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Landsat Applied to Landslide Mapping

Landsat imagery is not recommended for landslide mapping in Colorado.

Introduction

Landsat imagery has several properties that may make it useful for the mapping of landslides. Of prime importance, the small scale of the imagery may aid in the delimitation of large landslides, which may be obscured by the detail of large-scale underflight photography. Second, individual bands may contain different information applicable to landslide recognition. Also, because Landsat coverage is repetitive, seasonal conditions can be used for interpretation. Computer analysis of Landsat may prove to be a useful tool, particularly if spectral characteristics are of value to interpretation.

The objectives of this research were threefold. First, we investigated whether landslides can be identified and delimited on Landsat imagery, and which methods of inquiry are the most appropriate. Second, we determined the accuracy with which landslides can be identified and how this accuracy is influenced by terrain conditions. Third, we investigated whether Landsat can be used to map landslides on a regional basis, for instance, on a state-wide basis.

For the purpose of this study, a landslide is defined as having some or all of the characteristics illustrated in Figure 1. These are features mainly of rotational landslides; translational landslides and debris flows display other characteristics. However, the identification of the characteristics shown in Figure 1 is a simple test of landslide recognition on Landsat imagery.

Abstract: *A variety of features characteristic of rotational landslides may be identified on Landsat imagery. These include tonal mottling, tonal banding, major and secondary scarps, and ponds. Pseudostereoscopic viewing of 9 by 9 in. transparencies was useful for the detailed identification of landslides, whereas 1:250 000 prints enlarged from 70 mm negatives were most suitable for regional analysis. Band 7 (0.8-1.1 μm) is the most useful band for landslide recognition, due to accentuation of ponds and shadows. Examination of both bands 7 and 5 (0.6-0.7 μm), including vegetation information, was found to be most suitable. Although, given optimum terrain conditions, some landslides in Colorado may be recognized, many smaller landslides are not identifiable. Consequently, Landsat is not recommended for detailed regional mapping, or for use in areas similar to Colorado, where alternative (aircraft) imagery is available. However, Landsat may prove useful for preliminary landslide mapping in relatively unknown areas.*

Methods

Two procedures were followed during the study. First, we identified features from

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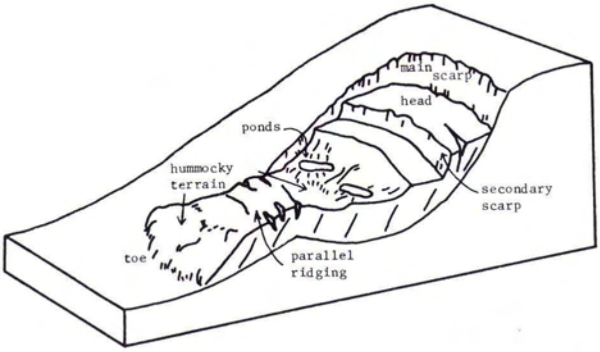

FIG. 1. Block diagram showing the characteristics of a rotational landslide (after Varnes, 1958).

known landslide areas recognizable on Landsat imagery. Second, we mapped landslides from Landsat imagery onto 1:250 000 topographic maps in unknown areas, without reference to any source except Landsat. Some of these areas later were checked against fieldwork and existing maps. Throughout the study, the most appropriate methods of utilizing Landsat imagery for landslide identification were sought. We investigated the suitability of different spectral bands and seasons of satellite bypass.

Two major methods of inquiry were used. Nine-by-nine in. transparencies were examined under a Bausch and Lomb Zoom 240 Stereoscope mounted on a Mims-3 light table. Also, 1:250 000 prints produced from Landsat 70 mm negative transparencies were analyzed. Generally, we found stereoscopic analysis most useful for detailed landslide identification, whereas the prints were suitable for regional analysis.

A maximum optimum magnification of 10 to 15 times was possible using the stereoscope. Prints could be enlarged to a maximum scale of about 1:250 000, after which scan-lines became distracting. Prints of about this scale were reasonably useful, because of their compatibility with landslide and geologic maps prepared at the same scale. Paired frames were viewed in pseudostereo using two bands of the same scene as a stereopair, and individual frames in mono.

IDENTIFICATION OF LANDSLIDE FEATURES

Various types of terrain in southern and western Colorado were investigated (Figure 2). These include areas of high relief (central San Juan Mountains) in the Durango 2 degree quadrangle; areas of predominantly fluvial dissection in the Grand Junction 2 degree quadrangle; the Sawatch Range and plateaus (the Grand Mesa region) in the Montrose 2 degree quadrangle; and areas of

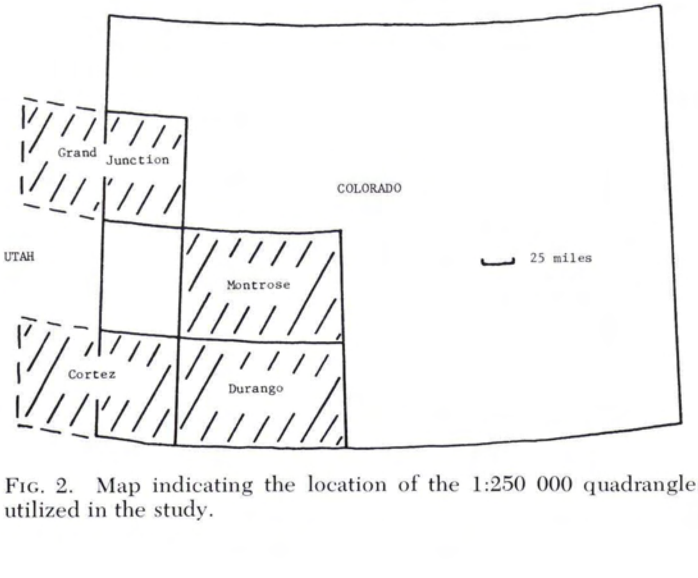

FIG. 2. Map indicating the location of the 1:250 000 quadrangles utilized in the study.

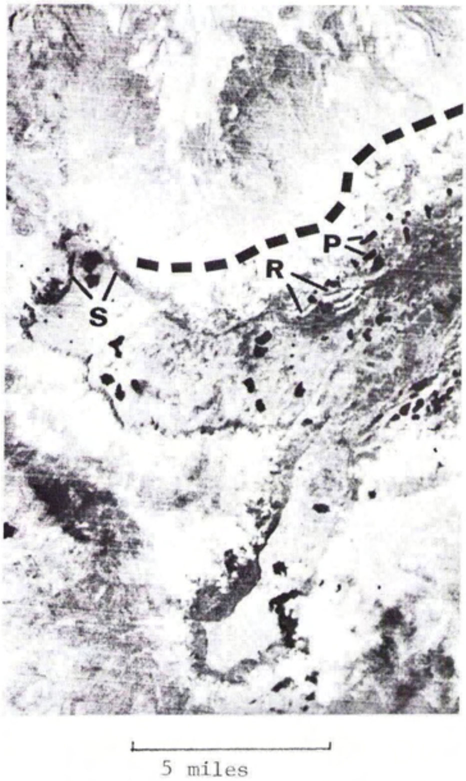

FIG. 3. Part of Landsat frame 2170-17141 (band 7), showing Grand Mesa Landslide (Grand Junction quadrangle). Interpreted from image: S—major scarp; R—parallel ridging; P—pond; broken line represents northern extent of landslide.

FIG. 4. Part of Landsat frame 2187-17080 (band 7), showing Cerro Summit landslide region (Montrose quadrangle). From ground truth: G—gravel terraces; broken line represents western and northern boundaries of landslide.

low relief in the eastern portion of the Cortez 2 degree quadrangle. The investigation included different scales of landsliding ranging from relatively large areas, for example the Grand Mesa and Cerro Summit areas (Figures 3 and 4), each over 30 mi², to intermediate slides, such as the Silver Mountain Landslide (Figure 5), of about 12 mi², and smaller slides of less than 1 mi².

Figure 1 shows a classic, fresh landslide form. Some or all of the features illustrated may be apparent in the field, depending on landslide development and the extent of alteration. In known landslide areas some of these features could be identified on Landsat imagery. In many cases one or only a few of the features were recognizable. Several types of patterns on the imagery were useful in identifying and delineating landslides:

- tonal mottling
- tonal banding
- major scarps
- secondary scarps
- ponds
- spatial relation of the features
- regional differentiation between landslides and the surrounding terrain.

In order of increasing utility, the principal patterns are mottling, a major scarp, regional differentiation, and ponds.

TONAL MOTTLING

Figures 3 and 5 illustrate tonal mottling, defined as a high degree of localized tonal variations. Mottling is thought to be a function of hummocky terrain caused by disruption from landsliding of the previous surface and its drainage network. Therefore, mottling is a function of variation in radiance due to aspect differences. Variations in vegetation type and cover may also affect tonal variation. In some landslides, small areas of high radiance may represent rotated blocks.

The area of mottling is thought to represent the area of the slipped mass and therefore, at best should give a minimum delimi-

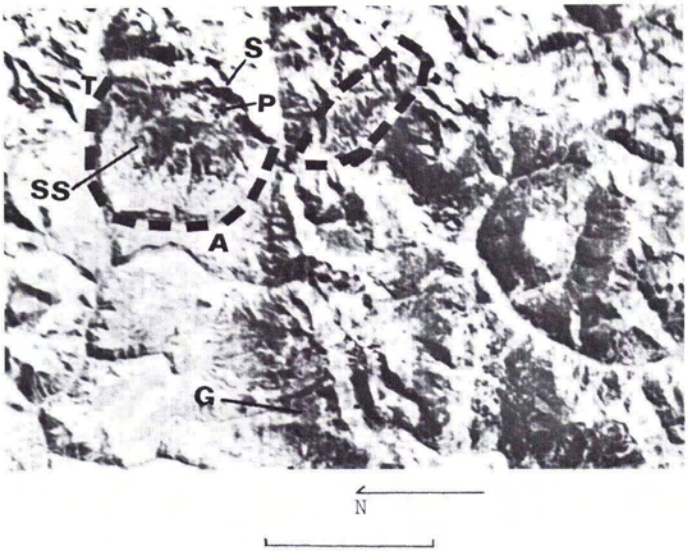

FIG. 5. Part of Landsat frame 1066-17254 (band 7), showing Silver and Yellow Mountain Landslides (Durango quadrangle). Interpreted from image: S—major scarp; SS—secondary scarp; P—pond. From ground truth: A—location of Ames Landslide; G—glacial drift; T—location of town of Telluride; broken lines delimit the Silver Mountain (north) and Yellow Mountain (south) Landslides.

tation of the landslide. However, other areas may have a similar textural appearance on Landsat imagery, for example, areas covered by glacial drift (Figure 5).

The mottling characteristic was generally found to be most useful for interpreting larger landslides, although there are major exceptions to this rule, for reasons to be discussed in the succeeding section. In smaller landslides, tonal differences were less easily identifiable due to the low resolution of the Landsat system.

Distinctive mottling characterized less than half the landslides present in the study area. A high degree of subjectivity is involved in differentiating mottling due to landsliding from extreme tonal variation caused by local complexities of other surface features.

TONAL BANDING

Associated with the mottling characteristic, tonal banding was observed locally in some landslides (Figure 3). The banding was interpreted as parallel ridging, which also affects radiance as a function of aspect. Tonal banding generally was used as supplementary evidence because confident interpretation could not be made on its presence alone. Where identified, tonal banding indicates the probable direction of landslide movement perpendicular to the bands.

MAJOR SCARPS

Due to the strong differences in radiance caused by aspect (shadows), scarp identification was especially useful for landslide recognition. Scarps were identified as dark arcuate features. In many landslides, particularly the smaller ones, such features were the only recognizable characteristics. This, however, presented a major problem because landslide scarps could be confused with other steep slopes or free faces, or even cirque headwalls in mountain regions. Spatial relations between the scarps and the local drainage patterns were helpful in recognizing landslides. In only a small fraction of landslides could major scarps be identified with confidence. This may be due either to their absence or to lack of expression on the Landsat imagery.

SECONDARY SCARPS

Secondary scarps are expressed on Landsat imagery as dark arcuate patterns located downslope of the main scarp. They are smaller than, and sub-parallel to the main scarp. Where a number of secondary scarps occur in a small area, they may form an imagery pattern similar to parallel ridging.

Secondary scarps were identified in only the larger landslide areas (Figure 5), and were used solely as additional evidence of landslide activity.

PONDS

Ponds in the hummocky terrain of a slipped mass are evident in landslides of different sizes (Figures 3 and 5). They are particularly obvious on band 7 images. Ponds are not restricted to landslide terrain and could be identified in less than a quarter of known landslide areas studied.

SPATIAL RELATIONSHIPS BETWEEN FEATURES

The spatial relationship between features was particularly useful in delimiting the larger landslides. Confidence of identification was greatly improved in accordance with the number of features that could be observed in any one particular landslide.

REGIONAL DIFFERENTIATION BETWEEN LANDSLIDES AND SURROUNDING TERRAIN

On a regional scale, changes in the appearance of otherwise uniform terrain may indicate landslide activity. There is no set rule for general differentiation, but marked textural differences and obvious changes in drainage patterns are good indications of landslide terrain (Figure 6).

BANDS AND SEASONS OF IMAGERY

Band 7 (0.8-1.1 μm) is the most useful individual band for landslide recognition, because ponds and topographic features are accentuated, due to the band's lack of sensitivity to blue reflectance from water bodies and shadows. Scarps stand out in band 7 due to shadow-enhancement and, possibly, vegetation differences. The recognition of vegetation is, however, easiest from band 5 (0.6-0.7 μm), due the band's lack of sensitivity to green reflectance. After band 7, band 6 (0.7-0.8 μm) was found to be the next most useful single band, being most similar to band 7. However, examination of bands 7 and 5 together provided most of the information.

Late-summer imagery (August to October) provided the most cloud-free coverage. Early-snow-season imagery is potentially useful for enhancing slight topographic variation from differential snow cover. However, the greater part of the information could be obtained from snow-free imagery.

CHECKING INTERPRETATION

Where interpretation was carried out in unknown areas, regional landslide and geo-

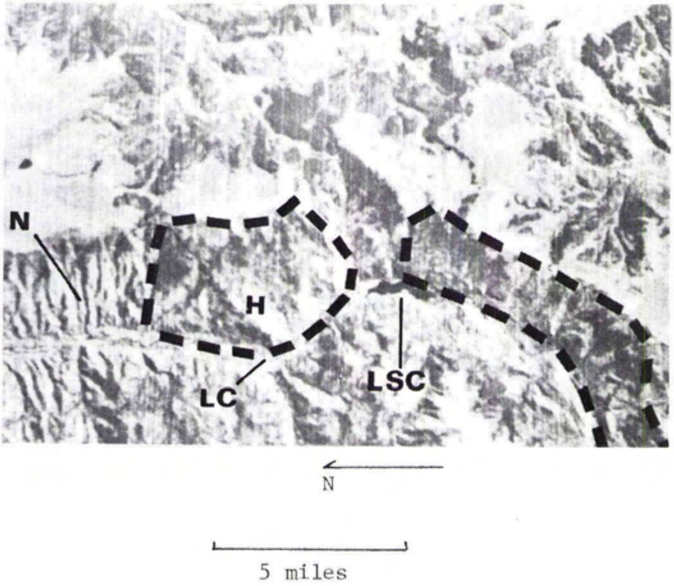

FIG. 6. Part of Landsat frame 1425-17190 (band 5), showing landslides in the area of Lake City, San Juan Mountains (Durango quadrangle). Interpreted from image: H—hummocky terrain; N—'normal' drainage pattern; broken lines represent limits of landslides recognized. From ground truth: LC—location of Lake City; LSC—location of Lake San Cristobal.

logic maps prepared by Colton *et al.* (1975a, 1975b, 1975c, 1975d), Steven *et al.* (1974), and Tweto *et al.* (1976) were used to check the results. Field-checking of landslides in one such area was also carried out in summer 1976.

Figure 6 shows a region where landslides were interpreted before field-checking. These areas were later confirmed as landslides, but numerous other smaller slides in the region were not recognized.

Limitations of Landsat imagery for use in identifying landslides stem from the lack of unique spectral characteristics and the scale of the imagery. The relationship between slope instability and vegetation is insufficiently consistent to warrant the use of tree species as an indicator of landslides. Known landslides are obscured by heavy coniferous forest. However, upper and lower treelines roughly correspond to the limits of a hillslope region in which landslides are most common.

Landslides occur within a wide range of surficial materials. Therefore, the spectral properties of these materials are not particularly useful in identifying landslide areas.

Since image tones vary according to slope aspect, the imagery expression of a landslide is a function of its position in relation to the sun and the Landsat satellite. For example, in Figure 5 the Silver Mountain and Ames Landslides border a common valley and face west and east respectively. During the satellite pass, the sun illuminated from the east. The topography of the Ames Landslide is completely illuminated and appears as an almost consistently bright slope. (Conversely, a landslide can be entirely in shadow, and therefore unidentifiable.) The Ames Landslide is considerably smaller than the slide on Silver Mountain. However, other smaller landslides are evident where illumination conditions are more favorable.

The morphology of a landslide is its most distinctive and easily recognizable characteristic. Unfortunately, topography is difficult to interpret on Landsat imagery due to the small scale. Pseudostereo viewing of two essentially identical Landsat frames does not substantially accentuate topography. However, enlargements of imagery, particularly in conjunction with pseudostereoscopic interpretation, reveal some landslide morphology. The effectiveness of this technique is limited by the decrease in image quality that accompanies the enlargement of imagery.

Even though the larger landslides are generally easier to identify than small ones, detectibility of the small slides varies greatly according to aspect, vegetation masking, the degree of topographic expression, development of the landslide, and the certainty with which topographic features could be identified. The influence of aspect is most prevalent in areas of high relief. The association between scale, relief, and aspect, and its effect upon landslide identification became apparent during the mapping of the Sawatch Mountains and the eastern portion of the Cortez 2 degree quadrangle. In neither case are large areas of hummocky landslide terrain evident, but smaller landslides of similar size occur in these contrasting terrains. However, the Sawatch Mountains are much more difficult to interpret and map because of the greater relief. Landslide scarps are easily confused with alpine free faces, since extreme aspect effects reduce the observation of downslope features. Several arcuate scarps in Mesa Verde National Park (Cortez sheet) exist in sharp constrast to the linearity of adjacent valleys. More even illumination of the shallow valleys in the Cortez area facilitates the observation of a greater number of landslide characteristics and, thus, increases identification capability. This example also demonstrates the importance of observing as many features as possible and utilizing the interpretation of associations between them. Otherwise, hummocky terrain, by itself, could just as well be interpreted as glacial drift, and a small grouping of ponds could simply reflect interception of the water table.

In general, the ability to identify landslides on Landsat imagery is limited by the fact that Landsat information is predominantly spectral, and landslides do not have characteristic spectral properties. The spectral appearance of a particular slide depends mostly on the nature of the surface and its orientation rather than the slide itself. The imagery expression of morphology, the most consistent characteristic of landslides, is variable on Landsat imagery. From experience, underflight photography reveals significantly greater and more consistent information on landslide location and character.

Also, accurate mapping of landslides is hindered by the inability to determine distinct boundaries. The upper limit of a landslide is generally marked by a main scarp, but the lower boundary is often vague. For example, the toe of a landslide may extend well below the limit evident on the Landsat imagery (Figure 3).

The recognition of landslide features varies according to conditions of terrain. Some of the larger landslide areas, such as those on Grand Mesa and Silver Mountain (Figures 3 and 5), display recognizable characteristics. In contrast, the Cerro Summit-Cimmaron Ridge region, despite its large size, displays few landslide characteristics on Landsat imagery (Figure 4). In all bands, this landslide area appears relatively uniformly gray, while localized white areas in the northern part of the region are due to the presence of gravel-topped plateaus. This information alone is insufficient to diagnose landsliding. There are a number of possible reasons for the lack of imagery evidence of landsliding:

(a) in the southern part of the landslide area, coniferous vegetation may obscure landslide features;

(b) much of the recent landslide activity, particularly in the northern region, is occurring in several small areas which may be too small to see on Landsat imagery; and

(c) in the northern portion of the area, relief is insufficient to accentuate topographic slope features.

It would seem, therefore, that there is an optimum amount of relief necessary for landslide identification, depending on site conditions. Whereas much relief obscures landslide information because of slope aspect effects, too little relief also appears to be undesirable.

Conclusions

Some landslides in Colorado can be identified and, to a degree, delimited on Landsat imagery, but the conditions of their identification are highly variable. Because of local topographic, geologic, structural, and vegetational variations, there is no unique landslide spectral appearance on Landsat imagery. Accordingly, in most cases, supplementary information is necessary in order to positively identify landslide areas.

Since morphometric features are not consistently recognizable, the mapping of landslides is subject to much variation in accuracy. Consequently, Landsat imagery is not recommended as a regional mapping tool in areas similar to Colorado. However, as has been described, some areas do demonstrate convincing evidence of landsliding. Therefore, it is possible that in other less well-known regions where the scale of activity is particularly large, where geologic conditions are more uniform, and where a strong case may be made for frequent monitoring of landslide activity, Landsat imagery may have greater application. Also, Landsat imagery may be a suitable tool for landslide mapping in areas where there is no alternative (larger-scale) imagery.

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