Study of the Reed Dolomite aided by remotely sensed imagery, central White-Inyo Range, easternmost California

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Abstract

Remote-sensing methods are of great value in assessing the stratigraphy and geologic structure of inaccessible terrains, especially where lithologic contrasts are marked. In this report, we show that such techniques can be successfully applied to a massive carbonate unit, the Reed Dolomite, exposed in the Waucoba Mountain, Blanco Mountain, and Mount Bar-croft quadrangles of east-central California. Airborne NS-001, plus satellite Landsat TM, and SPOT panchromatic imagery, combined with conventional geologic mapping, were employed in order to demonstrate that observed spectral variations on false-color images were caused by subtle compositional variations of the dolomite. Based on reflectance differences and field investigations, six discrete bedding units were recognized in exposures of the Reed Dolomite. From lower to upper, they are: (1) very coarse grained, granular, gray, pisolitic, blocky dolomite; (2) medium-grained, white, oolitic, massive dolomite; (3) fine- to coarse-grained, light-gray, oolitic, massive crystalline dolomite, rare interbedded rusty quartz arenite; (4) medium-fine grained, cross-stratified, locally ocherous brown, interlayered quartz arenite, tan siltstone, and sandy dolomite; (5) fine-grained, thin-bedded, sparsely oolitic, buff dolomite; and (6) fine-grained, fissile, dull-white dolomite.

Subunit (4) and underlying subunit (3) appear to inter-finger, with (4) representing a more proximal shelf facies. In the SE corner of the mapped area, subunit (4) is present whereas subunit (3) is absent, with the situation reversed along the western and northern portions of the range. Subunit (5) thins to a feather edge on the north near the Bar-croft Granodiorite. Thickness variations of the different Reed stratigraphic entities in the eastern and northern White-Inyo Range may reflect attenuation caused by granitoid intrusion, as well as original stratigraphic variations. The broad

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expanse of Reed Dolomite directly NE of the Sage Hen Flat pluton is due to NS-trending folds. Details of the White-Inyo anticlinorium are now better resolved in the central portion of the range where previously undetected folds, faults, and homoclinal sections are revealed in false-color imagery of the macroscopically featureless Reed Dolomite. Thickness trends and facies boundaries for the newly recognized subunits trend north-south or NNE throughout the studied area, locally reflecting the gentle WNW continental shelf paleoslope of the passive margin of western North America during latest Precambrian-Early Cambrian time.

This study is important to petroleum geologists because it demonstrates that detailed stratigraphy and structure can be determined using remote-sensing techniques in semi-and regions where massive, undistinctive carbonate units crop out. In some cases, no single processing method allows spectral discrimination of all lithostratigraphic entities; furthermore, the spectral characteristics of a specific unit have been shown to vary even within a single image. Hence, our work underscores the site-specific limitations of individual multispectral methods, and illustrates why a combination of diverse methods needs to be employed. Finally, geologic lessons learned within the study area may be extrapolated to similar terrains elsewhere within the Basin and Range Province.

Introduction

The White and Inyo Mountains constitute the westernmost range of the southwestern Great Basin. The general geology, extending from the NE-trending Barcroft pluton on the north in the White Mountains to the EW-trending Papoose Flat pluton on the south in the Inyo Mountains, has been studied intensively over the past 30 years. Consequently, detailed maps at scales of 1:24,000 and 1 :62,500 are available for the entire area (see Ernst, et al., 1993, for citations and a summary map). Location of the study area is shown in Fig. 1.

The regional structure consists of a NNW-trending anticlinorium flanked by marginal synclinoria. Intense folding, faulting, and scattered intrusion of Middle and Late Mesozoic granitoid bodies characterize the area. Outcrop patterns of the layered units support the inferred structural relationships. However, variable exposure widths for several thick, internally monotonous stratigraphic units, especially the Wyman, Reed, and Campito formations, were not explained by prior geologic mapping. Such variations might result from primary depositional patterns, structural complexities, or thermally induced deformation accompanying pluton emplacement. [Unfortunately, reasons for the differences in outcrop widths of these units cannot be ascertained readily employing conventional field methods because of lack of detailed strati graphic control.

Therefore, remote-sensing technology was employed in an attempt to provide new, detailed stratigraphic insights. The most massive unit of all, the Reed Dolomite, was selected for investigation using multispectral remote-sensing techniques in the hope of elucidating an internal, through-going stratigraphy which would provide constraints for more complete structural and paleoenvironmental interpretations. This paper reports success in achieving those objectives, and is important for two reasons: (1) It demonstrates the capabilities of remote-sensing techniques to assist in the detection and stratigraphic discrimination of very subtle differences in carbonate lithology. And (2), it highlights some limitations of remote-sensing methods. The appreciation of such limitations in a geologic context is crucial to the effective application of remote-sensing techniques.

Stratigraphy and Structure of the Range

The extent of the uppermost Proterozoic-Paleozoic stratified section, as well as the Mesozoic igneous rocks, of the central White-Inyo Range were mapped using conventional geologic field methods; an areal compilation is presented below (see Fig. 6 for both areal geologic relationships and localities mentioned in the text). Strata were deposited along an Atlantic-type margin during latest Proterozoic and early Paleozoic time as a succession of shallow carbonate bank deposits (Nelson, et al., 1991). The low-standing nature of the adjacent continental platform is attested to by the paucity, and chemically mature, multicycle nature, of associated elastic debris. A brief description of the sedimentary and volcanogenic units, along with their vegetative cover, is presented in Appendix 1.

The mountain block, which is elongated in a NNW direction, is cored by upper Proterozoic argillites of the Wyman Formation and uppermost Proterozoic-Lower Cambrian carbonate strata of the Reed Dolomite in the gently doubly plunging, NS-trending White Mountain anticlinorium north of Westgard Pass, and in the gently SE-plunging Inyo anticlinorium south of this topographic-structural saddle. The flanks of the White-Inyo Range contain the limbs of marginal synclinoria, and, along with an EW-trending low in the vicinity of Westgard Pass, expose Lower Cambrian strata of the Deep Spring, Campito, Poleta, and overlying Cambrian formations. The western margin of the range is truncated by the dextral-slip White Mountains shear zone; the eastern border is extensively invaded by middle and late Mesozoic talc-alktilic granitoids. On the north, the Barcroft Granodiorite occupies a profound, NE-trending structural disjuncture- the Barcroft break- -north of which overlying mid-Mesozoic White Mountain Peak volcanogenic arc rocks are down-dropped.

Folding and faulting both preceded and accompanied emplacement of the Mesozoic plutons (Dunne et al., 1978), revealed by locally deflected structural alignments and thermally induced stratigraphic thinning of the wall rocks (Paterson et al., 1991). Neogene regional extension caused gentle eastward tilting of the White Mountain block and westward tilting of the Inyo block, as indicated by east-dipping Mio-Pliocene plateau basalt flows in the White Mountains (Krauskopf, 1971), and west-dipping Plio-Pleistocene lake beds in the Waucobi Embayment area (Bachman, 1978), respectively. The site of the structural twist in the White-Inyo Range coincides with the EW crossfold near Westgard Pass. Glacial deposits are restricted to present high elevations. The mountains were thus low lying during Miocene basaltic extrusion, but uplifted by the time of Pleistocene alpine glaciation.

Research Methods

General Statement. We used Landsat Thematic Mapper (TM) and SPOT panchromatic data, airborne NS-001, and color infrared aerial photographs in our study of the Reed Dolomite. Ground investigations included conventional geological mapping and sample collection to check interpretations of the image data. Mineralogic and spectroscopic analyses of field samples were also conducted in order to better correlate the lithology with image interpretations. Descriptions of instruments and techniques utilized in this study, and discussions of their geologic utility can be found in Colwell (1983), Abrams~[g~(1985), 1,ang@(1987, 1990), Lang and Paylor (1 994), and Paylor *et al.* (1985, 1989).

Image Data Processing and Analysis, "I'M scenes were utilized as a base for this study because of their synoptic coverage and excellent geometric fidelity (Paylor *et al.*, 1985). Figure 2 provides a TM overview of the White-Inyo Range study area. Following coregistration of SPOT and NS-001 data to the TM scene, numerous color composites, band ratio composites, and principal component transformations were generated to produce images suitable for discrimination of the carbonate-rich units and for photogeologic interpretation (*e. g.*, Siegal and Gillespie, 1980).

TM data were most useful for *regional* mapping and correlation of strata and structures. In the southern, or Waucobi Embayment region, broad outcrop patterns were also amenable to detailed mapping and subdivision of stratigraphic units using 'I'M data. Where available, NS-001 and SPOT panchromatic data were particularly useful for *local* detailed stratigraphic mapping because of their smaller pixel sizes compared to the TM data (approximate y 10 meters compared to 30 meters for TM). Wavelength ranges in µm for TM bands 1-7, respectively, are: 0.4 S-0,S2; 0.52-0.60; 0.63-0.69; 0.76-0.90; 1.55- 1.75; 2,00-2.36; and 10.4-12,5. For NS-001 spectral data, an additional channel between the wavelengths 1.0- 1.3 µm (N S-001 band 5) is available.

Field Mapping. Field investigations were carried out during June and July, 1989-1993, in an attempt to refine the image-defined Reed stratigraphic sequence over the entire study area. Some outcrops of the Reed Dolomite remained massive even after image enhancement, chiefly because of the obscuring effects of soil and vegetative cover. These areas were mapped on the ground once stratigraphic relationships of the image subunits were established in control regions. Except for a relatively inaccessible part of the area NE of Waucobi Embayment, most Reed Dolomite members identified on image data subsequently were checked in the field. Subtle stratigraphic features in the Waucobi Embayment area were best elucidated by TM techniques, in the region between Sage Hen Flat and Birch Creek plutons by NS-001 imagery, and the area directly south of the Barcroft Granodiorite mainly by field examination.

Sample Analysis. In order to investigate the mineralogical and spectral characteristics of the Reed Dolomite subunits as they relate to image data, representative samples were collected for laboratory study. Spectral methods employed were described by Grove *et al.* (1992). Sixteen samples have been analyzed, ten of which were collected along two traverses covering well-defined

Reed Dolomite sequences on the imagery. One traverse is located at our type locality on the SW side of Waucobi Embayment, west of the Hines Road Jeep track (NW corner of Fig. 3; see also Fig. 6); the other is located on the west flank of the White Mountain anticlinorium near Goat Spring (see Fig. 6) where subunits were first recognized in the NS-001 image data. The purpose of the spectroscopic study was to demonstrate that observed spectral variations on images were caused by compositional variations on the outcrops; quantitative spectral analysis is beyond the scope of the present investigation which relied on relative brightness contrasts in order to differentiate lithostratigraphic units.

Results

Remotely sensed imagery combined with field investigations allowed us to identify and map discrete stratigraphic subunits of the Reed Dolomite. Subunits were recognized within the Waucobi Embayment area (Fig. 3) defining the Inyo anticlinorium, and within the Blanco Mountain (Fig. 5) and Mount Barcroft areas, chiefly along the west flank of the White Mountain anticlinorium. The most useful images, based on different processing techniques, were specific to each area. The Reed subunits identified from the imagery were not directly correlative along strike from locality to locality, or even within a single false-color image. This is a consequence of the complex overprint due to botanic cover, shadows caused by rugged topography and different illumination angles, narrow lithostratigraphic layers relative to image pixel sizes, mantling soils with varying moisture contents, and heterogeneous till wash. Accordingly, we utilized geologic field mapping to assist with the correlations, and traced strata along strike monitored by the remote-sensing images and topographic expression of the beds. Because the Reed is a featureless white carbonate unit, the layering we identified was quite subtle. Results for each area are discussed separately.

Waucobi Embayment area. Figure 3 is an enlargement of a TM principal components image (thermal band not included) of the Waucobi Embayment area where our type locality for the remotely-defined Reed Dolomite sequence crops out directly west of Hines Road. This area was chosen for detailed investigation because the section is well exposed, is undisturbed structurally, and is expressed well by the TM data, The section at this locality, depicted in the northwest corner of Fig. 3, is complete, as demonstrated by prior field investigations (Nelson, 1966a, b).

In this area, the dolomite is approximately 600 meters thick and had been previously divided locally into three units, the upper Reed, the Hines Tongue, and the lower Reed (Nelson, 1962; Mount and Signor, 1991). This division was based mainly on recognition of a thick, somewhat calcareous, crossbedded quartz- arenite member in the middle of the formation (Nelson, 1966a,b). The Deep Spring Formation, stratigraphically overlying the Reed, contains conspicuous marker horizons that appear as numerous thin beds of various colors (maroon, yellow, blue, and green) on the TM image of Fig. 3, providing excellent control to locate the Reed Dolomite stratigraphic sequence. The Wyman Formation below the Reed is also recognized easily as a homogeneous, smooth-textured, maroon-colored unit on the image, mainly due to the uniform but sparse grass and sagebrush cover developed on the argillite. Fortunately, Reed outcrops in this area support an empoverished vegetative cover.

As illustrated in Fig. 3, six spectrally-distinct subunits of the Reed were mapped south of Waucobi Embayment. Because spectral responses of the subunits change along strike, descriptions now to be presented refer to features exhibited at the Hines Road type section. On the image, the basal subunit (1) is characterized by a mottled yellow-green coloration. In the field, this unit is a dark-gray to tan-colored, coarse grained, pisolitic dolomite. It grades upward into massive, fine-grained, white to gray dolomite of subunit (2). On the TM image, subunit (2) is a relatively homogeneous, intense yellow, with green tints locally, Subunit (3) is pale blue-green and somewhat heterogeneous, Confined to the NW portion of the area covered by Fig. 3, it contains less resistant intervals with several quartz- arenite and shale beds interstratified with massive-to-oolitic dolomite. The dolomite is lighter in color, fine grained, and does not contain pisolites. Approximately 20 meters below the Hines Tongue (subunit 4), the dolomite in subunit (3) becomes coarse grained and locally, dark gray in color. Brown, limonitic rock fragments occur in these beds: apparently occurring at several different stratigraphic horizons, this zone constitutes a transitional between the brown-gray dolomite of the upper part of subunit (3) and the superjacent Hines Tongue Member. The frequency of quartz-arenite interbeds increases upsection toward the Hines Tongue. The latter, blue-green with yellow and red speckles on the TM image, is dominantly orthoquartzite interbedded with sandy dolomite. In contrast, the previously defined upper Reed is a fine grained, finely laminated dolomite; bedding becomes more massive. upwards. On the image, we were able to divide the upper Reed into two subunits, a lower subunit (5) typified by a mottled maroon + green pattern, and an upper subunit (6) characterized by pale yellow coloration, with red patches. On the ground, this corresponds to a color change from buff to white as well as a transition from fine laminations to more massive bedding. These subtle contrasts were first detected using TM image data. Limonitic detritus locally marks the contact between subunits (5) and (6).

Figure 4 presents visible and near-infrared reflectance spectra for fresh and weathered Reed Dolomite samples collected from our image-specific subunits (locally, fresh talus is nearly as abundant as weathered surfaces). Figure 4a illustrates spectra from four samples (WM-112, 2.35, 239, and 407) that represent pure dolomites collected in areas where no image subunits are distinguishable. The spectral absorption features near 2.32, 2.15, 1.97, and 1.85 µm are characteristic of the $Mg\text{-}CO_3$ stretching frequency in dolomite (see Clark et al., 1990; Hunt and Salisbury, 1971). An absorption feature near 1.0 µm in these samples is most likely due to absorption by Fe^{+2}. Two especially massive hand samples, WM-619A and 61911, exhibit little contrast between the left and right sides of the diagram, fresh and weathered lithologies, respectively (see also Russell et al., 1994).

Samples WM-624 through WM-627 were collected from subunits (1), (2), (4), and (S) in the type section south of Waucobi Embayment and directly west of Hines Road (Fig. 4b). All fresh samples (left side of illustration) have a spectral absorption feature in the 2.30-2.32 μm region, probably due to dolomite $Mg-CO_3$; dolomite absorption features in the other spectra on Fig. 4b are either too weak to detect or are masked by weathering features. The CO_3^{-2} absorption are shifted slightly toward longer wavelengths (2.32-2.34 μm) on the weathered surfaces of WM-624 and 626, (right side of illustration), indicating that calcite is present and maybe a weathering product in the samples (Gaffey, 1985, 1986). Spectra of fresh and weathered surfaces of WM-625 and WM-626 also have absorption features near 2.20-2.21 pm, probably related to minor amounts of illite (Hunt and Salisbury, 1970), or may represent illitic clays on the surface of the sample, similar to desert varnish (Russell, et al., 1994). The spectral variations due to clay and carbonate described here, however, are not separable in the TM data due to the broad band widths.

The most significant spectral differences are the overall reflectance contrasts and reflectance variations in the Fe absorption bands short of 1.1 pm; it is probably these contrasts that allowed differentiation of the subunits on the image data (Fig. 4b). Sample WM-624 exhibits the least contrast, less than 10% across the spectrum on the fresh surface and approximately 30% on the weathered surface, and probably is the cause of the gray color of this rock in the field. The other samples exhibit a minimum of 35% spectral variation on the weathered surfaces and 30% on the fresh surfaces. Samples WM-626 and 627 exhibit Fe^{+2} absorption features in the 0.9- 1.1 μm range. in addition, iron absorption features short of 0.7 μm are also present in spectra of WM-625, 626, and 627, especially on the weathering surfaces of these samples. Because Fig. 3 is a principal components image, the spectral features discussed above cannot be correlated directly with image colors.

Blanco Mountain area. Figure 5 is an NS-001 band ratio image of Reed Dolomite outcrops northwest of the Birch Creek pluton. The formation is about 650 meters thick (Ernst and Hall, 1987) and here can be subdivided into seven or eight subunits, based on the ratio-composite image (these have been lumped in the geologic map of Fig. 6). Exposures are more weathered, mechanically and chemically, than elsewhere in the mapped area. Residual soils support a substantial cover of sagebrush and scattered, stunted trees. In particular, bristlecone pines account for approximately 20-30 % ground cover, mostly on N-facing slopes. Large outcrops are limited and found mainly on steep slopes along the sides of the canyons, thus the area is not amenable to detailed analysis employing remote-sensing methods. Topography-induced shadows (purple colors on Fig. 5) partially obscure some of the beds delineated in the image. Nevertheless, the stratigraphic layering of the section is displayed.

Reflectance spectra for Reed samples from four subunits in the nearby Goat Spring section (WM-562 = subunit 5; WM-563 = subunit 3; WM-564 = subunit 2; WM-565, 566, and 567 =

subunit 1) are shown in Fig. 4c. Although we were unable to collect fresh samples in this area directly south of the Sage Hen Flat pluton due to poor exposures, samples of the super perjacent soils anti float were collected and analyzed. Each soil spectrum (left side of Fig. 4c) contains absorption features at 1.4 and 1.9 pm, probably due to absorbed water and/or Al-OH absorption (Hunt and Salisbury, 1970). Weak features near 2.21 μm are most likely due to absorption by OH from illite or montmorillonite. WM-563, 565, 566, and 567 exhibit weak 2.33 μm features related to CO_3^{-2} absorption, suggesting that calcite also may be present, Rock chips scattered across the surface in this area constitute 10-30 % of the ground cover, and as illustrated on the right side of Fig. 4c, their spectral response varies considerably. Generally, these spectra can be separated into two groups. WM-562, 565, and 567 each have relatively strong Fe^{+3} absorption features at 0.86 pm, Al-OH absorption features near 1.4 μm, and a 2.32 μm feature that may be due to $C03^{-2}$ absorption of dolomite. in addition, WM-565 and 567 exhibit strong features at 1.45, 1.54, 1.97, and 2.25 μm, which are representative of minor chlorite and talc ± tremolite. The other group, consisting of WM-563, 564, and 566 spectra, generally lacks strong iron-absorption features.

The Reed Dolomite subunits in the Blanco Mountain area, where not masked completely by vegetation, are separable in the image data. The distinction evidently is based on a combination of botanic cover and the composition of rock fragments in the float, and not necessarily on direct outcrop appearance, as is the case with the Waucobi Embayment area. Although the subunits are different in appearance on the images from those of Waucobi Embayment, we were able to correlate them with the same stratigraphic subunits based cm field characteristics including texture, composition, and sequence. The Hines Tongue is absent from the Blanco Mountain area, except in the outcrops along the eastern, nearly vertical limb of the White Mountain anticlinorium.

Mount Barcroft area. The area, located between the Barcroft pluton to the north and the Sage Hen Flat pluton to the south (see Fig. 6), is situated at high elevations (-3700 m) and lies above the tree line. in part due to a thin, scattered, tundra-like plant cover, the image data are of only limited use here. Steep slopes are obscured by Reed talus, and alpine glaciation deposited a discontinuous veneer of unsorted Barcroft till which obscures the spectral signature of the bedrock. Also, metamorphism near the pluton caused recrystallization which has obliterated the stratigraphic distinctions among the subunits (Russell et al., 1994). Mapping *in* this area was therefore accomplished by field-based methods alone.

Interpretation of Combined Remote Sensing and Surface Mapping

Stratigraphic results. Figure 6 presents a map of the regional geology derived from Nelson (1966a,b), Krauskopf (1971), Ernst and Han (1987), and Ernst et al. (1993), combined with our new results. Earlier maps did not possess sufficient stratigraphic control to portray structural details now evident. The newly recognized subunits of the Reed are shown, as well as minor modifications to formational boundaries derived from our image interpretation. Based on these integrated results, the lithostratigraphy involves six laterally continuous, mappable units. From top down these are:

unit	newly recognized stratigraphy using remote sensing and field work	previous designation
(6)	fine-grained, fissile, dull-white dolomite;	upper Reed
(5)	fine-grained, thin-bedded, sparsely oolitic, buff dolomite;	
(4)	medium-fine grained, cross-stratified, locally ocherous brown, interlayered quartz arenite, tan siltstone, and sandy dolomite;	Hines Tongue
(3)	fine- to coarse-grained, light-gray, oolitic, massive crystalline dolomite, rare interbedded rusty quartz arenite;	lower Reed
(2)	medium-grained, white, oolitic, massive dolomite;	
(1)	very coarse grained, granular, gray, pisolitic, blocky dolomite.	

Thus, from the standpoint of the stratigraphic code (North American Commission on Stratigraphic Nomenclature, 1983), we have used multispectral remote-sensing data to define and map six new informal members of the Reed Dolomite. Figure 7 depicts the northern limit of the lower member of the upper Reed Dolomite (subunit 5), the western pinchout of the Hines Tongue (subunit 4), and the eastern limit of the upper member of the lower Reed Dolomite (subunit 3). These are new stratigraphic interpretations based on our geologic mapping and remote-sensing results. in addition, Fig. 7 indicates the sites where we investigated stratigraphic sections in the field, and constructed stratigraphic columns derived from local outcrop widths measured on the geologic map of Fig. 6.

The stratigraphic columns constitute the basis for the panel diagrams presented in Fig. 8, in which the thicknesses and lateral continuity of the Reed subunits are summarized. These diagrams also provide DN (= digital number, or brightness of the reflected light as recorded by the sensor) profiles derived from the digital image data along the stratigraphic sections. The method, described by Lang and Paylor (1994), portrays surface reflectance of the stratigraphic units along the section, much as well logs display electrical or other properties of rocks in boreholes, and can be similarly used to aid in stratigraphic correlation. Based on similar shapes of the DN profiles, this method of correlation contrasts with multispectral scanning, which utilizes relative differences in false-color imagery. In the present case, the DN data were not calibrated to absolute reflectance (to remove instrumental and atmospheric effects) prior to profile construction. Assuming that these effects are constant within the band utilized and along the section profiled, the procedure can be employed as described by Lang and Paylor, with the qualification that the DN profiles would be representative of brightness of the rock units instead of reflectance. Selection of appropriate traverses to avoid steep slopes (strong shadows) and heavy vegetation assures that the DN profiles are representative of the intrinsic brightness of the lithologic units. TM band 4 was selected for our study because of the relatively marked brightness contrast of rocks as well as the sensitivity of this band to variations in absorption of ferrous iron- -an important element in the investigated carbonate samples as demonstrated in Fig. 4. Additionally, this band is strongly influenced by changes in vegetation that may be a response to differences in soil and/or bedrock, but we have attempted to avoid thick plant cover wherever possible.

As illustrated in Fig. 8, subunits (6) and (S) are depicted as bright peaks with medium brightness values on the TM band 4 DN profiles, and can be readily correlated among sections A, B, “‘ D, F, G, and I. Subunit (4) and locally, subunit (5) in the southern part of the area contain some of the brightest rocks in the study area. These bright peaks represent thick quartz-arenite intervals in the Hines Tongue , and can be correlated among sections A, B, D, and I. Subunit (3), the distal facies of the Hines Tongue, appears to retain its brightness in an interval near the base of the unit, and is readily correlated among sections A, F, G, I, and J. Except for sections J, D, and K, subunit (2) is rather featureless and is mid- to low-range in terms of overall brightness. Likewise, subunit (1) tends to be rather subdued, but has a bright interval that can be correlated in many sections including the top of B, D, 1, F, and G, and the bottom of D, J, F, and G. The individual subunits evidently range in thickness on a regional scale, so do not coincide precisely with the specific formational thicknesses reported by Nelson (1962).

Several conclusions may be drawn from the areal variations in thicknesses for the six new members of the Reed Dolomite (Figs. 6-8). For instance, subunit (4), limonitic quart?, arenite of the Hines Tongue, and underlying subunit (3), coarse-grained, oolitic dolomite containing rusty quartz-arenite interbeds, appear to inter-finger, with (4) representing the more proximal facies. Provided the correlation of the Reed Dolomite with the Stirling Quartzite is correct (Mount and Signor, 1991), geologic relationships in Death Valley approximately 100 km SE of the mapped area support this eastward *increase in* multicycle terrigenous material. Subunit (5), fine-grained, oolitic, buff dolomite directly below the capping, dull-white subunit (6), appears to thin m a feather edge in the northern White-Inyo Range, just south of the Barcroft Granodiorite. Thinning of several of the newly recognized members along the eastern and northern portions of the mapped area is probably due at least in part to attenuation accompanying granitic intrusion. Thickness trends of the newly recognized stratigraphic units and facies boundaries for the Reed Dolomite and its subunits appear to trend *north-south or* NNE across the central White-Inyo Range. We interpret these attitudes to reflect the subdued WNW-dipping paleoslope of the latest Precambrian-Early Cambrian shelf and continental margin (Burchfiel and Davis, 1975), rather than the Mesozoic structural grain which strikes NNW (Nelson, et al., 1991), with an inferred WSW paleoslope.

Structural results. The subunits described above have been investigated as far north as the southern border of the Bar-croft Granodiorite, and as far south as the northern margin of the Papoose Flat Granite. Subdivision of the lithostratigraphy employing remote-sensing techniques, as well as further field study, permitted us to differentiate extensive tracts of Reed Dolomite formerly regarded as massive, featureless exposures (especially problematic in sections lacking the Hines Tongue). The integrated stratigraphic mapping has allowed the recognition of several hitherto unknown structures.

Three approximately EW-trending, structural cross sections through the study area are presented as Fig. 9 in order to clarify details of the geology. Section A-A' provides an explanation for the broad expanse of Reed Dolomite cropping out between the Barcroft and Sage Hen Flat plutons. In this region, a broad anticline lies to the west of an adjoining syncline, and constitutes the core of the White-Inyo Range; the cross section intersects a NNE-trending normal fault that only slightly offsets the observed folds. South of Wyman Canyon along section B-B', the oldest rocks that are exposed make up a series of folds within [he Wyman Formation. The overlying Reed Dolomite occupies a small, gently south-plunging syncline, and a west-dipping homoclinal sequence near the western end of the canyon; to the east, a fi~ult-duplicated section stands almost vertically. Along the northern margin of Waucobi Embayment, the southernmost cross-section C-C, displays a series of broad, open folds with north-south axes, cut by subparallel, high-angle, predominately normal faults.

Conclusions

Geologic *results*. Conclusions obtained through our remote-sensing investigations are as follows: (a) Monoclinal sections on the south side of Waucobi Embayment in the Waucoba Mountain quadrangle are confirmed as mapped previously by Nelson (1966b), (b) Structureless "fingers" of Reed mapped by Nelson (1966a) and Ernst and Hall (1987) north of the Birch Creek pluton in the central Blanco Mountain quadrangle are, in fact, more complex. The southernmost "finger" is a north-dipping homocline, faulted on its northern margin. The next "finger" to the north consists of a faulted anticline-syncline pair. The northernmost "finger" is a syncline. (c) Reed outcrops near Blanco Mountain and at the eastern limit of the Ernst and Hall (1987) map are homoclinal successions as previously concluded. (d) The variable, but great width of exposure of the Reed Dolomite NW of the Sage Hen Flat Granite reflects the presence of a previously undetected NS-trending anticlinal fold and more easterly syncline paralleling the regional strike of the various formations. This structure, well shown in cross section AA' of Fig. 9, extends as a progressively more intensely compressed feature to the Barcroft pluton. (e) A large. outcrop of dolomite originally interpreted as interstratified within the Wyman (Nelson, 1966b; Ernst et al., 1993) is visible on the east side of the TM image of Fig. 3. Judging from recent investigation, C. A. Nelson (personal communication, 1994) now considers this massive unit to be a faulted slice of Recd. We were able to recognize individual subunits (1), (2), (4), (5), and (6) characteristic of the Reed Dolomite in the false-color image, so we have modified the geologic map (Fig. 6) accordingly. (f) In contrast, the discontinuous limestone layers interbedded with the Wyman argillites seem to be conformable with newly recognized stratigraphic subunits in the overlying basal Reed Dolomite throughout the map area, hence an angular unconformity at the contact between these formations seems improbable.

Remote-sensing results. NS-001 and TM data proved useful for subdividing the Reed Dolomite in different areas. This is due mainly to the spectral coverage allowing us to recognize subtle compositional and color changes that are not obvious in the field. The variations that we detected are related to minor changes in OH^-, CO_3^{-2} and Fe content--- all of which are difficult, if not impossible, to see on the ground. NS-001 data, although limited in spatial coverage due to narrow, sparse flight lines, were most useful because of the small pixel size compared to TM (10 vs. 30m). This study exemplifies the benefits of an integrated approach to stratigraphic analysis. Without the remote-sensing data, we would not have been able to recognize the lithologic subunits, and distinguish among (1), (2), and (3), and between (5) and (6). On the other hand, without the field work, we could not have correlated these stratigraphic members from one area to another. Even though the precise causes of spectral variations in the acquired image of the Reed Dolomite are difficult to explain quantitatively, the remotely sensed lithologic information has proven invaluable in assessing stratigraphy and structure in this region.

The significance of our investigation for the petroleum industry is that it demonstrates that detailed stratigraphy and structure can be adequately determined using remote-sensing methods in semi-arid regions where massive, undistinctive carbonate units are exposed. We were not engaged in the remote sensing of stratigraphic entities of strongly contrasting megascopic properties, but instead were subdividing massive, white rocks that had been previously lumped employing conventional field mapping techniques. In some areas, *no* single multispectral processing method allowed the discrimination of all lithostratigraphic entities present in the Reed Dolomite. In addition, the spectral characteristics of individual units were shown to vary along strike, even within a single image. Our study therefore underscores the site-specific and regional limitations of individual remote-sensing methods, and illustrates why a combination of diverse applications need to be employed in conjunction with on-the-ground inspection.

Remote-sensing technology should be applicable to other portions of the Great Basin and analogous semi-arid environments where differentiation of massive carbonate strata cannot be accomplished by conventional mapping alone. Better stratigraphic and structural information regarding featureless dolomites and limestones should facilite a more complete understanding of subsurface geology and reservoir characteristics of such sections. Elsewhere, as in our study, it will be crucial to employ a range of spectral techniques in order to obtain the desired stratigraphic control of geologic structures.

Appendix J.

Wyman Formation. The uppermost Proterozoic Wyman Formation consists mainly of calcareous and siliceous argillite interlayered with widespread, thin, discontinuous lenses of blue-gray limestone and rare calcareous sandstone. A minimum thickness for the Wyman of 2750 m has been estimated by Nelson (1962); the base of the formation is not exposed in the study area. Plant cover on the Wyman is impoverished, and is chiefly sagebrush.

Reed Dolomite. The uppermost Proterozoic-Lower Cambrian Reed Dolomite comprises approximately 650 m of massive, white to buff-colored, fine- to coarse-grained, crystalline dolomite (Nelson, 1962; Mount and Signor, 1991). Bedding is indistinct to nonexistant, even though oolitic horizons and/or stromatolitic reefs are present locally, The rock weathers to form dull-white, angular to spheroidal, erosion-resistant outcrops riven by joints. Small, diffuse patches, stringers, and pods of talc-silicate minerals occur sporadically. Vegetation on the Reed Dolomite consists of grasses and scattered sagebrush at lower elevations, chiefly bristlecone pine at higher elevations, particularly on north-facing slopes.

Deep *Spring Formation.* The Lower Cambrian Deep Spring Formation consists of about 400-570 m of interbedded limestone, dolomite, quartzite, sandstone, and siltstone (Ernst and Hall, 1987). Deep Spring quartzites weather slightly to rusty, quartz-rich sandstones. The formation supports a thin cover of sagebrush and piñon pine at lower elevations, grading to scattered limber and bristlecone pines along the higher elevations.

Campito Formation. The Lower Cambrian Campito Formation is composed of two members (Nelson, 1962; Mount, 1985). Trace fossils are widely but sparsely distributed in both units. "l"he Andrews Mountain Member consists of approximately 850 m of very massive, dark-brown to greenish black, fine-grained, blocky, magnetite-rich quartzite. "l"he overlying Montenegro Member is of variable thickness, but reaches a maximum of about 300 m west of the range crest. It consists of argillaceous, gray-green, thinly laminated siltstone and fine- to very fine-grained phyllitic quartzite. Vegetation is similar to that developed on the Deep Spring Formation.

Poleta Formation . The Poleta Formation is approximately 350 m thick, and consists of rhythmically interbedded buff and blue, limestones, interstratified with green or olive-drab, fissile shales and fine-grained quartzites (Nelson, 1966 a, b). Archaeocyathans are locally present. Plant cover is chiefly sagebrush in dryer, low elevations, and limber and bristlecone pines at higher elevations.

Overlying Cambrian strata. Above the Poleta Formation are up to 600 m of conformable Cambrian strata (top not exposed in the study *area).* Similar to the Lower Cambrian units, this superjacent section is represented predominantly by platform carbonates, fine-grained orthoquartzites, siltstones, and interstratified green or olive-drab, fissile shales, all feebly recrystallized (Nelson, 1966b). Vegetative cover is analogous to that of the underlying Poleta.

White Mountain Peak volcanic and sedimentary rocks. An approximately 3 km thick sequence of interbedded volcanic units crops out NW of the Barcroft pluton (Hanson, 1986). Flows range from mafic andesite to rhyodacite; the sequence also includes ash-flow tuffs, dikes, and sills. Volcanogenic metasedimentary units overlie the extrusives. This assemblage of rock types, confined to very high elevations just beyond the northern edge of the map area, is indistinctly covered by an arid, alpine-type tundra, and lacks a distinct weathering alteration.

Cenozoic surficial units. Younger geologic units have not been differentiated for present purposes; they include olivine basalt, lake beds, unconsolidated landslide and glacial deposits, and alluvium. Scattered vegetation is thinly developed, sagebrush at low elevations, succeeded upwards by piñon pines.

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W. G. Ernst is an experimental mineralogist/metamorphic petrologist concerned with the tectonic evolution of convergent plate junctions, especially in the Circumpacific and Alpine regions. Recent Californian interests include accretionary histories of the Coast Ranges, the central Klamaths, and the White-Inyo Range. He is also studing the genesis of ultrahigh-pressure metamorphosed terranes of the south Urals, northern Kazakhstan, and eastern China. A Stanford professor since 1989, Ernst taught geology at UCLA for nearly 30 years. Earnest D. Paylor, II is structural geologist interested *in* the tectonic and physiographic evolution of foreland regions, and the kinematic development of strike-slip fault systems. In addition, he is heavily involved in the applications of remote-sensing techniques for geologic analysis. Since 1993, he has been managing the Geology Program for NASA; during the ten years prior to that, he was a research geologist at the Jet Propulsion Laboratory.

Figure Captions

Fig. 1. Index map of California and Nevada. Locations of the White-Inyo Range overview (Fig. 2) and local false-color images (Figs. 3, and 5), the geologic map area (Fig. 6), and sites of the stratigraphic sections (Fig. 7) for the panel diagrams presented in Fig. 8 are also shown. Note that two nearby, but separate, parts of the range constitute the investigated terrain of Fig. 6.

Fig. 2. Landsat TM image of the White-Inyo Range, adjacent Sierra Nervada on the SW, and Great Basin on the NE, with areas delineated by black lines representing geologically mapped terrain (Fig. 6). This false-color infrared image was created using TM channels 2,3, and 4 (colored blue, green, and red, respectively). Within the geologic map area of Fig. 6, Reed Dolomite outcrops are white, whereas green vegetation presents an intense red coloration.

Fig. 3. Enlargement of the TM principal components image (principal components 1 = red, 2 = green, 3 = blue) of the Waucobi Embayment area, northern Inyo Mountains, including and east of the type section along Hines Road (see Figs. 1 and 6 for location). Our type section is situated in the NW corner of this scene. Numbers refer to subunits of the Reed Dolomite identified during image interpretation. The Wyman Formation lies to the east, the Deep Spring Formation to the west of the Reed. Geologic details shown in this scene have been simplified in the map of Fig. 6.

Fig. 4. Visible and near-infrared reflectance spectra for samples of Reed Dolomite. Spectra are offset vertically for clarity. See text for detailed discussion of individual subunit characteristics. Note how well spectra separate fresh from weathered samples and soil from rock chips. (a) Pure, massive dolomites lacking differentiatable subunits. (b) Type section along Hines Road. (c) Goat Spring traverse.

Fig. 5. NS-001 band-ratio images (ratios 6/7 = red, 6/5 = green, 3/1 = blue) of Reed Dolomite exposures NW of the Birch Creek pluton, southern White Mountains, showing outcrop "fingers" of dolomite (see Figs. 1 and 6 for location). Extra stratigraphic detail is shown in this image compared with the map compilation of Fig. 6. The Wyman Formation adjoins the Reed both directly north and south of the delineated stratigraphic subunits.

Fig. 6. Geologic map showing newly recognized stratigraphic members (1)-(6) of the Reed Dolomite, central White-Inyo Range, as determined by remote-sensing techniques and field study. Thin, rusty quartz-arenite lenses within the Reed Dolomite are indicated in black. The base map is slightly modified from the geologic compilation by Ernst et al. (1993); the two map portions presented here are separated north-south by about 9.5 km (see Fig. 2 for regional setting).

Fig. 7. Lateral extent of mapped stratigraphic subunits (3), (4), and (5) of the Reed Dolomite. Also indicated are location sites of the stratigraphic columns used in the north-south panel diagrams of Fig. 8: western = KFGEAB; and eastern = KHIJDB.

Fig. 8. Stratigraphic thickness diagrams showing north-south variations of the six newly recognized subunits in the Reed Dolomite (from Fig. 7): lower = western section; upper = eastern section. Both panels are at 10:1 vertical exaggeration. Note that the top of the formation is missing at site K, the base at site J, both due to igneous intrusion. Thicknesses were measured employing the new geologic map of the Reed Dolomite (Fig. 6) and 1:62,500 scale topographic base maps; they are considered accurate tot 25 m. The digital number (DN) profiles (solid lines) described in the text (Lang and Paylor, 1994), are generally compatible with the measured stratigraphic columns; brightness increases to the right.

Fig. 9. Cross sections A-A', B-B', and C-C' of the central While-lnyo Ranges featuring details of the Reed Dolomite stratigraphy and structure (for locations of transects, see Fig. 6). No vertical exaggeration.