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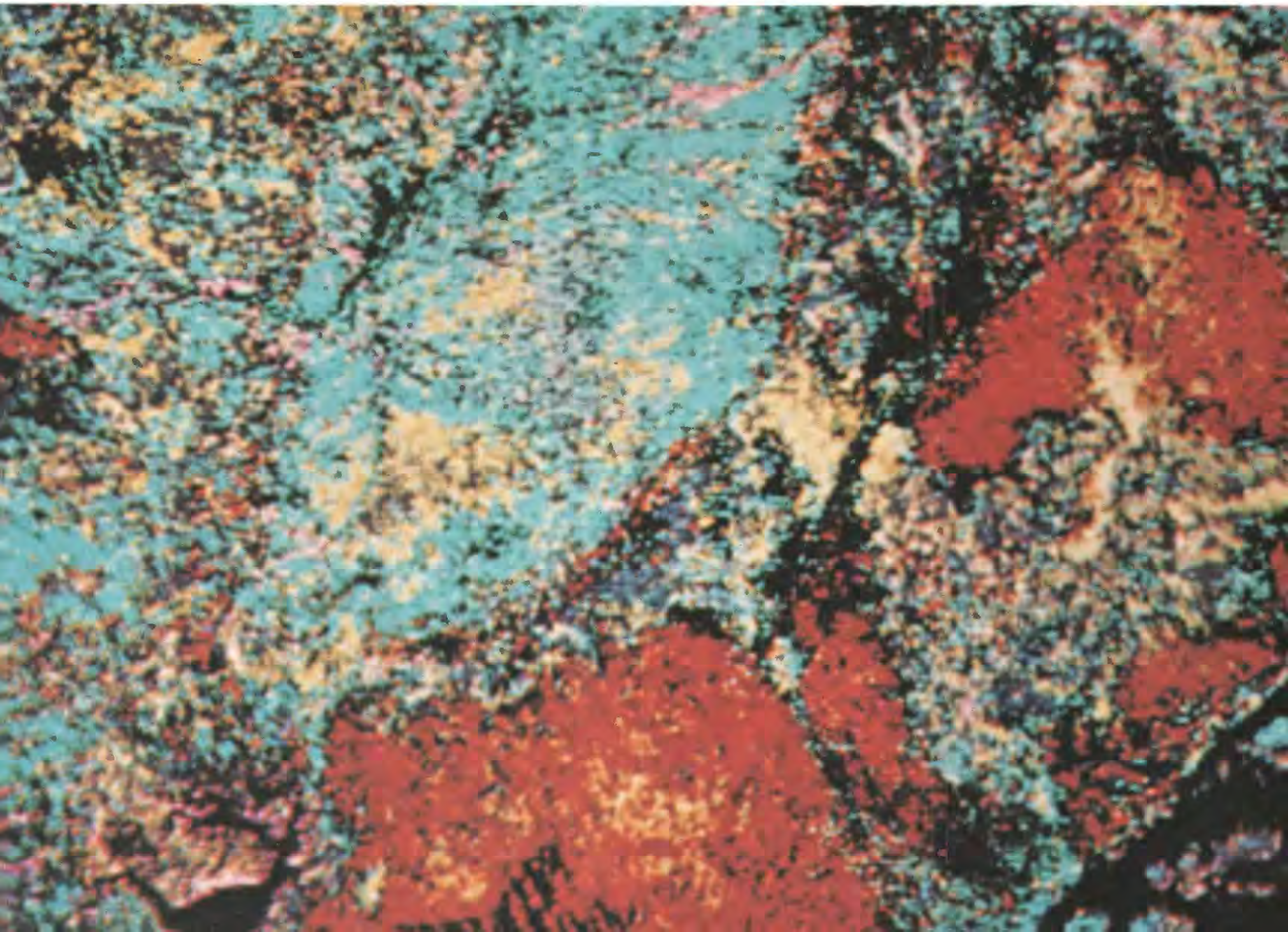
GEOLOGICAL SURVEY PROFESSIONAL PAPER 1102

Prepared in cooperation with the Queensland Department of Primary Industries, Australia



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INTEGRATED TERRAIN MAPPING WITH DIGITAL LANDSAT IMAGES IN QUEENSLAND, AUSTRALIA

By CHARLES J. ROBINOVE

ABSTRACT

Mapping with Landsat images usually is done by selecting single types of features, such as soils, vegetation, or rocks, and creating visually interpreted or digitally classified maps of each feature. Individual maps can then be overlaid on or combined with other maps to characterize the terrain. Integrated terrain mapping combines several terrain features into each map unit which, in many cases, is more directly related to uses of the land and to methods of land management than the single features alone. Terrain brightness, as measured by the multispectral scanners in Landsat 1 and 2, represents an integration of reflectance from the terrain features within the scanner's instantaneous field of view and is therefore more correlatable with integrated terrain units than with differentiated ones, such as rocks, soils, and vegetation.

A test of the feasibilty of the technique of mapping integrated terrain units was conducted in a part of southwestern Queensland, Australia, in cooperation with scientists of the Queensland Department of Primary Industries. The primary purpose was to test the use of digital classification techniques to create a "land systems map" usable for grazing land management. A recently published map of "land systems" in the area (made by aerial photograph interpretation and ground surveys), which are integrated terrain units composed of vegetation, soil, topography, and geomorphic features, was used as a basis for comparison with digitally classified Landsat multispectral images. The land systems, in turn, each have a specific grazing capacity for cattle (expressed in beasts per km^2) which is estimated following analysis of both research results and property carrying capacities.

Landsat images, in computer-compatible tape form, were first contrast-stretched to increase their visual interpretability, and digitally classified by the parallelepiped method into distinct spectral classes to determine their correspondence to the land systems classes and to areally smaller, but readily recognizable, "land units."

Many land systems appeared as distinct spectral classes or as acceptably homogeneous combinations of several spectral classes. The digitally classified map corresponded to the general geographic patterns of many of the land systems. Statistical correlation of the digitally classified map and the published map was not possible because the published map showed only land systems whereas the digitally classified map showed some land units as well as systems.

The general correspondence of spectral classes to the integrated terrain units means that the digital mapping of the units may precede fieldwork and act as a guide to field sampling and detailed terrain unit description as well as measuring of the location, area, and extent of each unit.

Extension of the Landsat mapping and classification technique to other arid and semi-arid regions of the world may be feasible.

INTRODUCTION

Maps and descriptions of "land" as a resource in order to provide basic information on its capabilities and limitations are presented in numerous ways. These include geologic maps, soil maps, vegetation maps, topographic maps, water resource maps, and a multitude of other thematic maps. Each one is usually specific to a single scientific discipline or to a single factor that characterizes the land. A method of describing and characterizing land which is widely used throughout the world, but is only minimally used in the United States, is the Australian land systems approach.

The Australian approach characterizes land as "* * * the land surface and all of its characteristics of importance to man's existence and success. It is the integration of all these factors rather than mere likeness or unlikeness in some of the more observable characteristics which determine the similarity or dissimilarity of areal subdivisions in respect to land use potential" (Christian and Stewart, 1968, p. 238). Christian (1958) and Christian and Stewart (1968) provide a complete description of the philosophy, methods, and results of surveys using the Australian land systems approach.

Since 1972, Landsat satellite imagery has been available and has been used for many types of land surveys. The imagery is uniform, repetitive, available worldwide, and is eminently suitable for reconnaissance investigations of large areas. It has the further advantage of being ideally suited for providing basic map data for surveys conducted by the Australian land systems approach.

The purpose of this report is to:

1. Describe a land mapping basis by which land can be classified, described, and mapped by the use of Landsat imagery.
2. Relate the description of land mapping by Landsat imagery to land system mapping by the well established Australian methods.
3. Describe a land system mapping experiment using Landsat images in southwestern Queensland, Australia, where conventional land system mapping was being done in 1975 and 1976.
4. Compare conventional and experimental methods of land mapping.
5. Recommend operational methods for use of Landsat imagery for land system mapping.

ACKNOWLEDGMENTS

The author is grateful for the advice and assistance given by many colleagues during this study. Special thanks go to William A. Fischer for many stimulating discussions of integrated terrain mapping principles. The cooperation of Noel Dawson, Desmond Boyland, Keith Hughes, and John Mills of the Queensland Department of Primary Industries was invaluable in the field and the office, and by correspondence. Since this study is based on their original mapping and descriptions of the terrain of southwestern Queensland, their help and advice made the study possible. The staff of the Data Analysis Laboratory at the EROS Data Center, including Fred Waltz, Dave Greenlee, Charlotte Muchow, and Charles Nelson made possible the analyses reported here. David Carneggie of the EROS Data Center provided an especially critical and helpful review of the manuscript.

METHODS OF TERRAIN CLASSIFICATION

Terrain classification, whether for general or specific purposes, may be based on genetic, parametric, or landscape criteria. Each of these has advantages and disadvantages related to mapping methods, format for display of map information, and usability by the reader of maps. Mabbutt (1968) has defined and explained the three approaches and has wisely predicted "Ultimately, there comes a level of investigation at which the greater precision and reliability of the parametric approach are needed and to the extent that improvements in (remote sensor) scanning render the method more comprehensive, its inherent advantages of reliability will be exploited even at the reconnaissance (landscape) level of investigation." (Mabbutt, 1968, p. 26).

Genetic methods of terrain classification are described by Mabbutt (1968, p. 12) who states, "Attempts to arrive at distinctive land units by repeated subdivision on the basis of causal environmental factors may be grouped as the genetic approach." Normal geologic mapping and geomorphological mapping are examples of the genetic approach. Maps made on the basis of genetic classification do not generally indicate land potential or land capability and, although such information can be derived in part from them, such derivation generally requires large amounts of corollary information from other sources and a reasonable means of correlating such information.

Parametric classifications are defined by Mabbutt (1968, p. 21) as "* * * the division and classification of land on the basis of selected attribute values." A slope map, depth-to-water-table map or lithologic map are examples of parametric maps. The reflection of light from the land surface can be considered as an attribute of the land, and thus the reflectance in several wavelength bands as measured by the multispectral scanner in Landsat can be mapped as "attributes" or "parameters." Individual parametric maps are generally prepared for a specific purpose of land development and management and may be difficult to correlate quantitatively or even qualitatively with other parametric maps. Correlation is generally done by means of map overlays. Maps of a given area may be made at different times by specialists in different disciplines, and at different scales. Such maps are often difficult to correlate to obtain information bearing on a specific development problem, although they may individually contain important and useful information.

The parametric approach provides, in its most rigorous application, a numerical terrain measurement which is calibratable and generally repeatable. This approach is more objective than landscape mapping but is of necessity more expensive and time consuming and, therefore, limited in application to large areas.

The landscape approach classifies land, particularly at the reconnaissance level, on the basis of a complex of factors and attributes. Mabbutt (1968, p. 16) states, "The land complex as a whole is the object of study, even where a particular attribute may be of prime interest to a land classifier."

Two major factors account for the success of the landscape approach; the use of integrated mapping units which combine geomorphic features, soils, and vegetation as the basis for mapping and the formation of an integrated mapping team consisting of specialists in several disciplines working in concert to produce the landscape maps and land descriptions. The approach is well described in two books, "Aerial surveys and integrated studies," (UNESCO, 1968) and "Land evaluation" papers of a Commonwealth Scientific and Industrial Research Organization of Australia (CSIRO) symposium organized in cooperation with UNESCO, (Stewart, 1968). Both books are listed in the references in this report and the reader is referred to them for details of the mapping, philosophy, methods, and results.

The landscape approach, developed by the CSIRO is now readily utilized by the Australian States and by workers in the United Kingdom and other countries. Similar parallel approaches are used in the Soviet Union (Mitchell, 1973).

Terrain classification in the landscape approach is based on four hierarchical categories as proposed by Christian and Stewart (1968). A **site** is part of the land surface which is for all practical purposes, uniform throughout its extent in landform, soil, and vegetation. A **land unit** is usually a group of related sites which have a particular landform within the land system and wherever the land unit occurs again it would have the same association of sites. A **land system** is an area or group of areas, throughout which there is a recurring pattern of topography, soils, and vegetation. A **land zone** is a grouping of genetically related land systems.

The landscape approach always involves some subjectivity in the assignment of each area of land to a specific unit, system, or zone—but particularly where an area is described as being a mixture of two or more systems or where two areas belonging to the same system contain identical land units but in different proportions.

In the approach used by the Queensland Department of Primary Industries in the arid lands, the attribute of prime interest is the grazing capacity of the land (beasts per km^2) in wet and dry years and the reaction of the land to grazing pressure, and yet the landscape approach is particularly suitable because the ultimate numerical parameter of interest can only be arrived at by integration of a number of other attributes, some of which are difficult or impossible to measure quantitatively. The main interest is how the land will react or how it has reacted to different land uses, particularly grazing, and how productivity might be increased or decreased to ensure long term stability. This is the basis for property planning.

Remote sensing has the capabiilty to provide some numerical measurements economically and efficiently for very large areas and thus is capable of forming a bridge between the objective (parametric) and subjective (landscape) approaches.

The hypotheses and experiment described in this report are an application of the parametric (quantitative) methods to the landscape approach.

HYPOTHESES BEING TESTED

One major and several minor hypotheses have been formulated and tested in this research on application of Landsat images to integrated terrain mapping. The major, and fundamental, hypothesis governing this study is that the radiance measured in a single Landsat picture element is an integration of the radiance of all features within the 0.45 ha area measured on the ground, such as vegetation, soil, rock, water, and artifacts, and a group of pixels therefore is statistically indicative of an integrated mapping unit that can characterize the similarities and differences of natural terrain units. Since the Australian land systems approach is based on integrated terrain units, the correspondence between maps made by the two systems should be high. Minor hypotheses are that the upland terrain units in the study area should be more readily differentiable in the wet season than in the dry and that repetitive monitoring can characterize changes in land systems that are of importance in land management decisions. Indeed, it is quite important to analyze data in the right year, usually one in which vegetation production is at a maximum.

It is further hypothesized that spectrally homogeneous units seen in Landsat images may actually be coherent terrain units (and consequently usable land management units) and can be properly named and described. This is the antithesis of the normal mapping method of deciding on a terrain inventory classification which will be used in a given area and then mapping and describing the features in accordance with the selected classification.

The combination of the integrated radiance measurement-integrated mapping unit may logically be extended to land inventory units, and from that to land capability units. One would not expect that the integrated units would correspond exactly in boundaries or descriptions with those mapped by the Australian land system approach or by other similar methods, but they may well be reasonable and usable units.

The Australian land system approach utilizes mapping units which include geomorphic features, soils, and vegetation in the description of each unit, rather than separate mapping of each category of information. Each Landsat pixel, which has the dimensions of approximately 59×79 meters on the ground (0.45 ha), measures the radiance of the terrain in four bands (green, red, and two bands in the near or reflected infrared). Because the measured radiance is that of all features of the ground, it is an areally integrated radiance unit. The major question is then: what is the relationship of an integrated radiance mapping unit (pixel) to the integrated attributes of the terrain mapping unit? Because the Australian land systems approach is a widely used one which utilizes integrated terrain units, this experiment is designed to see how closely Australian land systems maps can be made on the basis of integrated radiance measurements.

CHARACTERISTICS OF LANDSAT DATA

Landsat satellites provide worldwide multispectral images on a repeated basis. Landsat 1 operated between July 1972 and January 1978. Landsat 2 began operation in January 1975. The major sensor on both Landsats is a multispectral scanner which provides images of 185×185 km areas on an 18 day cycle. Each scene consists of four separate images:

Image	*Spectral Interval*	*Spectral Range*
Band 4	Green	500μm–600μm
Band 5	Red	600μm–700μm
Band 6	Infrared	700μm–800μm
Band 7	Infrared	800μm–1,100μm

Each band of each image set consists of 2,340 scan lines (perpendicular to the orbital track) and 3,240 picture elements (pixels) along each scan line, a total of 7.58×10^6 pixels per band per frame. Each pixel represents an area of approximately 0.45 ha on the ground.

One hundred twenty-eight radiance levels (7 bits) are recorded in bands 4, 5, and 6, and 64 radiance levels (6 bits) are recorded in band 7. The images may be produced in photographic form and analyzed either by photointerpretive techniques (including photo-optical image enhancement) or may be produced as computer-compatible magnetic tapes (CCT) and be analyzed by digital techniques. Further details of the Landsat image characteristics may be found in the "ERTS Data Users Handbook" (General Electric, 1972).

Landsat images in photographic form can be enlarged for practical purposes to scales as large as 1:100,000. Larger scales have been used by some investigators, but they require highly accurate photographic equipment and quality control. Digital images can be displayed at any reasonable scale, but the smallest area for which data is available is 0.45 ha. Once an image has been digitally enlarged and displayed so that each pixel can be seen by the eye, no further information is gained by further enlargement, but the images can be matched to larger scale maps. Landsat images are ideally suited to medium and small-scale mapping because of their uniformity over large areas.

Three methods of mapping with Landsat images are commonly employed. Each has its advantages and disadvantages which depend upon the purpose of the mapping, the skill and experience of the mapper, the interpretive and computer facilities available, and the cost.

Figure 1 shows schematically the three methods. The basic method (*A*) involves visual interpretation of the photographic images in color composite form at the desired scale. Interpretation for some purposes from the black and white prints is preferred by some interpreters but in general the color images are much more useful. Normal photointerpretive methods using photographic tone, texture, pattern, and spatial association are used, keeping in mind the small scale and large area portrayed.

The second method (*B*) involves enhancement of Landsat images to increase their contrast for greater discriminability and recognizability of features, ratioing of spectral bands of images to locate new interpretable combinations of radiance values, and scaling of brightness values of individual bands, which is a form of contrast enhancement. Contrast stretching can be done either photographically or digitally, but the digital processes can be calibrated and repeated more precisely and accurately than the photographic processes.

The third method (*C*) uses the radiance values measured by the multispectral scanner to classify the terrain and produces graphic maps (rather than solely enhanced images). Landsat computer-compatible tapes are utilized in a digital computer usually with an interactive image display. Successive iterations of radiance classifications are made and checked with ground information until the analyst is satisfied that a satisfactorily accurate map has been made and it is ready for field checking. A number of algorithms have been developed for multispectral classification ranging from the simple

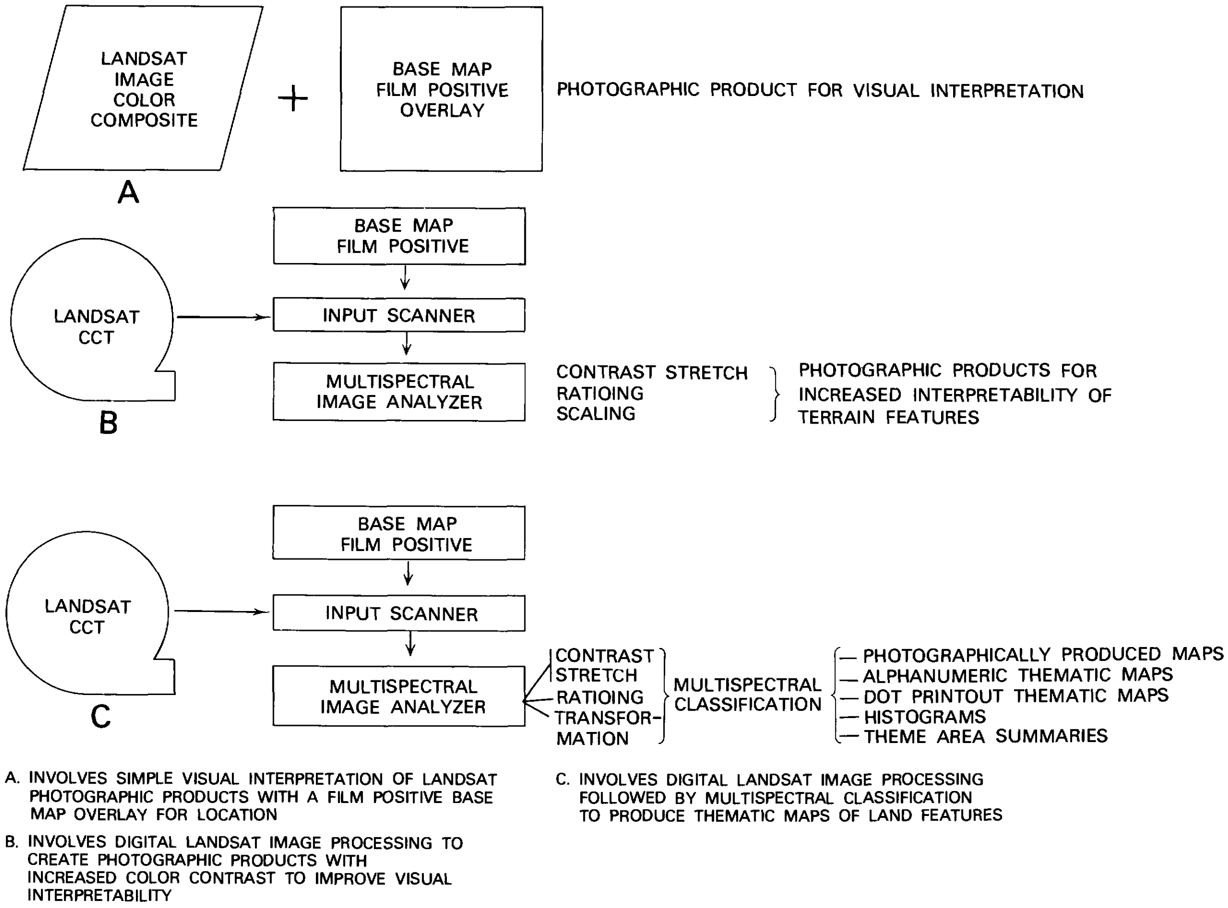


FIGURE 1.—Methods of mapping used with Landsat data.

parallelepiped method to the more complex maximum likelihood classification method.

Images and maps shown in this report were produced by the General Electric Image 100[1] multispectral analysis system at the EROS Data Center, Sioux Falls, S.D., and by the computers and programs of the Laboratory for Applications of Remote Sensing at Purdue University.

THE QUEENSLAND EXPERIMENT

Recent land systems maps in western Queensland (Division of Land Utilization, 1974) made by aerial photointerpretation and field checking were used as the basis for an experiment in application of Landsat images to land systems mapping. An area of about 148,000 km^2 was mapped at a scale of 1:500,000 and described by the Queensland Department of Primary Industries. At the time of this project, the map of Part 1 was published, but the map of Part 2 was in manuscript form and was used with permission of the authors. Landsat images were available for the area, and a set of Landsat images that covered portions of both Part 1 and Part 2 areas was selected for detailed analysis. Figure 2 shows the area covered by Landsat images and the available published and manuscript land system maps.

Cloud free Landsat images of the western part of the mapped area were taken on March 1, 1973, July 23, 1973, and February 6, 1974. The July 1973 image was taken during the dry season; the February 1974 image was taken during a major flood which inundated almost all of the Cooper Creek Valley. These two scenes (1365–23570 and 1563–23530) were analyzed as being representative of the dry and wet seasons. Unfortunately, the previous

[1] Trade names used in this report are solely for purposes of identification and do not constitute endorsements by the U.S. Geological Survey.

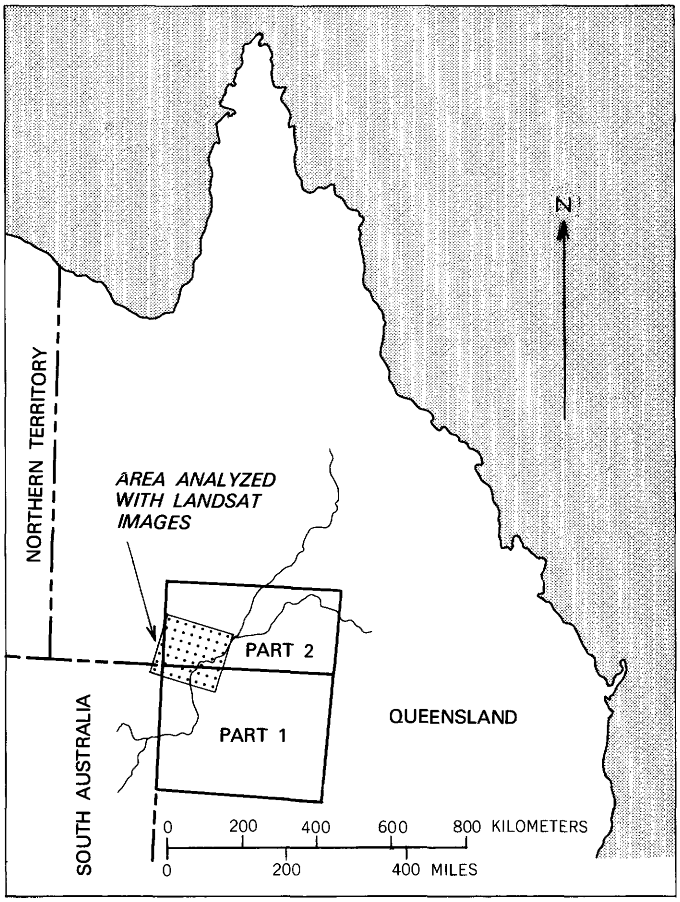


FIGURE 2.—Land system map information was available for almost all of the area covered by the Landsat image used. Part 1 was published (Division of Land Utilization, 1974) and Part 2 was in manuscript form when the study was done.

years were dry years, and it was not until 1975 and 1976 that full development of vegetation occurred. The greater growth of vegetation would have made it easier to separate land units in the silcrete-covered uplands.

In the Part I mapped area, 93 land units are grouped into 53 land systems, which in turn are grouped into 10 land zones. For example, the "dune fields" land zone includes eight types of sand-dune fields with varying geomorphic characteristics, vegetation, and soils. Each of the eight dune-field land systems is a fairly distinctive type, such as longitudinal dunes or reticulate dunes, but they may grade into each other without sharp boundaries. Within each of the dune-field systems various land units occur, such as the mobile dune crest, vegetated dune flank, and scalded dune margin. The available land systems maps are at a scale of 1:500,000 and show only the distribution of the land systems. A one-to-one correspondence was not expected between the map and multispectral classification of the Landsat images. The smallest area classified on the Landsat images is 0.45 ha (one pixel), too small to be shown on a 1:500,000-scale map.

The two Landsat images used in the experiment are shown in figures 3-6 and indicate the locations of the subscenes analysed in the following sections.

The image analysis method used is outlined as follows:

1. A selected sample of a Landsat scene was extracted from the digital tape, placed in the analysis system, and displayed on the cathode-ray color-display tube.
2. A film positive of the land systems map of the subscene area was scanned by a television camera, digitized, stored, and registered to the Landsat subscene by visual correlation of ground features.
3. Multispectral supervised parallelepiped classification of the subscene into a number of units was done and the resulting classified image was checked with the land systems map. The process was repeated until a map was obtained that corresponded closely to the land systems map or showed consistently mappable units whose specific identification required field checking.

WET SEASON IMAGE ANALYSIS

Landsat image 1563–23530 was taken during the wet season and during a major flood of Cooper Creek. It was selected for analysis of the upland areas because the vegetation is more vigorous and therefore more recognizable than during the dry season. Several subscenes of various sizes and the entire scene were analyzed to determine the recognizability and separability of various terrain types with various levels of sampling of the image data.

SUBSCENE 1

The initial subscene, an area in the uplands between Cooper Creek and Lake Yamma Yamma was selected for analysis and displayed on the screen. This subscene is a 512 by 369 pixel area, covers 85,000 ha, and was analyzed using every pixel. Figure 7 shows the subscene as it is displayed on the cathode ray tube. It is part of scene 1563–23530 that was taken during a major flood in the valley of Cooper Creek. The northwest and northeast corners of the subscene show the flood water.

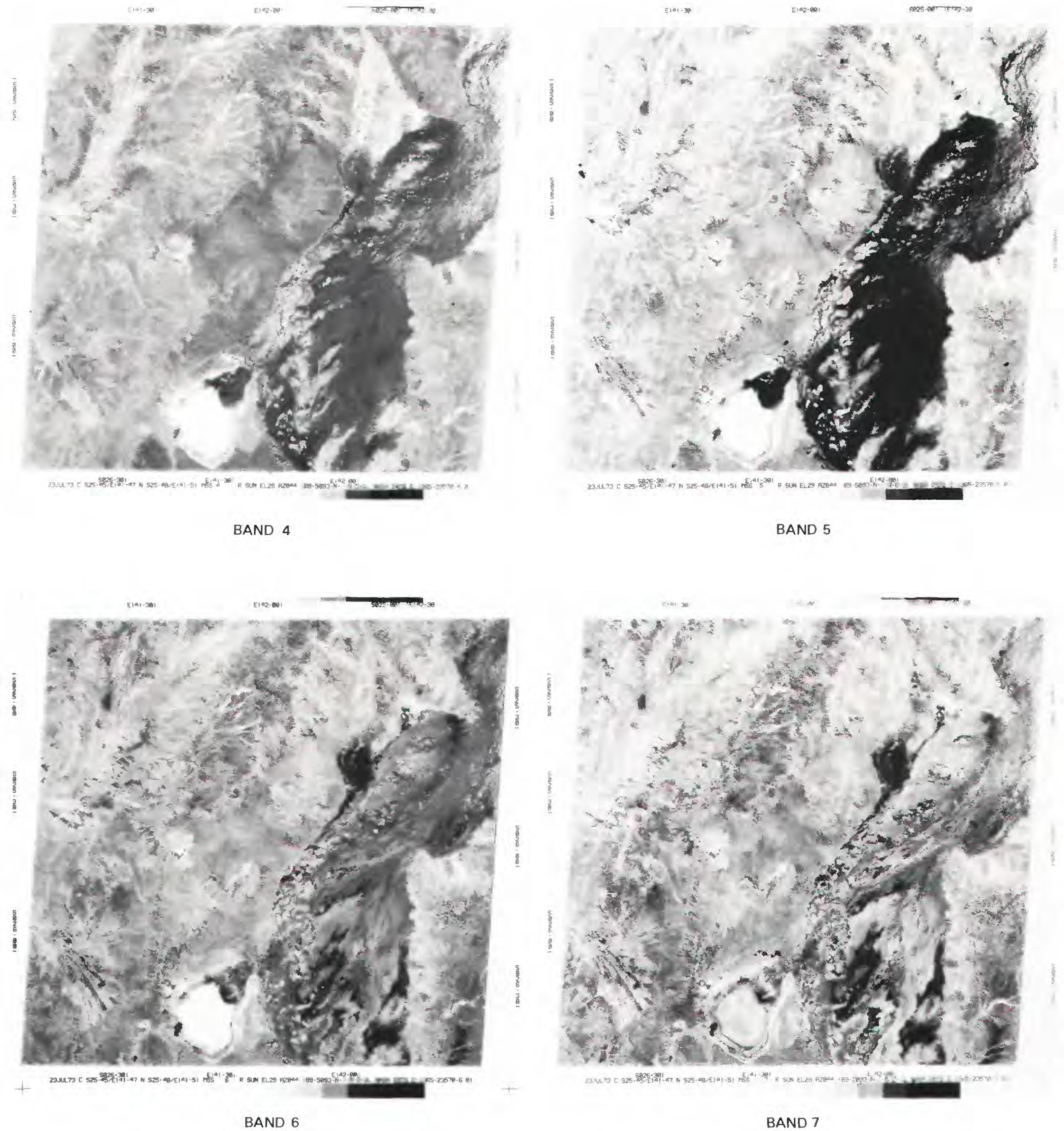


FIGURE 3.—Landsat Image 1365–23570 (dry season) showing the four bands.

The major land systems within the dune field zone were readily differentiated in this subscene. Figure 8 shows maps of 2 of the land systems as classified from small training sets of 4 to 12 picture elements that were located within each land system.

The descriptions of the two land systems as given in the legend of the published map are:

Arrabury-Plains with longitudinal dunes 5–19 meters high, some converging and diverging with mobile crests; spinifex shrubby hummock grassland; sandy red earths and red

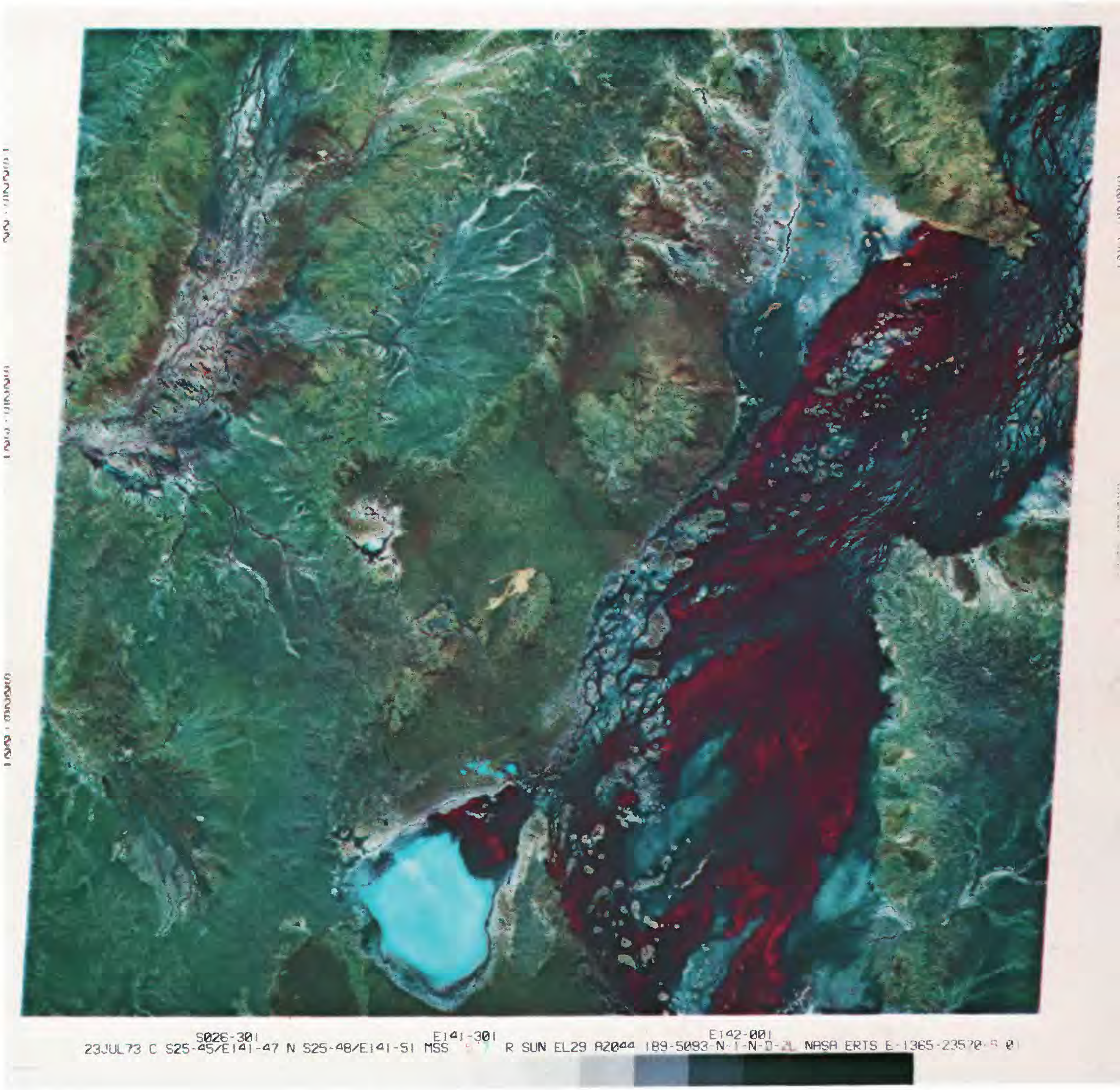


Figure 4.—Color composite of Landsat Image 1365–23570 showing dry season conditions (July, 1973) using bands, 4, 5, and 7.

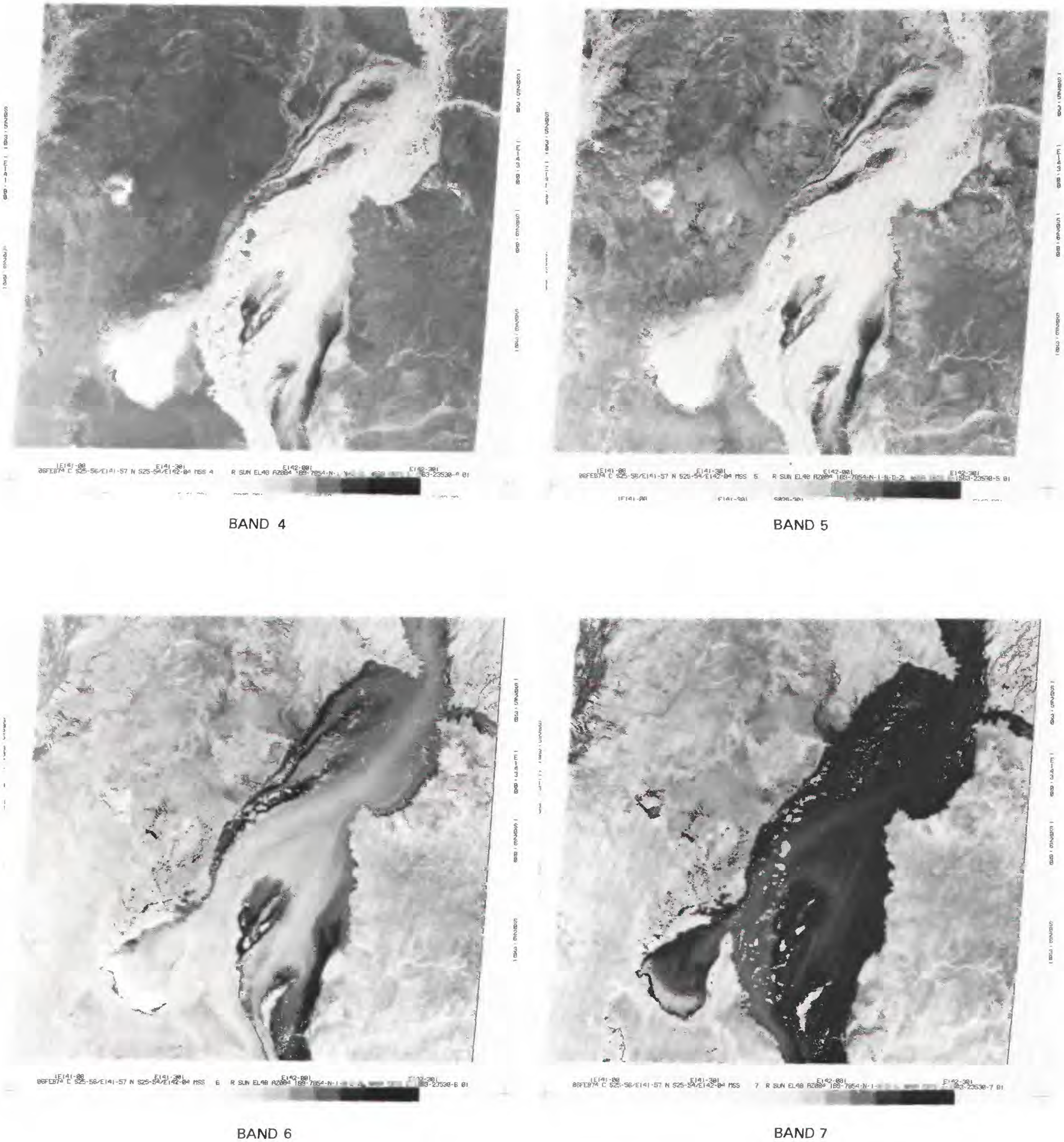


FIGURE 5.—Landsat Image 1563–23530 (wet season) showing the four bands.

earthy sands occur on the interdune area with red siliceous sands on the dunes.

Santos-Plains with converging and diverging dunes 4–8 meters high, sporadic mobile crests, spinifex shrubby hummock grassland; red earthy sands, sandy red earths and red siliceous sands with grey clays and texture contrast soils on the interdune clay pan.

From the above descriptions, one might not expect to see significant spectral differences between

FIGURE 6.—Color composite of Landsat Image 1563–23530 showing wet season (February, 1974) conditions using bands 4, 5, and Subscenes analyzed are outlined in black.

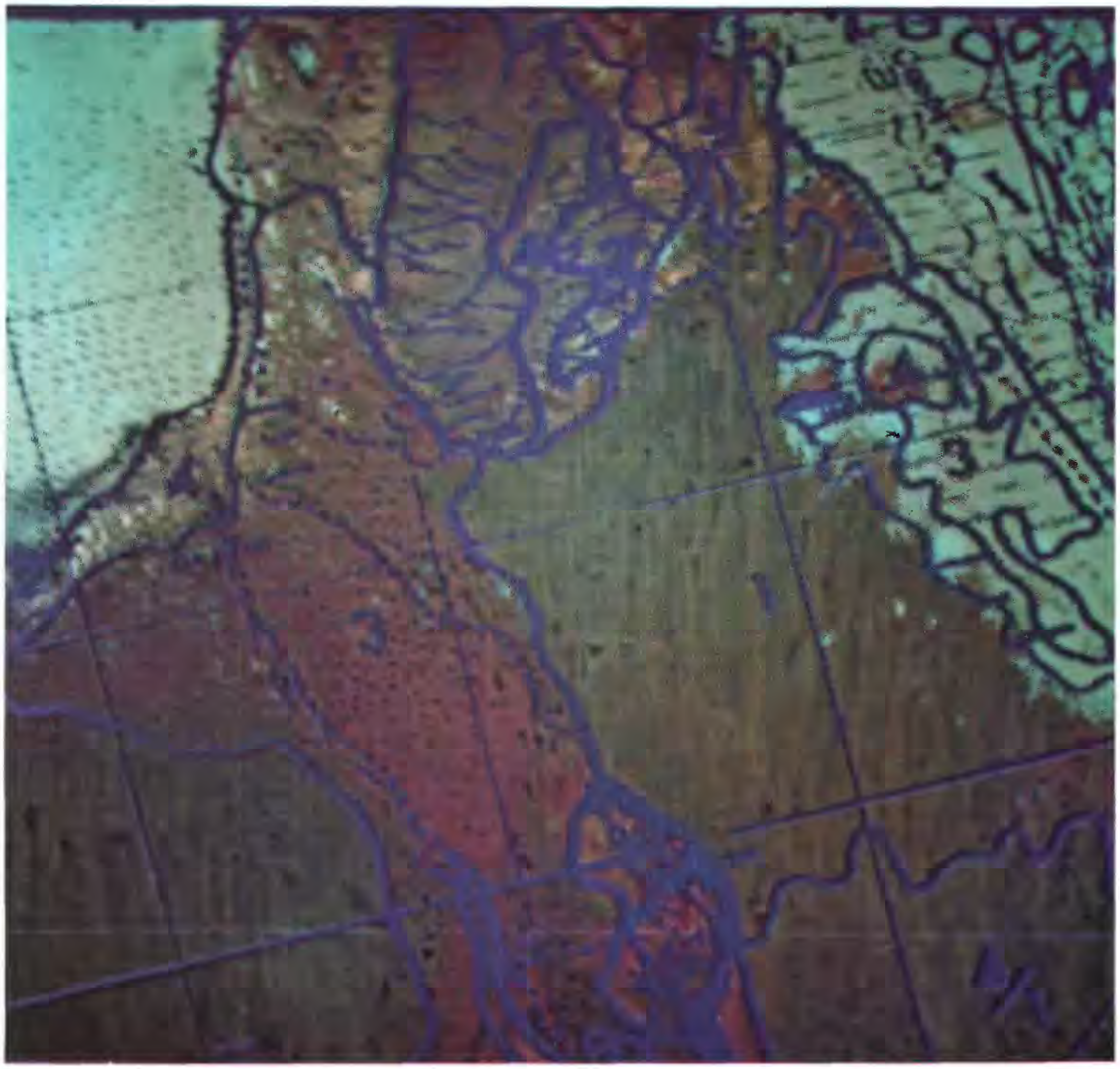


FIGURE 7.—Subscene 1 is displayed as a composite of bands, 4, 5, and 7. All pixels in the 512 by 369 area are displayed. The land systems map is overlaid on the image.

the two land systems except those caused by the soils in the clay pans, and yet they are readily differentiated by classifying the digital Landsat data.

Figure 9 shows photographs of the two land systems taken by the author from an aircraft at an altitude of about 300 meters. The differences in the multispectral data for the two systems are probably due to the shape of the dunes and interdune areas, to differing density of the vegetation, and to the clay pan soils.

The conclusion from the analysis of subscene 1 is that two land systems within the same land zone, which are basically similar, can be differentiated on the basis of a multispectral classification.

In the initial processes of classification, large training sets were used as the basis for classification. It was found, however, that a closer correspondence betwen the ground information and the classified Landsat data was achieved when smaller trainig sets were used. Table 1 compares the training set sizes and the multispectral data for classification of the Arrabury land systems with three sizes of training sets. Fewer errors of commission were present when smaller training sets were used, and although errors of omission increased slightly with the small training sets, the boundaries of the land system were more rigorously mapped with small training sets than with large ones.

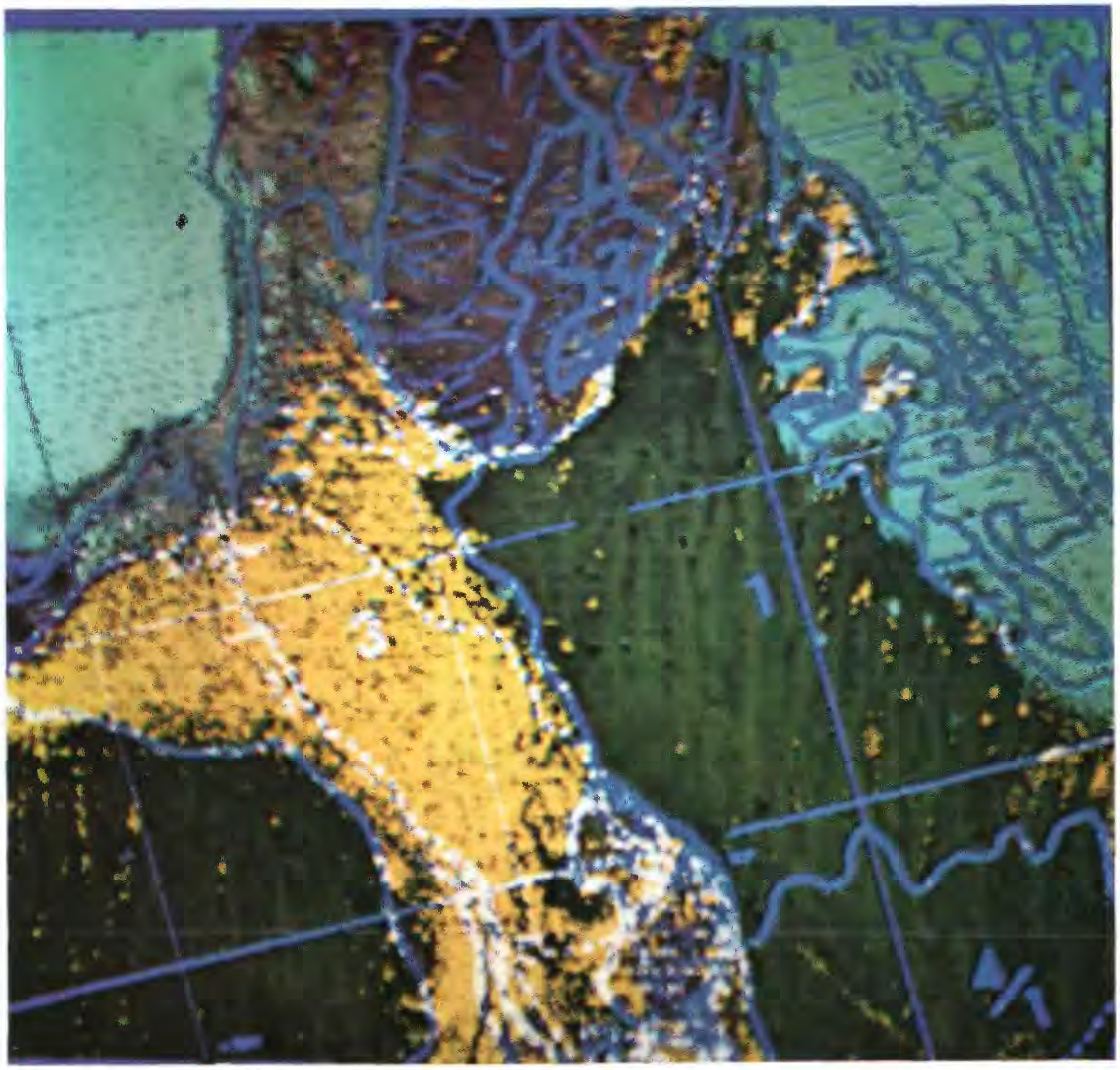


FIGURE 8.—The Arrabury (left, yellow) and Santos (right, light blue) land systems are multispectrally classified. Although the two land systems are quite similar except for the shape of the sand dunes and the density of vegetation, the multispectral separation is quite distinct.

TABLE 1.—*Lower radiance boundaries (LB) and upper radiance boundaries (UB) of training sets in the Arrabury Land system in subscene 1 and number of pixels classified with large, medium, and small training sets*

	6372 pixel training set		364 pixel training set		40 pixel training set	
	LB UB	Δ	LB UB	Δ	LB UB	Δ
Band 4	27 – 37	11	31 – 36	6	30 – 34	5
Band 5	26 – 53	28	36 – 49	14	31 – 47	17
Band 6	39 – 62	24	42 – 57	16	42 – 52	11
Band 7	30 – 46	17	36 – 48	13	32 – 44	13
Pixels classified	90,132		89,350		57,480	

SUBSCENE 2

A 1,022 by 738 pixel area (340,000 ha), including subscene 1 described in the previous section, was selected and displayed with the land systems map as ground control. Owing to the limited memory and display capacity of the multispectral analysis system, every other pixel in each row and column, or 25 percent of the total pixels in the subscene, could be analyzed and displayed. This provided an opportunity to test whether or not the classification accuracy would be as satisfactory as that achieved in subscene 1 where 100 percent of the pixels were used. Figure 10 shows this subscene in a composite of bands 4, 5, and 7 with an overlay of the land systems map. Training sets ranging in size from 8 to 16 pixels were used to develop 6 non-overlapping categories that covered a high percentage of the land area in the scene. The classified map is shown in figure 11. Note that almost all of the land area is

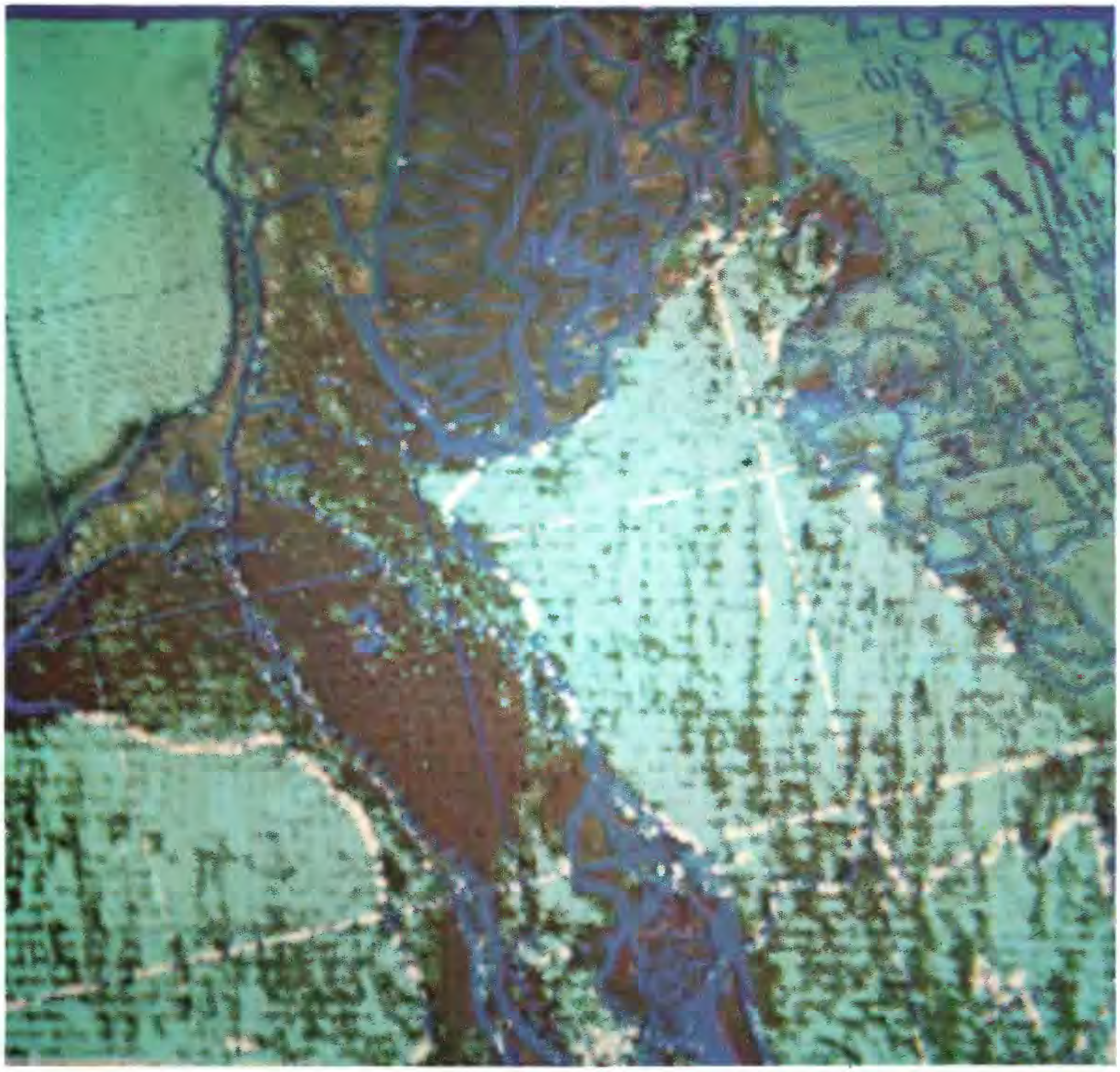


FIGURE 8.—Continued.

classified and that there is a reasonably good correspondence with the land systems map. Histograms showing the number of pixels of each brightness value for the six classes are shown in figure 12. Many of the histograms have small intervals indicating classes that may be practically unique.

Supervised classification produced a map that resembles the land systems (ground control map) in its gross characteristics, such as the boundaries of land systems, and correct classification of a large part of each land system. In addition, the use of only 25 percent of the available pixels provided an adequate sampling for analysis. The thematic map should, however, not be considered as a final product because additional interpretive judgment is needed.

SUBSCENE 3

The third subscene analyzed was a 1,536 by 1,107 pixel area (about 765,000 ha) covering the northwestern quarter of scene 1563–23530 that was analyzed on the multispectral system using as a sample every third pixel in every third line, or one-ninth of the pixels. Image enhancement by contract stretching and multispectral classification were both used. Figure 13 shows the standard color composite of bands 4, 5, and 7, and the contrast-stretched composite of the same bands. Figure 14 shows the histograms of the two data sets. The contrast-stretched image is displayed on the screen, the image data is classified, and each class is displayed as an overlay on the image. Decisions on the "correctness" of the

FIGURE 9.—Arrabury (upper) and Santos (lower) land systems. Aerial oblique photos from 300 meters altitude. The distinctive differences are mainly dune shape and spacing and density of vegetation.

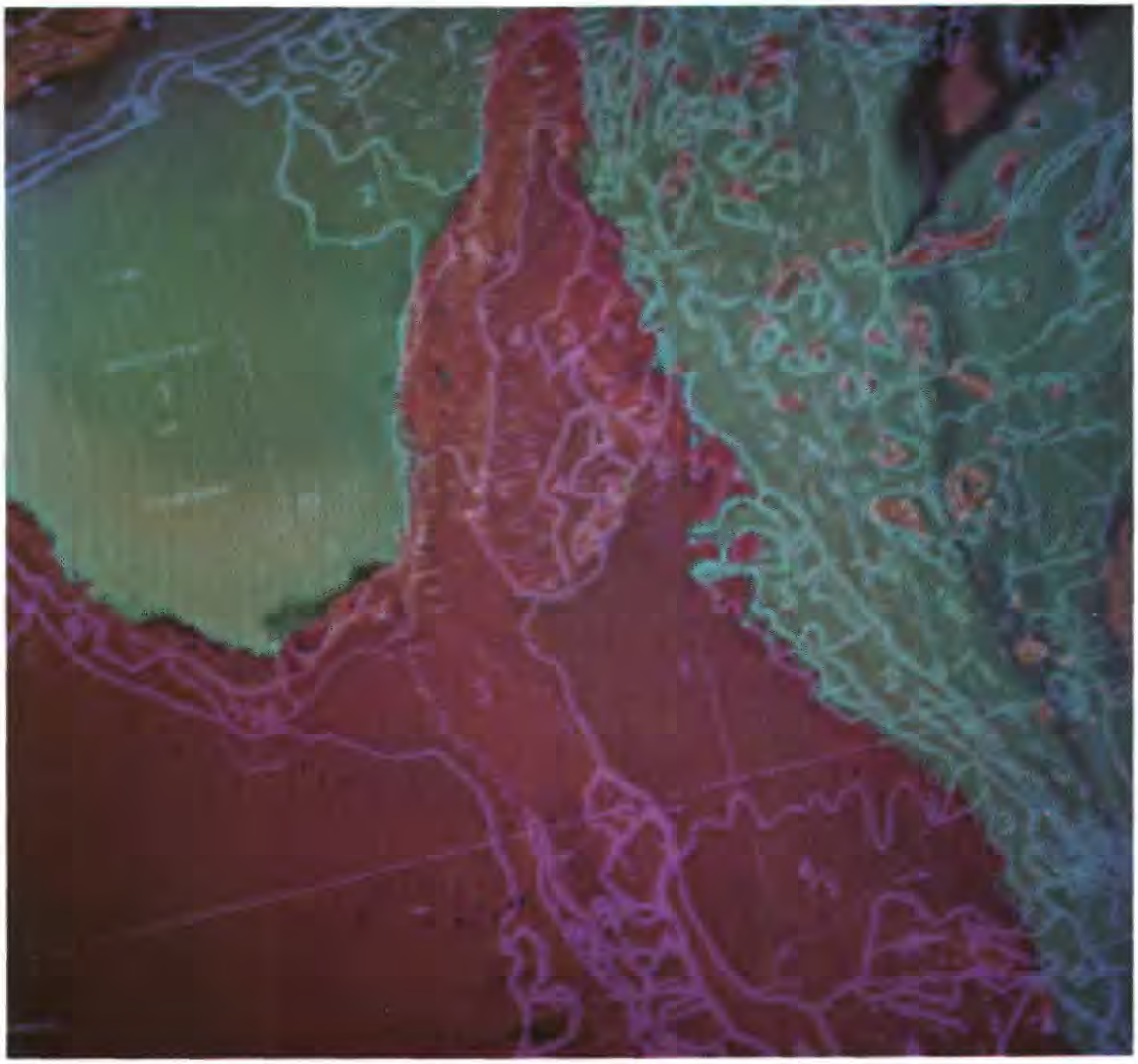


FIGURE 10.—Subscene 2, a 1022 by 738 pixel array with 25 percent of the pixels displayed, is overlaid with the land systems map and is used for multispectral classification.

classification are made on the basis of both ground information and photointerpretation of the image. The contrast-stretched image is more suitable for this purpose than the image displayed from the raw data.

Figure 15 shows the land systems map covering the area of subscene 3. The legend for the manuscript land systems map is not shown because of its detail. The important comparison to be made is between the features that are readily discriminated in the image and the general pattern shown on the land systems map. The purpose of the analysis of subscene 3 was to determine if a satisfactory classification could be achieved using only one-ninth of the pixels. This would be desirable for efficiency in computer mapping and in cartographic display of the classified map units. At a scale of 1:500,000, the normal publication scale of the Australian land systems maps, the area covered by a 3 by 3 pixel array is 0.36 mm by 0.48 mm (approximately 4 ha), which is about the size limit that can be shown cartographically and is also at about the limit that can readily be seen on a map with the naked eye.

CONTRAST STRETCHING

Subscene 3 was displayed on the screen and contrast stretched to increase the color contrast of the terrain features and to increase their visual interpretability. The contrast-stretch program used was

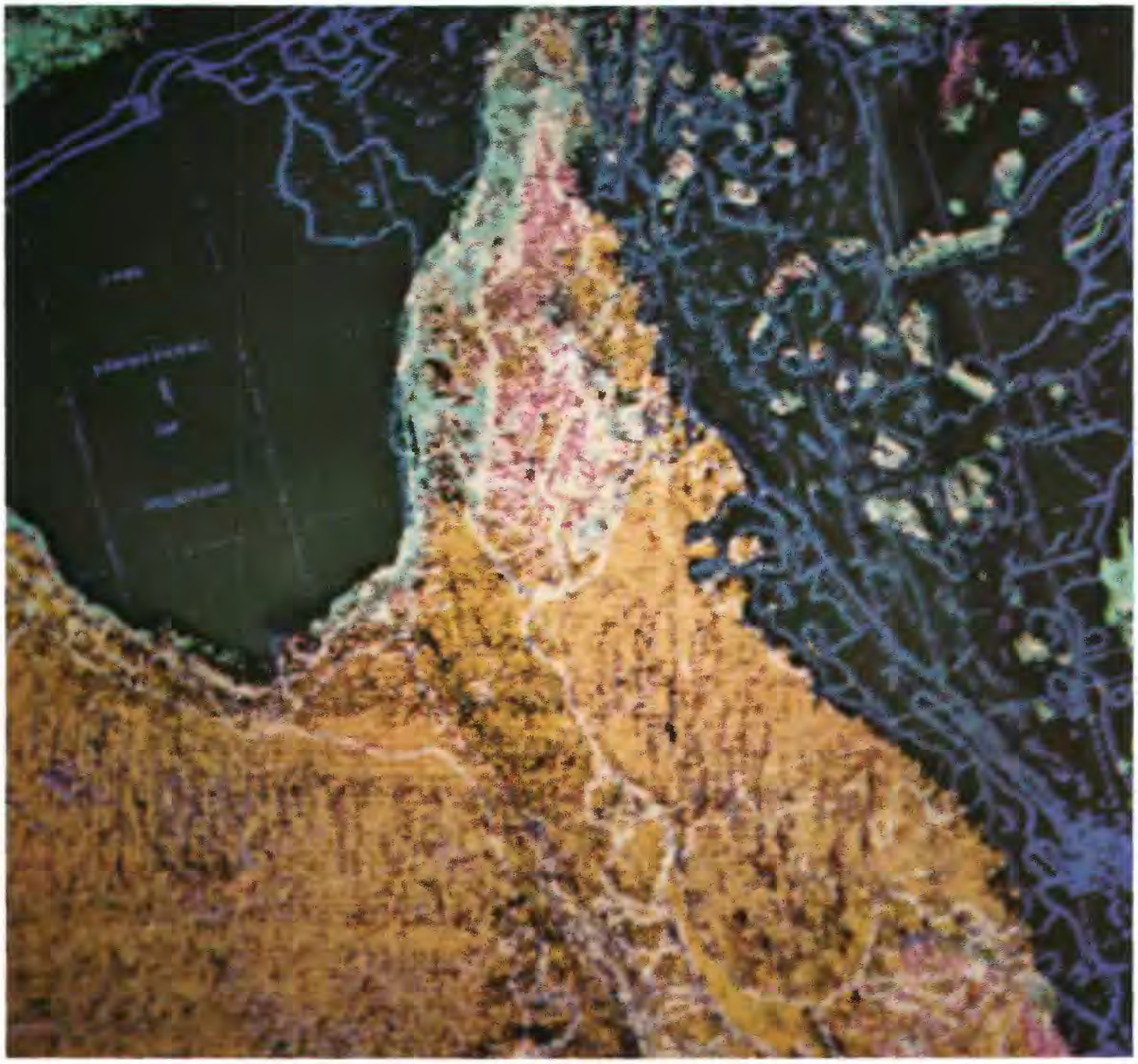


FIGURE 11.—Six category classified map of subscene 2 with land systems map overlay.

the proportional frequency distribution program,[2] which assigns an equal number of pixels to each unequal interval of digital counts. The contrast stretch utilizes the entire digital dynamic range and thus increases contrast in each band and subsequently in a multiband color composite. It does not affect the accuracy or precision of subsequent classification.

Comparison of the contrast stretched image with the standard digital display (fig. 12) and the land systems map (fig. 15) show that many terrain features are more highly contrasted with their surroundings. The dune fields and sand plains, particularly, show in green tones in contrast to the surrounding reddish and brownish tones. Distinctions between alluvial valleys and upland areas are more visible on the stretched image.

Visual interpretation of the stretched image should be done along with mapping of the land systems on the basis of enhanced spectral reflectance, texture, and shape. Because the color contrast is much greater than that of the standard color composite, the recognition of some, if not most, land systems should be easier and more reliable.

MULTISPECTRAL CLASSIFICATION

Classification of subscene 3 was done by supervised training methods. A training set was selected that represented a single homogeneous terrain feature and the multispectral analysis system searched

[2] Also termed "equal area stretch" or "histogram equalization stretch." A standard name has not yet been adopted.

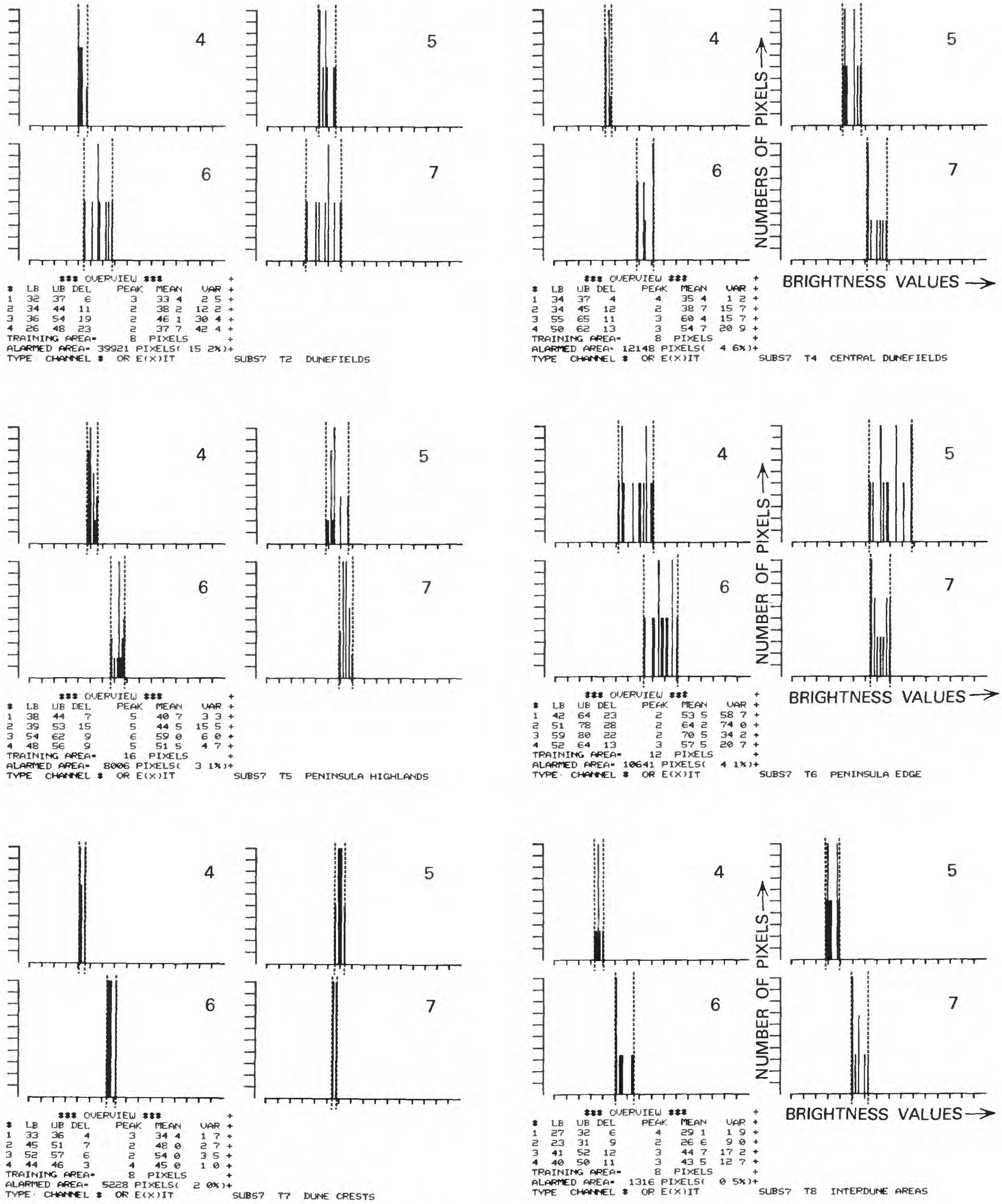


FIGURE 12.—Histograms of the six classes in subscene 2 which are mapped in figure 11.

TABLE 2.—*Statistical summary of seven themes classified for subscene 3*

Theme		Band	Radiance		Difference	Mean	Variance	Pixels classified	Percent pixels classified	Hectares
			Lower bound	Upper bound						
1	Dunefields	4	62	72	11	68.0	7.2	23,256	12.3	94670
		5	84	100	17	89.3	17.8			
		6	90	110	21	99.9	22.4			
		7	76	88	13	83.6	14.9			
2	Bare ground	4	68	84	17	76.2	24.5	9,362	5.0	38150
		5	101	154	54	108.5	42.3			
		6	92	168	77	120.6	74.3			
		7	76	136	61	102.9	76.9			
3	Lowlands	4	60	68	9	67.0	4.2	4,442	2.3	18080
		5	74	90	17	81.0	28.1			
		6	106	110	5	108.2	2.8			
		7	96	100	5	97.5	3.7			
4	Bright vegetation	4	60	73	14	67.4	12.6	8,897	4.7	36210
		5	46	67	22	61.6	25.2			
		6	100	118	19	107.8	20.4			
		7	99	124	26	104.9	26.4			
5	Bright valleys	4	88	108	21	93.7	31.0	4,025	2.1	16410
		5	92	148	57	117.5	133.6			
		6	118	150	33	132.5	64.0			
		7	104	136	33	114.8	51.5			
6	Medium vegetation	4	64	73	10	68.5	7.2	28,975	15.3	117900
		5	58	76	19	68.7	25.0			
		6	70	105	16	97.2	19.3			
		7	64	96	33	87.8	36.9			
7	Divides	4	72	80	9	73.6	5.7	6,398	2.4	26050
		5	74	86	13	79.9	17.1			
		6	106	112	7	108.5	4.2			
		7	91	100	10	96.9	8.5			
	Total	--	---	---	--	----	----	85,355	45.1	

the subscene for pixels whose combination of radiance values were within those of the training set pixels. It then classified each pixel according to those values and displayed them on the scene as a single theme. Table 2 shows a statistical summary of seven themes that were classified in the subscene. Figure 16 shows the combination of the seven themes.

The number of pixels, acres, and hectares for each theme are calculated by counting the number of pixels classified in each theme and are shown in the following table:

	Number of pixels	Acres	Hectares
Theme 1	209,241	234,000	94,700
Theme 2	84,312	94,300	38,100
Theme 3	39,951	44,700	18,100
Theme 4	80,037	89,500	36,200
Theme 5	36,261	40,500	16,400
Theme 6	260,613	291,000	118,000
Theme 7	57,573	64,000	26,000
Total	767,988		

Separability of the seven themes is established by a lack of overlap of the upper and lower radiance limits of pairs of themes in any single band although they may overlap in other bands. For example, themes 1 and 2 are separable in band 5, although they overlap in bands 4, 6, and 7. Table 3 shows the separability of the seven themes.

TABLE 3.—*Bands in which separability is produced between pairs of themes in the northwest subscene, 1365–23530*

Themes	1	2	3	4	5	6	7
1							
2	5						
3	7	5					
4	5, 7	5	5				
5	4, 6, 7	4	4, 5, 6, 7	4, 5			
6	5	5	6	7	4, 5, 6, 7		
7	7	5	4	5	4, 5, 6, 7	6	

Figure 17 shows the range, size, and relation of the brightness values of the seven themes based on their parallelepiped classification in bands 4, 5, and 7. The four-dimensional boundaries of the classes cannot be shown because of the three-dimensional nature of the diagram, but it does illustrate the closeness of the themes. Because only bands 4, 5, and 7 were used in construction of the diagram, it does not show well the separability of themes 3 and 6 and themes 6 and 7, and because they are separated only on the basis of band 6.

CORRESPONDENCE OF MULTISPECTRALLY CLASSIFIED THEMES WITH TERRAIN FEATURES

The themes that have been classified and mapped with the Landsat data are groupings of pixels with similar brightness values. In order to describe them

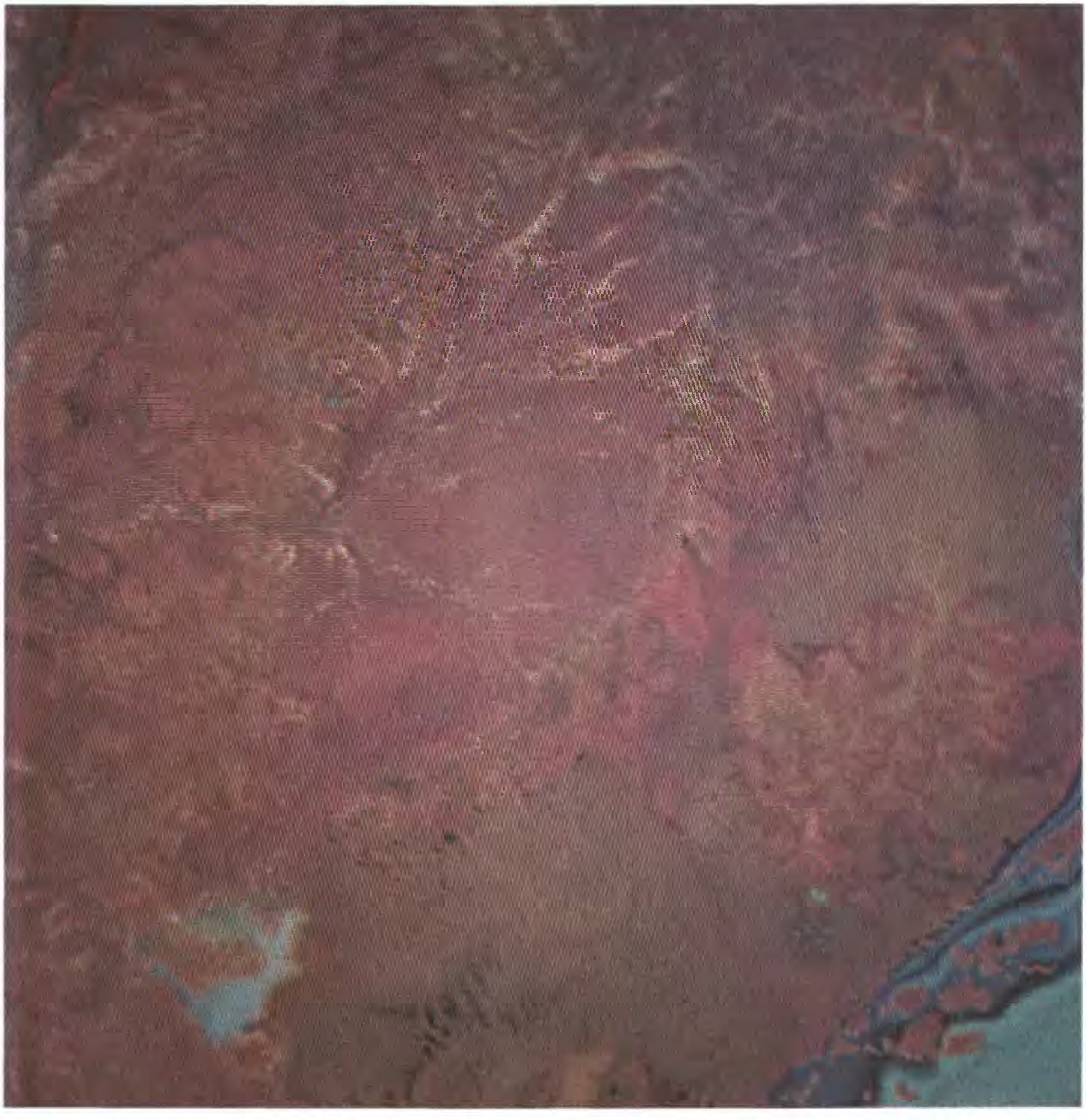


FIGURE 13.—Standard color composite of subscene 3, using every third pixel in every third row, of bands 4, 5, and 7 (left) and contrast-stretched composite of bands 4, 5, and 7 (right).

adequately in terms of terrain features, it is necessary to relate them to the previously mapped land systems. This was done by overlaying a film positive of the land systems map over a photographic print of the thematic map to see which themes occurred within each of the various land systems. Table 4 shows a descriptive comparison of the themes with the land systems.

No statistical correlation was attempted for several reasons. First, the original mapping was somewhat subjective and arbitrary. The aerial photo interpreter or field mapper may assign a given terrain

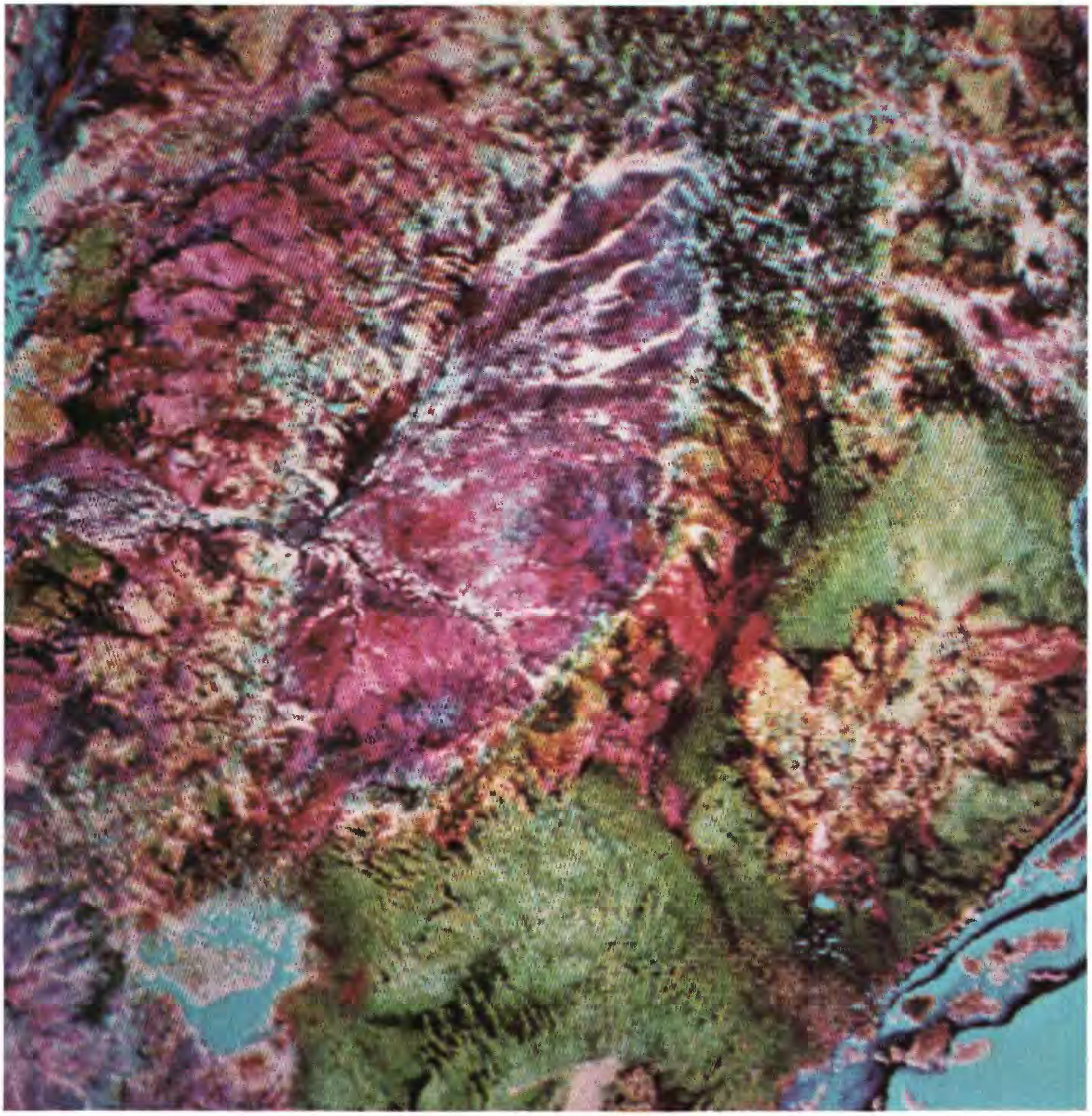
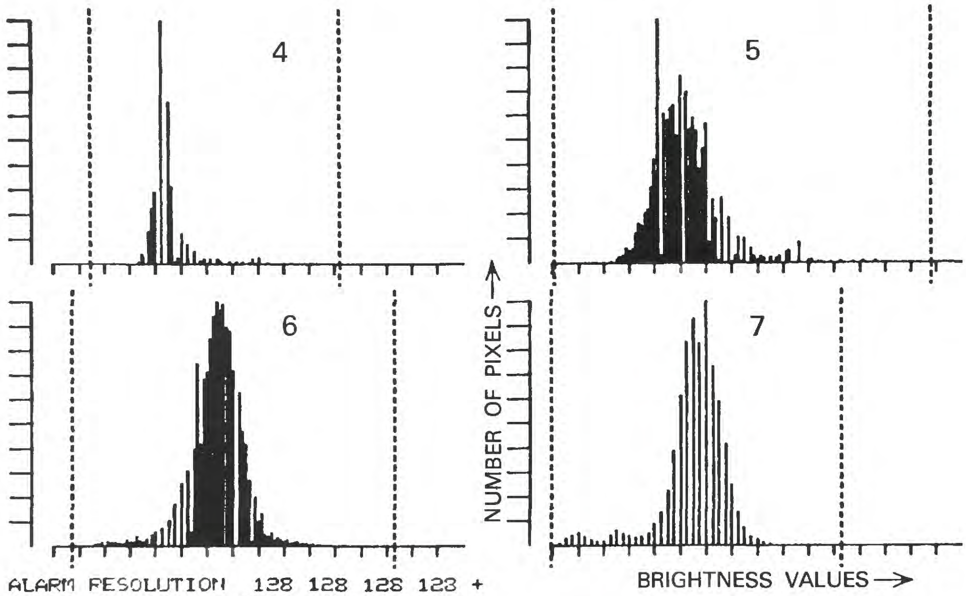
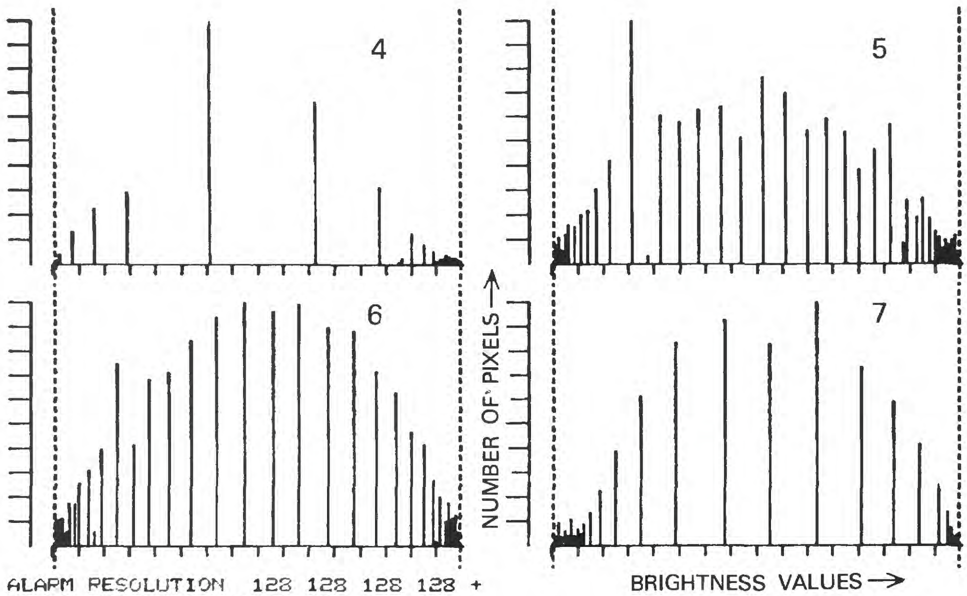


FIGURE 13.—Continued.

area to a given land system rather than to another based upon a subjective similarity or may group some units because of the small map scale. Second, some land units, rather than the larger land systems, are recognizable multispectrally and the same unit may occur in several land systems. An example is the mobile, unvegetated crests of dunes which occur in each of the eight dune field land systems. Third, a single feature may control the spectral reflectance and yet it may be only a single factor used in assigning a given area to a specific land system. As an example, dense vegetation or silcrete that com-




```
ALARM RESOLUTION   128 128 128 123 +
#   LB   UB  DEL      PEAK   MEAN    VAR +
1   12   89   78   58706.    36.0   37.5 +
2    1  118  118   15359.    41.2  101.9 +
3    6  106  101   13133.    51.1   62.1 +
4    0   90   91   23612.    44.2   92.4 +
TRAINING AREA=185196. PIXELS           +
ALARMED AREA=188928.PIXELS( 72.1%)+
TYPE CHANNEL (1-4), OR E(X)IT        NW SUBSCENE
```




```
ALARM RESOLUTION   128 128 128 128 +
#   LB   UB  DEL      PEAK   MEAN    VAR +
1    1  127  127   58716.    64.01275.2 +
2    1  127  127   15355.    64.01326.2 +
3    1  127  127   13138.    64.01329.4 +
4    1  127  127   23603.    64.11326.9 +
TRAINING AREA=185196. PIXELS           +
ALARMED AREA=188928.PIXELS( 72.1%)+
TYPE CHANNEL (1-4), OR E(X)IT        NW SUBSCENE EQ. AREA STRETCH
```

FIGURE 14.—Histograms of the unstretched and contrast-stretched subscene 3.

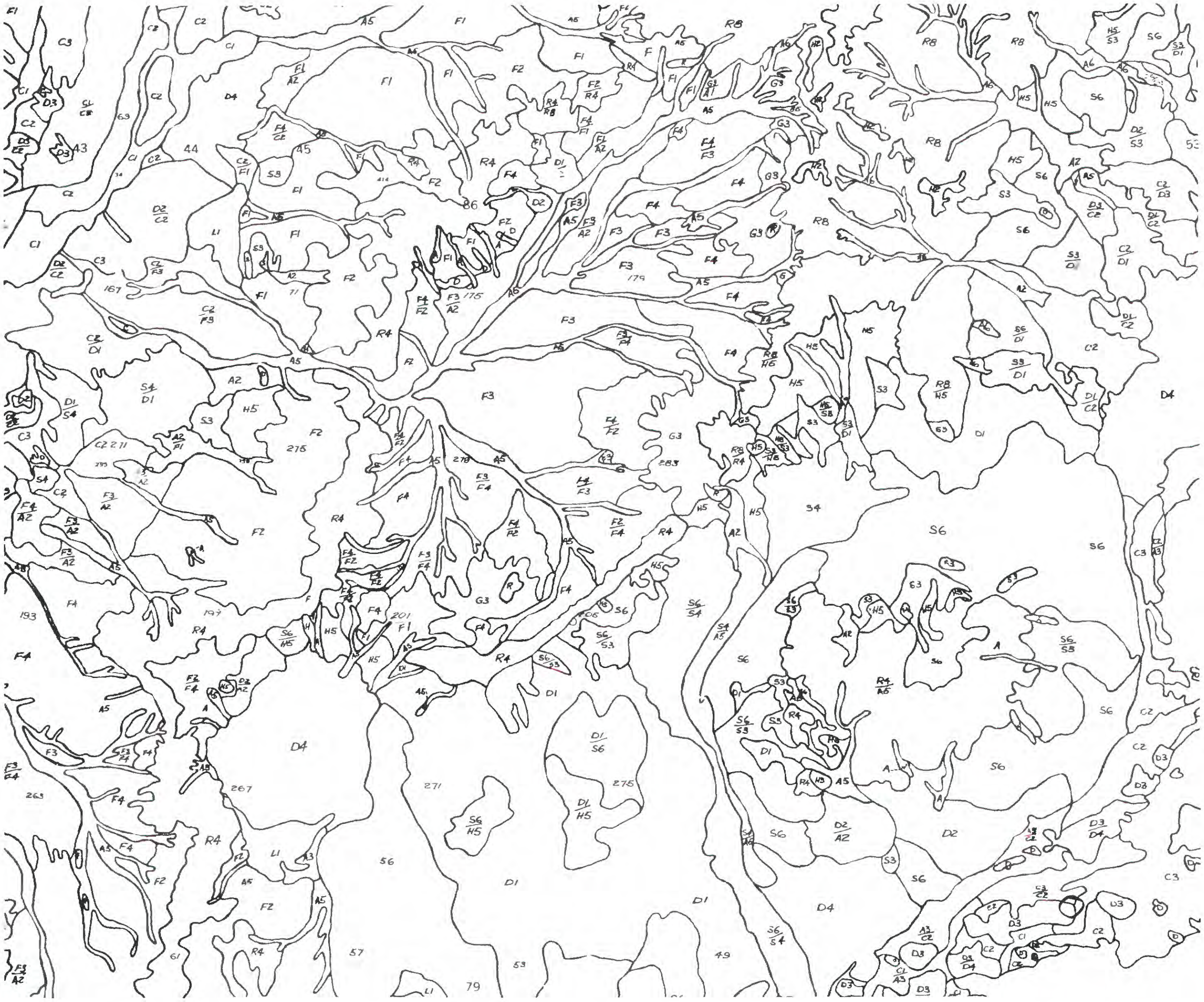


FIGURE 15.—Land system map of subscene 3. (Unpublished map from Queensland Department of Primary Industries.)

pletely covers the ground will control the spectral reflectance although the soil type may be highly significant in a land system assignment. The relation shown in Table 4 is valid in many cases, but it is not always highly correlated because of the reasons noted above.

The correspondence indicates that the map produced by digital classification may not represent a classical "land systems" map. However, it may be used for land management decisions. If, for some areas, the bedrock-soils-vegetation complex controls the spectral reflectance, the map is similar to a land systems map but if only a single terrain factor controls the reflectance at a particular point in time, that factor may not only be dominant in the analysis but may be a dominant control on land management and use.

A second method of correlating the multispectral analysis results with the published map involves a visual interpretation and mapping of data on the thematic map. Figure 18 shows subscene 3 (the northwest subscene) with boundaries drawn around single or multiple themes to create a generalized map. Varnes (1974, p. 4) states "The essence of mapping is to delineate areas that are homogeneous or acceptably heterogeneous *for the intended purpose of the map*" [italics are the author's]. Each theme (individual color) is homogeneous with respect to

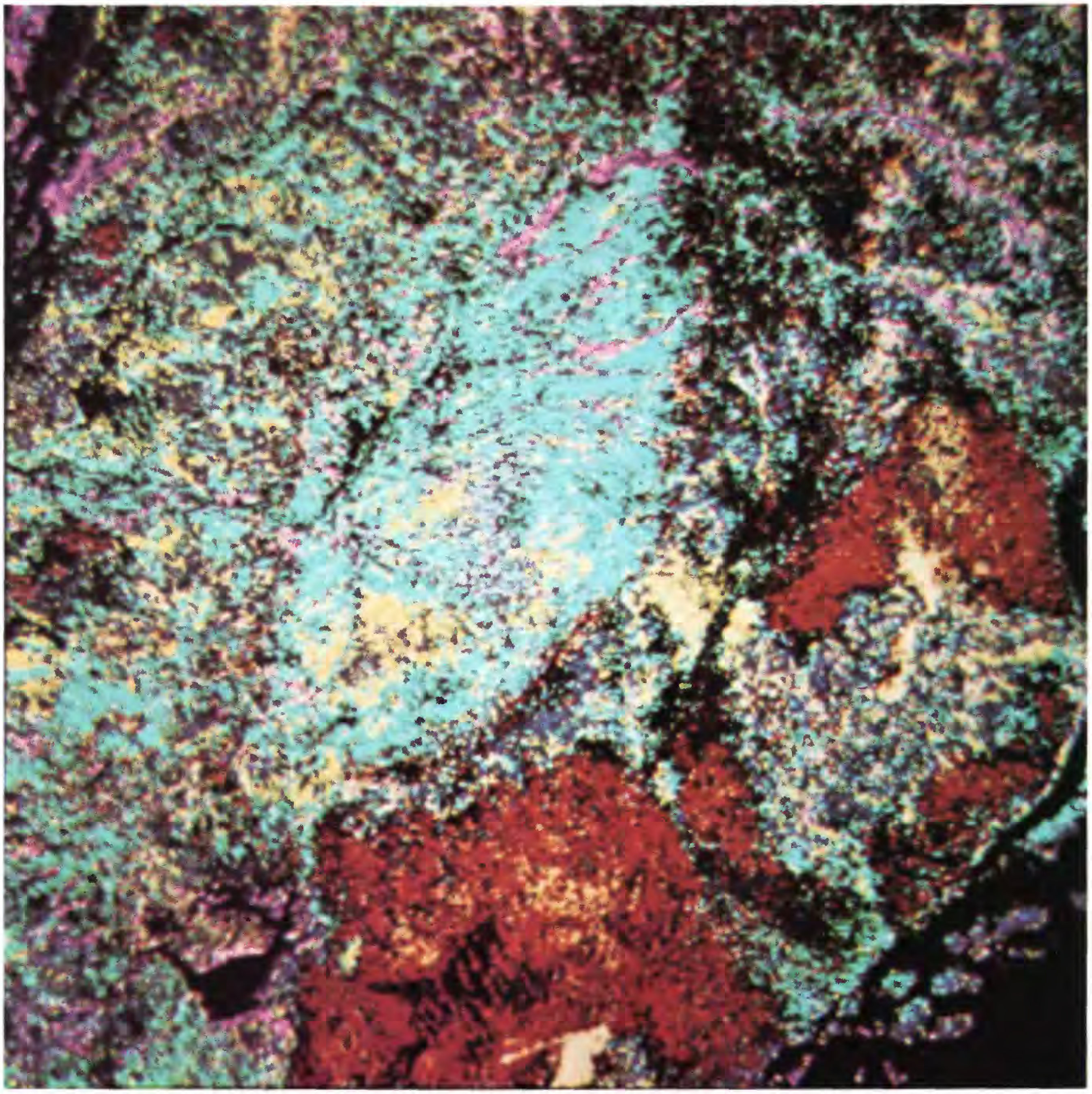


FIGURE 16.—Seven multispectrally classified themes in subscene 3.

a single terrain attribute, the brightness value in each band. Where a reasonably sized geographic area consists of a single theme, it may be considered to be a terrain mapping unit. Where a reasonably sized geographic area consists of a random appearing set of two or more themes, it may also be considered as a terrain mapping unit with "acceptable heterogeneity." Each of the lettered regions on the map is either "homogeneous" (A) or "acceptably heterogeneous." (B and C)

It should be recognized that mapping by the digital analysis of multispectral imagery is an *a priori* method of creating homogeneous map units (with respect to brightness values). Normal mapping methods involve drawing boundaries around areas which are determined to be internally homogeneous

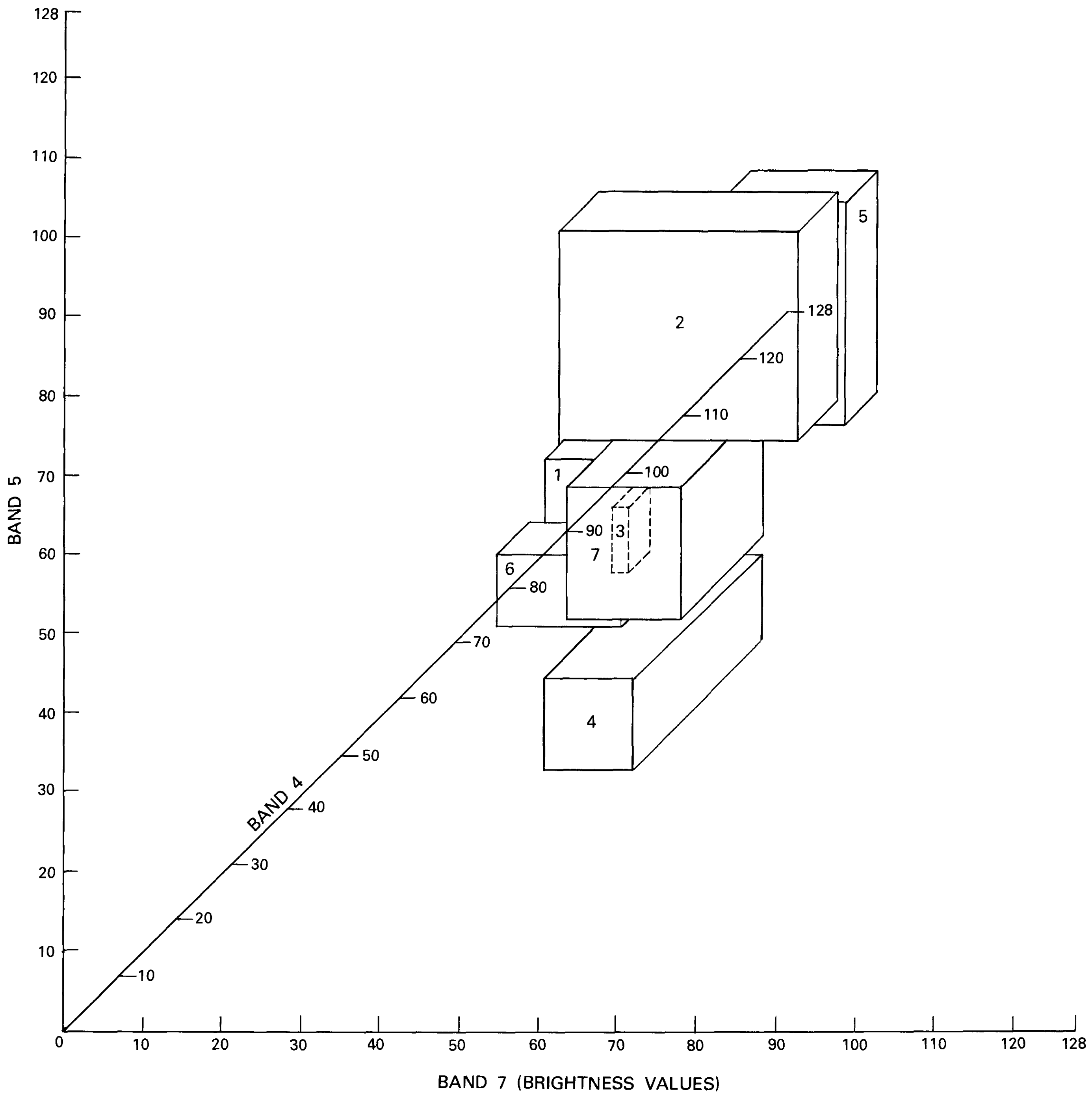


Figure 17.—Parallelepiped classification and separability of seven themes in the northwest subscene 1365–23570. Band 6 is not shown in the diagram but it provides the separability between themes 3 and 6 and between themes 6 and 7.

or acceptably heterogeneous by some limited sampling and testing method. However, multispectral analysis identifies areas which conform to rigorous numerical limits of radiance, which is an attribute of the terrain unit. Only after the area of a unit of similar (homogeneous) radiance is mapped is a boundary drawn around it. The choice of the boundary location can then be based on (1) drawing a boundary around a homogeneous radiance unit which can be considered representative of a terrain unit for the purposes of the map, or (2) drawing a boundary around a group of several individually

TABLE 4.—*Correspondence of multispectral themes with mapped land systems*

Theme classified	Land systems mapped and described on published map	Description of theme	Dominant features of theme reflectance	Remarks
1. Dunefields	D1 Arrabury and Kidd, D2 Poongamulla, S6 Galway with some mixed.	Sand dunes, both longitudinal and reticulate with spinifex hummock grassland, predominantly red earthy sands with some siliceous sands. Includes numerous areas of bare ground which are dune flanks, scalds, or clay pans.	Moderate reflectance in all four bands. The reflectance of the red sands is modified by the reflectance of the vegetation. This in turn is controlled, not by the type of vegetation, but basically by its density and cover.	
2. Bare ground (mainly red soils).	Occurs within almost every land system. Bare ground is not a land system in itself, but is diagnostic of lands that do not or cannot support vegetation and which have a light color.	Bare ground with little or no vegetation.	Low to moderate reflectance in the infrared bands indicating lack of vegetation.	May be a highly significant theme for monitoring purposes to detect changes in size of bare areas or detection of newly bare areas which indicate degradation of the vegetation by seasons or over grazing. May be related to increased erosion.
3. Lowlands	Primarily Durham with some areas of alluvium of small streams and hard mulgas.	They are quite scattered and interspersed with other themes. It may represent bare rock with a dark color.	Moderate reflectance with narrow boundaries in all four bands.	
4. Bright vegetation.	F1–4 Downs with some in A5 Dingera, H5 Noccunda, and S6 Galway.	May be areas of dense vigorous vegetation whether grasses or shrubs. Its occurrence in the downs indicates that it may be Mitchell grass or salt bush. It also occurs where mulga is abundant.	High reflectance in the infrared bands.	Because it occurs in both grassland and shrub areas it is diagnostic only of dense vigorous vegetation rather than any specific types.
5. Bright valleys	A2 Eromanga and A5 Dingera—alluvial valleys and in addition scalded areas in dunefields and in downs.	In the stretched color composite it shows as the brightest red areas. Alluvial plains of minor streams and scalded areas with little or no vegetation. Similar to clay pans and scalded areas.	High reflectance in all bands. Usually white on standard color composite image.	May be useful for monitoring changes and increase in erosion.
6. Medium vegetation.	Primarily associated with Downs (F) and gidgee lands (G).	Areas of trees on plains with a low density of vegetation.	Somewhat narrow reflectance intervals in all four bands.	Much lower radiance in band 7 than for theme 4, bright vegetation.
7. Divides	Occurs in conjunction with almost all land systems, generally along divides.	Difficult to describe because of its widespread occurrence in small areas and association with numerous land systems.	Very narrow radiance intervals with moderate reflectance.	Silcrete cover could be masking soil and vegetation differences.

homogeneous radiance units and defining their heterogeneity of radiance as representative of a terrain unit for the purposes of the map.

The method that follows from this description is that the digital mapping of areas should be done as a first step, boundaries should be drawn in a reasonable manner around various areas as a second step, and only then should the sampling and testing strategy (that is, field mapping) be applied. At this point, the mapper is aware of the relative proportions of the whole area that are described by each class and can plan the number and site of his field

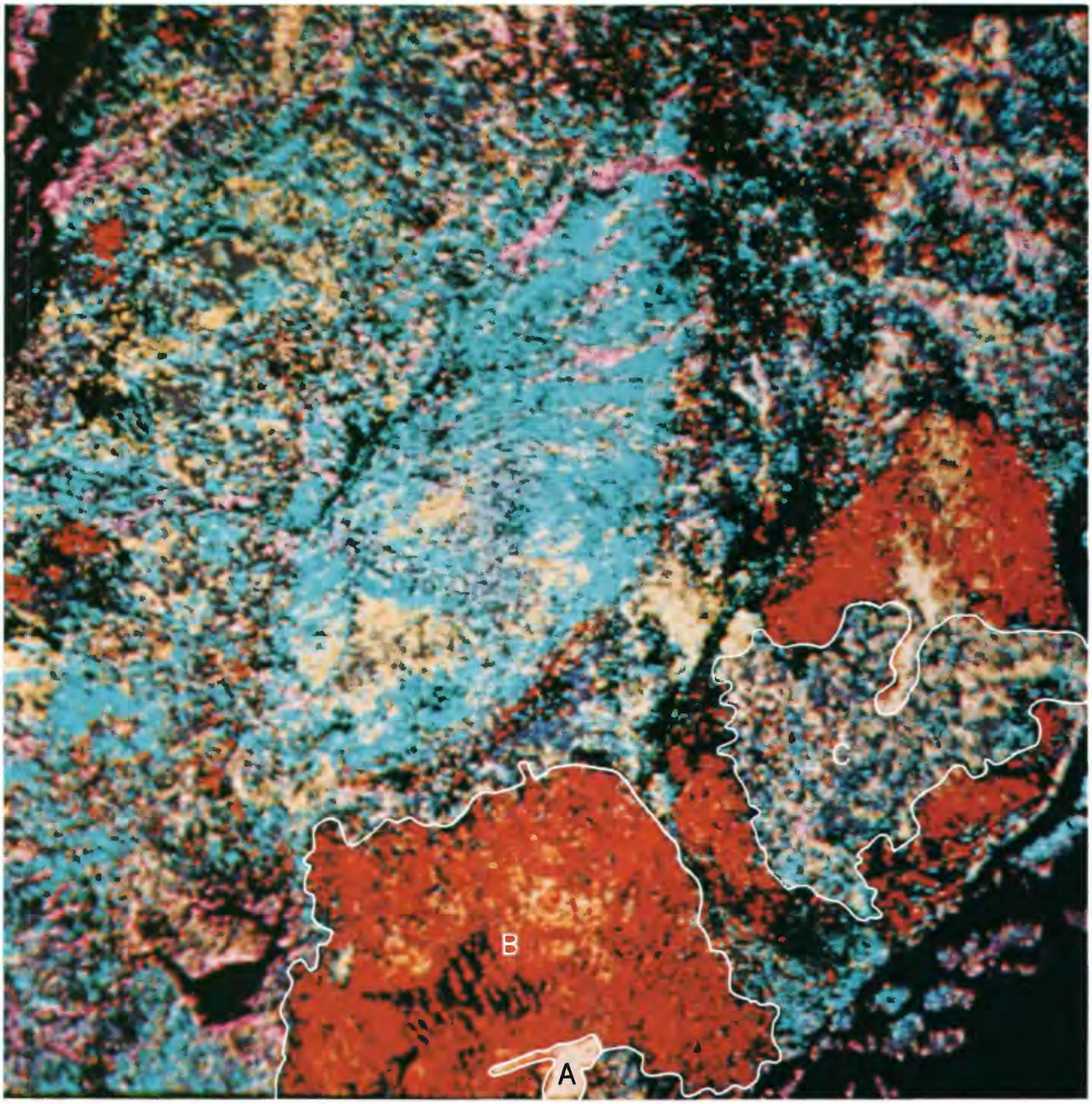


FIGURE 18.—Seven themes classified in subscene 3 with examples of interpretive boundaries around homogeneous classes and heterogeneous classes.

observations in accordance with a statistically valid sampling scheme and with due regard for field accessibility, logistics, and efficiency.

Figure 18 is presented as a first step in grouping themes into terrain categories. Figure 18 is the same as figure 16 with the addition of boundaries drawn around three areas, each presenting an example of a different decision for grouping themes. Area A is composed of one theme which occupies a reasonably sized mappable area and may be considered as a homogeneous theme. Area B consists of three themes (plus water) with the theme shown in red occupying over 70 percent of the area. It may be considered to be an "acceptably heterogeneous"

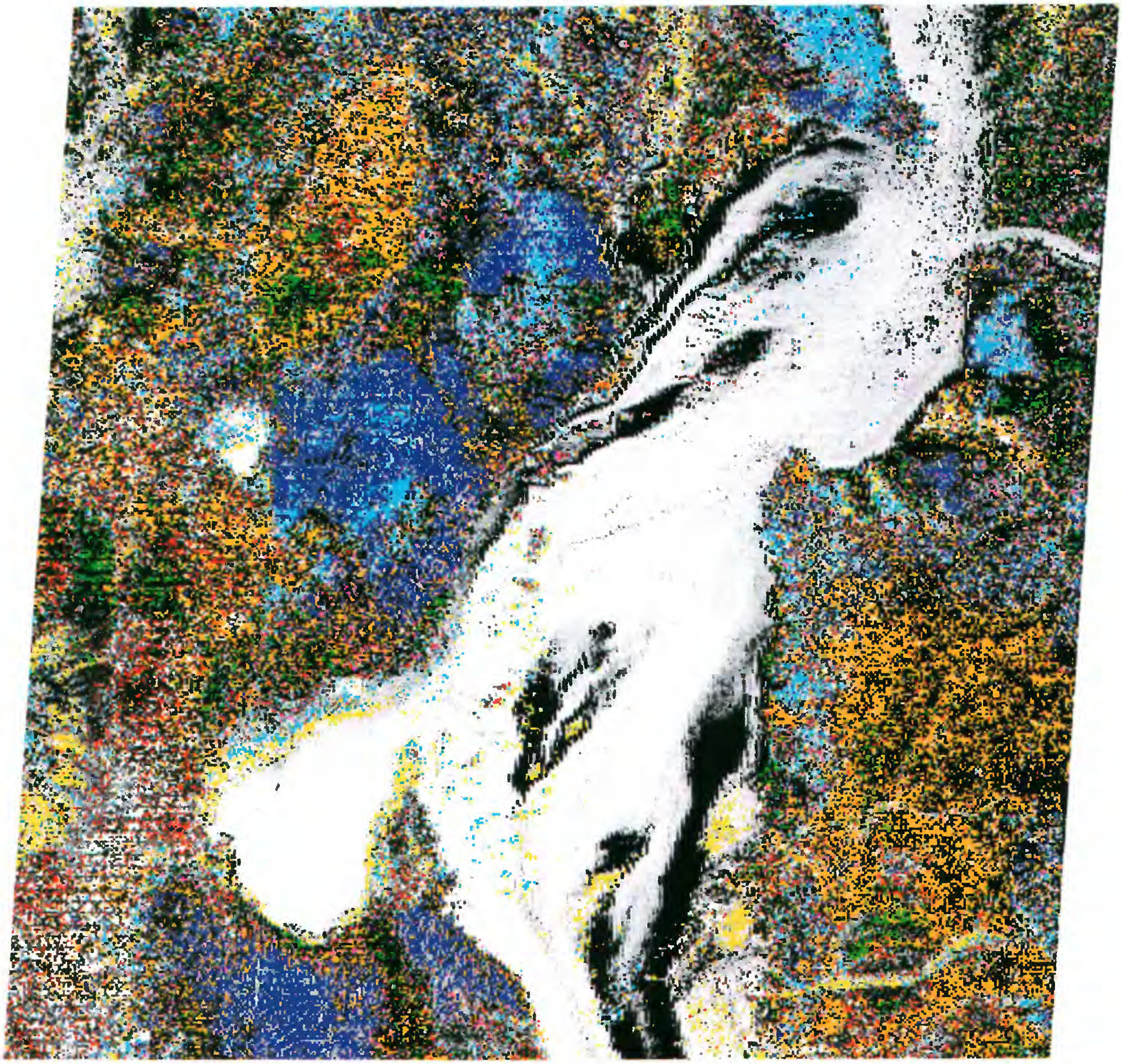


FIGURE 19.—Classification of the upland areas of Landsat scene 1563–23530, February 6, 1974. Band 5 is shown in black and white. Eight themes developed by multispectral classification are shown in color for upland areas. The alluvial valley of Cooper Creek is not classified because it is flooded. Areas are automatically computed from theme pixel counts. Unmapped areas are shown by the background image.

theme for the purpose of the map. Area C is occupied by a heterogeneous, but well distributed, mixture of five themes. It also may be considered to be "acceptably heterogeneous" for the purpose of the map.

EXTRAPOLATION OF PARTIAL SCENE CLASSIFICATIONS TO A FULL LANDSAT SCENE

Multispectral classification of the total Landsat scene can be done on a large general-purpose computer but it requires much time and is quite expen-

sive since either 7.58 by 10^6 pixels must be analyzed or the scene must be sampled. The analytical device used for the analysis in this report can only display and store an entire scene if a sampled array of 512 by 369 pixels issued. This is only 2.49 percent of the available data.

When the sampled image of an entire scene was used for supervised classification by selecting training sets, the resulting classification was very poor, with large errors of omission and commission. In order to overcome these errors, the brightness values in each band for each of the seven themes (which are listed in table 2) were read into the computer and the sampled full scene was then classified and mapped. Interpretive inspection showed few errors of commission but a moderate part of the full scene was not classified. A training set was then selected in the unclassified region, and this region was, for the most part, classified as an eighth theme. Figure 19 shows the eight themes overlaid on the band 5 image. The same procedures can be used to evaluate the full scene image as those used for the northwest subscene 3 previously.

DRY SEASON IMAGE ANALYSIS

Landsat scene 1365–23570 was imaged on July 23, 1973, during the dry season, and consequently is suitable for mapping land systems in the alluvial valley of Copper Creek, because the only water present is in water holes along deep reaches of the stream channels. Because of the simplicity of the alluvial land systems, it was not believed necessary to analyze a small subscene and extrapolate to the entire Landsat scene, but to analyze directly the whole scene. This was done by sampling and displaying 2.49 percent of the pixels and classifying the alluvial valley into four themes. Figure 20 shows the classification, which corresponds rather closely with the published map.

Mr. Brian Senior of the Geological Branch, Bureau of Mineral Resources, Geology, and Geophysics, Australia, has commented on this classification (personal communication, 1976)

> The vegetation classification of the alluviated lowlands is most convincing. Dark vegetation * * * corresponds to belts of large river gums which line trunk sectors of the major channels. Bright vegetation * * * corresponds with levees and flood plains which in favorable seasons support a thick cover of grass and flowering annuals. Both former categories correspond with land form unit Qa2 (reticulate channel, pointbar, and flood plains) on the 1:250,000-scale geologic and geomorphic map. The swamp areas * * * correspond with land form unit Qa3 (distributaries, floodouts, and marginal flood plains). Dry vegetation * * * coincides with 'islands' of aeolian sand which remain largely above the influence of flooding and support a thin cover of herbaceous perennials and a variable seasonal ground cover. For studies of land cover, the presentation is judged to be potentially useful as a planning document to guide more detailed work including ground checking.

The classification of the alluvial valley is not a difficult one and could be done by visual interpretation of the Landsat color-composite image. The digital classification, however, has a major advantage of consistency throughout the image which, when combined with the judgment of the interpreter, provides a more complete analysis than visual interpretation alone.

UNSUPERVISED CLASSIFICATION OF A FULL LANDSAT SCENE

An empirical experiment was conducted by performing an unsupervised classification of image 1563–23530 using the maximum-likelihood classification algorithm developed by the Purdue University Laboratory for Applications of Remote Sensing. Unsupervised classification simply separates the pixels into statistically distinct classes without selection by the interpreter. Figure 21 shows the results of

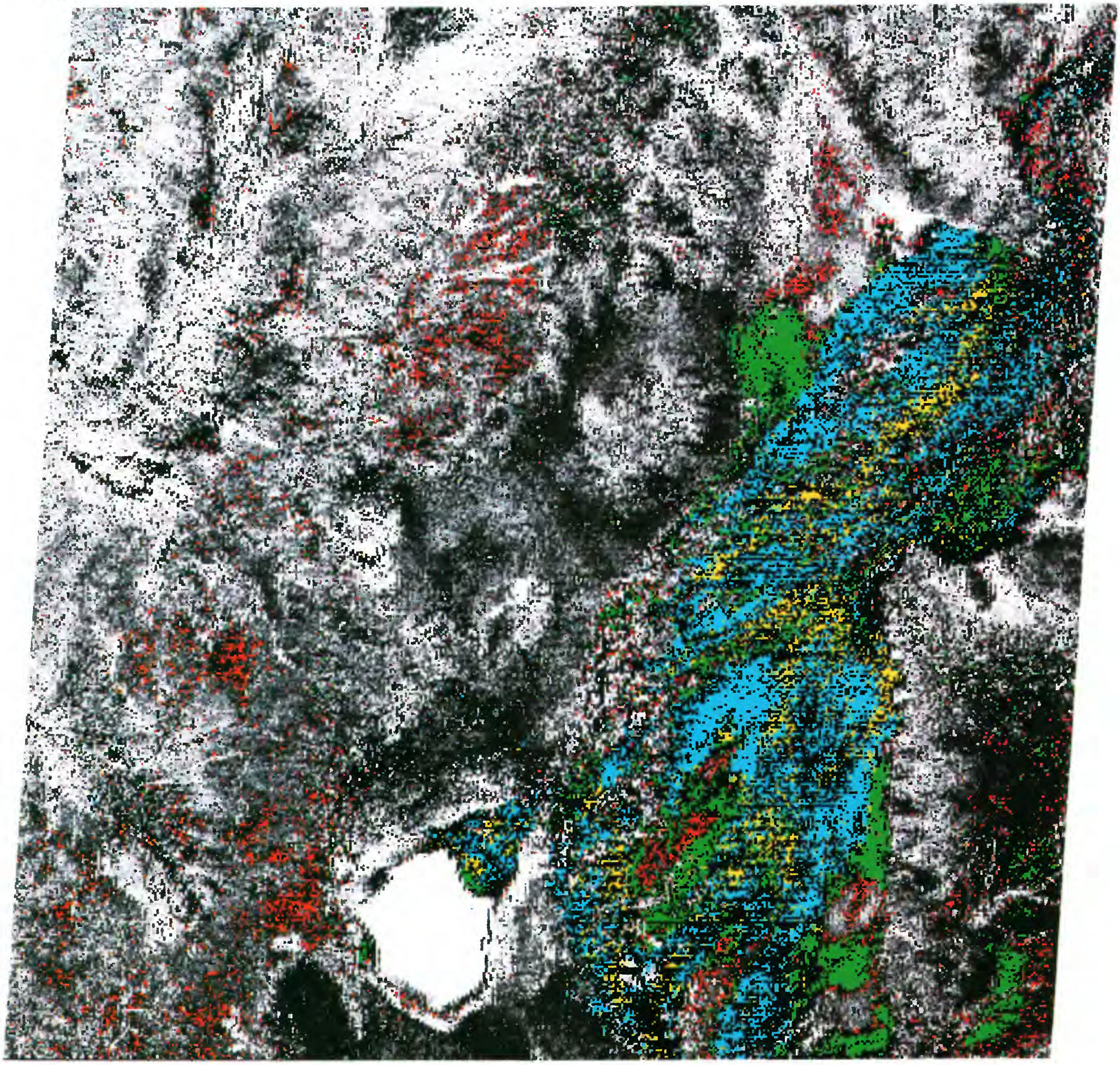


FIGURE 20.—Classification of the alluvial valley of Cooper Creek, Landsat scene 1365–23570, July 25, 1973. Band 5 is shown in black and white. Four themes developed by multispectral classification are shown in color for the alluvial valley of Cooper Creek and adjacent uplands. Areas are automatically computed from theme pixel counts. Unmapped areas are shown by the background image.

that classification. To minimize computing time and cost, the image was sampled by using every 23rd line and every 32nd column, thereby selecting 10,000 evenly spaced pixels in the 2340 line by 3240 column scene. Only 0.136 percent of the scene was used and therefore each pixel represented approximately 330 hectares. The sole classification instruction given was to classify the sampled scene into 20 clusters on the basis of statistical similarities. The resulting 20 clusters were combined into 12 groups. Thus, figure 21 shows 20 symbols but only 12 colors.

The unsupervised classified image was not geometrically corrected, but it does represent the major land systems present in the area in its patterns. Such a classification method might be applicable as a first step in analysis of an area. Modified clustering techniques might also provide equally good and possibly more accurate results, but were not explored in this study.

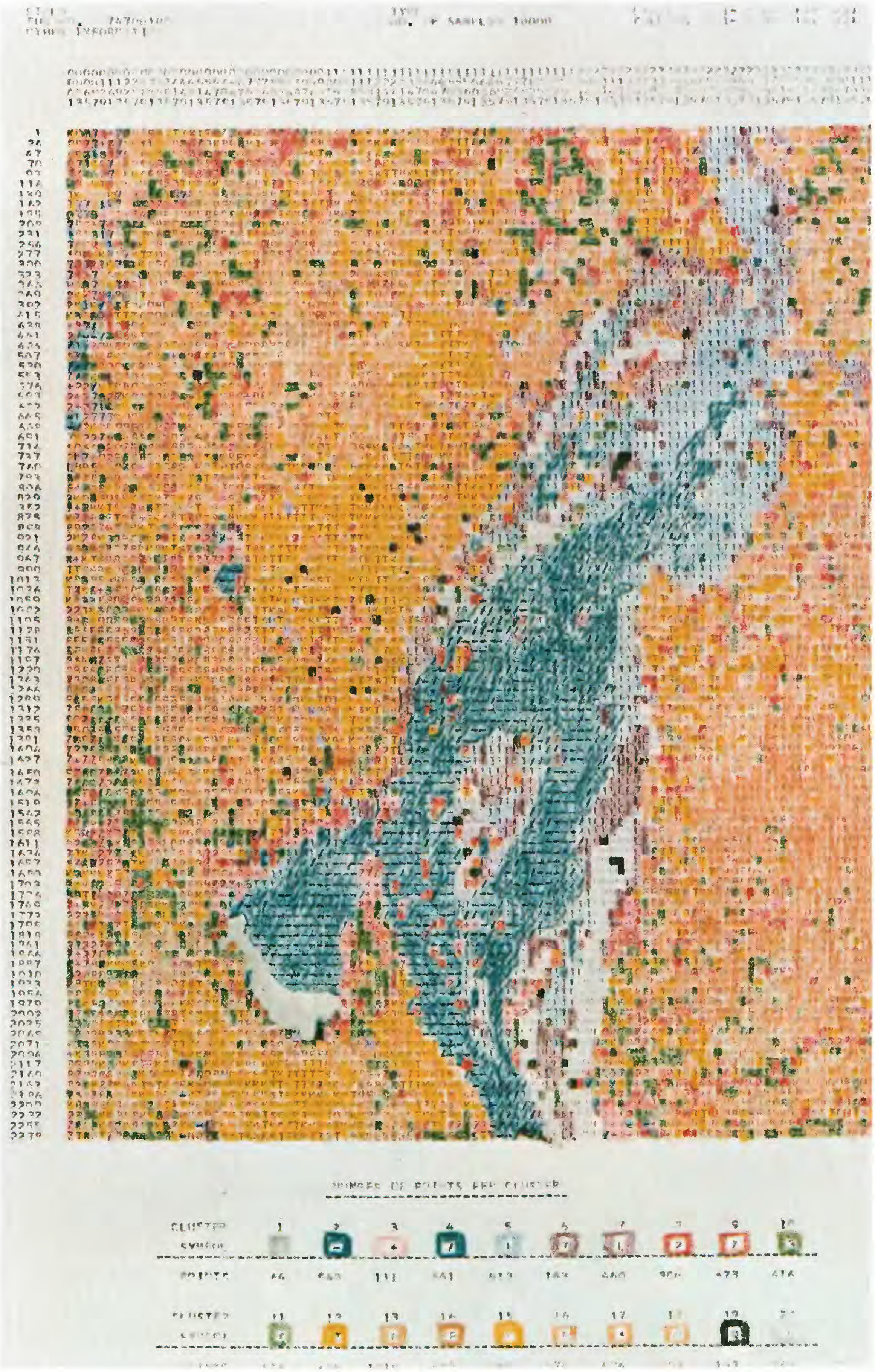
CONCLUSIONS

The major conclusion of the research reported here is that the integrated mapping of land by computer processing of Landsat images is feasible in situations where the dominant reflectance of the land is characteristic of terrain attributes of importance for the purpose of the map at the time the image is taken. Mapping of discrete classes with single attributes is more difficult and more prone to error than is the mapping of integrated classes.

Digital classification of the Queensland Landsat images into integrated units produced a map that is not identical to the published land systems map, but which resembles it in large part and is as useful. The classification of the land into homogeneous units based on the statistical distribution of brightness values provides a first map product by delineating areas of known attributes and radiance. The second map product, which includes the interpretive boundaries and the names and descriptions of the unit, provides an integrated map which can be used as a guide for field checking and sampling.

Interactive digital processing has proven to be highly useful because the terrain classifications displayed can be readily checked to see if they are "photointerpretively reasonable;" as well as statistically precise.

The analyses reported here were done by sampling pixels for large areas. In the future, it would be most practical to use an interactive system to analyze sample areas using every pixel in the area, developing the means and covariance matrices for each theme, and then using a statistically powerful but less interactive system for maximum likelihood classification of an entire Landsat scene using every pixel. Such a process would use the advantages of human interaction plus the statistical and computing advantages of a larger computer system and would maximize the advantages of each system for the analysis.



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