UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Landsat investigations of the northern Paradox basin, Utah and Colorado: implications for radioactive waste emplacement

Part 1. Lineaments and alignments

by

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Abstract

The first stages of a remote-sensing project on the Paradox basin, part of the USGS (U.S. Geological Survey) radioactive waste-emplacement program, consisted of a review and selection of the best available satellite scanner images to use in geomorphologic and tectonic investigations of the region. High-quality Landsat images in several spectral bands (E-2260-17124 and E-5165-17030), taken under low sun angle October 9 and 10, 1975, were processed via computer for planimetric rectification, histogram analysis, linear transformation of radiance values, and edge enhancement. A lineament map of the northern Paradox basin was subsequently compiled at 1:400,000 using the enhanced Landsat base. Numerous previously unmapped northeast-trending lineaments between the Green River and Yellowcat dome; confirmatory detail on the structural control of major segments of the Colorado, Gunnison, and Dolores Rivers; and new evidence for late Phanerozoic reactivation of Precambrian basement structures are among the new contributions to the tectonics of the region. Lineament trends appear to be compatible with the postulated Colorado lineament zone, with geophysical potential-field anomalies, and with a northeast-trending basement fault pattern. Combined Landsat, geologic, and geophysical field evidence for this interpretation includes the sinuousity of the composite Salt Valley anticline, the transection of the Moab-Spanish Valley anticline on its southeastern end by northeast-striking faults, and possible transection (?) of the Moab diapir. Similarly, northeast-trending lineaments in Cottonwood Canyon and elsewhere are interpreted as manifestations of structures associated

with northeasterly trends in the magnetic and gravity fields of the La Sal Mountains region. Other long northwesterly lineaments near the western termination of the Ryan Creek fault zone may be associated with the fault zone separating the Uncompahgre horst uplift from the Paradox basin.

Implications of the present investigation for a potential radioactive waste-emplacement site in Salt Valley include confirmation of lack of permanent surface drainage and absence of agricultural or other development in the area of northern Salt Valley. On the other hand, the existence of diapirism, salt-karst landforms, and extensive lineamentation of the northern Paradox basin suggest regional tectonic instability at least in the geologic past. Future reactivation of diapiric or other halokinetic processes, including lateral flow, would lead to plastic behavior of the halite that might cause emplaced waste containers to migrate within the diapir. At Salt Valley, existing diapiric boundary faults and intersecting joint sets in sandstone units on the anticlinal flanks could, if the hydraulic gradient is suitable, provide conduits to the halite core for circulating ground water from adjacent Mesozoic sandstones in synclinal areas between the salt diapirs. Moreover, the loci of major lineament intersections might be areas of somewhat elevated seismic risk. If the salt barrier of Salt Valley anticline should fail in the future, potentially water-bearing Mesozoic fissile shales and friable to quartzitic sandstones would be the ultimate repository of the emplaced radioactive waste.

Introduction

Remote-sensing investigations of the Paradox basin were begun in 1977 as part of a team approach in evaluating the geologic suitability of several anticlinal cores along the axis of maximum salt thickness for radioactive waste emplacement. Anticlinal cores in which piercement of overlying beds has occurred coincide with diapirically thickened masses of salt.

The first stage of the remote-sensing investigations consisted of a review of Landsat Multispectral-Scanner (MSS), Skylab S190A and B, and U-2 high-altitude photographic coverage of the region. The second stage consisted of selection of Landsat frames and assessment of the content of the frames for potential new contributions to the geology and geophysics of the Paradox basin in terms of the relation of surface lineaments to subsurface geophysical discontinuities. In the third stage, computer processing of selected frames was undertaken to rectify the Landsat images, enhance image quality, and bring out geologic features of particular interest. In the fourth stage, aerial reconnaissance and field investigations included a field study of joint sets and Landsat lineaments in part of the region, collection of samples of caprock over several salt diapirs, and laboratory determination of spectral reflectance of caprock lithologic types. Following field investigations, a map analysis of the Landsat lineaments was made. This report gives the status of these investigations as of July 1, 1978. The newly mapped lineaments observed by Landsat frames and described herein will be analyzed statistically for tectonic trends and will be compared with azimuthal trends of geophysical potential-field discontinuities at a later time.

Location of Paradox basin and area of salt tectonics

The Paradox sedimentary basin (fig. 1) is 250 km long and 125 km wide and occupies about 30,000 km^2. It is bounded on the north by the Book Cliffs, on the northeast by the Uncompahgre Plateau, and on the northwest by the San Rafael swell.

The region investigated is bounded on the north by the 40th parallel and on the south by the 38th parallel, except in Gypsum Valley where the area of interest extends south to lat 37°50' N. The region is bounded on the west by the 110th meridian and on the east by long 108°30' W.; this includes most of the Moab 2° quadrangle (1:250,000) in southeastern Utah and southwestern Colorado. The study area includes most of the Uncompahgre tectonic trough, which contains the thickest salt deposits of the Paradox basin. The most prominent features related to halokinetic tectonics and geomorphology in this area include (1) Salt Valley-Fisher Valley-Sinbad Valley anticline, (2) Castle Valley-Paradox Valley anticline, (3) Moab-Spanish Valley anticline, (4) Gypsum Valley anticline, (5) Cane Creek anticline, (6) Lisbon Valley anticline, (7) Lockhart anticline, (8) Rustler dome, and (9) Gibson dome. The surface area intercepted by the projection of the above-mentioned structures is about 520 km^2.

Figure 1.--Index map of Paradox basin showing salt anticlines and limits of saline facies and potash in the Paradox Member of the Hermosa Formation (from Hite, 1961).

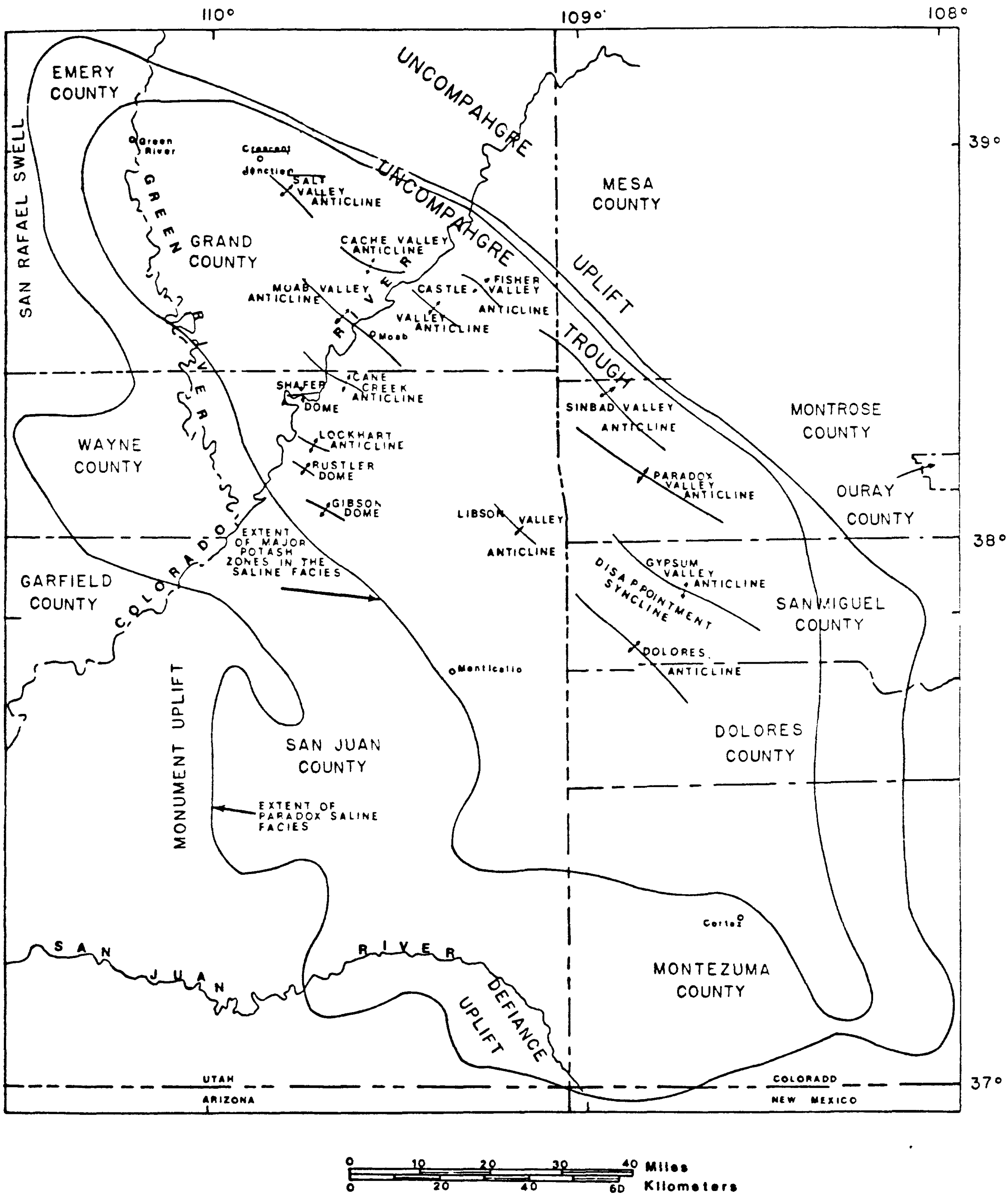

Figure 1. Index map of Paradox basin showing salt anticlines and limits of saline facies and potash in the Paradox Member of the Hermosa Formation (from Hite, 1961).

Geology of the salt anticlines of the northern Paradox basin

The most important salt-bearing stratigraphic unit in the Paradox basin is the Paradox Member of the Hermosa Formation of Pennsylvanian age. This unit is composed of interbedded black shale, dolomite, limestone, gypsum, anhydrite, halite, and potash salts; locally, it has been highly deformed.

The Paradox basin is tectonically characterized by a series of sharply delineated anticlines trending northwest, parallel to the Uncompahgre uplift. The location of these anticlines is related to basement faulting (Hite and Lohman, 1973, p. 25). The anticlines are closely spaced, are longer, and have greater amplitude in the central and northeastern parts of the basin, where their crests are deformed by solution and collapse. The collapse areas form segmented grabens many kilometers in length. Halokinetic activity occurred in these structures from Middle Pennsylvanian through at least Jurassic time; resulting incipient diapirs were covered by sediments of Cretaceous age. Groundwater solution of the near-surface salt caused overlying Mesozoic formations to collapse into the diapiric structures along the anticlinal crests, and subsequent Pleistocene to Holocene slumping and erosion has continued, primarily on the flanks of some of the diapirs. (Notable examples are present near the Onion Creek structure, part of Fisher Valley anticline, between Richardson amphitheater and Fisher Valley; slumping of immense blocks along the anticlinal flank has apparently initiated lateral salt flow, upward movement of caprock units, and significant dissection, which continues to the present time.) Detailed mapping and stratigraphic investigations[1/] of the faulted anticlines since the 1920's originally demonstrated that gypsum and salt have in the past risen as a semiplastic mass and pierced overlying sedimentary rocks; in places cells of evaporites resemble the cupolas of plutons.

Lateral flow of salt into the rising anticlines caused broad downwarping of the adjacent synclines and further accentuated the relationship of the linear, structural troughs to the area of upward movement of salt. Wells drilled in the Gypsum Valley and Sinbad Valley anticlines indicated 2400-3000 m of evaporite rocks, mainly salt, in parts of these anticlines. Gravity anomalies (Joesting and Byerly, 1956) of Sinbad Valley, Paradox Valley, and Gypsum Valley anticlines are compatible with the thickness indicated by wells and provide evidence of the flow of salt toward the anticlinal cores. This process may have resulted in the removal of nearly all the salt from the synclinal troughs contiguous to the Dolores and Sinbad Valley anticlines. Near complete removal has been

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1/ For a list of 67 references on the structure and stratigraphy of the Paradox basin, see Elston and Shoemaker (1961). For a selected bibliography of 97 references prior to 1962 on salt deposits of the Paradox basin see Friedman (1962, p. 11-22). Recent work by Cater (1970), Hite (1960, 1961, 1968, 1969, 1975, and 1977), Hite and Liming (1972), Hite and Lohman (1973), Peterson and Hite (1969), Sumison (1971), and Williams (1964) have greatly clarified the tectonics and stratigraphy of the region. Of these, Hite (1977) is of most value for assessment of the Paradox basin as a radioactive waste disposal site.

documented by drilling along the flanks of Gypsum and Paradox anticlines (R. J. Hite, oral commun., 1978). Some upward growth probably occurred on nearly all of the anticlines within the region of fairly thick evaporite deposits. But no evidence exists for piercement of anticlinal crests in the central and southern parts of the Paradox basin.

Although the depositional thickness of salt may have been between 1500 and 1800 m in the deepest, northeastern part of the sedimentary basin, the thickness of salt in the collapsed, segmented, and intricately faulted cores is now as much as 4175 m.[1/]

Estimates of maximum thickness of evaporites in Salt Valley-Fisher Creek anticline and Moab anticline are 3600 m to 3650 m, and 3050 m, respectively. Evaporites in the core of Castle Valley anticline may be as much as 3650 m thick, and in Paradox Valley, 4175 m thick.

The depth to the top of the salt depends on several factors, including structural position of the folds, amount of piercement of overlying rocks, and erosion. The shallowest salt in the Paradox basin occurs in Sinbad Valley, where a minimum depth of 123 m was reported by Hite and Lohman (1973, p. 45). The shallowest depth to the top of the salt in Salt Valley, reported prior to drilling operations in August 1978, was 236 m (Hite, 1977). Still shallower depths, in the 170 m range, have subsequently been drilled.

1/ Evaporite thicknesses cited are those of Hite and Lohman (1973).

Landsat Multispectral Scanner (MSS) image selection

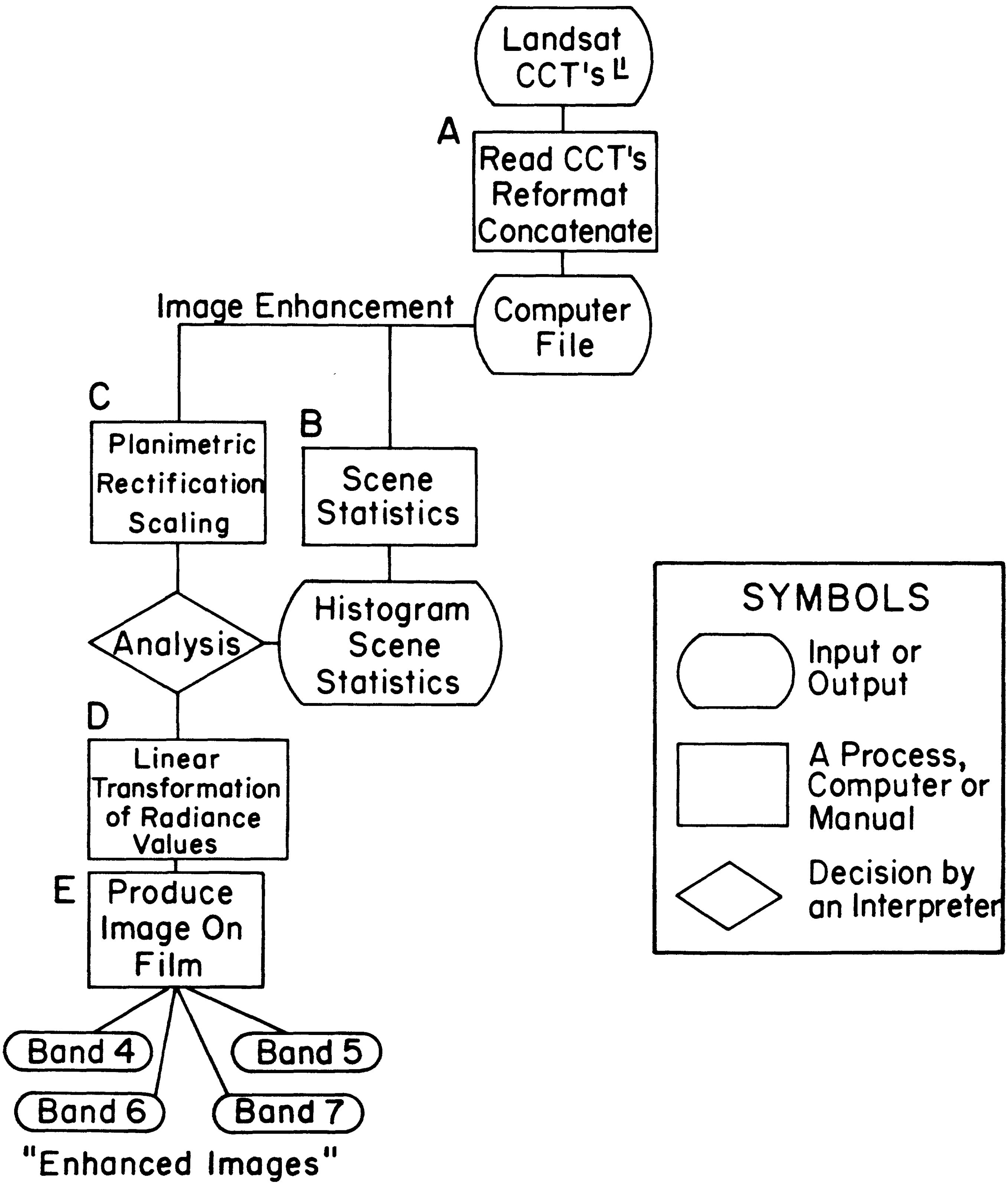
The first stage in the Paradox basin remote-sensing project included a computerized review of Landsat MSS coverage of the most critical part of the basin for frames giving optimum geographic coverage of the highest possible image quality; late fall, winter, and early spring images were eliminated to avoid excessive snow cover. Frames with more than 10 percent cloud cover were eliminated initially, and subsequently all frames having more than 0 percent cloud cover were eliminated. At this point, frames taken under low sun angles were selected for optimum display of landforms and surface textures, and frames at high sun angle were selected for optimum display of variations in albedo and spectral reflectivity.

The frames selected for image processing during fiscal year 1977 were the west half of E-2260-17124, taken October 9, 1975, at a sun elevation of 38° at an azimuth of 144°; and the east half of E-5165-17030, taken October 10, 1975, at a sun elevation of 38° at an azimuth of 137°. These relatively low sun angles are especially well suited for geomorphologic investigations.

Landsat image processing

The east and west halves of the selected MSS frames were processed through the following steps (fig. 2) by computer, using remote-sensing array procedures (REMAPP) designed by Sawatzky and Townsend (1976a,b):

(a) Computer-compatible digital tapes of the selected MSS frames were acquired from the EROS Data Center, Sioux Falls, S. Dak. Uncorrect-



[1] CCT's ARE COMPUTER COMPATIBLE TAPES

FIGURE 2 Simplified Landsat image-processing flow chart ed digital data were processed for compatibility with an OPTRONICS P-1700 system and were stored on 9-track 800-bpi magnetic tapes. During this transfer process, the quarter-frame format was changed to a half-frame format by means of a computerized concatenation program.

(b) Histograms giving radiance distributions were plotted for each spectral band via programs utilizing the Multics[1/] and Hewlett-Packard (HP) systems. (See Glossary.) Shade prints were made on the HP at this stage of the image processing to verify correctness of the data.

(c) A planimetric rectification program, based on an algorithm designed to eliminate the greatest geometric distortion inherent in the uncorrected digital data, was applied to bands 4, 5, 6, and 7. Included were (1) an aspect-ratio correction, (2) a correction for the near-polar orbit of the Landsat spacecraft, and (3) a correction for image skew caused by earth rotation (as a function of latitude). Equations for additional desirable though generally smaller corrections, not made at this stage of the image processing, are given in the Landsat Data Users' Handbook (National Aeronautics and Space Administration, 1971; Supplement, 1976, p. G-18, NASA Document Number 76SDS4258). The planimetric rectification program fits the Landsat images to a generalized universal transverse Mercator (UTM) grid, which gives the correct bearing of one point in relation to another and is, therefore, well suited to lineament analysis. It should be noted that the map projection used for the U.S.

[1/] Use of brand names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

Geological Survey topographic quadrangle maps of Utah and Colorado is a Lambert conformal polyconic projection whose dimensional accuracy at 40^{o}N. latitude is greater than that of the UTM projection. As plotted on these two projections, the location of a given point in the Moab quadrangle may differ by $\pm$ 400 m.

(d) Evaluation of the histogram plots of radiance distribution provided a means for determining the optimum linear transformation to be applied to the digital radiance values to take advantage of the dynamic range of the film recording device.

(e) At this stage, positive and negative image transparencies were produced at a scale of 1:800,000 on the film recording device, or OPTRONICS P-1700 system (figs. 3 and 4).

(f) Change of scale to 1:400,000 was achieved both photographically and via computer for scale compatibility with existing geologic and geophysical maps. The positive transparencies of the two half frames of band 7 were used in compiling a lineament map.

(g) Additional enhancement of band 7 was achieved using an edge-enhancement program. The edge-enhanced image (fig. 5) is equal to the normally processed image plus 0.5 times the Laplacian function of the image.

Geologic interpretation of Landsat frames of the northern Paradox basin

Lithology

More than 4 decades of geologic field mapping, during which the

Figure 3. Landsat frame E-2260-17124, band 7, west half. 1:800,000 October 9, 1975. Image enchanced by linear transformation of radidance values.

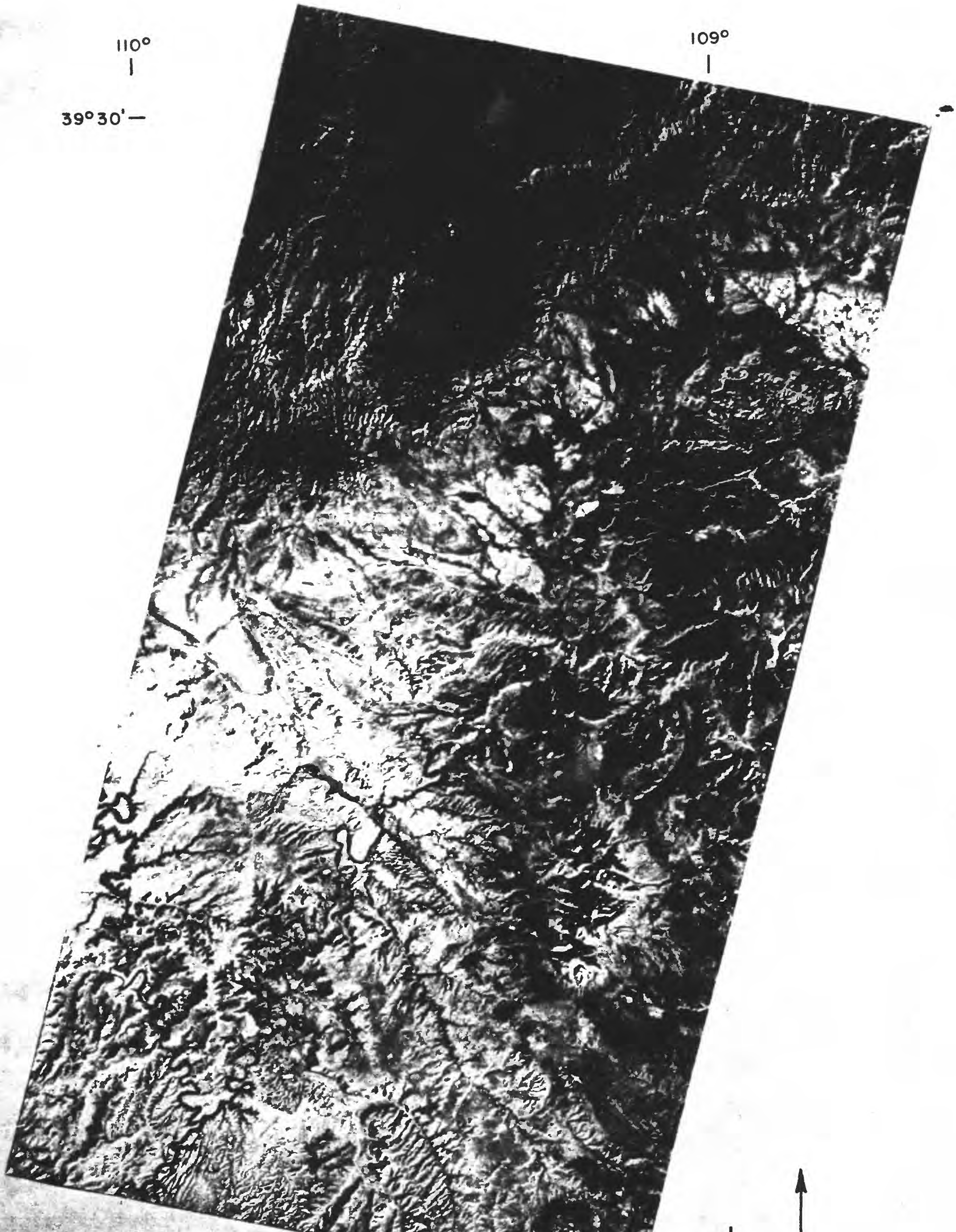


Figure 4. Landsat frame E-5165-17030, band 7, east half. 1:800,000. October 10, 1975. Image enhanced by linear transformation of radiance values.

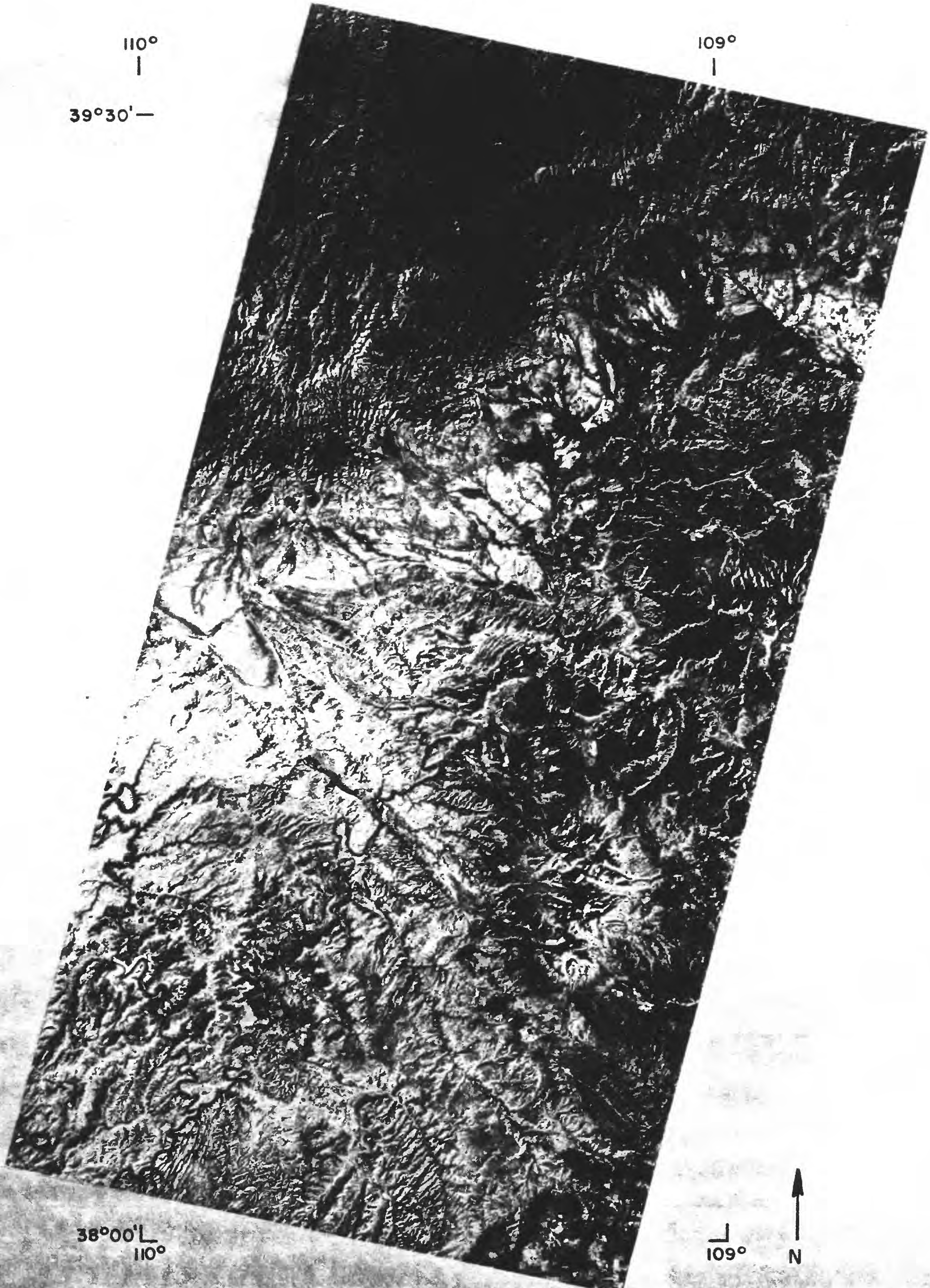


Figure 5 Landsat frame E-2260-17124, band 7, west half. 1:800,000. Edge enhanced.

complicated outcrop pattern and lithologic, structural, and stratigraphic relationships within the northern Paradox basin were gradually unfolded, are clearly summarized at a scale of 1:250,000 by Williams (1964).

The usefulness of Skylab S190 A and B composite photographs for lithologic mapping of large areas was also demonstrated for the Paradox basin by Lee and Weimer (1975).

The processed Landsat frames, because of their planimetric rectification and contrast enhancement, are of particular value in verifying the surface configuration and outcrop pattern of the leached Paradox Member of the Hermosa Formation in several breached anticlinal valleys: Paradox, Gypsum, Sinbad, and, to a lesser extent, Salt Valley. These outcrop areas display characteristically high albedo compared to surrounding soils and bedrock, and may display a high reflectance in MSS band 5 (0.6 to 0.7 m). Infrared spectrometric curves of samples of this unit from Paradox Valley display well delineated infrared absorption bands characteristic of gypsum.

Geomorphology and structure

The most direct geomorphic evidence available from the Landsat images at 1:800,000 for halokinetic tectonics in the Paradox basin is the depiction on the images of linear graben-like collapse or subsidence over some anticlinal crest areas, thus confirming extensive removal via solution by ground water of diapirically thickened salt in the anticlinal core areas. The thickness of the discrete beds of gypsum, shale, and dolomite that constitute the caprock provides a generalized indication of the original thickness of the salt. Although there is no evidence of extensive ground-water penetration of the halite, one possible solution-and-collapse process might involve ground-water penetration of the salt body along microfractures that remain temporarily open, especially under the low confining pressures near the surface (Fairbridge, 1968, p. 968). Leaching of the salt is followed by roof collapse along the anticlinal crests and concomitant lateral flow of salt. The resulting landform represents a stage of the salt-karst geomorphic cycle in which the flat valley floors of the anticlinal valleys have reached the base level represented by the valley of the Colorado River.

The following structures and associated landforms have attained their present form, at least in part, because of the halokinetic properties of the salt beds; they are clearly discernible on Landsat MSS frames E-2260-17124 and E-5165-17030 (figs. 3 and 4 and Plate 1):

1) Breached anticlines (recognizable on Landsat images) whose cores display salt piercement, collapse and lateral flow tectonics
   - a) Castle Valley anticline
   - b) Fisher Valley anticline
   - c) Gypsum Valley anticline
   - d) Moab anticline
   - *e) Paradox Valley anticline
   - f) Salt Valley anticline
   - g) Sinbad Valley anticline

2) Non-piercement salt anticlines that have collapse structures (recognizable on Landsat images)

   a) Lisbon Valley anticline

   b) Tenmile graben

   c) Cane Creek anticline

3) Structural domes (recognizable on Landsat images)

   a) Upheaval Dome

   b) Yellowcat dome

   c) Big Flat dome

4) Synclines (recognizable on Landsat images)

   *a) Courthouse syncline

   b) Dry Creek syncline

   c) Sagers Wash syncline

5) Fault zones recognizable on Landsat images through associated landforms

   a) The Needles fault zone

   b) Cane Creek fault zone

   *c) Cottonwood graben

   *d) Shay graben

   *e) Sandflat graben, Ute Creek graben, and Ryan Creek fault zone

   *f) Little Dolores River fault zone

* Previously unmapped faults associated with these structures identifiable on Landsat images

Lineaments and alignments from Landsat

The relationship of lineaments (O'Leary and others, 1976, p. 1463-1469) and alignments, as interpreted from Landsat at 1:400,000, to geologically mapped faults, fold axes, and the outcrop pattern of caprock of the Paradox Member of the Hermosa Formation is shown on plate 1.

Mapped, concealed, and inferred faults as well as fold axes are taken from Williams (1964) and Cashion (1973). The outcrop pattern of caprock over the salt diapirs of Paradox basin anticlines is modified from Elston and Shoemaker (1961).

Reliability

Reliability of interpretation of an individual linear feature or of the likelihood that a linear feature has a subsurface expression, as determined from Landsat frames, depends on two distinctly different criteria: (1) spatial coincidence with geologically[1/] mapped structures, and (2) morphology of the linear feature (e.g., linearity, distinctness, continuity, tonal contrasts, stratigraphic or lithologic offset relations, topographic offsets, linear geomorphic features, and alignment of drainage and landforms).

The plotted lineaments (pl. 1) of highest reliability are those that coincide with geologically mapped faults. The next, in decreasing order of reliability, are Landsat lineaments that connect segments of mapped faults or that constitute the projection of mapped faults. Also regarded

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1/ Spatial coincidence of lineaments with geophysical discontinuities and trends is the subject of continuing investigation.

as high in reliability are those lineaments that coincide with, or show clear proximity to concealed faults or those inferred on the basis of geological mapping.

Intrusive (i.e., plutonic) dome contacts based on Landsat images are of moderately high reliability, but in places are approximately located.

Major lineaments from Landsat, not previously mapped and generally more than 20 km in length, have been plotted primarily on the basis of linearity of landforms or of distinct tonal contrast with continuity over many kilometers. Lithologic or topographic offsets can be seen along several of these major lineaments. The shorter lineaments are similar, but many fit planimetric patterns in which one, two, or more azimuthal trends are dominant, suggesting that these lineaments represent landforms that have developed along specific joint directions.

Dashed lines indicate alignments that represent natural features of undetermined origin, or those with little continuity in trend, and have a lower reliability.

New Landsat contributions to the tectonic framework of the northern Paradox basin

The Landsat frames reveal the previously well mapped bounding landforms and structures of the intrusive domes of the La Sal Mountains, and the bounding landforms and structures of the salt anticlines as discussed in the previous section. A notable example of congruence between geological field mapping and the lineaments of the planimetrically rectified Landsat frames is the Moab fault system bounding the Moab-Spanish Valley anticline on its southwest flank. A special symbol is used for this congruency on plate 1. But, additionally, several tectonic elements of the northern Paradox basin, previously unrecognized, unmapped, or only partly mapped, are discernible as lineaments and alignments on the Landsat frames (plate 1) and constitute new geologic information; they are described below in approximate geographic order, from north to south, and are identified on figure 6 by the following paragraph numbers:

1) Book Cliffs lineaments

A prominent group of lineaments along the Book Cliffs (figs. 1,6) appears to be controlled by joints or fractures in the Castlegate (Cretaceous) and adjacent formations. No incontrovertible evidence of stratigraphic or other discontinuity is found along these lineaments, except for a very few short fault lines (Cashion, 1973). Here we must be circumspect, because the bounding structures of the Uncompahgre uplift may lie in this region.

2) Cisco Wash lineament, Sagers Wash lineament, Dolores River alignment, and Little Dolores River fault zone

Several northwest-trending lineaments, each longer than 20 km, transect the Grand Valley between the Colorado River and Book Cliffs to the northwest (border region of the Moab and Grand Junction 2° quadrangles). One example, the Cisco Wash lineament (2a on fig. 6) extends intermittently for more than 40 km, striking N. 21° W., from the point where the axis of Sagers Wash syncline intersects the Colorado River (T.

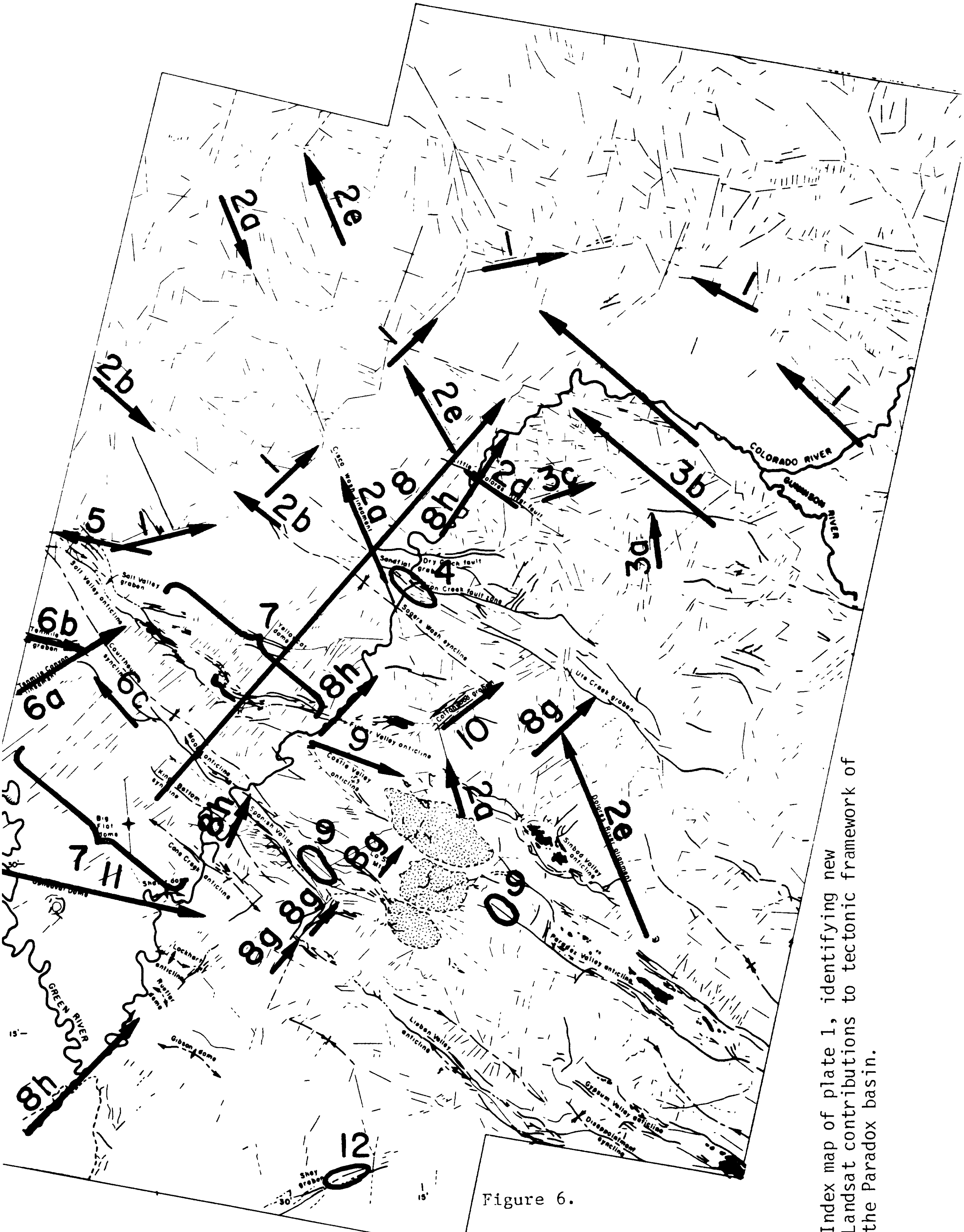

Figure 6.

Index map of plate 1, identifying new Landsat contributions to tectonic framework of the Paradox basin.

22 S., R. 24 E.) well into the Book Cliffs region northwest of Cisco. Sandflat graben and Ryan Creek fault zone appear to be truncated on their western extremities along this lineament. There is, however, no Landsat evidence of offset or other visible evidence of faulting along the Cisco Wash lineament. However, Stone (1977, p. 24, fig. 1), on the basis of widely spaced well data, aeromagnetic interpretations, and a "few older seismic lines tied to well control...," shows the major Uncompahgre fault zone, bounding the Paradox basin on the north, trending about N. 60° W. through this region, and transecting the Sandflat graben and Ryan Creek fault zone on the west. Another Landsat lineament (2b on fig. 6) following the projection of the axis of Sagers Wash syncline through the Book Cliffs, strikes N. 50° W., a structural trend more compatible with Stones' Uncompahgre fault zone.

Another lineament (2d on fig. 6) that strikes N. 55° W. extends about 20 km through T. 20 S., R. 25 E. and across the Colorado River at lat 39°05' N. This lineament coincides with the mapped Little Dolores River fault zone (Cashion, 1973).

Perhaps the longest alignment (2e on fig. 6) in the Uncompahgre region (within Landsat frame E-2260-17124) trends about N. 22° W. for 135 km from the Book Cliffs region across the Grand Valley and the Little Dolores River fault zone to the Dolores River north of Paradox Valley. The most linear segment of this feature is a 35-km section of the course of the Dolores River itself. Between the Little Dolores River fault zone and Unaweep Canyon, this remarkable feature, named here the Dolores River alignment, appears to be represented by short lineaments that strike in a more northerly direction. The entire alignment is most readily discernible at a Landsat scale of 1:2,500,000. Part of this alignment appears to be correlative with a synclinal axis associated with Laramide tectonic activity.

3) Uncompahgre Plateau lineaments

Inside the great bend of the Colorado River in the border region of the Grand Junction and Moab 2° quadrangles (centered at about 39° N. and 109° W.), numerous well-delineated but generally short lineaments form three sets, one with an average trend of N. 5° W. (3a on fig. 6) and two conjugate sets, trending at N. 48° W. (3b on fig. 6) and N. 75° E. (3c on fig. 6). These lineaments are interpreted as representing three dominant joint or fracture sets. It is perhaps significant that the N. 48° W. set approximately coincides with the average N. 47° W. strike of the major anticlinal and synclinal structures of the northern Paradox basin; two parallel lineaments of this set extend for more than 30 km near the great bend of the Colorado and appear to be associated with structures that control the course of the Gunnison River.

4) Ryan Creek fault zone

In the north-central part of the Moab 2° quadrangle, northwest-trending, presumably high-angle faults along the Ryan Creek fault zone (T. 22 S., R. 24 E.), are, on the basis of Landsat lineaments (4 on fig. 6), somewhat more ramified than they appear on geologic maps (Williams, 1964); one fault continues 3 to 6 km farther west than was previously mapped. The Ryan Creek fault zone probably terminates along the Uncompahgre boundary fault zone or a related lineament (See 2 on fig. 6).

5) Latitudinal lineament cutting northwestern part of Courthouse syncline

In the northwest corner of the Moab 2° quadrangle, an unmapped lineament (5 on fig. 6), trending E-ENE, extends from T. 21 S., R. 20 E., westward to the border of the Salina 2° quadrangle where it meets and coincides with a through-going fault. The Landsat frames show this lineament clearly offsetting lithologic units in the northwestern plunging part of Courthouse syncline in the Salina quadrangle (Williams and Hackman, 1971). The northwestern extension of Salt Valley anticline may thus be affected by this structure.

6) Ten Mile Canyon lineament

A northeast-trending lineament set (10 on fig. 6) extends through the incised meander pattern of the Green River to the area of Yellowcat dome (T. 23 S., R. 22 E.). The set includes, southwest of Crescent Junction, the heretofore unmapped Tenmile Canyon lineament (6a on fig. 6), trending about N. 40° E. and abutting the eastern termination of Tenmile graben (6b on fig. 6), which might be underlain by a salt anticline (Joesting and Case, 1962, p. 1888) at T. 22 S., R. 18 E.

On the basis of closure of gravity contours, the postulated salt mass beneath Tenmile graben is elongated along a northwesterly trend slightly askew to the axis of Tenmile graben. Tenmile graben might thus be a relatively superficial collapse structure in Phanerozoic rocks resulting from salt removal.

Tenmile Canyon lineament cuts Courthouse syncline, Moab anticline, and Salt Valley graben where previous structural mapping (Williams,

1964) suggested a major change in trend or possible dislocation of Salt Valley anticline and the Moab fault system (6c on fig. 6). The question of whether the Tenmile graben diapir was once continuous with the Moab diapir and has subsequently been dislocated or severed from the Moab structure (cf. Walton, 1956) along the proposed Tenmile Canyon lineament may be clarified by field geophysics and drilling.

Tenmile Canyon lineament coincides with a line of steepened gravity gradient associated with rejuvenated Paleozoic or Mesozoic tectonic features (Case and Joesting, 1972, pl. 1).

7) Northeast-trending tonal lineaments between the Green River and Yellowcat dome

Between the Green River and Yellowcat dome, a large number of parallel to subparallel tonal lineaments (7 on fig. 6), referred to in 6), form a set striking, on the average, N. 44° E. The major faults and fold axes in this same region trend N. 47° W. Although the lineament set is prominently developed, it has not been mapped heretofore. With the possible exception of the Tenmile Canyon lineament (see 6)), field investigations reveal no evidence of structural offsets along these N. 44° E. lineaments. They are, in fact, difficult to identify on the ground; in one area they coincide with well-developed northeast-trending joint sets that cut the Ferron Sandstone Member of the Mancos Shale (Cretaceous). Elsewhere, it is probable that the N. 44° E. lineaments, to some extent tonal in type, represent landforms (i.e., stream valleys, arroyos, and low divides) and rock and soil alteration developed along prominent individual joints, clusters of joints, or dilation fractures.

Field investigations indicate that several other well-developed joint sets (e.g., in the Entrada Sandstone) are, in places (T. 23 S., R. 20 E.), so closely spaced that most individual joints could not be resolved by the Landsat Multispectral Scanner and are not represented by Landsat lineaments. Several of these joint sets exhibit a spirographic pattern on the flanks of Salt Valley anticline (e.g., in the Moab tongue of the Entrada Sandstone at Klondike Buttes, fig. 7) and may be extension joints concentric to salt stocks that have in the past risen above the crowning level of the evaporite core, as suggested by E. M. Shoemaker (oral commun., 1978).

8) Colorado lineament zone

A summation of Landsat and field data for the region between the Green River and the Book Cliffs north of the great bend in the Colorado River west of Grand Junction adds to the growing mass of evidence of northeast-trending structures in the Phanerozoic sequence. These structures, which constitute the Colorado lineament zone (Warner, 1978), might have resulted from reactivation of similar structural trends in the Precambrian basement in this region. The combined evidence, including the Landsat contribution, for northeasterly structures follows: a) degradation in the linearity and sharp swings in the axial plane of the Salt Valley anticline; b) development of a suite of northeast- and northwest-trending joint or fracture sets in Mesozoic formational units (e.g., Ferron Sandstone Member of the Mancos Shale and Entrada Sandstone) on the limbs of Salt Valley anticline; c) concentration of joint and fracture clusters in weak zones of the Salt Valley

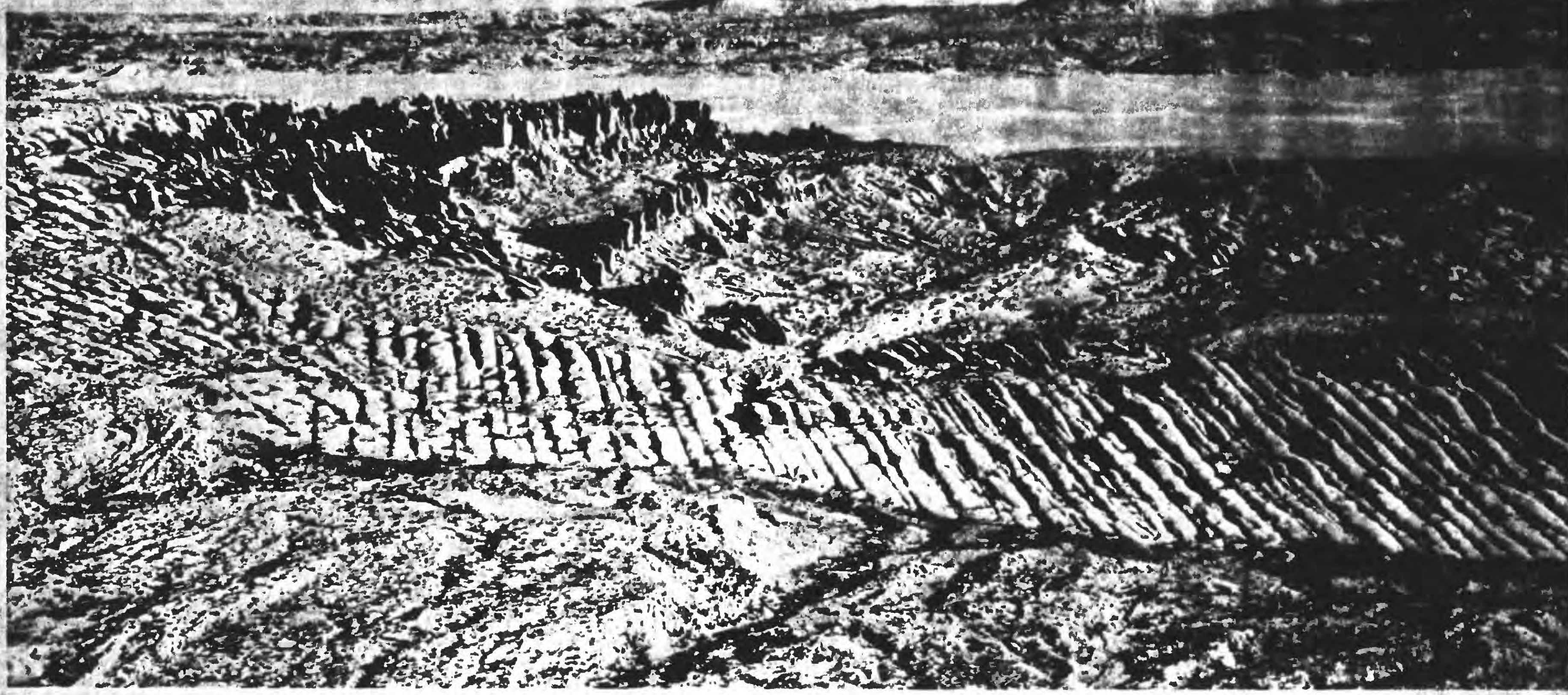

Figure 7.--Aerial oblique photograph of south flank of Salt Valley anticline (T. 23 S., R. 20 E.) showing closely spaced vertical joints in the Moab Sandstone tongue of the Entrada Formation of Jurassic age. View northeast across breached and subsided anticlinal core. Nikon Photograph taken by Jules D. Friedman.

anticline where swings in the anticlinal axis occur (e.g., in Cache Valley); d) possible structural offset along the Salt Valley and Moab diapirs; e) termination of Moab-Spanish Valley anticline on the southeast by northeast-trending faults which appear to continue the line along which the intrusive domes of the La Sal Mountains were injected (8 on fig. 6); f) alignment of a series of northeasterly magnetic- and gravity-field trends parallel to northeasterly lineament zones (8 on fig. 6) west and northwest of the La Sal Mountains (Case and others, 1963; Case and Joesting, 1972); and g) northeast-trending lineaments (8h on fig. 6) indicating detailed structural control of the Colorado River.

Mapping (pl. 1) of the northeast-trending lineaments of b) and g) is a direct result of the Landsat investigations. Many of these lineaments were previously unknown. Landsat has also provided confirmatory data for items a, d, e, and f.

The geologic evidence for the existence of northeast-striking structures is impressive; evidence for lateral displacement along these northeast structures where they cross the salt anticlines is less conclusive. The geometric distortion and abrupt terminations of the anticlines and some of the joint and fracture systems in the Phanerozoic sequence can be explained by vertical tectonic activity along tectonic lines inherited from the Precambrian basement.

9) Lineaments associated with northwest-trending bounding structures of breached salt anticlines

Several short lineaments (9 on fig. 6) and alignments that strike northwest, not heretofore mapped as faults, appear to be extensions of geologically mapped bounding structures of the Castle Valley, Paradox Valley, and Moab-Spanish Valley breached anticlines. In addition, a set of northeast-striking faults terminates the Moab-Spanish Valley anticline at its southeastern end, where one lineament continues 12 km along a projection of the fault alignments to the south-southwest.

10) Northeast-trending lineaments of Cottonwood Canyon

In Cottonwood Canyon (T. 24 S., R. 25 E.) on the northeast side of Fisher Valley, Landsat lineaments (10 on fig. 6) suggest a northeastward continuation of the Cottonwood graben faults. Parallel to and east of Cottonwood Canyon, a series of Landsat lineaments coincide with aligned discontinuities in geophysical potential fields (Case and Joesting, 1972).

11) Latitudinal lineament north of Upheaval Dome

The most notable east-west lineament mapped from Landsat (11 on fig. 6) in this region extends 35 km across the Green and Colorado Rivers just south of lat 38°30' N. and north of Upheaval Dome. This latitudinal lineament coincides with a latitudinal zone of steepened gradient of the gravity field (Case and Joesting, 1972; J. E. Case, written commun., 1978) related to Precambrian or Paleozoic features.

12) Shay graben

In the Shay graben (T. 32 S., R. 22 E.), on the margin between the Moab and Cortez 2° quadrangles, Landsat lineaments (fig. 6, 12) reveal a 4- to 9-km northeastward continuation of the geologically mapped graben boundary fault on the northwest side of the graben.

Summary

Landsat lineaments of the Paradox basin are interpreted largely as fault- or joint-type fractures. Many are clearly projections of geologically mapped structures whose dominant trend is northwest. There are, however, a significant number of northeast trends among both fault- and joint-type lineaments. The northeast-striking faults and their possible extensions constitute an important part of a growing body of evidence that structures of northeast trend in this region are more significant tectonically than was formerly recognized (cf. Case and Joesting, 1972; Hite, 1975; Warner, 1978) and might reflect reactivated Precambrian basement structures.

The course of the Colorado River north of the Needles fault zone (in the region of Meander anticline) in itself constitutes a significant northeast-trending lineament, probably structurally controlled (Mutschler and Hite, 1969, p. 57-58), and decidedly linear at small (1:2,500,000) Landsat scales. The Landsat frames suggest detailed structural control of the Colorado northeast of Meander anticline as well, although the overall pattern of the Colorado River is incontrovertibly antecedent.

These northeast-trending lineaments and mapped structures affect the salt anticlines in three distinct ways: (1) Some anticlines are literally terminated by northeast-trending faults, e.g., the southeastern end of Moab-Spanish Valley anticline. (2) The axis of the Salt Valley-Cache Valley-Fisher Valley-Sinbad Valley composite anticline has been offset possibly along northeast-trending basement faults. The

Tenmile graben continuation of the Moab anticline might have been offset or severed from the main diapir structure, possibly by a northeast-trending fault. Although the salt diapir cores would react plastically to the implied deforming stresses, salt nodes may have been formed at these locations (R. J. Hite, oral commun., 1978); (3) northeast-trending and other joints on the flanks of Salt Valley anticline may provide structural channelways in lithologies adjacent to the salt diapir, along which ground-water movement can reach the diapiric boundary faults.

Implications for radioactive waste emplacement

In evaluating a potential site for acceptability as a radioactive waste repository, the quality of the geologic barrier and the transport characteristics of the lithology (in reference to the pertinent radionuclides) are significant. A variety of geologic processes might be capable of generating the release of the emplaced radionuclides to the surface environment. Among these are faulting and seismicity, diapirism, magma intrusions, geomorphic changes and tectonic processes (e.g., isostatic adjustments and glacial rebound of the crust (Mörner, 1977)) that would lower the base level in such a way as to initiate erosion or change the position of the water table. However, the chief mechanism of migration of radionuclides below the surface is probably the movement of ground water (cf. de Marsily and others, 1977, p. 521). With these geologic processes in mind, what information relevant to assessment of a radioactive waste repository might we derive at this early stage in the analysis of Landsat coverage and existing geologic and geophysical literature on the Paradox basin?

With reference to the salt diapirs of the northern part of the basin, and with particular emphasis on the northwestern segment of Salt Valley anticline, which has elicited considerable interest, certain geologic and other characteristics emerge as potentially favorable and others as potentially unfavorable. Several important characteristics remain unknown.

Some of the potentially favorable characteristics are:

a) Easy access to the potential emplacement site in Salt Valley (Hite, 1977, p. 4, fig. 2) is provided by road and railroad.

b) The potential site is relatively dry at the surface; there is no permanent surface drainage between the Thompson Wash and Salt Wash drainage systems.

c) No agricultural or other development exists at the site. (Characteristics b and c are confirmed by Landsat data.)

d) The salt core is within about 170 m of the surface at or near the Salt Valley site.

e) The estimated thickness of the evaporite core is 3600 m (Hite, 1977, p. 2) at the site; a more precise figure will be determined by the drilling program, but it is evident that the site is within the zone of maximum thickness of the salt.

f) The total volume of the evaporite mass within the site area is about 27.5 km^3 (Hite, 1977, p. 6).

g) The evaporite core of Salt Valley is 87 percent halite (Hite, 1977, p. 7).

h) The permeability of halite is very low.

i) Halite deforms plastically, so at least minor fractures would be self-sealing.

Some potentially unfavorable characteristics are:

a) The very existence of diapirism in the Paradox basin, established by voluminous geologic and geophysical investigations and illustrated on the Landsat frames by the breached anticlinal stage of the salt-karst geomorphic cycle, indicates lack of tectonic stability of the region during long intervals of the geologic past. Continued diapirism may be capable in itself of generating the release of radioactive waste to the environment (de Marsily and others, 1977, p. 521).

b) The diapiric caprock, about 300 m thick at Salt Valley, represents the dissolution of 1562 m of evaporite core (Hite, 1977, p. 13), much of it occurring between Middle Pennsylvanian and Jurassic time when the anticlines reached maximum amplitude. Although the present rate of salt removal at the Salt Valley site remains unknown, the integrated rate of dissolution of the core since Middle Pennsylvanian time is 5.3 m^3 yr^{-1} km^{-2}. The present rate of removal of salt is most likely considerably less than this figure suggests, because the maximum dissolution probably occurred during the early period of most intense uplift in the diapiric process. Although this tells us very little about the current rate of salt removal, it does stand as a reminder that surface and/or ground water were able to circulate and dissolve the Salt Valley diapir under certain conditions in the geologic past. The implication for the future is that once even a minimal water circulation starts, the high mobility of salt would ensure significant removal over short periods of time.

c) If the diapiric process were to be reactivated or, indeed, if it has not yet been terminated (the geomorphic stage of the salt-karst cycle as observed on the Landsat frame and on the ground implies continuance), the plastic behavior of the halite might cause emplaced waste containers to migrate substantial distances within the evaporite core.

d) The diapiric boundary faults could provide a conduit by which circulating ground water from adjacent clastic lithologic units could reach the evaporite core and the ground surface. The possibility of marker-bed conduits for movement of ground water within the evaporite core has been noted by Hite (1977, p. 25).

e) Ground water may occur in Mesozoic sandstones underlying the Mancos Shale in synclinal areas between salt anticlines in the Paradox basin (Friedman, 1962, p. 23); e.g., Courthouse syncline between the Moab and Salt Valley diapirs. Landsat data reveal, and field investigations confirm, the presence of northeast-striking lineament sets (specifically, joint sets) on the anticlinal limbs of Salt Valley. These joints cut the Ferron Sandstone Member of the Mancos Shale and the Entrada Sandstone, and might provide access for ground-water movement from Courthouse syncline to the diapiric boundary faults of Salt Valley near the potential emplacement site.

f) Geological and structural mapping (Williams, 1964) and the present Landsat lineament data suggest that the Salt Valley anticline proper (as well as the Salt Valley-Fisher Valley-Sinbad Valley composite anticline) and, to some extent, the Moab-Spanish Valley anticline have been either tectonically deformed by northeast-southwest shear or other stresses, perhaps transmitted through and influenced by the basement complex, or have reached their present offset and curvilinear structural pattern through vertical tectonics, following block-offset structures in the Precambrian basement. Moreover, the loci of intersection of lineaments and geologically mapped structures (e.g., at the northwest end of Salt Valley anticline and the southeast end of the Moab-Spanish Valley anticline) might be areas of somewhat elevated seismic risk. Recent pattern-recognition work in California (Briggs and others, 1977, p. 168) and lineament analyses in the Middle East (Bune and others, 1976) give new evidence of the relationship between intersections of tectonic lineaments and the distribution of foci of large earthquakes.

g) If the salt barrier of the Salt Valley diapir should fail, potential aquifers of the black to fissile shales and friable to quartzitic sandstones of the adjacent Mesozoic formations would ultimately become the repository for the radioactive waste.

Important characteristics of the Salt Valley anticline that remain unknown include the following:

a) The hydraulic gradient in the area of Salt Valley is poorly known. It seems likely the area is not one of hydrologic recharge in which the hydraulic gradient is vertical and downward. If the horizontal gradient is too small to generate significant lateral movement of water, however, is the net hydraulic gradient essentially vertical and upward, i.e., does surface leakage occur? Would radionuclides be transported vertically upward from the repository to the ground surface? If so, what role would the extensive joint systems in the Mesozoic sequence and the diapiric boundary faults play in transport of nuclides? Corollary questions concern estimation of vertical and direction of horizontal hydraulic gradients from planned drill holes in the evaporite core. If the halite is essentially dry, what data will be available to estimate relative hydraulic gradients within the evaporite core and between the core and adjacent lithologic units?

Related questions concern the subsurface regime and water table associated with the Colorado River at Moab: is the river influent or effluent at this locality; what is its subsurface hydrologic regime; and radionuclides transported to the Colorado River via subsurface drainage?

b) The present rate of salt removal remains unknown.

c) The presence of open subsurface structures or cavities in the evaporite core of Salt Valley remains unknown. Deep drilling and subsurface geophysical methods may shed light on this question.

Geophysical recommendations

The following recommendations for continued remote sensing and geophysical investigations of the Paradox basin and, specifically, of the Salt valley anticline are not intended to be comprehensive. However, the requirement for these investigations has been made clear by the present Landsat study and the known geology and geophysics of the region.

We recommend these remote-sensing investigations:

1) Trend analyses of the tectonic and lineament map of the Paradox

basin (pl. 1) to statistically determine the dominant tectonic trends and delimitation of tectonic provinces on the basis of geologic age, as well as regional lineament density and loci of the greatest concentration of lineament intersections. This method may yield information on the distribution of reactivated structures in the basement complex.

2) Investigation of scale dependency in lineament plots from Landsat frames; trend analyses of item 1 should be made of lineament maps at several different scales to evaluate the significance of the synoptic effect at small scale.

3) Extension of the present Landsat investigations to the northwest and southeast to provide the base for a full lineament analysis of the Uncompahgre trough as a comprehensive tectonic unit, and to provide information on the tectonic relationship between the Uncompahgre fault zone, the Paradox basin, and the San Rafael swell. Return beam vidicon (RBV) images of Landsat should be evaluated in connection with this investigation because of their 40-m spatial resolution.

4) Analysis and photogeologic mapping of the Salt Valley anticline, Courthouse syncline, and Tenmile Canyon lineament area, using U-2 high-altitude photographs to provide an intermediate-scale link between Landsat and conventional geologic-map and 1:24,000 airphoto coverage. The U-2 photographs can provide data on the distribution of extension joints, possibly concentric to cupolas, in the anticlinal evaporite core. Skylab S190A and B photographs should also be evaluated in the transition from Landsat to data of higher spatial resolution.

5) Acquisition and analysis of side-looking radar (SLAR) cover-

age, having better than 10-m resolution, of the Salt Valley anticline and other parts of the Paradox basin as useful for a special detailed lineament analysis.

6) Thermal-infrared aerial-scanner coverage of Salt Valley and selected breached anticlines for detection of effluent springs, previously undetected fractures, possible lithologic discriminations (e.g., structurally associated lithologies in the caprock outcrops), and other thermal features. Landsat thermal-infrared data, at 250-m spatial resolution, might also be useful for structural and possible soil moisture information.

7) Color-ratio composite images made from Landsat MSS frames might be useful for structural information that depends on spectral reflectance contrasts rather than topography or albedo, and possibly for optimum delimitation of outcrop patterns of caprock units of the Paradox Member of the Hermosa Formation.

The following categories of geophysical investigations should, in the opinion of the geophysics and remote-sensing team of investigators, be included in the suite of investigations in the Paradox basin in view of the implications of the present report.

8) New, deep (>300-m depth) seismic-reflection profiles for gross structure of the Salt Valley diapir along transverse profiles where the structure of the diapir is inadequately known, as in the northwestern part of Salt Valley, where the axial trend is inferred but not adequately mapped, and in the northwestern corner of the Moab quadrangle, where the diapir may be transected by faults. Deep seismic-reflection profiles

would also be useful in outlining the structure of Tenmile graben diapir and its relation to the Moab diapir, and in ascertaining the existence and extent of salt dissolution at the bottom of the evaporite sequence. Deep seismic-reflection profiles across the postulated Uncompahgre fault zone would also be justified if they do not already exist in the private sector. Less expensive, detailed gravity surveys might also be helpful in tracing the subsurface continuity of these faults (R. D. Watts, oral commun., 1978).

9) Experimentation with radar (radio-echo) sounding to investigate the spectrum of size distribution of small cavities, and to locate structural dislocations or discontinuities in the evaporite core of Salt Valley. Hole-to-hole geophysical methods for tracing interbeds in the evaporite core of Salt Valley would also be useful (R. D. Watts, oral commun., 1978).

10) Selected geophysical techniques for detection of ground water in potential aquifers (e.g., Ferron Sandstone Member of the Mancos Shale) on the flanks of Salt Valley anticline and Courthouse syncline. Several electrical methods may be usefully applied to this problem in overlapping depth ranges, e.g., deep magnetotelluric methods for depths greater than 600 m, vertical electrical resistivity soundings of the Schlumberger type for the 150-600 m depth range, and a shallow electromagnetic method of the Slingram type for depths less than 150 m (J. J. Daniels, oral commun., 1978).

11) Installation of one or more tiltmeters in the diapiric caprock near the Salt Valley drill sites to test short-term tectonic stability of the evaporite core.

Glossary of selected terms

alignment	Any linear arrangement of terrestrial or extraterrestrial features, regardless of spacing or genetic association; a line connecting more or less widely spaced features such as ore deposits, intrusions, or volcanoes (from O'Leary and others, 1976, p. 1468).
diapirism	The process of piercing or rupturing domed or uplifted overlying rocks by core material in the plastic state, either by tectonic stress, as in anticlinal folds, or by the effect of geostatic load in sedimentary strata, as in salt domes (from Gary and others, 1972, p. 194).
halokinesis	Tectonic processes resulting from plastic flow and solution of subsurface rock salt.
Hewlett Packard 9640 System (HP)	A multiprogramming system thatconsists of a central processing unit, a disc drive, a 9-track 800-bpi digital tape unit, and a terminal, with a Varian Statos 33 printer/plotter.
Lambert conformal polyconic projection	A Lambert projection that seems to envelop the globe in a large number of cones, hence the term "polyconic," and in which the scale along the parallels is the same as along the meridians, hence the conformal aspect. The scale is the same in every direction at any point on the map. Distances are exactly accurate along the parallels where the projection coincides with the globe.

Landsat Multispectral Scanner — The Multispectral Scanner Subsystem (MSS) gathers data by imaging the surface of the earth in several spectral bands simultaneously through the same optical system. The MSS for Landsat 1 is a 4-band scanner operating in the solar-reflected spectral region from wavelengths of 0.5 to 1.1 micrometers. It scans crosstrack swaths 185 km in width, simultaneously imaging six scan lines across in each of the four spectral bands. The object plane is scanned by means of an oscillating flat mirror between the scene and a double-reflector, telescope-type optical chain. The 11.56-degree crosstrack field of view is scanned as the mirror oscillates ± 2.89 degrees about its nominal position. The instantaneous field of view for each detector subtends an earth-area square of 79 meters on a side from the nominal orbital altitude (National Aeronautics and Space Administration, 1971, p. A-8).

lineament — A mappable, simple or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon (O'Leary and others, 1976, p. 1467).

Multics	Multiplexed Information and Computing Service. A general-purpose computer system (Honeywell Information Systems) used by the U.S. Geological Survey.
OPTRONICS P-1700	A high-speed, high-precision, electro-mechanical, digital image-processing system.
Return Beam Vidicon	(RBV). The two panchromatic cameras of Landsat 3 are aligned to view side-by-side, nominal 99-km-square ground areas with a 15-km sidelap, yielding a 183- by 99-km scene pair. Two successive scene pairs nominally overlap each MSS frame. The Landsat 3 RBV camera system has a broadband spectral response from 0.5 to 0.75 micrometers.
salt karst	Characteristic landforms developed in a variant of the karst geomorphic cycle by a combination of solution of halite, gypsum, anhydrite, or other halogenic or evaporitic rocks and concomitant halokinetic processes.
universal transverse Mercator projection	A cylindrical map projection that gives the true direction of one point in relation to another, based on 60 north-south zones each 6° wide and a transverse Mercator projection drawn for each zone.

References cited

Briggs, P. L., Press, Frank, and Guberman, Sh. A., 1977, Pattern recognition applied to earthquake epicenters in California and Nevada: Geological Society of America Bulletin, v. 88, p. 161-173.

Bune, V. I., Skaryatin, V. D., Polyakova, T. P., and Shirokova, Ye. A., 1976, Skhema tektonicheskikh le lineamentov i raspredeleniye ochagov zemletryaseniy s $M \geq 6.3$ v Tsentral'nom uchastke al'piyskoy skladchatoy oblasti [Tectonic lineaments and distribution of foci of earthquakes with M - 6.3 in the central part of the Alpine fold region]: Doklady Akademii Nauk USSR, v. 230, no. 6, p. 1310-1313.

Case, J. E., 1966, Geophysical anomalies over Precambrian rocks, northwestern Uncompahgre Plateau, Utah and Colorado: American Association of Petroleum Geologists Bulletin, v. 50, no. 7, p. 1423-1443.

Case, J. E., and Joesting, H. R., 1972, Regional geophysical investigations in the central Colorado Plateau: U.S. Geological Survey Professional Paper 736, 31 p.

Case, J. E., Joesting, H. R., and Byerly, P. E., 1963, Regional geophysical investigations in the La Sal Mountains area, Utah and Colorado: U.S. Geological Survey Professional Paper 316-F, p. 91-116.

Cashion, W. B., 1973, Geologic and structure map of the Grand Junction quadrangle, Colorado and Utah: U.S. Geological Survey Miscellaneous Geological Investigations Map I-736.

Cater, F. W., 1970, Geology of the salt anticline region in southwestern Colorado: U.S. Geological Survey Professional Paper 637, 80 p.

Elston, D. P., and Shoemaker, E. M., 1961, Preliminary structure contour map on top of salt in the Paradox Member of the Hermosa Formation in the salt anticline region, Colorado and Utah: U.S. Geological Survey Oil and Gas Investigations Map OM-209.

Fairbridge, R. W., ed., 1968, Salt karst, in Encyclopedia of geomorphology: New York, Rheinhold Book Corp., Encyclopedia of Earth Science Series, v. III, p. 967-968.

Friedman, J. D., 1962, Offsite areas west of the Cordilleran front as possible special-purpose sites, No. 5. Rock-salt deposits: U.S. Geological Survey Technical Letter, Offsite studies-5., 30 p.

Gary, M., McAfee, R., Jr., and Wolf, C. L., eds., Glossary of geology: Washington, D. C., American Geological Institute, 805 p.

Hite, R. J., 1960, Stratigraphy of the saline facies of the Paradox Member of the Hermosa Formation of southeastern Utah and southwestern Colorado, in Geology of the Paradox basin fold and fault belt: Four Corners Geological Society Guidebook 3d Field Conference, p. 86-89.

______1961, Potash-bearing evaporite cycles in the salt anticlines of the Paradox basin, Colorado and Utah, in Short papers in the geologic and hydrologic sciences: U.S. Geological Survey Professional Paper 424-D, p. D135-D138.

______1968, Salt deposits of the Paradox basin, southeast Utah and southwest Colorado, in Saline deposits: Geological Society of America Special Paper 88, p. 319-330.

______1969, Shelf carbonate sedimentation controlled by salinity in the Paradox basin, southeast Utah, in Rau, J. L., and Dellwig, L. F., eds., Third Symposium on Salt: Northern Ohio Geological Society, v. 1, p. 48-66.

______1975, An unusual northeast-trending fracture zone and its relations to basement wrench faulting in northern Paradox basin, Utah and Colorado, in Canyonlands: Four Corners Geological Society Guidebook 8th Field Conference, p. 217-224.

______1977, Subsurface geology of a potential waste-emplacement site, Salt Valley anticline, Grand County, Utah: U.S. Geological Survey Open-File Report 77-761, 26 p., 11 figs.

Hite, R. J., and Liming, J. A., 1972, Stratigraphic section through the Pennsylvanian System in the Paradox basin, in Geologic atlas of the Rocky Mountain region: Denver, Rocky Mountain Association of Geologists, p. 134-135.

Hite, R. J., and Lohman, S. W., 1973, Geologic appraisal of Paradox basin salt deposits for waste emplacement. U.S. Geological Survey Open-file report, 75 p.

Joesting, H. R., and Byerly, P. E., 1956, Aeromagnetic and gravity profile across the Uravan area, Colorado, in Geology and economic deposits of east-central Utah: Intermountain Association of Petroleum Geologists Guidebook 7th Annual Field Conference, p. 38-41.

Joesting, H. R., and Case, J. E., 1962, Regional geophysical studies in Salt Valley-Cisco area, Utah and Colorado: American Association of Petroleum Geologists Bulletin, v. 46, no. 10, p. 1879-1889.

Joesting, H. R., Case, J. E., and Plouff, Donald, 1966, Regional geophysical investigations of the Moab-Needles area, Utah: U.S. Geological Survey Professional Paper 516-C, p. C1-C21, [1967].

Lee, Keenan, and Weimer, R. J., 1975, Geologic interpretation of Skylab photographs: Colorado School of Mines, Remote Sensing Report 75-6, NASA contract NAS9-13394, 77 p.

de Marsily, G., Ledoux, E., Barbreau, A., and Marcat, J., 1977, Nuclear waste disposal: Can the geologist guarantee isolation?: Science, v. 197, no. 4303, p. 519-527.

Mörner, Nils-Axel, 1977, Rörelser och instabilitet i den svenska berggrunden [Movement and instability in the Swedish bedrock]: Geologiska Institutionen, Stockholms Universitet, 11386 Stockholm, 36 p.

Mutschler, F. E., and Hite, R. J., 1969, Origin of the Meander anticline, Cataract Canyon, Utah, and basement fault control of Colorado River drainage: Geological Society of America Abstracts with Programs for 1969, part 5, p. 57-58.

National Aeronautics and Space Adminstration, 1971, Earth Resources Technology Satellite data users' handbook: NASA Goddard Space Flight Center, 218 p.

O'Leary, D. W., Friedman, J. D., and Pohn, H. A., 1976, Lineament, linear, lineation--some proposed new standards for old terms: Geological Society of America Bulletin, v. 87, p. 1463-1469.

Peterson, J. A., and Hite, R. J., 1969, Pennsylvanian evaporite-carbonate cycles and their relation to petroleum occurrences, southern

Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 53, no. 4, p. 884-908.

Sawatzky, D. L., and Townsend, T. E., 1976a, Programmer's guide for REMAPP remote sensing array processing procedures: Available only from National Technical Information Service, Springfield, VA 22161 as Report PB-256 693.

______1976b, OPTRIN and OPTAPE: Programs for interchange of data between REMAPP and OPTRONICS P-1700 photomation: Available only from National Technical Information Service, Springfield, VA 22161 as Report PB-256 692.

Stone, D. S., 1977, Tectonic history of the Uncompahgre uplift: Rocky Mountain Association of Geologists, Symposium, p. 23-30.

Sumison, C. T., 1971, Geology and water resources of the Spanish Valley area, Grand and San Juan Counties, Utah: Utah Department of Natural Resources Technical Publication 32, 45 p.

Walton, P. T., 1956, Structure of the north Salt Valley-Cisco area, Grand County, Utah: Intermountain Association of Petroleum Geologists Guidebook 7th Annual Field Conference, p. 186-189.

Warner, L. A., 1978, The Colorado lineament: A middle Precambrian wrench fault system: Geological Society of America Bulletin, v. 89, no. 2, p. 161-171.

Williams, P. L., 1964, Geology, structure, and uranium deposits of the Moab quadrangle, Colorado and Utah: U.S. Geological Survey Miscellaneous Geological Investigations Map I-360.

Williams, P. L., and Hackman, R. J., 1971, Geology, structure, and uranium deposits of the Salina quadrangle, Utah: U.S. Geological Survey Miscellaneous Geological Investigations Map I-591.