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Evaluating the Effectiveness of Landsat Data as a Tool for Locating Buried Pre-Glacial Valleys in Eastern South Dakota

Winter, spring, and early summer 1:500,000-scale Landsat mosaics provide the most useful information for locating pre-glacial buried valleys.

Abstract: *A rapid, low-cost procedure for delineating pre-glacial buried valley aquifers in eastern South Dakota from Landsat imagery was developed and evaluated. Curvilinear/linear, anomalous tonal pattern, and drainage overlays were prepared using winter and spring, Landsat band 5, band 7, and false-color infrared mosaics, and were analyzed to define subtle characteristics related to known buried valleys. Drainage characteristics, curvilinear/linear patterns, and anomalous sinuous tonal patterns, which do not correlate with the trends or characteristics of glacial features, were mapped as indicators of buried valleys. Subsequent drilling confirmed the effectiveness of this procedure.*

Due to till thicknesses and glacial dynamics, delineation of buried valley aquifers is most accurate near the Missouri River. The best guides to buried valleys are present day streams which reoccupy pre-glacial valleys, or anomalous chains of lakes, ponds, and depressions, and associated soils and vegetation which overlie unexhumed buried valleys.

Introduction

Buried pre-glacial alluvial valleys, which yield significant quantities of groundwater in eastern South Dakota, have traditionally been discovered by expensive, time-consuming drilling methods. The objective of this study was to develop a rapid and cost-effective method using Landsat data to delineate buried pre-glacial valleys and associated aquifers in eastern South Dakota. The primary goals are to determine which imagery best delineates buried valleys, to develop a method of manual spatial and spectral interpretation for predicting the locations of buried valleys, and to evaluate these techniques by comparing valley locations predicted by Landsat analysis with those subsequently located by the South Dakota State Survey's drilling program.

The regional study area, consisting of the Coteau du Missouri and James River Lowland provinces (lat. 43° −46°N, long. 97° −100°W), is located in eastern South Dakota, east of the Missouri River (Figure 1). Local study sites, including Jerauld, Aurora, and Walworth Counties, were chosen due to the availability of drill data subsequently acquired there (Figure 1).

Previous Work

Flint (1955) summarized the Pleistocene glacial geology and geomorphology that characterizes the surface of eastern South Dakota (Figure 2). He also discusses the subsurface geology as it pertains to the Coteau du Missouri and James River Lowland provinces (Figure 3). Ultimately, Flint (1955) comments on the geologic evolution of the Missouri River drainage (Figure 4). Tipton (1975)

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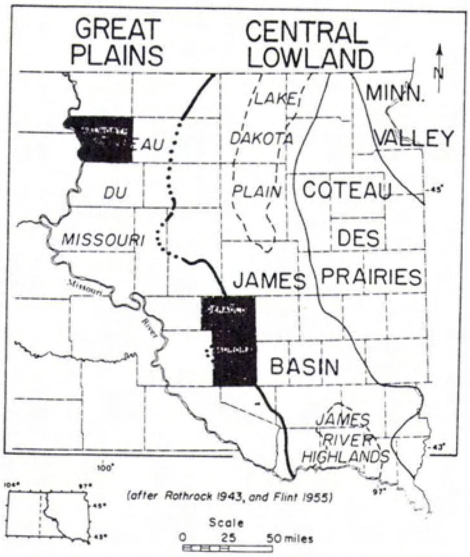

FIG. 1. Location of the study area in eastern South Dakota. Note that Walworth County is located entirely within the Coteau du Missouri of the Great Plains Province, whereas Jerauld and Aurora Counties are partially within the James Basin of the Central Lowland Province.

summarizes the more recent geologic and geohydrologic work pertaining to the region that has been completed by the South Dakota State and United States Geological Surveys.

Previous investigations show that Landsat may be used as a tool for locating shallow groundwater aquifers in South Dakota (Moore and Meyers, 1972a, 1972b; Myers and Moore, 1972; Rahn and Moore, 1977; Heinemann *et al.*, 1972). More deeply buried aquifers have been located in South Dakota (Hyland and Andrawis, 1977) using low altitude thermal imagery and in Indiana using Landsat imagery (Peterson *et al.*, 1975). Lucas and Taranik (1977) demonstrated that springtime Landsat scenes of the midwestern United States were superior for the regional interpretation of glacial features.

PROCEDURE

The general procedure employed in this study was to determine the surface characteristics exhibited by known buried valleys in the field, to delineate these characteristics on Landsat imagery, and to extrapolate these results to other areas where buried valleys have not been discovered. Generally, the field characteristics of buried valleys are subtle at best (e.g., soil changes) or nonexistent (Figure 5). Only large scale changes in the character of the land, such as topographic breaks in the Coteau or drainage pattern anomalies, can be used to delineate preglacial valleys. Therefore, Landsat mosaics, which provide a regional and seasonal view of the study area, are the most suitable tools for this study.

Preliminary Landsat investigations were conducted at the scales of 1:1,000,000 and 1:500,000. County maps showing areas of known pre-glacial bedrock surfaces (delineating pre-glacial valleys) were reduced to scales of 1:1,000,000 and 1:500,000 and combined to form one regional base map for each scale. The locations of known buried valleys were drafted directly from the base maps to acetate overlays. These overlays were then placed upon each of the Landsat mosaics in order

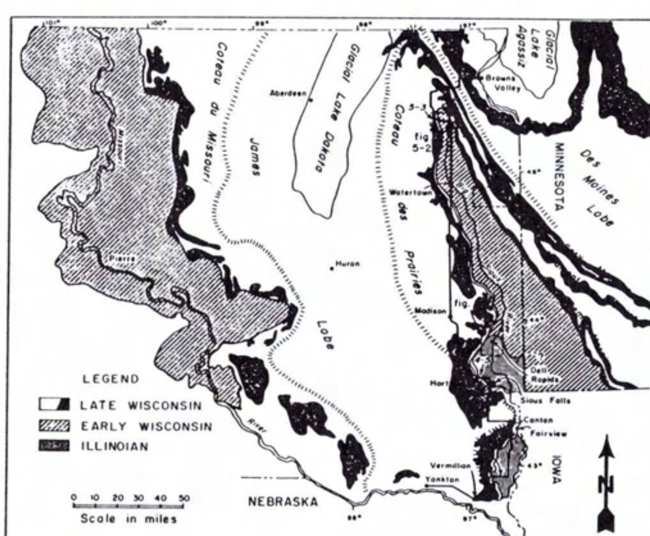

FIG. 2. Map of eastern South Dakota showing generalized Pleistocene glacial geology (after South Dakota State Geological Survey Education Series Map #2, 1971).

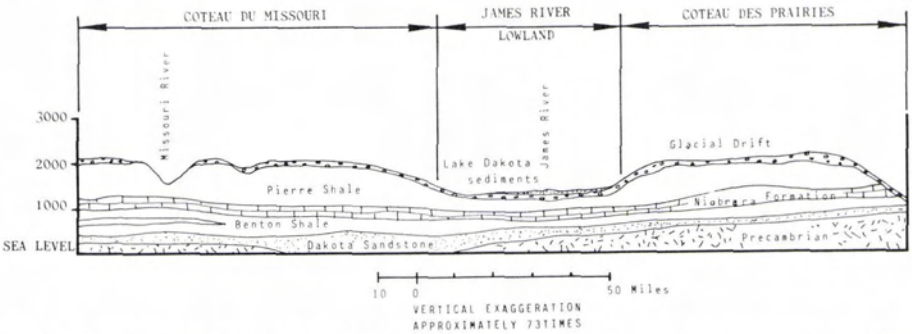

FIG. 3. East-west geologic cross-section of eastern South Dakota (after Darton, 1909; Flint, 1955) showing almost imperceptible dips of bedrock surfaces in the region.

to correlate areas of known buried valleys with spatial and spectral patterns and characteristics observed on Landsat imagery.

Five mosaics of Landsat scenes, each with 10 percent or less cloud cover, provide a regional view needed to study subtle surficial characteristics of buried valleys that extend for several miles (Table 1). A winter mosaic was constructed to study drainage and topographic characteristics associated with buried valleys (Table 1). Spring and summer mosaics were used to study the spectral characteristics of buried valleys associated with vegetation, soil type and soil moisture.

Landsat false-color infrared composites, and Band 5 and Band 7 scenes obtained from different seasons and years (wet versus dry) were compared using the methods of Lucas and Taranik (1977). Winter scenes were chosen for interpreting drainage patterns and density, and topographic features because the low solar angle and light snow cover enhance the landscape. Shadows that are created by low sun angles and sun azimuths outline and, therefore, enhance topography. A light, total snow cover eliminates most of the tonal and color variations due to cover type. Therefore, the surface appears to have a more uniform brightness, which is less distracting in drainage analyses.

Spring (April, May, early June) images have been determined as optimal for glacial studies in the midwest (Lucas and Taranik, 1977). During this season, such factors as minimal crop cover, limited land-use or farm practices, maximum open water (lakes and swamps, for example) and tonal contrast due to soil types and soil moisture, and

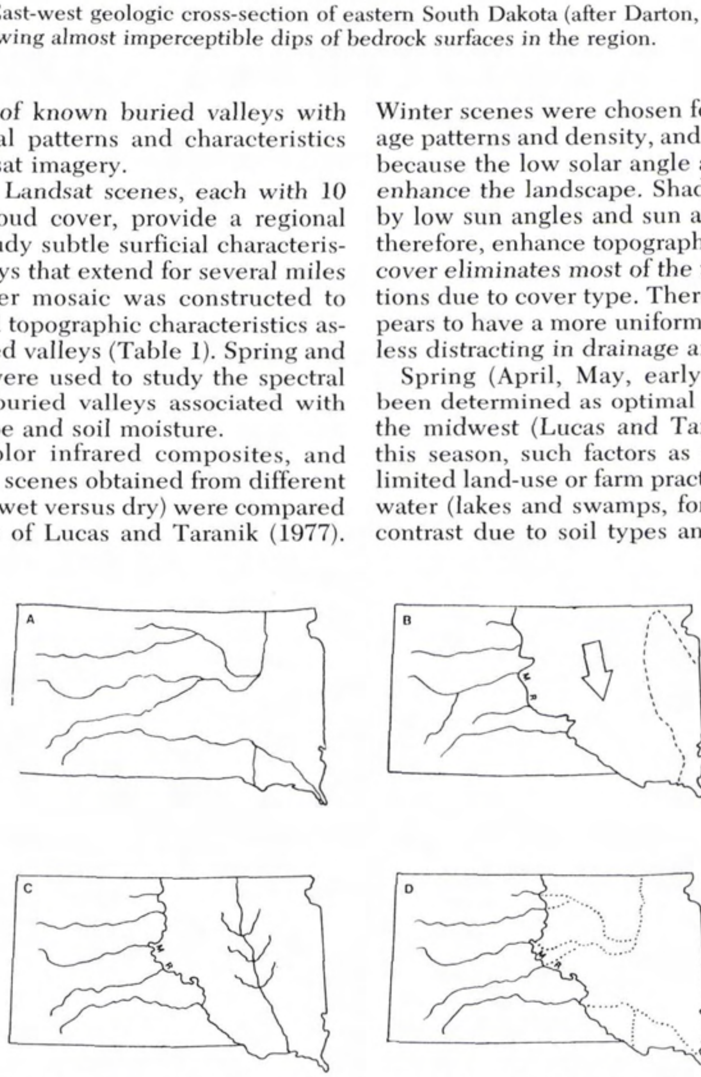

FIG. 4. Diagram of the State of South Dakota depicting the generalized evolution of the eastern South Dakota drainages. (A) Pre-glacial drainage: Note the east-west river trends; (B) Late Wisconsin glacial advance (arrow) and formation of Missouri River (MR): Missouri River and dotted line indicate approximate ice border; (C) Present day drainage: Note the lobate or curvilinear river trends east of the Missouri River due to strong glacial influence; (D) East-west trending, pre-glacial buried valleys (dotted) underlying glacial drift.

large vegetative vigor differences greatly enhance the utility of these images for analysis (Figures 6a, b, and c).

Surficial characteristics of buried valleys, including chains of lakes, closed depressions, and anomalous drainage patterns, are commonly best exhibited on springtime images (such as illustrated in Figures 6a, b, and c). In addition, spring snow melt provides low lying, poorly drained areas characteristic of some buried valleys with abundant water. As a result, there are distinctive reflectance differences between these areas and well-drained areas associated with the sloping lands of valley sides and moraines. These wet conditions prevent the farmer from planting in low lying areas during early spring, resulting in easily recognizable dark patterns on imagery (Figure 6a).

Early summer Landsat scenes may provide better buried valley patterns than springtime images at some localities. Both low lying depressions and adjacent unplanted uplands may appear uniformly dark gray on springtime imagery. On early summer scenes, however, these low lying depressions may show greater vigor than upland crops and grasslands. As the summer progresses, however, the masking effect of extensive crop canopy greatly reduces the utility of these images for interpretation.

Autumn Landsat scenes lack substantial open water and soil moisture, both of which are important to delineate buried valleys. During this season, surface moisture results from sporadic, convective storms rather than the gradual regional melting of snow. Also, vegetative vigor associated with soil moisture differences is minimal and plants are drying out or are dormant as winter approaches.

Springtime Landsat scenes of wet and dry years were compared for ease of interpretation (Figures 6a and b). Open water or dark moist soils occupying topographically low-lying areas associated with buried valleys are greatly enhanced by increased amounts of surface water. Therefore, soil differences and chains of ponds outlining topographic depressions will be more easily delineated during wet years (Figure 6a). For example, a known buried valley discovered recently in Aurora County can be seen as a dark, discontinuous pattern on 1978 springtime imagery (Figure 6a). The pattern cannot be seen on a 1974 spring image (Figure 6b). The dark pattern is caused by a chain of small ponds and depressions. In 1974, South Dakota was experiencing a drought, and these depressions and ponds were dry.

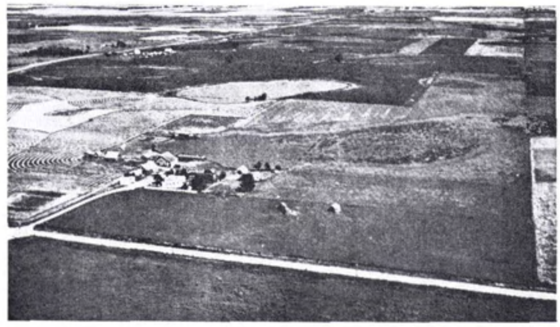

FIG. 5. Oblique aerial view of James River Lowland near Mitchell, South Dakota. This area is characterized by subtle depressions containing water, Tonka soils, and grassland vegetation (after Johnson *et al.*, 1974).

TABLE 1. LANDSAT MOSAICS USED TO CONSTRUCT DRAINAGE, CURVILINEAR/LINEAR, AND "ANOMALOUS" TONAL PATTERNS OVERLAYS

Season	Year	Scale	Wet vs. Dry
A. Winter	1974	1:500,000	Dry
B. Spring	1974, 1976	1:500,000	Dry
C. Spring	1974, 1976	1:1,000,000	Dry
D. Summer	1974	1:1,000,000	Dry
E. Spring	1976, 1978	1:500,000	Wet

False-color infrared composite images were compared with black-and-white, Band 5, and Band 7 Landsat scenes. Landsat Band 7 black-and-white winter images were most effective for delineating topography and drainage patterns due to the low atmospheric scatter associated with the infrared wavelengths. Band 7, spring-time imagery was also very effective for delineating lake chains as water is highly absorbent in the infrared wavelengths.

Cover types referred to in this study, such as grasslands (moderate reflectance), lakes (low reflectance), and croplands (high reflectance), are easily separated on spring and early summer Band 5 black-and-white images as well as false-color infrared composite images (Figure 6b). Vegetation is highly reflective and appears bright red on false-color infrared composite springtime imagery. Therefore, it promotes cropland pattern recognition. Band 5 images have a more uniform scene, causing the checkerboard cropland pattern to be greatly subdued and buried valley patterns to be enhanced (Figure 6a).

Springtime false-color infrared composites were most useful for delineating curvilinear patterns associated with glacial features.

MANUAL INTERPRETATION

Three overlays were made using Landsat mosaics: drainage patterns, curvilinears/linears, and anomalous tonal patterns. The drainage map was constructed by tracing all resolvable drainages directly onto an acetate overlay that was placed upon the 1:500,000-scale winter Band 7 Landsat mosaic. Surficial drainage patterns and density overlying buried valleys were studied using this overlay.

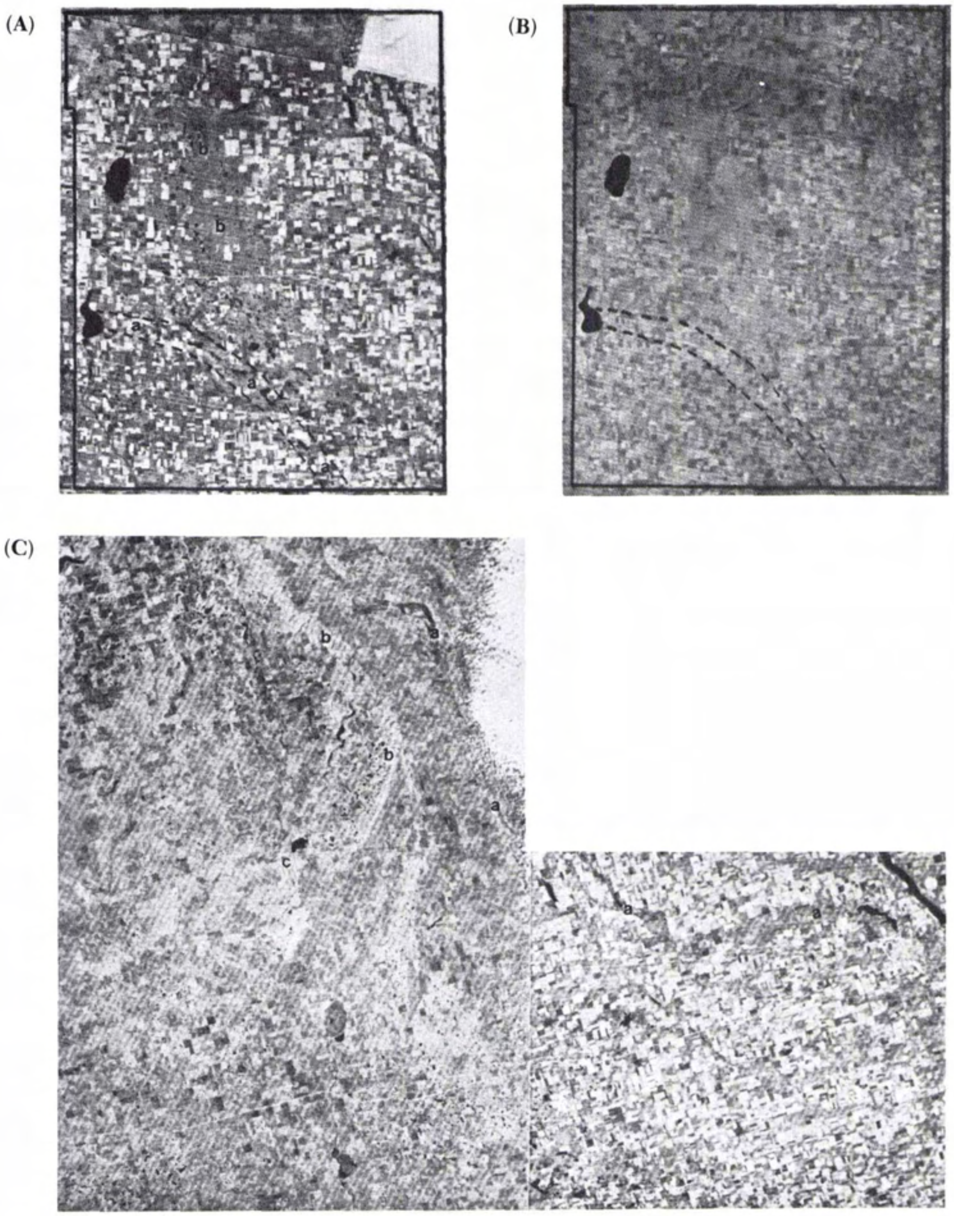

FIG. 6. Springtime Landsat images of study area. (A) Springtime (wet year) Band 5, Landsat image (21208-16144-5) of Aurora County (outlined in black, see Figure 1). Lake chains (a) and farmlands vs. well-drained morainal grasslands (b) can easily be distinguished. Parallel dashed lines delineate an "anomalous" curvilinear lake chain and associated soils overlying a pre-glacial valley. Note that the arc of this lake chain (a) deviates from glacial curvilinear trends. (Scale: 1:500,000, reduced to 1:769,000 for publication; north towards top of page.) (B) Springtime (dry year) Band 5, Landsat scene (2471-16382-5) of Aurora County (outlined in black, see Figure 1). Lake chains and associated soils (dashed parallel lines) are extremely difficult to delineate. (Scale: 1:500,000, reduced to 1:769,000 for publication; north towards top of page.) (C) Landsat springtime, Band 5 images (21208-16144-5, 2795-16271-5) of Firesteel Creek (a) which forms a curvilinear pattern as it flows from the Coteau du Missouri (b) towards the James River at Mitchell, South Dakota. The pattern appears dark due to wet soils which prevent the planting of crops in the early spring. Topographic break (valley) in the Coteau (c) is caused by a pre-glacial channel and is apparent due to vegetation and soil differences. Note the cloud cover in the upper right corner of the left image and the abrupt linear change in image contrast between the left and right images. (Scale: 1:500,000, reduced to 1:769,000 for publication; north towards top of page.)

Curvilinear and linear patterns were traced and mapped from 1:1,000,000-and 1:500,000-scale false-color infrared composite springtime Landsat mosaics onto an acetate overlay. Curvilinears are defined in this study as arcuate or curved large-scale tonal patterns whose width (0.2 cm on 1:500,000-scale imagery) is minor relative to length (1 cm). "Linear" describes the line-like character of an object or an array of objects (Sabins, 1978).

A single line is used to delineate a curvilinear pattern even if the pattern was considerably wider or narrower than the thickness of the pen line. For example, a moraine with an associated ice-marginal stream may appear as a curved pattern up to 0.2 cm wide, but it is traced as one curvilinear or linear line. The precise line width is not important because the purpose of this overlay is to study the trends or directions of glacial patterns rather than specific dimensions associated with glacial morphology or geology.

An anomalous tonal patterns overlay, constructed using springtime Landsat Band 5 imagery, outlined regions which appeared anomalously dark or light relative to their surrounding area and defined a sinuous or river valley-type pattern. Particular attention was given to any anomalous patterns which appeared to lie between, or connect one or more segments of, known buried valleys.

Geological Interpretation

Development of Surficial Expressions over Buried Valleys

Glacial erosion depends on the abundance, shape, and hardness of rock particles with which the glacial base is armored, the erodibility of the ground beneath the glacier, and the thickness and rate of movement of the glacier (Flint, 1971). A pre-glacial valley may be planed-off or totally filled in due to glacial processes and post-glacial deposition. Consequently, the surface expression of pre-glacial topography can be minimal or non-existent (Figure 7). However, glacial erosion and deposition did not totally obliterate all buried valleys. In some areas, slight depressions may still exist directly above a buried channel (Figure 7). Present-day glacially formed drainages may have anomalous bends where streams may deviate from the trend of other glacial features. It is hypothesized that east-west trending buried valleys in the region may deflect the course of glacially formed streams which erode downward and become influenced by the buried channel. These anomalous drainages and cross-cutting linears can be detected on drainage and linear/curvilinear overlays. Post-glacial erosional or depositional processes may subsequently fill in the slight depressions at some localities with fine-grained silts and clays, resulting in the formation of Argiaqualls, Haplaqualls, Fluvaquents, and Calciaqualls soils (Westin and Malo, 1978). These parameters were isolated on Landsat overlays as anomalous tonal patterns. In this study, patterns which cross-cut the trends of glacial features were considered as possible guides to buried valleys.

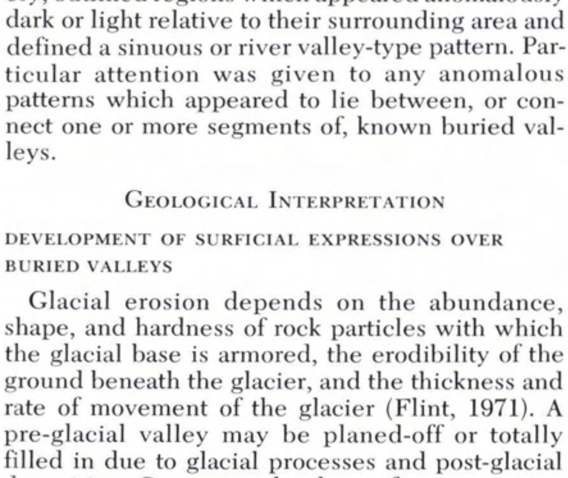

FIG. 7. Model of buried valleys beneath glacier tills. Slight depressions overlying buried valleys may be filled in with water and/or silts and clays. Soils and vegetation associated with depressions may be recognizable on Landsat scenes (A). In other areas, there is no surficial expression due to till thickness, glacial dynamics, or original shallow valley forms of pre-glacial channels (B).

In the study area, the glaciation factors discussed by Flint (1971) are relatively uniform except for the ice thickness and rates of movement. Flint (1955) observed that the ice was thinner and flowed more slowly near the Missouri River than it did farther to the east and north. Therefore, glacial erosion and obliteration of buried valleys should be less in Walworth County, which is located adjacent to the Missouri River, than in Aurora and Jerauld Counties, which lie farther east (Figure 1).

Drainage

Comparisons were made between the drainage patterns west and east of the Missouri River. A well developed dendritic drainage pattern is observed on the soft, flat-lying Pierre Shale west of the Missouri River. Larger meandering rivers draining from western South Dakota are entrenched and have developed many tributaries with a fine drainage density.

Drainage patterns observed in eastern South Dakota strongly reflect the effects of glaciation. The Missouri and James Rivers form the major drainage basins in the region. Tributaries to these major rivers were classified by Flint (1955) as follows:

- Valleys antedating one or more glaciations;
- Valleys cut by pro-glacial streams formed along the outer margins of end moraines; these valleys have no relation to any former valleys; and
- Minor streams in intermorainal swales, generally lacking outwash deposits and probably mostly glacial.

The latter two stream types of Flint (1955) exhibit curvilinear trends due to strong glacial influence, which help to separate them from valleys of the first type. These ice-marginal streams are commonly trapped between previously estab-

FIG. 8. Drainage patterns and density near the Fort Randall Dam on the Missouri River. Landsat, Band 5, springtime image (21208-16144-5) showing (a) the coarse to non-existent drainage density east of the Missouri River where large regions are drained into local ponds and depressions, (b) the dendritic, medium density west of the Missouri River, and (c) narrow band of dendritic drainage developed east of the Missouri River. (Scale: 1:500,000, reduced to 1:1,087,000 for reproduction; north towards top of page.)

lished recessional moraines and the retreating ice front (Flint, 1955). The larger ice-marginal streams (e.g., Firesteel Creek, Figure 6c) of glacial times remain as part of the present drainage system.

The trapping moraines in the James River Lowland are small. Therefore, the glacial streams in this region probably overflowed during times of high discharge, and were captured by the next ice-marginal stream down basin. As a result, a complex network of poorly developed or abandoned channels characterize the regional landscape.

To summarize, the youthful deranged drainage pattern east of the Missouri River is characterized by a paucity of well established channels or tributaries. The drainage density is coarse to non-existent because large areas are internally drained into local depressions (Figure 8) where groundwater systems are recharged or evaporation occurs.

Minor areas of dendritic drainage have developed in the study area, but are confined primarily to a narrow region adjacent to the Missouri River (Figure 8). Meandering and channel entrenchment in these areas are greatly subdued relative to areas west of the Missouri River.

Streams reoccupying pre-glacial valleys (Flint's first type) are the focus of this study. Some present-day eastern valleys are parallel to or lie in with western river counterparts (Figure 9). Similar drainage patterns or valley widths may be observed on both sides of the Missouri River. In these cases, the eastern stream is probably reoccupying a pre-glacial channel. In Walworth County, Swan Creek is an example of a present drainage which re-occupies a buried valley (Figure 9, Table 2).

Present drainages on the Coteau intersect perpendicularly with the Missouri River. Those which depart from this trend may indicate the presence of an underlying buried valley. Similarly, a modern channel may encounter a pre-glacial channel while down-cutting, resulting in a major channel deflection or alteration. For example, North Medicine Creek trends north-south, and then changes course about 45° towards the east near Blunt, South Dakota, possibly due to the presence of a buried channel (Table 2).

Some drainages are linear and cross-cut the north-south trend of the Coteau or the curvilinear glacial patterns. These linear drainages are considered anomalous and may indicate buried valley locations. Swan Creek in Walworth County trends east-west, thus cross-cutting trends of glaciation and the Coteau du Missouri (Figure 9, Table 2).

CURVILINEAR/LINEAR PATTERNS

Ice-marginal streams and associated moraines, such as the Firesteel Creek drainage near Mitchell, South Dakota, form curvilinear patterns on Landsat imagery (Figure 6c). Chains of glacial lakes, depressions, and ponds are also aligned in curved paths (Figure 6a and 6c). These curved features were formed by the retreating ice front during late Wisconsin time (Flint, 1955). Well developed features, such as Firesteel Creek, formed because the ice front maintained a stable position for an extended period of time.

Most glacially caused curvilinear patterns have a north-south trend along the Coteau and then bend towards the center of the James River Lowland (Figure 6c). Curvilinear patterns other than those arcing towards the James River are anomalous and may indicate buried valley locations (Figure 6a).

Linear patterns, caused by topographic or bedrock controls, are evident along the borders of the Coteau du Missouri and the Coteau des Prairies. These patterns are observed because of drainage (fine density, parallel versus non-existent), land-

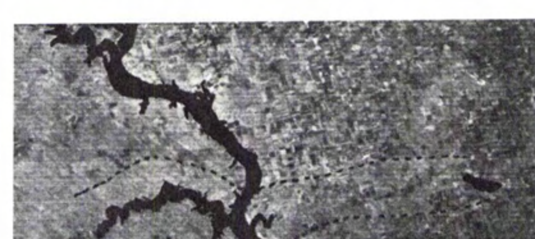

FIG. 9. Present valley of Swan Creek east of the Missouri River in Walworth County which reoccupies position of a former buried valley. Note that this valley lies in line with the Moreau River (western stream) and forms a pattern of approximately the same width. (Landsat scene 2472-16434; scale: 1:500,000,reduced to 1:1,087,000 for reproduction; north towards top of page.)

TABLE 2. THE LOCATION OF BURIED VALLEYS FROM THE INTERPRETATION OF LANDSAT IMAGERY: PREDICTIONS COMPARED WITH DRILL DATA

Anomalous Features	Location	Drilled	Confirmed by Drilling (Successful Landsat Analysis)
Lake chains cross-cutting trends of glaciation	Southern Aurora County (Figure 6a)	Yes	Yes
Elongate lake and depression cross-cutting trends of glaciation	Border of Aurora and Douglas Counties	Yes	No
Topographic break in the Coteau	Jerauld County	Yes	Yes
Bend or change in trend of glacially formed valley	North Medicine Creek, Sully County (Figure 6c)	No	Not drilled
Lake chain extending from known buried valley location to unknown region	Walworth County	Yes	Yes
Valleys with similar width, in line with western river counterpart	Swan Creek, Walworth County (Figure 11)	Yes	Yes

use or vegetation type (grassland versus cropland), and soil differences (well-drained versus poorly-drained) associated with the boundaries between the James River Lowland and the Coteaux (highlands).

COVER TYPES

Differences in soil type and moisture content and vegetation can be used to locate buried valleys. Well drained soils associated with rolling uplands, such as moraines and valley sides, can be distinguished from soils associated with lowland ponds, closed depressions, and valley bottoms (Figure 6a, Johnson *et al.*, 1974). As an example, the predominant soil types found to be overlying regions of known buried valleys in Campbell, Edmunds, and Hand Counties were of the Williams-Bowbells association (Table 3, Ensz, 1972). As shown in the diagrammatic sketch of Figure 10, Williams soils occur on the rises and Bowbells soils are formed in the swales. Minor soils of this association are Cresbard soils, found in some swales, and Heil, Nishon, Parnell, and Tonka soils associated with closed depressions (Ensz (1972) Figures 5 and 10). The poorly drained soils may have darker tonal reflectances that, if combined with a sinuous river-like pattern, may indicate the presence of a buried valley.

Vegetation and land use are directly related to differences in these soil types and their topographic positions. Runoff is slow on Williams and Bowbells soils. Water usually ponds on lowland Tonka-Nishon soils (Ensz, 1972; Figures 5 and 10). Williams-Bowbells soils are well suited to the production of most crops and hay or can be used as pasture lands. In some areas, upland slopes and valley sides are too steep for cultivation. As a result, grass becomes the predominate cover type. Lowland boggy areas, by comparison, are used for rangeland and wildlife management or are planted to later-sown crops including corn, sorghum, and alfalfa (Johnson *et al.*, 1974).

As observed on springtime Landsat false-color infrared images, newly plowed lowlands generally have a low reflectance, rangelands have a moderate reflectance, and fields of planted alfalfa have a high reflectance (Rahn and Moore, 1977; Figure 6a). This land-use practice enhances the location of Bowbells and Tonka-Nishon soils and may,

TABLE 3. SURFACE CHARACTERISTICS AND OCCURRENCES OF WILLIAMS-BOWBELLS SOILS ASSOCIATION

Soil	Color	Drainage Characteristics	Topographic Locations	Surface Compositions
Williams	Dark grayish-brown	Well drained	Rises	Loam
Bowbells	Dark grayish-brown	Mod. well drained	Swales	Loam
Cresbard	Dark-gray	Mod. well drained	Swales	Loam
Nishon	Dark-gray	Poorly drained	Closed depressions	Silt-loam
Parnell	Dark-gray	Very poorly drained	Closed depressions	Organics
Tonka	Dark-gray	Poorly drained	Closed depressions	Silt-loam

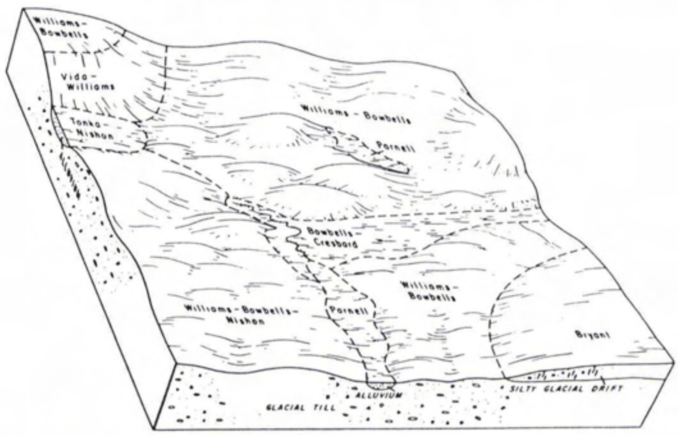

FIG. 10. Diagrammatic sketch illustrating topography and occurrence of Williams-Bowbells soil association (after Ensz, 1972). Note that Tonka-Nishon, Parnell, and Bowbells soils are associated with bottomlands.

therefore, enhance the pattern anomalies above pre-glacial valleys.

In some lowland areas when crops are planted during wet years, their growth is seriously retarded or the crops are drowned. This will reduce the reflectance of these areas. Other local variations in crop production or vigor and associated reflectances can be caused by the presence of a clay pan, sand, gravel or bedrock substratum, soil-profile texture, salinity or alkalinity, climate, and excessively-drained versus poorly-drained soils (Westin *et al.,* 1976; Moore and Meyers, 1972a, 1972b).

Data Synthesis and Drilling Verification

Anomalous drainage patterns, drainage densities, and valley characteristics were interpreted from the drainage overlay. Anomalous curvilinear and linear patterns were isolated on the curvilinear/linear overlay. Finally, all known buried valley locations in the study were combined with isolated anomalous patterns and interpreted for delineation of previously undiscovered buried valleys.

The effectiveness of using Landsat imagery for locating buried valleys in eastern South Dakota was tested in Jerauld, Aurora, and Walworth Counties (Figure 1). The South Dakota State Geological Survey supplied unpublished bedrock surface maps for these counties following their 1978 summer drilling program. A comparison between predicted and drilled buried valley locations was conducted (Table 2).

Results

The Landsat analysis of Walworth County was highly successful. Two buried valleys that were correctly delineated are correlated with drill data. The southernmost is a reoccupied, shallow buried valley (Figure 11, Table 2). It was delineated by a present day stream which has reoccupied the pre-glacial or pro-glacial valley. This valley lies in line with, and has a similar width as, a western river counterpart, and trends east-west rather than north-south. The northernmost pattern is related to a deeper, pre-glacial valley (Figure 11, Table 2). It is delineated by a minor chain of ponds and depressions which connect with the location of a known buried valley.

Mixed results were obtained in Aurora County (Table 2). Many lake chains and extensive morainal areas are observed in this area. A lake chain which begins on the western border of Aurora County and curves southwest towards Douglas County is related to a buried valley (Figures 6(A)(a) and 6(B); Table 2). This curvilinear lake chain anomalously cross-cuts the trend of moraines and ice-marginal streams. Several post-glacial drainages, and the relative abundance of lakes in and around the county, however, complicate the interpretation. As

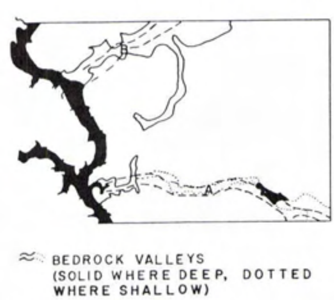

FIG. 11. Buried valleys predicted by Landsat analyses compared with valleys (subsequently) defined by drilling in Walworth County. (A) An exhuming, shallow buried valley, possibly proglacial and (B) a deeper, preglacial valley were correctly predicted using Landsat analyses. (Scale: 1:1,000,000; north towards top of page.)

a result, this buried valley was overlooked during the Landsat analysis for this county.

A portion of a buried valley is apparent in Jerauld County. A break in the Coteau, in the vicinity of Crow Lake, represents a pre-glacial valley through the Coteau (Figure 6c, Table 2). The curvilinear pattern associated with this break in the Coteau is oriented oppositely to those curvilinears related to glaciation. Accurate extension of the buried valley beyond Jerauld County could not be determined by Landsat analysis.

Defining buried valleys by Landsat analysis or by drilling cannot be totally accurate. Drilling grids of three miles or less are subjectively interpreted and the grid data are subjectively interpolated. Landsat interpretations are subjective due to the surficial expression of buried valleys and to resolution and scale problems inherent in the data. For example, Landsat drainage patterns associated with exhuming pre-glacial valleys (as demonstrated in Walworth County) appear to match quite closely with drill data. The precise boundaries of the underlying pre-glacial valley and its tributaries, however, cannot be accurately defined by either drill data or Landsat imagery. Therefore, correlation statistics are inappropriate to this study.

Conclusions

Winter, spring, and early summer, 1:500,000-scale Landsat mosaics provide the most useful information for locating pre-glacial buried valleys. Winter Band 7 Landsat images with a light snow cover are most effective for identifying drainage patterns, density and characteristics, and major topographic features. Minor drainage mapping refinements can be made using springtime false color infrared composite Landsat scenes.

Springtime Band 7 Landsat images obtained during wet years are most useful for delineating lake chains, ponds, closed depressions, curvilinear features, and some tonal anomalies. Springtime Band 5 Landsat scenes best delineate soil type and soil moisture differences. Spring images are, therefore, most effective in isolating tonal anomalies associated with soils and vegetation changes.

Springtime false-color infrared Landsat images best delineate curvilinear/linear features related to glaciation.

The following method proved most effective for locating pre-glacial valleys in eastern South Dakota:

(1) Construction of springtime (wet year) and winter mosaics at 1:500,000 scale.
(2) Construction of known buried valley overlay.
(3) Construction of drainage pattern, density, and valley characteristics overlay.
(4) Construction of curvilinear/linear overlay.
(5) Construction of "anomalous tonal pattern" overlay.
(6) Isolation of anomalous drainage characteristics, curvilinears and linears, and tonal patterns which meet the following criteria:
   (a) represent valleys which lie in line or on trend with a present-day western valley.
   (b) represent valleys which have similar widths as western counterparts.
   (c) represent valleys which have similar dendritic drainage patterns and/or densities as western valley equivalents.
   (d) represent valleys which depart from draining perpendicularly to the Missouri River or otherwise have a major anomalous change in direction.
   (e) represent linear and curvilinear patterns which cross-cut the north-south trend of the Missouri Coteau or the curvilinear patterns associated with glacially formed ice-marginal streams and moraines. These sinuous or curvilinear anomalous patterns are caused by chains of lakes, depressions, or soil or vegetation changes.
   (f) represent anomalous tonal patterns caused by distinct soil or vegetative changes which form a sinuous (valley like) path.
(7) Final integration of all analyses and manual interpretations (Steps 1–6) and transfer of information onto one map.
(8) Field checking by obtaining drill data.

Due to thin till thicknesses, glacial dynamics, and well entrenched pre-glacial channels on the Coteau, delineation of buried valleys is most accurate near the Missouri River. The best indicators or guides to buried valleys are present-day streams which now reoccupy pre-glacial valleys and chains of lakes, depressions, and associated soils which overlie yet-to-be-exhumed buried valleys (Table 2).

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