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Gary L. Raines and Keenan Lee

Remote Sensing Report 74-4

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DEPARTMENT OF GEOLOGY
COLORADO SCHOOL OF MINES • GOLDEN, COLORADO

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ABSTRACT

With the advent of ERTS and Skylab satellites, multiband imagery and photography have become readily available to geologists. This paper examines the ability of multiband photography to discriminate sedimentary rocks. More than 8600 <u>in situ</u> measurements of band reflectance of the sedimentary rocks of the Front Range, Colorado, were acquired. Statistical analysis of these measurements showed that (1) measurements from one site can be used at another site 100 miles away, (2) there is basically only one spectral reflectance curve for these rocks, with constant amplitude differences between the curves, and (3) the natural variation is so large that at least 150 measurements per formation are required to select "best" filters. These conclusions are supported by subjective tests with aerial multiband photography. The designed multiband photography concept for rock discrimination is not a practical method of improving sedimentary rock discrimination capabilities.

INTRODUCTION

Among researchers in remote sensing, the concept has developed that, by selection of the appropriate spectral band or bands of the electromagnetic spectrum, the tonal difference between targets can be preferentially enhanced so that targets are more easily discriminated. One particular application of this concept that seemed especially promising was multiband photography. Many geologists have proposed that multiband photography, with the selection of appropriate spectral bands in the photographic part of the electromagnetic spectrum (400-950 nanometers), is a means of obtaining increased tonal discrimination of rocks.

When making geologic interpretations of aerial photography the most significant recognition elements are texture, pattern, association of features, and tone (or color); lesser recognition elements are shape and size (Ray, 1960). Tone is an important aspect of all the recognition elements, since by tone these other recognition elements are used. Therefore, tone is one of the most important aspects of discrimination and recognition of targets on a photograph. This research is an evaluation of the concept that tonal differences between formations on aerial photography can be improved through the selection of the appropriate spectral bands.

The information presented and discussed in this paper has the following format. First, the specific test sites are described to supply an understanding of the geology. Second, the reflectance measurement procedures are described. Then with this background, rock reflectance measurements are summarized and analyzed. This analysis consists of statistical tests of the significance of the measurements and selection of best bands. Using this information, aerial multiband photography was acquired and is described, and a summary evaluation of multiband photography for rock discrimination is derived. Finally, recommendations for further research are offered.

TEST SITE GEOLOGY

In order to perform the evaluations proposed, two areas were selected as test sites (Fig. 1). The first area, the Canon City Test Site, was selected as the primary test site. The second area,

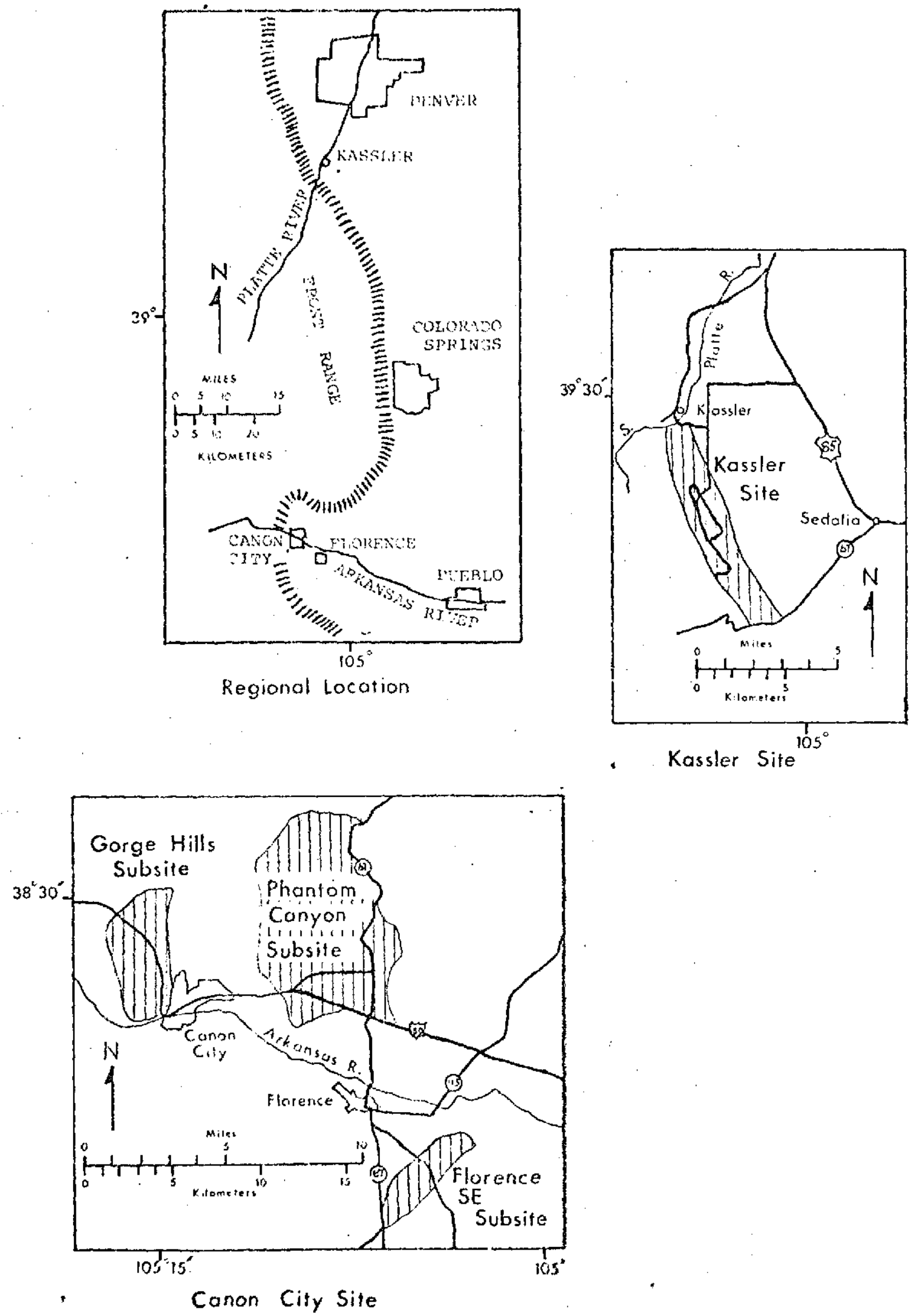


Figure 1: Location maps of the test sites.

the Kassler Test Site, was selected for an additional test of the conclusions and to test the ability to use measurements from one area in a distant area. These test sites are described more fully in Raines (1974) and Scott (1963a, 1963b).

The Canon City Test Site was divided into three subsites. These specific subsites were chosen for their varied rock types; a sedimentary sequence of sandstones, carbonates, and shales lies on Precambrian igneous and metamorphic rocks, with a discontinuous cover of Tertiary and Quaternary alluvium. Rock types include schists, gneisses, migmatites, arkosic and quartzose sandstones, conglomerates, shales, limestones, dolomites, and gypsum. These lithologies are well exposed in compact and accessible areas, and the geology is not complicated by faulting, folding, or significant lateral variation. Figure 2 is a generalized geologic map of the Canon City Test Site.

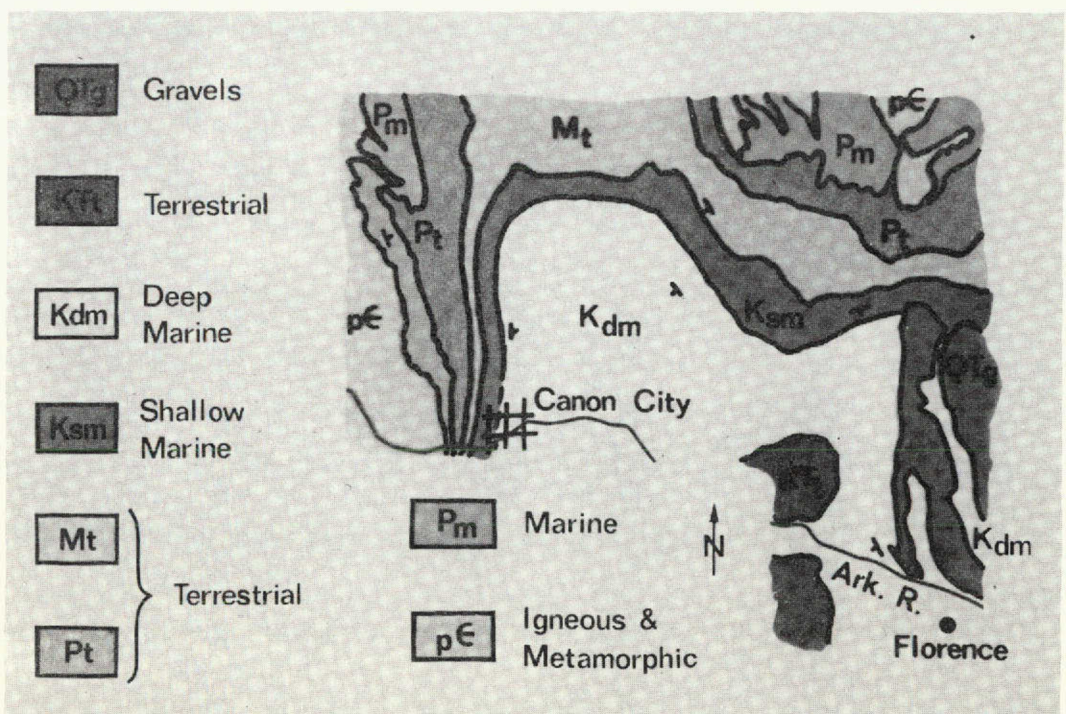


Figure 2: Generalized geologic map of the Canon City Test Site.

The Kassler Test Site was selected because it is geologically similar to the Canon City Test Site, it is readily accessible, and bedrock and surficial geologic maps are available (Scott, 1963a, 1963b).

ROCK REFLECTANCE

The first step in the design of multiband photography is to select a set of best spectral bands for the discrimination of the formations considered. To accomplish this, the spectral reflectance properties of the formations must be measured and analyzed to select the best set of spectral bands. This section describes how these measurements were obtained, summarizes the measurements, and discusses some implications. These subjects are discussed in more detail in Raines and Lee (in review), Raines and Lee (in preparation) and Raines (1974).

REFLECTANCE MEASUREMENTS

The *in situ* measurement procedure consists of using a simple filter wheel photometer (referred to as FWP), modified from an instrument used by Egbert and Ulaby (1972). The FWP consists of a photometer and a filter wheel with 13 filters. These filters are those Wratten filters that can easily be used for aerial photography. The pass bands of the 13 filters are shown in Fig. 3. Matte-surface neutral gray cards of known band reflectance are used as standards for calibration of the system. The measurement procedure in the field consists of (1) measurement of standards, (2) measurement of the target(s), and (3) re-measurement of the standards. Data reduction then consists of (1) averaging the two sets of standards measurements and (2) linear interpolation between the standards to reduce the unknown target measurements to band reflectance. Band reflectance is defined as the average spectral reflectance within a wavelength band, the width of which is defined by the transmission characteristics of the filter under consideration. Therefore, if

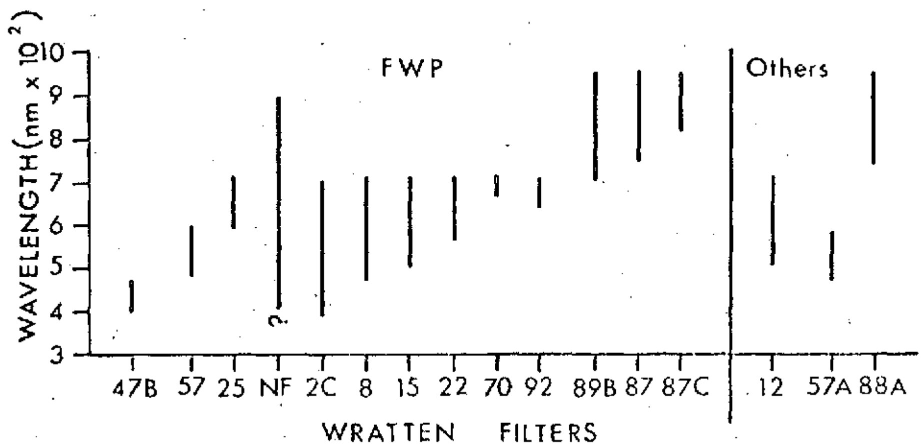


Figure 3: Passbands of filters. All of the filters are Wratten gelatin filters. All the filters except the 87, 87C, 88A, 89B, and NF are used with an infrared blocking filter (Corning 3961). NF means no filter.

an object reflects 20 percent of the incident energy in a wavelength interval, then its band reflectance for the wavelength interval is .20. The accuracy of this procedure is 20 percent of average band reflectance, and precision is approximately 3 to 5 percent of the average band reflectance. Correlation of in situ mean band reflectances with densities measured on aerial multiband photography gives a correlation coefficient ranging from .70 to .96.

ROCK REFLECTANCE PROPERTIES

Typical examples of the more than 8,600 in situ band reflectance measurements are presented in Fig. 4. Figure 4 shows the mean band reflectance for each formation and an 80 percent confidence interval about the mean, for a sample size of generally 12 measurements per band per formation. As has been suggested before, spectral reflectance in this part of the spectrum (400 to 950 nanometers) offers little opportunity for unique identification by use of the spectral character.

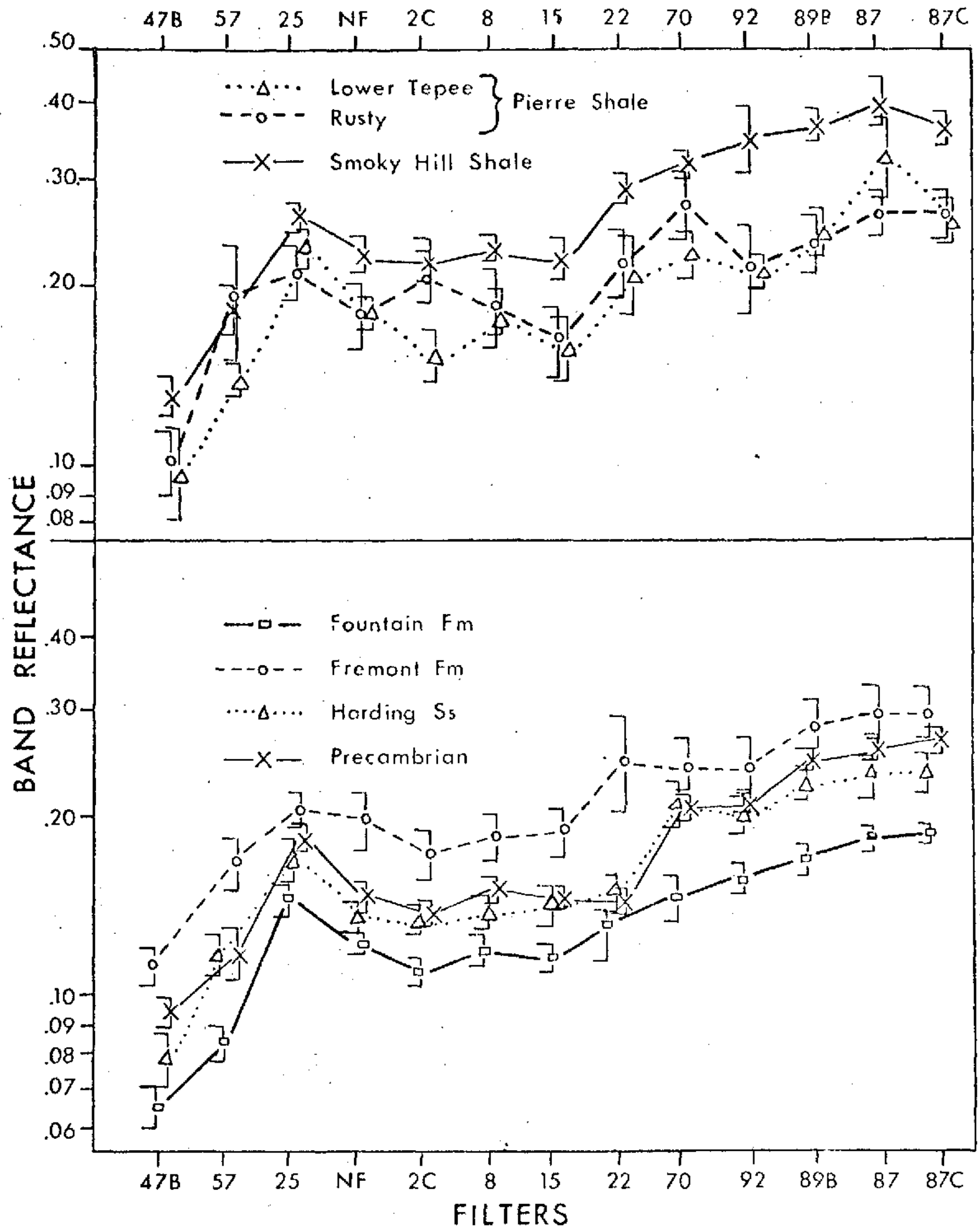


Figure 4: Mean band reflectance and 80 percent confidence intervals for some of the Phantom Canyon data. Lines connecting the points are to aid visualization only. Formations are listed in stratigraphic order.

The standard deviation is an estimate of the total variation within the reflectance data, and a summary of all the standard deviations observed is shown in Fig. 5. Total variation includes variation due to random error, measurement procedure, and natural target variability. As stated above, the variation due to random error and measurement procedure is 3 to 5 percent of the mean band reflectance; thus the observed variation is primarily due to natural variability.

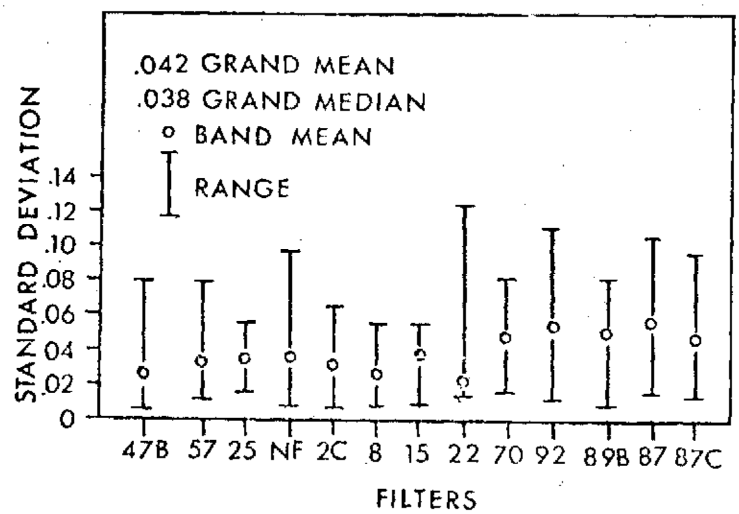


Figure 5: Sample standard deviations for the Phantom Canyon data. Eighty-five percent of the observed standard deviations are less than .07.

The grand mean of all the standard deviations is .0423 band reflectance, and analysis of the range shows that 85 percent of the observed standard deviations are less than or equal to .07. The grand median of the standard deviations is .0383. The significance of these standard deviations is best assessed by realizing that the grand mean band reflectance, using all the data, is approximately .20; therefore, the grand mean standard deviation (.0423) is about 20 percent of the grand mean of the mean band reflectances. Furthermore, the procedure used in the field was to measure "typical" areas; therefore, the mean standard deviation

(.0423) is a minimum estimate of the variation. Thus, the data indicate very significant variations of the band reflectance within a formation.

In order to further delimit the population standard deviation, two formations were measured extensively, specifically looking for variation and thus acquiring an estimate of the maximum standard deviation. These sample standard deviations are shown in Fig. 6.

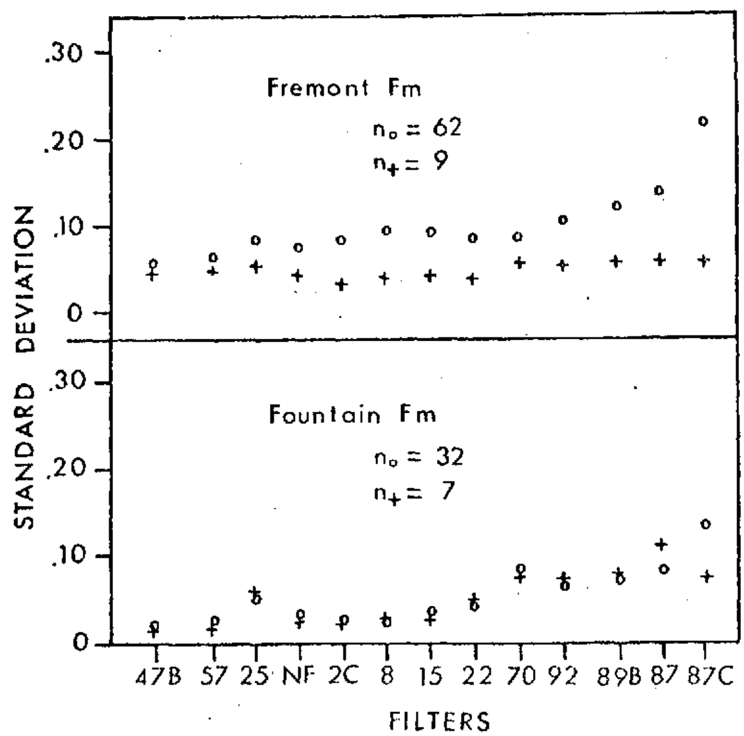


Figure 6: Sample standard deviations for the Fountain and Fremont formations. Circle (o) denotes the large sample where variation was sought; cross (+) denotes a small sample of measurements from "typical" outcrops. In all cases the mean confidence intervals for each band of both formations overlap, so the differences between the means from small samples and large samples is not significant.

From inspection of Fig. 6, the standard deviations increased half the time when variation was sought. From this test it is difficult to specify the population standard deviation; however, the test supports the idea derived above that .042 is an average minimum standard deviation, and an average population standard deviation might be a number around .07.

With regard to variation between formations, Fig. 7 summarizes the contrast ratios determined

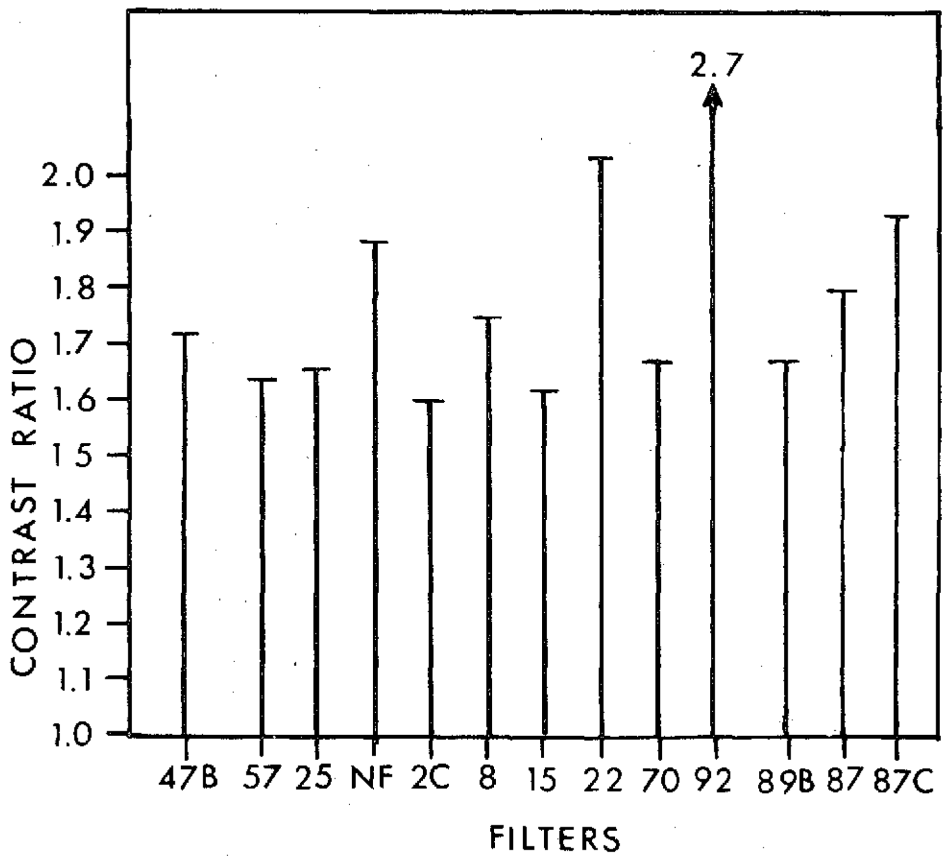


Figure 7: Range of the contrast ratios observed at the Phantom Canyon Site.

using mean band reflectances from the Phantom Canyon Subsite. Contrast ratio is the ratio of mean band reflectances, ratioed to give a number greater than (or equal to) 1.0. The contrast ratio is important because it is a numerical relationship that is proportional to the resultant density relationships of the targets on the aerial photography. The range of contrast ratios is very narrow, generally between 1.0 and 1.8, with very few greater than 1.8. The typical difference between contrast ratios, for the filter bands considered, is about 0.2. Therefore, in most cases, there are only small differences between the filter bands considered.

One very important aspect observed in all the data obtained is that not one single case of a significant crossover in band reflectance occurred (for example, see Fig. 4). A "significant crossover" is that case where the mean band reflectances do cross over (relative relationship of band reflectances from one band to the next is inverse) and the confidence intervals do not overlap.

EXTRAPOLATION TO DISTANT AREAS

A question of major importance is whether these measurements made in a local area (Phantom Canyon Subsite) can be used in other areas where the same formations are exposed at the surface. To answer this question, statistical comparisons were made between the same formations at the Phantom Canyon Subsite and the Gorge Hills Subsite about 10 miles away, and between the same formations at the Canon City Test Site and the Kassler Test Site, about 100 miles away.

The conclusion of the comparison of the Phantom Canyon data with the nearby Gorge Hills data is that the values are essentially the same. The means of band reflectance for each formation have a linear correlation coefficient of .97, and the standard deviations have a linear correlation coefficient of .67. Using a hypothesis test for equivalence of means, it was found that a systematic difference of .04 to .05 band reflectance exists between the Gorge Hills and Phantom Canyon subsites, with Gorge Hills values greater than Phantom Canyon. This may be due to (1) slight differences in operator techniques, (2) possible real differences between sites, or (3) possible errors in data reduction. Since this difference is systematic and small, it is not considered significant. The standard deviations do not correlate as well as the means, probably because the Gorge Hills standard deviations have a larger range and tend to be slightly larger. However, the minimum average standard deviation derived for the Phantom Canyon Subsite (.04) is a valid minimum average standard deviation for the Gorge Hills Subsite.

The conclusion of the comparison of the Kassler Test Site with the Canon City Test Sites is essentially the same. The means of band reflectance for each formation have a linear correlation of about .90 and are essentially the same. This is shown in Fig. 8, which is a comparison of the

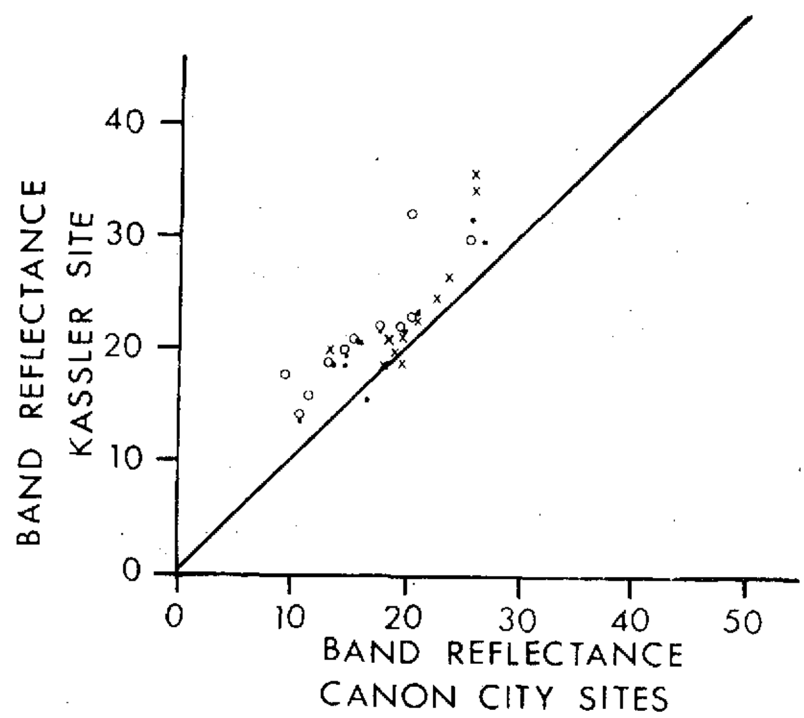


Figure 8: Comparison between band reflectance measurements from the Kassler Site and the Canon City Site. The formations considered are Dakota Group (upper member (.), the Fort Hays Limestone (x), and the Fountain Formation (o). The line is the line of perfect agreement.

Kassler data with the Canon City data. The average difference, where the difference is calculated as a least squares difference, is .04 band reflectance. The standard deviations correlate very poorly; however, .04 is a good estimate of the minimum average standard deviation.

Therefore, it is possible to make measurements of band reflectance in one area and to use those measurements for the same formation in another area with reasonable accuracy. This assumes, of course, that the formations do not show a great deal of lateral change.

IMPLICATIONS OF THE DATA

Once reflectance measurements have been made, these data theoretically can be used for the selection of a "best" spectral band for discriminating the measured formations by tonal contrast on aerial photography. The technique for selection of a "best" band is to select that band having the maximum contrast ratio for the formations being considered. The contrast ratio is used because it is a mathematical relationship that relates the resulting film density to the exposure on the film.

In order to select the band with the maximum contrast ratio, it is necessary to be confident that this ratio is larger than the contrast ratios of all other bands. Using the data from the previous sections, the question of being confident of which contrast ratio is largest can be answered in the following manner.

As depicted in Fig. 9, a min-max interval on the mean contrast ratio can be derived that is similar to, and derived from, the 80 percent confidence intervals on the band reflectance means of each band for two adjacent formations. Using this min-max interval on the contrast ratio, the equations for the 80 percent confidence interval on the band reflectance mean, and the data summarized in this paper, it is possible to calculate the

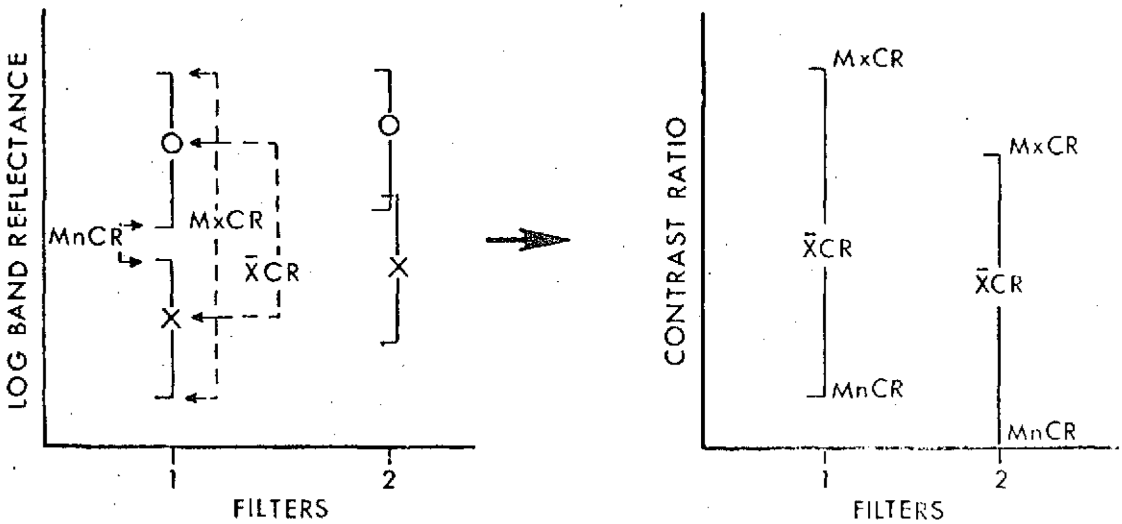


Figure 9: Definition of the min-max interval on the contrast ratio. The log band reflectance plot is used for comparison of formations X and O because with this plot the contrast ratio plot with min-max intervals can be visualized. It can be seen that the min-max intervals for filters 1 and 2 would overlap in the example given. Calculation of the min-max interval would be as follows: for the minimum value of the interval, ratio the antilog of the numbers marked by the MnCR bracket; for the maximum value, ratio the antilogs of the numbers marked by the MxCR bracket; and for the mean contrast ratio, ratio the antilogs of the numbers marked by the X̄CR dashed bracket. This min-max interval is used like a confidence interval.

required number of measurements per band per formation (sample size) to be confident that the contrast ratios are different (non-overlapping min-max intervals). Because of the lack of established statistical procedures for this type of calculation, the derived sample sizes can be treated only as order-of-magnitude figures. An example of the calculation procedure is given in Table 1 and the results in Table 2.

Table 1 Actual example of the calculation procedure used to determine the minimum sample size.

$\bar{w} \pm \frac{t \times s}{\sqrt{n}}$	Student's t confidence interval t = Student's t statistic s = sample standard deviation n = sample size, $\bar{w}$ = sample mean	
$\frac{.2600}{.2025} = 1.25$	Mean contrast ratio in a given band for two adjacent formations with mean band reflectances of .2600 and .2025 respectively	
$\frac{.2525}{.2100} = 1.20$	Minimum contrast ratio	±.0075 interval on the mean band reflectance and approximately a ±.08 interval on the contrast ratio
$\frac{.2675}{.1950} = 1.37$	Maximum contrast ratio	
$\frac{t \times s}{\sqrt{n}} = .0075$	From Student's t confidence interval assuming t = 1.3 and s = .042	
n = 53.76	Sample size = 54	

Table 2 Relationship between sample size (n), sample standard deviation (s) the differences between mean contrast ratios (D), and the length of the interval on the contrast ratio (LCR). These sample sizes are justified as order-of-magnitude estimates only.

s	.020	.038	.042	.070	.100	D	LCR
n	28	100	121	332	676	.10	±.05
n	12	45	54	147	300	.16	±.08
n	7	25	31	82	169	.22	±.11
n	2	7	8	21	42	.44	±.22

Thus from Table 2 and the generalizations that the typical minimum standard deviation is .042, that an average population standard deviation is about

.07, and that a typical difference between mean contrast ratios is .16; the number of measurements required in order to select the "best" band for the discrimination of two formations is much too large for a practical technique.

As a further test of this conclusion and as a suggested procedure for future research, the following observation is offered. If a confidence level of 95 percent on the band reflectance mean had been used instead of an 80 percent confidence interval, then in almost all cases the confidence intervals on a log band reflectance - filter plot (such as Fig. 8) would have overlapped. Thus, the same type of sample size conclusion would have been drawn more easily and rapidly. This observation, of course, is derived in retrospect and applies to these data only.

Further support of the conclusion that a "best" band cannot be practically selected can be derived by an analysis of the relative amplitude variation of band reflectance between formations. Fig. 10 was prepared by normalizing the grand mean band

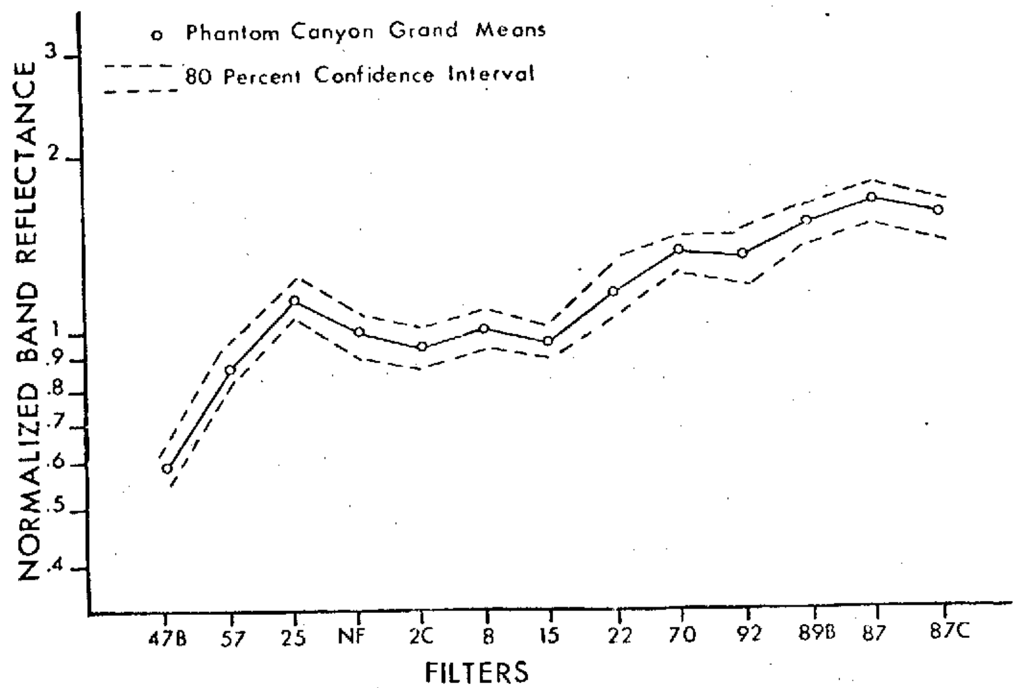


Figure 10: Normalized band reflectance.

reflectance data so that the NF band has a value of 1.00. The circles are normalized grand means of all formations and the dashed lines are the normalized 80 percent confidence interval. The circles and confidence intervals are connected between bands for visualization. Then, normalizing the mean data for each formation, it was found that all of the means were not statistically different from the grand mean at the 95 percent confidence level. Therefore, the differences between the band reflectance data for most formations have a constant relative difference that is independent of wavelength.

If this conclusion is valid, using one known band reflectance the band reflectance for the other 12 bands can be calculated. An empirical solution of this prediction takes the form:

$$B_i = B_m \times P_i$$

where

B_i = an unknown band reflectance, $i=1,\ldots,12$
B_m = the known or measured band reflectance
P_i = the proportionality factor between B_m and B_i, $i=1,\ldots,12$.

Selecting the NF band as the known band reflectance, because this band averages across the full spectrum, and using the grand mean data from the Phantom Canyon Subsite to derive Pi, the results in Table 3 were derived. The average error is a least squares-type error. From inspection of Table 3, it can be seen that the error is generally less than the minimum average standard deviation, .04 band reflectance.

DISCUSSION

In the previous section we have summarized the rock band reflectance properties of more than 8,600 measurements from the Canon City and Kassler test sites, and most significantly, determined that an impractically large number of observations is required in order to select best filters. With this

Table 3 Calculated band reflectance. Average error for all the Phantom Canyon data is .021. Grand average error of all the data shown is .035. Average error is a least-squares type error. P is the proportionality factor between the NF filter and the calculated values. M is the measured value, and C is the calculated value.

Phantom Canyon Data

Filter	Grand Mean Band Reflectance		Precambrian		Manitou Fm.		Fremont Fm.		Fountain Fm.		Rusty zone		Lower Tepee zone		C Unit		Average Row Error
		P	M	C	M	C	M	C	M	C	M	C	M	C	M	C	
NF	.166		.144		.120		.198		.122		.176		.181		.113		
47B	.099	0.596	.093	.086	.071	.072	.112	.118	.065	.073	.100	.105	.097	.108	.073	.067	.007
57	.147	0.886	.117	.126	.101	.106	.168	.175	.082	.108	.189	.156	.139	.160	.113	.100	.020
25	.192	1.157	.181	.167	.150	.139	.203	.229	.144	.141	.206	.204	.235	.209	.175	.131	.025
2C	.157	0.946	.136	.136	.124	.114	.173	.178	.108	.115	.204	.166	.154	.171	.117	.107	.019
8	.168	1.012	.149	.146	.120	.121	.185	.200	.118	.123	.183	.178	.180	.183	.112	.114	.007
15	.160	0.964	.145	.139	.120	.116	.189	.191	.116	.118	.160	.170	.157	.174	.145	.109	.017
22	.194	1.169	.143	.168	.125	.140	.249	.231	.130	.143	.215	.206	.212	.212	.141	.132	.016
70	.227	1.367	.205	.197	.174	.164	.243	.271	.145	.167	.270	.241	.227	.247	.174	.154	.023
92	.222	1.337	.211	.193	.163	.160	.241	.265	.157	.163	.211	.235	.212	.242	.132	.151	.021
89B	.253	1.524	.252	.219	.193	.183	.283	.302	.169	.186	.230	.268	.251	.270	.235	.172	.036
87	.273	1.645	.261	.237	.203	.197	.297	.326	.183	.201	.259	.290	.334	.298	.239	.186	.034
87C	.258	1.554	.268	.224	.205	.186	.297	.308	.187	.190	.259	.274	.260	.281	.189	.176	.023
Average Column Error			.021		.010		.019		.014		.025		.022		.032		

Gorge Hill-Florense SE Data

Filter	Fremont Fm.		Fountain Fm.		B Unit		D Unit	
	M	C	M	C	M	C	M	C
NF	.265		.112		.172		.137	
47B	.138	.158	.081	.067	.117	.103	.113	.082
57	.210	.235	.096	.099	.171	.152	.148	.121
25	.298	.307	.169	.130	.209	.199	.192	.159
2C	.233	.251	.103	.106	.156	.163	.135	.130
8	.253	.268	.103	.113	.147	.174	.127	.139
15	.293	.255	.119	.108	.159	.166	.130	.132
22	.282	.310	.151	.131	.183	.201	.171	.160
70	.202	.362	.215	.153	.207	.235	.210	.187
92	.299	.354	.189	.150	.199	.230	.203	.183
89B	.403	.404	.243	.171	.233	.262	.226	.209
87	.384	.436	.243	.184	.216	.283	.231	.226
87C	.383	.412	.253	.174			.284	.213
Average Column Error	.057		.045		.030		.029	

Kassler Data

Filter	Fountain Fm.		Lyons Sandstone		Glennon Limestone	
	M	C	M	C	M	C
NF	.146		.237		.329	
47B	.101	.087	.148	.141	.232	.196
57	.109	.129	.194	.210	.319	.291
25	.184	.169	.256	.274	.357	.381
2C	.118	.138	.220	.224	.330	.311
8	.119	.148	.246	.240	.235	.333
15	.118	.141	.239	.228	.338	.317
22	.151	.171	.237	.277	.356	.385
70	.315	.200	.295	.324	.373	.450
92	.247	.195	.259	.317	.357	.440
89B	.272	.223	.336	.361	.460	.501
87	.289	.240	.346	.390	.450	.541
87C			.394	.368	.395	.512
Average Column Error	.050		.030		.060	

foundation, we will discuss what this statistical analysis means with regard to rock discrimination by multiband photography.

Concerning the general applicability of the conclusions drawn, the formations considered have not been selected in a statistical manner that would allow statistical inferences to be made about all rocks, or even all sedimentary rock. However, there is no geologic reason to suspect that the rocks and formations considered have unique reflectance properties with regard to other sedimentary rocks. Therefore, the conclusions drawn apply in detail only to the formations considered; however, generalizations of conclusions are probably valid for most sedimentary rocks.

The first conclusion to be drawn from the previous section is that there is no practical numerical basis for selecting any particular spectral band as best for rock discrimination and, in most cases, there is little numerical basis for selecting better spectral bands. Therefore, useful information cannot be obtained from the spectral information considered here. This is because *in situ* measured rock band reflectance is so variable that is is not possible to predict tonal contrast between formations precisely enough to define which are the best spectral bands or, in most cases, even better spectral bands. The problem is further complicated when it is realized that many smaller shrubs and topographic effects cannot be resolved on aerial photography, and that the atmosphere and atmospheric effects can be significantly variable; thus, the variation that is encountered on aerial photography is even larger than that of rock band reflectance alone. Therefore the multiband photography concept does not have a practical numerical basis from which the concept can be applied to rock discrimination.

A second conclusion is that the information content of all spectral bands, or combinations of bands, should be the same.

Finally, a third conclusion is that the 13 mean band reflectances can be calculated by knowing one of those means. Therefore, similar differences of band reflectance exist between all the spectral bands for any two formations. Thus, there is no best band.

FILTER SELECTION

Realizing from the previous numerical analysis that there is (are) no "best" film/filter combination(s) to discriminate the formations at the Phantom Canyon Subsite, it was decided to select the best estimate of the "best" film/filter combination and to subjectively test this "best" photography to see what kind of a job it could do. The criterion used to select the "best" band for a formation contact is: that band is "best" that has no overlap of the confidence intervals of the two formations being considered and that has the maximum mean contrast ratio (i.e. maximum ratio of sample mean band reflectance). Then the "best" combination of bands is selected that will discriminate the largest number of formations with maximum redundancy. The maximum redundancy criterion is used when it is necessary to select between two filters that equally will increase the number of formations discriminated. Operationally, this definition of "best" is used by visually inspecting overlaid log band reflectance plots and compiling Table 4, described below. The number of bands selected and the film type are further restricted by the camera to be used. In this case a multiband camera that uses only one film type at a time was used.

Using the above criteria from Tables 4 and 5 for generating a selection matrix, with the added criteria that the actual sample range was inspected and the redundancy criterion was not used, another selection matrix was developed for the Gorge Hills and Florence SE subsites as shown in Table 6 and the four "best" filters are those in Table 9.

Table 4 Phantom Canyon selection matrix. "Good" filters are marked G and "best" filters are marked B. More than one "best" in a row means that any difference between those filters is insignificant. "Best" means no overlap of the 80 percent confidence intervals and maximum separation of the means or medians. "Good" means no overlap of the 80 percent confidence intervals. See Table 5 for the selected filters.

Lithologic Units	Filters												
	47B	57	25	NF	2C	8	15	22	70	92	89B	87	87C
Upper Transition-D					G					B			G
D-C	G	G		G	G	G		G	G	B	G	G	G
C-Upper Tepee		G				G			B				
Upper Tepee-Lower Tepee			G			G		B					G
Lower Tepee-Rusty					B								
Rusty-Smoky Hill	G		G			G	G	G	G	B	G	G	G
Fountain-Harding		B			G		G		B	G	G	G	G
Fountain-Fremont	G	B	G	G	G	G	G	G	G	G	G	G	G
Fountain-Precambrian	B	G	G	G	G	G	G		G	G	B	G	G
Fremont-Harding	B	B	G	G	G	G	G	G	G	G	G	G	G
Harding-Manitou							G	G		B			
Manitou-Precambrian	G		G			G	G	G	G	B	G	G	G
Quaternary gravel-Smoky Hill								B	G		G		
Quaternary gravel-Rusty		G	G	G	G	G		G	B			G	G
Quaternary gravel-Lower Tepee		G	B	G		G		G	G	G	G	G	G
Number of "Bests"	2	3	1	0	1	0	0	2	3	5	1	0	0

Table 5 The "best" filters and the formations discriminated "best".

"Best" Bands	Formations Discriminated "Best"
92	U.T.-D, D-C, Rusty-Smoky, Hard.-Man., Man.-Precamb.
57	Fount.-Hard., Fount.-Fre., Fre.-Hard.
70	C-U.T., Fount.-Hard., Grav.-Rusty.
22	L. Tepee-U. Tepee, Grav.-Smoky

Table 6 Gorge Hills-Florence SE matrix. Symbols are defined at the bottom of the table.

Formations	Filters: 47B	57	25	NF	2C	8	15	22	70	92	89B	87	87C
Upper Transition-CD	Q	G	G	G	G	F	F	G	N	P	G	G	N
CD-Upper Tepee	Q	G	G	G	G	G	G	G	N	P	G	Q	N
Upper Tepee-Lower Tepee	Q	P	P	P	P	P	P	P	N	Q	P	P	P
Lower Tepee-Rusty C	N	N	N	N	N	N	Q	N	N	N	N	N	N
Rusty C-Rusty,B	N	N	N	Q	Q	N	Q	N	N	N	N	Q	N
Ft Hays - Carlisle	F	N	P	P	P	P	P	P	P	P	P	P	P
Carlisle-Greenhorn	F	Q	P	P	P	Q	P	Q	P	Q	P	P	Q
Greenhorn-Graneros	F	P	F	P	P	P	F	P	F	F	F	F	F
Graneros-Dakota	P	F	F	F	F	F	F	F	F	F	P	F	F
Dakota-Purgatoire	G	G	G	G	G	G	G	G	F	F	F	F	F
Purgatoire-red Morrison	N	N	F	N	P	F	F	F	Q	F	F	P	P
red Morrison-green Morrison	P	F	G	G	G	G	G	G	Q	F	F	P	Q
green Morrison-Entrada	Q	P	P	P	P	P	P	P	N	N	N	N	N
Entrada-Fountain	G	G	Q	G	F	P	F	P	N	N	N	N	N
Fountain-Fremont	P	F	F	F	F	F	F	F	N	F	F	F	Q
Fremont Harding	N	P	N	N	P	P	P	P	Q	Q	N	N	N
Harding-Precambrian	P	P	P	P	P	P	P	P	P	P	P	G	P
Ranking	8	2	6	1	2	4	4	6	12	11	9	10	13

Symbols		Mean, Median	Confidence intervals	Distribution of raw data
G	Good	wide separation	wide sepafation	all separate
F	Fair	wide separation	separation	all separate
P	Poor	separation	separation	overlap
Q	Questionable	separation	some overlap	overlap
N	No Good	little separation	large overlap	overlap

The differences between these two sets of "best" filters can be explained by differences in selection criteria, subtle differences in the basic reflectance data that may be related to the number of samples necessary for selection of "best" bands, and differences in geologic expression. As an example of the significance of geologic expression, consider the diagrammatic geologic cross sections shown in Fig. 11. Thus, for the selection of best filters, it is necessary to consider the geologic expression and the geologic significance of the contact for the problem to be solved.

AERIAL MULTIBAND PHOTOGRAPHY

After having selected a set of "best" filters and decided upon an optimum film, it is necessary to acquire the multiband photography. This section discusses the acquisition of the multiband photography used in this research.

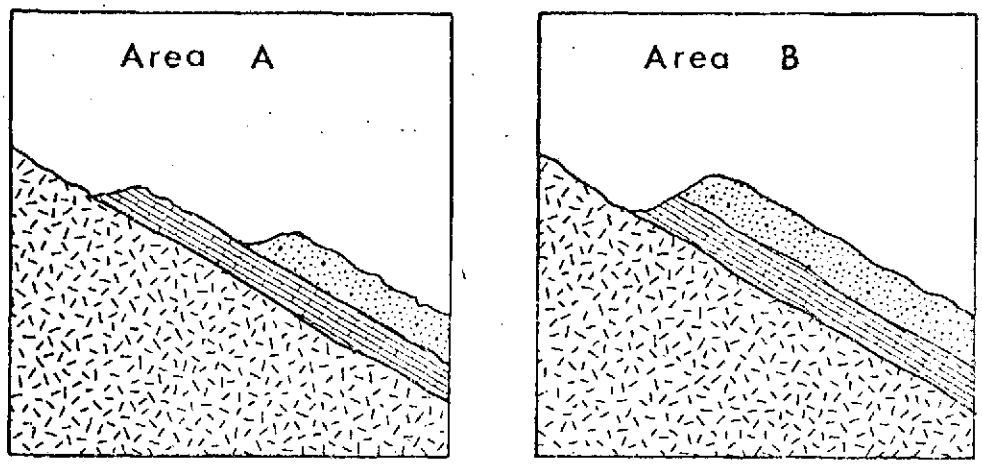


Figure 11: Effect of geologic expression upon selection of best filters. In Area A all three formations are significant; whereas in Area B the significant comparison is between the sandstone and the basement since the limestone would not be visible on aerial photography.

All aerial photography evaluated from which conclusions are drawn was acquired under subcontract by Mr. Robert Hardwick of Hardwick and Associates, Arvada, Colorado, using an International Imaging Systems (I^2S) multiband camera. This camera produces four simultaneous photographs in four spectral bands using a single roll of 9-inch film, in this case Kodak Infrared Aerographic Film Type 2424 (a negative black and white infrared film). Details of the camera system can be obtained from I^2S, Mountain View, California, and Ross (1973). The photography was flown generally at a 1:12,000 scale along north-south flight lines, within three hours of solar noon in the months of August and September, 1972 and 1973. Atmospheric conditions at the time of photo flights were generally excellent. The film was processed by Mead Technology Laboratories, Dayton, Ohio, to I^2S specifications (1971 specifications, Wratten 88A band processed to a gamma of 1.9), and positive transparencies were processed to a copy gamma of 1.0.

Problems were encountered with correct exposure. To determine the correct exposure, test aerial multiband photography was flown with all filters. The correct exposures were determined by inspection of these tests. Table 7 summarizes the conclusions of best exposures for each filter. Even with this testing, changes in the atmosphere and/or camera settings resulted in having to refly a few sets of filters in order to obtain good exposures. Thus, correct exposure is a very real problem when using multiband photography.

Table 7 Best exposures for the filters considered. Determined from test aerial photography over the Canon City Test Site in August and September near 1200 hours. For kodak Infrared Aerographic Film Type 2424. IRB means infrared blocking filter. All of the filters are Wratten gelatin filters.

Filter	f-stop	Speed
47B + IRB	4.5	1/250
57 + IRB	3.5	1/250
25 + IRB	3.5	1/250
NF + IRB	13.5	1/250
2C + IRB	9.5	1/250
8 + IRB	8	1/250
15 + IRB	6.8	1/250
12 + IRB	5.6	1/250
22 + IRB	6.8	1/250
70 + IRB	8	1/250
92 + IRB	4.5	1/250
89B	16	1/250
87	11	1/250
87C	8	1/250

Table 8 summarizes the cost of acquiring multiband photography, included to give a potential user of multiband photography an idea of costs. It should be recognized that the test sites were all local, therefore the costs include only the actual data acquisition and processing costs.

Table 8 Cost of acquiring multiband photography (December, 1973).

Item	Cost
1. Rental of I^2S camera and intervalometer, including shipping from Mountain View, California, to Denver, Colorado.	$850/month
2. Film, Kodak Infrared Aerographic Film Type 2424, two hundred-foot roll.	$120
3. Aerial photographer, pilot, and plane (Twin-engine Apache).	
Fuel.	$30/hour
Plane, pilot, and photographer.	$120/hour
Crew mobilization charge.	$120/day
4. Film processing.	
Negative (200 ft).	$180
Sensitometry, relative exposure	$10/filter
Shipping (Denver, Colo., to Dayton, Ohio).	$26
Positive transparency from negative (200 ft).	$250
Minimum cost for a one-day job (approximately 5 hours flying) and one roll of film. Assumes exposures known and no transit costs.	$2336

PHOTOGRAPHIC DATA ANALYSIS

The objective of the research reported in this paper was to evaluate multiband photography for rock discrimination. Therefore, even though the numerical analysis indicates that the essential first step of designing a "best" multiband configurations cannot be made, it is necessary (1) to test this conclusion subjectively, (2) to answer questions concerning the subjective significance of differences in contrast ratios, and (3) to determine if some other filter-selection procedure might allow users to use multiband photography successfully. The reason that these questions have to be answered from the analysis of aerial photography is that the numerical analysis assumes several simplifications; therefore, the conclusions need to be tested under actual working conditions. This discussion will consist of two parts, (1) a discussion of the aerial multiband photography and of the methods of using this photography and (2) a subjective evaluation of the results. Table 9 is a tabulation of the multiband configurations tested.

CAV DISPLAYS

There are three classes of film/filter configurations and several viewing methods that were considered during this research. The three classes are (1) the Standard Configuration, (2) the U.S. Geological Survey Configuration, and (3) the Designed Configurations, defined in Table 9. The

Table 9 Configurations of filters evaluated. See Fig. 3 for the passbands of these filters. The meaning of "Displays Produced" is discussed in the text.

Configuration Name	Films and Filters Used	Displays Produced
1. U.S. Geological Survey	Panchromatic 12 or 15	Black and white, MAC
2. Standard	Black and White IR, 47B,57,25, and 88A	Color, CIR, MAC
3. Phantom Canyon Design	Black and White IR 57,22,92, and 70	MAC
4. Gorge Hills-Florence SE Design	Black and White IR 47B,8,25, and 87	MAC
5. Contrast-ratio test	Black and White IR 8,15,70 and 92	To test the significance of predicted contrast-ratio difference

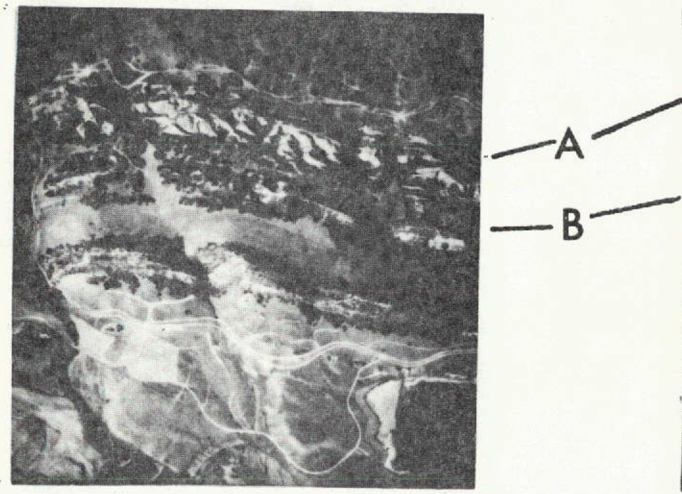
viewing methods are the various types of displays that can be produced from a film/filter configuration with a color additive viewer.

The Contrast ratio Test Configuration, number 5 in Table 9, was designed to test the question of the predicted differences in contrast ratios. Table 10 summarizes the data used and the predicted contrast for the Fountain and Lyons formations at the Kassler Test Site. See Figure 12 for examples of the resultant photography. Using the numerical analysis procedure described previously, the 8 and 15 filters are statistically better than the 70 and 92 filters; however it is not statistically possible to say which of the 8 or 15 is best nor which of the 70 or 92 is worse.

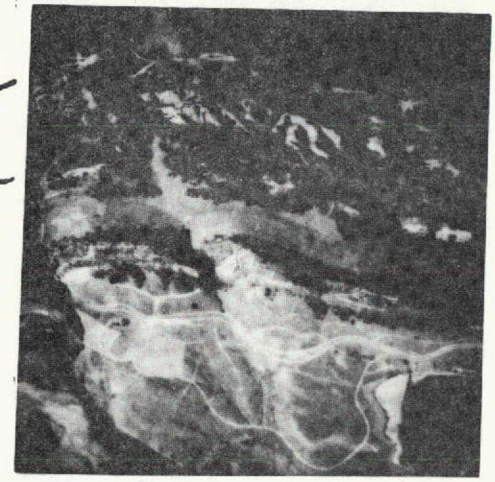
Table 10 Reflectance data and predictions concerning contrast of the Fountain and Lyons formations. Data are from the Kassler site and include 12 and 16 measurements, respectively.

	Mean Band Reflectance		Contrast Ratio			
Filter	Fountain Fm.	Lyons Fm.	Mean	Min.	Max.	Predicted Contrast
8	11.9	24.6	2.06	1.72	2.42	Good
15	11.8	23.8	2.02	1.75	2.31	Good
92	24.7	25.9	1.05	1.00	1.47	Poor
70	31.5	29.5	1.07	1.00	1.13	Poor

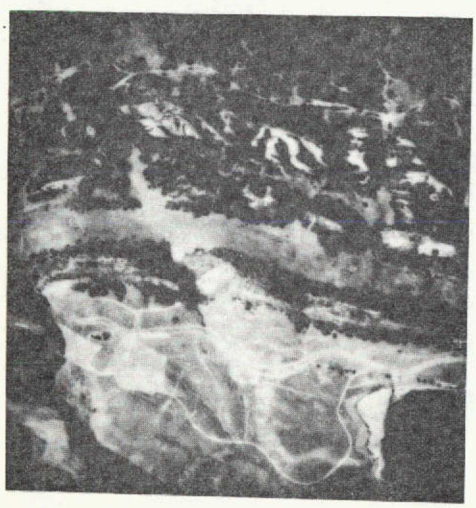
The use of the I^2S Mini-Addcol color additive viewer (CAV) to produce color and color infrared displays is defined in Table 11. The final procedure, the manipulated additive color displays (MAC displays), is also defined in Table 11. The term MAC display is used for any display other than color and CIR displays. A more detailed discussion of viewing methods and enhancement procedures is available in Raines (1974).



Wratten 8



Wratten 15



Wratten 92

Figure 12: Examples of the aerial multiband photography using the Contrast Ratio Test Configuration. The outcrop areas of the Fountain Formation (A) and the Lyons Formation (B) are noted in the margins of the photographs.

Table 11 Definition of Color, CIR, and MAC displays produce on the color additive viewer.

Display Name	Filter-Coding
Color Display	47B - blue, 57 - green, 25 - red
CIR Display	57 - blue, 25 - green, 88A - red
MAC Display	Any other coding method, including photographic manipulation of the original photography before coding.

EVALUATION OF AERIAL MULTIBAND PHOTOGRAPHY

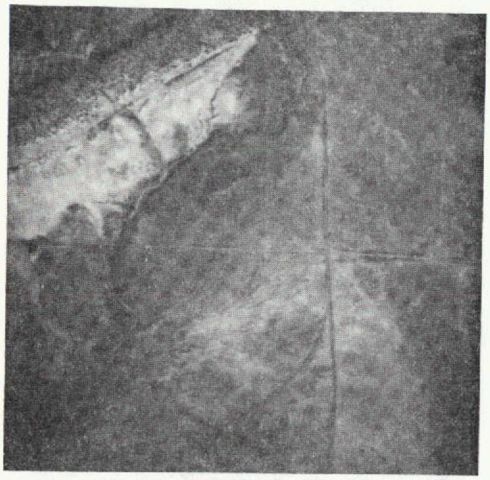
From the previous section it is obvious that numerous viewing methods can be used with multiband photography. A subjective analysis of the Contrast Ratio Test Designed Configuration and the individual photographs will be discussed. A more detailed discussion is available in Raines (1974). The conclusions to be presented are (1) the differences in contrast ratios between all the filters considered are not significant and (2) the spectral information in different bands is not advantageous.

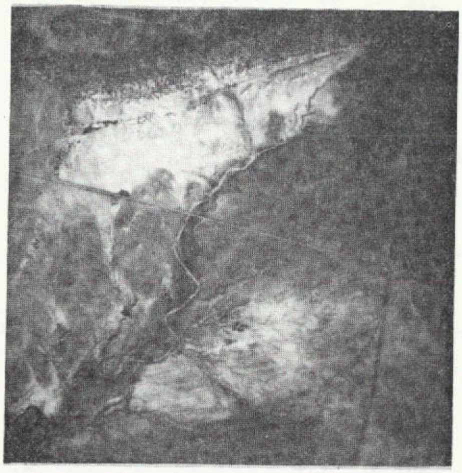
Fig. 12 shows aerial photography obtained with the Contrast Ratio Test Designed Configuration. It was predicted (see Table 10) that the 8 and 15 bands should be better than the 70 and 92 bands. From subjective visual evaluation of the original photography and from video-density-slicing techniques, it is concluded that there are not significant contrast differences between these four spectral bands. Therefore, even for differences in contrast ratios as large as 1.00 (from Table 13), improvement in contrast does not result. Thus, the typical difference in contrast ratio of 0.2 is not a significant difference and a difference of contrast ratios larger than 1.0 is probably necessary for significant improvement.

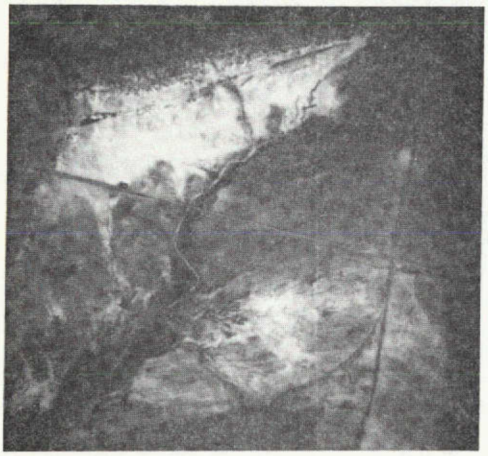
By comparing the photographs in Figs. 12 and 13 it can be seen that with regard to formation discrimination, all bands are essentially the same. To test if differences existed that were below the eye's threshold of detection, the contrast of these scenes was greatly increased by copying these photographs onto high-contrast film. In all cases we concluded that the photographs were still essentially the same with regards to formation discrimination.

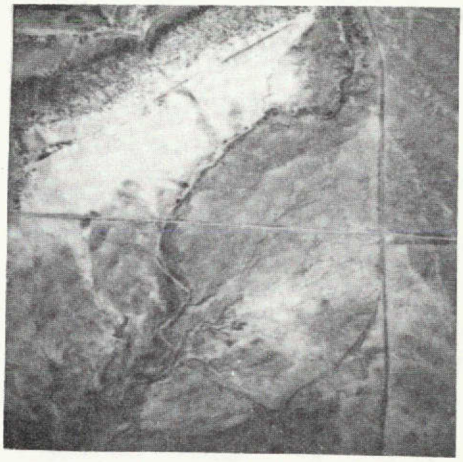
CONCLUSIONS

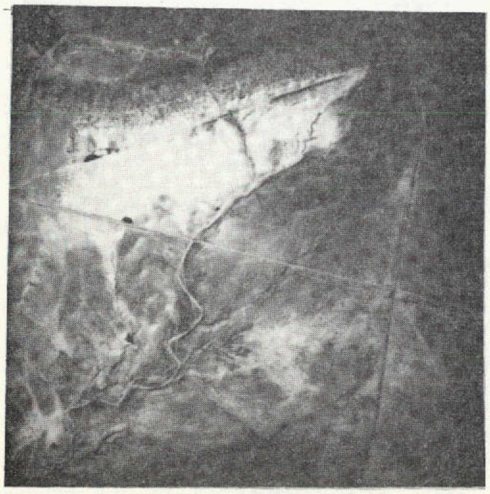
What is the value of designed multiband photography?

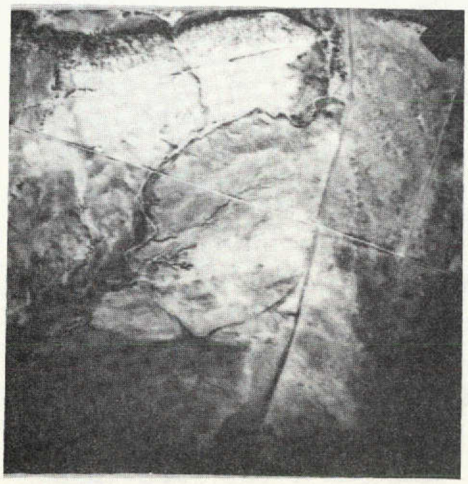

Wratten 12

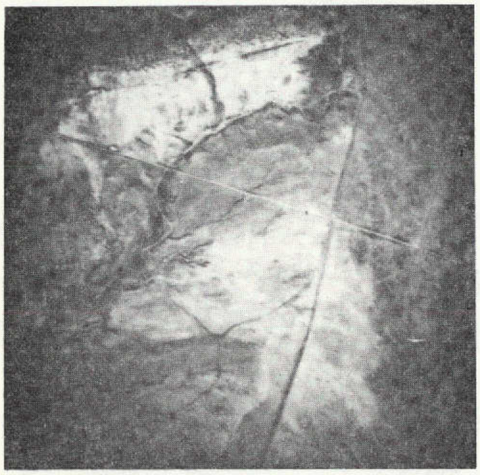

Wratten 47B


Wratten 57


Wratten 25


Wratten 88A


Wratten 22



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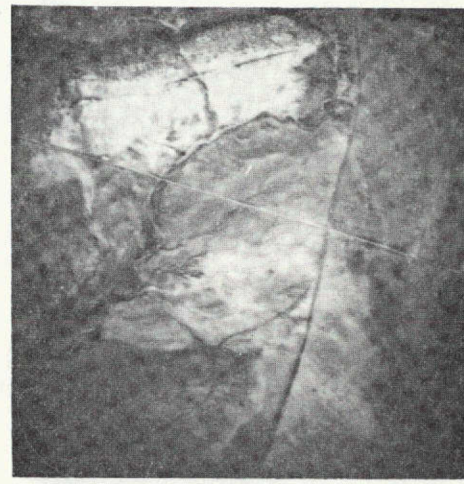
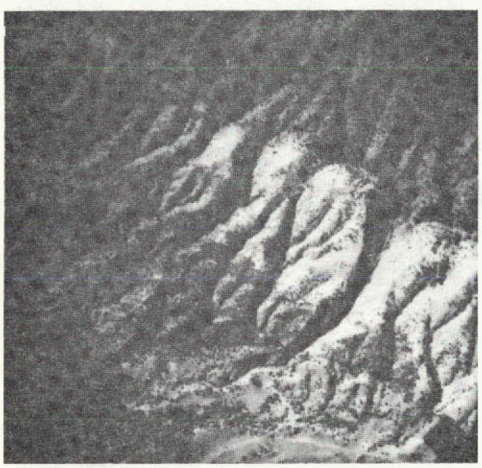
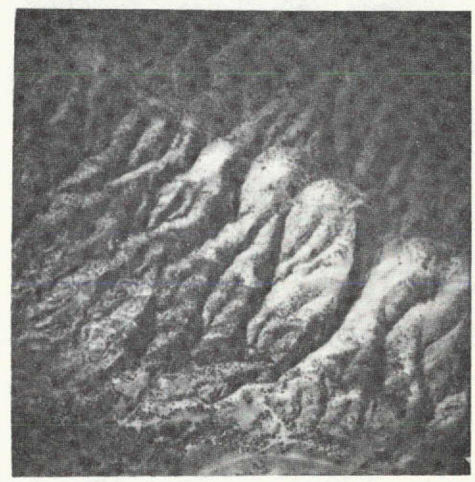


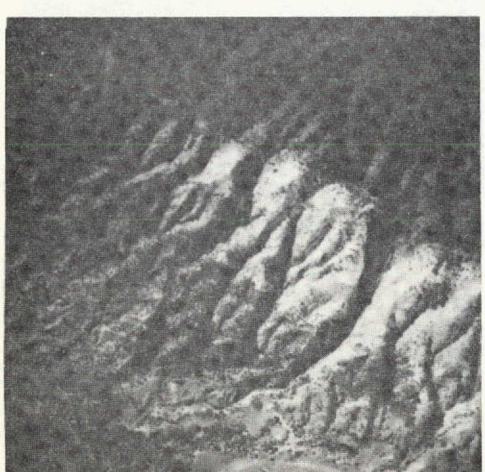
Wratten 70



Wratten 22



Wratten 70



Wratten 92

Figure 13 Examples of the aerial multiband photography that was evaluated. The filters used (Fig. 3) are as noted below each photograph.

For rock discrimination it is not statistically possible to select a set of best bands in a practical manner from _in situ_ rock reflectance measurements. The reason is that natural variation of formation band reflectance is large, and the differences in the contrast ratios for the bands considered are too small. Therefore, useful information cannot be obtained from practically-obtainable, _in situ_ reflectance measurements. Thus, multiband photography cannot be practically designed in the manner proposed.

However, equally good tonal rock discrimination can be obtained from any band. Therefore, the major significant difference in those rock reflectances observed is a relative reflectance difference that is fairly uniform throughout the photographic spectrum.

Thus, in conclusion, because of the difficulty in obtaining stereo pairs from the CAV, the registration problem, the increased problems of data acquisition, the time involved in data manipulation, and the lack of significant contrast, the designed multiband photography concept for rock discrimination, where rocks and soils are observed, is not a practical method of improving sedimentary rock discrimination capabilities. Concerning the general applicability of these conclusions, the formations considered have not been selected in a statistical manner that would allow statistical inferences to be made about all rocks, or even all sedimentary rocks. However, there is no geologic reason to suspect that the rocks and formations considered have unique reflectance properties with regard to other sedimentary rocks.

From these conclusions come numerous implications. It is implied that there is equal information in the U.S. Geological Survey Configuration and the Standard Configuration. Both the numerical and the subjective photographic analysis support this implication. Some researchers have proposed that two formations having the same or very similar Munsell color may have differences in band reflectance that can be used. Apparently, this is not significant, since the numerical data suggest that color differences are associated with band reflectance differences. See Table 12 for examples of this. Therefore, from the standpoint of information content, the generalization that all bands have equal information content is valid as a first approximation.

However, when very subtle color discriminations are desired, we believe that the Standard Configuration provides some additional information in comparison with all other types of photography. This conclusion is drawn only because (1) it is easier to make subtle personally-useful color changes with the CAV if stereo pairs are not required, (2) it is easier to make MAC displays from black and white photographs than from color photographs, (3) band reflectance data do not supply a rationale for designing a Designed Configuration, and (4) colors similar to true color provide a psychological interpretation advantage.

Table 12 Formation colors. See Fig. 4 for the band reflectances for these formations.

Formation	Munsell Color
Lower Tepee	Light dusky yellow (5Y 6/2)
Rusty	Pale yellowish brown (10YR 5/3)
Smoky Hill Shale	Moderate yellowish orange (10YR 6/4)
Fountain Fm.	Dark reddish brown (10R 3/4)
Fremont Fm.	Pale red (10R 6/2)
Harding Ss.	Moderate reddish brown (10R 5/4)
Precambrian	Grayish red to pink (5R var.)

It was not the purpose of this research to make a comparison of multiband photography with color and color infrared photography. However, from our experience, we have come to several personal conclusions. For a general sedimentary rock mapping problem where aerial photography is not available the best procedure is to use color or color infrared films. This is not because there is more information in the color or color infrared photographs, but because the information is in a more interpretable form so more information will be obtained in a shorter time.

RECOMMENDATIONS FOR FURTHER RESEARCH

Because of the conclusions reached in this research, there are only a few recommendations for further research that are warranted. Concerning the evaluation of the multiband concept for rock discrimination, there are three avenues that might be followed. The first would be to investigate rock reflectance properties in igneous and metamorphic environments. Two factors might allow for more success in these environments: (1) the natural variation might be significantly less, or (2) the differences in contrast ratios might be larger. From limited work in an area of altered volcanic rocks near Ophir, Colorado, it was found that the natural variation, sample variance, was as large as those observed for sedimentary rocks. Due to weather problems, the question of larger differences in contrast ratios could not be investigated.

A second avenue of investigation that might be worthwhile would be to use a multichannel scanner, which is capable of narrower band widths and has higher radiometric resolution than photographic systems (Kenneth Watson, 1973, personal communication). With this approach a resolution cell could be treated as a sample, and sufficient samples could be acquired to satisfy the sample size requirements. In addition, all channels are acquired at once: therefore, field spectral reflectance measurements would not be required. Then with purely numerical data, numerous statistical techniques could be applied to select the best spectral bands, and signal-stretching and ratioing techniques could be used for enhancement. This second avenue assumes that the conclusions from the research reported here are only good as a first approximation. That is, for the radiometric accuracy of photographic systems (the first approximation) the rock reflectance differences are essentially constant relative differences; however, for a more radiometrically-accurate system, such as a multichannel scanner, there might be second-order differences that can be used advantageously.

A third avenue approaches the rock discrimination problem differently. Instead of observing soils and rocks to discriminate those rocks, the vegetation growing in and on those soils and rocks is observed. The justification for this approach is that at the Phantom Canyon Subsite the Pierre Shale had easily mappable lithologic zones that could be mapped on the ground using shrubs alone. Furthermore, the Paleozoic section could be readily differentiated on the basis of timber density on aerial photography. Lithologic, and possibly geochemical, information might be available through this approach.

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