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ACTIVE SEISMIC RECONNAISSANCE OF THE
MT. PRINCETON AREA
BUENA VISTA, COLORADO

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Active Seismic Reconnaissance of the

Mt. Princeton Area

Buena Vista, Colorado

ABSTRACT

During October 20th through October 24th, 1975, a reconnaissance active seismic survey was conducted utilizing large mining blasts near Buena Vista, Colorado. The results indicate that a high velocity ridge, striking east-west, exists in the subsurface in Chalk Creek, south of Buena Vista. The results also suggest a low velocity zone directly north of Chalk Creek. This survey demonstrates that a modified version of the active seismic reconnaissance technique could be a very cost-effective means of surveying the velocity and structural character of a large area.

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INTRODUCTION

During October 20th through October 24th, 1975, an active seismic survey was conducted near Buena Vista, Colorado in the upper Arkansas Valley (see location map Figure 1). The survey objective was to aid in the evaluation of the geothermal potential of the area.

Structural and velocity information that an active seismic survey can supply have become increasingly important in the integrated geologic and geophysical interpretation. A cost effective means of seismically surveying a large area can be affected by utilizing any natural seismic events or man-made events such as large mine shots. The purpose of this survey was to monitor any seismic event on a multi-station seismic array and then use the recorded seismic signals to describe the structural and velocity character of the area. A secondary purpose was to demonstrate, study and optimize this reconnaissance method for the particular needs of geothermal prospecting.

The geologic description of the upper Arkansas Valley is summarized below. The upper Arkansas River Valley is a narrow, north-trending down-dropped trough of mid-Tertiary age. It is bounded in the east by highlands composed of Pre-Cambrian gneisses overlain by Tertiary volcanic flows and pryoclastic rocks. The

LOCATION MAP

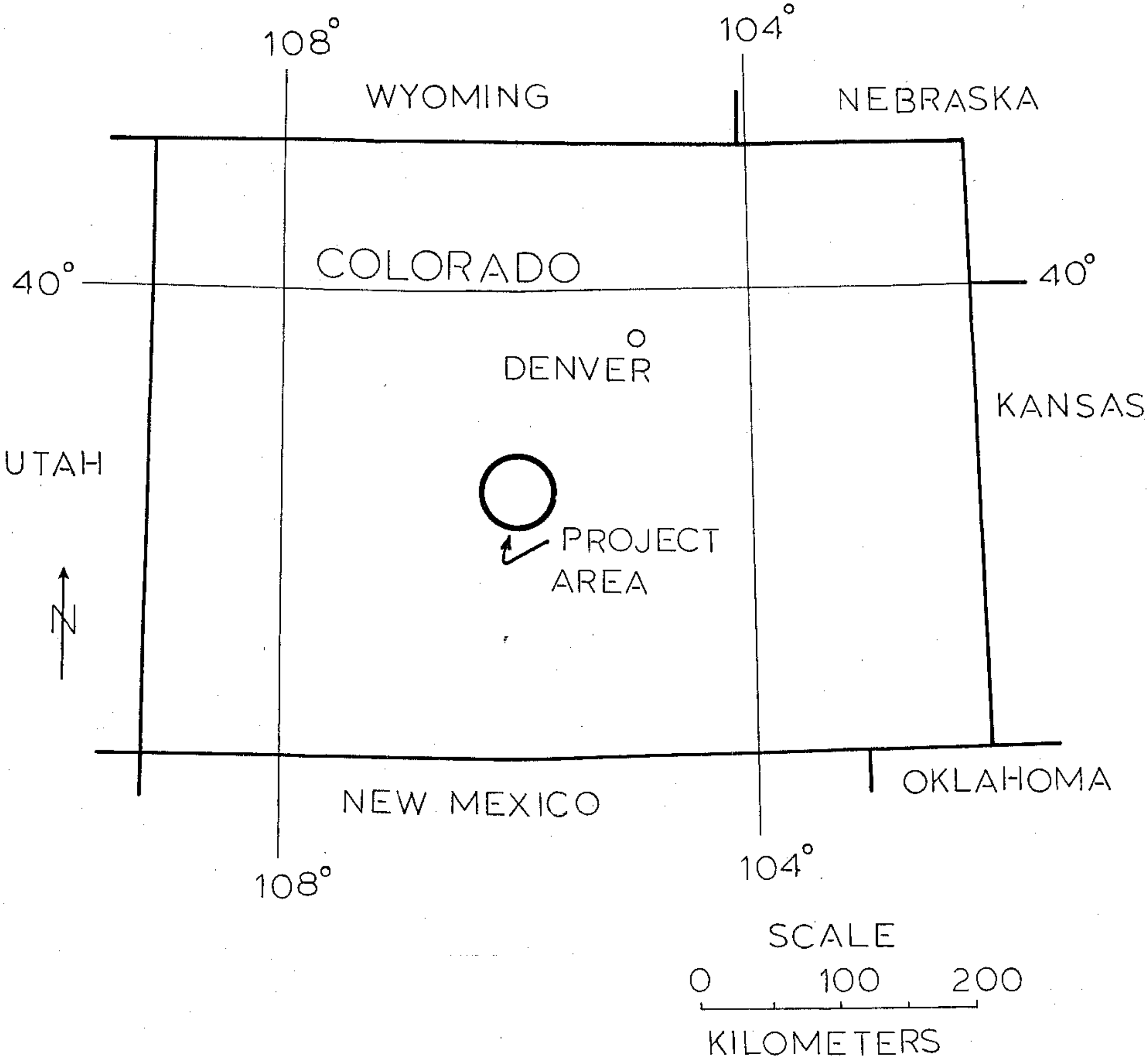


Figure 1

valley is bounded on the west by the quartz-diorite Precambrian batholiths and the lower Tertiary quartz-monsonite batholith of Mount Princeton of the Collegiate Range. The sediments in the Arkansas Valley are river deposits of the Dry Union Formation of Miocene and Pliocene age and glacial deposits of Quaternary age.

The following report includes sections on Field Operations, Observations, Interpretations followed by Conclusions and Recommendations.

OPERATIONS

The survey was designed to take advantage of existing sources of seismic energy. These include the mining blasts at Climax, Colorado, directly north of the prospect area approximately 40 km, the Questa mines at Questa, New Mexico, directly south 275 km and the Monarch Pass limestone quarry, south 30° west at a distance of 25 km. Approximate times of blasting to aid in the identification of sources, were obtained by directly contacting the operators of the mines. Ed Torrgeson of Amax, Inc. and Cal Brown of Climax were most responsive to requests for information.

Each station for this seismic survey consisted of a smoked drum MEQ-800-B microearthquake system. These seismographs are capable of recording time of arrivals with uncertainties in timing of less than $\pm$ 30 ms. The essential independence of each station makes these instruments extremely versatile with respect to location and ideal for use in a reconnaissance large-scale active-seismic survey. The details of the instrumentation are discussed in the appendix.

Because the sources are north and south of the survey area the stations were deployed in roughly N-S lines to allow an interpretation of the results as an in-line, conventional seismic-refraction profile. Line A was established October 21st in the valley and after a full day of recording the stations were moved westward to the mountain front to establish Line B (see Figure 2). Three stations were common to Line A and Line B and acted as ties between these lines.

Figure 2 shows the station locations and Table 1 lists their coordinates. Plate 1 also shows the station locations. A summary of the field operation follows:

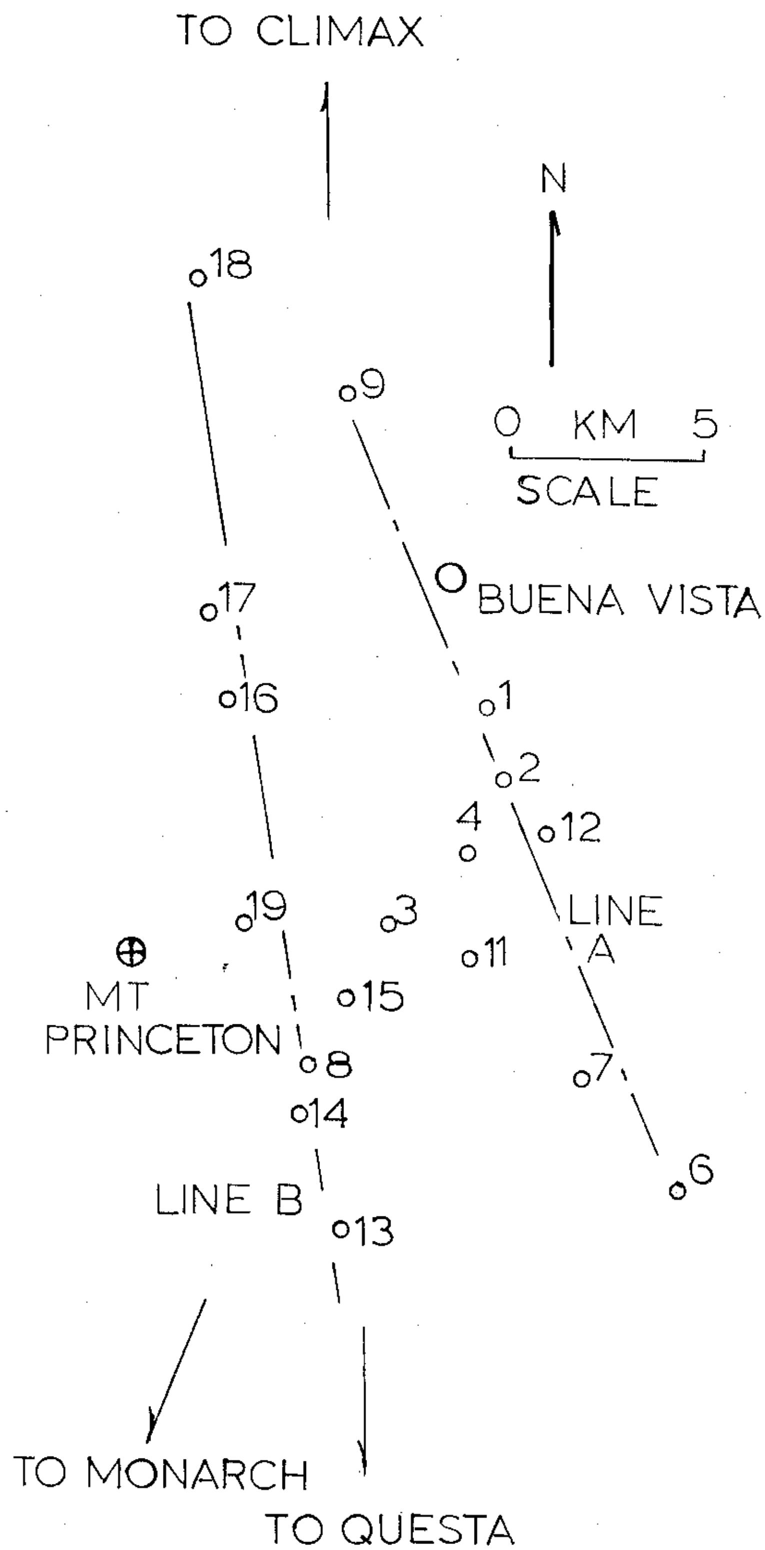
<u>October 20th</u> - Arrived in Buena Vista, set up two stations to monitor Climax shot as calibration, then set up three more stations.

<u>October 21st</u> - Set up five more stations to complete Line A, relocated two stations for better geometry.

<u>October 22nd</u> - Relocated seven stations to establish Line B, Stations #3, #8, #11 left as ties for all further shots.

<u>October 23rd</u> - Relocated station fourteen for better gain. Station nineteen removed due to operation problems with snow.

<u>October 24th</u> - Equipment pick up and return to Golden.



Station Location Map

Figure 2

Table 1

Station Location

Station #	X	Y	Z	Line Geometry	Distance From Climax
1	+11.8	+6.7	+0.2	A	61.4
2	+11.2	+4.6	+0.2	A	63.5
3	+14.3	+0.8	+0.0	Base	67.2
4	+12.2	+2.6	+0.1	A	65.4
5	+12.7	-0.2	+0.1	A	68.2
6	+ 6.7	-6.3	+0.2	A	74.7
7	+ 9.2	-3.3	-0.2	A	71.5
8	+16.4	-2.8	-0.1	B	70.8
9	+15.4	+14.6	+0.1	A	53.4
10	+13.7	+12.2	+0.1	A	55.8
11	+12.2	-0.2	+0.1	A	68.2
12	+10.1	+3.1	+0.2	A	65.0
13	+15.6	-7.3	-0.3	B	75.3
14	+16.6	-4.1	+0.0	B	72.1
15	+15.5	-1.3	-0.1	B	69.3
16	+18.5	+6.6	+0.0	B	61.6
17	+18.9	+9.1	-0.1	B	59.1
18	+19.3	+17.8	-0.2	B	50.5
19	+18.1	+0.9	-0.5	B	67.2
20	+17.3	-4.6	-0.1	B	72.7

Origin at 38°45'N
106°00'W

Elevation datum at 8570' (Station #3)

+X is west and +Y is north

+Z is down

Coordinates in kilometers

OBSERVATIONS

During the four days of field work, ten seismic events were recorded that were of useful quality. Three of these events were identified as teleseisms, four as near-regional events, and the remaining five events were identified as mining blasts. Four blasts were from Climax and one from Monarch Pass.

Conspicious by their absence are the events from the Questa Mine. Table 2 lists the events recorded. Times for five events from Questa were known to the record reader, but no signals were identified as occurring at those times on any records.

Figures 3 through Figure 6 represent the time-distance plots of the recorded events. Normally the travel time of an event to each station is plotted against the horizontal distance to the source. For large source-receiver distances, such as those in this survey, the distance from the stations to the source may not reflect the true travel path distances. The azimuth of arrival of a wave front near a local array may be considerably different than the actual azimuth to the source due to horizontal refractions or lateral changes in velocity. Therefore the distance plotted in the figures is the relative distance between stations as projected on the normal to the local wave front. The origin time of the events is not generally known, therefore the travel time used in the figures has an arbitrary beginning.

The line on the plots represents the expected arrival times

Table 2

Day	UTC Time	# of Stations	Type of Event
294	1210	5	USSR Teleseism
	2100	7	Climax
295	0301	5	Regional
	0521	8	Kurils teleseism
	2113	5	Climax
	2202	7	Regional
	2252	7	Climax
296	0125	5	Mexico teleseism
	2045	7	Monarch
	2355	9	Climax

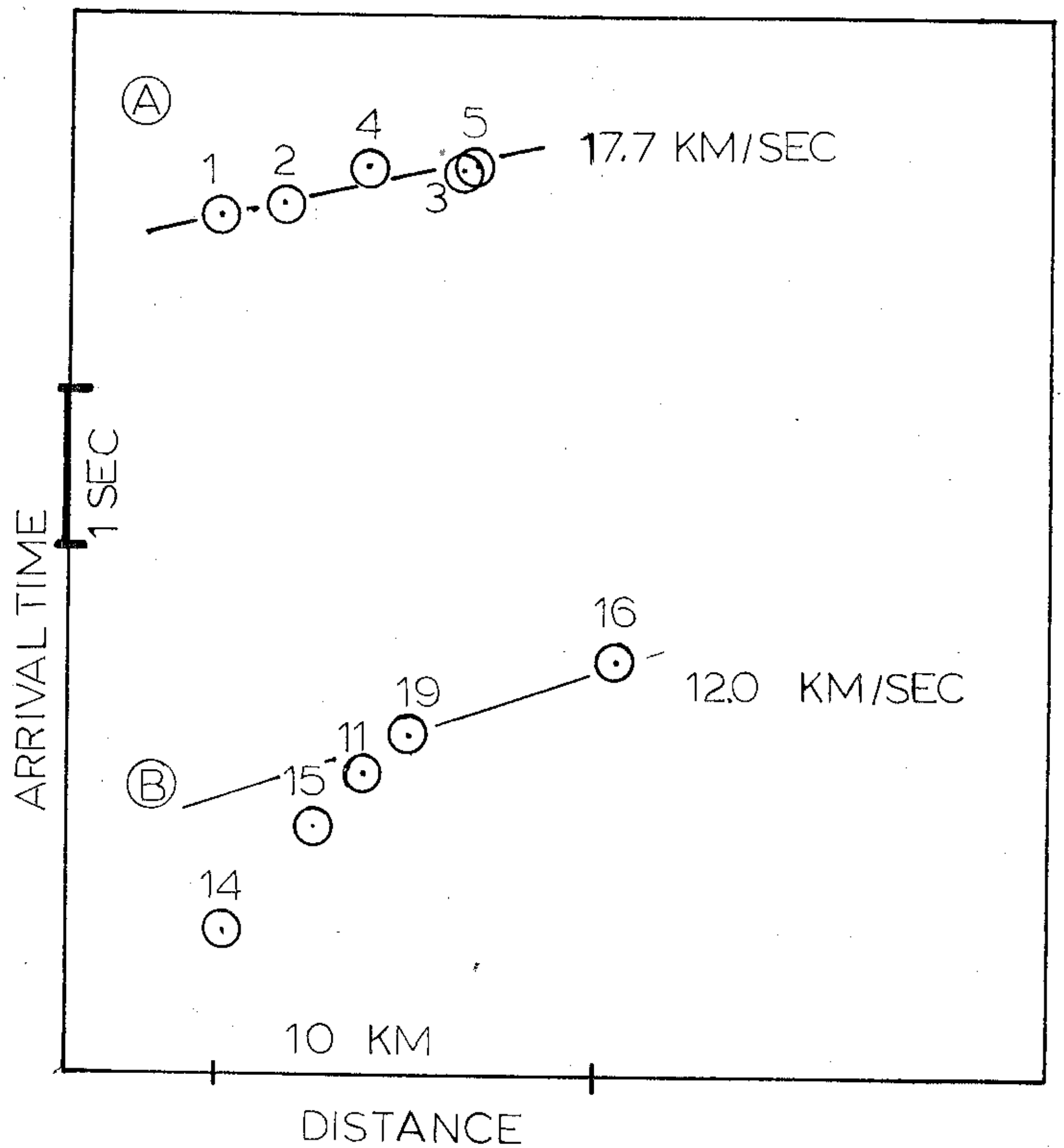


Figure 3

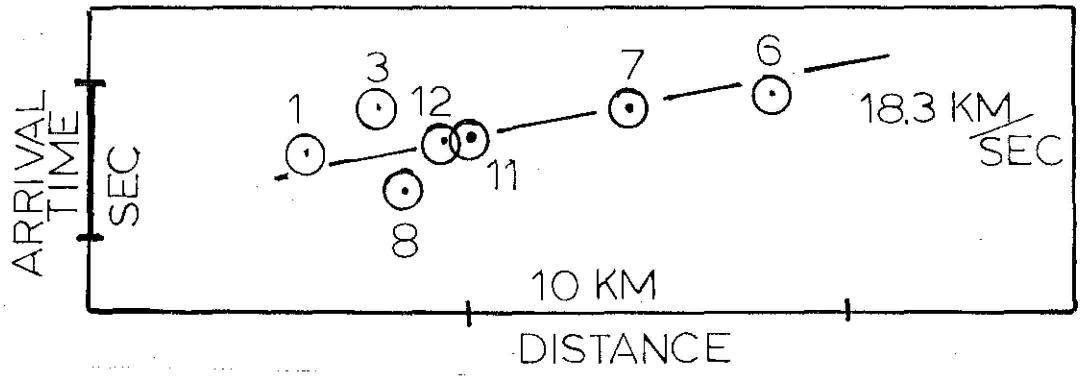
A. a) Teleseism (USSR) N5°E
Distance 7500 km azimuth 5°E
Day Time UTC

295 0521

b) 17.7 km/sec is expected phase velocity

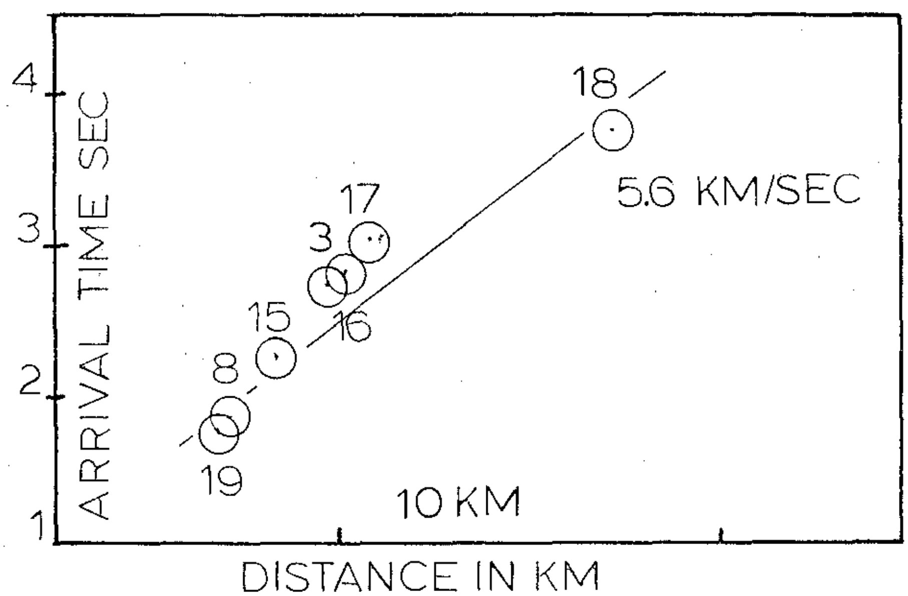
B. a) Teleseism Mexico
Distance 3100 km azimuth 02° W
Day Time
UTC
296 0125

b) 1210 km/sec is expected phase velocity



A) Teleseism Kurils Islands
Distance 7700 km
Azimuth N50°W
Day Time UTC
295 0521

B) 18.3 km/sec is expected phase velocities

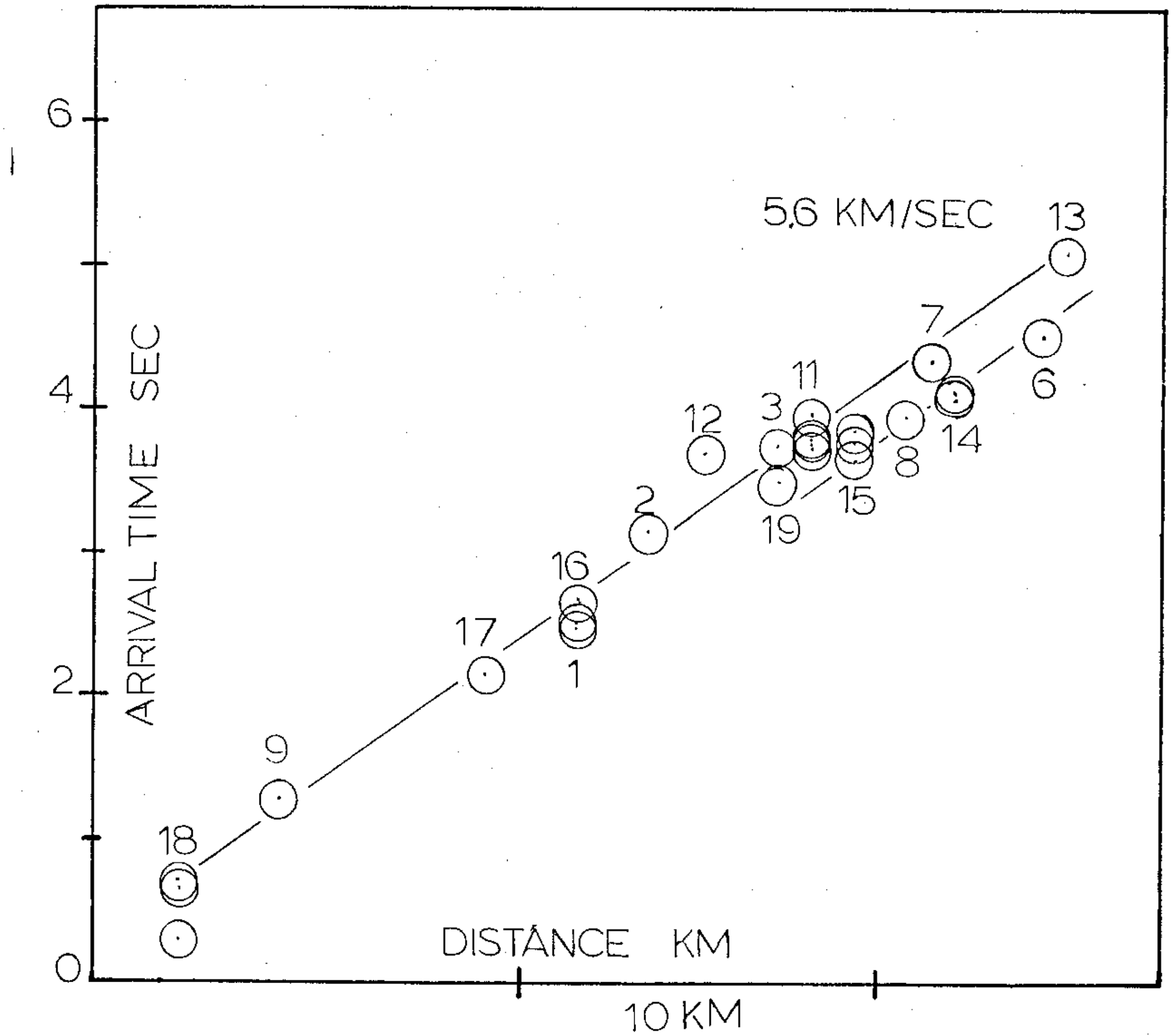


A. Monarch Pass Event
Distance 30 km
Day Time
UTC
296 2045

B. 5.6 is expected phase velocity

C. Apparent azimuth S 50°W
True azimuth S 30° W

Figure 4



A. Climax Shots
Distance 60 km

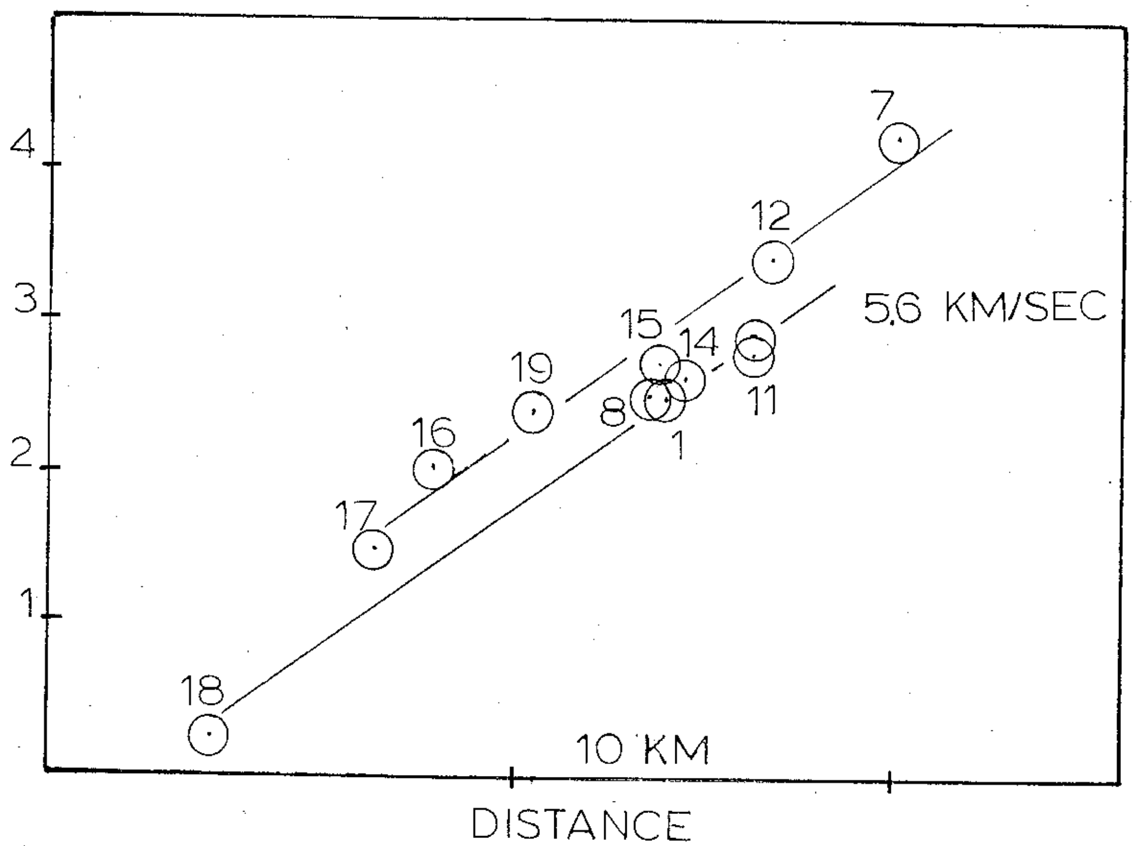
Day	UTC Time
294	2100
295	2113
295	2252
296	2355

B. Data from four similar events were combined by assuming that relative timing difference between stations remained constant.

C. 5.6 km/sec is the expected phase velocity from Climax.

D. Apparent azimuth N 20° E
True azimuth N

Figure 5



A. Events from N 65° W Near Regionals
Distance 180 km
Day UTC
Time
295 0301
295 2202

B. Data from two similar events were combined by assuming that relative timing difference between station remained constant.

C. 5.6 km was expected phase velocity

D. Apparent azimuth N 65° W

Figure 6

assuming the normal J-B travel time curves. Therefore the data base for interpretation produced from these plots are the time residuals from a normal crustal model and comparisons of the apparent azimuths of the shots with true azimuths. The uncertainties of the estimated first arrival times is illustrated in Figure 5. Stations 18, 16, 11, 14 and 15 have multiple picks presumably from sources in the same place. Therefore these relative differences should be an estimate of the uncertainties. This value is determined to be $\pm$ 100 ms.

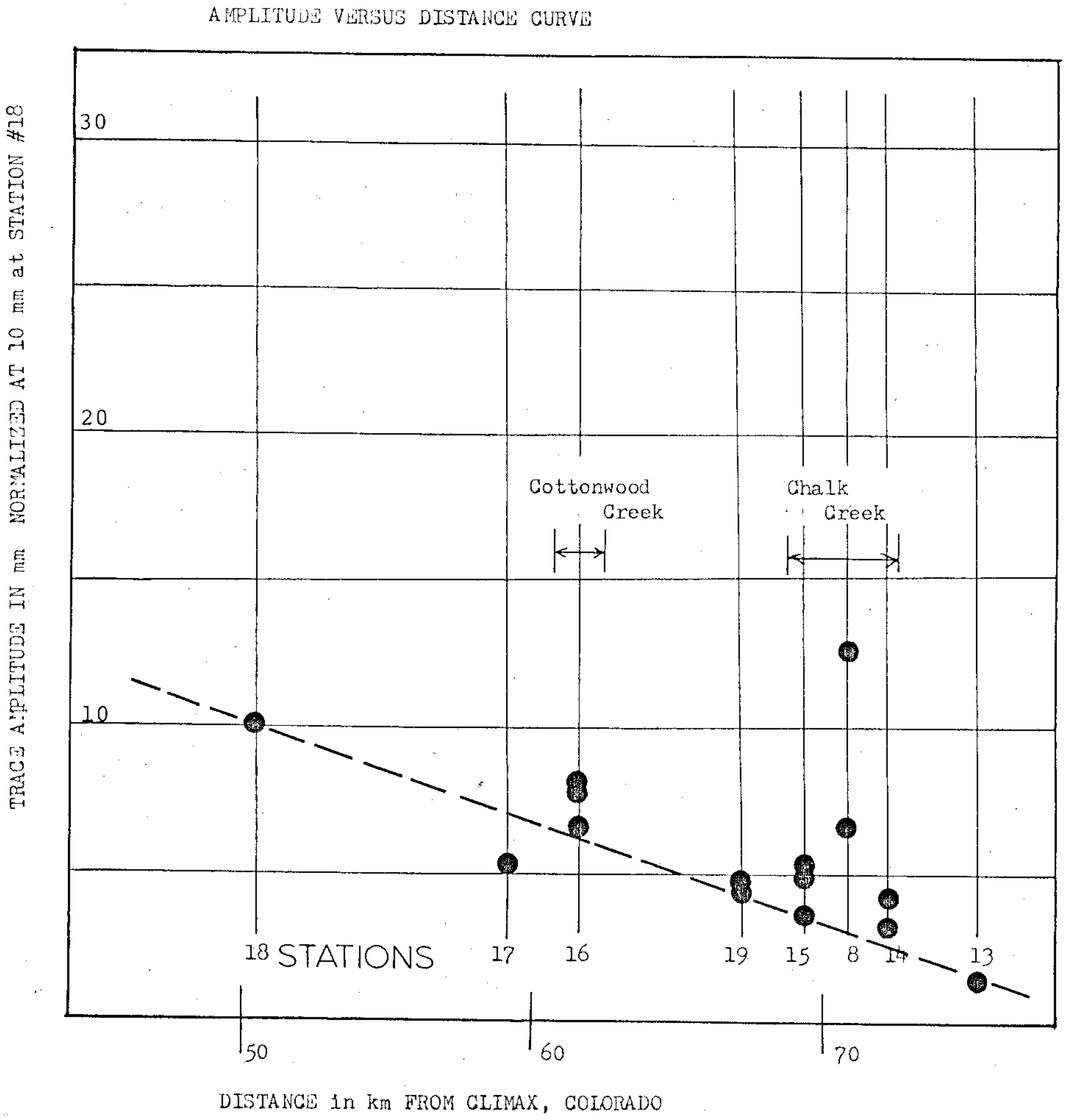
The results of each plot are discussed below. Figure 3 shows two teleseisms plotted with their respective expected phase velocities. The residuals in Figure 3b are largest for station 14 and 15. The residual at station 14 is 6-700ms and at station 15 more than 250ms. These stations represent "fast times" with respect to the other stations. The other residuals are not considered significant.

The Kuril Islands events in Figure 4 shows significant residuals for stations 3 and 8. Station 3 is "slow" by about 300ms and Station 8 is "fast" by more than 200 ms. These residuals are differences of the observations from a least-squares fit of the expected phase velocity for the events. Figure 4 also shows the Monarch Pass event with stations 3, 17 and 16 slow by more than 200ms with respect to station 19, 8, 15 and 18.

Figure 5 is a composite time distance plot of 4 events from Climax. These events were combined assuming that the relative station time differences remain constant with sources at similar locations. The stations that were common to many of the shots from Climax are station 18, 11 and 15. Again these data can be used to estimate that the uncertainties in the observed arrival times are less than ± 100ms. Figure 5 shows that stations 15, 8, 14, 1 and 6 and possibly 18 are fast with respect to the other stations with station 12 significantly slow.

The last time distance curve Figure 6 is also a combination of two events with similar sources. The source is approximately 180 km distance at N 65^{O} W from the survey area. It is not known whether these events are natural events or large mine shots in the coal mining area of northwestern Colorado. Figure 6 shows that stations 18, 8, 1, 14, 11 and possibly 15 are fast with respect to stations 17, 16, 19, 12 and 7.

Figure 7 is a plot of the amplitudes of the seismic signals from Climax at several stations of Line B along the western mountain front. The amplitudes are normalized at station 18 and 7. Therefore the rest of the station amplitudes are relative to station 18. The line through the data is an approximation to an expected exponetial-amplitude decay with distance or expected attenuation curve. Station 8 in the plot shows the largest residual amplitudes. An estimate of the dominant frequency at each station was made by a simple measurement of a few cycles of the wave form of the first arrivals. The signals at station 8 were higher in frequency than those observed at the other stations. The attenuation and dominant frequency analysis was restricted to the Climax shots due to the fact that the other seismic signals did not produce the necessary redundancy in the data to do an effective analysis.



Amplitude with distance

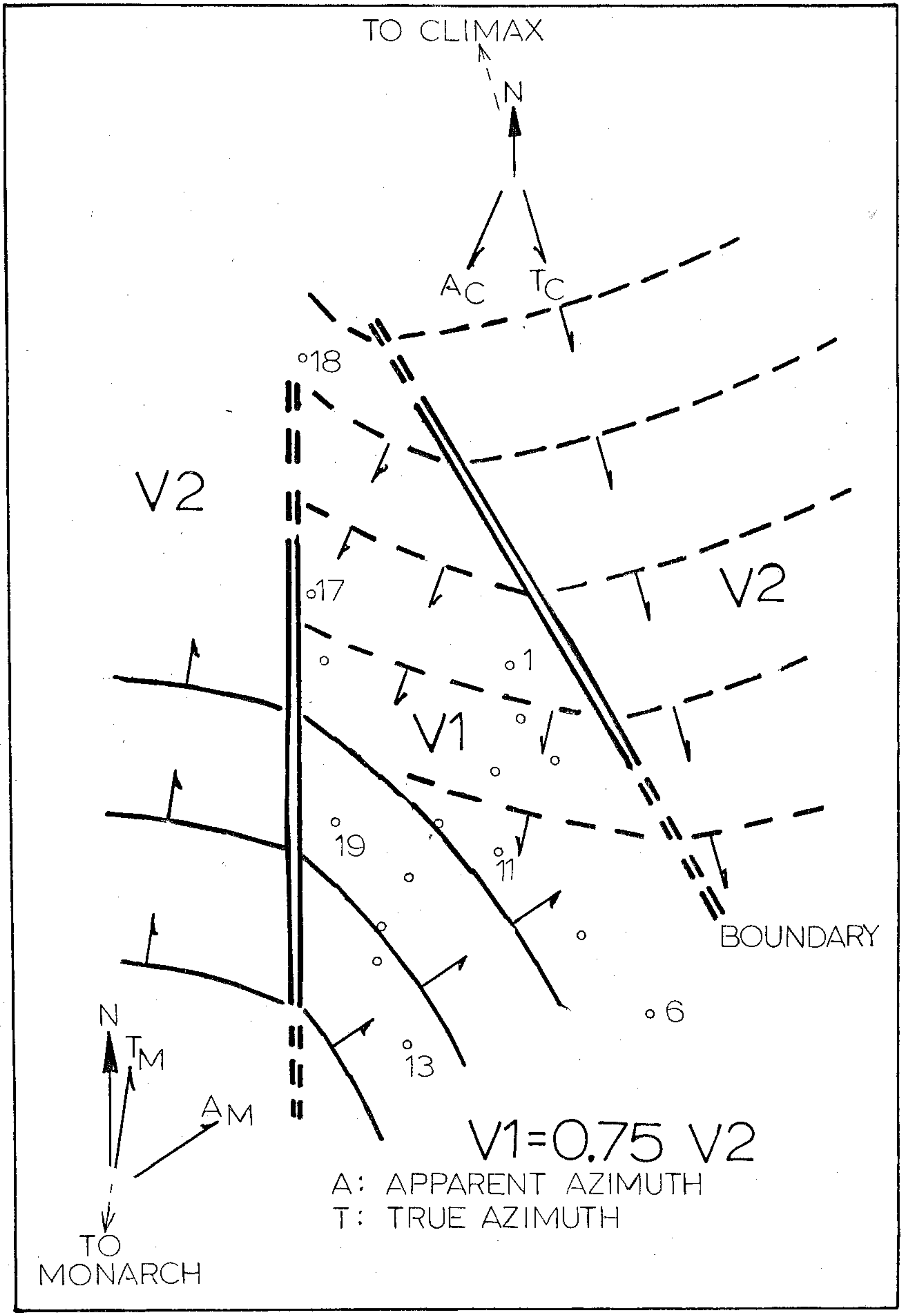
Figure 7

INTERPRETATION

The data to be interpreted includes the P-wave travel time residuals, the attenuation observation and the differences in apparent wave front arrival azimuths vs the azimuth to known source locations. Though the data is sparse, significant evidence of lateral velocity inhomogenity was observed

The comparison of the local apparent azimuth as recorded at the array and the known true azimuth to the source can give valuable information as to the horizontal velocity distribution between the local array and the source. The mine at Climax is north of the array, however, the Climax wave front had an apparent azimuth of N 20^{o} E. The topography of the valley suggests a velocity boundary on the east side of the valley near Buena Vista striking N 30^{o} W. If we assume a vertical boundary, then the change in wave front azimuth can be modeled by a refraction where the average velocity in the valley or to the west of the boundary is 75% of the eastern velocity. Additional data from the Monarch Pass event suggests a second boundary striking N - S on the western edge of the valley with a similar velocity contrast of 75%. An interpretative illustration of how the wave fronts are refracted is shown in Figure 8.

This interpretation, however, is not unique. A different velocity contrast would produce different strikes on the boundaries.



Interpreted wave fronts from Climax (dotted) and Monarch (solid). Stations are shown by circles

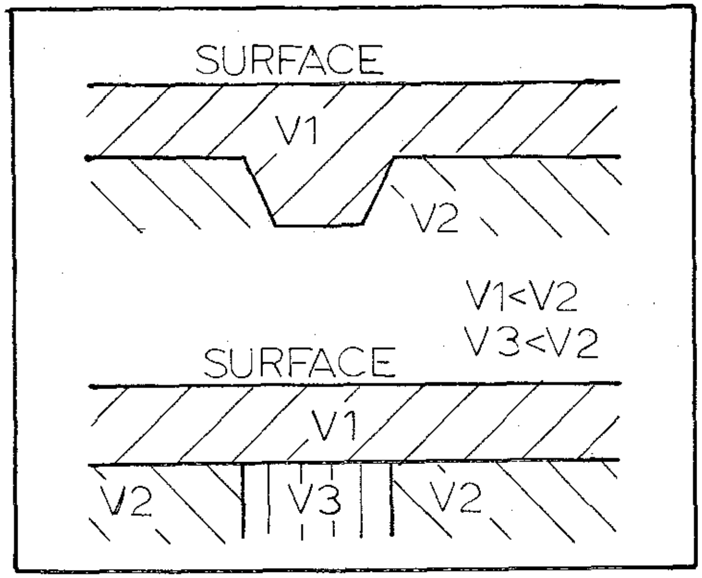
Figure 8

The placement of these boundaries is also non-unique. The boundary to the west, however, is placed with greater control than the boundary to the east. The western boundary must pass between the array and the Monarch pass quarry. The western boundary must be placed west of and within 5 km of Mount Princeton. In contrast, the boundary to the east can be placed as close to the array as Buena Vista or as far as 15 km east of the town. However, the topographic boundary just east of Buena Vista would seem to be the most likely position. The strike and locations of these boundaries were chosen to honor the probable geology of the area. These structural boundaries are illustrated in Plate 1.

Travel time residuals can result from either a velocity change along the travel path, a structural change at depth or both. Figure 9 illustrates two models that could produce similar travel time curves. The two models could not be distinguished.

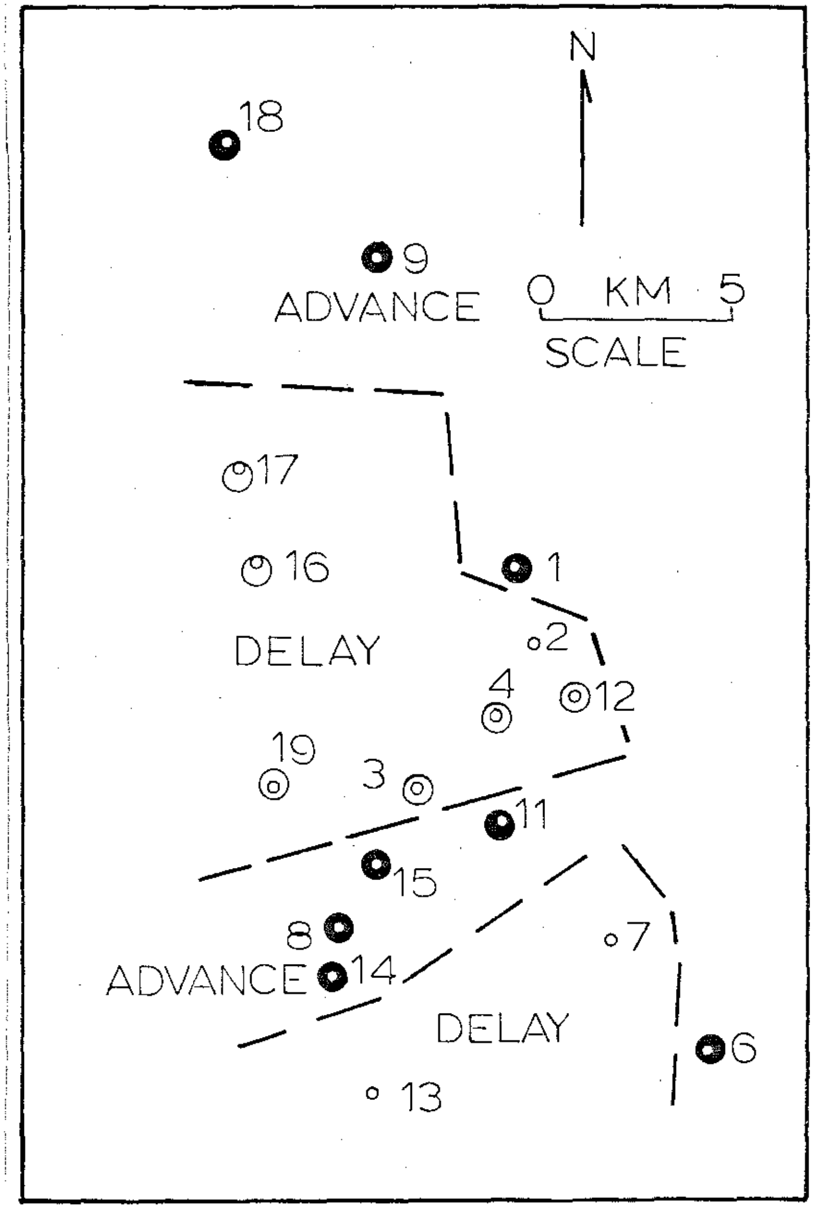
Model 1 is a fault model with the lower velocity material faulted down. This model produces delay patterns similar to those observed. The second model is a velocity variation model and produces a similar delay. Of course Model 2 is Model 1 if V3 = V1, however this does point out that lateral variations in velocity can be mistakenly interpreted as structural changes in the subsurface.

Model I



Model II

Travel time models



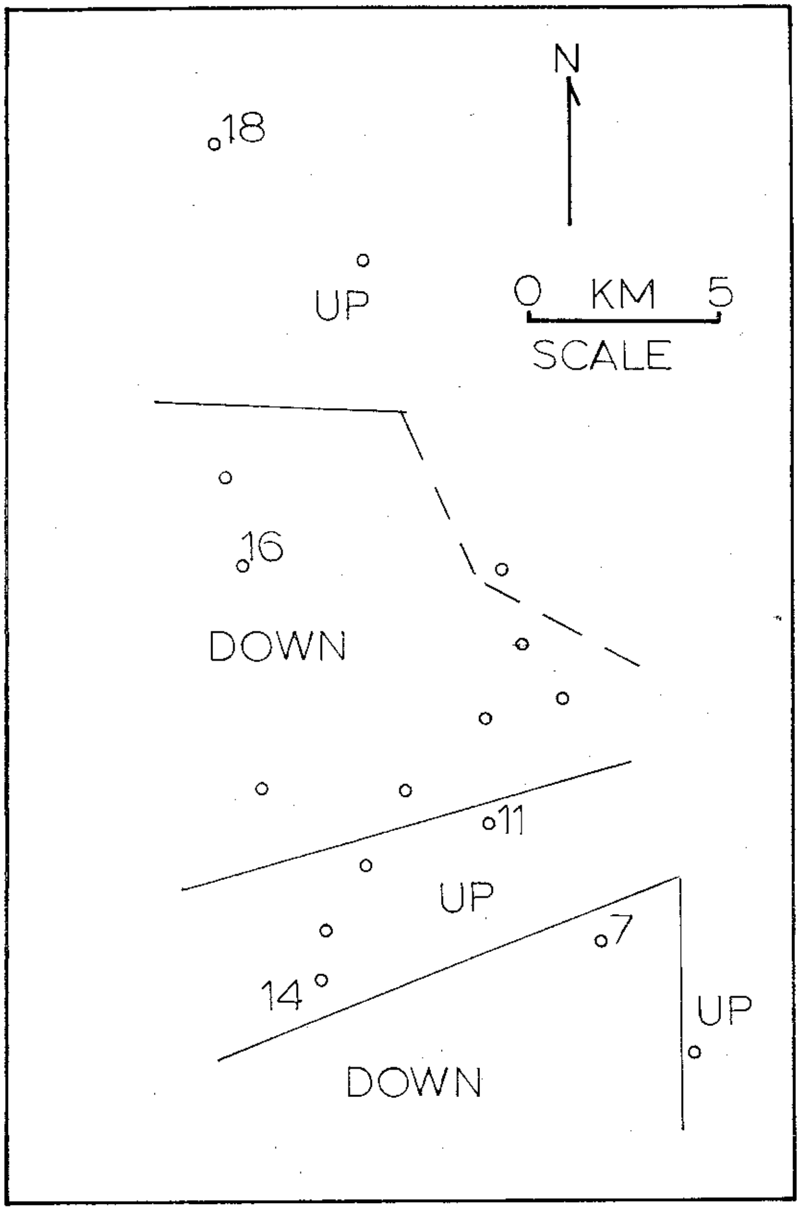
Summary of P-wave residuals

Figure 9

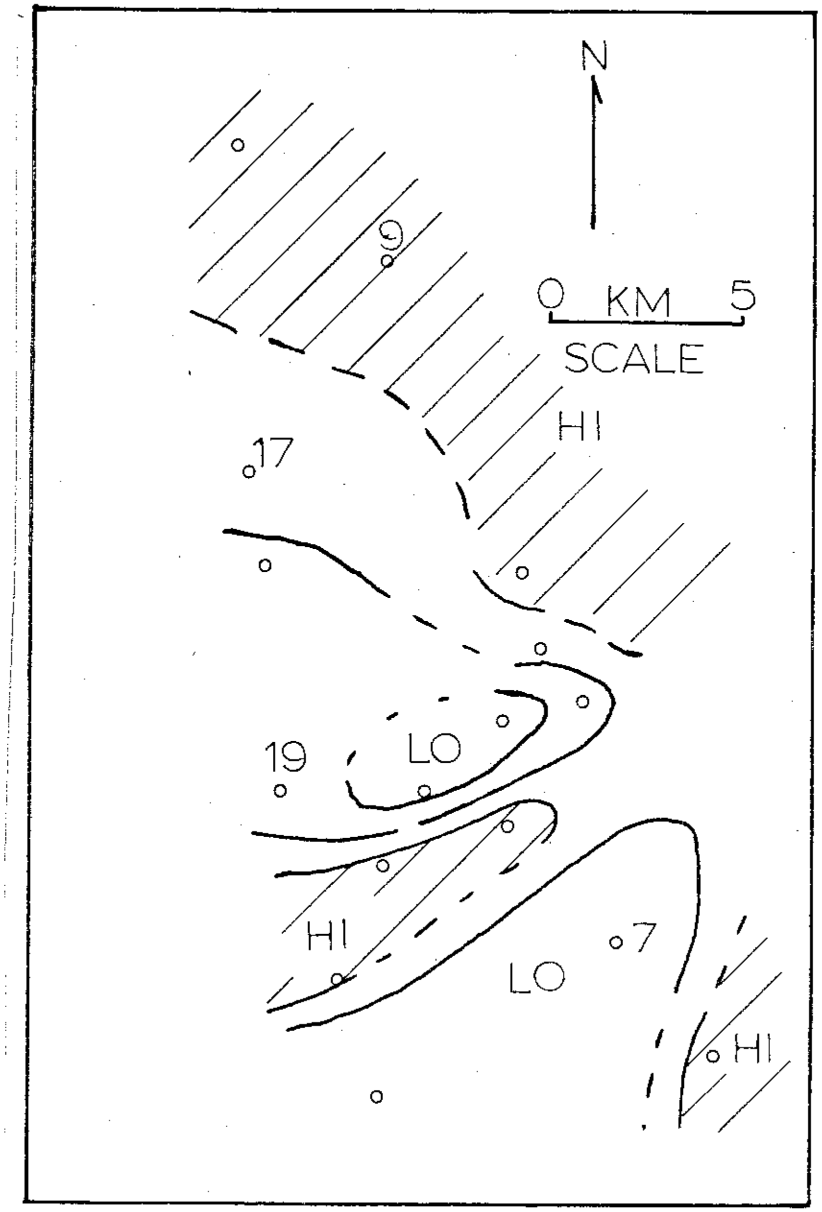
Figure 10

Shown in Figure 10 is a summary of the P-wave delay data. The small circles are stations with large open circles denoting delays and large darkened circles denoting advances. The delays and advances are with respect to the normal stations denoted by small circles (Station 2, 7, 13). Because the P-wave delay is a function of azimuth, azimuthal direction is shown by offsetting the large circles in the direction of the incident wavefront such as station 16. Station 16 showed a delay from the south and no delay or normal times for events to the north. Figure 10 is a summary and is meant to show the relative relationships between stations.

Figure 11 illustrates two interpretations of the P-wave delay data. Figure 11a is a structural interpretation. This structural model shows an upthrown ridge at Chalk Creek with a downthrown block between Cottonwood Creek and Chalk Creek. The second model, a velocity variation model, shows a high velocity ridge at Chalk Creek with a low velocity section just north of Chalk Creek. Both models are consistent with less attenuation in Chalk Creek and with the observation of a higher domenant frequency at station 8. However, an upthrown structure consisting of a thin ridge seems less appropriate than a high velocity ridge. Plate 1 illustrates the velocity variation interpretation. A high velocity ridge could be interpreted as a fault zone in Chalk Creek that has undergone a change that



Fault Model
Figure 11a



Velocity Variation Model
Figure 11b

would make the rock more dense than its surroundings. Secondary deposits could have this effect. It should be emphasized that a choice between, or even of, these models is severely speculative. However, any other geological or geophysical model of the area must be consistent with the observations in this survey.

The second part of the interpretation involves evaluating and optimizing this survey method. Several points with respect to improving this type of survey are listed below.

1. The apparent azimuths near a local array can be considerably different than actual azimuth to a known source. Therefore a better control on apparent azimuths is critical.

2. The scatter or error in the station residuals are less than ± 100 ms. This error can be attributed to near station pertabations in the geology or small changes in the source location. Therefore, better knowledge of the source location, origin time and near station geology is critical.

3. P-wave delay and attenuation are probably a function of arrival azimuth and emergence angle of the wave front. Therefore receiving data from many azimuths and emergence angles is critical.

The above difficulties can be mitigated by the following procedures.

1. Several stations should be placed outside the survey area in a permanent fashion i.e., for the duration of the survey. These stations will act as control stations for large geologic features and source identification.

2. Several stations inside the array should be permanent i.e., they should not be moved for the duration of the survey. These stations will act as local control on arrival azimuth and tie points for the roaming stations.

3. The stations must be placed in an array such that the apparent wave front can be accurately described from any azimuth.

4. The roaming stations must be left in a location until sufficient sampling of available azimuths is obtained.

5. The density of stations must be high to insure statistical significance of obtained data.

6. At least one origin time must be obtained from each of the mining areas. This is to control the absolute residuals and to describe the large scale model better.

7. Local sources (small explosions) could provide useful measurements of the station conditions within the array.

CONCLUSIONS

1. Significant P-wave time residuals (greater than 100ms) were obtained near Buena Vista, Colorado. These residuals may be explained by the existence of a high velocity zone striking E - W in Chaulk Creek and a low velocity zone just north of Chaulk Creek.

2. Significant velocity and structural information can be gathered using a modified version of the active seismic survey method.

RECOMMENDATIONS

1. The high velocity ridge interpretation should be tested with other data. These might include a detailed gravity survey and a detailed refraction survey across Chaulk Creek and extended to the north.

2. This survey technique should be applied wherever subsurface velocity or structural information is needed over a large area and where blast or sources of seismic energy are readily available.