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APPLICATION OF LANDSAT IMAGERY TO GEOLOGIC MAPPING IN THE ICE-FREE VALLEYS OF ANTARCTICA

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ABSTRACT

The Ice-Free Valleys region of Antarctica provides a test site in which the LANDSAT imagery can be applied to geologic studies with minimum interference of the effects of vegetation cover and chemical weathering. Geologic interpretation in several areas near McMurdo Station confirmed that the LANDSAT imagery is useful as a regional mapping tool in these areas. The imagery provides the necessary base for correlation of available geologic information. The imagery can also provide the essential information to supplement available field data for compilation of composite regional maps. Comparisons between available mapping and LANDSAT image interpretations were made in the Ice-Free Valleys and Koettlitz-Blue Glacier areas. An improved composite geologic map was compiled for the Ice-Free Valleys.

Density analyses and color-additions were evaluated as techniques for enhancement of significant tonal and spectral contrasts. Field photometric measurements and samples were taken to help establish relationships between lithologies and their corresponding spectral reflectance values.

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INTRODUCTION

The Ice-Free Valleys area of Antarctica was selected as a geologic study site to assess the potential for geologic mapping in an area where vegetative cover is absent and chemical weathering is minimal. All exposed rock surfaces in this region are essentially fresh and were expected to present investigators with a situation in which the image brightness values could be related to the spectral reflectances of the rocks with little interference from complicating factors.

Field observations were necessarily restricted, due to the logistic problems, but Wyoming investigators were able to obtain some field spectral readings and rock samples through the efforts of Dr. Edward Decker and Mr. Edward Pruss. With these field data, the University of Wyoming investigators were not only able to apply the LANDSAT imagery to compilation of regional geologic maps, but also to study some particular spectral relationships between selected rocks and their image presentation.

OBJECTIVES

The study of the Ice-Free Valleys, Antarctica was designed to evaluate the LANDSAT data for geologic applications in an area of well-exposed, fresh rock where regional mapping is needed. Available geologic maps of the area are of varying detail and quality. Consequently, there is considerable need for compilation of uniform regional maps from both available maps and field data and from information interpreted from imagery.

The proposed objectives of this Ice-Free Valleys study were to:

1. Prepare regional geologic and structural maps based on prior studies.

2. Determine the reflectance spectra of key rock samples.

3. Occupy calibration sites during ERTS passes.

4. Construct color-enhanced, band-composite images for study area.

5. Evaluate microdensitometric measurements as a tool in geologic study.

6. Produce improved regional geologic maps of the area.

7. Assess the contribution of LANDSAT data in this work.

The success of the initial geologic studies in key areas of the Ice-Free Valleys suggested that it would be worthwhile to search the Antarctic imagery and determine if other areas might be suitable for geologic mapping. This effort was undertaken at no additional cost to NASA utilizing unexpended funds from the initial study.

The objectives of this study were as follows:

1. All available LANDSAT-1 imagery of Antarctica was reviewed to determine where coverage and exposures permit geologic mapping.

2. Additional areas adjacent to the previously mapped Ice-Free Valleys or in other exposed regions of Antarctica were selected for study based on these reviews. The Koettlitz-Blue Glacier area was selected.

3. Geologic mapping was attempted in selected new areas and checked against field data and available geologic maps.

SUMMARY OF SIGNIFICANT RESULTS

Studies in the Ice-Free Valleys area resulted in the compilation of a sizeable library of maps and publications. A bibliography of geologic information was compiled for the Ice-Free Valleys and Ross Ice-Shelf areas, and a regional geologic map was compiled (at 1:100,000 scale) from all available data for the Ice-Free Valleys.

Rock reflectance measurements were taken during the Antarctic summer of 1973 by Dr. Edward Decker, who was in Antarctica to obtain borehole heat-flow measurements as part of another University of Wyoming research program. Spectral reflectances of rocks (mostly mafic lava flows) in the McMurdo and Ice-Free Valleys areas were measured using a filter-wheel photometer (Raines and Lee, 1974) equipped to measure reflectances in the four LANDSAT bands (Appendix A). However, the photometer was not operating well and many of the readings are of questionable accuracy or cannot be properly related to the reflectance standard. Most of the readings do give some measure of relative rock reflectance in ERTS bands. We have since concluded that reliable field spectral measurements on rocks and minerals should be made with a more sophisticated instrument (such as the field spectrometer designed by NASA/Jet Propulsion Laboratory). The JPL spectrometer is, unfortunately, a one-of-a-kind item. Practical field spectrometers are not yet commercially available.

A series of samples were collected at regular intervals across a large, differentiated, mafic sill near Lake Vida in the Ice-Free Valleys. These samples were collected to determine the cause of tonal variations observed in LANDSAT images. Chemical analyses of the sample suggest that the tonal variations in this sill are controlled by changes in the iron content of the rock.

False-color images were prepared for a number of areas by the diazo method and with an optical multispectral viewer. These images were useful in defining boundaries of sea ice, snow cover, and in the study of ablating glaciers, but were not very useful for rock discrimination.

The Joyce Loebl/Tech Ops isodensitracer and the Spatial Data Systems video analyzer were used to prepare density slices of selected Antarctic images. The approach involved training on specific rock types and extrapolation of equidensity characteristics from known to unknown areas. The results were not satisfactory for the preparation of geologic maps, but density slicing was useful in detailed study of selected areas where contrasts depicting lithologic boundaries were difficult to delineate by eye.

It was determined that adequate regional geologic maps could be prepared with LANDSAT images for Antarctica only when basic information on the nature and distribution of rock types is known. It is <u>not</u> possible to use LANDSAT images for geologic mapping, even in vegetation-free areas, without some knowledge of the geologic section. In the preparation of regional geologic maps, the LANDSAT images proved to be of greatest value in up-dating and improving reconnaissance maps.

Successful application of the LANDSAT imagery to geologic mapping in the Ice-Free Valleys encouraged us to extend the study to other snow-free areas. All available LANDSAT imagery through 1974 was reviewed on microfilm. A number of images were then ordered and examined to determine their suitability for geologic mapping. Only areas adjacent to the Ice-Free Valleys were found suitably exposed. One of the best exposed areas lies south of the Ice-Free Valleys and southwest of McMurdo Station (the Koettlitz-Blue Glacier region). In this area, the LANDSAT coverage is excellent and can be readily applied as a mapping tool. New Zealand geologists and geomorphologists have prepared a reconnaissance geologic and geomorphic map of the area. The Koettlitz-

Blue Glacier area was mapped from the LANDSAT imagery by a geologist entirely unfamiliar with the area. The results of this interpretation demonstrate that some major lithologic distinctions can be made, but accurate identification of various lithologic units is impossible without some prior knowledge of the lithologies present.

GEOLOGIC MAPPING

Pre-Quaternary Geology of the Ice-Free Valleys Area

A geologic map (Plate 1) was compiled from published and unpublished maps of the Ice-Free (Dry) Valleys (Fig. 1) using the new United States Geological Survey 1:100,000 base. It includes unpublished work of the University of Wyoming Antarctic parties 1967-1972, and is the most complete geologic map of this area currently available. Plate 1 does not depict deposits of Quaternary age.

The Ice-Free Valleys are underlain by rocks that can be divided into three major groups. The oldest group is the "basement" complex which comprises metasedimentary rocks, gneiss, schist and associated syntectonic and post-tectonic felsic intrusions. The metasedimentary rocks are mostly Cambrian in age but may include some rocks of Late Precambrian age (Warren, 1969). The metasedimentary and metamorphic rocks are meta-limestones, marbles, biotite and hornblende gneisses, and diopsidic gneisses and schists. These rocks have been assigned to the Asgard Formation of the Koettlitz Group of the Ross Supergroup by Grindley and Warren (1964). They are included in metasediments on Plate 1. With the exception of the marbles and metalimestones that show a light tone (high reflectance) on LANDSAT band 7, these units

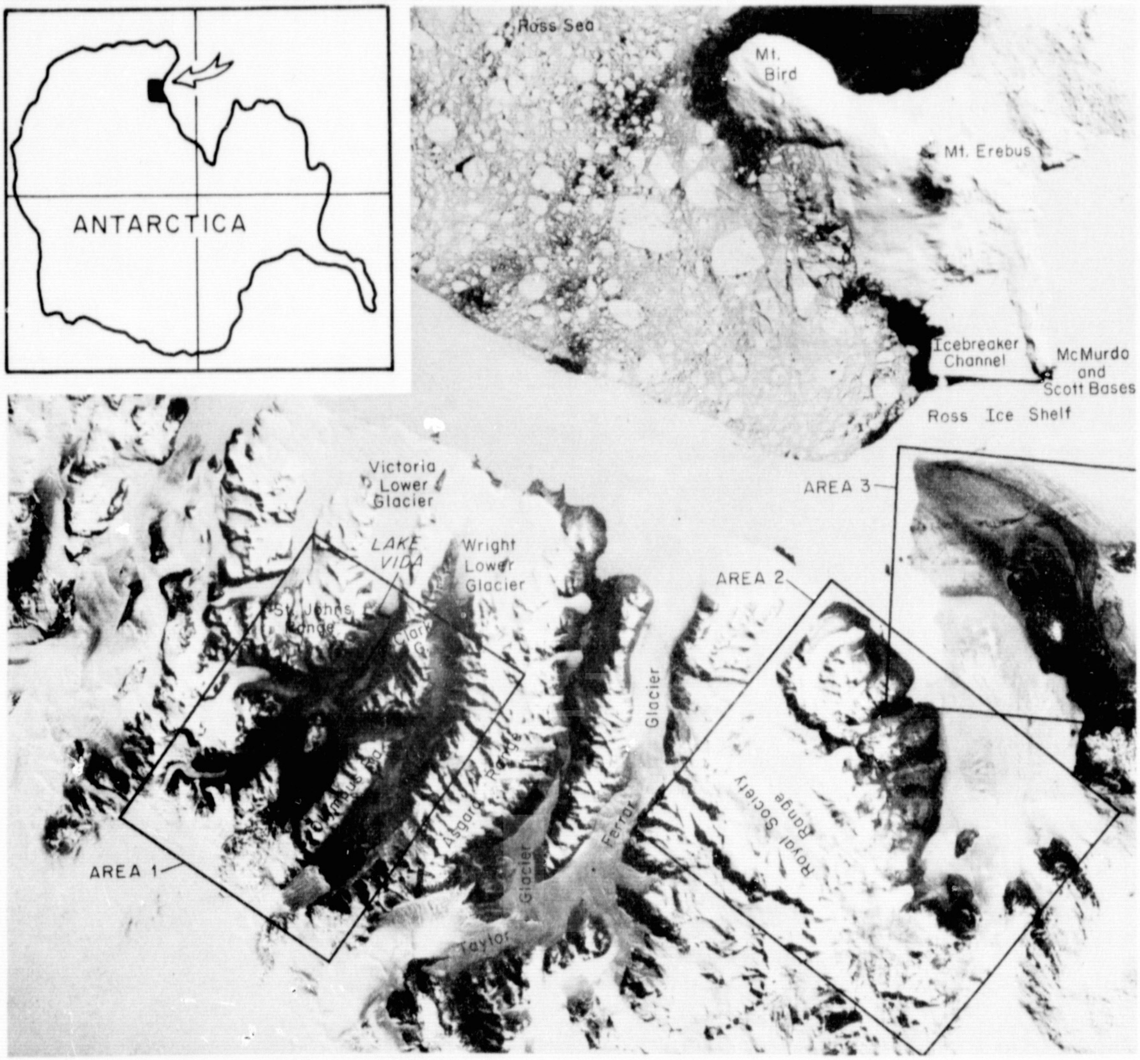


Figure 1. LANDSAT band 7 image of the McMurdo/ Ice-Free Valleys area, Antarctica showing major physiographic features and the areas mapped in this study.

show intermediate to dark tones because they have a higher proportion of mafic minerals (dark colored minerals usually richer in iron).

Syntectonic (originated during orogeny) felsic intrusives include gneissic bodies that commonly grade into metamorphic rocks. These rocks usually show a great variety of textures and structures as well as variations in composition. Such units may include rocks that are pre-orogenic (Olympus Granite-Gneiss of Gunn and Warren, 1962 (shown as augen gneiss (ag) on Plate 1)) and syn-orogenic (Larsen Granodiorite and Theseus Granodiorite of Gunn and Warren, 1962, (shown as C01 on Plate 1)), or may simply be various facies of reconstituted metasedimentary rock (Smithson and others, 1971). The more homogeneous facies (usually more felsic) of such units may show a higher reflectance on LANDSAT band 7 than associated metamorphic rocks, but their complex compositional variation suggests that they will show a wide range in reflectance and thus be difficult to distinguish from metasedimentary and metamorphic rocks.

All students of the Ice-Free Valleys geology agree that the Irizar Granite (C0i on plate 1) is post-tectonic (originated after orogeny). Such granites clearly cross-cut other rocks and are more felsic (less iron, more silica) in composition than most associated rocks. These felsic rocks have a high albido and produce a uniform, light tone on LANDSAT band 7 imagery.

Group two rocks consist of flat-lying, sedimentary rocks that unconformably overly the basement complex. This sequence is referred to as the Beacon Sandstone (DJb on Plate 1). At the type section (Hamilton and Hayes, 1963) these sedimentary rocks are approximately 1200 meters thick and consist mostly of sandstone. A basal conglomerate is present in some areas, and the upper part of the sequence contains carbonaceous shale and sandstone. Locally, siltstones, shales, and pebble conglomerates are present. These sedimentary rocks range from Devonian to Jurassic in age. Relatively pure, high-silica rocks, such as the Beacon Sandstone, are normally light-toned, high-albido rocks.

Group three comprises the most distinctive rocks in the area. Certainly, the rocks that should be most readily identified on ERTS band 7 are the great diabase sills (referred to as the Ferrar Dolerites) that intrude rocks of the basement complex and the Beacon Sandstone. These sills may be as much as 450 meters thick. Three of these thick sills (shown as Jda, Jdb and Jdc on Plate 1) are present in the map area, along with a number of related dikes and smaller sills. The lowermost sill intrudes the basement complex, the middle sill follows the unconformity between the basement complex and the Beacon Sandstone (Kukri Peneplain of Gunn and Warren, 1962), and the upper sill (Jda) is within the Beacon Sandstone. These sills are considered Late Triassic to Early Late Jurassic in age (Warren, 1969).

Mafic igneous rocks (rich in ferrous iron) normally show a strong absorption (decrease in reflectance) in the near infrared (Rowan, 1972; Vincent, 1972) which results in very dark tones on the ERTS band 7 image. Such units normally contrast strongly in reflectance with felsic rocks, and are readily distinguished from granite and sandstone.

The Ice-Free Valleys basement complex is cut by hundreds of dikes (mafic dikes shown by lines on Plate 1) that range in composition from basaltic to granitic. Most of these dikes are too small to be resolved on ERTS images; but, in areas where they are especially abundant, faint lines can be noted on the images that parallel the direction of strike of the dikes and probably represent areas where several small dikes are close together and appear as a single, narrow band.

A geologic map of the same area shown on Plate 1 was prepared by interpretation of an enlarged LANDSAT band 7 image. The enlarged image (scale 1:250,000) was fitted to a topographic base. A pseudo-stereo effect was obtained by taking advantage of side-lap of adjacent LANDSAT tracks (greater than 70% in Antractica) at the high latitudes. Two positive transparencies were placed on a Richards image-interpretation table and the stereo effect was obtained by observing the images with a Bausch and Lomb stereo-zoom microscope. The stereo effect was especially helpful in the study of the high-relief, U-shaped, glacial valleys. As expected, the LANDSAT band 7 image showed the greatest contrast between lithologic units.

Visual comparison of the enlarged portion of 1) the LANDSAT image (band 7) used for compilation of geology (Fig. 2); 2) the LANDSAT photogeologic map (Fig. 3); and 3) the geologic map of the area, compiled from the literature (Fig. 4) shows that the interpretation of the LANDSAT image is a useful reconnaissance geologic map. The three major units (basement complex, Beacon Sandstone, and Ferrar Dolerite) were mapped with 60-70% accuracy. The writers believe that these major subdivisions

Figure 2. Enlargement of a portion of LANDSAT image 1174-19433-7 of the Ice-Free Valleys area, Antarctica. The area shown corresponds to Figure 1, area 1.

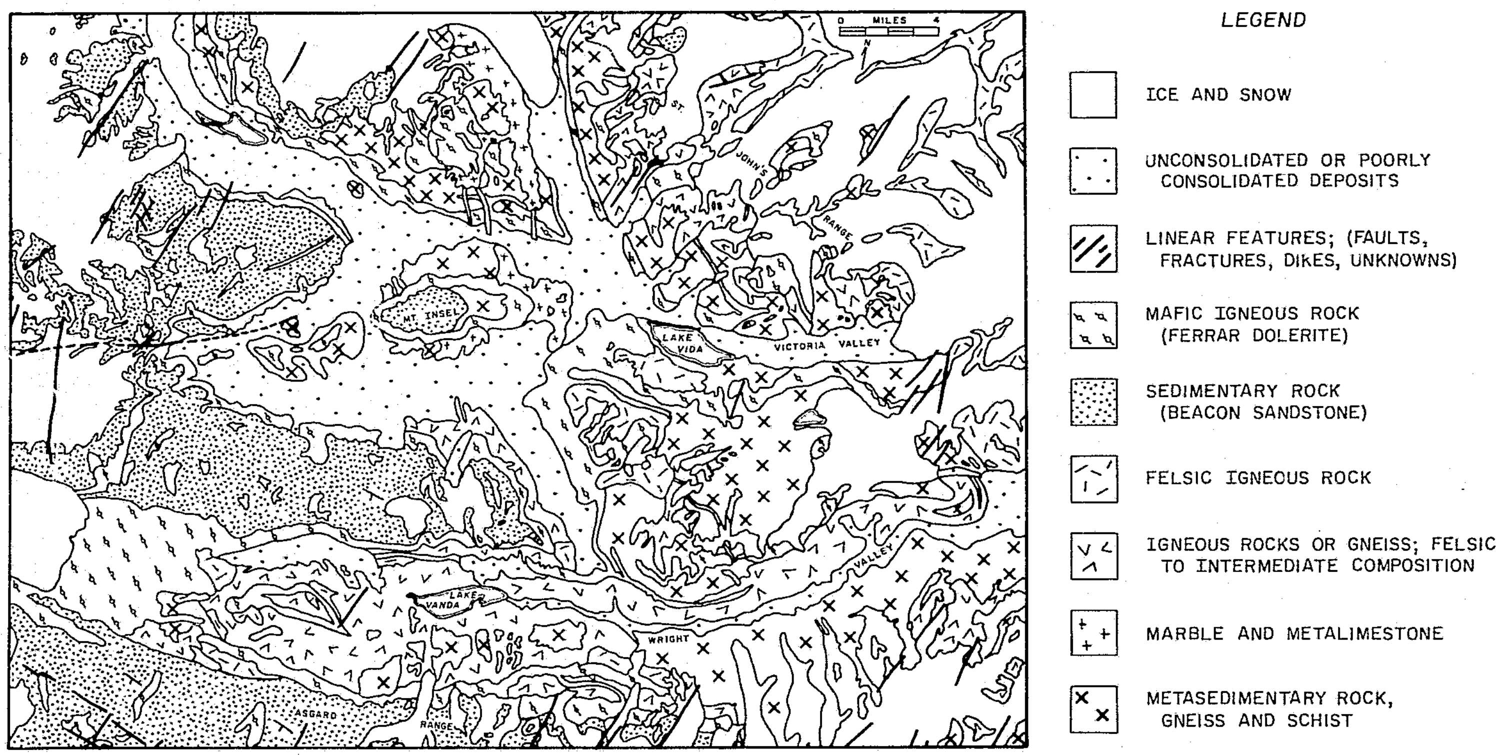


Figure 3. Photogeologic map prepared from pseudo-stereo viewing of positive transparency LANDSAT images. Map prepared from infrared band 7 images.

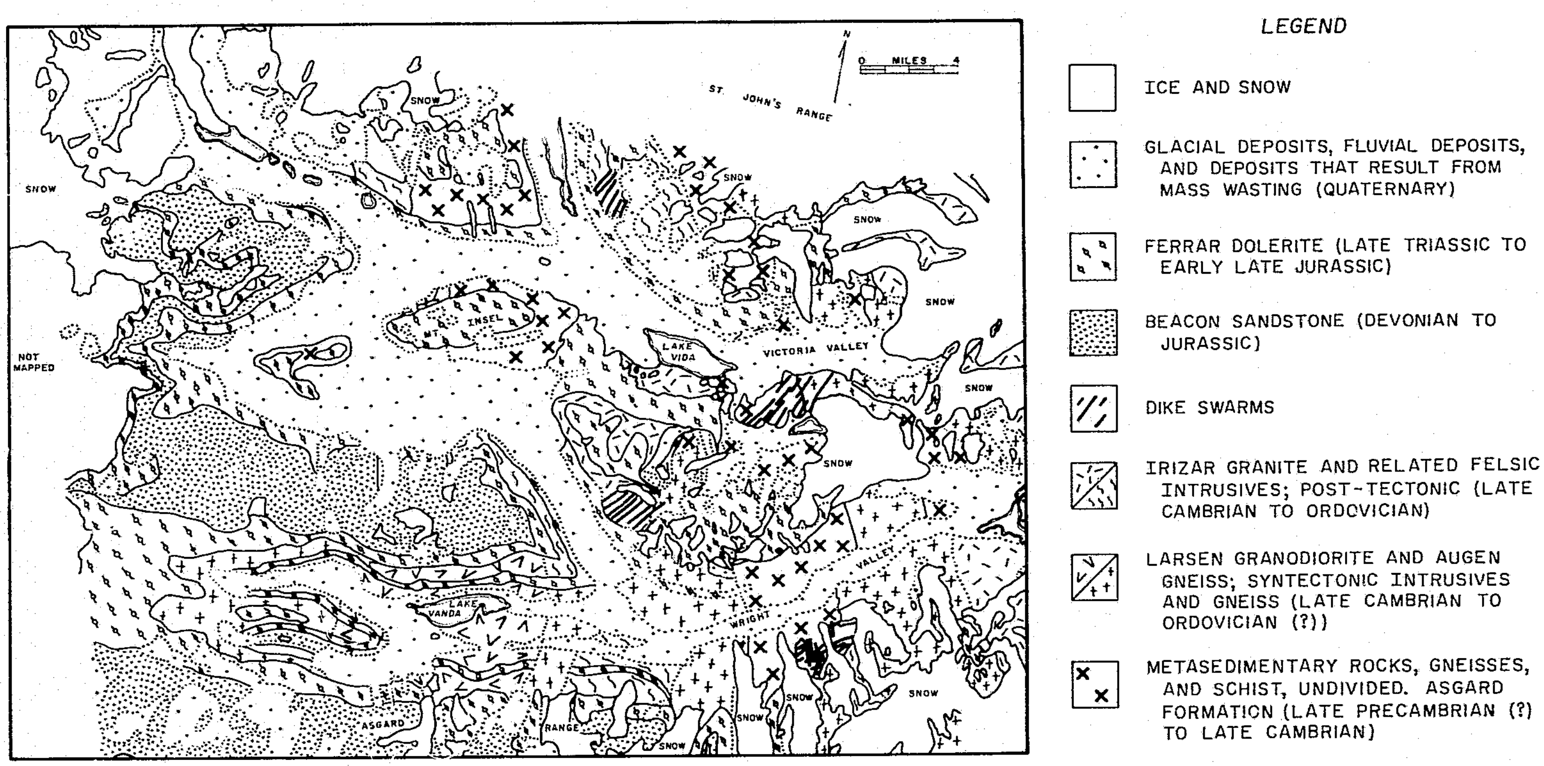


Figure 4. Geologic map of the area between St. John's Range and Asgard Range, Ice-Free Valleys, Antarctica. Generalized from Gunn and Warren (1962), McKelvey and Webb (1962), Allen and Gibson (1962), Fikkan (1968), Smithson (1967-70), Murphy (1971), and Lopatin (1970).

could be made by an experienced photogeologist whether or not he was familiar with the area.

The Beacon Sandstone can be recognized as a sedimentary rock by its bedded nature. Its relatively high reflectance in band 7 would suggest that the unit is a sandstone, limestone, or dolomite. The Ferrar Dolerite would be considered a mafic igneous rock because of its very strong absorption (dark tone) in the infrared. The basement rocks would, undoubtedly, be more difficult to identify; but the areas underlain by Irizar Granite and other light-colored igneous rocks might be identified as felsic igneous rocks on the basis of their non-layered appearance and high reflectance (light tone) in band 7. The irregular contacts of the felsic igneous rocks would also suggest rocks of igneous origin. It is probable that any photogeologist would have made three subdivisions of the basement complex. The units of low reflectance (dark tone) would be interpreted as mafic rocks (probably metamorphic). The units of intermediate reflectance would be interpreted as igneous rocks of intermediate composition; and the units of high reflectance might be interpreted as felsic igneous rocks. The marbles that crop out in the Insel area might also be interpreted as felsic igneous rocks because of a similarity in character and reflectance of marble and granite. The reflectance similarity illustrates the necessity for some type of ground truth (field checks or reconnaissance) when photogeologic techniques are employed.

Figure 3 is an example of the type of geologic map that might be prepared from a LANDSAT image if limited field checks are possible or if geologic maps are available in local areas. A distinction was made between granite and marble which could not be made without ground truth. A number of units are identified inaccurately because the writers feel that they would have been interpreted in this manner by most photogeologists. For example, Beacon Sandtone is shown to cap Mt. Insel, despite the fact that geologic maps of this area show the top of the mountain to be capped by Ferrar Dolerite. Thus, Figure 3 represents an attempt to present the type of geologic map that could be prepared from LANDSAT imagery by a photogeologist who has a limited knowledge of the lithologies exposed in the area.

Quaternary Geology of the Ice-Free Valleys Area

Sediments of direct or indirect glacial origin are the most important deposits of Quaternary age in the Ice-Free Valleys. Calkin (1964) recognizes two major episodes of glaciation in the Ice-Free Valleys which he designates as Insel and Victoria glaciations. The Insel glaciation resulted from a strong advance of inland ice (ice from the Antarctic continent) that moved eastward into the Ice-Free Valleys. Calkin (1964, p. 27-28) describes Insel drift as very silty, fairly homogeneous, containing clasts that are chiefly mafic igneous rocks from the Ferrar Dolerite, and, as being extensively mantled by solifluction. The Victoria glacial deposits resulted from a westward advance of glaciers from the seaward side of the Ice-Free Valleys. Calkin (1964) was able to subdivide these younger deposits into three parts; each related to an advance from the seaward side the Valley and subsequent retreat. The Victoria drift is described as less silty and somewhat more heterogeneous (in lithology of clasts) than the Insel drift. These younger deposits exhibit well-developed glacial topography (especially the deposits of the most recent episode of glaciation). Other Quaternary deposits comprise alluvial sand and gravel, dune sand, unsorted material in debris fans, lake silts, and various deposits of mass wasting (such as talus, mudflows, and solifluction sheets).

Quaternary deposits cover more than one-third of the area mapped in Figures 3 and 4, as can be seen by inspection of Calkin's (1964) map of the Quaternary deposits of Victoria Valley (Fig. 5). These glacial deposits are very difficult to distinguish from bedrock using LANDSAT images. This difficulty arises from several factors: 1) lack of characteristic vegetation that often helps distinguish Quaternary deposits outside of Antarctica; 2) a dominance of mechanical over chemical weathering that results in less chemical change (and less color change) between bedrock and clastic deposits derived from bedrock; and 3) pseudo-stereo viewing fails in the areas of low topography where the Quaternary deposits are usually located.

Some of the deposits that result from mass wasting (such as debris fans and large masses of talus) can be recognized; but none of the deposits of drift or alluvium can be distinguished with certainty. A dark-toned area south of the Insel Range (compare Figs. 2 and 5) is probably Insel drift. The eastern contact between the Insel drift and a markedly lighter-toned Victoria drift is clearly seen on LANDSAT images. Probably, in this area, the Insel drift has a greater proportion of boulders and pebbles of mafic igneous rock; so that it is darker in

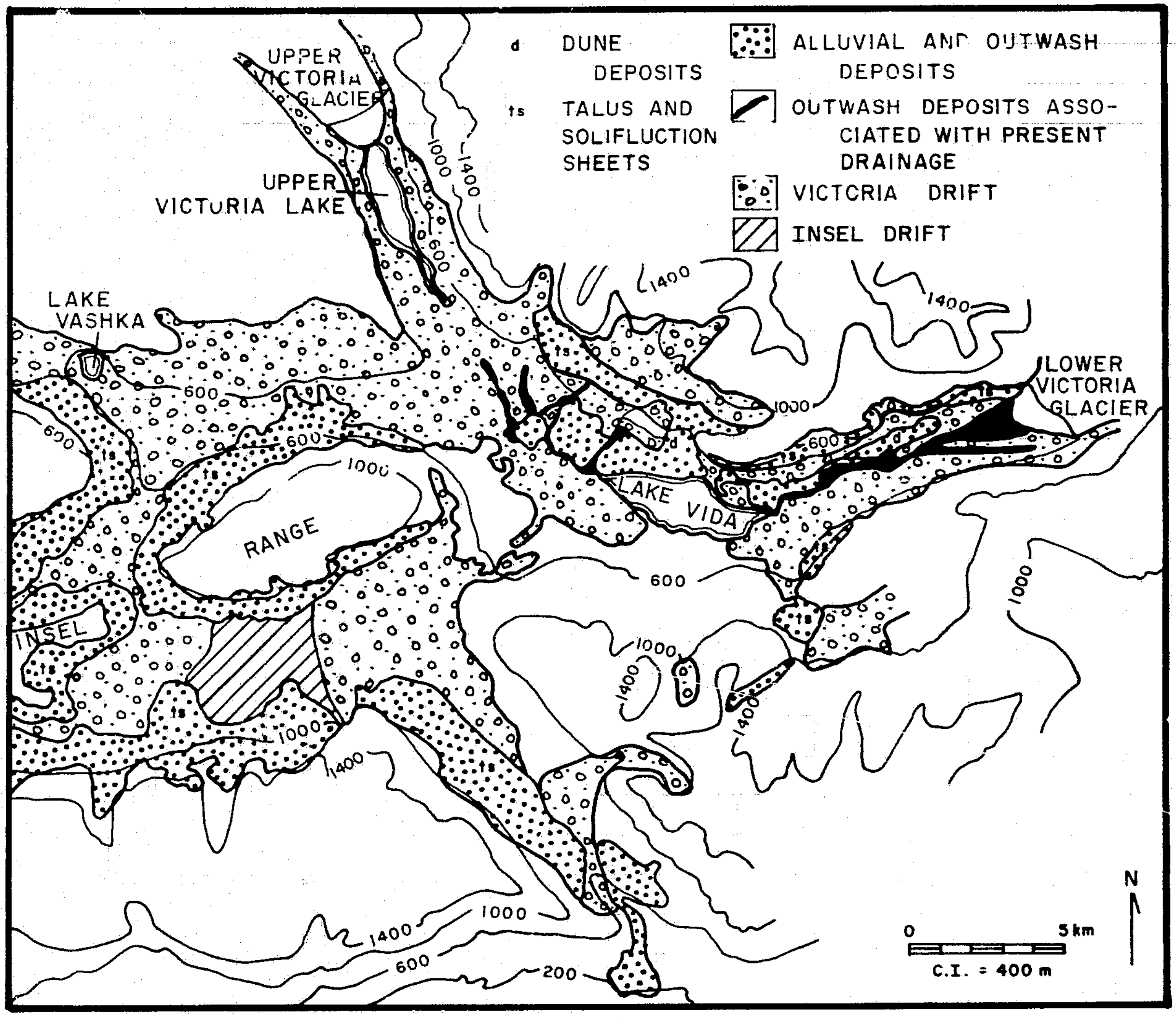


Figure 5. Glacial geology in the Victory Valley region (generalized from Calkin, 1964).

tone than the Victoria drift. But, Victoria drift is also present west of the Insel drift; and here, the two types cannot be distinguished. This may be because both have a high proportion of mafic rocks in this second area.

Sand dunes are readily recognized on LANDSAT images in most parts of the world (Kolm, 1974; Houston and Short, 1973; McKee, 1973), but they are difficult to distinguish in this area. Several large areas of dune deposits are present north and east of Lake Vida (Fig. 5). They appear as areas of somewhat lighter tone on the LANDSAT image; but, these areas cannot be identified as dunes, nor can they be readily separated from other rock types.

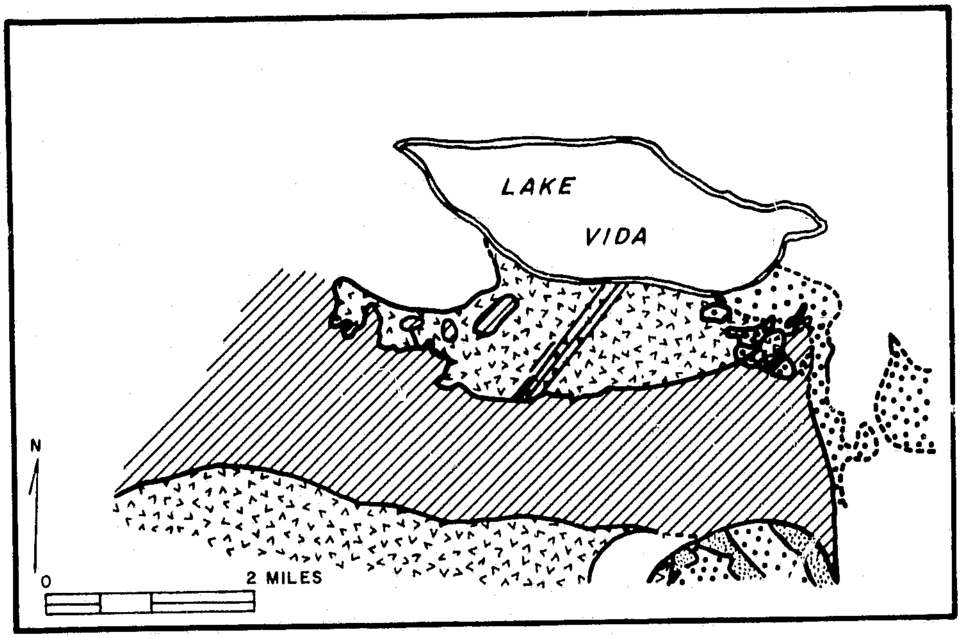
It seems clear that the LANDSAT images could be helpful in tracing contacts between Quaternary units; but these units would have to be identified through interpretation of low-altitude aircraft images or by field work before any meaningful mapping could be done.

Lack of vegetation in Antarctica has great advantages to the individual interested in mapping bedrock. However, the absence of vegetation is a definite disadvantage in the mapping of unconsolidated Quaternary deposits that, in other regions, are characterized by some distinctive vegetation. In Antarctica, bedrock is difficult to distinguish from the unvegetated Quaternary deposits; so, without ground control, additional mapping errors are likely. A number of such errors can be noted by comparing Figures 2 and 3, where, in the southwest part of the map, large areas of Quaternary deposits are mapped as intermediate igneous rocks or felsic gneiss.

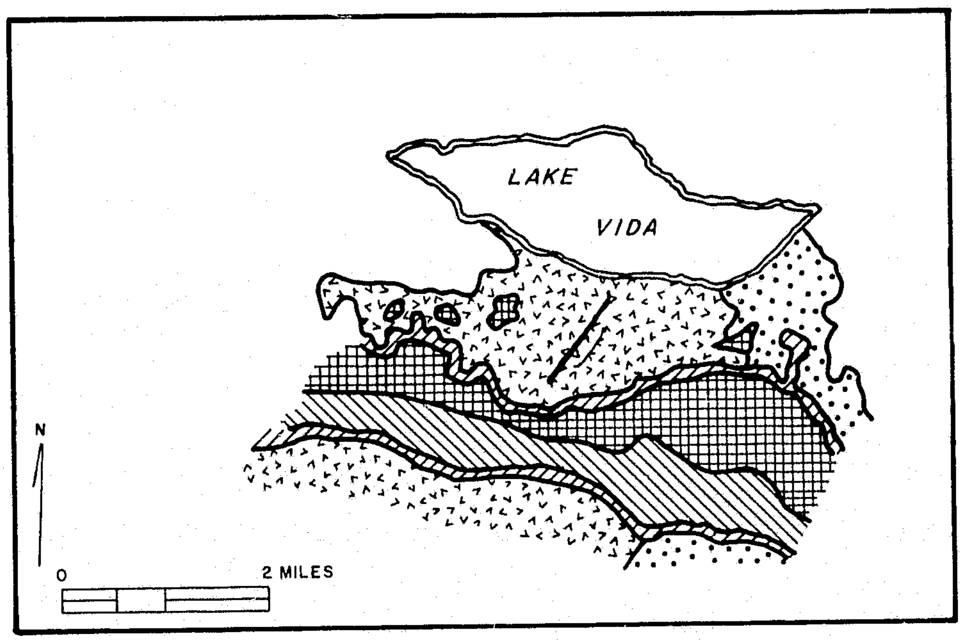
Detailed Geologic Mapping With LANDSAT Imagery

The clarity of the images in Antarctica is remarkable. Of hundreds of images from the Western United States and from areas outside the United States, very few show the detail that can be seen on imagery of Antarctica. One illustration of this is the contact between the Irizar Granite and Ferrar Dolerite south of Lake Vida (Figs. 2 and 3). Careful comparison of this contact, as mapped from LANDSAT, with the same contact, mapped by Fikkan (1968) at the scale of 1:25,000 shows excellent correspondence between the two (Fig. 6). The Ferrar Dolerite sill of this area intrudes the Irizar Granite, probably following a horizontal fracture system in the granite. The dolerite is both overlain and underlain by granite. The contact, at the south border of Lake Vida, is developed by erosion of the base of the sill which has exposed the underlying Irizar Granite. Several patches (less than 50 meters in width) of basal dolerite, lying on the Irizar Granite, can be recognized. Several dikes that cut the granite (less than 14 meters in width) can be recognized as a linear feature although they may not be individually resolved.

Another interesting aspect of this area is that the basal part of the Ferrar Dolerite sill is darker than the upper part. In fact, the sill can be divided into 4 zones: 1) a thin very dark zone at the base, 2) a thick zone of slightly lighter tone above this, 3) a thick zone of gray tone above this, and 4) a thin dark zone near the top of the sill. This zonation can be seen on the LANDSAT image (Fig. 2). This same zonation in the Ferrar Dolerite sill can be seen in United States Navy oblique photographs taken of this area in 1971 (Fig. 7). The tonal

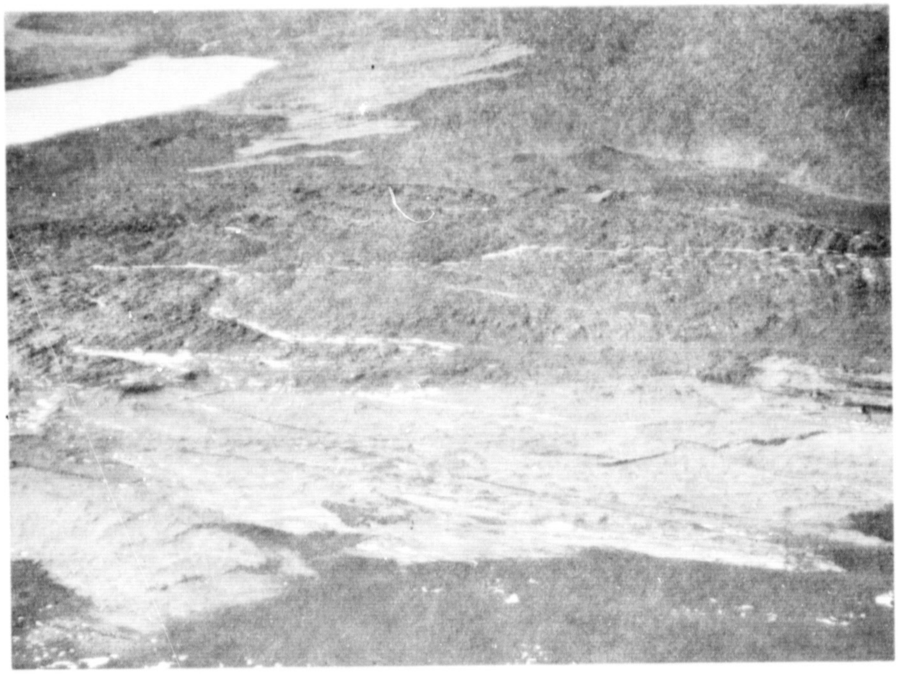


A.



B.

Figure 6. Comparison of (A) a geologic map (Fikkan, 1968) originally made at 1:25,000 scale with (B) a photogeologic map prepared from a portion of LANDSAT image 1174-19433.



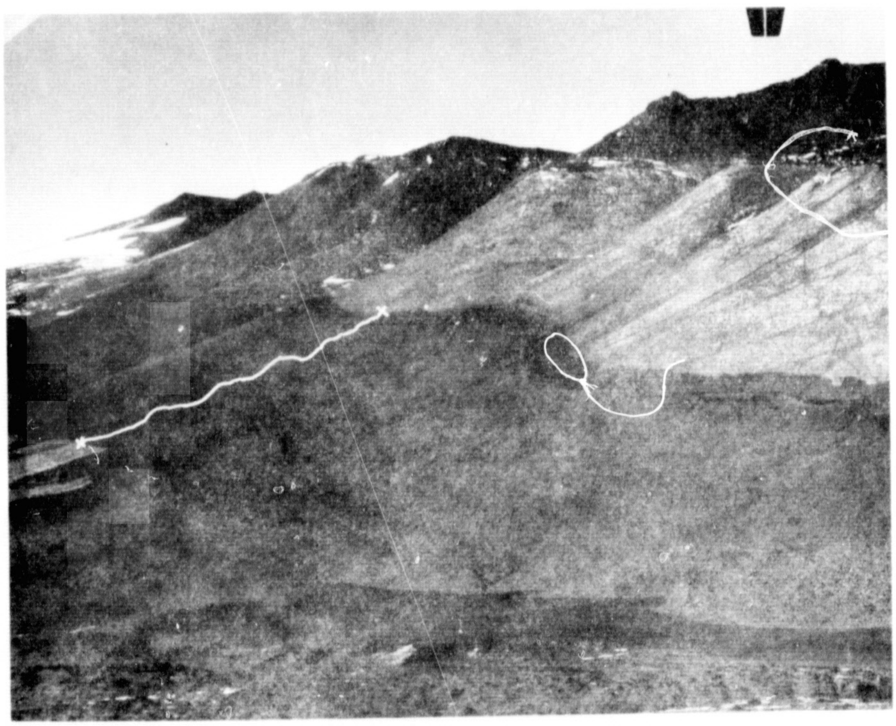


Figure 7. United States Navy photographs showing (A) frozen Lake Vida in left background, Irizar granite (light gray) to right of lake, layered sill of Ferrar Dolerite to the right of the granite, and Irizar granite in upper right; and (B) the strong zonation of the Ferrar dolerite sill in the area of the sample transect. Note that the sill is zoned with a dark layer at base, a dark gray unit above this, a unit of intermediate tone above this, and a dark layer at the top. The sample transect is denoted by the line connecting points marked "X".

changes in the sill must be related to texture and mineralogical composition; but this particular sill had not been subdivided in the field, nor had it been sampled adequately so that variation in mineral percentages could be determined. Webb and McKelvey (1959, p. 134-135) state that this sill has been sampled at 200-foot intervals, but their petrography is too generalized to determine if the sill is differentiated. Gunn (1962, p. 820-863) described a sill located in the Kukri Hills south of Lake Vida locality, in the same stratigraphic position as this sill and probably a part of the same sill discussed here. Gunn (1962, p. 826-836) shows that the Kukri Hills sill is differentiated and that the lower two-thirds of the sill is richer in mafic minerals (dark-colored pyroxene), and the upper one-third richer in felsic minerals (light-colored feldspar).

Relationships Between Image Brightness and Rock Characteristics

In the Antarctic summer of 1973, Edward F. Pruss of the University of Wyoming Antarctic party sampled the dolerite sill near Lake Vida (at intervals of one and one-half meters) in a locality one mile east of the lake (Fig. 7b). The sill has dark-colored, fine-grained, chill borders at top and bottom, where it is in contact with Irizar Granite. These border zones are about 12 meters thick. The lower two-thirds of the sill is a medium-grained gabbro containing about 50 percent mafic minerals. The upper two-thirds of the sill is slightly coarser-grained and more leucocratic. The sill becomes progressively richer in feldspar towards the top. The color changes seen on the LANDSAT image (Fig. 2) and on the Navy photographs (Fig. 7) are attributed to the mineralogical and textural changes in the sill.

The tonal changes seen on the LANDSAT image may be related to the iron content of these rocks. The relatively simple geologic and mineralogic relationships shown by the Ferrar Dolerite sill and Irizar Granite provide an ideal situation in which to test this relationship. The image brightness representing a given rock unit is a function of many variables. For example, image brightness might be expressed as a function of the following parameters: B = f(g, o, w, v, sa, sz, vg, sl, t, ws, ac, al, sh, at, ch, m)

where
- g = grain size
- o = grain orientation
- w = degree of weathering
- v = vegetation (species and biomass)
- sa = sun angle
- sz = sun azimuth
- vg = viewing geometry
- sl = slope angle
- t = temperature
- ws - water saturation
- ac = atmospheric conditions
- al = depth of atmospheric column
- sh = shadowing
- at = attitude of rock units
- ch = chemistry of rocks
- m = mineralogy of rocks

Ideally, the geologist searches for a situation where tone (in a given band or combination of bands) might relate directly to either the chemistry or mineralogy of the rocks. There are very few natural areas, outside the laboratory, where this can be done. To achieve this, one must be able to eliminate most of the variables and determine the effects of the remaining variables. In the Lake Vida area the situation is simplified. Here B = f (g, ch, m) because grain orientation is horizontal; weathering is minimal and the same in all rocks; vegetation is non-existent; water saturation is very low since rainfall is less than 1/2 inch per year; sun angle, sun azimuth, viewing geometry, slope angle, temperature, atmospheric conditions, and depth of the atmospheric column can be considered constant. Shadowing is constant since these rocks are exposed on a slope having a uniform angle of repose; and, finally, all rock units have about the same attitude of planar structure.

The grain size variable cannot be immediately eliminated. The sill shows definite trends in grain size that correlate with albido differences. Still, because chemical and mineralogical changes also parallel the changes in albido and grain size changes, one cannot assume a cause-and-effect relationship in either case.

Fortunately, the central part of the sill is composed of rocks of nearly uniform grain size. Here, we may assume that the tonal changes are related to either mineralogical or chemical composition of the rocks. This assumption may be tested. The LANDSAT bands should show a difference in contrast between mafic and felsic igneous rocks that might be related to the percentage of opaque minerals or the iron content of the rocks, or both. Absorption bands for ferrous iron lie between 950 and 1100 nm and for ferric iron between 850 and 950 nm. The LANDSAT band 7 records information in the 900- to 1100-nm band and, therefore, should include the entire ferrous iron absorption band. Since the other LANDSAT spectral bands do not include this absoprtion band, rocks that have a higher ferrous iron content should show a lower reflectance in band 7 than in bands 4, 5, or 6. This assumption is also supported by laboratory experiments of Hunt, Salisbury, and Lenhoff (1974), which show that basic rock spectra display a broad ferrous iron feature near 1000 nm. Figure 8 is an image density profile across the Irizar Granite and Ferrar Dolerite in the Lake Vida area. The rocks having the greatest contrast in ferrous iron are the Irizar Granite[1] and the basal part of the Ferrar Dolerite. A typical sample of Irizar Granite from this area is very low in ferromagnesium minerals and contains 0.46 weight percent ferrous iron (Fikkan, 1968, p. 55). The lower part of the Ferrar Dolerite at Lake Vida averages near 12 percent ferrous iron (Table 1). Therefore, if we assume that ferrous iron is the principal cause of the tonal changes, LANDSAT band 7 should show the greatest contrast between the Irizar Granite and the lower part of the Ferrar Dolerite. This is shown to be the case in Figure 8.

A second way to test this assumption is to examine the variation between the upper and lower parts of the Ferrar Dolerite. Examination of Figure 8 shows that the sill is relatively featureless in LANDSAT bands 4, 5, and 6; but it shows a distinct tonal contrast between the upper and lower parts in band 7. As noted above, the Ferrar Dolerite is differentiated, and the lower part has a higher percentage of mafic minerals and ferrous iron than the upper part (Table 1). Thus, band 7 shows the predicted characteristics across both contacts.

[1]Granite grain size is about like that of the rocks of the sill, excluding border zones.

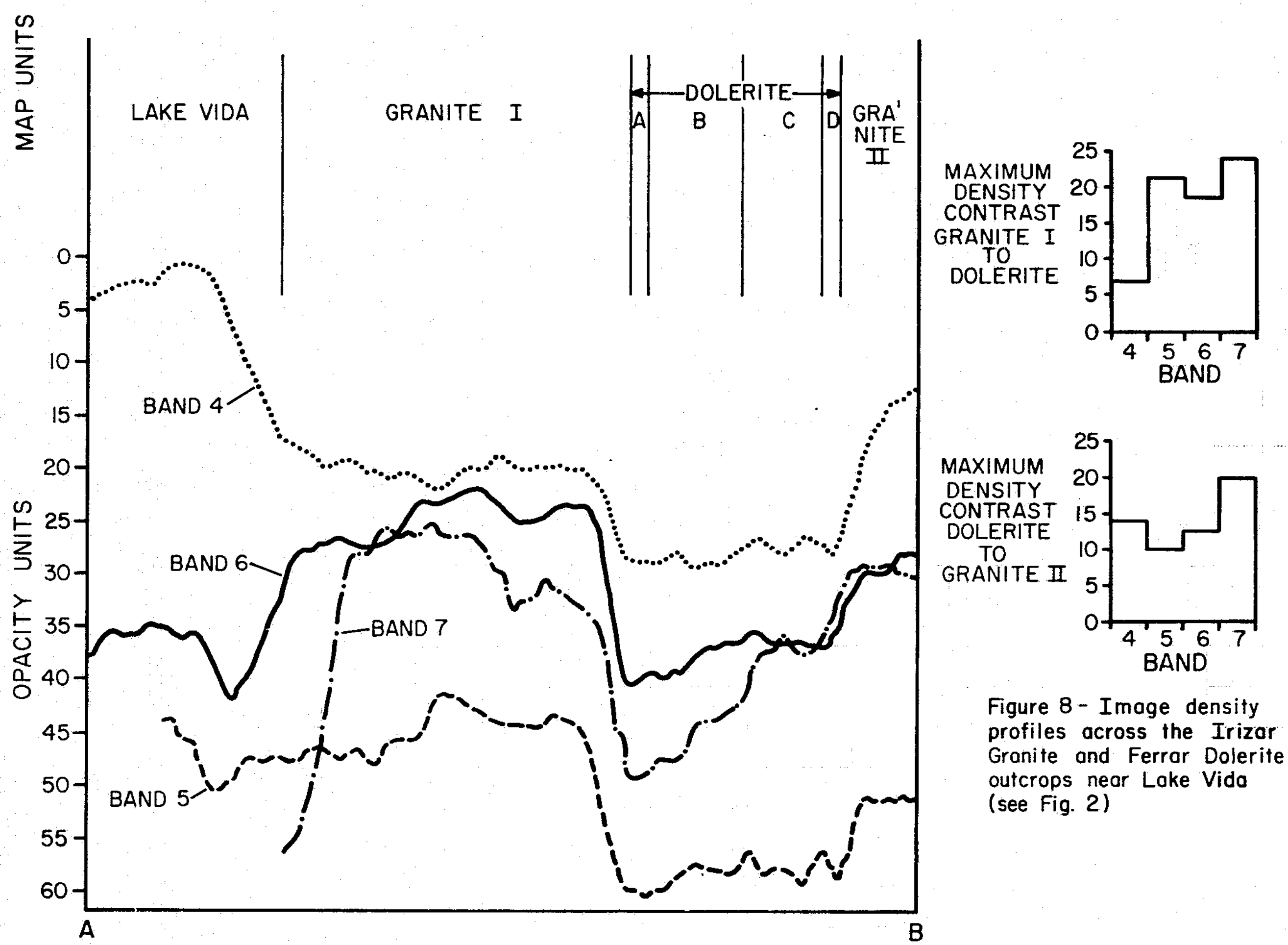


Figure 8. Image density profiles across the Irizar Granite and Ferrar Dolerite outcrops near Lake Vida.

TABLE 1

Iron and Iron Oxide Values Determined For

7 Samples From the Ferrar Dolerite Sill Near Lake Vida

Sample No's	% Fe Total	% Fe_2O_3 Total	% Fe (II)*	% FeO	% Fe (III)	% Fe_2O_3	
F-2	6.46	9.24	9.50	12.2	---	---	Fine-grained border (lower)
F-21	6.13	8.77	5.68	7.30	0.45	0.64	Lower mafic portion
F-57	6.54	9.35	3.45	4.44	3.09	4.42	
F-99	6.16	8.81	1.51	1.94	4.65	6.65	Upper felsic portion
F-119	4.65	6.65	1.14	1.47	3.51	5.02	
F-165	6.46	9.24	2.70	3.47	3.76	5.37	
F-170	7.16	10.24	6.42	8.26	0.74	1.06	Fine-grained border (upper)

*Fe(II) determined by Wilson method, which determines total oxidizable species by V(V). Thus, reduced Mn, Ti, S species interfere to give high results. Determinations by Jack Murphy, Univ. of Wyoming analytical laboratory.

Mineralogy may also play an important role in determining the image brightness. Magnetite and other opaque minerals (such as ilmenite and chromite) that are common in mafic igneous rocks tend to reduce the total reflectivity and also mask spectral features, such as the iron absorption bands (Hunt, Salisbury, and Lenhoff, 1971). Therefore, a rock rich in magnetite should have a dark tone; but this tone should be the same in all bands. Clearly, this effect is not evident in the Lake Vida area (Fig. 8). Therefore, the assumption might be made that the percentage of magnetite is low and does not vary markedly in these rocks. From examination of samples collected by Mr. Pruss, and from studies by Gunn (1962), it is clear that Ferrar Dolerites are not rich in opaque minerals. For example, modes of 15 samples from the Ferrar Dolerite in Wright Valley averaged 0.40 percent opaque minerals and only one sample exceeded 3% (Gunn, 1962, p. 908).

In summary, all evidence supports the assumption that tonal variations seen in the Ferrar Dolerite are largely a result of changing concentration of ferrous iron; and that, under optimum imaging conditions (such as those in Antarctica), usful information might be obtained about rock chemistry by comparing tonal variations in different spectral bands. Tonal variations recorded in band 7 that are not seen in other LANDSAT bands are probably due to variations in ferrous iron content of the rocks.

The use of the iron absorption band in mapping selected rock units is not a new concept in remote sensing (Vincent, 1972; Rowan, 1972). It has been applied to LANDSAT data (Vincent, 1973; Rowan, 1973) in other areas of relatively sparse vegetation. These applications have required ratio methods to enhance small spectral differences between LANDSAT bands. However, the contrast in the Antarctic example is strong enough to be detected by visual comparison of the image bands. This example leaves little doubt that the LANDSAT system can, under ideal conditions, be used in the study of rock chemistry.

Map Correction and Revision

Inability to confidently identify from LANDSAT rocks exposed under natural conditions essentially limits geologic mapping to areas where some ground truth is available. However, LANDSAT images are very useful in filling gaps in geologic mapping and in correcting errors in reconnaissance mapping.

An example of this is a mapping problem encountered in the Bull Pass area of the Ice-Free Valleys. In the Bull Pass area two reconnaissance geologic maps showed different relationships between the basement complex and the lower Ferrar Dolerite sill. The LANDSAT band 7 image (Fig. 2) showed a split in this sill with one layer following the valley of Bull Pass and another running, at a lower level, along the north wall of Wright Valley. This problem area was re-studied using oblique aerial photographs. It was determined that the LANDSAT interpretation was correct. Both Figures 3 and 4 show the sill mapped correctly.

Mapping in the Koettlitz-Blue Glacier Area

A follow-up study included an examination of LANDSAT images of Antarctica to determine whether or not other areas could be mapped or maps updated using LANDSAT images. All LANDSAT imagery was reviewed (through 1974) on microfilm. Selected images of snow-free areas were ordered. No areas outside of the Ice-Free Valleys were found suitable for geologic mapping. The best exposed areas are all adjacent to the Ice-Free Valleys. The entire region is shown on the LANDSAT image mosaic (Plate 2).

Mapping was attempted in several exposed areas, but, in most of the areas, the small rock outcrops were not adequate for defining mappable units. It was possible to extract detail from these individual outcrops by use of the isodensitracer, but this technique proved to be too time-consuming for effective use.

One of the largest of the exposed areas is the Koettlitz-Blue Glacier area, which lies south of the Ice-Free Valleys and southwest of McMurdo Station. This area was selected for a simple test of the geologic mapping utility of LANDSAT imagery. Imagery of the area is excellent (Fig. 9).

In this test, the band 7 LANDSAT image area was enlarged (10X) to a scale of 1:100,000 to provide an adequate mapping base. Interpretation was then made by a geologist who was entirely unfamiliar with the area and who did not know the lithologies of the area. The map resulting from this interpretation (Plate 3) was later compared to a geologic map (Plate 4) compiled by geologists from the University of Wellington and the New Zealand Geological Survey. The comparison shows that the LANDSAT offers very little of the detail necessary for compilation of an intermediate-scale geologic map. The distinction between rock and glacial debris is made with fairly good accuracy; but none of the three major rock types (volcanic, igneous, metasedimentary) could be reliably distinguished by interpretation.

Although the results of the geologic interpretation in this area were somewhat disappointing, it was noted, in the comparison of the field geologic and interpretive maps, that the configuration of the snow-free area and the shape of many of the minor physiographic features do not correspond well. Some of the differences were attributed to differences in the area of snow cover. However, it was concluded that many of these differences reflected distortions of the base map on which the field geology was compiled (compiled from U.S. Navy photography). This base could be improved considerably by adjustment to a skew corrected LANDSAT image base.

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Figure 9. Enlargement of LANDSAT image 1530-19175-7 of the Koettlitz-Blue Glacier area, Antarctica (See Fig. 1, area 2).

IMAGE ENHANCEMENT TECHNIQUES

An attempt was made to enhance differences between lithologic units through density analysis and color-additive combinations of the LANDSAT multispectral bands. The density analyses were made both with video and optical/mechanical equipment. The video system used was a Spatial Data Systems, model 401, 12-color, image analyzer. The optical/mechanical system was a Joyce Lœbl/Tech Ops, four-color isodensitracer.

Density Analyses

Both density analysis systems produce either an image density profile across a selected traverse or a colored isodensity contour map (compare Figures 10a and 10b, Plate 5). Each system has advantages and disadvantages. For example, the video system can produce a density contour map almost instantaneously, but the isodensitracer requires several hours to contour the same area. The video system operates effectively over a 3-D density range with $\pm$ .02D accuracy. The isodensitracer has about the same range capability but has an accuracy of .005D. The video system offers greater input/output scale flexibility, but the isodensitracer offers greater sampling flexibility (spot size and shape adjustment). The isodensitracer provides direct, hard-copy print out; the video monitor must be photographed.

In brief, the video system is most effective for rapid analyses or in situations where many different density analyses must be tried before selecting the "best" one. The isodensitracer provides greater accuracy and control which is useful for extremely precise, low-volume, density analyses.

Figures 10a and 10b are isodensity contour maps of the Brown Peninsular, which lies west of McMurdo Station and north of Mount Discovery (Fig. 1, area 3). This area is underlain by volcanic rocks of an alkaline olivine-basalt association (known as the McMurdo Volcanics). The McMurdo Volcanics are largely mafic volcanic rocks and are recorded in very dark tones on LANDSAT band 7 imagery.

A comparison of Figure 10a with Figure 11, which is an enlargement of the LANDSAT band 7 image, shows that the isodensitracing is useful in delineating glacial ice (shown in red), and morainal deposits lying on the glacial ice (shown in blue and green). Textural details are brought out in the ice (lower left of Figure 10a) and morainal deposits are separated into two units that probably relate to age or thickness of the moraines. The primary problem with this identification by density is the failure to properly distinguish the mafic volcanic rocks. The volcanic rocks are shown in black on the tracing but they are mapped in shadowed areas only. The volcanics on the east side of the Brown Peninsular are shown in the same pattern as moraine.

Attempts to use these density analyses for geologic interpretations suggest that density slicing is of limited value in geologic mapping, even where there are no more than four map units. However, the density maps do help in defining tonal detail within individual units.

Isodensitracings were also constructed for the Ice-Free Valley test area (Fig. 1, area 1). This area provides a broader region of rock exposure uncomplicated by vegetation, soil, or cultural features. Because the band 7 image had shown predictable contrasts between mafic and

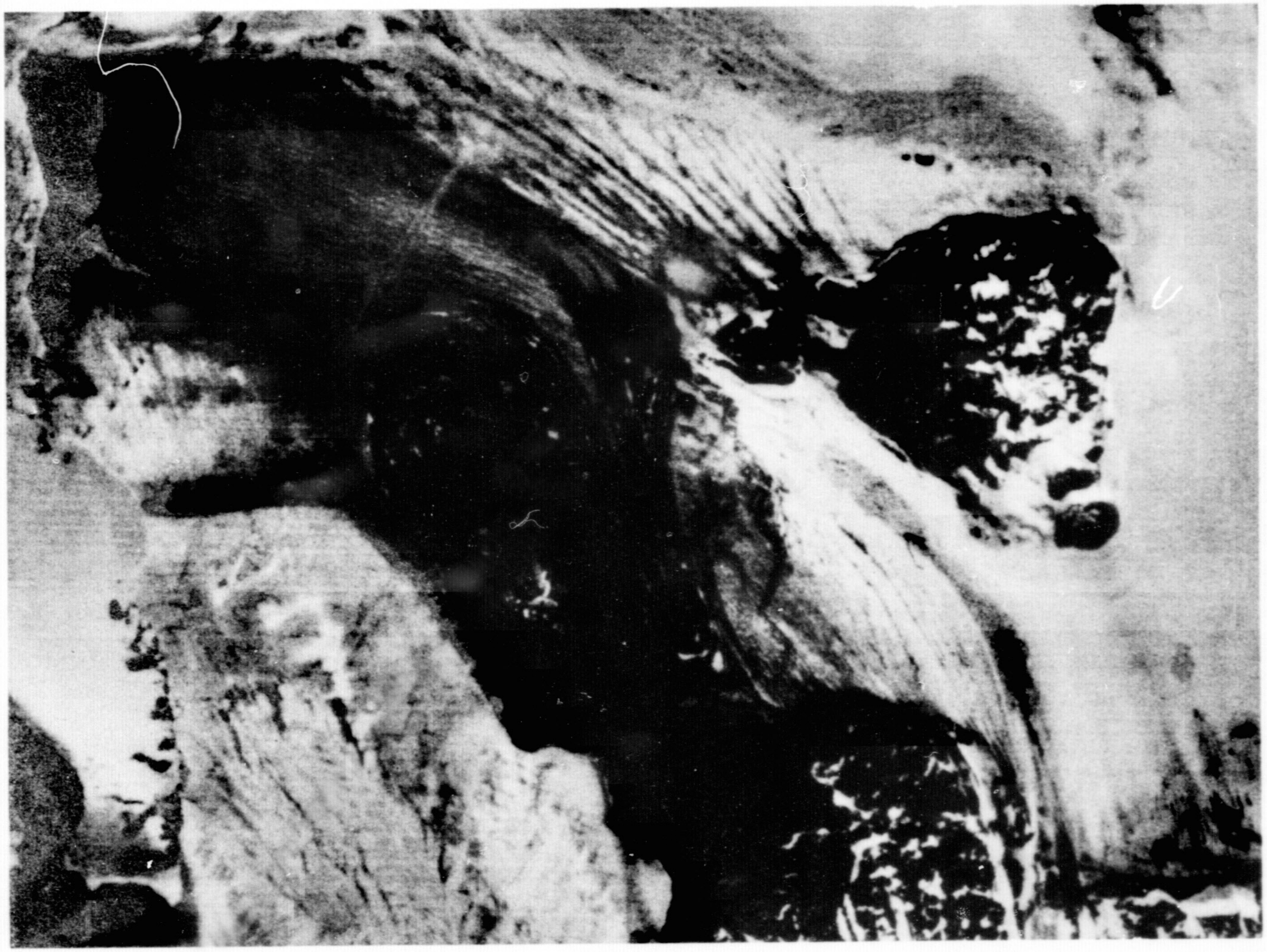

Figure 11. Enlargement of a portion of LANDSAT image 1529-19121-7 showing the Brown Peninsular Region (see Fig. 1, area 3).

felsic units, an attempt was made to use density analysis as a means of differentiating these lithologies. The isodensitracer was set to differentiate the four major rock types cropping out in this area: 1) Beacon Sandstone, 2) Ferrar Dolerite, 3) Irizar Granite, and 4) metasedimentary rocks. Snow-cover was programmed as blank or uncolored. The rock types were programmed into the isodensitracer by training the small aperature on selected image areas corresponding to known outcrops of the different rock types (identified by field geologists). Figure 12 (Plate 6) shows the resulting density contour map. Comparison of the density contour map with the geologic map (Fig. 4) illustrates that, even in Antarctica, a simple technique of this type is not applicable to automated mapping, because of the wide range of gray levels representing each of the rock types. For comparison, a similar density contour map (Fig. 13, Plate 7) was constructed with the Spatial Data Systems video density analyzer. Even the multiple slice and display flexibility of this system failed to produce a contour map that would satisfactorily depict the geologic units throughout the Ice-Free Valleys area; although several presentations were made on which certain local contacts and outcrop patterns were defined by the density contours. The density contour maps do produce a fairly accurate map of snow cover, but the image brightness values are such that ablating ice of the Ferrar Glacier is mapped in the same color pattern as Irizar Granite.

Figure 14 (Plate 7) is a isodensity contour map of a part of a smaller area near Lake Vida (See Fig. 6). This map illustrates the type of detail that can be extracted from the image by use of the density analysis, and shows that, in local areas of relatively simple geology and uniform lithologies, it is possible to map lithologic units with reasonable accuracy.

Color-Additive Band Composites

Separate density analysis of each of the LANDSAT bands shows that brightness contrasts between typical rock units are greatest in band 7 (Houston and others, 1976). This was confirmed by the earlier reported visual analyses in the Lake Vida area. In addition, band 7 shows details of flow structure and ablation of glaciers much better than in any of the other bands. The amount of structural detail that can be seen in glaciers increases progressively from band 4 to band 7. The contrast between the reflectivity of two lakes, Vida of Victoria Valley and Vanda of Wright Valley, is instructive in this regard.

Lake Vida and Lake Vanda are perennially ice-covered. Vanda is a stratified lake with fresh water at the top and saline water at deeper levels. Vida is probably similarly stratified (at least, melt water at its margins is potable in the summer). Both of these lakes thaw somewhat in the Antarctic summer and develop a moat of meltwater (up to 12 meters wide in some areas) around their margins. Meltwater from glaciers flows into the lakes and adds to the water around the margin of the lakes. Study of images shows several streams of meltwater entering Lake Vida, but there is no evidence of meltwater entering Lake Vanda. Lake Vida shows light tonal shades in band 4 and becomes progressively darker on other bands, especially at its margins, until it is almost as dark as sea water in band 7. Lake Vanda shows a slight tonal darkening from band 4 to 7, but darkening is about the same as shown by the glaciers.

These observations suggest a possible application of band-combination techniques in detecting the presence of water on the toe of ablating glaciers. The progressive darkening of Lake Vida from band 4 to band 7 reflects the strong absorption of the infrared by water. Melt water on glaciers and frozen lakes should also show a perceptible darkening, even though these bodies of ice may not have begun to thaw extensively. Our field observations at the Shelton Glacier of Antarctica in late December of 1969 confirm that some ablation does occur during the summer.

These observations also suggest that moisture content of rocks may play a role in bringing out the strong contrasts between felsic and mafic rocks observed on band 7 imagery. However, there is no evidence that these rocks vary in moisture content, so no definite conclusion was reached on this point.

Color-additive band combinations were constructed for the Ice-Free Valleys (Figs. 16a and 16b, Plate 8). These were originally constructed with a Spectral Data color-additive projector/viewer. The best combinations were then duplicated with diazo composites.

Figure 16a represents a band 4 image (blue filter or black and white diazo) combined with band 7 (no filter or blue diazo). It shows the contact between the Irizar Granite and Ferrar Dolerite with strong contrast between the mafic and felsic units (compare with Fig. 15). Visually, the contact appears to be better defined on the composite than in band 7 alone. In addition, this band combination shows the apparent snow-free and ablating portions of the glaciers and Lake Vanda in light blue and Lake Vida (lake with more melt water) in dark blue.

The color composite appears to give a better presentation than does band 7 alone.

A combination of band 5 (displayed in red, or as a green diazo) and band 7 (displayed in green, or red diazo) also shows a distinct enhancement of the snow-free and/or ablating glaciers in shades of deep pink and a deep red for Lake Vida (Fig. 16b). This band brings out contrasts in felsic units, such as Irizar Granite and Larsen Granodiorite; but they are subtle and appear to be displayed no better than in band 7 alone (except perhaps for a greater ability of the human eye to interpret changes in hue on the colored image).

The color-additive band composite of the Ice-Free Valleys area were judged very useful for defining areas of glacial melt. No additional geologic information was gained through this work, and the improvement in presentation of geologic contrasts was slight.

CONCLUSIONS

LANDSAT imagery is useful for regional geologic mapping, but the image interpretations should be supported by field-checks and/or a background knowledge of the lithologies and structural style of the area under study. The image interpretations are particularly useful for revision of existing geologic base maps and compilation of composite images from available data supplemented by interpreted data.

Rock reflectance measurements and chemical or mineralogic analyses are useful for determining cause-and-effect relationships between the lithologies and their spectral reflectances. The absence of vegetation and relatively fresh conditions of the rock surfaces in Antarctica simplify these correlations, but they hamper segregation of glacial material and other surficial deposits from bedrock.

Density analyses can assist the interpreter in accurately defining lithologic contacts and subtle tonal contrasts; but cannot serve as a means of automated mapping. Image brightness values are not sufficiently unique (except in small, selected areas) to give a reasonable representation of outcrop patterns.

Color-additive combinations produce enhancement of ice-melt patterns and some flow patterns in glaciers. However, little enhancement of lithologic contrasts was realized by color-addition.

Band 7 was shown to be the most useful LANDSAT band for geologic mapping in this area.

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APPENDIX A: SPECTRAL PHOTOMETRIC MEASUREMENTS, McMURDO AREA, ANTARCTICA

Station No.	Location-Description	Comment	Photometer Reading Channel (LANDSAT equivalent) 1 Targ.	1 Ref.	2 Targ.	2 Ref.	3 Targ.	3 Ref.	4 Targ.	4 Ref.
1	Young knobs of olivine-pyroxene basalt near Douglas Installation	Some snow on outcrop	5.0	43.0	4.5	22.0	4.5	33.0	.78	2.6
1a	Young knobs of olivine-pyroxene basalt near Douglas Installation	Different outcrop	5.0	34.0	4.0	21.5	4.2	27.0	.85	2.0
2	Observation Hill -Lower Quarry, trachyte		8.5	43.0	5.5	26.8	6.5	37.5	.72	3.4
3	Upper Quarry, trachyte	West-facing slope	7.5	49.0	5.0	32.0	6.0	46.0	1.4	3.9
6	Hut Point Penn. Vinnce's Cross, olivine basalt		10.5	12.0	4.5	5.5	5.0	8.0	1.0	0.5
6a	Hut Point Penn-Vinnce's Cross, olivine basalt	Near Station 6	7.5	16.0	5.0	8.0	5.0	10.5	---	---
6b	Hut Point Penn-Vinnce's Cross, olivine basalt	Near Station 6	7.0	14.0	3.0	8.0	5.0	10.0	0.24	1.5
7	Our Lady of Snows, hornblende basalt		14.0	---	6.0	---	7.5	---	0.45	---
8	DVDP Drill Hole #1 -Red scraped area, olivine basalt, dunite inclusions		7.5	11.0	14.0	5.0	6.5	---	1.0	---
8a	Repeat of Station 8	Gear Problems	11.0	11.0	25.0	5.0	6.5	4.0	2.0	0.2
9	Near Cosmic Ray Lab		7.5	10.5	17.0	6.5	4.0	4.0	0.6	.55

APPENDIX A: SPECTRAL PHOTOMETRIC MEASUREMENTS, McMURDO AREA, ANTARCTICA

Station No.	Location-Description	Comment	Photometer Reading Channel (LANDSAT equivalent) 1		2		3		4	
			Targ.	Ref.	Targ.	Ref.	Targ.	Ref.	Targ.	Ref.
10	Near Earth Science Lab? Vesicular hornblende basalt		2.5	4.0	2.0	1.8	4.8	2.0	9.5	2.5
10a	Hornblende basalt- Scattered snow	Near Station 10	2.0	3.8	1.8	2.0	2.6	2.2	1.0	1.0
10b	Hornblende basalt	Near Station 10	7.0	4.5	6.1	3.0	9.0	1.9	1.1	.26
11	Upper helicopter Pad, Basalt flow with olivine and dunite inclusions		.32	2.1	.30	1.0	.25	1.3	.05	.08

Figure 10a. Isodensity contour map of the Brown Peninsula, constructed using a Joyce Loebl/Tech Ops, four-color isodensitracer.

Figure 10b. Isodensity contour map of the Brown Peninsula, photographed from the video monitor of a Spatial Data Systems, model 704, image analyzer.

PLATE 5

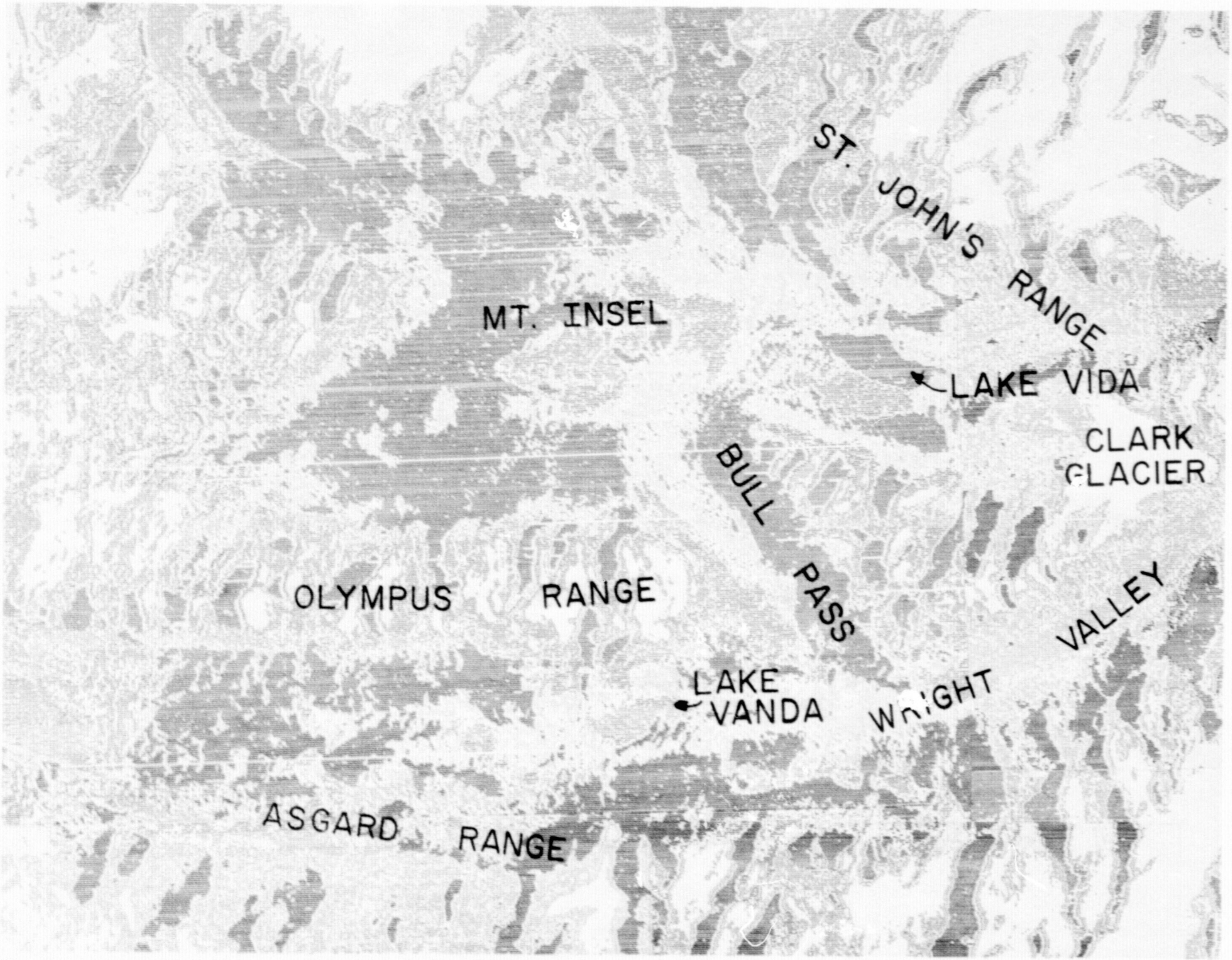

Figure 12. Isodensity contour map of a portion of the Ice-Free Valleys of Antartica from LANDSAT image 1174-19433-7. This contour map was produced by the Joyce Loebl/Tech Ops isodensitracer.

PLATE 6

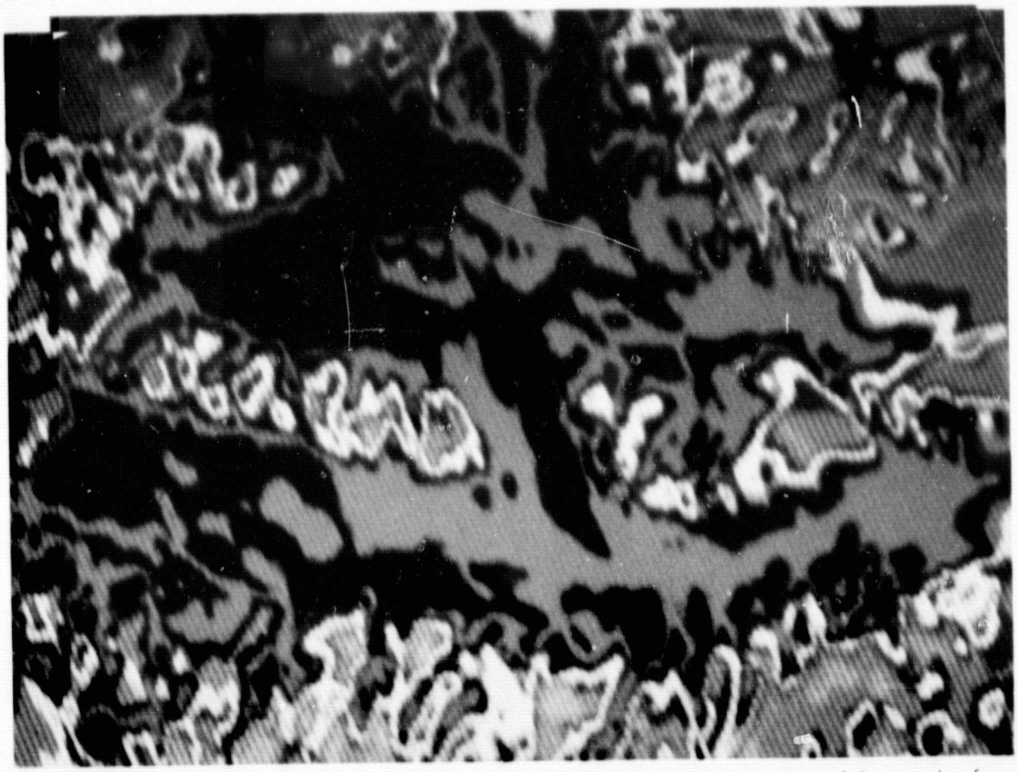

Figure 13. Video density contour map of a portion of the Ice-Free Valleys of Antarctica from LANDSAT image 1174-19433-7 (see Fig. 1, area 1).

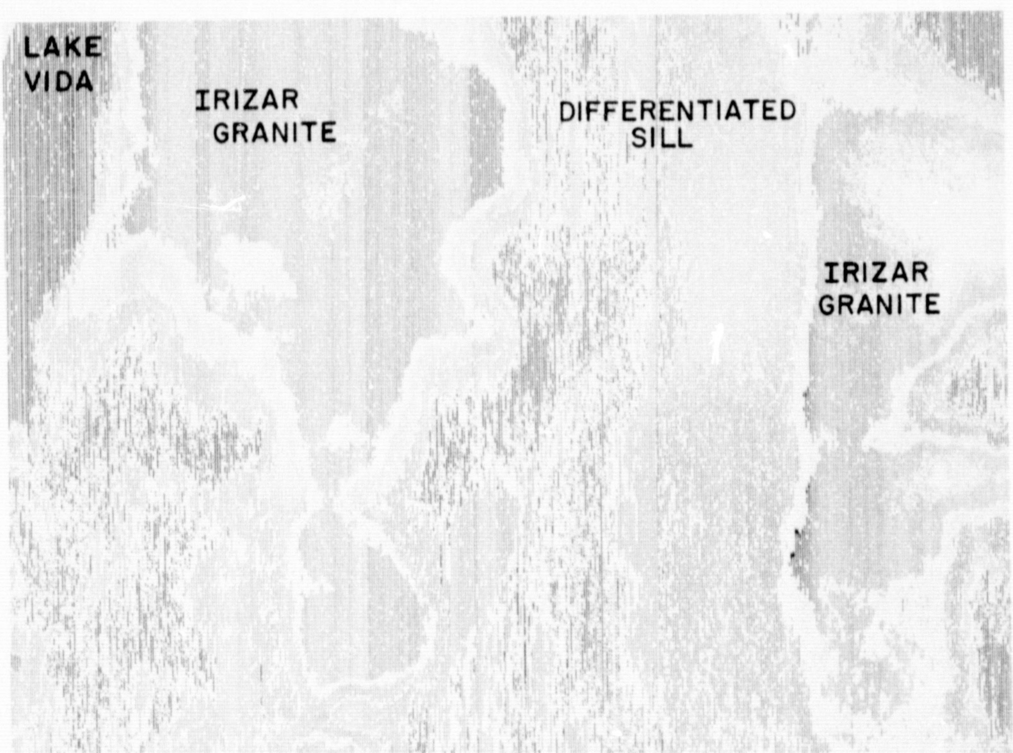

Figure 14. Detailed isodensity contour map of a horizontally differentiated sill of Ferrar Dolerite near Lake Vida.

PLATE 7

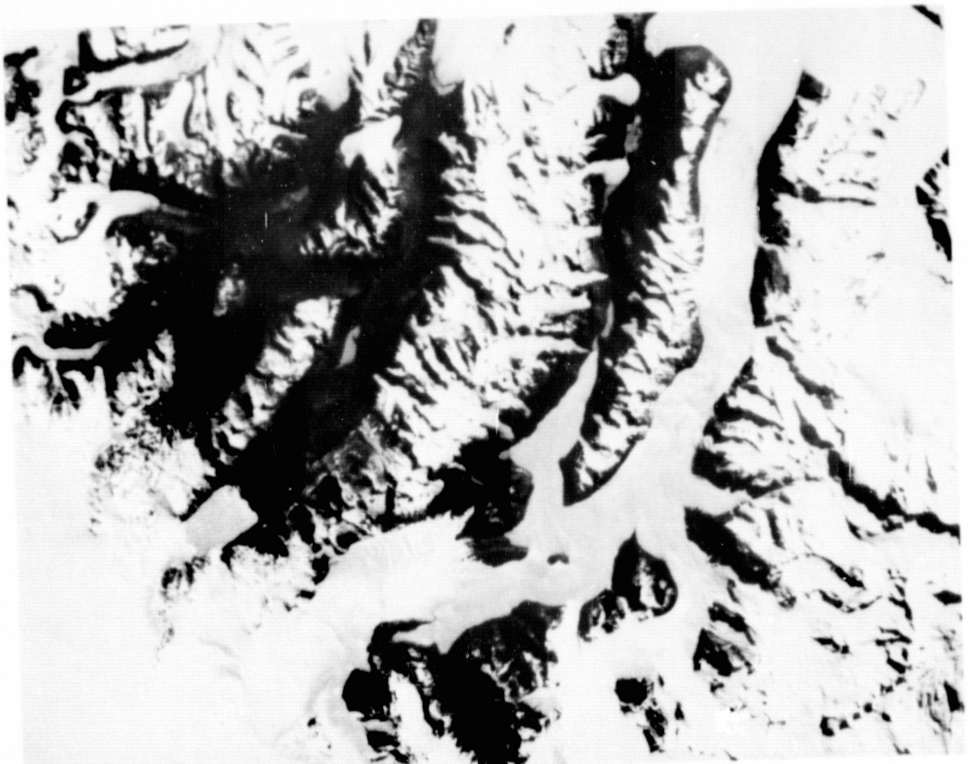

Figure 15a. Diazo color-composite LANDSAT image of the Ice-Free Valleys, Antarctica (1174-19433-4 = black-and-white; 1174-19433-7 = blue).

Figure 15b. Diazo color-composite LANDSAT image of the Ice-Free Valleys, Antarctica (1174-19433-5 = green; 1174-19433-7 = red).

PLATE 8