas. The panchromatic Band 8 of TM imagery was selected because it provides 15m resolution and,

similar to aerial photography, is sensitive to all or most of the visible spectrum. The processing was done with ARC/INFO GIS software, although any GIS software with raster and vector formats could be used.

DEM derivatives (slope and curvature, which is a measure of the change of slope) were used to subdivide the large scale geomorphic features of the region. The slope grid was used to subdivide the terrain into three domains: bedrock, alluvial fans or pediments, and playas (Figure 3 and 4). The bedrock highland areas surrounding the basins were excluded from subsequent processing. The curvature grids were used to isolate the oldest (Q_1) from all the younger fan units (Q_{2-4}), and to improve the boundary between the steep-sloping bedrock domain and the adjacent basin domain. The quality of the available DEM's, which is variable for the study area, influences the quality of the derivative map.

Spectral ranges were used to subdivide the basin units (see below; Figure 5a and b) . Spectral ranges corresponding to each surficial unit (Figure 4; Table 2) were obtained by quantitative analysis of basin units mapped by Hunt and Mabey (1966) in central Death Valley, and by Workman et al (2002) across the entire area of Figure 1. Further constraints on the spectral ranges of surficial units were provided by values obtained from field point observations. Each of these steps in the digital mapping process are described in more detail.

The sequence of processing was: 1.) subdivide area into slope domains to distinguish bedrock, pediment or alluvial fan, and playa areas; 2) subdivide the pediments and fan defined slope areas into Q_{2-4} and eolian units using spectral data classification; 3.) subdivide the playa defined slope area into playa, marginal seep and marsh, and active wash using spectral data classification (supervised); 4.) delineate Q_1 and/or QTs using profile and plan curvature in conjunction with a slope delimited area; augment the bedrock area with curvature 5.) merge results into single grid; and 6.) evaluate results.   Details of processing, method for selecting spectral ranges and characteristics of the units that lend themselves to digital manipulation are provided below.   Units that are discriminated based on their morphological character alone include bedrock, older alluvial fan surfaces, and playas. Units that require a combination of terrain and spectral discrimination include dunes, active discharge areas and paleoground water discharge. Units that can be mapped from spectral data, after isolating bedrock from basin domains, includes active washes and subdivisions within alluvial fan complexes (i.e., Q_2, Q_3, Q_4).

Slope domains

Digital terrain data (30 m DEM's) are used to delineate the basic first-order topographic domains with similar slope characteristics. The slope domains are obtained by classifying the slope map into three areas, 0-1.0, 1.1-16, and >16 degrees (Figure 3 and Table 3). These domains generally discriminate the areas underlain by playa, alluvial fan deposits and bedrock surfaces, respectively, although the cutoff values can be adjusted empirically to best fit the given area.

The slope ranges for the bedrock cutoff were selected by histogram cutoffs (Figure 3) and querying the slope grid using a rasterized version of Hunt and Mabey (1966). There is some overlap between bedrock and alluvial fan deposits in the slope range from 7-16 degrees in the Amargosa area, especially where Neogene deposits are gently folded or faulted. However, for the purposes of surficial deposits mapping it is most important to include all the area of surficial deposits, even if some areas of gently sloping bedrock are also captured. Most regions have 1:250,000 scale maps of the bedrock geology, so a bedrock boundary can be digitized if greater accuracy of that boundary is required.

Alluvial fans are characterized by low slopes ranging from negligible to 20 degrees, but generally do not exceed 10 degrees and typically range between 3 to 6 degrees (Bull, 1977). The areas underlain by Q_2-Q_4 units are mainly represented by the area with 1-7 degrees slope range using 30 m DEM's, whereas Q_1 and QTs also include slopes ranging between 7 to16 degrees (Figure 3 and Table 3). The 16 degree cutoff effectively includes about ~98-99% of the alluvial deposits in the study area. However, a smaller, ~10 degree cutoff is even better suited for the Amargosa area to the east of Death Valley, which is more tectonically stable, thus contains more eroded highlands with more extensive development of pediment surfaces. A smaller slope cutoff of around 0.25 to 0.5 degrees would better delineate the distal fan and playa units in the Amargosa region, however the presently available 30 m DEM's do not have not sufficient resolution to map slopes within this range.

The playa slope domain is the most sensitive to the quality of the DEM which affects the sharpness of the boundary edge and the abundance of spurious data (Figure 4). The slope domains can be cleaned by 1.) generating a grid of the desired slope range and setting the rest of the area to nodata or a null value; 2.) setting the resultant slope grid to a constant value and then filtering the grid to fill in gaps and edges with the majority value within a user specified small search area (i.e. 2-3x the grid spacing). Although the quality of available 30m DEM's is presently variable, and

locally poor, we found this processing to be extremely useful, and will only be enhanced as DEM quality improves in the future. The poor DEM quality was most noticeable in the broad distal fan areas adjacent to the playas, where DEM irregularities in the 0-1 degree range impact smooth delineation of the playa boundary.

Imagery classification

We next classify the remote sensing data into the alluvial fan and playa units. The fan and playa areas that were isolated by slope analysis are each classified separately to generate the subdivisions of the Q_2 to Q_4, active wash and playa units. The classification process takes the raw image data, which has a possible range of 255 values, and categorizes them into a few meaningful groups of values (for example 6-8 groups) by applying user defined ranges. The classification of the spectral data can be simply dividing the features based on spectral data alone (unsupervised classification) or applying prior knowledge to help define features (supervised classification). There are several different ways to achieve a best-fit classification of the spectral ranges to represent the surficial map units, the options depend on the availability of pre-existing mapping and field observations.

We looked at three methods (1.) using natural steps or discontinuities in the spectral data that occur within the alluvial fan and playa slope domains (unsupervised) (2.) applying spectral means and majority ranges obtained by querying existing maps that were digitized for the exercise (supervised), and (3.) using spectral ranges obtained by querying the imagery with field locations with ground observations (supervised). And, used a combination of method 2 and 3 for the classification based on empirical comparison of the result to published geologic mapping.

For the Death Valley area, we digitized the Hunt and Mabey (1966) geologic map and rasterized it to use the unit zone grid to query for spectral ranges from the imagery (Figures 5a and b). We also had a vector copy of the surficial mapping from the Death Valley Regional Flow Model (Workman et al, 2002) covering the entire study area, as well as field observations of units with GPS-determined locations. Figure 5a and 5b show histograms of the spectral values found in the fan and playa units defined by Hunt and Mabey (1966), and Table 4 shows the statistics for values for alluvial and playa units. The cutoff and ranges, were refined empirically from the mean and majority values and cutoffs were refined with the ground truth data (Table 5, supervised classification) and the Death Valley Regional Flow Model (Table 6, supervised classification). The TM data for the fan and playa domains were then classified (Table 7) and the resulting thematic

11

surficial deposits map was compared with unit boundaries from published geologic maps (Figure 6).

If a high degree of certainty is needed and the reliability of the published maps is in question, then a test area can be mapped in detail (referred to as training sites) and used to help delineate the appropriate spectral ranges to use for classification. A classification scheme, once established by calibration in a given map area, can then be applied to digital mapping of other unmapped areas with similar topography and types of deposits. The resulting digital map may also be improved by adjusting the cutoff values to make better agreement with published geologic map (supervised classification).

If there are no existing field observations or available mapping for calibration, the classification ranges can be selected empirically from natural steps that can be observed by generating a histogram of the spectral data. This method will breakout mappable units that can be field checked for their prominent surface characteristics, and can be improved with additional ground truth information. If reliable mapping at an appropriate scale or level of detail is available for correlation, then the thresholds based on natural steps in the spectrum can be combined by trial and error to find a best fit to published map unit areas.

Curvature: fan domain

The older, late Pliocene and/or early-middle Quaternary alluvial units (Q_1 and/or QTs) cannot be readily differentiated from the younger (Q_{2-4}) surfaces with spectral data alone because of similar reflectance characteristics. The similarity occurs because internal dissection of the old fan commonly degrades previously-developed varnished pavements on the interfluves, and bioturbation and/or erosion typically exposes abundant chips of secondary carbonate from the underlying petrocalcic soils. The net effect is to develop light tones and higher reflectivity on the images that commonly overlap with the spectral ranges principally associated with younger less varnished but undissected deposits including Q_3 or even Q_4 units.

However, the older fan units (Q_1 and QTs) are generally characterized morphologically by strong dissection and bajada morphology that can be used to isolate them from the weakly or undissected younger surfaces using curvature (second derivative of the DEM = change of slope) to define the amount of internal dissection. The curvature can be calculated with respect either to a vertical (profile) or horizontal (plan) plane (Figure 7). The profile curvature is a tool that enhances

escarpments by defining sharp breaks of slope at the margins of interfluves and gullies. The curvature is calculated over 60m area with 30m DEM's. In profile, curvature, which generally ranges from about 5 to –5 (units =1/100 m), is displayed with positive curvature (convex upward) and negative curvature (concave upward), and flat where the curvature is near 0 (Figure 7). Cutoff values greater than 0.45 and less than –0.45 in the fan areas defined by the 1-16 degree slope domains were used to select the (Q_1 and/or QTs) from the younger fan units. In plan, curvature with values of greater than 0.25 and less than –0.25 (~ 1 standard deviation from the mean) in the fan areas defined by 1-16 degree slopes, further augments the margins of interfluves and gullies within the Q_1 and QTs units. Grids defining the dissected older units were composited from the profile and plan curvature grids (Figure 7 and 8). Delineation of the Q_1 and QTs units is mainly limited by the quality of the DEMs which tends to be poorer in lower slope areas, and will only improve as higher quality DEM's become available in the future.

The extreme plan and profile curvature values can also be used to improve the boundary and inclusion of data cells within the area underlain by the highlands bedrock domain that represents bedrock but was not isolated by high slope value. This is done by compositing the slope defined bedrock domain with the extreme plan and profile curvature areas that exclude the fan and playa area (Figure 8). Likewise, the highlands bedrock domain can be further improved by adding TM Band 8 data cells representing the data from the slope-defined fan domain (1-16 degrees) that lie in the low spectral values (ie ~ 0 to 40). In a similar fashion the area of Q_{2-4} fans can be further isolated by subtracting the grid representing composited bedrock plus Q_1 and QTs defined by curvature.

Results

We generate thematic surficial deposit maps by combining classified imagery (panchromatic TM Landsat 7 or 15m SPOT, Jayko and Pritchett, (1999) with morphologically defined areas derived from 30m digital elevation models (DEM) . These maps can be empirically compared with (a) published geologic maps where surficial deposits have been mapped from air photo interpretation and field studies, for example, Hunt and Mabey (1966) 1:96,000 scale (Jayko and Pritchett, 1999), and with (b) preliminary regional surficial-deposit maps that have been developed from more conventional interpretative mapping of Landsat 7 TM satellite imagery plotted at

1:100,000 to 1:250,000 scales with reconnaissance field observations (Menges et al, 2001; Workman et al, 2002), or c.) other relevant data layers such as shaded relief maps.

Figures 9a-d show examples of the preliminary basin deposit maps for the Central Death Valley area generated from digital processing of DEM's and TM Landsat 7, BAND 8 data using classification ranges derived from spectral values characteristic of Quaternary units mapped by Hunt and Mabey (1966) and Workman et al (2002). GPS point localities where the identification of units was made in the field are shown on Figure 9a. Table 8 and Figure 5a and b shows the variation in the spectral values of units that are classified on the thematic surficial deposits map. Table 9 shows the terms used for the qualitative assessment of the resulting thematic map in the discussion below.

Classification ranges calibrated from Hunt and Mabey (1966) geologic map of Death Valley work very well for differentiating correlative deposits in the Amargosa desert to the east. The surficial mapping of Workman et al (2002), which includes this study area, was also used to refine the classification scheme for surficial units over the entire study area including Death Valley in order to test whether more broadly based calibration could produce a digital map that closely replicates original map contacts across the area. This refinement of the a classification scheme initially based on spectral ranges derived from the Hunt and Mabey (1966) unit boundaries alone, improved the correspondence between the digital map and the Workman et al (2002) map units as well as the areas lying east of Death Valley.

The digital mapping technique was most successful where source areas for adjoining fan complexes contain lithologies susceptible to varnish development such as intermediate and siliceous volcanics, most quartzitic units, and metamorphic rocks. The digital mapping also appears to be more successful in the more tectonically active area (Death Valley proper) where there is greater contrast in morphological relief within different parts of the basin system than in the more tectonically stable Amargosa area. In general, the technique performed excellently for distinguishing Holocene deposits, in particular, Qp, Qlc, Q_4, and Qsc in all areas. The technique underperformed for Q_2 units where watersheds are dominated by mafic volcanic rock, especially basalt, which develop varnish on dark-colored initial surfaces that commonly resemble strongly varnished older surfaces on deposits with lighter-colored clast lithologies.

Preliminary results indicate a satisfactory to very good correspondence between the digital map result and field data and published maps (Figure 9a and b). There is generally satisfactory

correspondence in most of the alluvial fan areas, especially Q_4, Q_3 and Q_2 units. Discrimination of alluvial deposits, especially Q_3 versus Q_2, still presents problems in some parts of the digital map when compared with the conventional mapping. For example, Q_2 is over represented relative to Q_3 on piedmont fans primarily derived from the Wood Canyon Formation in the southeastern part of the map area (Figure 9c), which produces dark-toned detritus in monochromatic images even on parts of the fan with young Q_3 deposits. In contrast, Q_2 deposits are under represented relative to Q_3 deposits on piedmont fans derived from the southwest flank of the southern Funeral Mountains (Figure 9c) and on the northwestern section of Greenwater Valley (Figure 9d). This unsatisfactory differentiation results from the predominance of clast lithologies that do not easily develop or preserve varnish, such as carbonate rocks in the Funeral Mountains piedmont and granitic and altered volcanic rocks in the Greenwater Valley.

The lack of varnish development on deposits of successively greater age causes a relatively high reflectance for both old and young (Q_2 and Q_3) deposits that is locally enhanced by degradation of pavements and reworking of underlying petrocalcic soils in the more dissected Q_2 units. The unit differentiation is improved somewhat by use of the DEM data to distinguish slope curvatures related to the greater internal dissection in Q_2 deposits. Additional digital processing with curvature captures a large part of the Q_1 (older dissected fans) but, at this stage of the work, under represents its distribution, and so some Q_1 tends to be classified primarily with Q_2 instead. However, although improved by DEM curvature analysis, there are still problems in the differentiation of Q_1 in both areas related to (a) the depth and spacing of Q_1 dissection relative to the 30-m DEM resolution, and (b) spurious data points in the DEM data, which produce noise in the digital mapping in these areas as well as many other parts of the map (Figs. 9a-c). Acquisition of higher resolution and better quality DEM data would improve the quality of digital mapping throughout the map, but particularly in areas with significant amounts of the older fan unit Q_1 that relies extensively on DEM curvature magnitude for the differentiation.

The composite map on Figure 10 is a shaded relief and stream network map generated from the DEM. The lines delineate surficial basin unit boundaries derived in this study and were generated by vectorizing the raster version of the basin unit map and digitally overlaying the coverage on the DEM base. For example, active channel wash units selected spectrally from the remote sensing image can be cross-checked and verified not only by comparing them with published geologic maps but also evaluating them against other digital data such as hydrologic digital line graphs

(DLG) base layers, stream channels generated from DEM's, overlays with low-angle shaded relief maps, or digital contour maps. There is excellent agreement between the bedrock range front boundary and the alluvial piedmont, many fan units, and the distal fan boundary.

Conclusions

Preliminary work suggests the technique presented here shows promise as a tool for rapid objective and consistent mapping of large regions, at a regional scales (ie 1:100,000 to 1:250,000). One of the challenges of analog mapping by conventional techniques is to consistently define boundaries around areas with similar aerial photo characteristics. Variations in conventional mapping can be induced by changing air photo scales, photo reproduction quality, interpretive biases in mapping unit boundaries among individuals, and subjective decisions that can drift during the mapping process, which may require months, if not years, of mapping effort.

The technique is best suited for mapping surficial deposits in basins in arid to semiarid desert largely devoid of vegetation (Figure 1). The method is particularly useful in the hyperarid to arid lower elevation areas where vegetation density is very low, the dominant scrub vegetation is sparse creosote, and varnished pavements are well developed on older surfaces with clast lithologies susceptible to varnish development. Alluvial unit discrimination was less successful where the basins lie above 4000 to 4500' such as the Greenwater basin east of central Death Valley where greater precipitation supports more closely spaced and robust vegetation, although many well developed Q_2 type pavements could be consistently identified even in these areas.

Surficial units in the Death Valley basin are more distinctive and thus, are easier to digitally characterize, than those of the Amargosa basin and higher elevation basins such as in the Greenwater Valley. This is in part due to (1.) the high rate of tectonism that affects slope and incision properties, and (2.) higher temperatures and very low precipitation that results in extremely low vegetation and dominance of salts in both soils and on the basin floor in Death Valley. Thus, the digital tools can greatly assist delineating surficial units, but still require fundamental field based studies and understanding of the geomorphic context.

Digital surficial deposits maps generated from remote sensing and DEM data also provide significant detail in unit distributions in many areas (eg., complex intermixing of Q_4 and Q_3 deposits in areas of active and recent fan deposition) that, although easily generalized to accommodate map-scale requirements, may be of interest for more specialized or topical studies.

The correspondence is especially good between various Q_2, Q_3, and Q_4 alluvial deposits on many piedmont fans with parent lithologies sensitive to varnish development (eg., those in southwest and southeast sides of central Amargosa Desert basin (Figure 9c). The digital mapping also sharply discriminates active or very young channels from older surfaces along the complex axial channels system of the Amargosa River as well as areas of extensive exposures of paleodischarge deposits in Ash Meadows in northern and central parts of the Amargosa Desert (Figure 9c).

Acknowledgements

References

Brogan, G.E., Kelloge, K.S., Slemmons, D.B., and Terhune, C.L., 1991, late Quaternary faulting along the Death Valley-Furnace creek system, California and Nevada: U.S. Geological Survey Bulletin 1991, 23p.

Bull, W.B., 1997, The alluvial fan environment: Progress in Physical Geography, v. 1, p. 222-270.

Bull, W.B., 1991, Geomorphic Responses to Climatic Change: Oxford University Press, New York, 326 pp.

Christenson, G.E. and Purcell, C., 1985, Correlation and age of Quaternary alluvial-fan sequences, Basin and Range province, southwestern United States: Geological Society of America Special Paper 203, p. 115-122.

Crowley, J.K, 1993, Mapping playa evaporite minerals with AVIRIS data; a first report from Death Valley, California: Remote Sensing of Environment, vol.44, no.2-3, p.337-356.

Crowley, J.K; Hook, S. J., 1996, Mapping playa evaporite minerals and associated sediments in Death Valley, California, multispectral thermal infrared images: Journal of Geophysical Research, B, Solid Earth and Planets, vol. 101, no. 1, p. 643-660.

Denny, C.S., 1965, Alluvial fans in the Death Valley region, California and Nevada: U.S. Geological Survey Professional Paper 466, 62 p.

Denny, C.S., and Drewes, H., 1965, Geology of the Ash Meadows Quadrangle, Nevada-California: U.S. Geological Survey Bulletin 1181-L, L1-L56, map scale 1:62,500.

Farr, T. G., 1996, Use of digital topography and remote sensing to map tectonic activity of range fronts: Geological Society of America, Abstracts with Programs - v. 28, n. 7, p. 463.

Farr, T. G. and Chadwick, O.A., 1996, Geomorphic processes and remote sensing signatures of alluvial fans in the Kun Lun Mountains, China: Journal of Geophysical Research, v 101, p. 23091-23100.

Farr, T. G. and Gillespie, A.R., 1984, Measurement of micro-relief on alluvial fans and its relation to age, lithology, and radar response: Geological Society of America, Abstracts with Programs v. 16, p. 506.

Fox, L. III, Fischer, A.F., III, Gillespie, A.R., and Smith, M.O., 1990, Investigation of AVIRIS imagery for application in differentiating soil chronosequences: Proceedings of the Second Airborne Visible/Infrared Imaging Spectrometer (AVRIS) Workshop, Jet Propulsion Laboratory Publication 90-54, Pasadena, p. 94-99.

Gillespie, A. R., 1999, Thirty years of remote sensing in Death Valley-What have we learned?: in Slate, J. L. ed, Proceedings of Conference on Status of Geologic Research and Mapping in Death Valley National Park, Las Vegas, Nevada, April 9-11: U.S. Geological Survey Open-File Report 99-153, p. 85-89.

Gillespie, A.R., Kahle, A.B., and Palluconi, F.D., 1984, Mapping alluvial fans in Death Valley, California using multichannel thermal infrared images: Geophysical Letters, v.11, p. 1153-1156.

Hooke, R. LeB. 1972, Geomorphic Evidence for Late-Wisconsin and Holocene Tectonic Deformation, Death Valley, California: Geological Society of America Bulletin, v. 83, p. 2073-2097.

Hooke, R.L., 1968, Processes on Arid-Region Alluvial Fans: Journal of Geology, v. 75, p. 438-460.

Hunt, C.B., and Mabey, D.R., 1966, Stratigraphy and Structure, Death Valley, California: U.S. Geological Survey Professional Paper 494-A, p. 1-162.

Jayko, A.S. and Menges, C.M., 2001, A short note on developing digital methods for regional mapping of surficial deposits in arid regions using remote-sensing and DEM data: in Machette, M.N., Johnson, M.L. and Slate, J.L., eds, Quaternary and Late Pliocene Geology of the Death Valley region: Recent observations on Tectonics, Stratigraphy and Lake Cycles: U.S. Geological Survey Open-File Report 01-51, p. 167-172.

Jayko, A.S. and Pritchett, D.W., 1999, Regional 1:100,000 mapping of Quaternary units from SPOT images and 30-m DEM's, in Slate, J., ed., Proceedings of Conference on Status of Geologic Research and Mapping in Death Valley National Park, Las Vegas, Nevada, April 9-11: U.S. Geological Survey Open-File Report, 99-153, p.106.

Klinger, R.E., 2002, Quaternary stratigraphy, soil geomorphology, and tephrochronology of northern Death Valley fault zone: Univ. Colorado, Boulder, Ph.D. dissertation.

Klinger, R.E., and Piety, L.A., 2000, Late Quaternary tectonic activity on the Death Valley and Furnace Creek faults, Death Valley, California: Geologic and geophysical characterization studies of Yucca Mountain, Nevada: Reston, U. S. Geological Survey, p. 16.

Knott, J.R., 1998, Late Cenozoic tephrochronology, stratigraphy, geomorphology, and neotectonics of the western Black Mountains Piedmont, Death Valley, California; implications for the spatial and temporal evolution of the Death Valley fault zone: Ph.D. dissertation, University of California, Riverside.

Kruse, F.A., Lefkoff, A.B., and Dietz, J.B., 1993, Expert System-based mineral mapping in northern Death Valley, California/Nevada, using the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS): Remote Sensing of Environment, v. 44, p. 309-336.

Lustig, L.K., 1965, Clastic sedimentation in Deep Springs Valley, California: U.S. Geological Survey Professional Paper 352-F, p. 192.

Machette, M.N., Johnson, M.L., and Slate, J.L., 2001, Quaternary and Late Pliocene Geology of the Death Valley Region: recent observations on tectonics, Stratigraphy, and lake cycles: U.S. Geological Survey Open-File Report 01-51, p. 246.

McKittrick, M.A., 1988, Surficial geologic map of the Resting Springs and Nopah Ranges, Inyo County California and Nye County, Nevada: U.S. Geological Survey Miscellaneous Field Studies Map MF-1941, 1 plate, scale 1:62,500.

Menges C. M., Taylor, E. M; Slate, J. L. and Dohrenwend, J. C., 1999, Strategy for mapping Quaternary surficial deposits in support of the Death Valley regional flow, *in* Slate, J., ed., Proceedings of Conference on Status of Geologic Research and Mapping in Death Valley National Park, Las Vegas, Nevada, April 9-11: U.S. Geological Survey Open-File Report: 99-153, p. 81-82.

Menges, C.M., Taylor, E.T., Workman, J.B., and Jayko, A.S., 2001, Regional surficial-deposit mapping in the Death Valley area of California and Nevada in support of ground-water modeling: *in* Machette, M.N., Johnson, M.L. and Slate, J.L., eds, Quaternary and Late Pliocene Geology of the Death Valley region: Recent observations on Tectonics, Stratigraphy and Lake Cycles: U.S. Geological Survey Open-File Report 01-51, p. 151-166.

Miliaresis, G.C., 2001, Extraction of bajadas from digital eleation models and satellite imagery: Computers and Geosciences, v. 27, p. 1157-1168.

Miliaresis, G. C. and Argialas, D.P., 2000, Extraction and delineation of alluvial fans from digital elevation models and Landsat Thematic Mapper images: Photogrammetric engineering and remote sensing, v. 66, p. 1093-1101.

Quade, J.; Mifflin, M. D.; Pratt, W. L., McCoy, W., and Burckle, L., 1995, Fossil spring deposits in the southern Great Basin and their implications for changes in water-table levels near Yucca Mountain, Nevada, during Quaternary time: Geological Society of America Bulletin, v.107, p. 213-230.

Reheis, M.C., and Noller, J.S., 1991, Aerial Photographic interpretation of lineaments and faults in Late Cenozoic deposits in the Eastern Part of the Benton Range 1:100,000 quadrangle and the Goldfield, Last Chance Range, Beatty and Death Valley Junction 1:100,000 quadrangles, Nevada and California: U.S. Geological Survey Open-File Report 90-41, scale 1:100,000.

Slate, J.L. and Berry, M.E., 1999, Preliminary surficial geologic map of the Beatty 30 X 60-minute quadrangle, Nevada-California, *in* Slate, J.L., ed., Proceedings of conference on status of geologic research and mapping, Death Valley National Park: U.S. Geological Survey, Open-File Report 99-0153, pp.78-80, 1999.

Smith, G.I., Barczak, V.J., Moulton, G.F., and Liddicoat, J.C., 1983, Core KM-3, a surface-to-bedrock record of late Cenozoic sedimentation in Searles Valley, California: U.S. Geological Survey Professional Paper 1256, p. 1-24.

Smith, M.O., Ustin, S.L., Adams, J.B., and Gillespie, A.R., 1990. Vegetation in deserts: I. A regional measure of abundance from multispectral images. Remote Sens. Environ. v. 31, p. 1-26.

Stearns, S.V., van der Horst, E., and Swihart, G., 1999, Hyperspectral mapping of borate minerals in Death Valley, California: Proceedings of the Thematic Conference on Geologic Remote Sensing, vol.13, no.1, pp.81-85.

Thiessen, R.L and Farr, T.G., 1996, GIS and remote sensing study of alluvial fans in Death Valley, Nevada: Proceedings of the Thematic Conference on Geologic Remote Sensing, vol.11, pp. I.299-I.308.

Workman, J.B. Menges, C.M. Page, W.R. Taylor, E.M. Ekren, E.B. Rowley, P.D. Dixon, G.L. Thompson, RA. and Wright, L.A., 2002, Death Valley Regional Flow System geologic map: U.S. Geological Survey Miscellaneous Field Studies map, MF-2381, scale 1:250,000.

Wright, L.A., and Troxel, B.W., 1993, Geologic map of the central and northern Funeral Mountains and adjacent areas, Death Valley region, southern California: U.S. Geological Survey Miscellaneous Investigations Series Map I-2305, scale 1:48,000.

Figures
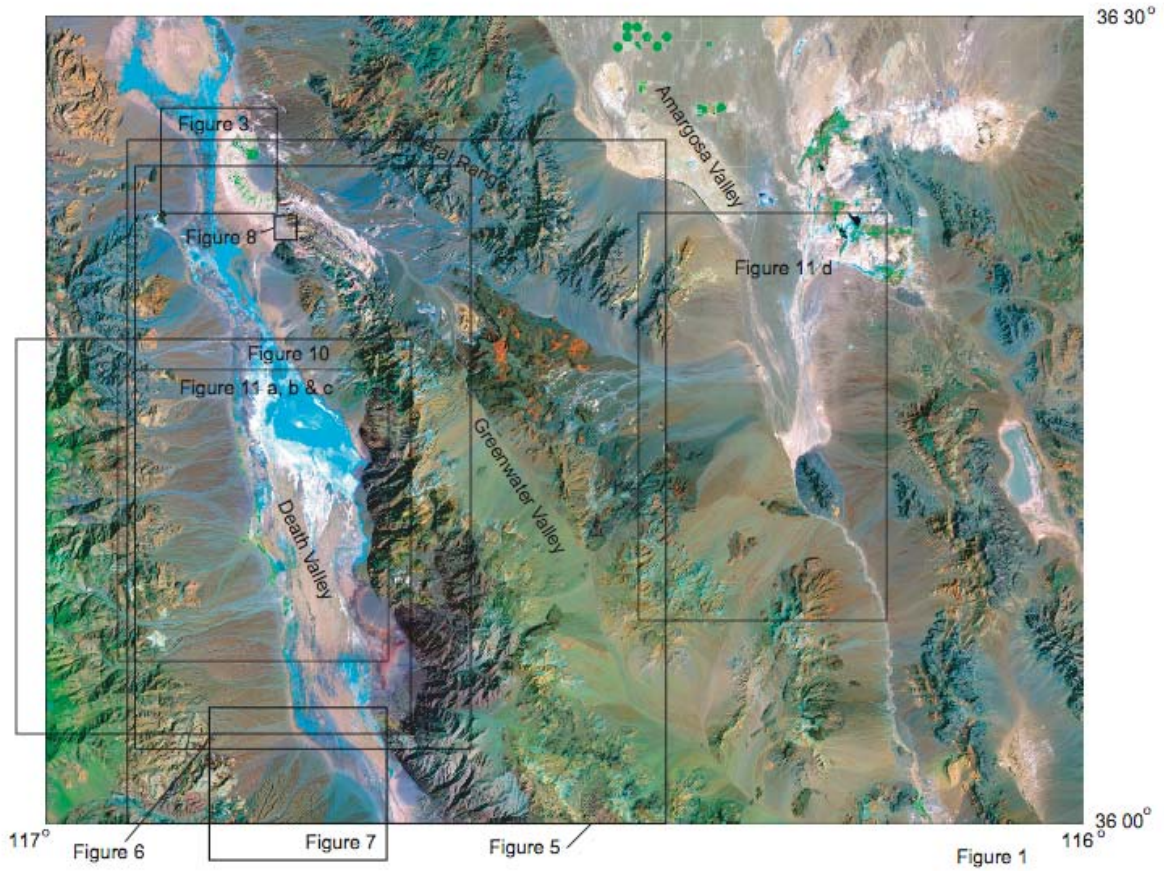
Figure 1.   Landsat7 TM image scene, central Death Valley and southern Amargosa area showing
         location of Figures 3 to 11.
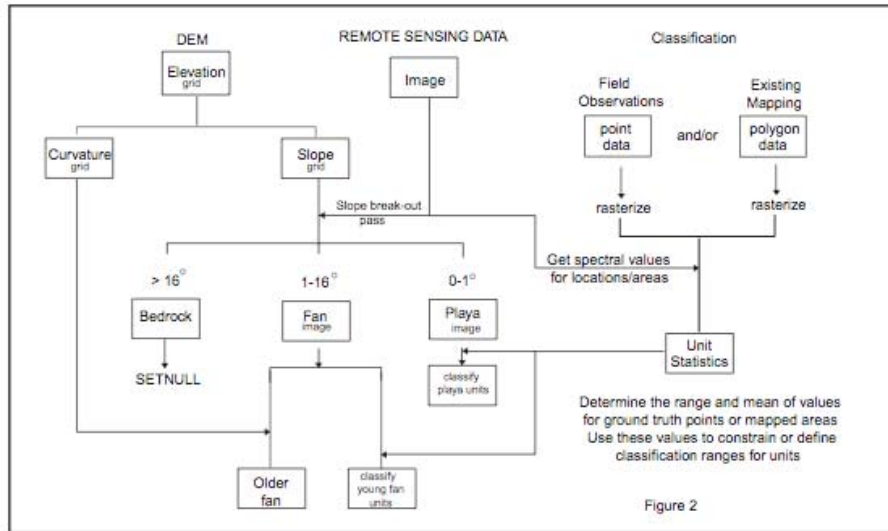
Figure 2.   Flow chart diagram for producing digital surficial units map from remote sensing and DEM data.
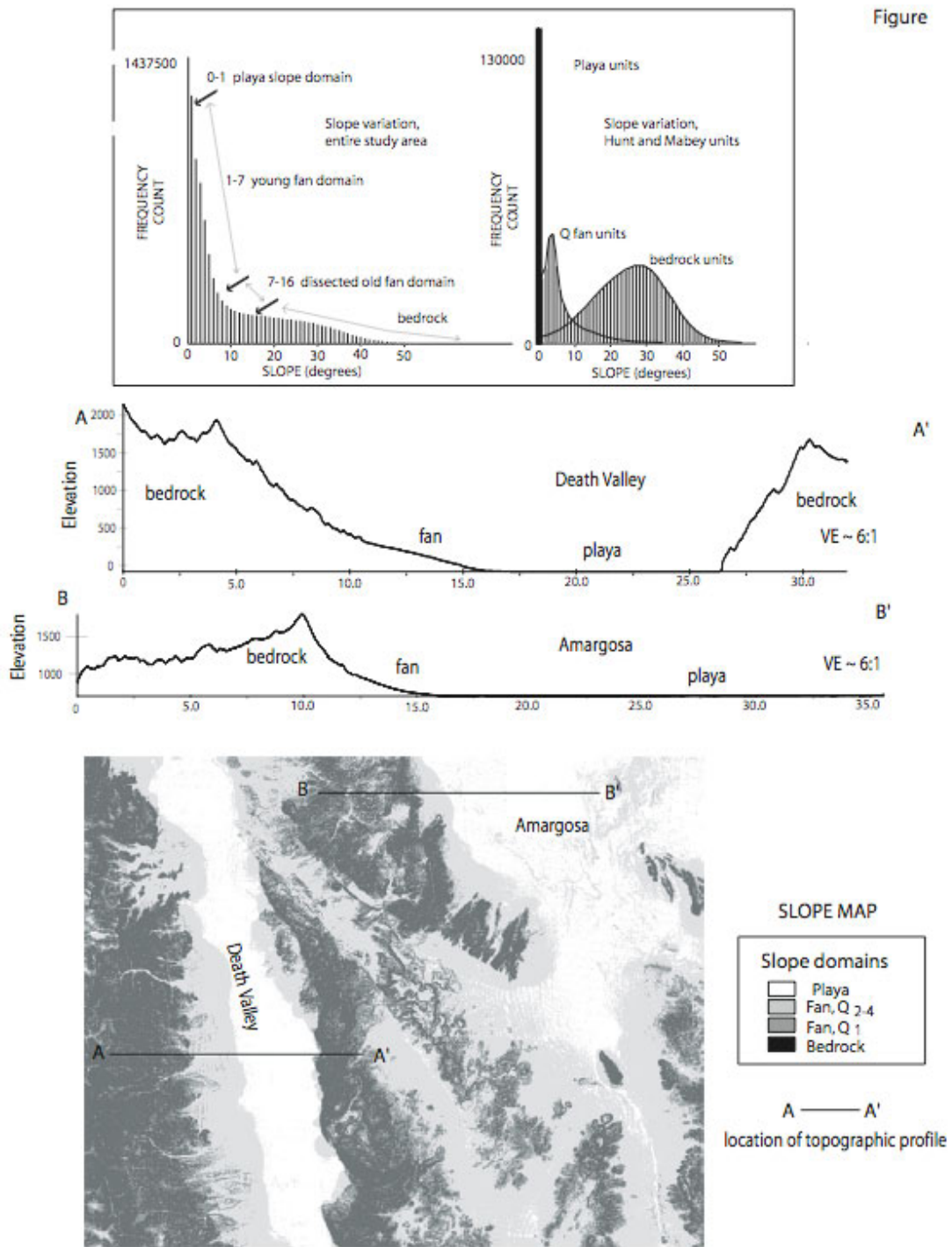
Figure 3.   Histograms showing range in slope values for the bedrock, alluvial fan and playa
domains; and slope map showing the distribution of bedrock terrain in ranges and
range flanks generated from the slope grid.
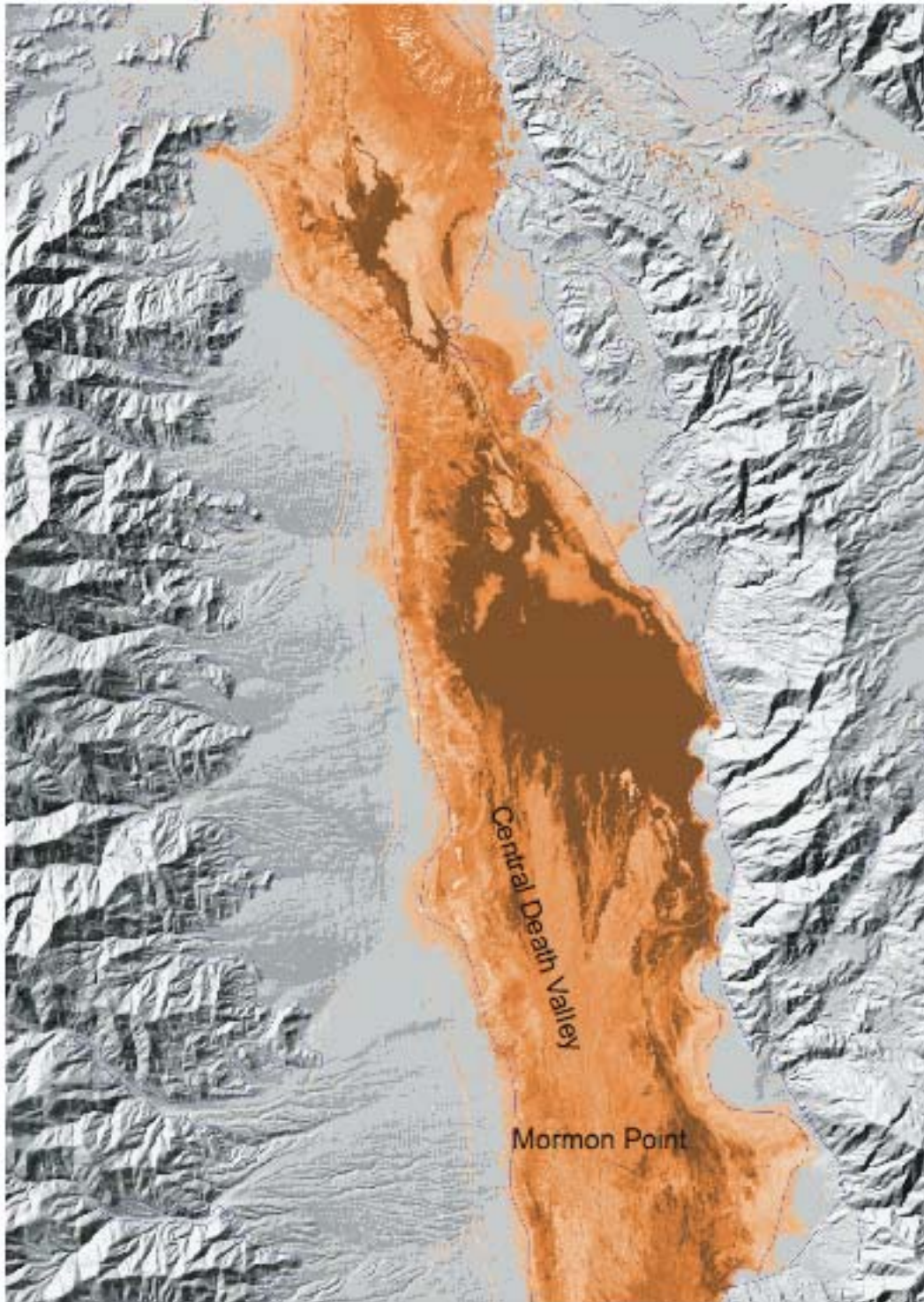
Figure 4. Map showing distribution of playa terrain generated from the slope grid and inset with SPOT 15m monochromatic imagery compared with the geologic boundary of fans and bedrock from the Death Valley Regional Flow model, geologic layer, 1:250,000 scale (purple lines).
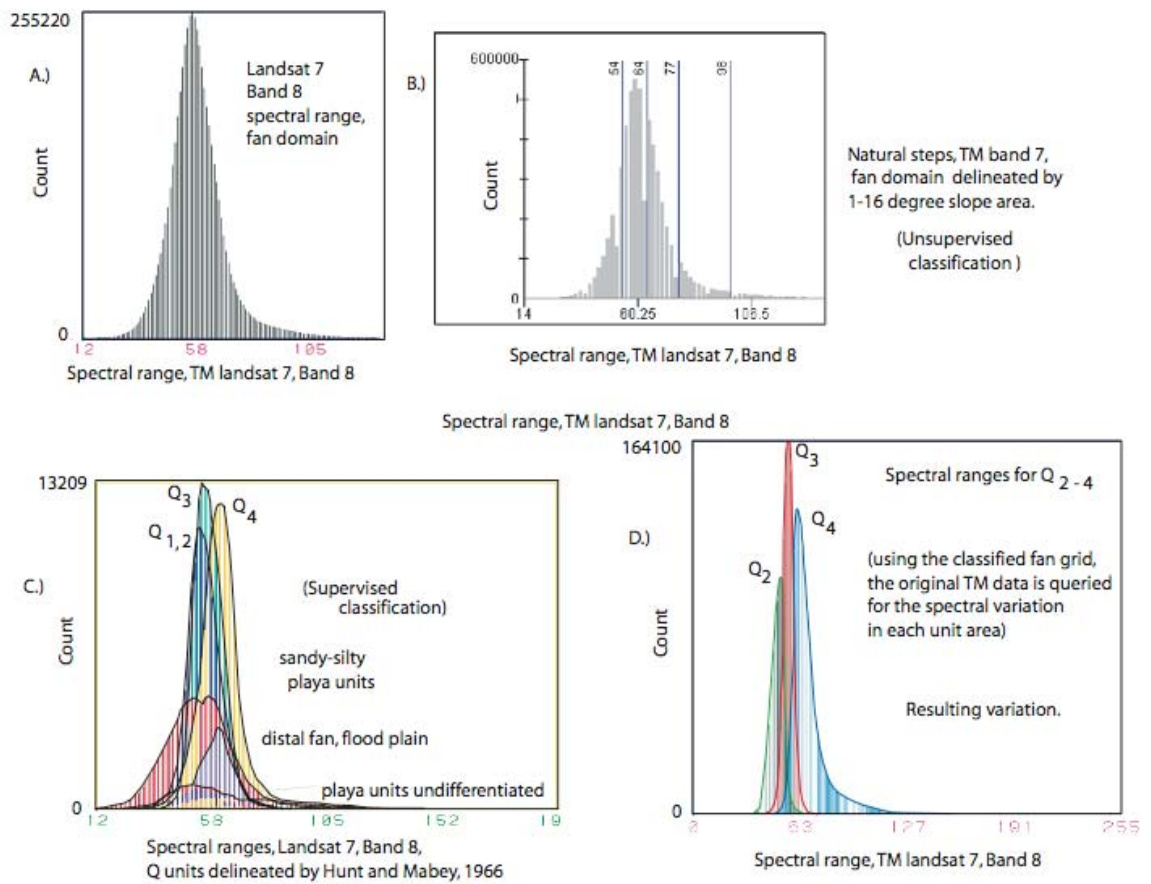
Figure 5a. Histograms of alluvial fan units, a.) entire fan domain, b.) natural breaks, c.) Hunt and Mabey (1966) Quaternary units, and d.) classified Q_{2-4} units from thematic surficial deposits map.

A. Spectral range for playa slope domain, TM Landsat 7, Band 8

B. Natural steps, TM Landsat7, Band 8, playa domain defined by 0-1 degree slope area.

C. Hunt and Mabey units queried for spectral ranges from DVTM_n27

D. DVRFM playa units queried for spectral ranges from DVTM_n27

E. Resulting spectral ranges for classified playa area
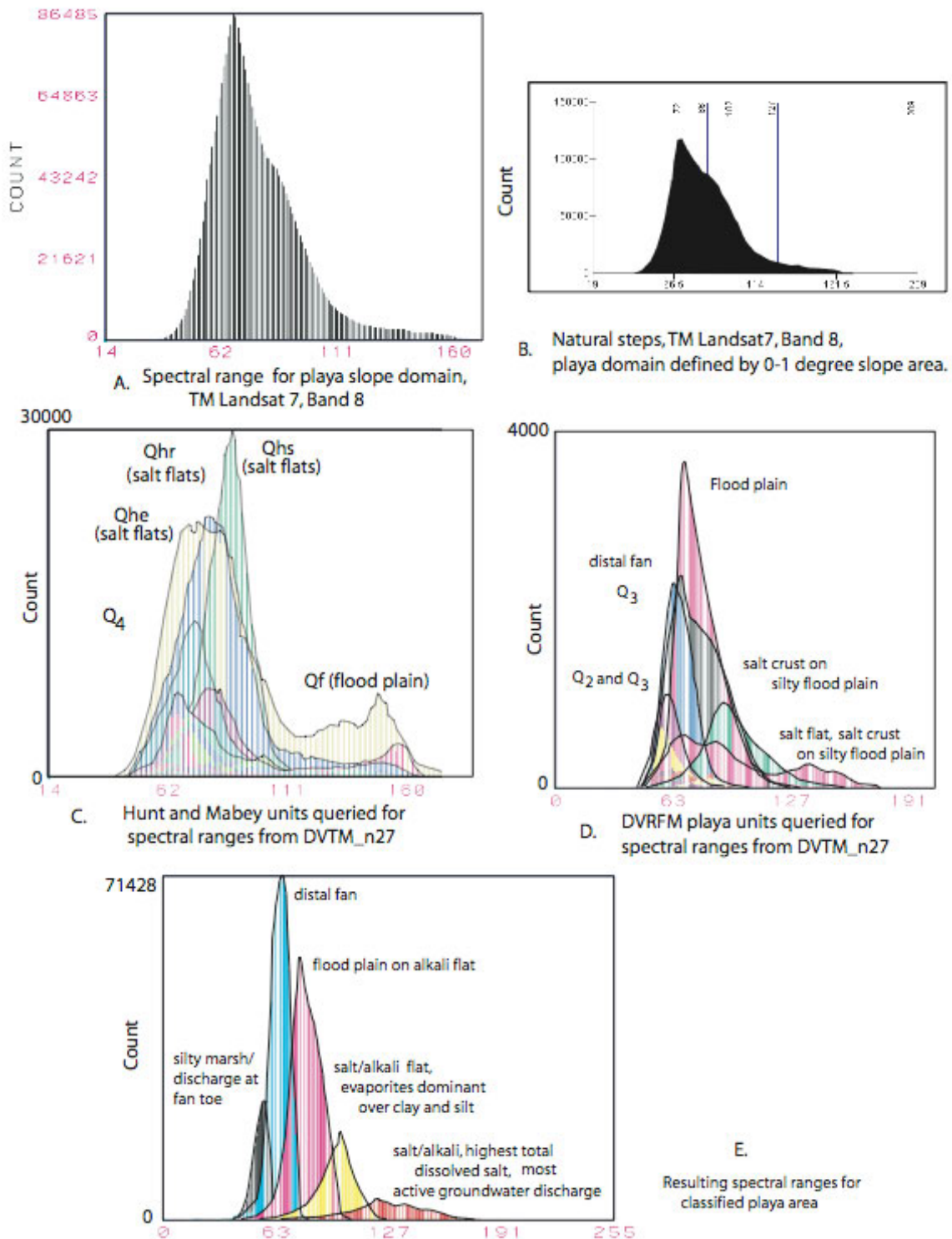
Figure 5b. Histograms of playa units, a.) entire fan domain, b.) natural breaks, c.) Hunt and Mabey (1966) Quaternary units, d.) classified playa units from Death Valley Regional Flow Model, ande.) classified playa units from thematic surfical deposits map.
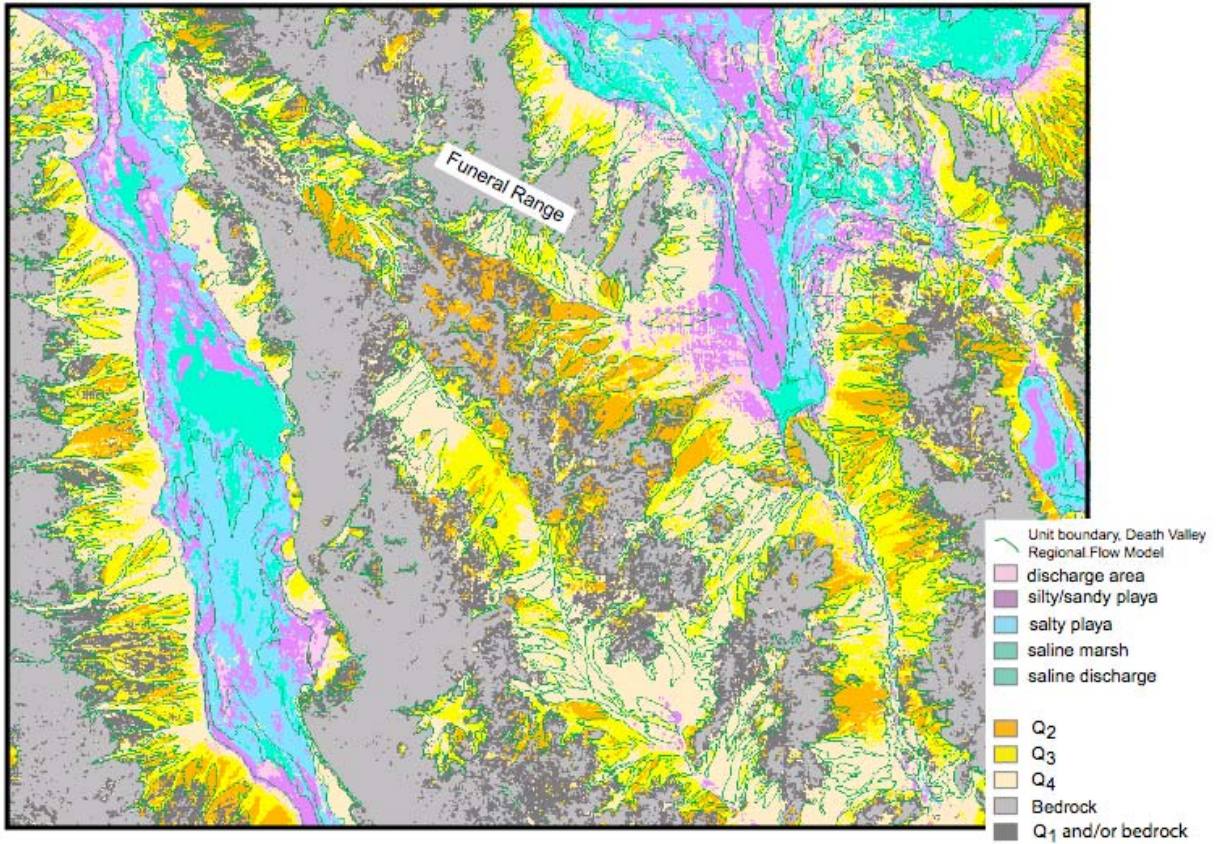
Figure 6.   Thematic surfical deposits map with unit boundaries from the Death Valley Regional Goundwater Flow model overlain for comparison. Classification ranges for this map was selected to best fit the ground truth and Workman and others (2002).
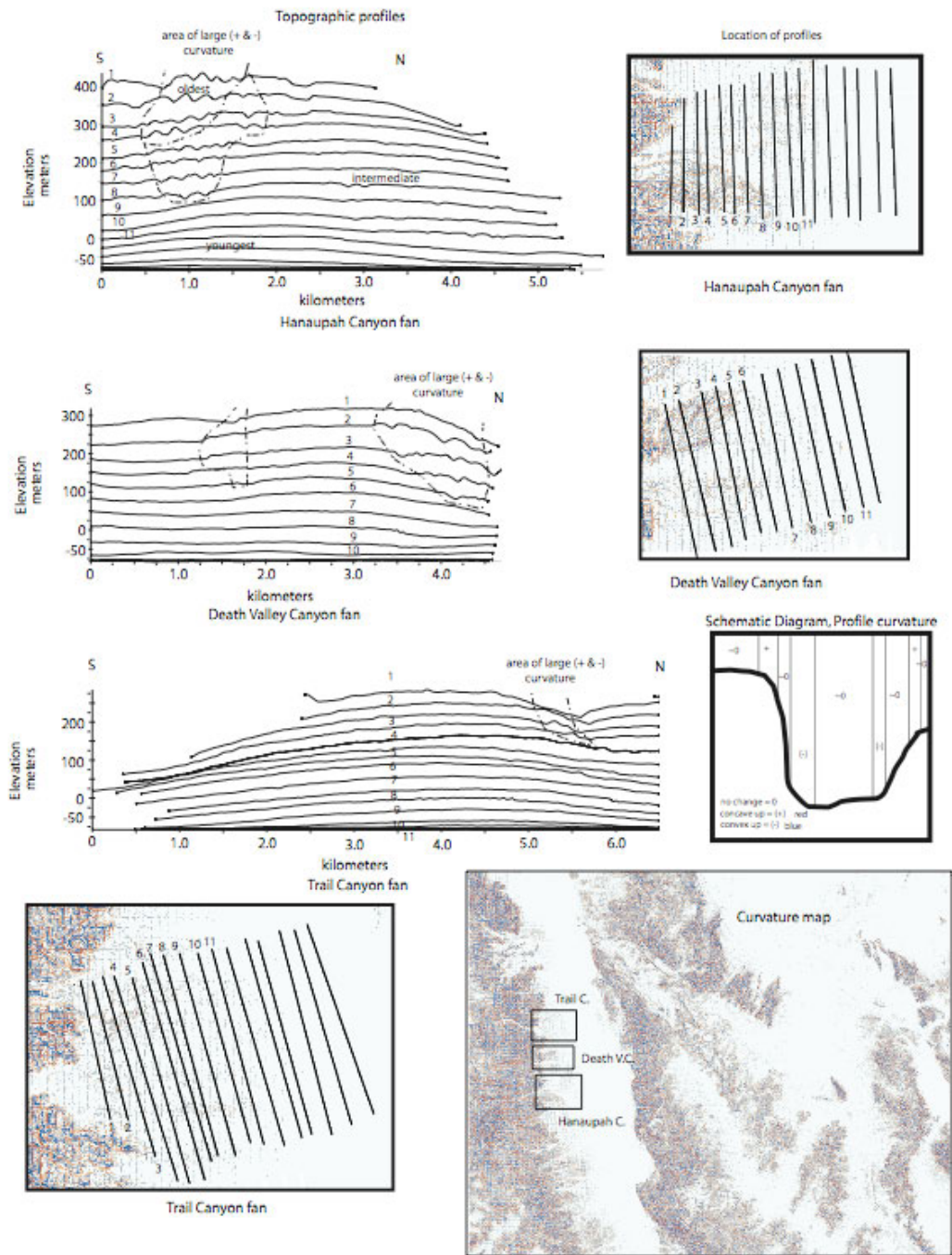
Figure 7. Topographic profiles through selected fan on the west side of Death Valley showing areas of fan with extreme profile curfature. Numbered profiles on the curvature maps correspond to numbers on the topographic profiles. Inset schematic diagram showing example of areas underlain by (+), (-) and (0) profile curvature.
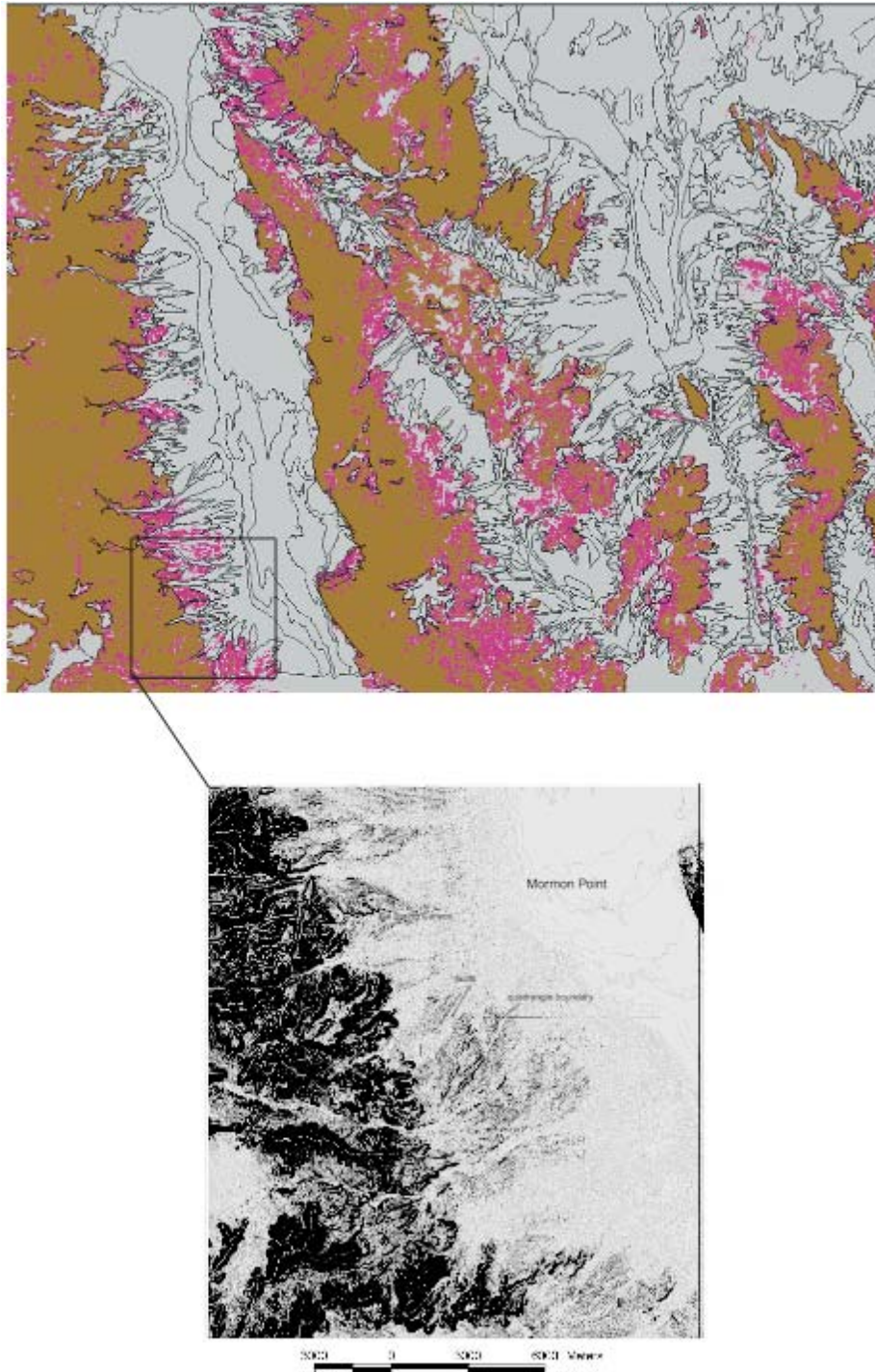
Figure 8.   Mapshowing area underlain by bedrock and dissected fan derived from areas of slope greater than 16 degress and extreme curvature for the study area. Inset map showing an example of an older Q1 fan unit on the west side of Death Valley near Six Spring Canyon, west of Mormon Point, illustrating contrast in dissection enhanced by curvature. Very dark areas are bedrock, medium grays dissected fan surfaces and light gray areas are playa and Q2-Q4 areas of alluvial fans.
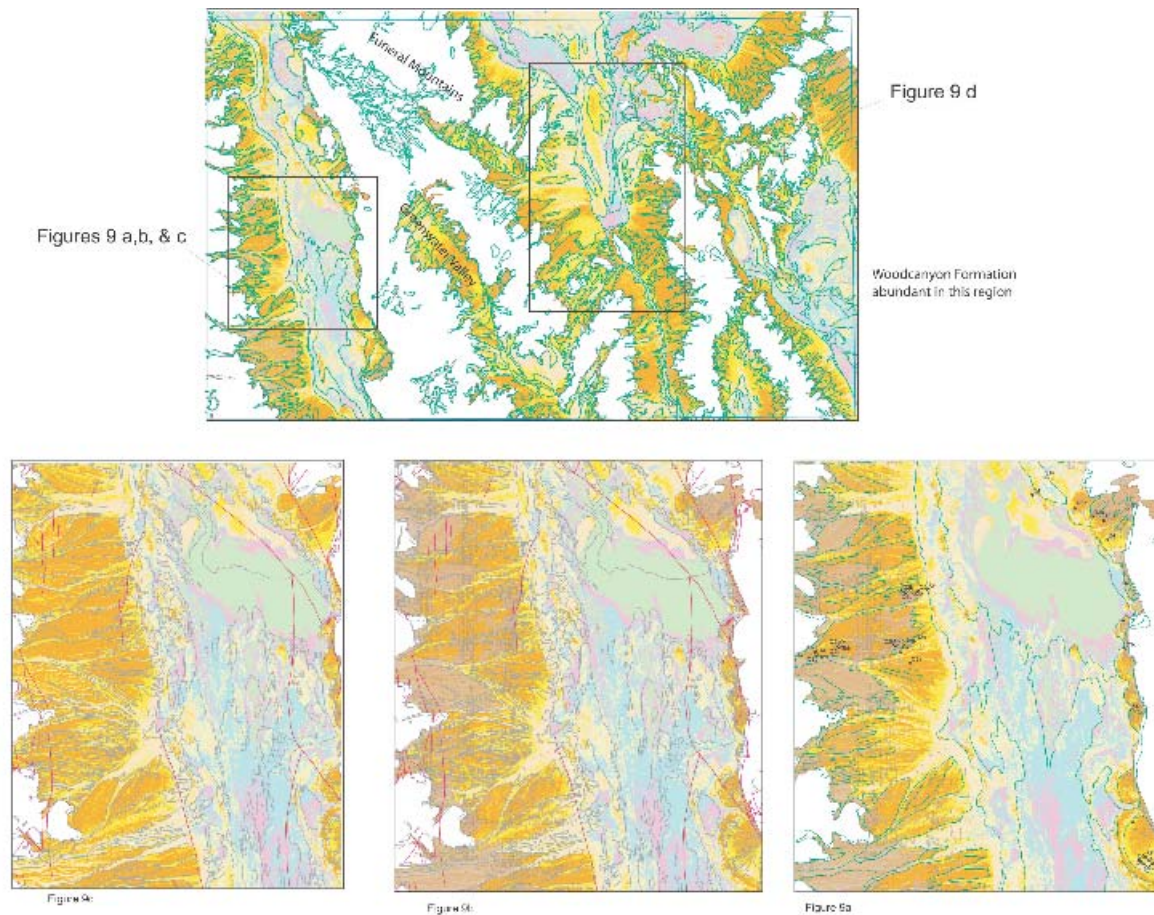
Figure 9   Area of the Death Valley Junction 1:100,000 map showing surficial basin units mapped from TM Landsat 7 Band 8 data and DEM data with units from Workman et al (2002) shown in green lines. Classification values for this version of the surficial deposits map were selected for agreement with Hunt and Mabey (1966). Locations of figures 9a-d shown by inset boxes.

9a.   Surficial basin units in the central Death Valley area discriminated by classification of TM Landsat 7 Band 8 data and DEM data with point localities and units discriminated in the field (Menges et al, 2001) and Workman et al, 2002) shown in green lines.

9b. Surficial basin units in the central Death Valley area discriminated by classification of TM Landsat 7 Band 8 data and DEM data with unit boundaries mapped by Hunt and Mabey (1966) shown in gray lines.

9c. Surficial basin units in the central Death Valley area discriminated by classification of TM Landsat7 Band 8 data and DEM data, excluding Q1 alluvial fan unit with unit boundaries mapped by Hunt and Mabey (1966) shown in gray lines

9d. Surficial basin units in the southern Amargosa area discriminated by classification of TM 7 Band 8 data and DEM data with point localities and units discriminated in the field (Menges et al, 2001) and Workman et al, 2002).

Unedited vector (line) coverage of surficial units
shown with streamorders and shaded relief base.

Figure 10.   Map showing the unit boundaries from the thematic surficial deposits map overlain on
a shaded relief base with digitally generated stream channels.

Table 1. Summary of selected surficial deposit units mapped in DVRFS area.

[Table summarizes characteristics of the most common and distinctive surficial-deposit units used as calibration and verification for digital mapping. The table mainly describes surficial units of Workman and others (2002) and then correlates these units to those of Hunt and Mabey (1966) and Bull (1991). The table is 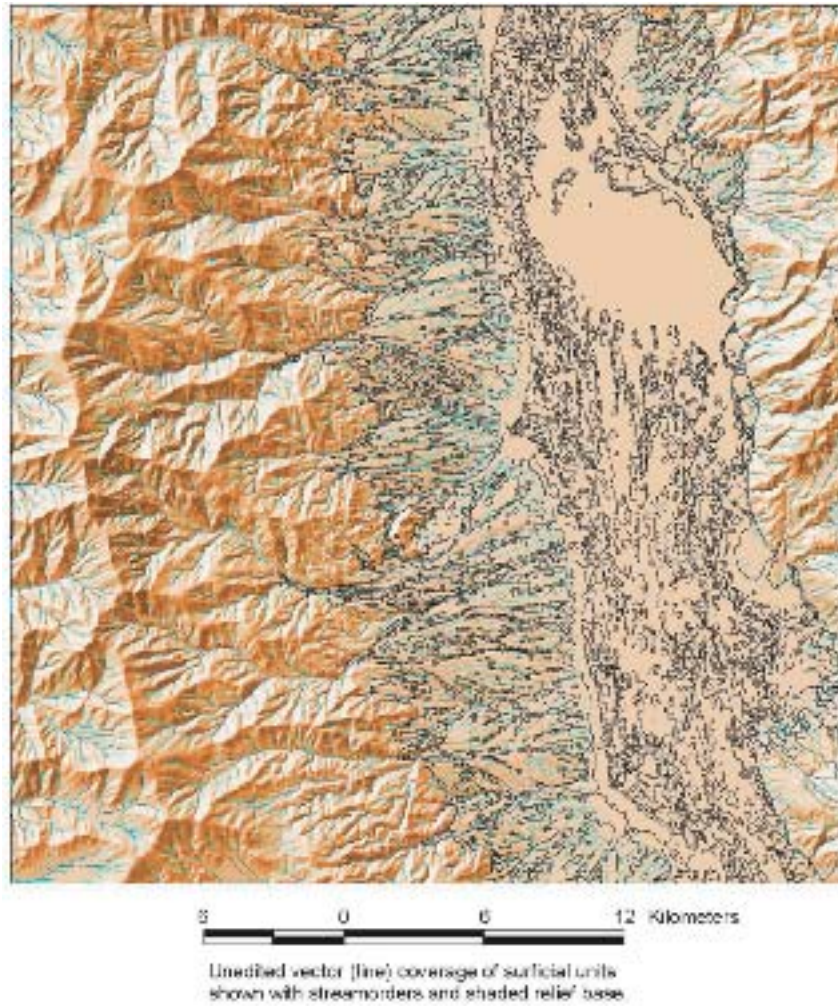subdivided primarily into alluvial units and other types of deposits. Mixed undifferentiated units (Qau and QTau) are not included because they consist of various proportions of other units listed below and thus lack a consistent set of characteristics. QTls, the bedrock landslide unit, is not included, because it resembles bedrock on the images and aerial photography and in the field consists of brecciated bedrock outcrop. Qayfe is not listed separately, as it is a variant of Qayf distinguished only by a thin crust of carbonate or salt on the surface of the deposit (see unit descriptions). The first three columns list map nomenclature, general character, and age range estimated from correlations with specific local to regional scale studies with independent age control in and adjacent to the map area of Workman and others (2002) (see in accompanying text and Menges and others, 2001). The next two columns list characteristics of units observed in the satellite image maps and black-white aerial photography used to interpret and compile units for map. The remainder of the columns list characteristics of deposits and related geomorphic surfaces that are primarily based on observations from field traverses of Workman and others (2002). N/A indicates Not Applicable.]

Units[1]			Type[2]	Age[3]	Image/Photo Characteristics[4]		Surface Characteristics[7]				Varnish[8]	General Soil Characteristics[9]	Typical Grain Size[10]
Workman and others	Hunt and Mabey	Bull			Landsat 7 Images	Panchromatic Satellite and Aerial Photography	Physiographic Position[5]	Internal Dissection[6]	Pavement	Bar and Swale			
Alluvial													
Qc	Qg4, Qf	Q4	Channel alluvium	Recent	Variable, light colored to white; light blue where salt encrusted	White to light gray	Intrarange valleys, piedmonts, and axial basin drainages	None to minor thalweg incision	None	Unmodified primary	None (only inherited)	None	Variable, from mixed gravel to fine sand
Qay	Qg3	Q3 (a,b,c)	Medium - to coarse- grained alluvium	Recent to Holocene, locally latest Pleistocene	Light to dark colors, including browns; rough to medium textures	Light to medium gray	Proximal to distal piedmonts, terraces, coarse axial drainages	None to minor (mostly primary)	None to weak, locally moderate	Unmodified to faint (but discernable)	None to moderate	None to weak (cambic and Stage I calcic horizons)	Coarse to fine gravel and sand
Qayo		Q3a,b	Medium - to coarse- grained alluvium	Middle to early Holocene, locally latest Pleistocene	Medium to dark colors, including browns; medium textures	Medium to dark grays	Proximal to distal piedmonts, terraces	None to minor	Weak to locally moderate	Faint, but discernable	Weak to moderate	Weak (cambic and Stage I calcic horizons)	Coarse to fine gravel and sand
Qayf			Fine- grained alluvium	Recent to Holocene, locally latest Pleistocene	Light to medium colors, including brown; light blue where salt encrusted; smooth to medium textures	White and light to medium grays	Mostly fine- grained axial drainages and interior alluvial plains, some distal piedmonts	None to very minor	None to weak, locally moderate	None to faint	None to moderate	None to weak (cambic and Stage I carbonate horizons)	Sand, silt, minor fine gravel
Qao	Qg2	Q2b,c	Medium- to coarse- grained alluvium	Pleistocene	Light to dark colors, including brown to reddish brown; smooth to medium textures	Light to medium grays	Proximal to medial, and locally distal, piedmonts; terraces in intrarange valleys	Commonly moderate to strong; locally minor	Strong to moderate; present on interfluves where dissected	None	Strong to moderate	Strong to moderate; includes argillic and (or) Stage II-IV calcic to petrocalcic horizons	Coarse to fine gravel and sand

Units[1]			Type[2]	Age[3]	Image/Photo Characteristics[4]		Surface Characteristics[7]						
Workman and others	Hunt and Mabey	Bull			Landsat 7 Images	Panchromatic Satellite and Aerial Photography	Physiographic Position[5]	Internal Dissection[6]	Pavement	Bar and Swale	Varnish[8]	General Soil Characteristics[9]	Typical Grain Size[10]
QTa	QTg1	Q2a, Q1	Medium - to coarse-grained alluvium	Early- middle Pleistocene to Pliocene	Light to medium colors, possible light brown tint; smooth to medium textures	Light to medium grays	Proximal to locally medial piedmonts; range-front embayments; intrarange valleys	Commonly strong and deep (ballena topography)	None to weak, commonly with carbonate chips	None	None to weakly preserved	Strong to moderate; variably eroded Stage III-V petrocalcic where preserved	Coarse to fine gravel and sand
Qlc	<u>Other</u> L		Medium to coarse-grained lacustrine deposits	Late to middle Pleistocene	Light to dark colors, including brown to reddish brown; smooth to medium textures	Light to medium grays	Mostly medial to distal piedmonts	Commonly moderate to strong; locally minor	Strong to moderate, but present on interfluves where dissected	None	Strong to moderate	Strong to moderate; includes argillic and (or) Stage II-IV calcic to petrocalcic horizons)	Medium- to fine gravel and sand (moderately to well sorted)
QTsf	QTg1, Tf		Fine-grained lacustrine, inactive playa, and alluvial deposits	Pleistocene to Pliocene	White to light colors; medium to smooth textures	White to light grays	Variable, including proximal to distal fans and basin interiors	Moderate to strong, in dissected basins; locally none	N/A	N/A	N/A	Local buried paleosols, variable weak to strong development	Silt, clay, fine sand; local gravel interbeds
Qp	Qc, Qs, Qh		Active playa and salt flat deposits	Recent to late Holocene	White to variegated light and pastel colors; light blue where moist; smooth textures	White to light grays	Basin interiors	None	None	None	None	None; local near-surface encrustations on salt pans	Clay and silt; local fine sand
QTd	Qsm, Qcm, Qt		Inactive and active discharge deposits	Recent to Pliocene	White to variegated light and pastel colors; light blue where moist; smooth to medium textures; local green vegetation	White to light grays	Mostly distal piedmonts and basin interiors; locally proximal to medial piedmonts	None to moderate	None; locally weak to moderate on alluvial caps	N/A; none to weak on alluvial caps)	None to weak (on alluvial caps)	None to moderate (may include St I-II calcic horizons)	Clay, silt, fine sand; local fine gravels and organic mats
Qe	Qd		Eolian deposits	Holocene to middle Pleistocene	Light brown,, pinkish gray to pink; medium textures	Light grays	Mostly basin interiors; locally variable piedmont	None	None	N/A	None	None	Fine to medium sand; silt

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1. Labels used to identify surficial units for three surficial mapping studies used in the digital mapping, as discussed in text. These include Workman and others (2002), Hunt and Mabey (1966) and

Bull (1991). Units are subdivided into alluvial and other (ie., lacustrine, playa/salt flat, eolian, ground-water discharge). Bull (1991) only includes alluvial units. Excluded from table are composite or mixed age-range alluvial units (Qau and QTau) and the bedrock landslide unit (QTls) for reasons explained in table header.

2. General type or classification of deposit, including general size range of coarse fraction, such that medium- to coarse-grained refers to gravel and sand and fine-grained refers to sand, silt and clay.

3. Age range of deposits, based on correlations to local or regional studies with geochronologic control listed in Menges and others (2001).

4.Typical characteristics of units observed in satellite image maps and aerial photography used in digital mapping and Workman and others (2002). This includes specially processed Landsat 7 Thematic Mapper images (composite bands 2,5,7) and panchromatic satellite images (Band 8, Landsat 7 TM and SPOT) and black/white high-altitude aerial photogrpahy.

5. Typical physiographic positions of unit within landscape, commonly given in reference to alluvial basins and (or) bedrock ranges.

6. Relative amount of local dissection or incision of drainages within or along margins of given mapped area of deposit.   Common depth ranges include 0-2 m (minor), 2-5 m (moderate) and > 5 m (strong).

7. Characteristics of geomorphic surface associated with a given unit deposit. Subcategories listed are: qualitative strength of surface pavement development, including smoothness and degree of interlocking clasts, and the preservation of original depositional form, given in reference to bar and swale morphology (ie., original channel bars and distributary channels, respectively).

8. Degree of desert varnish observed at surface, given qualitatively in reference to darkening of tops and (or) reddening of undersides of surface clasts.

9. General strength of maximum soil development associated with upper surface of deposits, typically as observed in natural outcrops (gullies) or road cuts, or as exposed in shallow pits. Soil pits exposing the full depth range of deep profiles could not be excavated during the reconnaissance field traverses required for this project. Observations focused on relative degree of development of horizons of secondary accumulation of carbonate, after Machette (1985) and locally salt or silica, and presence or absence of cambic or argillic horizons. In some cases, generalized soil characteristics were inferred less reliably where soil were not exposed on undissected surfaces from features on surface, including carbonate chips, carbonate rinds on clasts, and materials brought up from burrowing insects or rodents.

10. Typical textural size range of deposits, given for gravels in terms of coarse (cobble to boulder) or fine (pebble to cobble) grained.

Table 2
Summary of spectral means for surficial basin units

Regional Flow Model			HUNT AND MABEY			MENGES, field observations		
MEAN	Unit		MEAN	Unit		MEAN	Unit	
53	**bedrock**		52	**bedrock**		53	**bedrock**	
67	**Qtaf**	tecopa	76	**Tf**	furnace creek fm	56	**Ts**	Ts
			55	**Tg**	granite			
			54	**Tsr**	sedimentary			
			57	**Td**	dikes			
49	**Qb**	basalt	57	**Tv**	volcanic			
71	**QTb**	basalt						
63	**Qta**	Q1, ballena	56	**Qg2**		61	**Qta**	Qt1
56	**Qtau**	Q1,2,3 undifferentiated						
59	**Qfo**	Q2	58	**Qg3**		64	**Qao**	Q2
59	**Qau**	Q3 and Q2, but mainly Q3				65	**Qau**	Q3/Q2
63	**Qfy**	Q3	66	**Qg4**	similar to Qf	67	**Qay**	Q3
76	**Qay**	Q3, fine grained, Q4				79	**Qayf**	Q3 (fg)
60	**Qfi**	Q3a and Q3b						
81	**Qac**	stream channel, Q4	85	**Qf**	fan flood plane	74	**Qc**	channel
96	**QTd**	discharge?						
81	**QTpd**	marsh/discharge	78	**Qsm**	marsh, sulfate	88	**QTd**	discharge (marsh)
53	**Ql**	lacustrine	57	**lacustrine**		54	**Qlc**	Qlc lake gravels Q2
77	**Qe**	eolian	74	**Qd**	dune sand	78	**Qe**	eolian
97	**Qp**	playa	94	**Qsh**	salt, sulfate, surface layer			
			79	**Qsc**	sandy playa, carbonate			
			77	**Qch**	saline, surface carbonate			
			77	**Qsci**	silty playa, carbonate			
83	**Qaye**	Q3 with evaporative crust	105	**Qh**	salt, massive rock salt			
			85	**Qhe**	salt, chlorite zone			

74	**Qhr**	silty rock salt rough
89	**Qhs**	silty rock salt, smooth
92	**Qsg**	salt, massive gypsum
48	**Qt**	travertine
56	**Qe**	mislabled

Table 3
Slope values for surficial units from Hunt and Mabey (1966)

Hunt and Mabey (1966) unit	median	mean	std	majority	Lithologic description
	degrees	degrees		degrees	
Qsm	0	2.18	7.2	0	marsh
Qcm	0	0.42	0.5	0	marsh 2
Qcs	0	0.35	0.9	0	sand facies
Qcsi	0	0.10	0.4	0	silt, playa
Qd	0	0.27	0.5	0	dune sand, non saline
Qf	0	1.15	3.0	0	flood plains, non saline
Qh	0	0.01	0.1	0	massive rock salt
Qhe	0	0.02	0.1	0	eroded salt
Qhr	0	0.04	0.2	0	silty rock salt
Qhs	0	0.04	0.3	0	silty rock salt
Qsg	0	0.07	0.3	0	massive gypsum
Qsh	0	0.05	0.2	0	saline facies of carbonate/sulfate zones
Qch	0	0.14	0.5	0	saline facies of carbonate zones
Qg2	5	6.58	4.9	4	Q1 of Bull, may include some QTs and Q2
Qg3	4	4.29	3.4	3	has desert pavement = Q2 & 3 of Bull
Qg4	3	4.90	5.4	3	youngest alluvial fan, washes and flood plain
Tl	9	9.77	4.8	8	older lake beds
Tsr	8	9.30	5.9	5	sedimentary rocks
Tf	9	11.38	8.5	4	Furnace Creek Formation
Qt	19	20.59	8.9	14	travertine
Td	20	20.93	9.1	19	dikes
Tg	20	21.87	14.5	7	granitic intrusion
Tv	22	22.20	10.9	23	volcanic
bedrock	26	25.08	9.9	28	bedrock

Table 4
Landsat TM Band 8 spectral values found in
Hunt and Mabey (1966) Quaternary units

ALLUVIAL FAN UNITS

Hunt and Mabey (1966) unit symbol	minimum	maximum	range	mean	STD	majority	median
bedrock	15	141	126	56	14	54	55
Qd	41	117	76	71	10	69	70
Qf	24	185	161	101	30	87	89
Qg2 (Bull, 1991)	22	104	82	57	7	54	56
Qg3 (Bull, 1991)	20	107	87	58	5	57	57
Qg4 (Bull, 1991)	21	184	163	65	12	64	64
Td	24	107	83	59	13	54	58
Tv	15	136	121	61	16	62	60

PLAYA UNITS

unit	minimum	maximum	range	mean	STD	majority	median
Qcm	45	113	68	66	11	65	65
Qh	52	170	118	105	39	66	93
Qf	20	183	163	91	28	69	83
Qsc	31	118	87	79	14	70	74
Qd	44	135	91	74	13	70	71
Qcsi	46	175	129	77	11	74	76
Qhr	42	180	138	75	14	74	73
Qch	43	144	101	80	14	80	80
Qhe	44	177	133	85	20	81	82
Qhs	48	173	125	89	13	89	88
Qsg	45	138	93	91	14	89	89
Qsm	43	143	100	82	14	89	83
Qsh	49	183	134	94	13	91	93

Table 5
Landsat TM Band 8 spectral values found in
GPS ground truth points Quaternary units

GPS ground truth points	minimum	maximum	range	mean	STD	majority	median
bedrock	36	128	92	60.6923	17.0115	61	36
Q1	52	52	0	52	0	52	52
QTs	52	73	21	60.8462	6.7007	54	52
Q1,2,3 u	77	77	0	77	0	77	77
basalt	65	136	71	91.0588	17.9164	101	65
Qch	45	96	51	64.0262	9.6154	60	45
Qsm	52	74	22	65.5	6.994	52	52
Qsc	42	113	71	67.2314	10.8097	65	42
Qsci	62	99	37	78.4545	8.5638	72	62
Qe	51	108	57	72.3104	13.9978	62	51
Qf	69	83	14	78.8	5.0754	69	69
Tg	51	51	0	51	0	51	51
Tsr	58	58	0	58	0	58	58
Qg2	52	59	7	55.75	2.4875	56	52

Table 6
Landsat TM Band 8 spectral values found in
Workman and other (2002) Quaternary units

UNIT	min	max	range	mean	std	majority	median
Q2/Q3	36	144	108	62.1212	8.3978	60	61
Q2	41	114	73	61.934	6.97	63	61
Q3,	39	170	131	67.5699	8.5885	64	67
basaltic-fan??	40	119	79	72.0999	12.1056	67	71
Q 3,4 active wash	27	198	171	77.3419	14.6808	68	76
flood plain	34	179	145	78.6575	13.1066	70	76
salt flat	40	186	146	96.5454	30.1269	70	88
mislabled?	44	143	99	80.947	11.3958	84	81
flood plain/salt crust	24	209	185	96.9033	17.074	91	95

Table 7
TM 7   Classification Ranges
Of BAND 8 spectral data

Playa
Range	Lithology
0 - 49	active discharge
50 - 61	marsh
62 - 76	silty, sandy, active axial wash
77 - 99	salt flats, Qsm, discharge, silty-sandy-carbonate- mainly rims playa
100 - 119	saline marsh?
120 - 255	salt flat, playa

Fan
Range	Lithology
0 - 41	bedrock
42 - 53	$Q_{2/3}$ Hunt and Mabey (1966), Q_2 Bull (1991)
54 - 59	Q_4 Hunt and Mabey (1966), Q_3 Bull (1991)
60 - 100	Qf Hunt and Mabey (1966), Q_4 Bull (1991)
100 - 255	Q4, +/- paleodischarge

Table 8
Landsat TM Band 8 spectral values found in
Quaternary units of the thematic surficial deposits map

database code	cell count	minimum	maximum	range	mean	STD	majority	median	Lithology /unit
0	8,813	14	75	61	41.5	7.7	47	43	bedrock
1	109,376	22	98	76	56.7	4.0	59	57	marsh
2	723,867	21	165	144	69.1	5.1	69	69	Silty/sandy playa
3	831,582	27	160	133	85.7	8.2	83	85	flood plain
4	168,682	32	204	172	105.5	9.0	103	105	salt flat 1
5	106,999	28	209	181	135.7	15.8	126	135	salt falt 2
100	562	39	100	61	62.0	9.6	64	62	nulldata
101	671,337	26	107	81	49.6	3.4	51	50	Q2
103	1,154,344	26	108	82	56.1	2.8	56	56	Q3
104	2,065,606	20	182	162	68.1	11.1	61	65	Q4
149	2,842,100	10	197	187	49.6	15.7	42	49	Q1 +/- bedrock
198	1,449,198	14	199	185	55.7	11.2	53	55	bedrock

Table 9
Table showing qualitative evalution of
thematic surfical deposits map

Assessment	Agreement to exisitng Map Area	Agreement to exisiting Map boundary
Excellent	95% or better	95% or better
Very Good/Well	90-95%	90-95%
Satisfactory	85-90%	85-90%
Unsatisfactory	75-85%	75-85%
Poor	less than 75%	less than 75%