A SEISMIC SURVEY OF THE RALSTON AREA, JEFFERSON COUNTY, COLORADO

by

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1976

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A Thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science in Geophysics.

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ABSTRACT

The Ralston area, north of Golden, Colorado, has been an area of geologic controversy for several decades. In an effort to interpret the geology of the area a multifold seismic reflection survey was conducted over a two-mile east-west line.

The Vibroseis (Continental Oil Company trademark) system of seismic reflection data acquisition was used throughout the survey to obtain six-fold data over most of the line. The data were processed on a Phoenix (Seismograph Service Corp. trademark) computer to produce a stacked seismic section and a migrated section. No modeling of the data was attempted.

Interpretation of the data reveals that the Ralston dike does not continue to depth, but is a sill which has been lifted and rotated by movement along the Golden fault zone. Beds of sedimentary rocks are shown to continue at low-dip under the Ralston dike. The Golden fault is interpreted as a zone with at least two faults in this area with a combined total throw of about 8000 feet. There is evidence of faulting in the lower stratigraphic section and of drape-folding in the upper stratigraphic section. A basin-margin fault has been recognized. By developement of the drape-fold model, a mechanism for slumping to the southeast of the Ralston dike has been postulated.

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ACKNOWLEDGMENTS

I wish to thank Dr. T. L. Davis for suggesting the topic of this thesis and for his continued guidance, encouragement, and friendship throughout the course of my study and the supervision of this work. I would also like to express appreciation to those students who gave of their time to help in data acquisition and processing. A special note of gratitude is due to Charles Powell, without whose continuing help this work would not have been possible.

I am grateful to the owners of the property in the study area for generously allowing access to their lands: Mr. Paul Pattridge, Mrs. Gladys Ramstetter, Mr. Robert Young, and The Adolf Coors Corporation.

Financial support from the Colorado School of Mines enabled the study to be undertaken.

Finally, I would like to thank Dr. Cecil H. Green for his encouragement and guidance since my decision to enter this field of study.

INTRODUCTION

The Ralston dike has been a topic of geologic controversy for nearly a century since two reports of the United States Geologic Survey described the source of the Table Mountain basalts near Golden, Colorado, as being attributed first to a pipe under North Table Mountain, and then to the Ralston dike as the plug in the vent for these flows (Marvine, 1873; White, 1877). The theory that the Ralston dike filled the vent for the Table Mountain flows seems to have found more support over the years than the North Table Mountain pipe theory (Waldschmidt, 1939).

A gravity and magnetic survey conducted over the dike by the Colorado School of Mines Geophysics Department in the early 1950's suggested that the "dike" did not continue to depth further than about 500 feet (Hollister, personal communication). This information was not published or included in any related thesis of this period, so its worth has generally not been recognized.

Van Horn (1972) revised his map of the geology of the Golden Quadrangle to show a cross section through the intrusive body. Working only from surface geology in this area, he mapped the "dike" as a disconcordant intrusive mass which, on his cross section, appears to have been intruded through the Golden Fault to its present position (Figure 2).

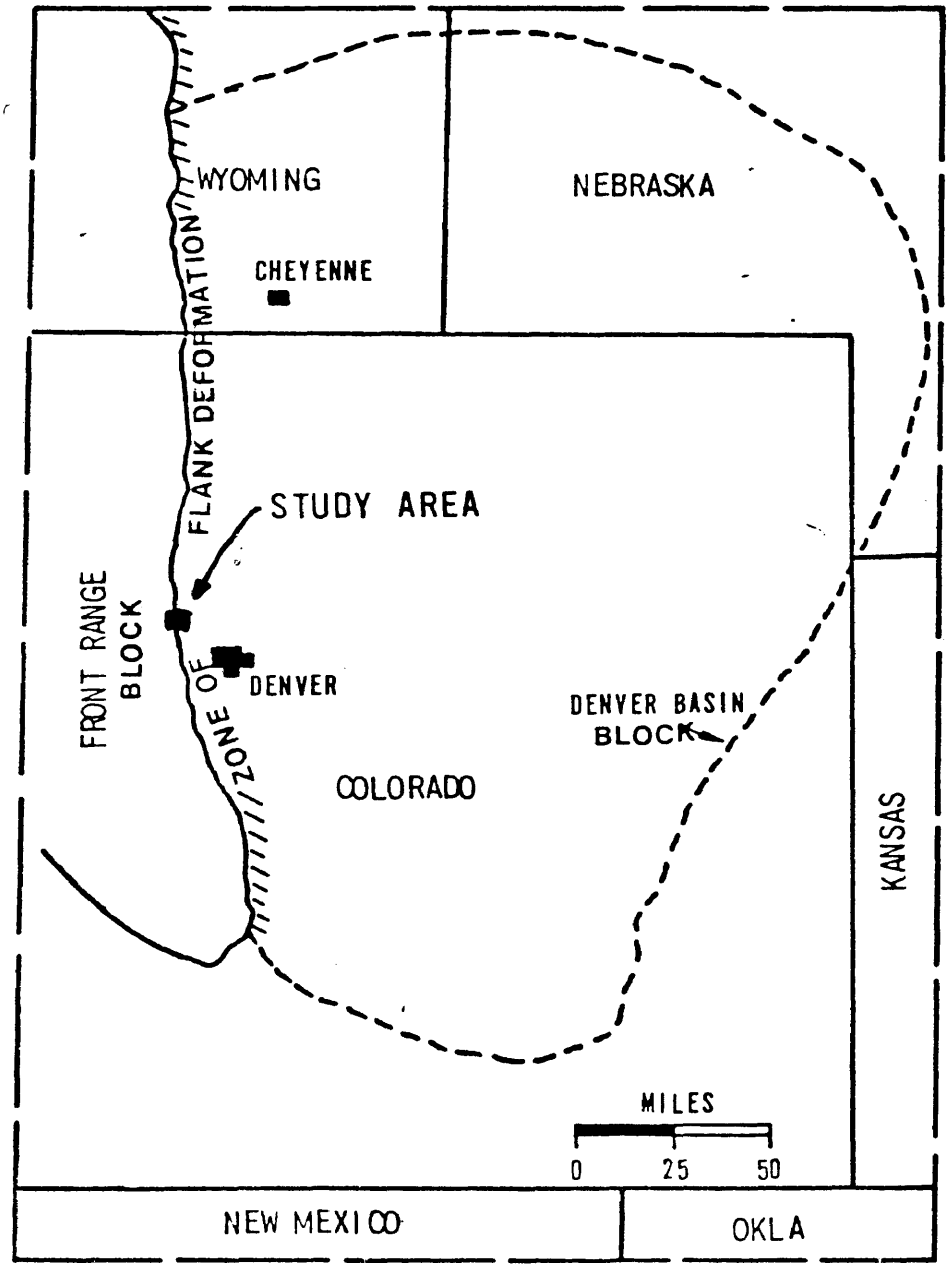

Figure 1. Location map of study area. (modified after Davis, 1974)

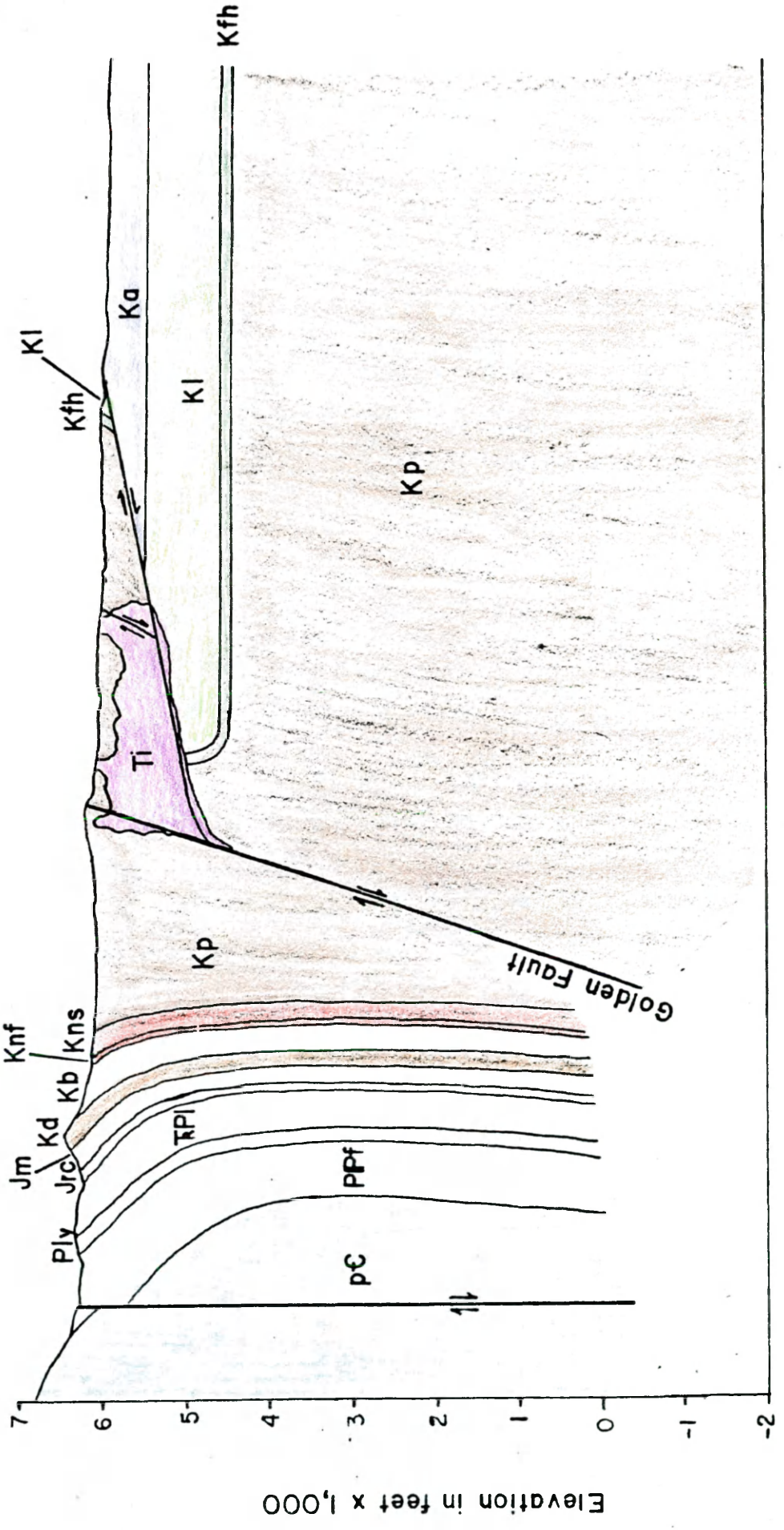

Figure 2. Geologic Cross Section (after Van Horn, 1972)

In 1975 a paleomagnetic study of the Ralston intrusive and the Table Mountain flows was published (Hoblitt and Larson, 1975). This article showed that the Ralston Dike and the middle of the three flows comprising South Table Mountain were of approximately the same age; 61.9±2.5 million years for the Ralston intrusive, and 64.3 million years for the South Table Mountain flow (Hoblitt and Larson, 1975; Scott, 1972, in Hoblitt and Larson, 1975). Hoblitt and Larson showed that by rotation of the intrusive body from an angle of 60 degrees east dip to horizontal, that the paleomagnetic orientations of the intrusive and the flow aligned within allowed margins of error. It was concluded in the article that the "dike" was a rotated sill which was intruded at approximately the same time as the middle flow of South Table Mountain was extruded.

The Golden fault has also been a subject of much controversy in this area. The fault's trace has been reinterpreted several times and its dip has been postulated to be a very low-angle thrust or a high angle reverse fault. Van Horn has mapped the Golden fault as running essentially through or under the "dike" (1972) at a position far to the east of the Ralston dike (1957) on two different maps of the Golden Quadrangle. On the later 1972 map he chose to draw a cross section of a line approximately one quarter mile south of the seismic line used for this research (Figure 2). On this section Van Horn shows the Golden fault as a high-angle reverse fault. Stommel and Stewart, in coincident

theses in geophysics and geology respectively, have interpreted the Golden fault as a very low-angle thrust, by which a relatively thin section of high-dip sediments and Precambrian metamorphic rocks are shown to be thrust over predominantly low-dip sedimentary rocks (Stommel, 1951; Stewart, 1953). These low-dip sedimentary rocks are shown to be drag-folded to nearly vertical dips near the fault (Figure 3).

The seismic data used by Stommel and Stewart in the formulation of their interpretation of a low-angle thrust fault is of the "spot-correlation" type, commonly in use in the early 1950's. Two or three shots were used per cross-sectional line. These records were then correlated across the gap between them by the dominant reflections on the records to give an interpolated subsurface cross section. These data are subject to serious problems which may affect the interpretation of the data. The first of these problems stems from the use of short offsets of the far geophones from the shot, which can lead to poor velocity control, particularly in an area with high-velocity sedimentary rocks. This velocity problem, along with the necessary interpolation between records could lead to many varying interpretations in an area of complex geology.

Evidence in the Morrison, Colorado area shows the Golden fault zone to be high angle with reverse movement (Berg, 1962). These data come from two exploratory wells drilled through the fault zone. The Johnson No. 1 well produced a small quantity of oil from the lower portion of the

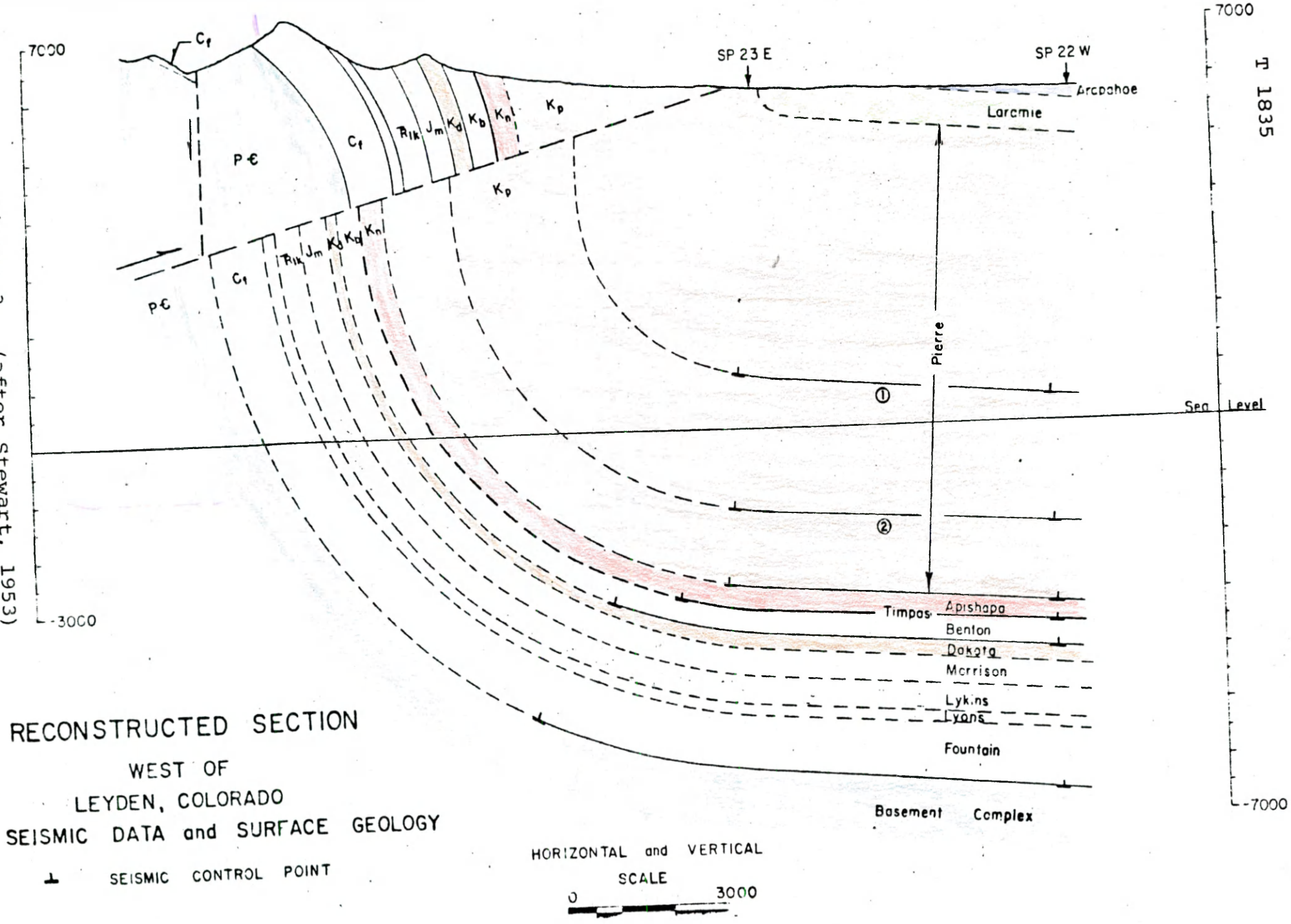

Figure 3. (after Stewart, 1953)

Niobrara Formation on the downthrown side of the fault (Figure 4).

Because the surface of the Ralston area is largely covered with Quaternary colluvium and Rocky Flats alluvium and because of a general lack of bedrock exposure in the area which could be continued to depth with confidence, it was decided to run a modern, multifold seismic line over the Ralston area to improve interpretations of the two major geologic features, and to aid in resolving the long-standing controversies.

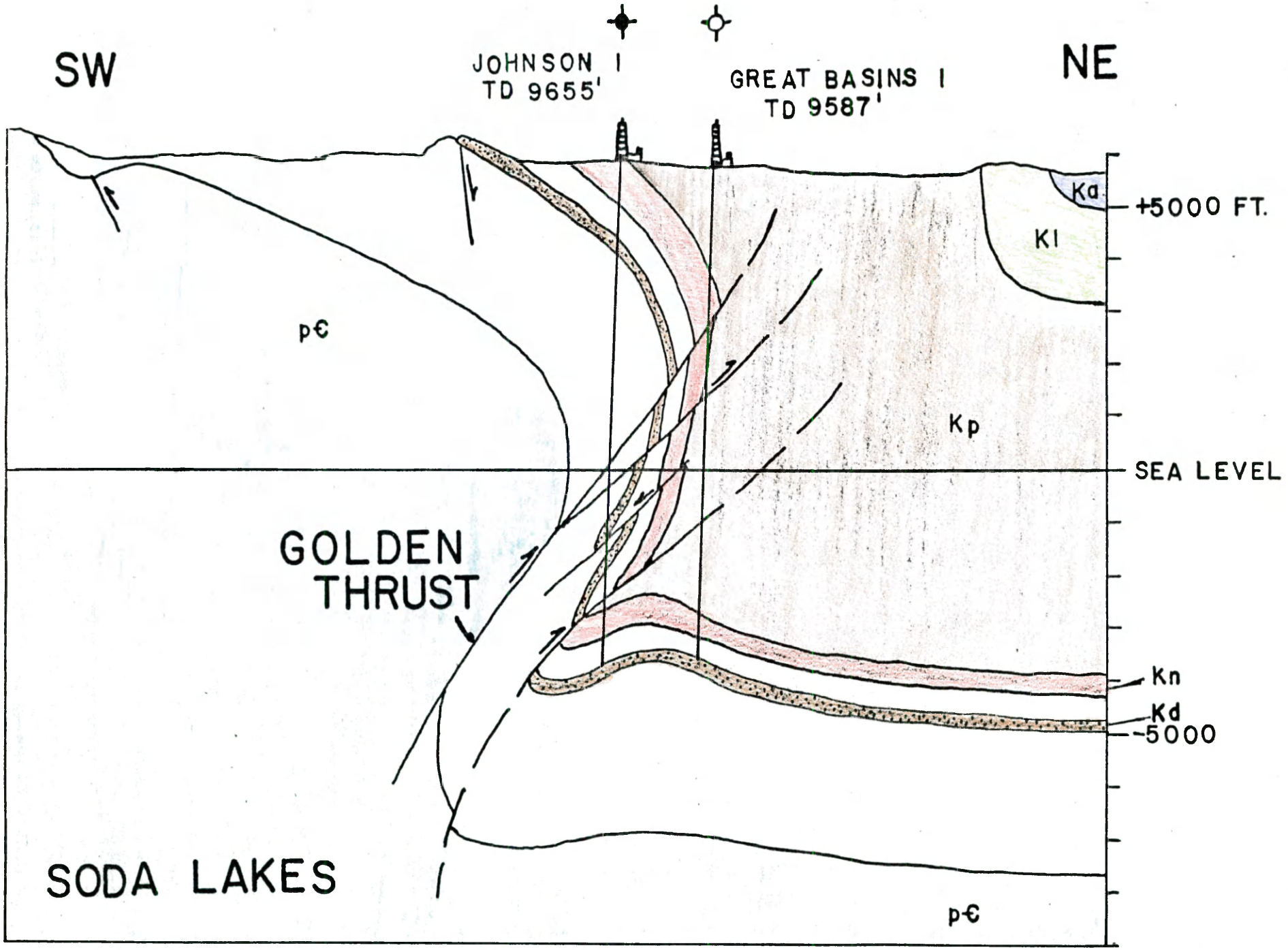

Figure 4. Geologic Cross Section (after Berg, 1962)

GEOLOGY OF RALSTON AREA

Stratigraphy

The stratigraphy of the general area has been described by LeRoy and Weimer (1971), (Figure 5), Stewart, (1953), and Davis (1974) (Figure 6) The lower section of sedimentary rocks consists of several sandstones and siltstones which are not definable on seismic data. The oldest of these sedimentary formations, the Permian-Pennsylvanian Fountain Formation, rests nonconformably on the Precambrian gneiss and schist which comprise the basement rock of the area. The Fountain is about 1000 feet thick and can be distinguished on some seismic data, but usually is not picked as a marker horizon because of its proximity to the basement. The Lyons, Lykins, Ralston Creek, and Morrison Formations make up about 1000 feet of fine-grained sandstone and siltstone. This interval is of little or no economic interest at depth where it would be noticeable on seismic data, and because of the large-scale homogeneity of the interval it does not show up well on seismic data. These sediments range from Permian to Jurassic in age. The Lower Cretaceous Dakota Group consists of about 360 feet of fine- to coarse-grained sandstones, interbedded shales, and siltstone. Upper Dakota sandstones are of interest for petroleum exploration. The Dakota is a noticeable, but not outstanding, seismic marker horizon.

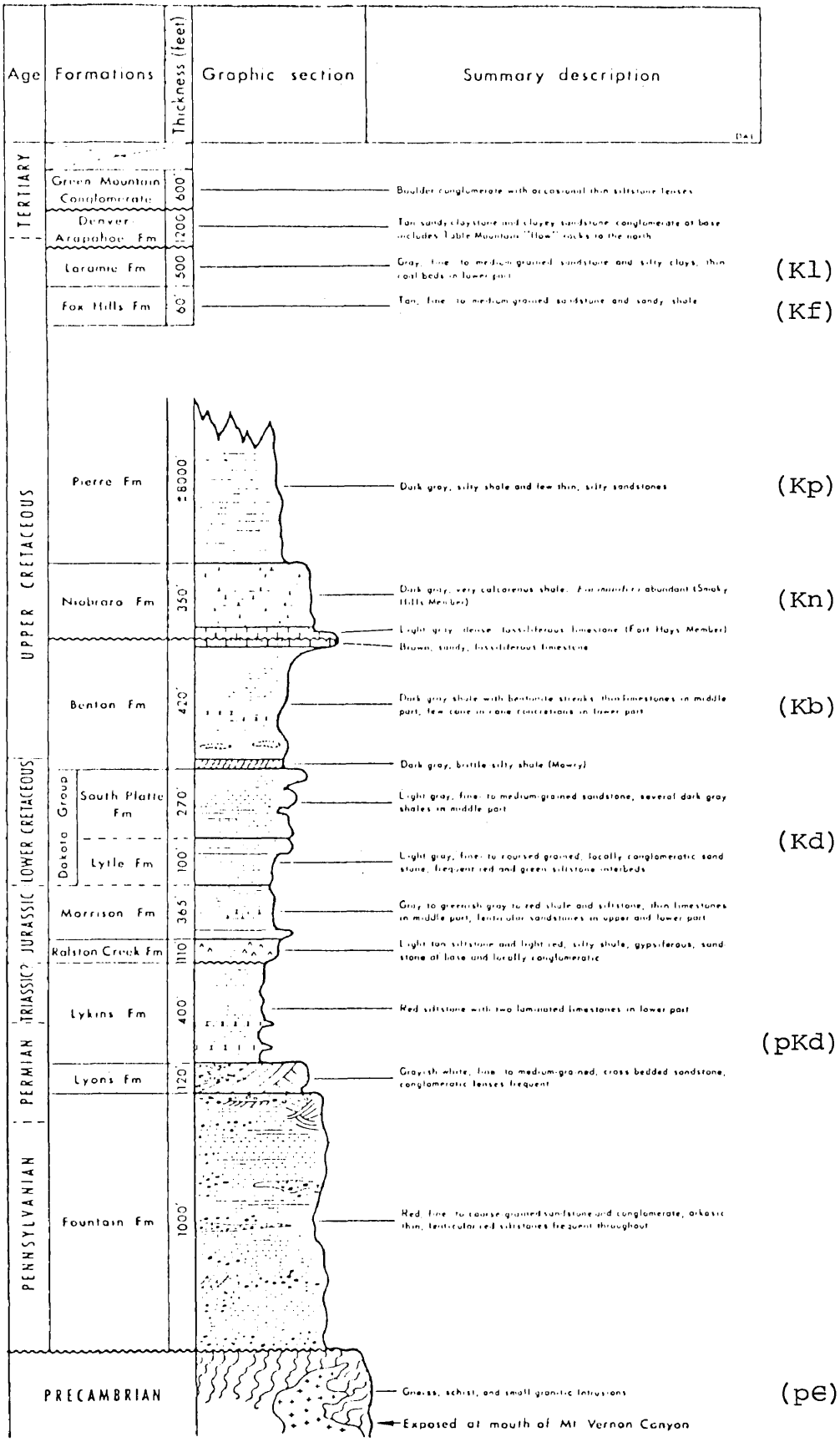

Figure 5. Generalized Stratigraphy of the Golden Area (after Leroy and Weimer, 1971)

About 420 feet of Cretaceous Benton Shale separates the Dakota Group and the Niobrara Formation. The Niobrara is a very calcareous shale with a dense basal limestone. It is a good reflecting horizon because of the higher velocities associated with carbonates.

Overlying the Niobrara is the Upper Cretaceous Pierre Shale which varies from 7000 to 8000 feet in thickness in this area. The Pierre consists of silty shales with a few silty sandstones. One sandier interval is known as the Hygiene Zone (Figure 6). The top and bottom of this zone both show up as good seismic horizons (Davis, 1974).

The Pierre is overlain by the Fox Hills Formation which consists of about 60 feet of sandstones and siltstones. The Fox Hills grades into the sandstones and silty clays of the Laramie Formation. Both formations are of Late Cretaceous age. The Laramie is about 1000 feet thick and has a few thin coal beds in the lower part. The youngest formation present in the study area is the Cretaceous-Tertiary Denver-Arapahoe Formation. This formation is about 1200 feet thick. It consists largely of sandy claystone and contains the Paleocene flows on the Table Mountains and the Ralston intrusive.

Structure

The study area lies in the zone of flank deformation between the Front Range uplift and the Denver basin, these two major features being separated by the Golden Fault (Figure 1). In the study area the Front Range block consists of a

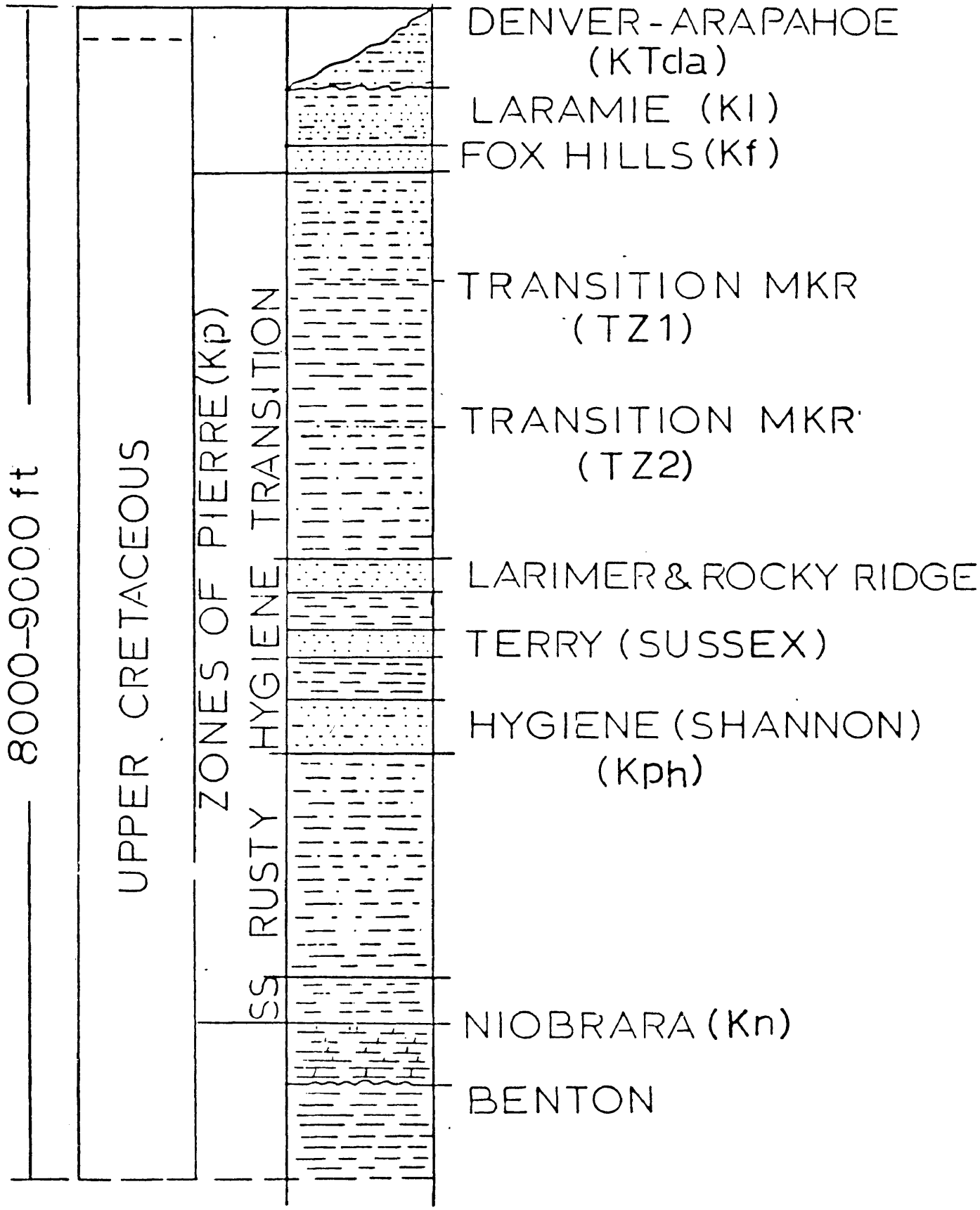

Figure 6. Stratigraphy of the Pierre Shale (after Davis, 1974)

mass of Precambrian metamorphic rocks. The Denver basin has up to 13,000 feet of sedimentary rocks in the area of this study (Davis, 1974).

RALSTON SEISMIC SURVEY PROCEDURE

Location of Survey

This study concentrated on an area about three miles north of Golden, Colorado, in Township 3 S, Range 70 W, sections 4, 5, and 9 (Figure 7).

Equipment Used

The Vibroseis system (Continental Oil Company trademark) of data acquisition was used throughout this survey. This method of seismic data acquisition uses a servohydraulic vibrator as a seismic source. The "source-pulse" of the vibrator differs from the spike-like pulse of dynamite in that it is actually a sweep of frequencies with a sinusoidal waveform of several seconds duration (Laing, 1973). The entire sweep of frequencies is reflected from each reflecting horizon. The record length must be equal to the length of the sweep plus the length of time of data desired in the area surveyed. Raw field records show no discernible reflecting horizons because the "pulse" is spread over a length of several seconds. The data must be cross-correlated with the original sweep of frequencies before it may be viewed as an equivalent of a dynamite data record. Cross-correlation is a mathematical process equivalent to convolution of the two waveforms, but with one waveform reversed in time. Cross-correlation of the sweep with itself, that is auto-correlation,

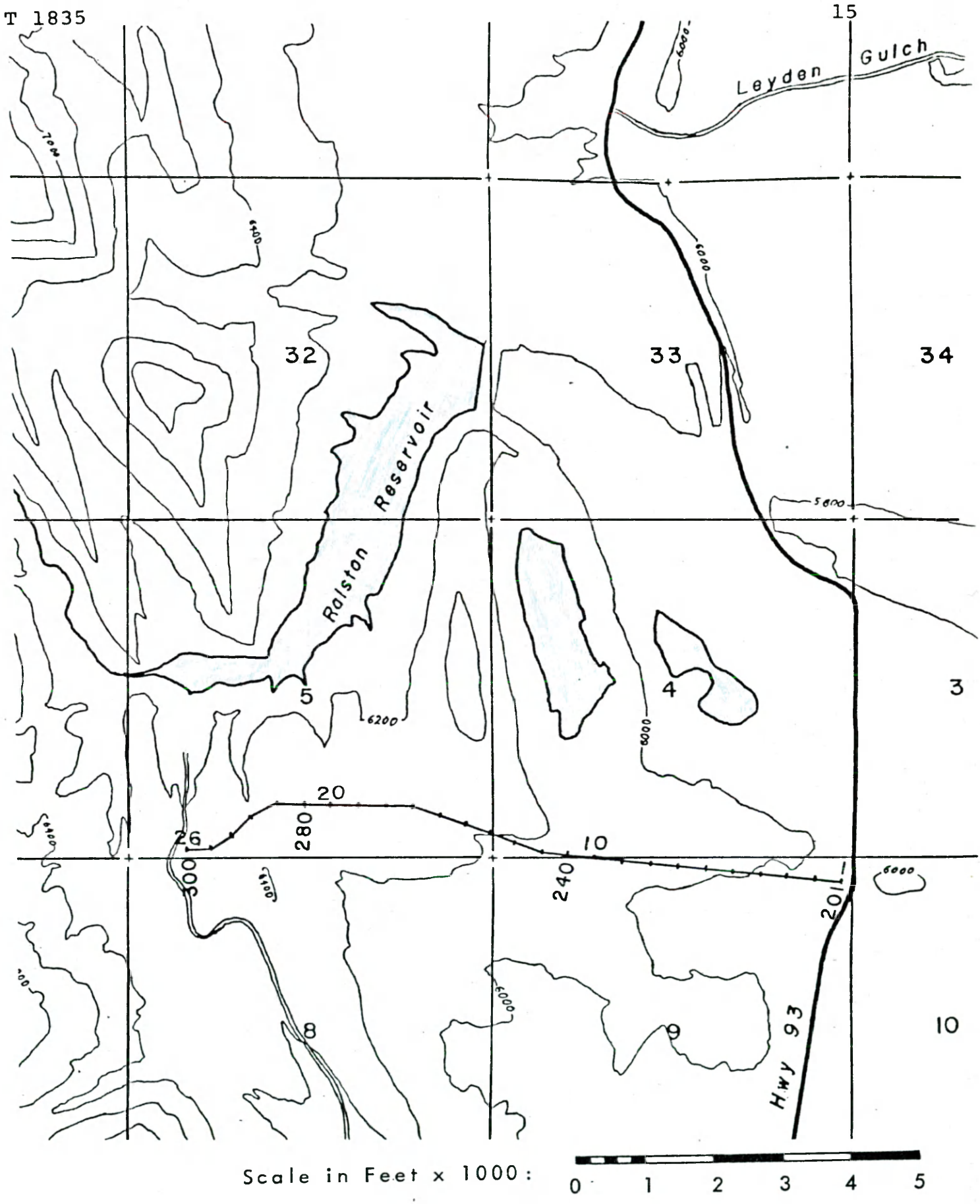

Figure 7. Location Map of Seismic Line.

results in a pulse which is equivalent to the input pulse to an already cross-correlated record. One disadvantage of Vibroseis is that, when using a sweep from high to low frequencies (a downsweep), a harmonic "ghost" appears at a certain predictable time after zero time. This ghost is no problem if it occurs after all desired data have been recorded (Seriff and Kim, 1970). The arrival of the ghost can be calculated by the equation:

$$\text{Arrival Time} = \frac{T\ fo}{W}$$

where T is the length of the sweep, fo is the lowest frequency in the sweep, and W is the range of frequencies in the sweep.

The major advantages of Vibroseis over dynamite are: (a) no shot holes need be drilled, (b) a certain frequency range may be chosen for the particular data area, (c) all frequencies recorded other than those in the sweep are eliminated in the cross-correlation process, and (d) the Vibroseis correlated pulse has a zero-phase characteristic, i.e., the pulse is centered at the time zero and does not have the inherent time delay of the dynamite pulse.

In this survey, a single truck-mounted servo-hydraulic vibrator, rated at a two-ton output force was used as the seismic source. The sweep of frequencies was transmitted by FM radio from the recording truck to the vibrator. Recording was done by a Texas Instruments DFS 10,000 recording system onto 21-track magnetic tape. The recorder was equipped with a sweep adapter, a memory unit which stores the sweep which

is to be sent to the vibrator. The geophones, made by Geospace, consisted of 14 geophones per 200-foot string.

Noise Spread

A noise spread was shot on September 19, 1975 to determine the length of spread and geophone arrays to be used. Twenty-four of the Colorado School of Mines Geophysics Department's refraction geophones were placed in-line, twenty feet apart, over a distance of 460 feet. For the first station, eight vibrator records were recorded from a stationary vibrator position twenty feet off-end from the nearest geophone station. The vibrator was then moved 480 feet and vibrated another eight times for the second position (Figure 8).

The noise spread confirmed that the proposed geophone-array length of 200 feet would effectively contribute to cancellation of the low frequency ground roll. The noise spread also gave good weathering and subweathering velocities of 4,000 and 8,000 feet per second respectively. A very irregular weathering surface can be seen from the noise spread (Figure 8). This irregular surface is suggested by the irregular first break, or refraction data. A depth to weathering of about 60 feet was calculated from the first breaks on the noise spread.

Acquisition of Reflection Data

On September 26, 1975, the first of the reflection data were gathered using 200-foot geophone intervals and 400-foot

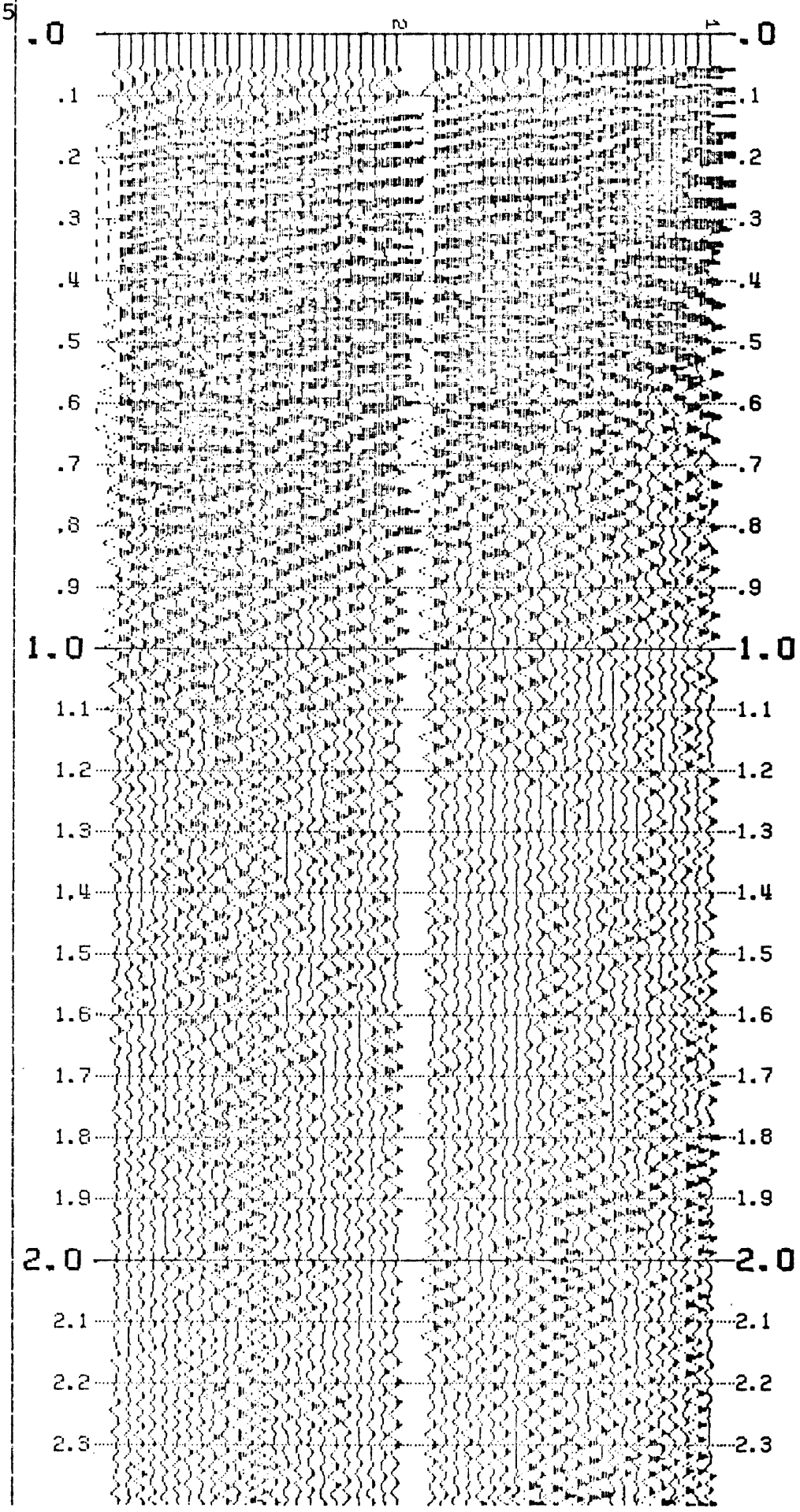

Figure 8. Noise Spread

vibrator intervals to obtain six-fold data. A split-spread, with a 200-foot vibrator source array in the center of the spread, was used throughout. A 58-12 hertz, eight-second, downsweep was used for the source and four seconds of data were recorded after the sweep to give a total record length of twelve seconds. Twenty-four of these twelve-second records were recorded on each 21-track field tape. For reasons of greater depth penetration and noise cancellation, twenty-four sweeps per vibrator station, spread over the in-line source array distance of 200 feet, were used as the source. These twenty-four records would be summed before processing the data.

After acquiring data in this manner through vibrator station 18, it was decided to acquire more data by continuing the line to the west as far as possible. Starting at vibrator station 15, twenty-four geophone stations with 200-foot intervals were laid out to the west. This additional data made a total of 26 vibrator stations with 400-foot intervals. All twenty-four geophone stations were recorded for each vibrator point reported. This procedure resulted in up to twelve-fold data under vibrator station 20. The longer offsets helped in obtaining better velocity information.

Another difference between this data and the previously recorded data was the use of a 48-8 hertz downsweep instead of the previously used 58-12 hertz downsweep. The lower frequency sweep was used because of the dominance of frequencies between 15 and 30 hertz on the first data obtained and a lack

of data above a frequency of 45 hertz. Record length was reduced from twelve to eleven seconds because no useful data was obtainable below three seconds. Twenty-eight individual records were recorded on each field tape. The harmonic ghost for this sweep arrives at 1.6 seconds, but does not affect the data until about 2.2 seconds because of filtering of the high frequencies. The effective arrival of the ghost could be pushed still lower in time by further filtering the high frequencies, but this was not necessary. Vibrator station 23 was skipped because it was on a steep hill. This was the only vibrator station on the line not vibrated.

Data Processing

The field tapes were first demultiplexed so they would be compatible with the Phoenix (Seismograph Service Corporation trademark) trace-sequential format. During this process a mild digital trim was applied for trace equalization and the sample rate of the data was changed from two to four milliseconds for compatibility with later programs. Any records which were short or had more than 100 sync errors were dropped at this point. Those records common to a single vibrator point were then summed. Again, a mild digital trim was applied to scale the amplitudes. The summing process resulted in one record for each vibrator station. These records were then cross-correlated with the sweep on the data tape. The records were then viewed for data quality after plotting (Figure 9).

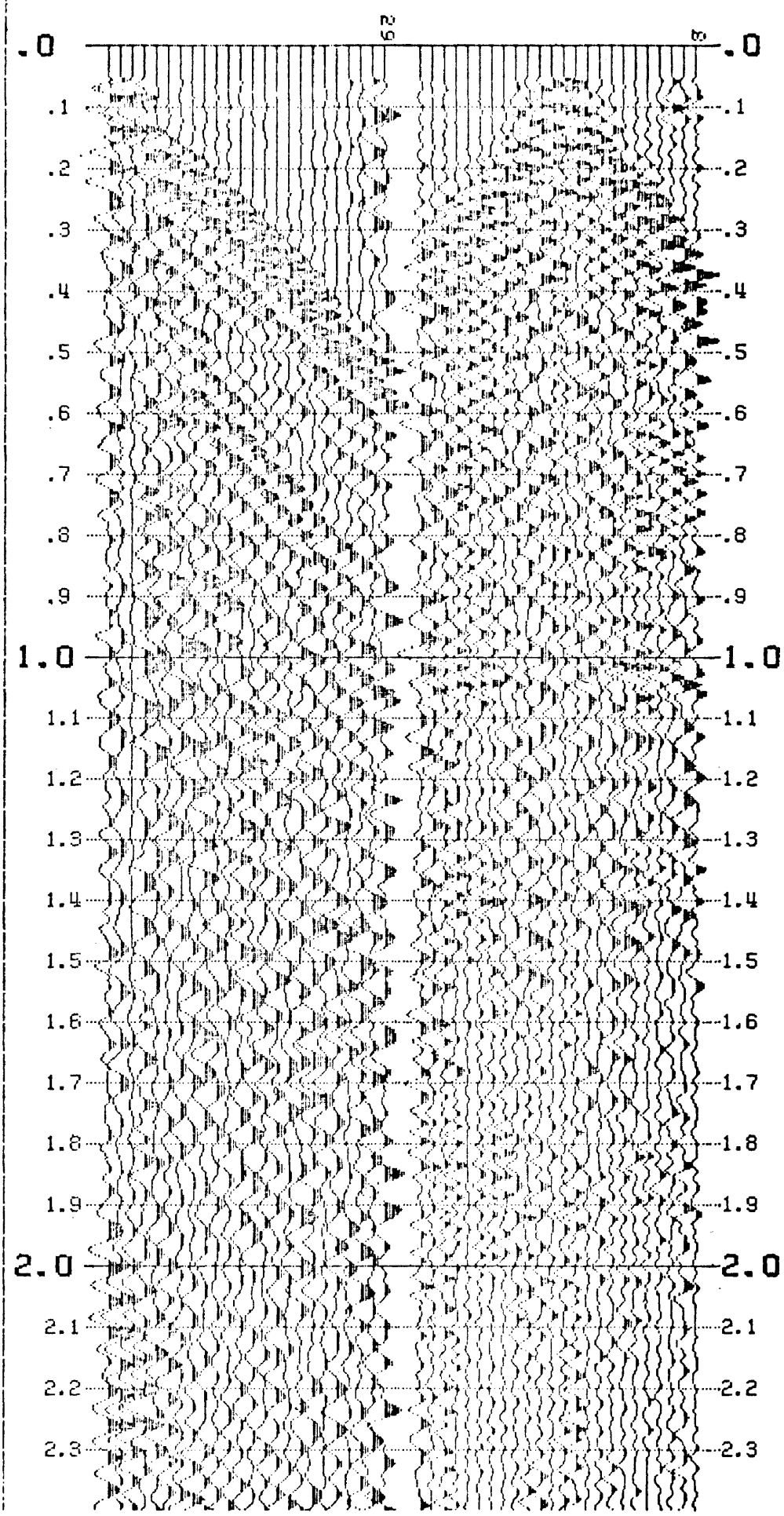

Figure 9. Two Cross-correlated Records
Record 8 is Vibrator Station 8
Record 29 is Vibrator Station 26

Digital trim was then applied to the data to equalize amplitude between the first data acquired using the 58-12 hertz sweep and the second section of data acquired using a 48-8 hertz sweep. This trim also served as an automatic gain control to equalize amplitude between the upper and lower time section. A filter with a Hanning taper of 11, 13, 45, 50 hertz was then applied to reduce the very low frequencies in the 48-8 hertz sweep data so that its waveform would resemble that of the 58-12 hertz sweep data. This filter also cancelled any high frequency noise present.

The traces of the individual records were then sorted into common-depth-point (CDP) gathers. As much as twelve fold was recovered on the west end of the line. That is, there was repeated coverage of a single point in the subsurface and this repeated coverage was on twelve traces of the combined individual records. Each of these subsurface points where there is repeated coverage is termed a common depth point and the traces which have the information of that point repeated among them are grouped together in the sort to form common-depth-point gathers. The number of traces in a gather is termed the fold of data at that point. Six-fold data was recovered over most of the line.

A velocity analysis program was then run over the section of maximum fold data. This analysis was accomplished by use of a constant velocity stack of 25 traces at velocities ranging from 8,000 to 15,000 feet per second. The velocities

could then be picked at different time levels by whichever velocity appeared to give the best reflection stack at that time. These velocities were used for the east part of the section where there is relatively low dip. For the high-dip section to the west, velocities used for stacking data acquired in the vicinity of Coal Creek Canyon in January 1976 were used. These velocities on the west end of the section could be expected to be higher than the velocities in the low dip section to the east for several reasons. Two major reasons are that the section has been uplifted on the west, bringing higher velocity sedimentary rocks nearer the surface, and that there is higher dip on the rocks on the west end of the seismic line, resulting in increased stacking velocities. This is illustrated by the normal move-out equation:

$$Tx^2 = To^2 + \frac{x^2 \cos^2 \theta}{v^2}$$

where Tx is the ray-path time from source to receiver, To is the travel time for a wave with normal incidence at the reflector, x is the source-receiver horizontal distance, θ is the angle of dip of the reflecting horizon, and v is the stacking velocity required to correct for normal move-out. It can be seen from this equation that an increase in dip of a reflector will result in an increase in stacking velocities. The following are the velocities used to stack the Ralston seismic line:

West	time (seconds)	velocity (fps)
	0.20	9000
	0.35	10000
	1.00	12500
	1.65	14500
	4.00	16500
East		
	0.40	9000
	0.50	9400
	0.60	9700
	1.10	10500
	2.00	12000

A "brute stack" was then produced which had very obvious statics problems associated with it. Statics problems, which result from variations in weathered zone velocities and thicknesses, are common when using a surface source such as a vibrator with no control on variations in weathering thickness and velocity. These variations in weathering will cause the data traces to be shifted, plus or minus, by several milliseconds. A "dip-statics" program was then run to correct for these minor variations in statics. This use of automatic statics programs is very common when using a surface seismic source. This program removes dip from the data along a certain horizon which has been picked by the processor. Several points are picked along the horizon by common-depth-point number and time. All points on the horizon are then adjusted to the lowest time picked by shifting the entire trace. An automatic statics program (CSTAT) was then run on the data using a five-trace operator, 80% weighting, 1.2 second window. The CSTAT program produces an autocorrelation function of

each trace in the window specified. These autocorrelation functions are then shifted into alignment across the section in overlapping groups. The traces adjacent to the center trace of a group are weighted according to a percentage specified by the processor. The amount of shift applied to the autocorrelation functions is then applied to the corresponding data traces. The dip was then restored to produce a section which had been corrected for statics. Finally, a digital trim was applied to equalize amplitudes across the section which differed because of the difference in fold across the section (Figure 10).

A migrated seismic section was also produced using a 24 trace mix for the operator (Figure 11). The chief purpose of this program was to eliminate diffractions and correct reflecting horizons to their true dip.

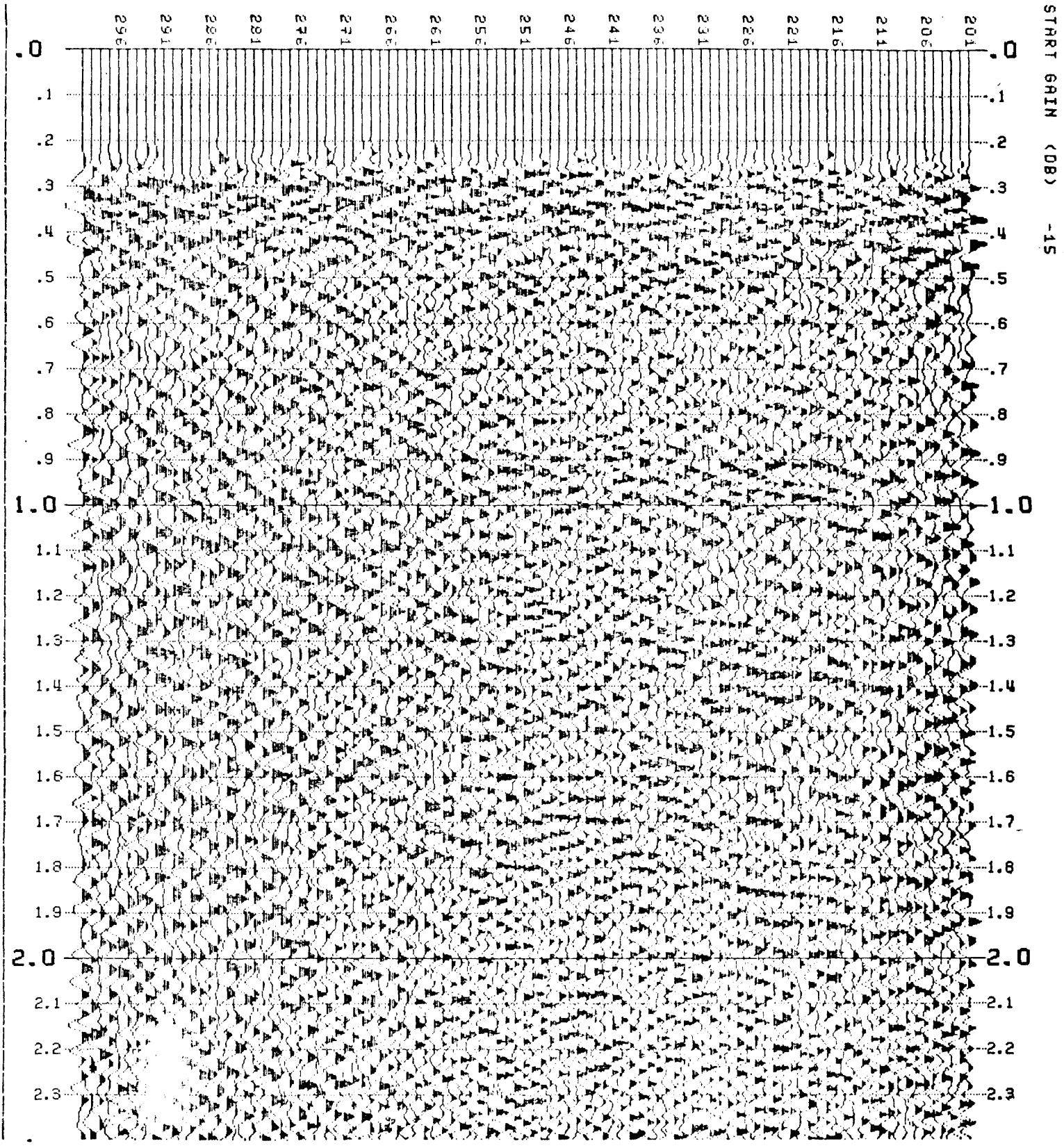

Figure 10. Stacked Seismic Section

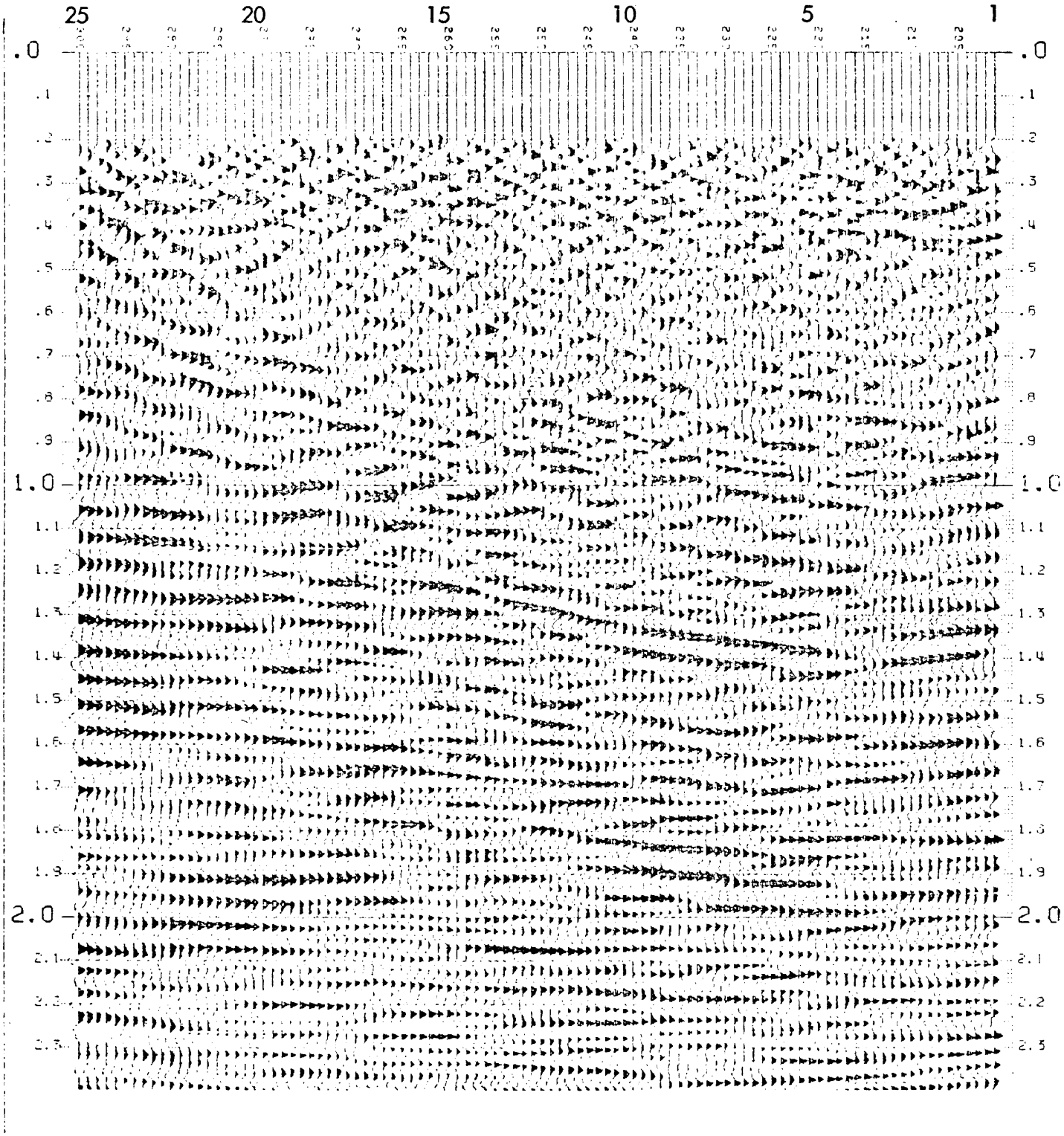

Figure 11. Migrated Seismic Section

RESULTS OF RALSTON SEISMIC SURVEY

Correlation

Correlation of the data to known horizons was accomplished by tying to a seismic line in Leyden Gulch, about two miles north of the study area, and by working with thicknesses of intervals known with reasonable accuracy from the general stratigraphy of the area (Figure 7). The Precambrian basement, Niobrara, and top of Hygiene Zone horizons correlate well with the Leyden Gulch seismic line after aligning the two lines properly with respect to sedimentary thicknesses. On the far west end of the Ralston line the basement reflecting horizon could be extrapolated directly to the surface geology outcrop for a reliable correlation, (Figure 13), and the basement in the central fault block has been correlated by depth from the Hygiene Sandstone outcrop on the surface (Scott and Cobban, 1965; Sheridan, et al., 1967). The seismic data shows relatively low dip beds on the eastern end of the section and under the Ralston dike, in sharp contrast with the high dips shown by surface geology. The continuation of the low-dip beds to the west end of the line on the migrated section has been caused by the migration program. Both sections, migrated and unmigrated must be used for the interpretation.

Structure of Ralston Area

Three faults which lie in the zone of flank deformation are evident on the seismic data (Figure 13). All three faults

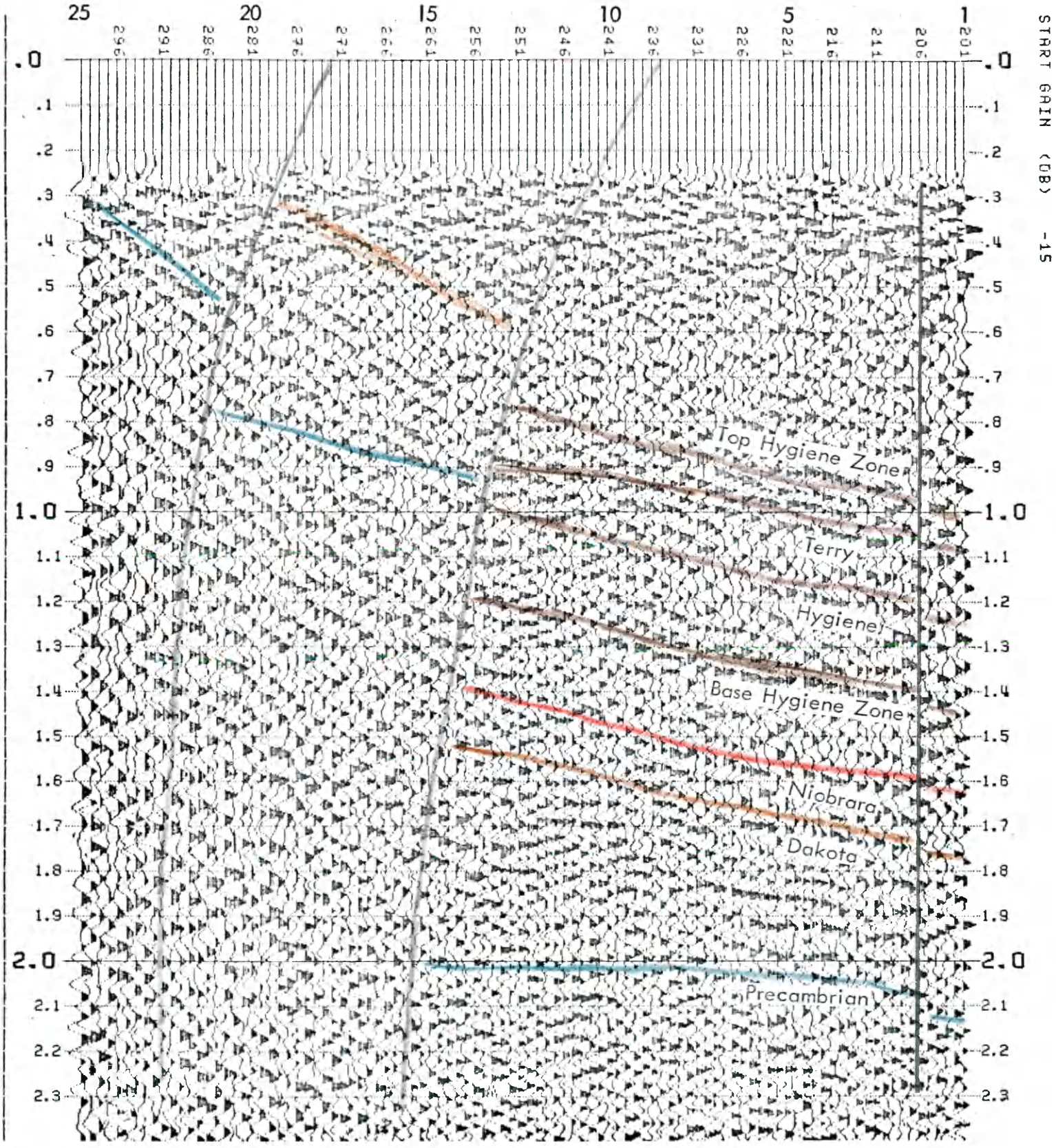

Figure 12. Interpreted Seismic Section

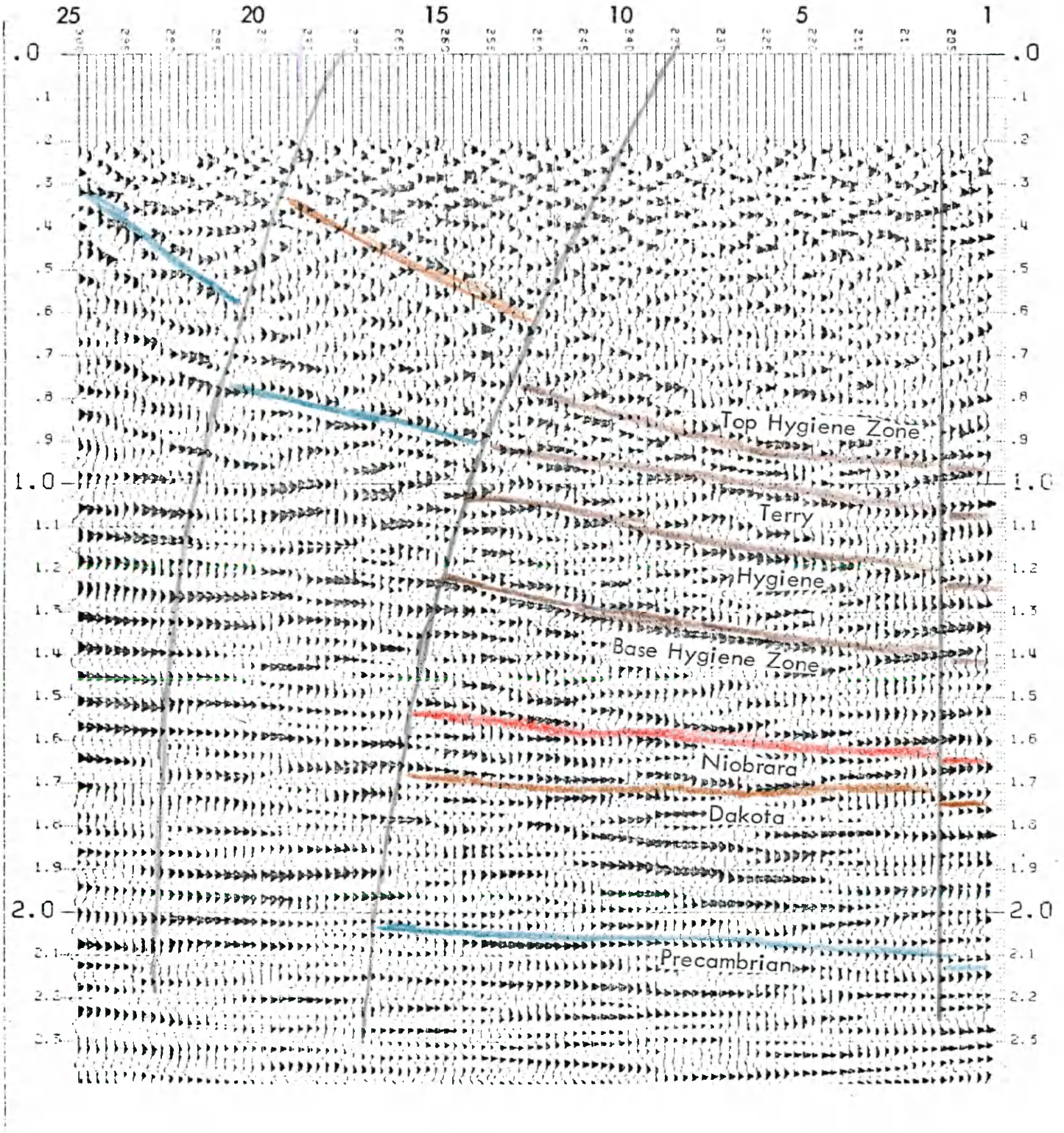

Figure 13. Interpreted Migrated Seismic Section

are high angle and appear to be basement controlled.

The two western faults may be termed the Golden fault zone. The middle fault, which has about 5500 feet of displacement, has been mapped at the surface by Scott and Cobban (1965). The western-most fault has about 2000 feet of displacement, which combined with the middle fault, gives about 8000 feet of displacement along the zone of faulting.

The eastern-most fault has been termed a basin-margin fault (Weimer, 1973). This fault may be correlated with a fault on seismic data to the north and south of the Ralston area. The basin-margin fault has a small displacement of about 200 feet and its dip is vertical.

The low-angle thrust mapped by Van Horn in this area is not evident on the seismic data (1972). The seismic data start below this feature because of necessary muting of the first break data during processing. Interpretation of this feature may not be made directly from the seismic data, but the data can help by aiding in construction of a model of the geology of the Ralston area.

The Ralston dike does not appear on the seismic data, suggesting that the dike does not continue to depth and supporting the evidence of the gravity and magnetic survey of the early 1950's (Hollister, personal communication) and evidence of an aeromagnetic survey of the late 1940's (Moore, personal communication).

The trace of the Golden fault, as mapped by Scott and Cobban

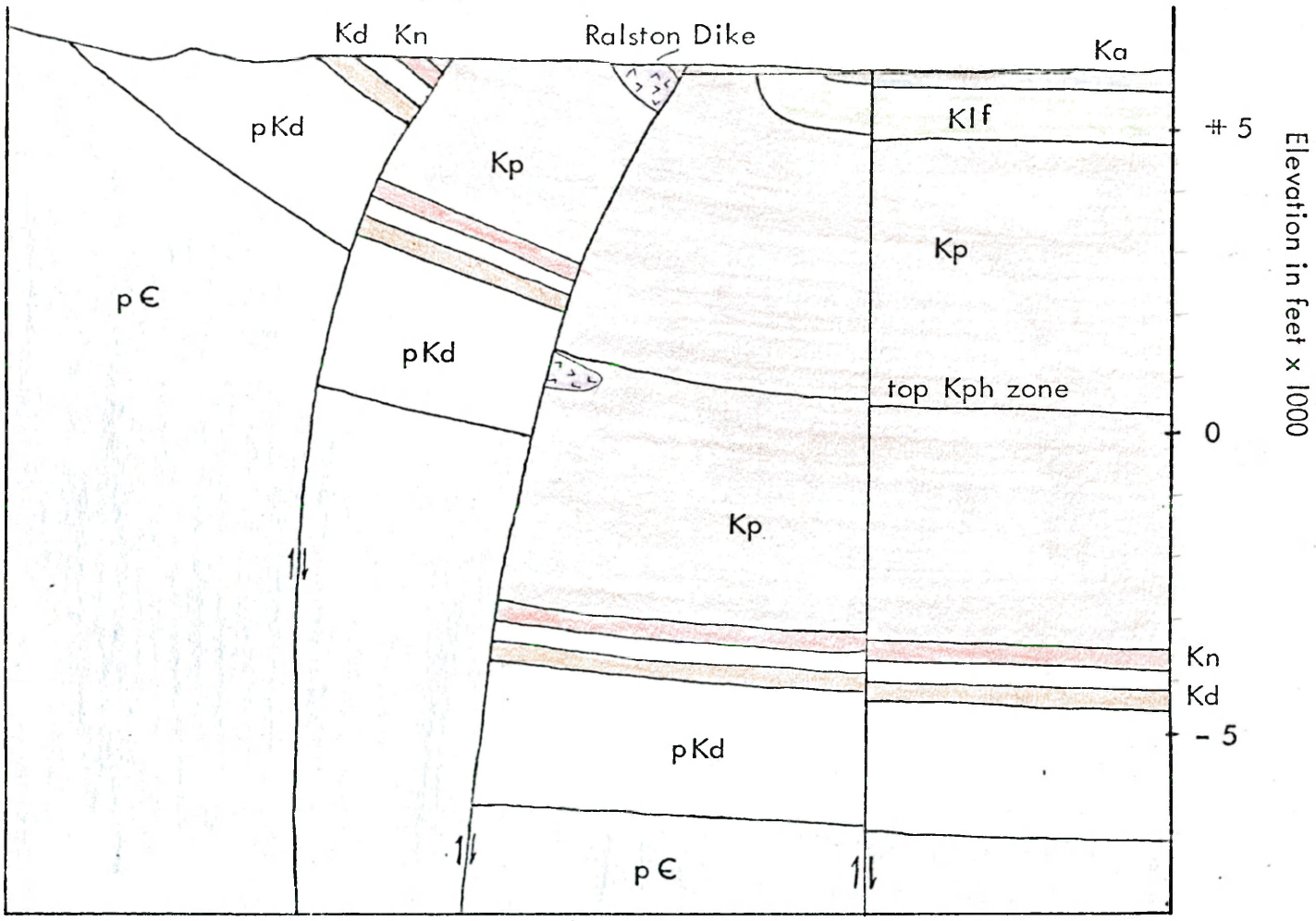

Figure 14. Geologic Cross Section of Ralston Area from seismic data and surface geology (surface geology after Scott and Cobban, 1965; Sheridan, et al., 1967; and Van Horn, 1972). Refer to figures 5 and 6 for symbols.

(1965) and the corresponding fault, evident at depth on the Ralston seismic data, lies immediately to the east of the dike. This evidence shows the dike to be part of the block between the two faults of the Golden fault zone, allowing a mechanism for the rotation required in Hoblitt and Larson's interpretation of the dike as a sill (1975).

The dike is mapped by Scott and Cobban as resting stratigraphically near the top of the Hygiene Zone of the Pierre Shale (1965). Other masses of intrusive basalt rest to the southeast and south of the dike, stratigraphically higher than the dike in the Pierre Shale (Figure 18). There appears to be an indication of a sill on the Ralston seismic data (Figure 13). This sill on the seismic data is probably part of the Ralston dike which was sheared from the surface mass by the Golden fault.

Geologic Model of Ralston Area

By radiometric dating of the Ralston intrusive, it has been established that the basalt was intruded during the Paleocene epoch (Hoblitt and Larson, 1975). Hoblitt and Larson have also established that the sill was intruded very nearly horizontally and has since been rotated to approximately 60 degrees east dip. From these radiometric and paleomagnetic data and from the seismic evidence cited above, it is evident that the Ralston dike was intruded as a sill into the horizontal beds of the Upper Hygiene Zone during Paleocene age (Figure 15).

Subsequent to the intrusion of the basalt, movement occured

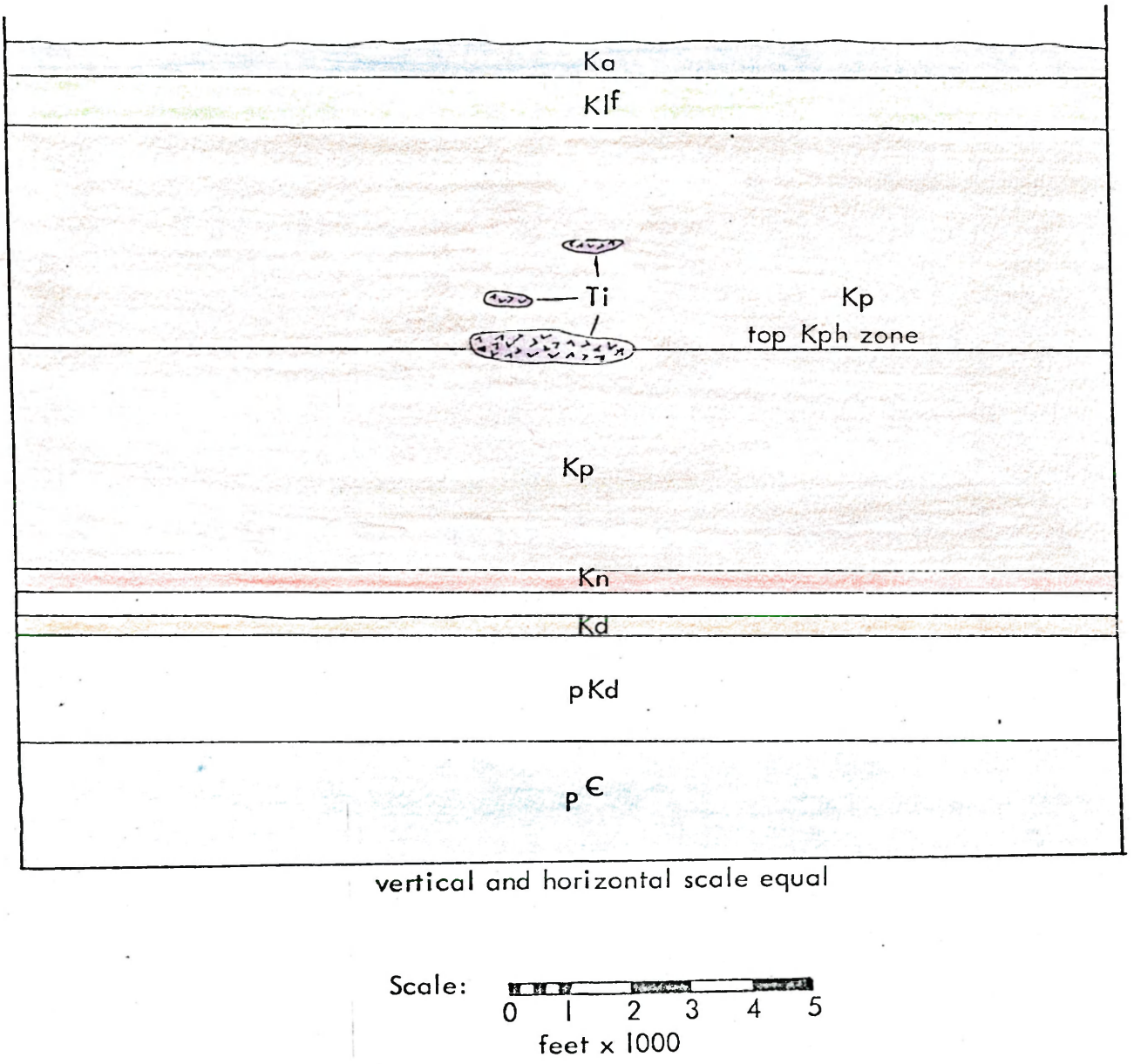

Figure 15. Geologic Cross Section of Ralston Area after basalt intrusion. Refer to figures 5 and 6 for symbols.

along the Golden fault zone. This movement raised the intrusive about 5500 feet and rotated it to its present orientation of 60 degrees east dip (Hoblitt and Larson, 1975). The pre-Pierre sedimentary rocks were deformed by brittle fracture faulting. The post-Pierre sedimentary rocks appear to have been deformed by the mechanism referred to as drape-folding. The Pierre formation apprears to have taken the role of the plastic shales required in Stearns' drape-fold model (1971).

Stearns' drape-fold model of sedimentary deformation has been applied to many areas in the Rocky Mountain region. This model requires a brittle basement overlain by plastic shales which are in turn overlain by more competent sedimentary rocks. The brittle basement deforms by faulting, causing plastic deformation of the shales, and folding rather than faulting of the overlying competent sedimentary rocks. The competent sedimentary rocks may be folded to vertical or overturned dips along the fault zone (Stearns, 1971).

In the Ralston area, drape-folding offers an explanation for the high dip sedimentary rocks of the Fox Hills and Laramie formations which lie to the east of the major faults of the Golden fault zone. According to the drape-fold model, these beds of more competent rocks may be tilted to vertical or overturned dips on the downthrown side of the fault. When applying the drape-fold model to the Ralston area, the pre-Pierre sediments have been grouped with the basement because of the brittle deformation of these rocks, the Pierre Shale takes the role of

the plastic shale section, and the Arapahoe, Laramie, and Fox Hills formations act as the more competent sedimentary rocks which have been draped over the fault zone (Figure 16).

The drape-fold model described above helps to explain the area to the east and southeast of the dike which Van Horn has interpreted as a low-angle thrust fault (1972), (Figure 18). This feature is peculiar to the Ralston area and is very likely associated with the intrusive rocks scattered through the displaced sedimentary rocks (Scott, personal communication). It is likely, when assuming a drape-fold model of the area, that a thick section of Pierre Shale was raised to the west of the Golden fault trace as mapped by Scott and Cobban (1965), (Figure 18). This section was probably very unstable because of the inherent incompetence of the Pierre Shale (Scott, personal communication), the added weight of the basalt intrusives, and the suggested presence of localized over-pressured shale masses within the upper Pierre Shale in this area (Davis, 1974). This unstable mass of shale, deformed in the zone of plastic deformation and flow as illustrated by the drape-fold model, could then slump or gravity fault into the location of the area of sedimentary rocks which has been previously interpreted as a low-angle thrust fault (Figure 17).

The existence of this slump structure, as opposed to other similar structures which may have occured in the area, is very likely due to the number of intrusive rocks in the area which add competence to the sedimentary rocks (Scott, personal com-

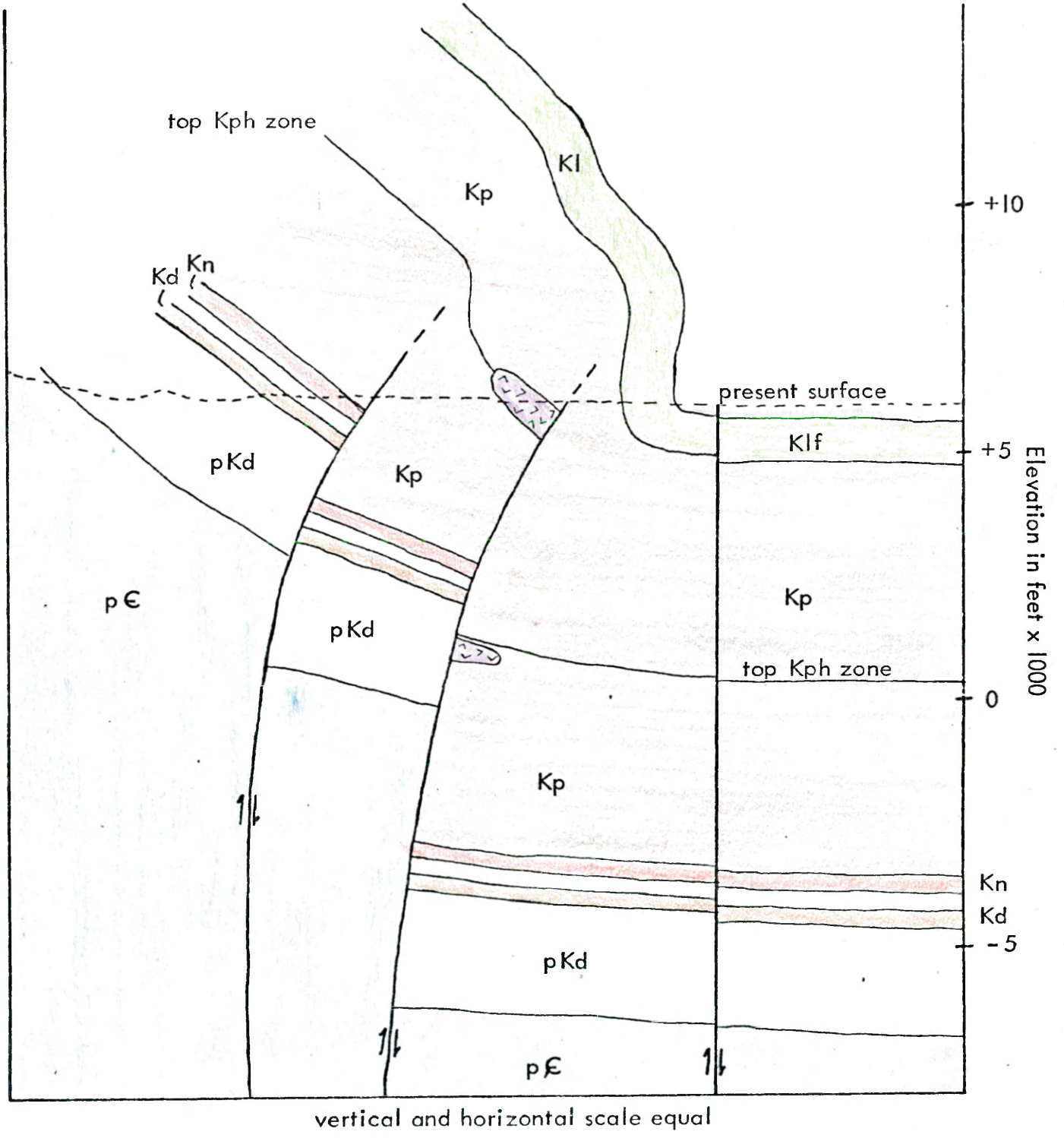

Figure 16. Geologic Cross Section of Drape-fold Structure. Refer to figures 5 and 6 for symbols.

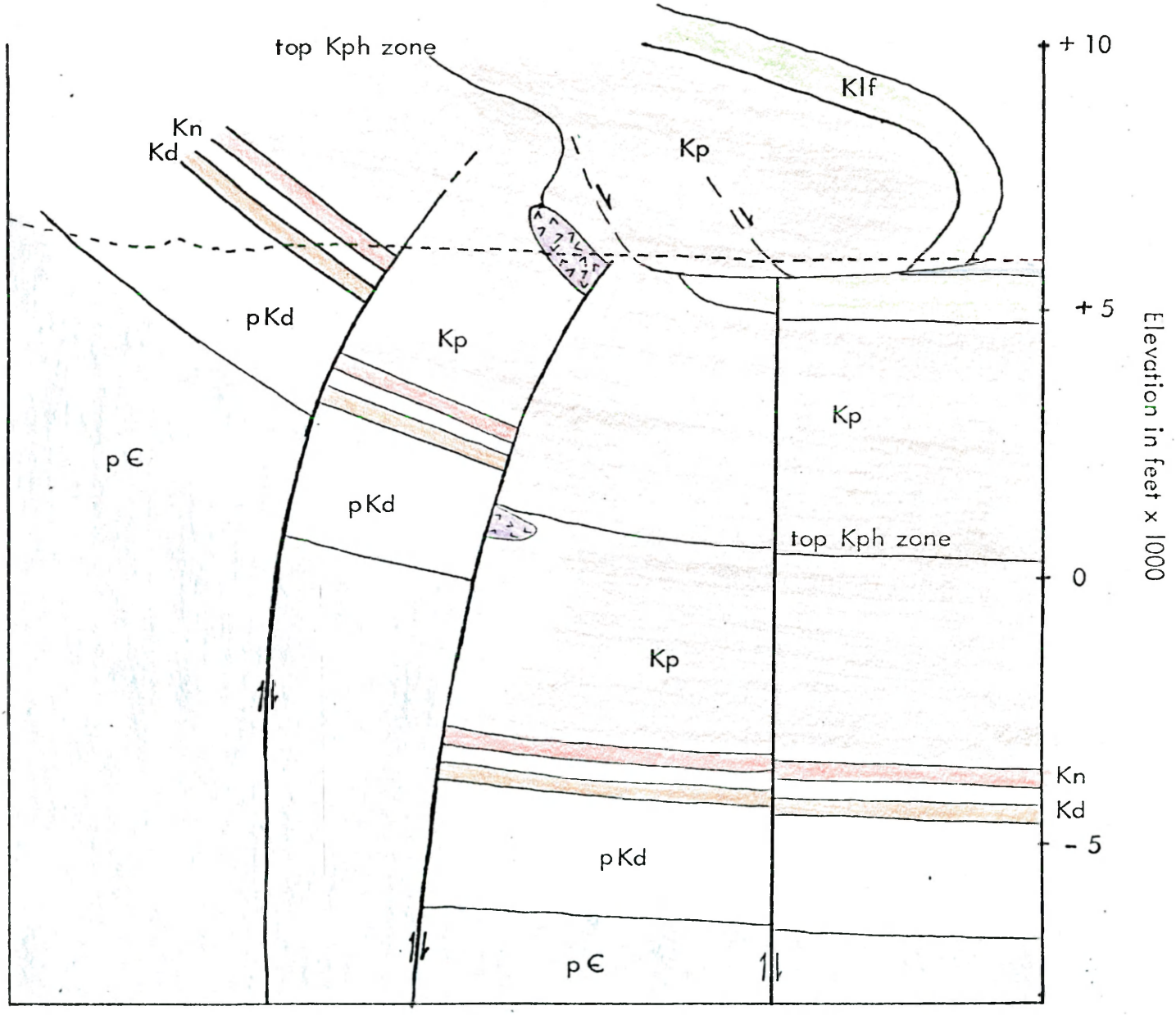

Figure 17. Geologic Cross Section of Slump Mechanism
Refer to figures 5 and 6 for symbols.

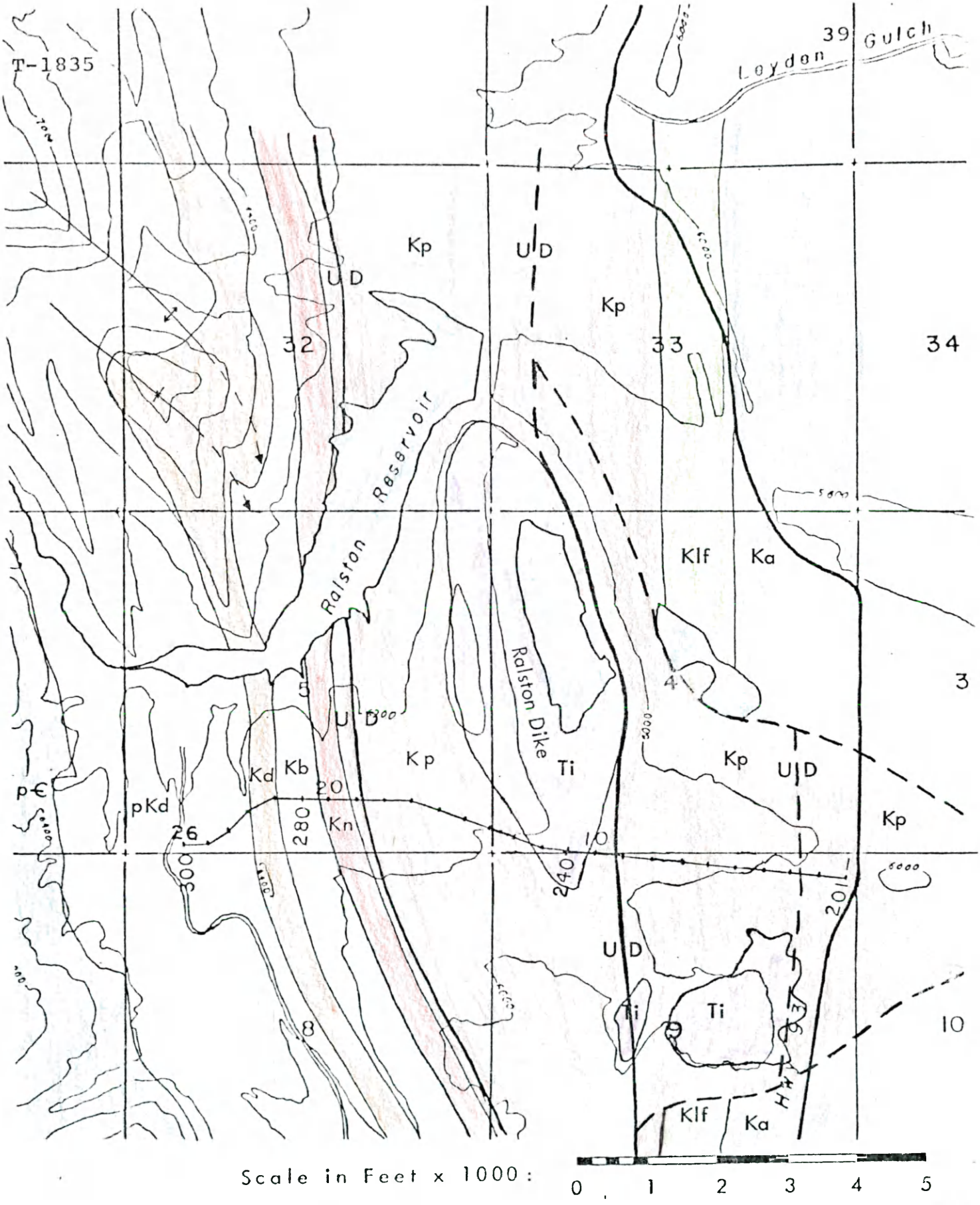

Figure 18. Tectonic Map of the Ralston Area. (modified after Scott and Cobban, 1965; Sheridan, et al., 1967; and Van Horn, 1972). Refer to figure 5 for symbols.

The location of the Ralston dike has diverted watershed from the slump area, helping to preserve the feature.

Erosion and deposition of Quaternary sedimentary rocks have resulted in the present geology and topography of the Ralston area (Figures 14 and 18).

Alternate Interpretations

The interpretation of the Golden fault as a low-angle thrust, by Stommel (1951) and Stewart (1951), is not compatible with the data obtained in the Ralston seismic survey. It is possible that a reinterpretation of the older data could lead to an interpretation similar to that of the Ralston data interpretation presented here. The location of the trace of the Golden fault far to the east of the Ralston dike is not consistent with either surface geology (Scott and Cobban, 1965) or with the location by the subsurface Ralston seismic data.

The interpretation of the Golden fault by Van Horn (1972) is very similar to the interpretation of the fault as derived herein, when considering trace location and dip angle. The following exceptions may be noted in the two interpretations: 1) Van Horn does not mention the western fault of the Golden fault zone or the basin-margin fault, 2) Van Horn shows vertical subsurface dips on the rocks to the west of the Golden fault whereas the interpretation of the Ralston line shows dips less than or equal to 60 degrees, 3) Van Horn shows a low-angle thrust fault near the surface associated with the Golden fault whereas the interpretation of this area using the data of the

Ralston seismic line and the drape-fold model, shows a slump.

The differing interpretations of the feature which has been described as a slump could be resolved by acquisition of more seismic data over the feature. This data should be of very high frequency, directed at obtaining data to a time of only about one-half second.

CONCLUSIONS

The data acquired for and used in this thesis are of sufficient quality and reliability to determine much more about the subsurface geology of the Ralston area than has been previously postulated from surface geology. From these seismic data and from previously published data, the following conclusions may be drawn:

1) The Ralston intrusive is a sill which has been rotated from an initial horizontal position to an orientation of 60 degrees east dip. This rotation occured as the sill was uplifted from the top of the Hygiene Zone of the Pierre Shale, to its present position. The Ralston intrusive does not continue to great depth in its present position.

2) The Golden fault zone is high angle with reverse movement in the Ralston area. The total displacement on the zone of faulting is about 8000 feet. The displacement is distributed between two major faults on the east and west of the zone. There is definite faulting in the pre-Pierre sedimentary rocks, but in the post-Pierre sedimentary rocks, drape-folding is the most probable method of deformation along the fault zone.

3) It is very likely that the area of displaced sedimentary rocks to the southeast of the Ralston dike was caused by a slump of the Pierre Shale. A mechanism for the slump, utilizing the drape-fold model to raise the shale to sufficient height, has

been described.

4) Specific contributions to the understanding of the geology of the Ralston area include: recognition of basin-margin fault in the Ralston area, recognition of the western fault of the Golden fault zone, the discovery of low-dip beds of sedimentary rocks under the Ralston dike, a mechanism for the displacement of the Ralston dike, and a mechanism which describes a slump to the southeast of the Ralston dike.

REFERENCES

Berg, R., 1962, Mountain flank thrusting in Rocky Mountain foreland, Wyoming and Colorado: Am. Assoc. Petroleum Geologists Bull., v. 46, p. 2019-2032.

Davis, T. L., 1974, Seismic investigation of late Cretaceous faulting along the east flank of the central Front Range, Colorado: Ph.D. thesis, Colorado School of Mines, 65 p.

Hoblitt, R., and E. Larson, 1975, Paleomagnetic and geochronologic data bearing on the structural evolution of the northeastern margin of the northeastern margin of the Front Range, Colorado: Geological Soc. of America Bull., v. 86, p. 237-242.

Laing, W. E., 1973, The "Vibroseis" system of exploration correlation theory - applications: Budapest International Fair, Budapest, Hungary.

LeRoy, L. W. and R. J. Weimer, 1971, Geology of the I-70 roadcut, Jefferson County, Colorado: Colorado School of Mines Prof. Contrib. No. 7.

Marvine, A. R., 1873, The annual report of the United States Geological Survey of the Territories, p. 129, 130.

Scott, G. R., 1972, Geologic map of the Morrison quadrangle, Jefferson County, Colorado: United States Geological Survey map I-790A, Scale 1:24,000.

_____ and W. A. Cobban, 1965, Geologic and biostatigraphic map of the Pierre Shale between Jarre Creek and Loveland, Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-439.

Seriff, A. J. and W. H. Kim, 1970, The effect of harmonic distortion in the use of vibratory surface sources: Geophysics, v. 35, p. 234-246.

Sheridan, D. M., et al., 1967, Geology and uranium deposits of the Ralston Buttes district, Jefferson County, Colorado: U. S. Geol. Survey Prof. Paper 520.

Stearns, D. W., 1971, Mechanisms of drape folding in the Wyoming Province: in Wyoming Geol. Assoc. Guidebook, 23rd Ann. Field Conf.

Stewart, W. A., 1953, Structure and oil possibilities of the west flank of the Denver Basin, North-central, Colorado: Ph.D. thesis, Colorado School of Mines, 121 p.

Stommel, H. E., 1951, Seismic investigations in the Golden-Denver area: Ph.D. thesis, Colorado School of Mines, 83 p.

Van Horn, R., 1957, Bedrock geology of the Golden quadrangle, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-103.

_____ 1972, Surficial and bedrock geologic map of the Golden quadrangle, Jefferson County, Colorado: U.S. Geol. Survey Geol. Quad. Map I-761-A.

Waldschmidt, W. A., 1939, Table Mountain lavas and associated igneous rocks near Golden, Colorado: Colorado School of Mines Quarterly, v. 34, no. 3, 62 p.

Weimer, R. J., 1973, Guide to Uppermost Cretaceous stratigraphy, Central Front Range, Colorado: Deltaic sedimentation, growth faulting, and early Laramide crustal movement: The Mountain Geologist, v. 10, no. 3, p. 53-97.

White, C. A., 1877, The annual report of the United States Geological Survey of the Territories, p. 195.