Spatial and Temporal Variations of the Pilot Valley Playa Interpreted From Remotely Sensed Images

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SPATIAL AND TEMPORAL VARIATIONS OF THE
PILOT VALLEY PLAYA INTERPRETED FROM
REMOTELY SENSED IMAGES

by
Llyn Doremus

A thesis submitted in partial fulfillment
of the requirements for the degree
of
MASTER OF SCIENCE
in
Geology

Approved:

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1992
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Llyn Doremus
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ABSTRACT

Interpretation of Hydrologic Processes
Present at the Pilot Valley Playa
Using Remotely Sensed Images

by

Llyn Doremus, Master of Science
Utah State University, 1991

Major Professor: Dr. Craig Forster
Department: Geology

In the Basin and Range Province, the geologic regime of the Pilot Valley, linear trending block faults have isolated many valleys both topographically and hydrologically. Discharge from these arid, closed basins occurs only as evaporation. Minerals dissolved in discharging fluid are precipitated at the valley floor as the liquid evaporates. The resulting salt flats and high density brines are known as playas.

The Pilot Valley Playa surface was sampled concurrently with the recording of a Thematic Mapper remotely sensed image to define the surface conditions that correspond to image data. An association was found between the band 7 (infrared wavelength radiation) image data and the measured depth to water; and between the visible wavelength data and the evaporite mineral deposits on the playa. The specific gravity
of the shallow subsurface brine was found to increase as the liquid brine surface approached the elevation of the valley floor. By using the observed relationships, three remotely sensed images were interpreted with respect to temporal changes in the areal extent of playa evaporite deposits and water depth between 1984 and 1988. The visible wavelength data indicated that the areal extent of the evaporite deposits diminished during the study period. The water level at the playa margins was interpreted to have dropped, and at the playa center to have remained stable. These interpretations suggest that a decrease in the extent of evaporite deposition is related to a drop in the water level around the playa margins.

The interpreted changes of the playa surface are used to draw the following conclusions about the hydrology of the Pilot Valley. The distinct variation in depth to water around the playa margin suggests that these areas are influenced by the discharge from the surrounding ranges. The relatively stable water depth in the central playa and the associated thicker evaporite deposits suggest that the subsurface brine acts here as a buffer to discharge variations. If the temporal changes of the playa margins do result from discharge variation, the discharge zone at the base of the Silver Island Range is wider than that of the adjacent, higher elevation Pilot Range.
INTRODUCTION

The structure of the Basin and Range Province and the arid climate of the Western United States have created an unusual hydrologic regime in which block-faulted linear trending ranges isolate down-dropped valleys. In the prevailing arid climate, discharge from these hydrologically closed valleys occurs only in the vapor phase. The lack of surface or groundwater drainage results in the accumulation at the valley floor of water and minerals leached from the surrounding mountains. Evaporative discharge of water to the atmosphere causes mineral precipitation at the valley floor and accumulation of a high concentration brine in the subsurface. The unique hydrologic regime and resulting mineral deposits are known together as a playa.

The playa formation in the Pilot Valley inspired an interest in the hydrology and geology of the Pilot Valley that resulted in the realization of this project. The study of the playa surface evolution and its spatial diversity was accomplished using remotely sensed images; and an effort to better understand the hydrology of closed desert basins was undertaken.

Remotely sensed images have been used to examine basin scale changes in playa surface moisture content and water accumulation playas (Neal, 1965, 1969, and 1975; Motts, 1970a and b; Kovalik and Carter, 1971; and Krinsley 1972). Spatial variation of playa morphology has been studied at scales...
ranging from microfractures to drainage basins, and has been attributed to the groundwater discharge from the playa surface and subsurface. Nolan (1927), Lines (1979), Neal (1975), and others have observed that the effects of groundwater level oscillation on the capillary movement and evaporation rates contribute to the spatial diversity of the playa evaporite deposits and soil moisture content. Neal and Motts (1967) observed a variety of playa sediment textures that related to variations in the depth of groundwater beneath the surface. Hunt and Washburn (1966) suggested that surface cracking observed during their study was caused by variations in playa sediment moisture content caused by groundwater table elevation changes. Lines (1979) noted a low area in the water table of the Pilot Valley that corresponds to a concentric pattern in the minerals deposited on the playa surface.

Playa surface morphology also varies over a wide range of time scales. Groundwater table elevation fluctuations occur: diurnally, with precipitation events (D. Donohue, oral communication); seasonally (Lines, 1979); over years and decades (Nolan, 1927). Precipitation, temperature, wind speed, and solar radiation each vary according to unique time frames. Together these parameters contribute to changes in the playa surface that occur daily, weekly, and seasonally (Neal, 1969), as well as in cycles that last decades and centuries (Nolan, 1927).
Previous studies have shown that playa surface features are defined by a complex relationship between the surface or ground water, evaporation of water from the surface or subsurface, and the sediments deposited in the basin. The extent to which each parameter influences another and the processes active at the playa surface are not well understood. With a data base of remotely sensed images extending over four years, both the spatial and temporal variability of the playa will be examined. Interpretation of the playa surface conditions with respect to the processes in which they form will be facilitated by examining the features of the entire playa surface as represented in remotely sensed images and by viewing the playa surface at different times by comparing images. Insight into the hydrologic system which drives these processes will be gained by examining playa temporal and spatial variation using remotely sensed images.

Study Objectives and Approach

The objectives of this study were to: (1) determine if a relationship between sampled surface parameters and remotely sensed images exists and define that relationship, (2) interpret temporal change at the playa surface using the defined relationships to examine previously recorded images, (3) use that information to evaluate a model for groundwater movement beneath a playa, (4) assess the value of remotely
sensed images as a data source for future study of playas and
the hydrology of closed desert basins.

To define spatial variation of the playa surface the
playa surface and shallow subsurface moisture and sediment
properties were sampled at the same time the Landsat
satellite recorded the Thematic Mapper August 28, 1988 image.

By sampling the playa surface when the image was recorded
the sampled parameters could be compared with remotely sensed
image data. The correlation between sampled parameters and
corresponding image pixel values allowed the remotely sensed
images recorded previously (in 1984 and 1985) to be
interpreted with respect to those sampled parameters.
Spatial variation of playa surface morphology was then
examined at the three different time windows defined by the
three images.

Temporal changes in the playa surface were interpreted
by comparing the three different images. This interpretation
was enhanced by constructing difference images from the
computed differences between corresponding pixel values for
each of the three sets of two images.

Annual change of the playa surface over a four year
period was studied using available remotely sensed images of
the Pilot Valley. The three images obtained for this project
were recorded during the same season, during similar weather
conditions, and at the same time of day. Due to the
similarities at the time of recording the influence of
precipitation, season, and time of day on playa, evolution was assumed to be relatively constant for all of the remotely sensed images used. An emphasis was made on interpretation of annual change due to changes in the recharge to and discharge from the hydrologic system.

Data from previous playa studies (Nolan, 1927; Lines, 1979; Bowler, 1986; Duffy and Al-Hassan, 1988) were compared with the interpretations drawn from relationships found in this study to further define the mechanisms by which playas form, and groundwater moves in a closed basin.

Location of Study

Geology

The desert basins of the Basin and Range Province in the Western United States, where this study was conducted, were formed by Tertiary extensional faulting (Cook et al., 1964). Fault blocks uplifted by Tertiary extensional tectonics create the horst and graben structure which closes the Pilot Valley topographically and hydrologically. Alluvial runoff deposits from the faulted mountain blocks have accumulated to form extensive alluvial fans in the larger drainages. In basins with high topographic relief, alluvial fans coalesce into bajadas. The coarse-grained alluvial fan deposits transport melting snow and flood water from the ranges to the valley floor, creating aquifers of low dissolved solid
concentration water (Lines, 1979). The location of the Pilot Valley study area in the Great Basin is shown in Figure 1. The general hydrogeology is shown in Figure 2.

Since the early Quaternary Period, the Pilot Valley basin has been accumulating sediments to a present thickness of over 1000 meters (Cook et al., 1964), shown schematically in Figure 3. Depositional sequences of alluvium transported from surrounding ranges and lacustrine sediments deposited during wetter periods reflect the long-term cycles in meteorologic conditions present since the formation of the basin (Nolan, 1927).

Drier conditions caused evaporation of the prehistoric lakes and deposition of the minerals once dissolved in the lake waters. Nolan (1927) suggests that gypsum and halite have been deposited throughout the Great Salt Lake Desert by the desiccation following the most recent lake cycle.

Coarse-grained alluvial fan deposits interfinger with the fine-grained lacustrine deposits along the playa edge, causing a sharp change in hydraulic conductivity. Water accumulates in the alluvial sediments deposited in the basin, forming aquifers that are confined by finer-grained lacustrine deposits. The concentrations of dissolved solids in aquifers below the playa surface range between 200,000 and 350,000 mg/l, making the water unusable for human consumption
Figure 1. Study site location within the Great Basin from Duffy and Al-Hassan (1988) after Morrison (1965).
Figure 2. Generalized hydrogeologic map of the Pilot Valley. Explanation on page 8, cross section A-A' on page 9, as modified from Stephens and Hood (1973). (Figure continues)
The Great Salt Lake is the most recent in a series of lakes that have occupied the Great Salt Lake Basin. Prehistoric Lake Bonneville shorelines were formed between 1250 and 1550 meter elevations. Lake levels fluctuated over a period between 100,000 to 10,000 years ago (Currey and Oviatt, 1985). Lake shorelines surrounding the entire Pilot Valley are visible on the remotely sensed images used for this study. Approximately twenty four hundred years ago Lake Bonneville remained at a relatively constant water level of 1538 meters (4260 feet) for an extended period. The consistent lake level allowed fine grained lacustrine sediments to be deposited at a uniform elevation creating what is known as the Gilbert shoreline.

Pilot Valley Hydrology

The Pilot Valley receives recharge as runoff from the surrounding mountains and subsurface inflow from surrounding basins (Stephens and Hood, 1973). Infiltration from precipitation on the mountain ranges surrounding the valley dissolves and transports minerals from the mountains through the alluvial fan aquifers to the valley floor. The shallow groundwater directly beneath the playa is generally not recharged by direct precipitation on the playa; playa surfaces are usually impervious to rainwater infiltration.
(Neal, 1969). Additionally, an evaporation rate which exceeds the precipitation rate by an order of magnitude causes the dominant direction of water movement to be upward as discharge from the playa to the atmosphere (Lines, 1979).

In many locations along the western edge of the valley the groundwater transported in the alluvial fans discharges at the surface, forming springs which may be observed on remotely sensed images used for this study. Spring discharge at a consistent 4260 foot (1538 meter) elevation suggests that the hydraulic conductivity contrast between the fine-grained deposits of the Gilbert shoreline and the coarse sediments of the alluvial fans induces surface discharge. Duffy and Al-Hassan (1988) have suggested that the change in slope present where the alluvial deposits meet the flat playa surface causes an intersection of the ground surface with the water table and allows water to discharge as springs here.

Discharge by evaporation of groundwater beneath the playa and transpiration by phreatophytes (Stephens and Hood, 1973) leave the salts and minerals leached from the surrounding mountains at the playa surface. The resulting high-concentration brine in the groundwater directly beneath the playa is composed primarily of sodium, chloride and carbonate, with smaller amounts of calcium, magnesium, sulfide and potassium present (Lines, 1979).
Previous Work

Playa Surface Study

The character of a playa surface is strongly influenced by the water discharged as liquid or vapor from the basin, as mentioned in the introduction; in addition to the effects of the atmosphere, particularly precipitation and temperature. Motts (1965) and Neal (1975) consider playa surface features to be controlled by either surface water, or groundwater processes, or an interplay of the two.

The presence of surface water on a playa creates a hard, even crust (Motts, 1970a). Because surface water dissolves salts, minerals in solution may be moved to areas of lower elevation and redeposited to leave a smooth surface when the surface water evaporates. Dissolved minerals and salts may be transferred from the playa surface to the underlying groundwater by infiltration and diffusion. Often surface water movement on a playa results in deposition of clastic sediments, with small amounts of non-clastics also deposited by precipitation (Motts, 1970a).

Groundwater processes control playa surface character if the water level lies below the surface, but is not deep enough to constrain evaporation (below about an eight meter depth, Neal, 1969). Discharge by capillary flow and subsequent evaporation deposits salts and minerals in the
subsurface capillary zone, and at the playa surface. Non-elastic deposition dominates and there is a thick salt crust present at the surface that may be broken into salt thrust polygons (Neal, 1975). Deposition of minerals in the shallow subsurface breaks up the sediments (Bowler, 1986). These sediments are susceptible to wind deflation which creates a puffy, uneven surface. If the water level is at or very near the surface, a soft, sticky playa texture is present (Neal, 1965), and a high evaporation rate is possible (Hillel, 1971).

Groundwater discharge through a playa is indicated by other features besides surface texture. A discharging playa often supports or is surrounded by phreatophytes sustained by water in the subsurface or discharging from springs. A high concentration brine is present in the subsurface, as well as silty sediments with high transmissivities (Motts, 1965).

If the depth to water is more than approximately eight meters, water moves through the subsurface to be discharged in a neighboring basin with a valley floor of lower elevation (Neal, 1969). Playas formed in basins with deep groundwater flow are composed of very fine sediments. Occasional surface water flooding from springs and flash floods determine the texture of the playa surface (Neal and Motts, 1967).
The level of the groundwater surface has a strong influence on whether erosion or deposition occurs at the playa surface. The water table acts as a base level; a drop in its elevation results in erosion, while a rise in its surface allows aggradation of sediments (Motts, 1965). Bowler (1986) has observed a groundwater bevelling process in which the water level acts as a base level to which deflation and weathering adjust, similar to the situation described by Motts.

The areal extent of the playa is also influenced by the depth of the groundwater level below the surface. A drop in the water level may cause the playa to expand. Phreatophytes surrounding a playa will be adversely affected in two ways by a drop in the piezometric surface. Plant roots may not reach to water or the dissolved mineral concentration in the groundwater may increase. Either situation can kill phreatophytes. Once plants die, the playa expands to where they were (Motts, 1968).

Influence of the Hydrologic System on the Playa Surface

The playa surface may be considered as a plane that intersects the path of water flux from the basin subsurface to the atmosphere. Variations of the surface deposits and moisture content at the playa surface reflect changes in the water flux through the system (Neal, 1965, 1975; Neal and
Motts, 1967; Motts, 1970b), and playa surface conditions have been found to influence discharge from the hydrologic system. A graphic representation of the interactions between factors present at the playa surface and shallow subsurface (and the remotely sensed data recorded) is shown in Figure 4.

Figure 4. Interactions (shown by the solid arrows) between factors influencing the playa surface, the subsurface moisture content, depth to water, and brine specific gravity. The flux of moisture from the subsurface to the atmosphere dominates the processes portrayed.
The water level (either below or above the surface) is influenced by the precipitation the entire basin receives and the hydrologic system which transports water that recharges and discharges from the system (Krinsley, 1972). Neal and Motts (1967) observed that a decrease in precipitation received by a basin lowers the water level below the playa. They suggest that discharge in closed basins is directly proportional to recharge, which in the Pilot Valley is approximately half the precipitation the basin receives (Stephens and Hood, 1973).

Discharge (evaporation), influenced by the groundwater elevation, the dissolved solids in the groundwater, the hydraulic conductivity of the sediments, and atmospheric conditions (Hillel, 1971) is both a function of the groundwater level, and a factor which determines groundwater level elevation. An increase in discharge (evaporation) caused by a water level rise may eventually lower the groundwater level if the recharge rate does not supply enough water to replace the volume evaporated. If the groundwater level consequently drops the evaporation rate decreases again (Hillel, 1971). An increase in evaporative discharge also causes an increase in the mineral concentration in solution (shown by the double tipped arrow between the depth to water and the brine specific gravity in Figure 4). Brine concentration influences the evaporation rate; as the
concentration increases the rate of evaporation declines. Evaporation eventually ceases when a critical brine concentration is reached.

By influencing the evaporative discharge rate, groundwater level influences the moisture content of the subsurface sediments (shown by the positive arrow between the groundwater level and the sediment moisture content in Figure 4) and the mineral precipitation from the groundwater brine (shown by the positive arrow between the depth to water and the evaporites in Figure 4). The atmospheric factors of temperature, solar radiance, humidity, and wind speed also influence the evaporation rate, and thereby the sediment moisture content and the evaporite precipitation. However, the atmospheric effects on playa surface morphology were not examined for this study, and are therefore not included in system diagram presented in Figure 4.

Duffy and Al-Hassan (1988) and Lines (1979) consider the groundwater level beneath the playa to be influenced by the water density; a higher density brine having a lower water level than groundwater of lower density in an equivalent environment. Brine density is a function of the recharge and discharge volumes and rates, which determine how minerals are supplied, accumulated and concentrated in the subsurface brine.

The high rate of evaporative discharge from the Pilot
Valley results in the potential to discharge more water from the hydrologic system than enters as recharge. Consequently, the volume and rate of recharge, the system components which determine the amount of water available for discharge (evaporation), are the factors which determine the rate of discharge from the hydrologic system.

**Evaporative Flux at the Playa Surface**

Evaporation at the playa surface is influenced by the meteorologic conditions of the basin, the playa sediments and the groundwater level. Evaporation of groundwater requires a heat source to supply the latent heat of evaporation, and a lower vapor pressure in the surrounding atmosphere than that created by the evaporating water body. Whether these factors are present is determined by the meteorologic conditions of air temperature, humidity, wind velocity and solar radiation. Together these parameters determine the rate at which water can be vaporized by the atmosphere.

If the atmosphere is capable of evaporating water, and a continual water source from below the ground surface is supplied, a moisture gradient between the atmosphere and the groundwater is created. The rate of water rise due to capillary transport and the consequent evaporation rate are controlled by the magnitude of this gradient, which is also defined by the depth of the water below the surface. The
hydraulic conductivity of the soil through which the water moves is the upper limit on the rate of capillary transport (Hillel, 1971).

The evaporative process is complicated by the presence of the evaporite crust at the playa surface. Evaporite minerals maintain a distinct hydraulic conductivity from that of the underlying soil, and a unique water absorption capability. The hydraulic conductivity of dried evaporites is significantly less than that of the underlying soil and may limit the water flux to the surface. Water absorbed from the atmosphere by evaporites may be transferred to the soil, reversing the flux. During evaporation precipitation of evaporites may reduce the latent heat available, and influence the evaporative flux rate (L. Hipps, oral communication).

Playas with coarse grained sediments have a higher permeability that allows more subsurface water circulation (Kerr and Langer, 1965). High capillary flux is possible when the subsurface is composed of sands and silts, increasing the hydraulic conductivity, and causing thick mineral crusts to be deposited at the surface (Neal, 1975).

Coarse grained sediments with silty and sandy textures have a lower moisture content than finer grained sediments (Hillel, 1971). Playas composed of fine grained sediments have a lower capillary flow and surface water movement.
contributes primarily to formation of playa surface texture (Motts 1965).

Model For Groundwater Circulation In Closed Basins

To interpret the observed conditions of the closed desert basins in the Western United States several interpretive models of the basin hydrology have been proposed. Nolan (1927) found the concentration of potassium in groundwater to decrease from the playa margin toward the central playa, with a relatively constant sodium, sulfate and chloride concentration throughout the basin. He postulated that groundwater moves from the basin margin towards its center.

Nolan's interpretation of the hydrologic system which created this brine chemistry follows. Water from mountain ranges surrounding the basin dissolves potassium, and magnesium and calcium carbonates from the host rock. The calcium, magnesium, and carbonate precipitate relatively rapidly during discharge leaving potassium as the predominant ion in the water that reaches the playa margin. The relatively fresh water entering the basin from the surrounding ranges, although high in potassium, was still fresh enough to dilute the concentration of the brines it encountered at the valley floor. The uniform concentrations of halite and gypsum observed to extend across the basin floor were due to desiccation of Lake Bonneville or other
prehistoric lakes. The high concentration of potassium at the playa edge resulted from discharge of water relatively higher in potassium content. That potassium accumulated where it entered the valley, at the basin margin.

Models describing the movement of groundwater in a closed basin playa proposed by Duffy and Al-Hassan (1988) and Bowler (1986) suggest that discharge from the surrounding mountains is concentrated at the basin margin. Water either evaporates or transpires at the basin margin, or is transported across the playa. Depending upon the amount of water present in the basin, movement of water toward the center of the basin occurs either on the surface or in the shallow subsurface. As water moves toward the center of the playa evaporation of water at the surface and in the shallow subsurface increases the total dissolved solid concentration.

Although moisture content was observed to vary with grain size at Coyote Playa, Rosamond Playa and Rogers Playa in California, Motts and Carpenter (1968) observed an increase in moisture content with depth in sediments of the same grain size, suggesting a deeper aquifer moisture source, and an insignificant amount of infiltration from the surface.

If the evaporation remains high with respect to precipitation for thousands of years dissolved minerals accumulate in a high density brine pool beneath the playa. The brine creates a sharp interface with the relatively
fresh water discharge from the surrounding ranges. A pressure gradient forms between the fresher water and the high density brine that decreases outward from the playa center. The gradient forces the fresh water discharging at the playa margin to the surface as springs or to the shallow subsurface beneath the playa. Results of the SLEADS (Salt Lake Evaporites and Aeolian Deposits, initiated at the Australian National University) drilling project at Lake

Figure 5. Brine pool configuration below Lake Frome Playa, Australia as defined by the SLEADS drilling project (Bowler, 1986). Contour lines indicate parts per thousand concentration of dissolved solids in the subsurface brine.
Freme, Australia reveal a brine pool with concentration decreasing horizontally and vertically away from the surface of the playa center (Bowler, 1986). The brine pool forms in the shape of a wedge that extends downward and outward from the central playa as illustrated in Figure 5.

Work by D. Donohue (oral communication) confirms a brine pool which decreases in concentration downward and horizontally away from the playa center. Lines (1979) has shown (Figure 6) that the water table elevation attains a minimum elevation in the area of the highest brine concentration, the playa center. Duffy and Al-Hassan (1988) propose that the depression in the groundwater surface at the playa center, in combination with the discharge from the surrounding mountains, induces shallow surface and subsurface movement of water from the playa margin toward the closed depression in the groundwater table.

During the winter months the evaporation rate decreases and the groundwater level rises (Donohue, oral communication). Surface water dissolves evaporites and transports them to the areas of lower elevation; located at the northwestern portion of the Pilot Valley. With warmer weather the evaporation rate increases and the groundwater surface elevation drops. Salts precipitate to form a new crust. The rapid evaporation of water from the shallow subsurface beneath the playa crust results in the
Figure 6. Contour maps of total dissolved solids (a) and water table elevation (b) for the shallow brine aquifer in the Pilot Valley adapted from Lines (1979) by Duffy and Al-Hassan (1988). Transects along which samples were taken are marked.
accumulation of a high concentration, high density fluid immediately underlying the playa surface. Water contained in the deeper aquifer, beneath the shallow subsurface, is of lower concentration than the high density fluid directly overlying it. Duffy and Al-Hassan (1988) consider that the position of high density fluid over liquid of lower density creates an unstable configuration capable of driving a convection cell (shown in Figure 7). High density brine would have a tendency to sink; a relatively lower groundwater elevation at the playa center suggests that brine may drop here. The heavier brines are then transported laterally, at depth, toward the playa margin. At the playa margin brines are stored in the high density wedge, or

Figure 7. Theoretical model for groundwater movement within an arid closed basin. Convection cells beneath the valley floor are caused by density driven flow. No vertical scale intended; schematic representation only. Axes show relative volume of recharge and discharge for the basin.
recirculated in the convection cell.

Bowler (1986) suggests that once minerals are precipitated at the playa surface, diffusion becomes the dominant means of transport through the underlying sediments. By this mechanism minerals are transported away from the playa surface and stored deeper in the basin. The diffusion transport mechanism is supported by the results of the SLEADS drilling project which defined a brine concentration that gradually decreases laterally and vertically away from the playa surface, as shown in Figure 5.

Each model suggests that minerals are transported to the surface or shallow subsurface by discharging water. Minerals accumulated by evaporation are transported downward from the playa surface either by density driven convection (Duffy and Al-Hassan, 1988) or by diffusion of dissolved solids from the playa center laterally and vertically (Bowler, 1986).

Remote Sensing Use in Playa Investigations

As the physical character of a playa surface changes in response to the factors discussed in the previous section, the spectral reflectance properties of the playa surface change as well. The amount of incident electromagnetic radiation from the sun in the visible and infrared spectrum ranges that is reflected by the ground surface is determined by properties of that surface including the surface moisture, its density
and the compositional differences in surface materials. In general, with increasing spectral wavelength (from the blue to red visible wavelengths extending into the infrared wavelengths) an increase in reflectance is observed. However, visible and infrared electromagnetic radiation wavelengths react differently to specific surface conditions. Near infrared (1 to 5 micron wavelength radiation) reflectance variations are strongly influenced by moisture content and density contrasts between different surface materials. For example, a higher density material would retain heat longer and reflect more infrared radiation than a lower density material (Molineux et al., 1971). An increase in moisture content of surficial materials decreases reflection of radiation in the visible spectrum, but even more strongly influences the reflectance of infrared radiation. Water absorbs infrared radiation efficiently, causing moist zones to reflect less infrared radiation and appear darker (Molineux et al., 1971).

Krinsley (1972), Neal (1969, 1975), Motts (1965, 1970b), and Kovalik and Carter (1971) have used remotely sensed data in playa mapping studies. The Multispectral Scanner satellite (MSS) images used for those studies had four wavelength bands of data; three in the visible wavelength range (0.5-0.6 µm, 0.6-0.7 µm, 0.7-0.8 µm), and one in the near infrared (0.8-1.1 µm). Previous investigators were able
to define variations in playa moisture conditions, and determine where water accumulation occurred on the playa surface with the MSS images.

For this study, Thematic Mapper (TM) images composed of seven radiation wavelength bands were used. Bands 1 (0.45-0.52 \( \mu \text{m} \) wavelength radiation), 2 (0.52-0.60 \( \mu \text{m} \)), and 3 (0.63-0.69 \( \mu \text{m} \)) of the TM data record visible wavelength radiation which corresponds to blue, green and red respectively. Bands 4 (0.76-0.90 \( \mu \text{m} \)), 5 (1.55-1.75 \( \mu \text{m} \)) and 7 (2.08-2.35 \( \mu \text{m} \)) are infrared wavelength bands and band 6 (10.4-12.5 \( \mu \text{m} \)) is a thermal infrared waveband whose response is governed by surface temperature.

The spatial and temporal variations in playa evaporites were examined with the remotely sensed images. The presence of a salt crust is known to generally increase reflectance of visible wavelength radiation over that of other crustal material. The parameters of sediment moisture, evaporite mineralogy, groundwater level and density were sampled at the playa surface to compare with the pixel values of the remotely sensed images and interpret spatial and temporal variation of these conditions.
METHODOLOGY

The locations chosen for sampling were the areas of the playa that showed the most distinct spatial variation as interpreted from the 1985 remotely sensed image of the Pilot Valley. The northwest portion of the basin was found to show the most distinct contrast in image pixel values in both the visible and infrared wavelengths. Samples were taken along two transects (shown in Figure 8) that crossed in the area of maximum variation. Lines (1979) defined the location where the transects intersect to be the lowest elevation of the water table. Samples were taken in this area in order to better define the relationship between the decrease in groundwater level elevation and the distinct image pixel value variations. Spacing between sites sampled along the transects varied between 100 and 500 meters.

Prior to transect sampling, grid sampling was conducted within a 30 meter square area to define the surface variation within one pixel (a pixel being the surface resolution of the thematic mapper remotely sensed data). Grid sampling was intended to resolve whether the values of the surface parameters sampled at one point within a pixel (30 meter square) would actually be representative of that entire pixel area. If a large variability in the sampled parameters was present within one pixel, the pixel value would represent
Figure 8. Remotely sensed image of the Pilot Valley Playa constructed from visible wavelenght radiation: bands 1, 2, 3, recorded August 28, 1988. Location of transects along which samples were taken are marked by black lines; grid sampling locations are marked by white circles.
only one of a range of possible surface conditions and a good correlation between image pixel values and sampled surface parameters would not be possible.

Samples of soil moisture, and surface mineralogy were taken in a grid configuration at a spacing of 7.5 meters. Grid samples were taken on July 17 and 18, 1988.

Samples were gathered along the transects on August 3, 4, 30 and 31, 1988. The image with which this data was correlated was recorded August 14, 1988. Little surface variation is assumed to have occurred over this time period. There was only one precipitation event recorded in Wendover (30 km southwest of Pilot Valley) on August 11 of 0.01 inches during the month of August. This amount of precipitation is likely to have evaporated on the same day it fell. Lines (1979) estimated from pan evaporation measurements that 95.1 inches of water was evaporated in 1976, 60% (or 57 inches) of it between May and August. If this amount is divided between the 4 months (120 days) between May and August an approximate evaporation rate of 0.48 inches a day is defined, enough to eliminate the effects of 0.01 inches of precipitation on the playa surface within three days.

Sample Locations

Grid sampling (7.5 meter spacing) was done at two locations. The first grid was sampled near the southwestern
playa edge and numbered TS 1-11 and GS 1-8. The second set was on the northwest edge of the playa, numbered TN 1-8 and GN 1-13 (locations are shown on Appendix F, in pocket).

The two sample transects (shown in Figure 7) extended generally from west to east, and from north to south. The TW transect extended from the northwestern edge of the playa for a distance of 11 kilometers along a line oriented South 76 East. Sites along this transect were numbered TW1 to TW50. The north to south transect traversed from the northern edge of the playa along a line oriented South 10 East for 3.2 kilometers (sites numbered NS1 to NS18). This transect crosses the TW traverse at site TW18. From the point of intersection the NS transect continued due south for a distance of five kilometers (sites SL1 to SL10). Sites TW1-TW21 and NS1-NS18 were sampled on August 3 and 4, 1988. Sites SL1-SL10 and TW23-TW50 were sampled August 30 and 31, 1988. Transects and grid sampling sites are illustrated on Figure 8, and Appendix F (in pocket). Spacings between sampled sites are listed in Appendix B.

Sample sites were located initially (August 3 and 4, 1988) by a Brunton and pace survey from a BLM benchmark at South Patterson Spring (shown in Appendix F). The second set of samples (taken August 30 and 31) were taken using four wheeled all terrain vehicles with a bicycle wheel attached to the back of one. The bicycle wheel was equipped with a
small computer which measured distance travelled along a line defined using a Brunton compass. At each sample site a sample of the playa surface was collected for later mineralogy determination, specific gravity of groundwater and depth to water were measured and a description of the playa surface was made. Soil samples were also collected for later determination of moisture content.

Sampling Procedures

**Depth-to-Water Measurements**

At each sample site a 2 inch diameter hole was drilled with a hand held auger until water was observed flowing into the hole, or until it was inferred that water would later be present above the bottom of the hole. The depths of holes drilled ranged from 2 meters to 20 centimeters. Each hole was allowed to recover at least one hour before depth-to-water measurements were made. At most sites water levels were allowed to recover for more than 6 hours. The holes on the west to east traverse were measured at least twice. It was found that the depth to water measurements often varied by over 10 centimeters over the period from August 1 to 31.

Depth-to-water measurements were taken by laying a straight edge across the top of the hole on the ground and extending a tape measure down into the hole until the water surface was disturbed. The depth to water was sufficiently
shallow that it was possible to observe the ripple reflection of the water. This method provided measurements of depth-to-water accurate to the nearest 0.1 centimeter. All depth to water measurements, and the times they were taken are recorded in Appendix B.

Moisture Content Measurements

Sediment moisture content was determined at 31 of the sample sites. Preliminary moisture content determinations made from samples taken in the grid configuration to characterize the variability within a pixel indicated that sediment moisture content varied by less than 1% in the shallow playa subsurface. Because the range in variability was small, it was not necessary to sample the playa subsurface for moisture content at each location. Moisture content samples were therefore collected at sites along transects only where the surface mineral precipitate or moisture conditions appeared to fluctuate from those of the previous sample site. Locations of sites sampled for sediment moisture content are indicated on the site map (Appendix F).

Moisture content samples were collected by digging a shallow hole with a trowel, and scooping a piece of undisturbed soil from a depth of 10 cm or less. The sample was placed immediately in a metal canister, covered with a lid, and the container was sealed with adhesive packing tape.
In all cases the samples were returned to the lab within three days for analysis in order to minimize moisture loss.

**Mineralogy Samples**

A sample of the evaporite deposits found at the ground surface was collected at each site. In the sampling procedure, care was taken to exclude clays or soil by visual inspection of the sampled material. Samples were placed in a plastic bag, or paper packet, and marked with the site number. Samples of mineral crystals were also collected when observed in the sediments.

**Observations of Surface Conditions**

At each sample site the presence or absence of evaporite deposits was noted, the thickness of the evaporite deposit measured, and the areal extent of the evaporite deposit estimated. At many locations the salt crust has been broken into polygonal pieces that were measured for size and thickness. Other features such as ripples formed in both the sediment and the salt crust were noted. Inferred variations in grain size and the presence of depositional layers in the shallow subsurface were also noted.

**Specific Gravity Measurements**

Once the depth to water measurements were taken at each sample site, groundwater was pumped to the surface using a
Black and Decker Rabbit Pump. Water pumped to the surface for this measurement had been allowed to settle in the drilled hole at least one hour before being disturbed for sampling; and water was pumped only from the uppermost portion of that accumulated in the drillhole to minimize the amount of suspended solids in solution. Water collected into a small cup was drawn into a PAAR Densiometer by vacuum suction. This instrument measures the density of the liquid that has been drawn into its compartment by oscillating the liquid over a constant distance. The period of oscillation depends only on the sample's density and the temperature of the sample. The instrument reads temperature and has a built-in processor to calculate the effect of temperature using the equation: \( p = A \left( t^2 - t_0^2 \right) \), where \( p \) = density, \( t \) = the actual period, \( t_0 \) = the period of the empty oscillator, and \( A \) being a calibration constant. The specific gravity of the sample is determined and displayed in real time. Each measurement was repeated twice, or until the reading was constant.

Laboratory Procedures

X-Ray Diffraction

Specimens collected from the playa surface were analyzed using x-ray diffraction techniques to determine the presence of the minerals halite, gypsum, calcite, quartz and sylvite. The samples were ground using a mortar and pestle to a grain
size that would fit through a size 200 soil sieve. The grains were affixed to a slide with petroleum jelly, and the slide inserted into a Siemens Crystaloflex 4 x-ray diffraction machine.

The radiation reflected by the sample in a particular angle is associated with a specific mineral. Copper tube nickel filtered K-alpha radiation was directed at the sample while the slide was rotated through the angles of 10 to 40 degrees 20. The XRD recording device prints out a continuous plot over the range of angles through which the x-rays have been directed at the sample. The readout of the analysis shows peaks at the angles where x-ray radiation is diffracted. The angles at which halite, gypsum, and calcite diffract radiation are within the 10 to 40 degree range. These minerals were observed by Lines (1979) to be present at the Pilot Valley Playa surface.

The result of the x-ray diffraction (XRD) analysis for mineral identification of the playa surface gives only a rough estimate of the relative amounts of minerals in a sample; the technique is intended only to identify what minerals are present. The higher the peak (10 is the maximum peak height as defined by the paper on which results were printed), the more radiation is diffracted indicating a proportionally larger amount of mineral presence. The relative heights of the peaks (from 0 to 10) were compared for this analysis.
The results of the x-ray diffraction analyses showed variation within the individual mineral samples analyzed. This is interpreted to be caused by heterogeneities in the sample composition; each sample was composed of an assembly of the minerals present at the playa surface. Each time a random sample was removed from the assembly a different relative proportion of each mineral was collected. Samples taken from the same location that were analyzed twice showed different amounts of minerals present because of the heterogeneities in the sampled material and the variations in thickness of the mineral coating on the slide that diffracted the x-rays. However, results showed consistently that the same relative amount of those minerals detected were present. The scale used to compare the amounts of specific minerals present in the samples was accurate enough to define trends in the relative amounts of the minerals present, but not quantify the amounts of mineral present at the playa surface.

**Gravimetric Analysis of Soil Moisture Content**

Soil samples collected from the playa surface were analyzed to determine their moisture content using gravimetric methods. Sample collection and storage has previously been described. Sample containers were opened in the laboratory and the sample and bottom half of the container were weighed with a Metler balance to an accuracy of 0.0001 gram.
Sample tins were marked with sample numbers and dried in an oven at 150° F. After at least 48 hours the samples and tins were weighed again, and returned to the oven to continue drying. Samples were weighed again after 24 hours. If the second dried weight was within 0.01 grams of the first dried weight, the final weight was recorded. If not, the drying process was continued until the dried weight was constant to a 0.01 gram accuracy, allowing an accuracy of 0.01% when reporting moisture content values to the 0.1% accuracy by weight.

Once a constant weight was determined, the samples were washed out of the containers. The clean containers were returned to the oven and once again heated and weighed; under conditions similar to those of the previous weighing.

To calculate the sample moisture content, the following equation was used:

\[
\frac{W_T - (W_D + W_c)}{W_T - W_c} = \text{sediment moisture content}
\]

where \( W_T \) = total initial weight of moist sample plus container, \( W_D \) = weight of sample after drying minus the container weight, \( W_c \) = container weight. The final container weight was subtracted from both the initial moist sample weight and from the dried sample weight. The difference between the resulting moist and dry weight was divided by the initial moist weight of the sample, and the moisture content
is defined as a percentage of the total initial sample weight.

Error may have been introduced into this measurement if moisture escaped during transport from the field site to the laboratory. Moisture may have equilibrated in the sample tin, so that the vapor pressure was in equilibrium with the soil moisture. Upon opening the sample tin this vapor would escape without being weighed. The moisture content of the air space is likely to have been a small percentage of the moisture contained in the soil sample, so an error of less than 0.1% was probably introduced. This error may be equivalent to the spatial variation within one pixel area; moisture contents were interpreted to vary in the range of 1% within one pixel area (a 30 by 30 meter square) in the grid sampling exercise.

Remotely Sensed Images

Remotely sensed data recording can be explained conceptually by using an analogy with a photograph. A photograph records images by allowing light sensitive film to be briefly exposed to a scene. A scene is composed of the objects that preferentially absorb or reflect visible wavelength electromagnetic radiation. For black and white film a grid of light (visible wavelength radiation) sensitive chemical dots are on the film surface. Each one of these dots reacts chemically in proportion to the amount of light to which it is briefly exposed when the shutter opens.
Seven sensors are mounted in parallel on a remote sensing satellite. Each sensor is sensitive to a group (or band) of different radiation wavelengths (the equivalent to seven different chemical dots at each single dot location on the black and white film). The 'dots' of the satellite sensor record a brightness value for each 30 by 30 meter pixel square for each of the seven specific wavelength bands reflected from the scene (in this case the surface of the earth) at the brief moment the shutter opens (or in this case, the sensor records). The image is recorded as a brightness value (ranging from 0 to 255 in each of the seven wavebands) for each pixel. These values are recorded as digital data and transmitted back to the earth's surface to a recording computer.

The Landsat satellite orbits the earth in a longitudinal direction repeating the recording procedure at a specific time interval. The interval is spaced so that each image recorded overlaps the previous one by approximately ten percent of the image size.

On each complete circumference of the planet, the satellite moves a few more degrees to the west, and records an area at an adjacent latitude the following day at the same time of day. It takes 16 days for the entire surface of the earth to be recorded by the satellite, hence the temporal resolution of the TM data is 16 days. Images are consistently
recorded at the same time of day for each location.

There is a complication with remotely sensing electromagnetic radiation that is not present with the photographic procedure. This complication is caused by the atmosphere through which the sensors detect the radiation reflected or emitted from the surface. The atmosphere is composed of a variety of gases and particulate matter that alter the radiation reflected or emitted from the earth’s surface in an unknown manner. For the purposes of this study, the amount of alteration caused by the gases in the earth’s atmosphere is assumed constant for all images, and any difference due to its effect is ignored. Although not used in this study, the techniques available for atmospheric correction will be discussed in the Atmospheric Correction section.

**Image Acquisition**

The images used for this study are located with reference to the Worldwide Reference System for Landsat 4 and 5 images on path 39 and row 32, quad 1. The scene image identification numbers are #5012317425 for the July 28, 1984 image, #5047517442 for the July 3, 1985 image, and #Y5162717450X0 for the August 14, 1988 image.

Images of the study site were obtained as digital data on magnetic computer compatible tapes. Tapes are permanently
stored in the Civil Engineering Department at Utah State University in Logan, in the custody of Bob Gunderson. Data was read from the tapes by the Earth Resources Data Assessment Software (ERDAS).

Geometric Rectification

The three remotely sensed images used for this study were each geographically corrected to the Universal Transverse Mercator coordinate system using a nearest neighbor interpolation technique (Jensen, 1986). Geometric rectification required matching points on the image (pixels) to points on a 7.5 minute United States Geological Survey topographic quadrangle map. This was accomplished using a digitizing tablet and the GCP program of the ERDAS software. The topographic maps used for the correction were the Graham Peak, Silver Island Pass, Lemay Island, Crater Island, Crater Island NW and Crater Island SW, Miner's Canyon, Patterson Pass, and Pilot Peak Quadrangles. Points for rectification were chosen on the mountains and alluvial fans surrounding the playa, that could be identified on both the image and the topographic maps. Rectification points are included in Appendix E.
Atmospheric Correction

An atmospheric correction was not done on any of the images used for this study because current techniques for atmospheric correction were not applicable to the Pilot Valley Playa images. Methods considered, and determined to be inapplicable were the histogram minimum technique (Chavez, 1975), the slope intercept method (Jensen, 1986), and atmospheric modeling.

Some atmospheric correction techniques uniformly add or subtract a constant pixel value (histogram minimum technique and the slope intercept method) to an entire waveband in order to adjust the pixel values in that band either higher or lower. Because the emphasis of this study was on the determination of spatial diversity, an overall adjustment in the band values of a single image would not have affected detection of spatial variation within an image. An adjustment of the waveband values of one image would have affected the results when pixel values were compared between several images. Although the overall spatial pattern of the image differences would remain the same, the absolute values of those changes (pixel value differences) would have been altered. However, the absolute value of pixel differences was not used in this study to define change quantitatively because a relationship between pixel values and measured parameters was not well quantified. Application of these
atmospheric corrections would have had little influence on the findings of this study.

An atmospheric correction model has been proposed which corrects the effect that atmospheric absorption of radiation by water vapor in the thermal infrared wavelengths (which corresponds to band 6 of the TM images) has on data recorded by Landsat. As the radiation wavelength becomes shorter, the water vapor acts to increasingly refract the radiation, as well as absorb it. Thus, the effect of moisture in the atmosphere becomes more complex. In the visible range, the radiation wavelength is short enough that a large proportion of radiation is refracted. Enough visible wavelength radiation is refracted in so many directions that the problem of correcting for the effect of water vapor in the atmosphere for visible wavelength radiation is considered intractable. In the near infrared range modeling of this phenomena is considered difficult and is yet an unsolved problem (L. Hippa, oral communication). Water vapor is one of numerous gases that affect radiation transfer in the atmosphere. At present, it is the only one whose influence on remotely sensed data acquisition (recording) has been modeled. For lack of a better method, an equivalent atmospheric influence on radiation transport in the atmosphere for the weather conditions during which these images were recorded was assumed to exist.
Change Detection On Images

To compare the changes between images, the pixel values for a specific waveband from one image were subtracted from the pixel value for the identical location from another image. The difference values were used to produce a difference image. Difference images were constructed for one band in the visible range (band 2, 0.52-0.60 \( \mu \text{m} \) wavelength) and one band in the near infrared range (band 7, 2.08-2.35 \( \mu \text{m} \) wavelength). Three sets of difference maps were constructed for each of the two bands, between the 1984 and 1985 images, between the 1985 and 1988 images, and between the 1984 and 1988 images.

Of the three bands (1, 2, and 3) in the visible range, band 2 was chosen for comparison with field sampled parameters and for analysis of spatial and temporal variation. The band 1 data was not used because this wavelength is subject to significant atmospheric scatter resulting in more homogeneous pixel values. The observed spatial variation of an image constructed from that waveband was thereby decreased. The band 3 data was eliminated because its radiation wavelength is closer to that of the near infrared data than the band 2 radiation, and potentially more influenced by infrared radiation response than the band 2 data.

The infrared wavelengths were analyzed using band 7 (2.08-2.35 \( \mu \text{m} \) wavelength) data because this wavelength of radiation is most efficiently absorbed by water.
Consequently, changes in moisture content of the surface are more apparent in data from this waveband.

Negative pixel difference values were eliminated from difference images by adding a value of 100 to the band 2 differences and adding a value of 120 to the band 7 differences. An example of the equations used to construct the final difference maps is $B7(84) - B7(85) + 120 = \text{Value}$.

In order to simplify the interpretation of change on the difference maps, the adjusted pixel difference values were grouped into ten sets of 25 or 26. A color was assigned to each of the ten groups according to the ROYGBV color scheme. The lowest difference value (i.e., 1-26) is black, and the highest value (i.e., 230-255) is the color red. These two groups of values (colored areas) indicate zones with most change. Negative changes between images (i.e., an increase in pixel values over time) are indicated by a black, purple, navy or royal blue color. Positive changes are successively larger in magnitude as the colors progress from a green color to a red color. The areas corresponding to zero or minimal change (pixel values of 100-126 in the band 2 range and the band 7 range) were changed to white from an aqua blue color to emphasize constant conditions over the time period between both image recordings.
<table>
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<tr>
<th>Color</th>
<th>Pixel Value</th>
<th>Relative Difference</th>
<th>Interpreted Change</th>
<th>B7</th>
<th>B2</th>
</tr>
</thead>
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<tr>
<td>black</td>
<td>1-25</td>
<td>-</td>
<td>increase in depth</td>
<td>increase in evaporite deposition</td>
<td></td>
</tr>
<tr>
<td>purple</td>
<td>26-50</td>
<td>-</td>
<td>to water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>violet</td>
<td>51-76</td>
<td>-</td>
<td>decrease in depth</td>
<td>decrease in evaporite deposition</td>
<td></td>
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<tr>
<td>blue</td>
<td>77-102</td>
<td>-</td>
<td>increase in depth</td>
<td>increase in evaporite deposition</td>
<td></td>
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<tr>
<td>white</td>
<td>103-128</td>
<td>0</td>
<td>stable water level</td>
<td>constant surface</td>
<td></td>
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<tr>
<td>forest</td>
<td>129-154</td>
<td>+</td>
<td>decrease in depth</td>
<td>decrease in evaporite deposition</td>
<td></td>
</tr>
<tr>
<td>green</td>
<td>155-180</td>
<td>+</td>
<td>to water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>yellow</td>
<td>181-207</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>orange</td>
<td>208-229</td>
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<td>red</td>
<td>230-255</td>
<td>+</td>
<td></td>
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RESULTS

Field Sampling Results from Grids

In order to relate the results of playa transect sampling with the remotely sensed image pixel values preliminary sampling was done on a small scale to define the spatial variation within one pixel. Samples were taken from locations narrowly spaced in a grid configuration. Sediment moisture content and surface mineral precipitate samples were gathered in two locations along the western margin of the playa (see Appendix F for exact locations). The sampled sediment moisture content was determined to vary slightly within the 30 meter square sampled (less than 1.1% by weight) at both grid sample locations. The mean value of the 14 samples taken in the north grid was 24.52% water by weight, with a standard deviation of 1.09. At the south grid location the mean moisture content for the 11 samples taken was 22.23% and the standard deviation 1.07. Samples taken of a single location within a pixel, or at larger spacing (100 to 500 meters) along transects were assumed to represent the entire area. Sediment moisture content determinations were used for comparison with pixel values and depth to water measurements, as discussed in the following chapter.

Mineral precipitates, analyzed by x-ray diffraction, of samples taken within the grid spacing were found to vary with
respect to the absolute amount of refraction by the minerals present. Detection of the minerals composing a relatively small percentage (approximately less than 15%) of the sample was inconsistent. The relative amounts of specific minerals present in a sample remained constant.

Differences between the refraction peak values are interpreted to be the result of the x-ray diffraction analysis process (discussed in the x-ray diffraction procedure section of the methodology chapter) or specifically caused by the small amount of sample analyzed by the x-ray diffraction technique relative to the heterogeneity in mineral content within the sample itself.

Although the relative amounts of minerals determined to be present were compared with other parameters sampled (as discussed later in this chapter), no relationships were found. This may have been the result of inaccuracies in the analysis process, or a consequence of the physical playa evaporite processes. The results of the precipitate mineralogy analyses were not used for comparison with pixel values because the spectral reflectance properties of the minerals present (halite, gypsum, sylvite and calcite) were similar enough in the wavebands recorded by the Thematic Mapper Satellite to make them indistinguishable on the images.

The narrow spaced grid sampling showed that there was small variability in the precipitate mineralogy and the
sediment moisture content within a 30 meter square pixel. Along the sampled transects sediment moisture content ranged from 19 to 32 percent by weight, a range in values that is an order of magnitude greater than the variation within one pixel. A relatively homogeneous playa surface with a small range of variability within the pixel square is suggested from the grid sampling results. Sampled points were therefore assumed to be representative of the sampled parameters within the entire pixel.

Field Sampling Results from Traverses

Depth to Water Measurements

The measured depth to water on the playa surface varied between 10 cm and 2 meters. An apparent similarity was found between the lateral variation in the depth-to-water measurements and the band 7 pixel values when the two data sets are plotted as a function of distance along the transect (Figure 9). Plotting the pixel values as a function of the depth to water indicates an association; increasing depth to water is related to an increase in band 7 pixel values (Figure 10). However, the relationship does not appear to hold true below a depth of water of approximately one meter. The depth to water measurements are listed in Appendix B.
Figure 9. The band 7 pixel values and corresponding depth to water measurements plotted as a function of distance along the transect. The numbers on the y axis represent two different sets of values; the pixel brightness values, and the depth to water measured in centimeters. a. west to east transect b. north to south transect. Circled points indicate where transects intersect.
Figure 10. Depth to water measurements plotted versus the band 7 pixel values (from the 1988 image) for all sampled sites.
Figure 11. The specific gravity of the brines beneath the playa as a function of distance along the (a) west-east transect and (b) north-south transect. Circled points indicate where transects intersect.
Brine Specific Gravity

The specific gravity of the brine ranged between values of 1.12 and 1.22 and is plotted as a function of distance along each transect in Figure 11. The lowest values of specific gravity brine were found at the westernmost sample sites. The values from west to east increased fairly consistently as they progressed from the playa margin toward the center, with the highest values being associated with the lowest elevation of the groundwater (as defined by Lines, 1979). Continuing eastward, past the central playa, the brine specific gravity decreased relatively consistently. Along the north to south transect, specific gravity values increased from the north to the south, reaching a high of 1.21 and then decreased slightly. Lines' sampling at one mile intervals (locations shown in Appendix F) of the total dissolved solids in the brine defined a similar pattern to that found here, as shown by the contours on Figure 6.

Comparing specific gravity values with depth-to-water measurements indicates a rough inverse relationship (Figure 12); an increase in the depth to water appears to correspond to a decrease in the specific gravity. Maximum specific gravity of the brine and minimum depths to water were found in the center of the northwest portion of the playa; the same area that showed the maximum gradients in pixel values on the remotely sensed images (as discussed later in this chapter).
Elevation measurements taken by Lines (1979) in 1976 defined a surface relief of 0.3 feet (9 cms) over the area covered by the salt crust. If a similar surface topography is assumed to be present at the time of this study, the variation in surface topography is minimal when compared the depth to water (ranging from 10 cm to 2 m).

Figure 12. The specific gravity of the playa brines plotted versus the groundwater depth at the site where they were measured for the west-east transect and the north-south transect sites.
Observed Surface Conditions

Evaporites were present in different thicknesses, spacing and crystal forms at all sample locations. Zones of thick evaporite deposits were present at sites TW-22 to TW-26, at a distance of approximately 3.5 kilometers east of the playa margin extending approximately 1.2 kilometers across. Thick evaporites were also present at sites SL-2 to SL-10, extending north to south for a length of approximately 4.5 kilometers and continuing further south from the southernmost sampled site (SL-10). A quantitative description of evaporite deposition was not derived for this study because its application was not anticipated before sampling.

Along the west to east traverse from sites TW-2 to TW-14 (distance of 1.5 kilometers) the surface was rippled, with the appearance of a carpet that had been pushed up from the surface beneath, and left in wrinkled piles. An algae layer seemed to hold the 'carpet' surface in a coherent layer. The wind may have lifted uneven edges of the algal mats and pushed them into piles when water accumulation on the playa reduced surface friction. A green algae layer was observed growing directly on the ground surface and separating it from the overlying salt crust. Algae was also observed between sites TW16-19 (600 meters distance), TW22-25 (1200 meters distance), TW32-36 (with minimal thickness and 800 meters distance), TW37-40 (1500 meters distance), NS1-9 (1600 meters distance)
distance), NS11-12 (200 meters distance).

Sediments in the subsurface were observed to be composed of clays with black sulfurous odor laminae at depths that varied between 5 and 40 cms. Subhedral gypsum crystals were present in the subsurface with diameters up to 1 cm at sites extending eastward from TW10 (located approximately 1 km from the western playa edge). Formation of gypsum crystals in the subsurface sediments was observed to continue across the playa and end at site TW47 (located about 3 km from the eastern edge of the playa).

The sediment textures encountered on the playa ranged from clay to a mixture of clay and sand. The most coarse grained sediments were found beneath the very thickest evaporite deposits in the playa center. These coarse grained shallow sediments are mostly likely to be the result of in situ gypsum precipitation, as indicated by the x-ray diffraction analyses of sampled crystals (discussed in the following section).

Results of Laboratory Analyses

**Surface Mineralogy**

The x-ray diffraction results obtained for each sample have been tabulated from the height of each diffracted peak on a relative scale from 0 to 10 as a function of the angle from which the x-rays were directed. The highest diffraction
peaks associated with halite and gypsum for each sample site were used for comparison with other data. X-ray diffraction peak values and other data sets were plotted as a function of distance along transects and compared visually. To consider a relationship that may not have been obvious upon inspection, gypsum mineral peaks were plotted versus other data sets on x-y coordinates. Gypsum peaks were chosen for comparison because peak values vary most within the samples, and consequently reflect the trend in surface mineralogy most clearly. Halite diffraction peak values were at a maximum fairly consistently (a value of 10); the calcite, quartz and sylvite values were often absent, and consistently low (less than 1.5). The results of surface and some subsurface XRD analyses are printed in Appendix C.

Approximately 70% of surface samples were essentially composed of halite with little gypsum, and less calcite, quartz or sylvite present. In two locations along the west to east traverse (shown on Figure 13a), the proportional amount of halite decreases, and the amount of gypsum increases; at locations .5 km from the western edge of the playa, extending 1.5 km across, and 6 kilometers from the edge, 2.5 km in extent. The other minerals present do not vary with the halite and gypsum ratio fluctuations. The locations where the proportional amount of halite decreases (and gypsum increases) do not appear to be related to the
Figure 13. Results of the x-ray diffraction analysis of the minerals sampled from the playa surface, plotted as a function of distance along the west-east transect (a) and north-south transect (b). The values for each sample are the highest diffraction peak of each mineral in the sample. Plots showing relationships between x-ray diffraction results and other data sampled are included in Appendix D.
amount of evaporites deposited at the surface or any other parameter measured for this study. (See plots of gypsum diffraction peaks versus other sampled parameters in Appendix D). Increases in gypsum content did correspond with the absence of the algal layer observed at the surface. These algal layers may be using the sulfur necessary to form gypsum (calcium sulfate) and thereby preventing gypsum formation where the algal mats are present. Subsurface sulfurous layers may be records of previous algal mats, suggesting the use of sulfur by the algae. These sulfurous layers were observed in the playa sediments of New Mexico and Texas to be associated with the presence of algal layers by Hussain and Warren (1985).

**Soil Moisture Content Determinations**

Soil moisture content was determined to vary between 20% and 32% by weight in all samples analyzed.

Comparison of the soil moisture content with the measured depth to water indicates a weak inverse relationship (plotted in Figure 14); an increase in the depth of groundwater below the surface generally corresponds to a decrease in the moisture content of sediments sampled at the surface. Figures 14 and 15 indicate that an increase in the band 7 pixel values appears to correspond to an increase in the depth of water below the surface. These results together
Figure 14. Depth of water measured from the playa surface plotted with respect to the moisture content of soil sediments measured at the same site along both traverses suggest a weak inverse relationship.
Figure 15. Plot of band 7 pixel values versus the soil moisture content of that site for the west-east transect shows little relationship between soil moisture and the values recorded by the satellite sensor. However, when the band 7 pixel values are plotted with the moisture content determinations (Figure 15) a distinct relationship between the band 7 data and the soil moisture is not evident; little connection between moisture content of sediments in the shallow subsurface and the band 7 pixel values is shown. If the sampled area had been larger in areal extent, including the margins of the alluvial fan, the larger
data set might have shown whether a relationship exists between sediment moisture content and band 7 sensor response.

How are the band 7 pixel values, a record of the infrared radiation reflected from the playa surface, related to the depth of water below the surface? The effect of the distance between the groundwater surface and the playa surface on the communication of moisture to the playa surface would be expected to be evidenced in the moisture content of the sediments through which the moisture is transported. The sediment moisture content would then be expected to influence the reflectance of infrared radiation (that wavelength radiation being particularly well absorbed by water) from the ground surface. Without a demonstrated relationship between moisture content and band 7 data, it remains to identify another substance, or process influencing the reflectance of infrared radiation from the ground surface. The only other substance between the groundwater and the atmosphere (besides the sediments) is the salt crust deposited at the playa surface. The reflectance character of the salt must somehow be influenced by the depth of water below the surface. The possible mechanisms by which this may occur are examined in the next section.
Remotely Sensed Images

The images used for analysis are presented here in three sets. Composite images showing the overall changes at the playa surface in both the visible band 2 (0.52-.60 μm) and the infrared bands 4 and 5 (0.79-.90 μm and 1.55-1.75 μm, respectively) are shown in Figure 16 for each of the three images (1984, 1985, and 1988). The spectral bands used for the composite images were chosen to show the playa surface and surroundings with colors closest to those actually present, while still emphasizing the variations at the playa surface. The yellow colored area represents evaporite deposition at the playa surface. The orange color indicates standing water, the grey and white areas are playa surface that has a thin or absent salt layer. The blue-purple color indicates vegetation on the mountains and alluvial fans surrounding the playa. On the left margin of the playa is a ranch with fields that are being irrigated (green and white patches).

The visible bands (1 .45-.52 μm, 2 .52-.60 μm, and 3 .63-.69 μm) from each image were combined to construct the images shown in Figure 17. Observations made during surface sampling (described in the Field Sampling Results from Traverse section) of evaporite areal extent and thickness
Figure 16. Composite images of the Pilot Valley Playa recorded (a) July 28, 1984, (b) July 3, 1985 and (c) August 14, 1988 showing bands 2 (.52-.60 /m), 4 (.79-.90 /m) and 5 (1.55-1.79 /m) of TM data.
Figure 17. Visible wavelength bands 1 (.45-.52 μm), 2 (.52-.60 μm) and 3 (.63-.69 μm) are combined to construct images of (a) July 28, 1984, (b) July 3, 1985, and (c) August 14, 1988. Visible wavelength radiation reflection is influenced by the presence of evaporites on the playa surface. Evaporite deposits are interpreted to have decreased in areal extent over the period these images were recorded.
indicate that areas of higher pixel values in the visible wavebands correspond to locations of thick evaporite deposition. These are located between sample site TW22 to TW29 and SL2 to SL10, and have band 2 pixel values of 160 to 220. Plots of the band 2 pixel values along the sampled traverses are shown in Figure 18. Greater reflectance by halite, gypsum and calcite of visible wavelength radiation suggests that reflectance in the band 2 waveband from the playa surface is dominated by evaporite minerals. Clay minerals, also present at the playa surface show weaker reflectance capabilities in the visible range (Sabins, 1987). The presence of a thick evaporite crust is not demarcated by a line, but grades over a distance of what probably corresponds to several pixels, so that a distinct border is difficult to define. The observed evaporite deposits appear to correspond well with increases in the band 2 pixel values, although a quantitative comparison was not made.

Other features of the playa surface, that were not observed for this study, may also be influencing the reflectance of visible wavelength radiation. The size of evaporite crystals, and the density of the evaporite crust may influence spectral reflectance of visible light. Spectral reflectance of visible wavelength radiation at those locations where evaporites are not present may be influenced by the moisture content or other properties of the underlying
Figure 18. The band 2 (0.52-0.60 μm) pixel values for the (a) north-south transect and the (b) west-east transect are plotted as a function of distance along the transect.
sediments.

If the three images constructed from visible bands are interpreted with respect to evaporite deposition, a progressive decrease in the areal extent of the salt crust can be inferred. The northwest portion of the playa (where the transects intersect) shows the most distinct variation with respect to the visible wavelength radiation, suggesting that processes influencing evaporite deposition are more active here.

When the band 2 pixel values were compared with associated values for depth to water, soil moisture content, XRD mineral diffraction peaks, and brine specific gravity a relationship was not defined. Plots indicating the lack of correlation between these various parameters and the band 2 data are included in appendix D.

Band 7 (2.08-2.35 μm wavelength) pixel values were used to construct the images from which the variation of infrared radiation reflectance were interpreted (shown in Figure 19). This waveband is absorbed by water more readily than other infrared wavebands recorded by the Thematic Mapper Satellite, and variation in pixel values was expected to correspond to changes in moisture at the playa surface. The band 7 pixel values were observed to relate to the depth of groundwater below the playa surface (Figures 9 and 10), although a correspondence between the moisture content of sediments
Figure 19. Infrared wavelength band 7 (1.98-2.12 μm) of images from (a) July 28, 1984, (b) July 3, 1985 and (c) August 14, 1988.
present at the playa surface and the band 7 pixel values was not found (see the previous discussion in the Soil Moisture Content Determination section).

The concept of a connection between the depth to water, band 7 pixel values and the evaporite crust was introduced in the previous section on soil moisture contents (page 65). Comparing the band 2 (Figure 17) and band 7 (Figure 19) images indicates that areas of low infrared reflectance or small pixel values (inferred to be areas of shallow groundwater depth) are of similar areal distribution to those areas interpreted to have a thick evaporite crust (the brightest areas on Figure 17). A relationship between evaporites and depth to water may be caused by the capacity of evaporite minerals to absorb moisture. The proximity of the groundwater surface to the playa controls the rate at which water is transported to and evaporated from the playa surface. A shallow groundwater depth causing increased evaporation would result in the deposition of a greater volume of precipitates, in addition to making more water available for absorption by the evaporites. The increased amount of evaporites (expressed as a thicker crust) present at the surface would retain a proportionally greater volume of water. The larger volume of water would be expressed in the band 7 images as a decrease in the spectral reflectance at that location.
Difference Images

Difference images were constructed to aid in the interpretation of playa surface variation over time. Three visible difference images were constructed from the band 2 data and three infrared difference images were constructed from the band 7 data for each combination of the two possible image sets (i.e., 1984 to 1985, 1985 to 1988, and 1984 to 1988). Relationships observed between sampled data and image pixel values suggest that band 2 difference images may be used to examine evaporite deposition, and band 7 images be used to interpret changes in the depth to water.

The visible waveband images shown in Figure 17 indicate a progressive decrease in the number of bright valued pixels (values of approximately 160 to 220 for band 2), interpreted to correspond to decreased evaporite deposition at the playa surface over time. The difference images (Figure 20) show a predominance of green to red colors, indicating a decrease in pixel brightness values over the period between the recording of the first and second image. The red areas, corresponding to the highest pixel difference value (230-255) are the areas where evaporite deposition has decreased most significantly. The black, purple and blue colors, which represent a negative difference value, indicate areas that the reflectance of visible light from the playa has increased
The difference maps show the changes over the period between when images are recorded for (a) 1984-1987, (b) 1985-1988 and (c) 1984-1988 in the visible band 2 wavelength. A black, purple or navy color indicates negative changes, green-red color indicates positive changes, and white color indicates no change (see table on page 49).
over the period between the recording of the two images. This is interpreted to be the result of increased evaporite deposition on the playa at this location. The white color indicates no change between the pixel values of the two images, or no variation in the evaporite deposition.

The relationship observed between the depth to water measurements and the band 7 data (see Figures 9 and 10) is used to interpret the band 7 difference images (Figure 21). The colors on the difference images suggest a relative change in the groundwater level. Negative difference values, corresponding to the black, purple, navy and royal blue colors, are interpreted to be caused by a progressive drop in the groundwater level over the period between the recording of the first and second images. The positive values (green to red colors) indicate a progressive rise in the groundwater level. More specifically: a rise in the groundwater level correlates with a decrease in the pixel value of the same location. A progressive increase in the groundwater level (decrease in pixel value) would result in a positive difference when the two were compared, and an association with the green to red colors. A larger increase in the water level results in a larger difference value, with the red areas representing the greatest increase in groundwater surface elevation.

How do the depths to water measured for this study and
The difference maps show the changes over the period between when images are recorded for (a) 1984-1985-1988 and (c) 1984-1988 in the infrared band length. A black, purple or navy color indicates changes, green-red color indicates positive changes, and blue color indicates no change (see Table on page 49).
those interpreted from the band 7 pixel values compare with the depth to water measurements made for previous studies; i.e., those of Lines (1979), and Nolan (1927)? Nolan and Lines both measured the depth to water along the Township lines in the north and south parts of the Pilot Valley Playa (shown in Appendix F). The north Township line (dividing T4N from T5N) measurements were made at a similar location as the west to east traverse for this study. The depths measured by Lines and Nolan are plotted with the groundwater levels estimated from the remotely sensed images for the same locations (Figure 22). Estimates were made using a linear regression equation derived from the groundwater level measurements taken and the satellite band 7 pixel values for the corresponding locations. The equation derived by linear regression was:

$$DTW = 0.57(B7) - 1.46$$

(DTW in centimeters) with an $R^2$ value of 0.569.

The groundwater level comparison shown in Figure 22 suggests that depth to water estimates from the Remotely Sensed data give values that are similar to the depth to water measurements made by others. The difference between Nolan's data and Lines' data (and estimates made for this study) is the result of a difference in the amount of precipitation the basin received over approximately a decade prior to the recording of the depth to water measurements by
Figure 22. Depth to water measurements made along the north traverse of the Pilot Valley by Lines (1979), Nolan (1927) compared with estimates made from the remotely sensed band 7 data from 1984, 1985 and 1988.

Lines and Nolan. Between 1910 and 1924 the average annual precipitation was 11.73 cms (4.62 inches). Between 1952 and 1974 (prior to Lines study) the average annual precipitation was 14.50 cms (5.71 inches).

Overall it may be interpreted from the band 7 difference images that the groundwater level changes are most pronounced around the playa margins, and that in these areas the groundwater level dropped between 1984 and 1985, and rose
between 1985 and 1988. The groundwater level in the central playa remained relatively constant over the study period, as shown by the white color on Figure 21. Differences in the band 7 data may be grouped into three distinct zones which correspond to the easternmost edge of the playa, the central area, and the westernmost portion of the playa. These zones may be observed on the band 2 difference maps also. However, the changes that occur in the band 7 data are of different magnitudes than those changes in the band 2 data. When the two waveband pixel values were compared on a x-y plot, a relationship was not defined (the plot is included in Appendix D). The presence of a variety of surficial deposits, having different spectral reflectance properties, makes a correspondence between the band 7 and band 2 pixel values along the two transects difficult to define.
DISCUSSION

This discussion integrates the connections found between the various data sets collected over the course of this study. The potential of the different playa surface parameters to influence each other is examined in the context of the processes discussed in the introduction. These processes are synthesized to reinterpret the hydrologic system in light of previously collected data, and previously proposed models of the hydrologic system.

Relationships Found In This Study

Density, Depth to Water and Evaporite Deposition

The data gathered over the course of this study show that brine density increases with decreased depth to water (Figure 12). This finding suggests that an increase in the subsurface brine concentration may be caused by its proximity to the playa surface, or that the brine itself causes the surface elevation of the playa above it to decrease (by enhancing the erosion of the overlying sediments).

Brine density may be influenced by the groundwater depth from the playa surface because of the effect that depth to water has on the evaporation rate. A brine of higher density would accumulate in groundwater nearer to the playa surface. Bowler (1986) suggests the brine concentration configuration
shown in Figure 5 evolved by this mechanism. In addition, a thicker mineral precipitate would be deposited at the playa surface above where the evaporation rate is elevated. A thicker mineral crust is interpreted to overly areas of high brine density from the visible waveband remotely sensed images (Figure 17).

Lines (1979) found the location of highest brine density in the Pilot Valley Playa (at the northwest portion of the playa, where the sampled transects cross for this study) to coincide with the lowest elevation of the groundwater surface. He attributed this to the gravitational force acting on the higher density brine causing a decrease in the groundwater surface elevation.

A higher density brine, and the associated decrease in the groundwater surface elevation observed by Lines, gives the relatively drier overlying sediments a greater susceptibility to wind deflation. In addition, a higher density brine may be associated with an increase in mineral precipitation within the soil matrix. Bowler (1986) suggests that minerals precipitated within the soil-sediment matrix disturb the integrity of that matrix making it more susceptible to wind deflation. With increased erosion the volume of the overlying sediments gradually decreases and the ground surface elevation above the higher density brine drops. If this process continued over time a huge "hole"
would erode into the playa surface; a feature not observed during this study, or by any previous workers. Evaporation eventually concentrates the brine to a high enough density that the evaporative process is restricted. The evaporation rate is effectively "capped" at a high enough brine concentration and the associated erosion from the playa surface limited.

Surface elevation data for the Pilot Valley Playa is not available to support or contest the effects of wind deflation in areas overlying high density brine. Lines (1979) did observe that the surface elevation of the northwest portion of the playa varied by less than 10 cms (0.3 feet), and that the elevation of the remaining playa varies between 4,241 and 4,260 feet (1,305 and 1310 meters). Lines also measured the most shallow depth to water to be in the northwest portion of the playa (Figure 23), coinciding with the results of this study. The fact that higher density brines were found to be closer to the playa surface, and that the highest density brines are also found at the lowest groundwater elevation suggests that brine density is associated with a lower surface elevation. Evidence of a drop in the surface elevation at the northwest poriton or the playa may be taken from the fact that this portion of the playa corresponds to the location at which water ponding is interpreted from the 1984 remotely sensed image (Figure 16). Water may have
accumulated on the northwestern playa because of its lower elevation. It is equally possible that water transported by wind across the playa was left at the western playa margin because the wind velocity decreased upon encountering the topographic rise at the playa margin. The ensuing decrease in its sediment and moisture load capacity would result in the formation of a pond.

The mountain peaks of the Pilot Range attain their highest elevation directly west of where the sampled transects intersect. Conceivably, a larger volume of water discharges from these peaks to the adjacent basin. The larger volume of water moving through mountain slopes would
bring to the adjoining basin a larger volume of minerals to accumulate there. Initially a groundwater level depression in the northwest portion of the playa may have been caused by the high quantity of minerals in the groundwater accumulated from the greater discharge volume. Increased playa susceptibility to erosion and deflation due to the lower groundwater level would have eventually decreased the surface elevation. A lower ground surface, decreasing the distance between the land surface and the groundwater surface, would cause an increase in the evaporation potential, the brine concentration, and the mineral precipitation at the surface. A consequent correspondence between lower groundwater elevation and higher density brine may have been thereby established.

Influences on Band 7 Spectral Response

The evaporation rate dependence upon the depth of water from the surface may be used to explain the positive relationship found between band 7 pixel values and the depth to water measurements. A greater evaporation rate (resulting from a shallow groundwater surface) is likely to first increase capillary movement of water to the playa surface (Hillel, 1971) and second increase evaporite deposition there. The unique properties of evaporite minerals may contribute to the enhanced surface expression of subsurface
moisture content and moisture transport. Evaporite minerals have a greater affinity for dissolution in water, due to their high ionization potentials, than subsurface sediments; as evidenced by the precipitation mechanism by which they are deposited. Accordingly, these minerals also possess a greater potential to react with water and absorb moisture than sediments do. A greater evaporite sensitivity to the distance at which water is available for absorption would result from the minerals' enhanced capability for moisture absorption. Surface expression of the depth to water would then be a consequence of the evaporites' (present on the playa surface) sensitivity to water available for absorption, the distance of that water from the evaporites and the corresponding rate of subsurface capillary moisture transport by the evaporative process (a function of the distance of that water from the surface evaporites). A correspondence between areas of thick evaporite deposition (indicated by brighter visible waveband pixel values shown in Figure 17) and areas of high surface moisture content (indicated by the darker band 7 pixel values shown on Figure 19) is evident if Figures 17 and 19 are compared.

Although a general relationship between shallow sediment moisture content and depth to groundwater was defined (Figure 14), a connection between moisture content and the band 7 pixel values (Figure 15) was ambiguous. The band 7
relationship to depth to water is more likely to have been influenced by the moisture content of surface evaporites than the sediment moisture content because evaporites are deposited above the sediments. This relationship could be better defined if the moisture content of the evaporites was compared with the depth to water measurements. However, evaporite moisture contents were not determined for this study.

If band 7 pixel response is defined by the moisture content of the playa evaporites at the surface, then the processes which might obscure the evaporites from the view of the satellite sensor must be examined. Wind speed is high on the Pilot Valley Playa, capable of transporting a large enough volume of sediment to blanket playa evaporites. Wind may also be capable of transporting precipitated evaporite crystals from the playa surface, exposing the underlying sediments. Although the energy of the wind is certainly capable of transporting sediments to and from the playa surface, the flat topography of the playa surface does not offer the wind resistance necessary to cause deposition of entrained sediments. The flat topography may also be why minimal transport of evaporites from the playa surface occurs. In addition to the chemical bonds between salt crystals, the wind resistance of a flat playa is not likely to be enough to allow the salt crystals to be broken off and
Entrained.

Evaporites may possibly be hidden from surface view by physical mixing with the underlying sediments if a churning process occurred at the playa surface. However, a physical process that would supply the magnitude of energy required to churn up an area the size of the Pilot Valley Playa would be cataclysmic, and unlikely to occur on a time scale frequent enough to influence observations done on an annual time scale. Evaporite "sheets" or carpets appeared to have been piled and corrugated near the playa margin; attributed to wind disruption of algal mats formed at the interface between the evaporites and sediments. However, sediments and evaporites were not mixed together as a result of this phenomena.

An increase in the moisture present at the playa surface may allow evaporites to dissolve and infiltrate into the subsurface brine. Lines (1979) has suggested that the difference in the areal extent of evaporite deposition on the Pilot Valley Playa observed by him and by Nolan (1927) was due to an increase in the average precipitation received by the basin over a 14 year period prior to their observations. The associated increase in moisture content caused the dissolution and infiltration of previously deposited evaporites. Both Lines and Nolan suggested that cycles of deposition that occur on different time scales on playas of
the Basin and Range Province. During the winter months the decrease in the evaporation rate allows the accumulation of moisture at the playa surface and dissolution of evaporites. With the warmer weather of spring and summer the playa surface is covered with evaporite crystals. Of the processes listed, this one is the most likely to obscure evaporites from the view of a remote sensor.

**Groundwater Level Fluctuations**

Although depth to water measurements were found to correlate with band 7 pixel values in the northern playa region; in the southern region a similar relationship was not observed. The depth to water estimates from band 7 data along the north traverse fall within the range of those depth to water measurements taken by previous workers (Lines, 1979; Nolan, 1927), as shown on Figure 22. Depth to water measurements made over the course of the Lines study (Figure 23) show a similar trend to those taken for this study (Figure 9). The depths to water in June of 1977, 1978, and 1979 show a similar pattern; the water level rises to within a foot of the surface over a distance of two miles from the western playa margin and drops again to the east. Those measurements taken in October of 1977, 1978 and 1988 also show a similar pattern. The water level is relatively constant to a distance of approximately four miles east
across the playa and progressively decreases from there to a distance of eight miles. The water level in 1988 (shown on Figure 9) is consistently more shallow than in the late 1970s.

Estimates from band 7 pixel values of depth to water in the southern region of the playa do not fall within the same range, nor do they have a similar pattern as those previously measured groundwater depths. Lines measured comparable depths to water in the northern and southern portions of the playa. Figure 24 shows measurements taken by Lines and Nolan along the southern Township line, and by the author (in October of 1988). Figure 24 also shows estimates of groundwater depths for 1984, 1985 and 1988 from the remotely sensed images using the linear regression equation previously defined (in Results chapter). The fact that all three of depth to water estimates from the remotely sensed image data appear to be inaccurate supports the interpretation that below a depth of approximately one meter relative depth to water is not expressed at the surface.

Temporal Changes at the Playa Surface

Difference images constructed from the band 2 pixel values (Figure 20) suggest that the areal extent of evaporite deposition in the northwest area of the playa has decreased from 1984 to 1988. Interpretation of the band 7 difference
Figure 24. (a) Estimates of depth to water along the south traverse made from the remotely sensed image band 7 data. (b) Depth to water measurements taken along the southern traverse by Lines (1979), Nolan (1927) and in the fall of 1988.
images (Figure 21) with respect to the groundwater levels for the same period indicates a relative increase in the depth to water (or decrease in the water level elevation) around the playa margins, followed by a relative decrease in the depth to water. Overall, interpretation of the band 7 difference images suggests that between 1984 and 1988 there was a relative drop in the groundwater level around the playa margins, with a fairly constant water level at the center of the playa. Considered together, the band 2 and band 7 difference images suggest that a decrease in surface evaporite deposition is associated with an increase in depth to water.

The relationship observed between brine density and the depth to water suggests that surface evaporite deposition is influenced by the density of the subsurface brine pool, in addition to the depth to water. There is a dynamic interplay between the amount of minerals available in solution, the rate at which the solution is evaporated, and minerals deposited at the surface. The optimum conditions for evaporite mineral deposition at the playa surface appear to be a combination of a brine specific gravity of approximately 1.2 and a depth to water of at least 30 centimeters, but not more than 50 centimeters. When the water level drops below this depth, not only does the evaporation rate decrease, but the associated decrease in the moisture content of the
evaporites may increase evaporite susceptibility to wind transport.

From the visible and infrared 1984 to 1988 satellite images a distinct change in the northwest area of the playa in particular was interpreted. The "hole" developing in the evaporite deposition (Figures 17 and 20) corresponds to an increase in band 7 pixel values (Figure 19) in the same area. Assuming a relationship between evaporite moisture content, groundwater level and band 7 satellite data is valid here, there are two possible mechanisms to explain the development of the "hole." An increase in the depth to water in this area would allow more erosion and deflation (as previously discussed), or the enlarged distance between the water level and the ground surface would cause a decrease in surface evaporite deposition. Increased erosion and deflation are likely to result from a decrease in the groundwater level elevation and the consequent decrease in capillary forces binding the lower moisture content sediments. In addition, the smaller amount of mineral precipitate present at the playa surface would absorb a smaller amount of moisture, and contribute to a reduced expression of groundwater depth at the surface. Measurements taken by Donohue and Oliver indicate that the water level in the southern portion of the playa has steadily decreased between 1986 and 1988 (Doug Oliver, oral communication), supporting the interpretation
of the influence of water level decline on diminished evaporite presence.

Lines (1979) observed a difference in mapped areal extent of evaporite deposits between 1925 (Nolan, 1927) and 1977. Nolan recorded an evaporite deposit of 22 miles$^2$ (56.3 km$^2$), while Lines observed 7 mi$^2$ (17.92 km$^2$). Lines considers the higher water level in 1925 to have dissolved the minerals deposited on the surface at that time. His interpretation together with the findings of this study suggest that evaporite deposition occurs at an optimum water depth and brine density; further evidence of a dynamic system in which brine density, water level and surface deposition interact.

The groundwater depths measured at the northwest portion of the playa were not significantly different than those at locations measured further east or south in 1988. The question remains: why would this location be subject to a more distinct change in water level, and how is it related to the decrease in surface evaporite deposits? To explain the "hole" in the evaporite deposits will require the effects of brine density and the mechanism for surface expression of water level to be examined further; as well as examining parameters not measured for this study.
Model Interpretation

The differences between images shown in Figures 17, 19, 20, and 21 suggest that there are three distinct zones over which changes occur at the playa surface. The first is the area covered by the thick evaporite deposits along the northwestern and central portions of the playa. The band 7 difference images (Figure 21) show this area as predominantly white, with patches of royal blue and dark green. These colors suggest small variations in the interpreted depth to water, or surface evaporite moisture content, over the study period. The second zone is a narrow strip along the western margin of the playa which broadens at the southern portion of the study area. The band 7 values increase in this zone between 1984 and 1985, and decrease from 1985 to 1988. The third zone is the area east of the thick evaporite deposits which extends north and south to the east of the Silver Island Range. The changes in the band 7 data in this zone are similar to those in the second zone.

These three zones suggest the influence of three different hydrologic regimes. The thicker evaporite deposits which characterize the elongate round-shaped central zone indicate the presence of a subsurface mineral source, that of a high density brine pool. This central zone may be isolated from direct discharge from either of the surrounding ranges by the high density brine pool directly underlying it.
The narrow strip along the western margin is characterized by a more shallow groundwater level than the rest of the playa. A large proportion of the water which discharges from the Pilot Range surfaces as springs along this western playa margin (Stephens and Hood, 1973). The narrow shape of this discharge zone may be influenced by the high density brine pool directly east of it. The high concentration brine with its stable groundwater level (as interpreted from the band 7 difference images in Figure 21) may impede subsurface transport of the discharge released from the Pilot Range. In effect the discharge is trapped and forced to the surface either by the wedge shaped brine pool shown in Figure 4, decreases in the hydraulic conductivity caused by lacustrine sediments along the playa margin, or an inflection point caused by the change in slope from the alluvial fans to the playa floor. The result is the narrow shape of this zone and a large discharge volume along the western margin.

The depth to water at the northwestern playa margin was measured to be the largest of any along the two playa transects. Between 1984 and 1985 the water level at the western margin was interpreted to decrease from the difference image shown in Figure 21a. A slight rise in the groundwater level is interpreted between 1985 and 1988 from Figure 21b. D. Oliver and D. Donohue (D. Oliver, oral communication) have measured a water level decrease over the
period between 1986 and 1988, suggesting that either the interpretation made from the difference image is inaccurate, or that the water level rose in 1985 or 1986 before subsequently dropping.

The eastern and southern playa areas are characterized by thinner evaporite deposits and may reflect the influence of the Silver Island Range. Its lower elevation attracts less precipitation and consequently releases less discharge. The smaller volume of water moving through its hydrologic system is likely to dissolve and transport proportionally less minerals to the playa surface. Simulations of an asymmetric closed basin (a basin surrounded by mountain ranges of different elevation) done by McCleary (1989) suggest a wider discharge zone develops adjacent to the range with lower elevation. The depth to water measurements made during this study and by Lines (1979) and Nolan (1927) are greater at the eastern portion of the playa than the west also suggesting a lower volume of discharge to the east. Interpretation of the band 7 difference images suggests lower groundwater elevations and higher variability in groundwater levels at the eastern playa margin than the western playa. The interpreted variations in the groundwater level from the band 7 data of the remotely sensed images suggest that the water level is influenced by differences in the volume of discharge. However, the depth to water rendering from the
band 7 data is likely to be subject to other factors, whose influence is yet undetermined.

Both the brine density and depth to water showed a similar trend: a general increase in the brine density and decrease in the depth to water progressing from the playa edge toward the center, followed by the opposite trend toward the other end of the playa. This brine density configuration, also found by Lines (1979), is suggested by Bowler (1986) to be the result of diffusion from a brine pool accumulated at the playa center. The interpreted groundwater level of this pool appears to vary most at the "hole" discussed previously, indicating that brine density is likely to be related to the relative elevation of the groundwater surface and communication of brine with the playa surface.

Variation in brine density may well be a factor controlling the deposition of surface evaporites, suggesting that the evaporite minerals are a surface expression of brine pool variations. The measured decrease in water level between 1986 and 1988 (D. Oliver, oral communication) along the playa margins may then indicate an overall decrease in the extent of the subsurface brine pool.
CONCLUSIONS

The objectives of this study were to determine whether a relationship could be defined between remotely sensed image data and sampled surface parameters. From that determination remotely sensed images were examined as a valid data source for playa study and, if found to be so, interpretations about spatial and temporal variability of the Pilot Valley Playa would be made.

Image data was found to relate to the areal distribution of evaporite deposits and the depth of water beneath the playa. Reflection of visible wavelength radiation from the playa was found to be dominated by evaporite mineral deposits; high pixel values in the visible wavebands corresponded to zones of thick evaporite deposition. A relationship between the depth to water beneath the playa surface and the band 7 (1.98-2.12 μm wavelength) image data was interpreted to result from the effect that the depth of water from the surface has on the moisture content of the evaporite minerals deposited on the surface. The relationship did not hold for the southern part of the Pilot Valley Playa, possibly because the depth of water below the playa surface was enough to impede surface expression of its position.

To evaluate the changes on the Pilot Valley Playa
surface, remotely sensed images recorded in 1984, 1985 and 1988 were compared. It was inferred that the areal extent of evaporite deposition had decreased over the study period and the depth to water had generally increased. The depth to water is interpreted to have decreased between 1984 and 1985, and increased from 1985 to 1988. These changes appeared to be concentrated at the playa margins, while the water level beneath the central portion of playa is interpreted to have remained relatively constant. Measurements taken by Oliver and Donohue (D. Oliver, oral communication) indicate that water levels had been progressively decreasing between 1986 and 1988 beneath the Pilot Valley Playa. Possible explanations for this discrepancy are that the interpretation made from the images is inaccurate, that the measured location was not representative of the larger playa region, or that the water level rose in 1985 or 1986 before subsequently dropping.

If the variations in the interpreted water levels at the playa margins are attributed to the influence of discharge from the adjacent range, the spatial extent of the active discharge zone can be interpreted from the remotely sensed images. That the interpreted depth to water changes were most distinctive at the playa margins suggests that water depths there are more directly influenced by the discharge from the adjacent ranges, and by plant transpiration. The
discharge zone interpreted in the area west of the Silver Island Range appears to be wider in areal extent on the images (Figures 21 and 22) than that of the Pilot Range on the opposite side of the valley. A similar configuration of discharge zones in an asymmetric closed basin was defined from computer simulations done by McCleary (1989). The brine underlying the central playa appears to be relatively isolated from the influences of discharge from the surrounding mountains. The brine may act as a barrier to subsurface discharge to the central playa; as indicated by the formation of springs at the playa margins, and the interpreted groundwater level variations.

The specific gravity of the subsurface brine was found to decrease with increased depths of water below the playa surface. A general pattern of increased brine concentration and shallower water levels toward the playa center was observed, similar to observations made by Lines (1979). Lines determined the highest concentration brine to be associated with the northwest portion of the playa where water depth was measured to be most shallow for this study.

Areas of thickest salt deposition were found to be related to subsurface brine specific gravities of 1.2 or greater. A relationship between shallow groundwater levels, high density brine and evaporite deposition was indicated. An explanation for this relationship is that as the water
level becomes more shallow the evaporation potential increases. With increased evaporation the total dissolved solids accumulating in the remaining solution increases. Eventually, with a high enough concentration minerals are precipitated at the playa surface.

If a relationship between the changes interpreted from the band 2 and band 7 data, and the observed depth to water, specific gravity and evaporite deposition process is assumed to be valid, then the decrease in the areal extent of the evaporite deposits can be attributed to the increase in the depth to water at the playa margins. Decreasing evaporite deposition at the playa surface may potentially indicate a decrease in the subsurface areal extent or specific gravity of the brine pool.

Remotely sensed images are particularly useful for study of playa hydrology because the basin discharges through the playa surface. In addition, spatial variation in the sediment and evaporite moisture content, evaporite deposits and depth to water are expressed at the playa surface and are evident in remotely sensed images. Interpretation of these features is facilitated by the lack of vegetation on the playa surface.
RECOMMENDATIONS FOR FURTHER STUDY

The objective of this study was to relate sampled data from a playa surface to remotely sensed images, and determine the validity of using that relationship to interpret different images. The results suggest that relationships do exist, but work remains to define them in detail. To do this a more extensive surface sampling program is necessary, done in conjunction with image recording. Recommended parameters for sampling, in addition to those taken for this study, are: evaporite moisture content, sediment mineralogy and particle size, hydraulic conductivity of shallow subsurface sediments as well as a quantitative description of the areal extent of evaporite deposits.

The most distinct variation of the playa surface was interpreted to be along the playa margins. However, minimal sampling was done at these locations for this study. Depth to water measurements along the playa margin over time used in conjunction with precipitation records and remotely sensed images recorded concurrently would help define how discharge is expressed at the playa surface. This data could be used to examine the interaction between discharge from the playa margin and through the subsurface brine.

The relationship between brine concentration, its subsurface extent, the depth to water and the surface
evaporite deposition could be used to examine the influence of the subsurface brine on the pattern of evaporite deposition at the surface. Study of the geochemical properties of the subsurface brine and the surface evaporites may allow a better definition of the evaporation and deposition processes influencing whether minerals are present in solid or dissolved states.

One limitation of this study was that sampling of the surface parameters was limited to one day. To better understand the temporal variation at the playa surface, sampling should be repeated over an extended time period. In addition, multiple remotely sensed images should be examined from dates as close together as possible with respect to the repeated sampling results. This would facilitate a definition of temporal surface change within a time frame of weeks or months which would help define the active processes at the surface. Sampling in conjunction with more than one image recording would also help define the accuracy of interpreted relationships between surface parameters and image data.

Defining the effects of seasonal variations on the playa surface, as well as changes occurring on an annual basis and over longer time frames, using some of the techniques suggested, would aid in interpreting the influence of the hydrologic system on the surface characteristics of the
playa.
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APPENDICES
APPENDIX A

Precipitation data recorded at Wendover, Utah; monthly between 1935 and 1988.
APPENDIX B

Table of sample site numbers, distances between sites, depth to water measurements, moisture content determinations, and specific gravity of brine.
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**tw-42**
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- 36.5 1 qtz (low)

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**tw-44**
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**tw-45**
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APPENDIX D

Plots of relationships between sampled data, and remotely sensed image data with $R^2$ correlation values of 1 or less
BAND 7 PIXEL VALUES VS SPECIFIC GRAVITY

Pilot Valley West-East Traverse

BAND 2 PIXEL VALUES VS SPECIFIC GRAVITY

Pilot Valley West-East Traverse
BAND 2 VRS BAND 7 PIXEL VALUES

Plot Valley North-South Traverse

Band 2 pixel values vs Band 7 pixel values.
APPENDIX E

Ground control points used to geometrically correct remotely sensed images.
Ground control points used for Geometric rectification:

July 28, 1984, Thematic Mapper Image, Path 39, Row 32,

Pixels numbered: (x) 1300 to 2500, (y) 1 to 750.

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July 3, 1985, Thematic Mapper Image, Path 39, Row 32, Pixels numbered: (x) 1200 to 2400, (y) 2 to 750.

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August 14, 1988 Thematic Mapper Image, Path 39, Row 32,
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