BOISE STATE UNIVERSITY • 1910 UNIVERSITY DRIVE • BOISE, IDAHO 83725

DEPARTMENT OF GEOLOGY & GEOPHYSICS

May 21, 1980

Dennis Goldman
E.G. & G.
550 Second St.
Idaho Falls, ID 83401

Dear Dennis:

Enclosed is the long awaited summary of the X-ray data collected over the last few years from Raft River. We never got to do the samples from hole 7 as we never recieved them. I decided to go ahead and write up the report as I am leaving BSU to go work for a DOE sub-contractor looking at the nuclear waste storage potential of salt domes. I hope the report will be of use to you. If you need to get in touch with me, my new address will be:

Jim Saunders
% Law Engineering Testing Co.
2749 Delk RD SE
Marietta, GA 30067

Sincerely,

Jim Saunders

LOW TEMPERATURE HYDROTHERMAL ALTERATION OF THE RAFT RIVER GEOTHERMAL AREA, IDAHO

May 12, 1980

James A. Saunders
Department of Geology and Geophysics
Boise State University

This report is for the Department of Energy and EG&G, Inc., from Boise State University under Department of Energy Contract No. DE-AS07-76ID01585 (formerly EY-76-S-07-1585).

LOW TEMPERATURE HYDROTHERMAL ALTERATION OF THE RAFT RIVER GEOTHERMAL AREA, IDAHO

INTRODUCTION

Many studies have been done recently on the hydrothermal alteration associated with high temperature geothermal systems such as Wairakei (Coombs and others, 1959), Roosevelt Hot Springs, Utah (Ballantyne and Parry, 1978), and Broadlands, New Zealand (Browne and Ellis, 1970). Alteration studies of low to moderate temperature geothermal systems are sparse, presumably due to their lesser economic importance. The present study attempts to characterize the alteration at one such geothermal system: the Raft River geothermal area. X-ray diffraction techniques were used to identify alteration minerals from samples of six of the deep geothermal wells drilled at Raft River.

LOCATION AND GENERAL GEOLOGY

The Raft River valley lies south of the Snake River plain in Cassia County, Idaho. The Raft River valley is a north-trending, down-faulted basin which is approximately 60 km long and 20 km wide. Seven deep wells have been drilled near the western edge of the valley to evaluate the geothermal potential (figure 1).

Tertiary clastic and volcaniclastic sediments and tuffs of the Salt Lake Formation overlie a Precambrian metamorphic complex within the Raft River basin (Devine and Bonnichsen, 1979). The Salt Lake Formation is 1600 m thick and is predominantly composed of gray to green tuffaceous siltstone and sandstone, minor claystone, conglomerate, tuffs, and minor rhyolite flows. The sediments are poorly sorted and contain highly angular detrital grains which suggests rapid

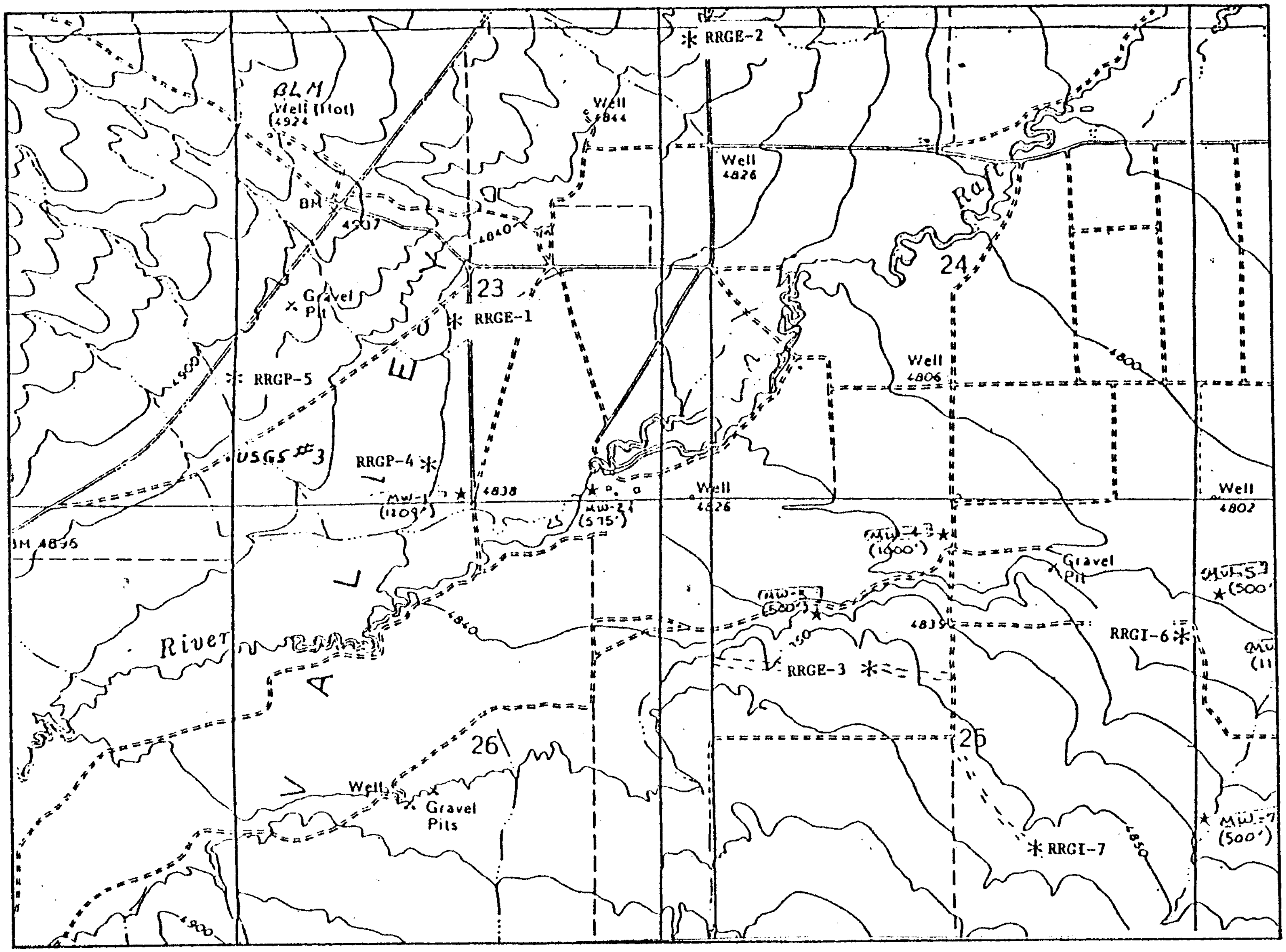

Figure 1. Location of geothermal wells in the Raft River valley.

deposition of the sediments. Rock fragments in the Salt Lake Formation suggest that the source area for the sediments is the surrounding mountain ranges. (Devine and Bonnichsen, 1979).

The Precambrian metamorphic rocks which underlie the Salt Lake Formation have been equated by Covington (1977a, 1977b, 1977c, 1977d, 1978, 1979a, 1979b, 1979c) to the metamorphic rocks exposed in the nearby Albion and Raft River ranges. Quartzite, muscovite schist, biotite, schist, muscovite biotite schist, and massive quartzo-feldspathic gneiss are the predominant metamorphic lithologies (Compton, 1972).

ANALYTICAL PROCEDURE

Well cuttings and a small amount of core from six deep geothermal wells from Raft River were analyzed using X-ray diffraction techniques. Samples chosen for analysis were based on lithological differences expressed by grain size, color, fissility, and mineralogy of the well cuttings. Sample intervals ranged from 10 to 30 feet, which corresponded to the sampling interval originally collected at the drill site.

After the samples were picked for analysis in the lab, they were split and crushed. Two seperate slides were prepared for each sample interval: a powdered slide made from the pulverized cuttings, and a sedimented slide. The sedimented slide was prepared by seperating colloidal size minerals from the coarser grains in water agitated by ultrasonic vibrations. After the agitation process, the colloidal size minerals are pipetted on a glass slide and allowed to dry. This procedure aids in the identification of clay minerals as it imparts a preferred orientation to the planar minerals and enhances peak height.

All of the samples were analyzed with a Siemens (type F) X-ray diffractometer and recording chart. Relative peak heights were used to give a semi-quantitative estimate of amounts of individual minerals present in the sample. A machine setting of 35 kv and 18 ma with a time constant of one second was used on all samples. The slides were scanned at a rate of one degree per one inch per one minute (1°/1"/1 min.) over a range of 2 - 32° 2θ.

Four scans were done for each sample set following the procedure of Carroll (1970). The powdered and sedimented were scanned initially and recorded on seperate charts. The sedimented slide is then glycolated by placing the slide in a desiccator containing ethylene glycol and heated to 40°C for one hour. Glycolation shifts peaks for certain clay minerals (notably montmorillonite) and aids in the interpretation of the pattern. The glycolated slide is then scanned and plotted on the sedimented slide chart in a different color. Next, the sedimented slide is heated to 600°C for one hour. This process destroys some clay minerals (kaolinite, montmorillonite) which eliminates their characteristic peaks. This scan is also superimposed on the sedimented chart which allows for quick interpretation after the scans are completed (Figure 2).

HYDROTHERMAL ALTERATION

The geothermal water at Raft River is believed to be associated with a localized heat source caused by the insulating effect of the Salt Lake Formation sediments in an area of anomalous heat flow (Applegate and Donaldson, 1977). Faults at the western edge of the Raft River basin serve as conduits for the upward movement of the hot water into the Salt Lake Formation sediments. The interaction of the hot water with the sediments (and the underlying metamorphics) caused the hydrothermal alteration observed at Raft River.

Several factors control the extent and intensity of the hydrothermal alteration (Browne and Ellis, 1970): temperature of the water, permeability and porosity of the rock, composition of the rock, composition of the water, pressure, and time for reaction to take place. Of these, the first three are the most important.

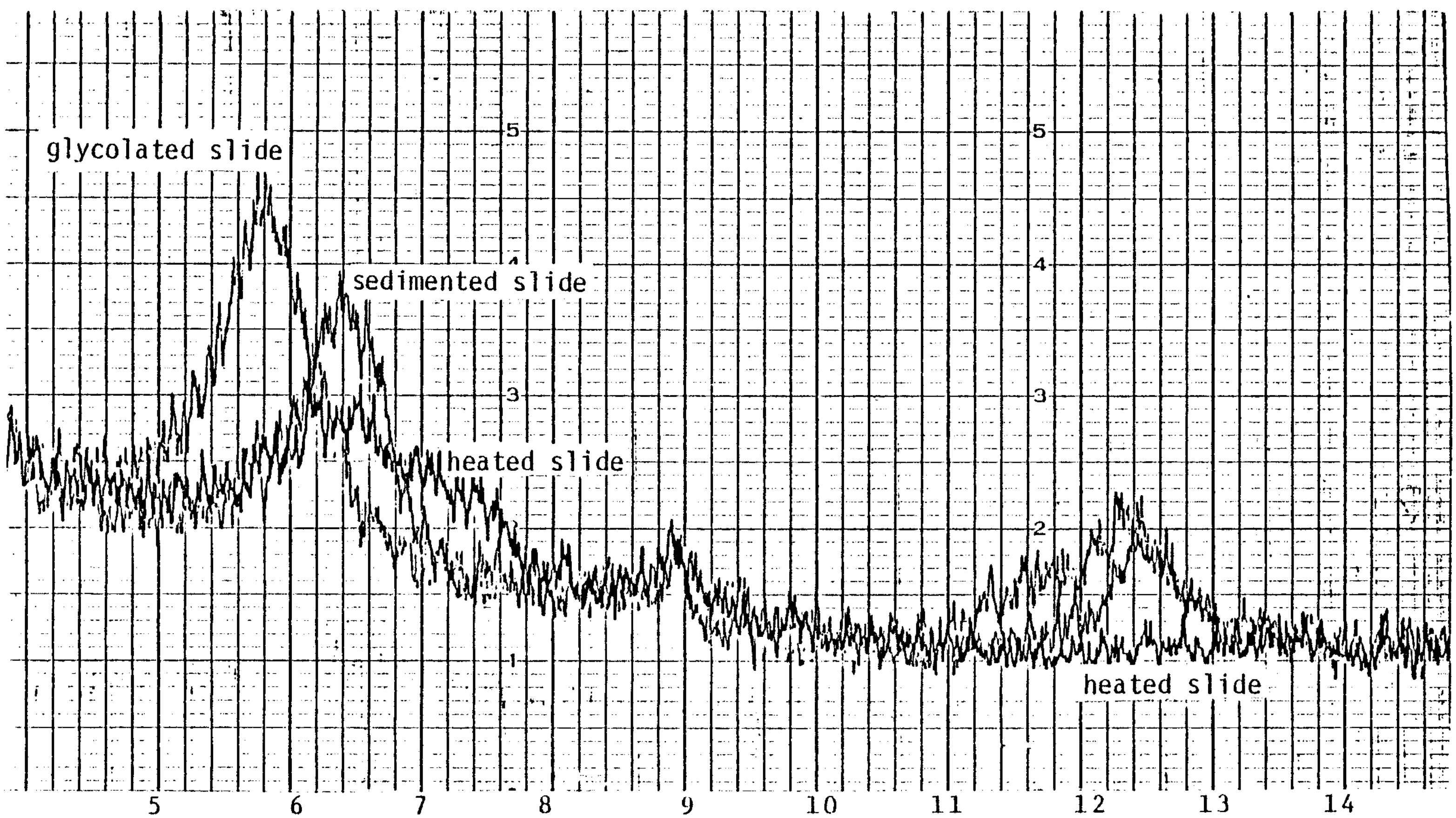

Figure 2. Effect of glycolation and heat on montmorillonite peak (left) and kaolinite (right). Horizontal scale is in degrees 2θ.

The most intense zones of alteration at Raft River presumably would form near the faults that served as the conduits for the geothermal water. As the water traveled into the aquifers, it would mix with cooler ground water decreasing the intensity of alteration.

The geothermal water at Raft River has a pH of 7.0-7.6, and a maximum temperature of 150° in RRGE-3 (Allen and others, 1979). Production ranges from a low of 571/min. in RRGP-4 to a high of 4739 l/min. in RRGE-1. Water composition ranges from 1161-6330 μg/ml total dissolved solids, most of which is Na^+ and Cl^-. Compared to other geothermal systems, the water at Raft River has a fairly low salinity and apparently is not a major factor in the hydrothermal alteration.

Several different alteration reactions are interpreted to have taken place at Raft River based on the original composition of the sediments. Ashy volcanic detritus is abundant throughout the sediments. The volcanic glass is extremely unstable when exposed to hot water, and will react quickly to form clay minerals (Steiner, 1963). The first clay mineral to form from the silicic glass would be montmorillonite, which grades into a mixed layer montmorillonite clay and then illite at higher temperature. Devine and Bonnichsen (1979) report numerous examples of the alteration of the ash to clay in their study of the thin section petrography of the Salt Lake Formation sediments. Volcanic ash also commonly reacts to form the zeolite analcime during hydrothermal alteration (Coombs and others, 1959).

Alteration of the primary clays within the sediments is also very common. Montmorillonite would be the most common clay mineral present in a soda or alkaline lake environment (Pettijohn, 1957), such as the Great Salt Lake. Minor amounts of illite may have also been primary. The primary montmorillonite would first react to form illite and possibly kaolinite at higher temperatures.

Feldspars are unstable in the presence of hot water and commonly alter to calcite and sericite. Devine and Bonnichsen (1979) report that this is quite common in the thin sections from Raft River. This alteration can be explained by the simple hydrolysis reaction for orthoclase:

$$\underset{\text{orth.}}{3KAlSi_3O_8} + 2H^+aq = \underset{\text{musc.}}{KAl_2Si_3AlO_{10}(OH)_2} + 2K^+ + 6SiO_2$$ (Meyer and Hemley, 1967)

A similar reaction can be written for plagioclase if some excess potassium is available (possibly from the above reaction if both feldspars are present). Ca^{++} would be one of the reaction products which would combine with CO_2 in the water to form calcite.

Ca and Al released by the alteration of plagioclase can also react to form zeolites. Zeolites commonly occur in veins with calcite in the sediments (Devine and Bonnichsen, 1979) and several different species have been identified with the X-ray unit.

The metamorphic rocks which underlie the sediments have also undergone hydrothermal alteration even though their porosity and permeability are significantly different. Clay minerals, zeolites, and chlorite are present in the cuttings and apparently form from the alteration of feldspars and biotite.

Some of the reactions described above may have also taken place during diagenesis. It is impossible at this stage to differentiate between purely hydrothermal reactions and diagenetic processes. In dealing with temperatures of alteration this low, the difference may only be in semantics.

ALTERATION MINERALOGY

A number of minerals have been identified using the X-ray diffractometer which are interpreted to be hydrothermal alteration minerals. The alteration minerals are plotted with the lithologic data from Covington in the appendix.

Layer Silicates

Montmorillonite is the most abundant clay mineral identified from drill cuttings from the Raft River geothermal wells. Montmorillonite is a 3-layer clay mineral with a formula that can be expressed as $Al_4(Si_4O_{10})_2(OH)_4$. Mg, Fe, and Ca commonly substitute in the octahedral layer. It is found in all of the lithologies of the Salt Lake Formation, but is most abundant in the tuffs and tuffaceous siltstones and sandstones. There is no apparent change in the abundance of montmorillonite with depth. Montmorillonite is rarely found in the metamorphic rocks that underlie the Salt Lake Formation sediments.

Other clay minerals commonly found in the sediments are illite [3-layer, $K_{0-2}Al_4(Si_{18}Al_{0-2})O_{20}(OH)_4$] and kaolinite [2-layer, $Al_4Si_4O_{10}(OH)_8$]. Both of these minerals are found in most of the sedimentary lithologies as well as the underlying metamorphics. The abundance of kaolinite and illite generally shows no relation to depth except in RRGP-4, where the abundance increases significantly between 4000-5000 feet (see appendix). The distribution of illite is fairly constant in all of the holes (except for the 4000-5000 foot interval of RRGP-4), while kaolinite apparently is much more abundant in RRGP-4. Mixed layer clays have also been identified, but are not very abundant.

Chlorite and muscovite are also present in many of the samples. Secondary muscovite forms from the alteration of the feldspars and chlorite commonly forms as an alteration product of biotite.

Zeolites

The most abundant zeolite mineral found in the samples is analcime ($NaAlSi_2O_6 \cdot H_2O$). Chabazite, $CaAl_2Si_4O_{12} 6H_2O$, and clinoptilolite, $(Na, K, Ca)_{2-3}Al_3(Al, Si)_2 Si_{13}O_{36} \cdot 12H_2O$, are less abundant than analclime. Laumonite, $CaAl_2Si_4O_{12} \cdot 4H_2O$, has been tentatively identified in two samples. The zeolites show no relation to depth in the holes and do not appear to be related to specific rock types. Devine and

Bonnichsen (1979) have identified secondary calcite and zeolite veins from the thin sections of the Salt Lake Formation. The zeolites also occur in the metamorphic lithologies. This imples that the formation of the zeolites is due at least in part to hydrothermal alteration and not entirely as the result of diagenesis, as Devine and Bonnichsen have indicated.

Calcite

Calcite occurs as primary cement in the sediments and as an alteration mineral in many of the samples. It occurs as an alteration product of the feldspars and in secondary veins with zeolites. Calcite has almost completely replaced the original rock in some cases, and the modal amount of calcite increases with depth (Devine and Bonnichsen, 1979).

DISCUSSION

The alteration mineral assemblage at Raft River is similar to the minerals present in the low temperature zones of higher temperature geothermal systems. At Wairakei, New Zealand, felsic pyroclastic rocks exhibit a distinct zonation of the hydrothermal alteration minerals related to increasing down-hole temperature of low salinity geothermal water (Coombs and others, 1979). Montmorillonite and chlorite are present between 100°C-150°C, and mordenite, a low temperature zeolite, is present between temperatures of 130°C-155°C. At Salton Sea, California, highly saline geothermal water has hydrothermally altered upper Cenozoic sediments in a zoned pattern. Montmorillonite is present at temperatures below 100°C, but is converted to illite at 100°C (Muffler and White, 1969). A mixed layer montmorillonite-illite mineral also forms about 100°C. Chlorite first appears at 150° and apparently forms as a reaction product of montmorillonite or kaolinite.

The comparison of Raft River to Wairakei and Salton Sea is significant because the Salt Lake Formation at Raft River can be considered a combination of the felsic volcanic rocks at Wairakei and the sediments at Salton Sea. The similarities of mineral assemblages between the three geothermal systems at 150° suggest that montmorillonite, illite, and low-temperature zeolite (± kaolinite) form an equilibrium mineral assemblage for this temperature and rock composition. The studies at Salton indicate that K-feldspar, K-mica, chlorite, and higher temperature zeolites (i.e., Wairkite) are present at higher temperatures.

One aspect of the hydrothermal alteration that deserves consideration is the effect of the alteration on the porosity and permeability of the host rocks. As mentioned above, the production zone of RRGP-4 (4000-5000 feet) appeared to be the most intensely altered zone (high content of clay minerals kaolinite and illite) at Raft River. Pump tests show that RRGP-4 could produce only 57 l/min., while RRGE-1, RRGE-2, and RRGP-5 produce over 2000 l/min. This suggests that intensive alteration of the rocks to clay minerals can greatly decrease the porosity and permeability, both in the sediments and in the fractured metamorphic rocks. Applegate and Moens (1980) have shown by cross-plotting geophysical well log parameters that the lack of production from RRGP-4 was the result of a lack of fracturing in the metamorphics coupled with alteration (porosity decrease) in the sediments.

SUMMARY AND CONCLUSIONS

Clay minerals,zeolites, and calcite have formed at Raft River from the hydrothermal alteration of clastic and volcaniclastic sediments by geothermal water in the range of 100°-150°C. Kaolinite is the clay mineral most abundant in the most intensively altered zones, but montmorillonite is most abundant overall. The amount of alteration can affect porosity and permeability of the country rocks, and more importantly, the economics of the geothermal resource. The alteration mineral assemblage should serve as an aid for exploration for other low temperature geothermal resources in similar geologic terrains.

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APPENDIX

PLOT OF ALTERATION MINERALOGY WITH LITHOLOGY*

Abbreviations of Alteration Minerals

Mm	montmorillonite
K	kaolinite
I	illite
Z	zeolites
Cc	calcite
Cl	chlorite
Ml	mixed layer clay

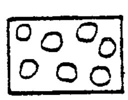
Abbreviations of Alteration Intensities

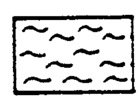
Vs	very strong
S	strong
Ms	moderate to strong
M	moderate
Wm	weak to moderate
W	weak

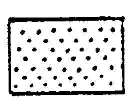
Abbreviations of Lithologies

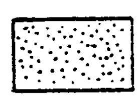
congl.	conglomerate
l.s.	limestone
monz.	monzonite
qzt.	quartzite
rhy.	rhyolite
s.s.	sandstone
sist.	siltstone

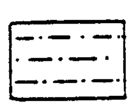
KEY TO LITHOLOGIC SYMBOLS

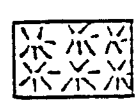
 conglomerate

 schist

 sandstone

 quartzite

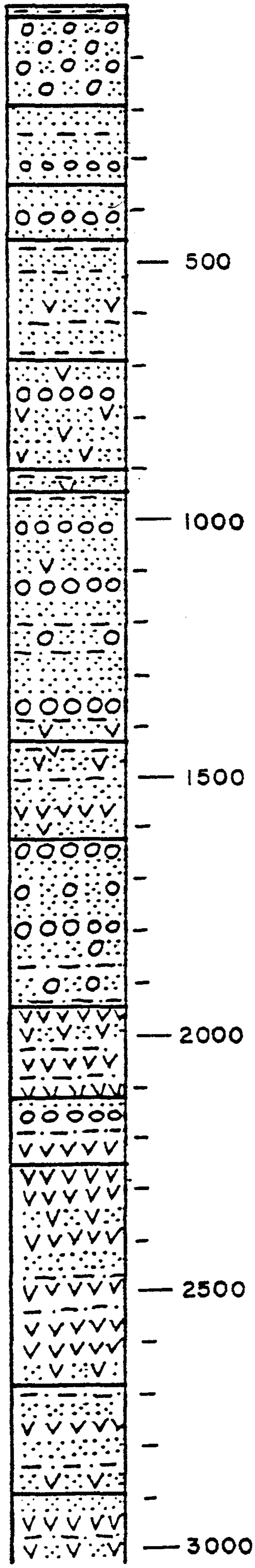
 siltstone

 quartz monzonite

 tuff

*Lithologic interpretation condensed from Covington (1977-1979)

RRGE-1



Loess, tan si, f.s.

RAFT Fm.
Tan s. & grav., subgranular pebl., cobl.

Tertiary lava of SALT LAKE Fm. (Tsj)

Green-gray f.-c.s.-si., 50-70% qz. & qzt.

SALT LAKE Fm.
Green-gray,s.s. & sist., qz & Tsj
Fresh glass shards

Green-gray c.g. tuff., s.s. & congl., alt: Tsj, qz,qzt,w/ 1% pyr.

Gray tuff. s.s. & tan calc. sis

Gray tuff., f.g.-m.g. s.s., Tss pebl.

Lt.-green tuff.,s.s. & sist. & interbedded tan weakly calc. sist.

Tan calc. sist.

S.s. & congl. of Tsj & qzt.

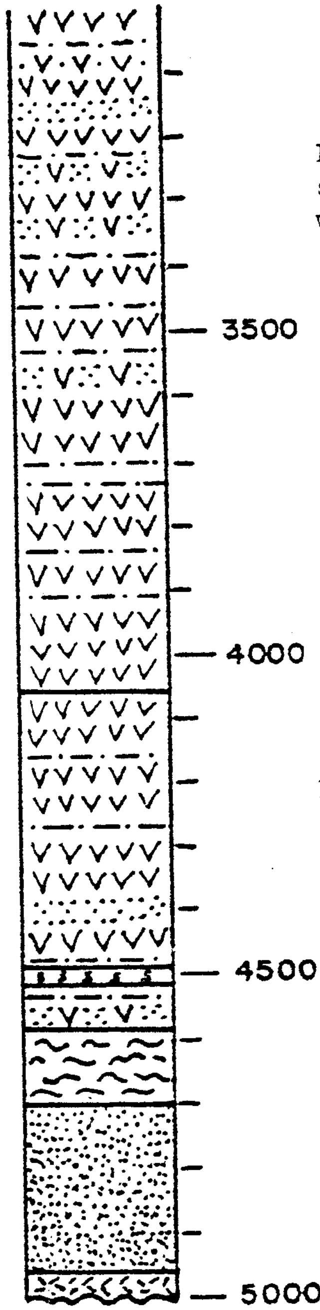
Lt.-green tuff & sist.

S.s. & congl. of Tsj & qzt. w/ lt.-green tuff & tan calc. sist.

Lt.-green tuff & sist. & s.s.

S.s.,tuff. w/ interbedded lt-green tuff & calc. silt.

RRGE-1



M-I,W-K,Z,M-Cc,M-Cl
W-Mm,M-I,Z,M-Cc
S-Mm,M-K,M-I,Z,M-Cc
M-Mm,M-I,M-K,M-Cc

Lt.-green & white sili. tuff., sist., & f.g. s.s. interbedded w/ weakly calc. sist.

M-Mm,M-I,M-K,Z,M-Cc

W-Mm,M-I,S-K,M-Cl

M-Mm,M-I,M-K,Z,M-Cc
W-Mm,M-I,S-K,M-Cl

Lt-green & white tuff & sist.

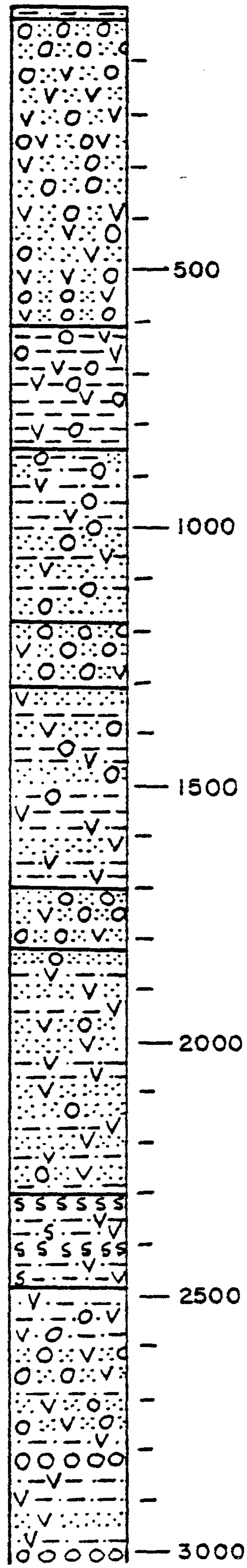
M-Mm,M-I.,M-K,Z

M-Mm,M-I,M-K,Z,M-Cc

S-I,S-K,M-Cl

Green speckled cellular sili., frac. slick, parent mater. is probably s.s. & sist.
Dk. gray, calc. c.s. & lt. gray tuff., s.s. cut by vert. frac.
SCHIST of UPPER NARROWS
Dk. gray qzt. w/ graphite & biot. schist., vugs w/ cal. & qz. xls in frac.
ELBA QZT.
Qzt., clear to white g. micaceous qt. xls in frac.
QZ. MONZ.

RRGE-2



S-Mm, W-Cc, Z

W-Mm, W-Cc, Z

S-Mm, Z

M-Mm, S-I, W-Cc, Z

S-Mm, W-Cc, Z

S-Mm, W-Cc

M-Mm, W-Cc, M-Ml

S-Ml

W-Cc, S-Ml

S-Ml

S-I, W-Cc, S-Cl

W-Cc, S-Ml

S-Cl, Wm-Ml

M-Ml

Wm-Ml

S-Ml

M-Cl

Grav. composed of pebl. & cobl. of Tert. lava of SALT LAKE Fm. (Tsj), tuff & qzt., s. matrix of qz. & tuff g. SALT LAKE Fm.

Tuff. cl., green calc., scattered pebl. of Tsj

Sist.-sandy to s.s. w/ si. interbeds, tan si., tuff., non to slight calc., green-gray s., tuff. slightly calc., scattered pebl. of Tsj

Grav. & s. of Tsj, tuff. & qzt., clayey calc. matrix w/ cal. & biot. flakes

Interbedded cl., si., & s., gray to gray-green calc., tuff., scattered pebl. of Tsj tuff, qzt.

S. & grav., primarily qzt., minor Tsj & tuff. pyr & biot.

Si. & s., gray, tuff., calc. scattered pebl. of Tsj, tuff, qzt. & l.s., pyr. & cal.

Magnetite below 2,120 ft.

Sist., gray-green, tuff., sili.

Si, s. & grav. interbedded, green, calc., tuff., grav. is Tsj, tuff, qzt & l.s.

RRGE-2

W-Ml
W-Cl,W-K
S-Mm,S-I,M-K,S-Cc,Z
W-Cl,M-K
W-Cl,M-K
S-Cl,S-K
S-Cl
M-Cl,W-K
S-Cl,Ms-Ml
S-Cl,Ms-Ml
S-Cl,M-Ml
M-Mm,M-Cl,S-K,M-Cc
Wm-Cl
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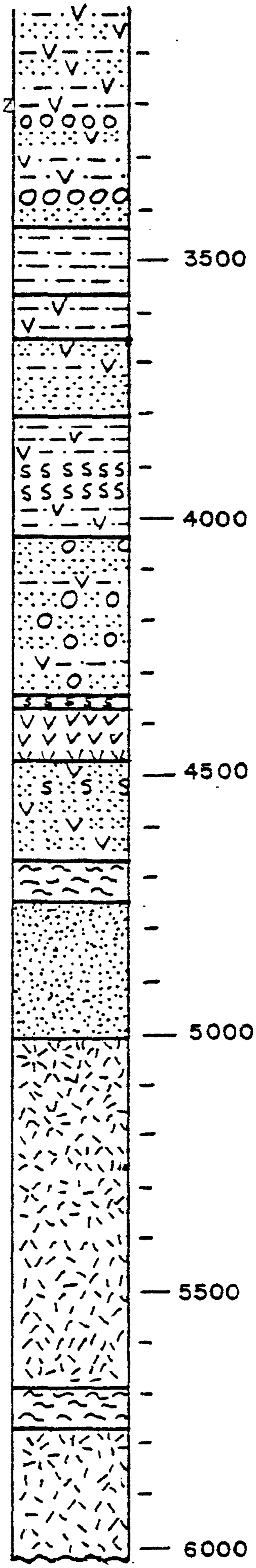


Sist, tan, calc.

Sist., green, tuff., pyr., minor Tsj, & qzt. pebl.
S.s., f. to m.g., sub-well rounded, minor tuff., sist. beds & scattered pebl. of Tsj, tuff., & qzt., pyr.
Alt. tan & lt. green calc. & tuff. w/ pyr. & sili. zone from 3,920 to 3,980ft.

S.s., abundant micas, scattered pebl. of qzt. & l.s., thin tuff. sist. beds, cal. flakes & abundant pyr.

Sili. sist., minor pyr.
Calc. tuff, dk. brown to gray, abundant cal. & qz. xls, frac., minor pyr.

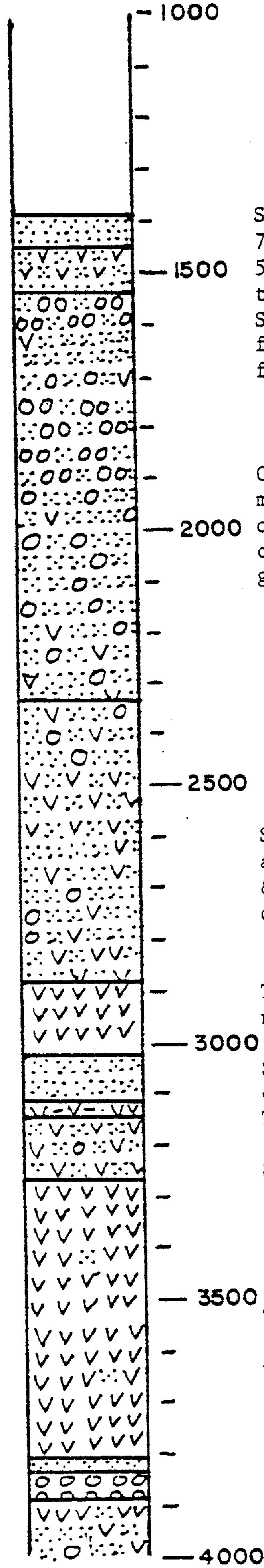
S.s., tuff., sili. zones, abundant pyr.,cal., & qz. xls
SCHIST OF UPPER NARROWS
Dk. gray qzt. & biot. schist, abundant magnetite.
ELBA QZT.
Qzt., clean, clear to white gray, trace of felds.

QZ. MONZ.

Gneissic, lt. greenish gray. white to clear qz. & felds., black to green chl. boit.

Chl. Schist, dk. green to brownish black
Gneissic, lt. greenish-gray, white to clear qz. & black to green chl. boit.

RRGE-3



S.s., lt. gray, slightly calc., 75% qz. & felds, 15% rhy., 5% tuff, 2% boit., 2% pyr., trace musc. & magnetite

S.s. lt. gray, tuff., calc, f.g., 50% tuff, 45% qz. & felds, 5% rhy.

Congl. & s.s., gray calc., minor tuff. congl. clasts of rhy. in a qz. s. matrix. c. s.s., angular to sub rounded g. of qz. & rhy.

S.s., gray to grayish brown, alt. calc. to non-calc., & tuff. w/ thin interbeds of rhy. pebl. congl.

S-Mm, M-I, W-K, Z, M-Cc

Tuff., lt. & dk. green laminae, non-calc.

S.s, qz. brown to gray tuff., calc, m.g.

Tuff., brown, calc, silty to sandy.

S.s., qz., brown to gray, tuff., calc., c. to m.g.

W-Mm, W-I, M-K, M-Cc, Cl

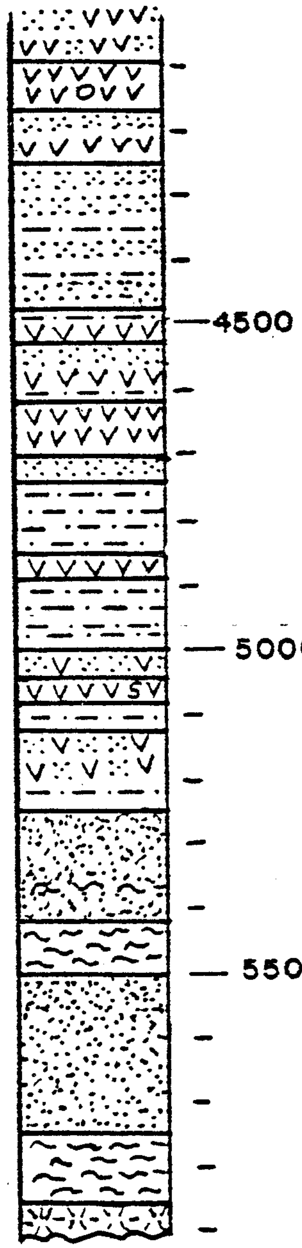
Tuff., greenish gray, slightly calc., silty to sandy, w/ scattered pebl. of rhy. & qzt.

S.s., qz., lt. gray, calc., m.g.

Congl., qz., qzt., & rhy. clast w/ a f.g., lt. gray, cal.c s. matrix

S-Mm, W-I, W-K, Z, M-Cc

RRGE-3



S.s., w/ interbeds of tuff, si, & congl.

S.s., qz., lt. gray, & calc. w/ abundant musc.

Tuff., alt. lt. brown & lt. green laminae, calc.

S.s., qz., brown to gray, calc. tuff, & tan, calc. sist. w/ qzt. pebl.

Alt. tan sist., & green tuff, calc

S.s., qz, tan & calc.

S.s., qz., tan, calc.

Sist., tan & calc.

Tuff., lt. green, sili., abundant pyr.

Sist., tan & calc. w/ scattered pyr. & thin qz. s. interbeds

S.s., gray, calc., tuff., f.g. w/ cal. flakes

Tuff., lt. green, calc. top, sili. bottom, abundant pyr.

Sist., tan to brown, calc., scattered pyr. & cal flakes

S.s., white to lt. green, tuff., slightly calc.

QZT. OF YOST., white

Schistose lenses of silvery to green micas

SCHIST of the UPPER NARROWS, qtz-boit-musc, abundant pyr. & magnetite

ELBA QZT., white to green w/ musc. on bedding surf.

OLDER SCHIST., boit.-chl-musc.-qzt., brown, abundant magnetite

QZ. MONZ., 40% qz., 40% felds., 20% boit. & chl., greenish gray w/ minor pyr. & magnetite

S-Mm, W-I, M-K, Z, M-Cc, Cl

S-Mm, M-I, M-K, M-Cc, M-Cl

S-Mm, W-I, M-K, M-Cc, M-Cl

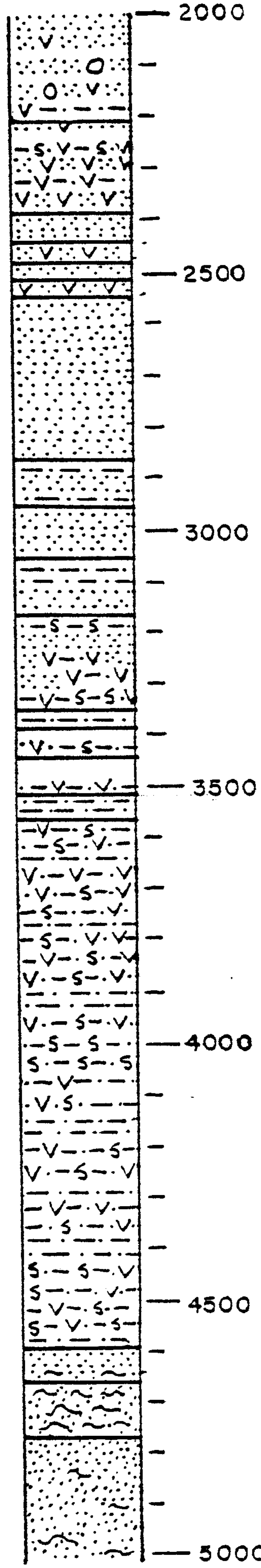
S-Mm, S-I, M-K, M-Cc

S-Mm, S-I, Wm-K, M-Cc

W-Mm, S-I, M-K, M-Cc

RRGP-4

W-K
W-Mm
W-Mm,M-I,S-K,Z,W-Cl
Wm-K,M-Cc,W-Cl
Ms-I,Vs-K,S-Cl
W-Mm
M-Mm,W-I,W-K,M-Cc
W-Mm,W-I,W-K,M-Cc
W-Mm,W-K,Z,W-Cc
W-Mm,W-K
S-Mm,W-I,W-K,M-Cc
W-I,W-K,W-Cc
W-Mm,W-I,M-K,M-Cc,W-Cl
M-Mm,W-I,M-K,Z,W-Cc
M-Mm,M-I,M-K,Z
M-Mm,M-I,W-K,S-Cc,W-Cl
W-Mm,M-I,S-Cc
W-I,W-K,Z
M-I,S-K,Z
M-Mm,M-I,W-K,S-Cc
S-Mm,W-I,W-K,Z,M-Cc
S-Mm,Z,W-Cc
M-Mm,W-I,S-K,Z,M-Cc,W-Cl
W-Mm,M-K,Z,M-Cc,W-Cl
W-Mm,M-K,Z,M-Cl
S-K,Z,W-Cl
W-Mm,W-I,S-K,M-Cl
S-K,Z,W-Cl
S-K,Z,W-Cl
W-Mn,M-I,S-K,W-Cc
S-K,Z,W-Cl
M-K
W-I,M-K,W-Cc,W-Cl
W-I,M-K,Z,W-Cl
S-I,M-K,W-Cl
S-I,M-K,W-Cl
S-I,M-K,W-Cl
W-I,M-K,W-Cl



S.s., sist., lt green, tuff, partly sili., micas.
S.s., gray-green, c.g.
S.s., tan-green, m.g., w/ micas, tuff.
S.s., c.g., calc. w/ micas.
S.s., tan, m.g., micaceous.

S.s., gray-green, f.g.-c.g., micaceous.
S.s., gray-green, micaceous, f.g.-c.g.
S.s., gray-green, f.g.-c.g., calc., micaceous, w/ analcite

S.s. & sist., gray-green, tuff., mica, calc., partly sili.

Sist., gray, micaceous, calc.

Sist., lt. green, tuff.

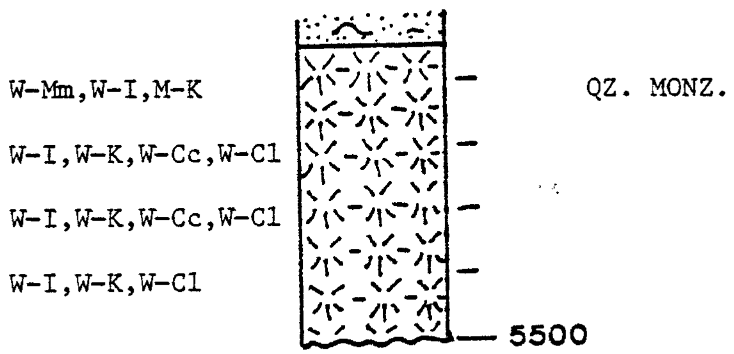
Sist, gray to tan micaceous, calc.

Sist., lt. gray-green to white, tuff., slightly calc.

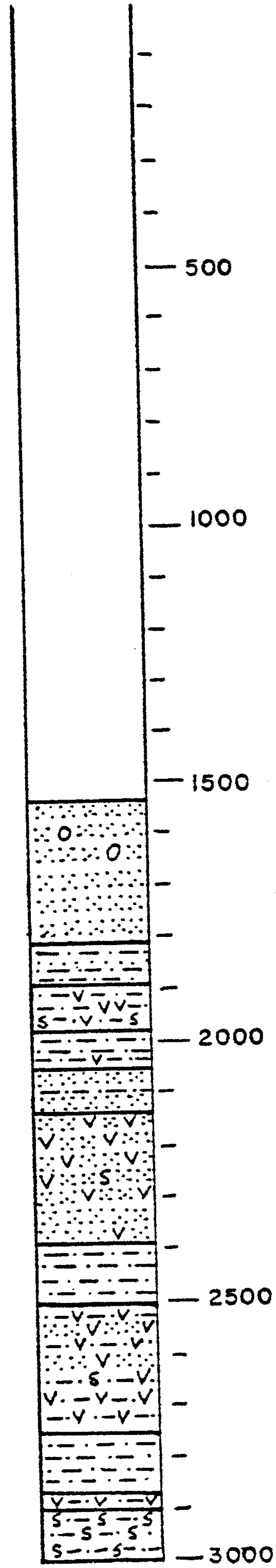
QZT. of YOST; 40% qz., 50% green, black,white micas, 5% felds.
SCHIST of UPPER NARROWS
qz. schist, micas w/ qzt.

ELBA QZT; 5-10% felds. w/ interbedded schist.

RRGP-4



RRGP-5



W-Mm
W-Mm,W-I,M-Cc
Ms-Mm,S-I,Wm-Cc,W-Cl

Wm-Mm,W-I,Wm-K,Z,W-Cl
W-Mm,Wm-I
S-Mm,Ms-I,W-K,M-Cl

S-Mm
S-Mm,W-I,W-K,M-Cl,Z

S-Mm,Wm-I,W-K

S-Mm,W-I,W-K,Z,W-Cc
Wm-K,Z,M-Cl

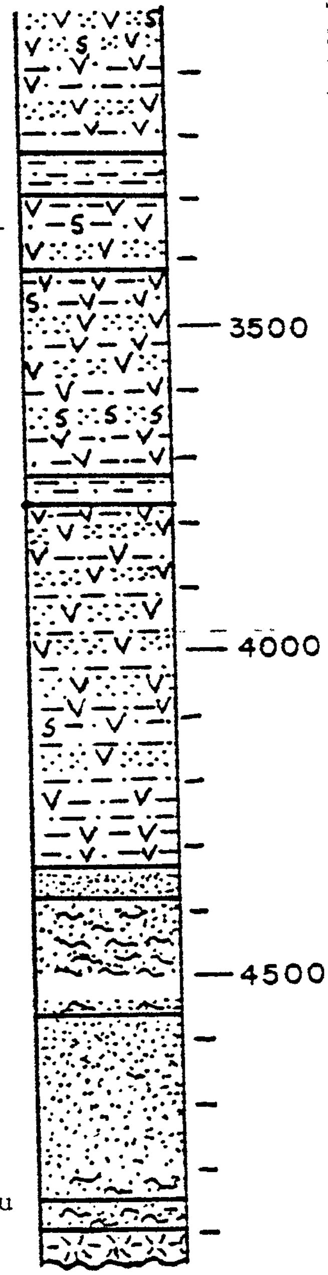
Wm-K,Z,M-Cl

W-Mm,Wm-I,Wm-K,Z,W-Cl

W-Mm,Z,W-Cc

S.s., c.g., poorly consol., qz., felds, qz. monz., l.s., clasts
Sist., tan to gray, calc., micaceous, & sandy
Sist., lt. gray-green, tuff., micas, sandy
Sist., tan calc., micas.
S.s., f.g., calc., micaceous, clasts of Tjs, qz, felds, qzt. sist., lt. gray to tan, calc., micaceous.
S.s., f.g., lt. green-gray, calc., tuff. & micaceous
Sist., gray-green, calc., tuff.
Sist. interbeds of f.g. s.s. & gray tan, calc, clst.
Sist. & f.g. s.s., lt. tan to gray, slightly calc., partly tuff. w/ little sili.
Sist., tan to gray, calc. & micaceous, partly sili.
Sist., lt.-green, tuff., abundant pyr & cal.
Sist., tan-gray, sili w/ abundant pyr, mica & cal. flakes.

RRGP-5



M-Mm,Z,S-Cc,W-Cl
M-Mm,W-I,W-K,Z,M-Cc,W-Cl

W-K,Z,W-Cc,W-Cl

W-K,Z,W-Cl

W-I,Wm-K,Z
W-I,Wm-K,Z
W-I,Wm-K,Z,W-Cl

W-Mm,W-I,Wm-K,Z,W-Cl

W-Mm,W-I,Wm-K

W-Mm,Wm-I,W-K,W-Cc,Mu

W-Mm,Ms-I,W-K,W-Cl,W-Mu

W-Mm,Wm-I,W-K,Z,W-Cl,
W-Mu

S.s. & sist., lt. greenish-
gray, partly calc. to sili.,
tuff., & micaceous, w/ abundant
pyr & cal. flakes

Sist., tan, calc., & micaceous

Sist. & s.s., partly sili.
sist, lt. green, tuff., slightly
calc., w/ abundant pyr & gyp.
S.s., f.-m.g., lt. green,
tuff., slightly calc.

Sist., lt.-dk. gray, calc.,
micaceous w/ abundant cal. g.

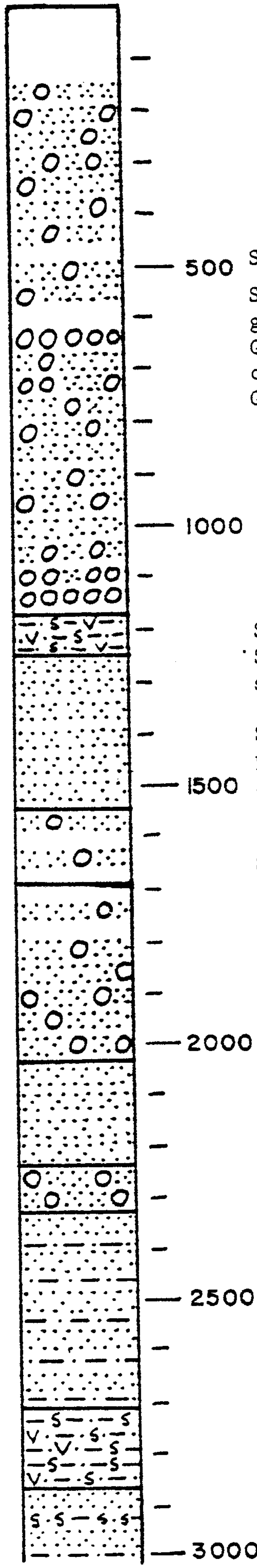
Sist. & f.g. qz., s.s. lt.
green, calc., tuff. & micaceous
w/ pyr & gyp. g.

C.g. s.s. w/ clasts of qzt.,
Qz. Monz., schist & felds.
QZT. OF YOST; clean to white,
10% felds, 5% boit. & chl.

SCHIST of UPPER NARROWS
Qz. schist, gray to brown,
25-75% qzt.
ELBA QZT; clear to milky
white, 5% felds., free qz.
xls & cal. flakes.

OLDER SCHIST; 20-50% qzt.,
clear to white w/ 5% felds.
schist, 50-80%, musc, chl.
QZ. MONZ., 40% qz., 30% felds,
30% plag.

RRGI-6



W-Cl,W-Mm

S. & grav. poorly consol.

S., c., subangular to well rounded g. of qz., schist, & rhy.

Grav., subangular to well rounded clasts of rhy.

Grav. beds w/ clasts.

Ms-Mm,M-I,Z

SALT LAKE FM.

Sist., lt. green, tuff, partly sili & calc.

Ms-Mm,M-I,Z

S.s., lt. green, m. to c.g., poorly consol., 60-80% qz, 20-40% rhy.

S-Mm,M-I,Z,W-Cc

S. & grav., 60-80% s., 20-40% grav., poorly consol.

Ms-Mm,M-I,Z

S-Mm,S-I
Wm-Mm,Wm-I

S., lt. green, c.g. & poorly consol., subangular to rounded qz. g., weak calc. cement.

W-Mm,W-I

Grav., poorly consol., w/ qz. s. matrix & weak calc., matrix rhy & qzt. clasts.

S-Mm,Ms-I,Wm-K,Z,W-Cl

S-Mm,Wm-I,W-K

S.s. & sist., alt. beds, cal. flakes, si, lt. gray, calc & micaceous, s., m. to c.g. poorly consol., subangular to subrounded g. of qz & rhy.

M-Mm,Wm-I,W-K,Wm-Cl
M-Mm,M-I,W-K,Z,W-Cl

W-Mm,Wm-I,Z,W-Cl

Sist., lt. green, tuff., partly sili.

M-Mm,M-I,Z,W-Cl
Ms-Mm,Ms-I,Wm-K,Z,M-Cl

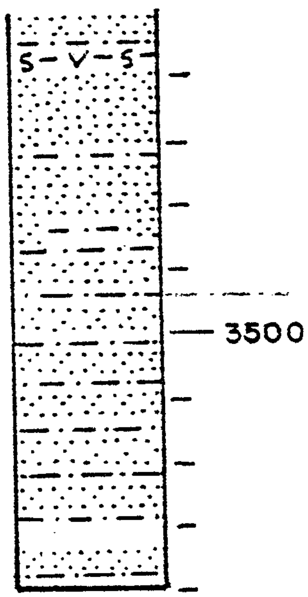
RRGI-6

M-Mm,Wm-I,M-K,Z,W-Cc,
W-Cl
Wm-I,M-K,Z,M-Cl

M-Mm,Wm-I,W-K,Wm-Cl

M-Mm,M-I,M-K,Z,Wm-Cc,
M-Cl

M-Mm,M-I,M-K,Z,M-Cl
Ms-Mm,Wm-I,M-K,Z,M-Cl



S.s. & sist., alt. beds
S.s., lt. gray to green-gray, f. to c.g., calc. w/ qz & rhy.
Sist., lt. gray-green, calc., micaceous.

be correlated with three post-Provo rises of the lake discovered by Morrison (1961) at successively lower altitudes below the Provo shoreline.

The glaciers probably disappeared entirely from the mountains and the lake was again dry during the "altithermal age" of Antevs (1948). Subsequently, two sets of small moraines or rock glaciers have formed in the cirques. These represent the Temple Lake and historic stades [1] of neoglaciation [2], both of which occurred during the "little ice age" of Matthes (1939).

Numerous workers, including Gilbert (1890, p. 309–310), Atwood (1909, p. 92–93), Antevs (1945, p. 74–77), Blackwelder (1931, p. 915–916), Ives (1950, p. 115), and Hunt, Varnes, and Thomas (1953, p. 41), have concluded that the second rise of Lake Bonneville—that which attained the Bonneville shoreline and was lowered by erosion at its outlet to the Provo shoreline—was correlative with the last Pleistocene glaciation of the mountains. The present evidence indicates the deposits of the rise to the Bonneville shoreline and of the stillstand at the Provo shoreline are correlative with the later of two stades of Bull Lake glaciation. Only certain lower fluctuations of the lake following post-Provo dessication and preceding the "altithermal age" are correlative with the last or Pinedale glaciation.

The Pinedale glaciation, on the basis of a radiocarbon date of 27,000±800 years from its outer moraine in Jackson Hole, Wyo. (Rubin and Alexander, 1958) seems to include all of the Wisconsin stage as defined by Leighton (1933), for the Farmdale loess of Illinois is probably not much older than 26,100±600 years (Frye and Willman, 1960). The deposits of the Bull Lak. glaciation are stratigraphically lower than those of the Pinedale, and are separated from them by deglaciation, erosion and the development of a mature zonal soil. No such pronounced climatic break has been recognized in the classical succession of Wisconsin deposits in Illinois. Thus, it may be concluded that the deposits of the two high-level rises of Lake Bonneville is recognized by Gilbert (1890), including those of the standstill at the Provo shoreline, are older than Wisconsin.

[1] A stade is defined as a climatic episode within a glaciation during which a secondary advance of glaciers took place (American Commission on Stratigraphic Nomenclature, 1961, p. 660).

[2] The neoglaciation is hereby defined as the last glaciation in the Rocky Mountain region. It is of post-Pleistocene (Recent) age.

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335. MAGNITUDE OF THRUST FAULTING IN NORTHERN UTAH

By MAX D. CRITTENDEN, JR., MENLO PARK, CALIF.

The Bannock, Willard, Charleston, and Nebo faults are part of a discontinuously exposed belt of overthrusts that extends from Montana and Idaho to southeastern Nevada. So far as known, all are rooted to the west, and all have brought thicker basin-type facies over thinner shelf-type rocks to the east. The resulting contrast in thickness or character is evident in rocks ranging in age from Precambrian to Permian.

In Utah, the northernmost segment of this thrust belt extends from a branch of the Bannock thrust near

U.S. Geological Survey, Professional Papers. 1961, Page 128-131.

Bear Lake to the Willard thrust on the crest of the Wasatch Range near Ogden. Together these thrusts define an overriding structural block that is characterized by a thick basal Cambrian quartzite resting on at least 6,000 feet of Precambrian sedimentary rocks. The block beneath the thrusts is characterized by a thin basal Cambrian quartzite, which rests directly on highly metamorphosed Precambrian rocks older than those of the upper plate. The structure within the block is that of a simple syncline; the same Cambrian formations can be traced around the fold, and serve to establish structural continuity from one thrust to the other.

The southern segment of the belt of overthrusts consists of the Charleston and Nebo thrusts, which together outline a bulging lobe of basin-type rocks that extends eastward to the edge of the Uinta Basin. The overriding block in this segment is characterized by some 30,000 feet of beds between the Humbug formation of Mississippian age and the Park City formation of Permian age, whereas in the autochthon to the east the same stratigraphic interval contains less than 2,000 feet of beds.

The structural continuity between the northern and southern segments of this belt is speculative because neither the thick unmetamorphosed Precambrian sedimentary rocks of the northern block nor the thick Pennsylvanian and Permian rocks of the southern block extend unbroken from one block into the other. Nevertheless, parts of the Oquirrh formation have been identified by Olson (1956) in the Promontory Range, where they are in sequence above thick unmetamorphosed Precambrian rocks. This relation serves to establish the kinship of the two blocks, though the thrust itself is concealed. The trace shown on figure 335.1 is regarded as the likeliest of several possibilities. Antelope Island, underlain largely by highly metamorphosed Precambrian rocks, is regarded as autochthonous. The thin (288-foot) wedge of Precambrian shale, dolomite, and tillite reported there by Larsen[1] may be the landward edge of a depositional basin that originally lay to the west. Overlying tan or pink conglomeratic quartzites are believed to be equivalent to the Tintic quartzite and are therefore not of Precambrian age. Deformation of these quartzites into nearly isoclinal folds in which there was sufficient axial plane shearing to produce marked stretching of quartzite pebbles, suggests that the thrust plane passes close to the northwestern tip of Antelope Island, and that the thick sequences of unmetamorphosed Precambrian rock on Fremont Island and Promontory Point are allochthonous.

[1] Larsen, W. N., 1957, Petrology and structure of Antelope Island, Davis County, Utah: Utah Univ., unpublished Ph. D. thesis.

Estimates of the displacement on thrusts of this belt range from as little as 12 miles (Hintze, 1960, p. 2062) to as much as 75 miles (Eardley, 1951, p. 330). The first estimate is based entirely on observations within the allochthon, and hence does not give information about the total movement with respect to the autochthon. The second, though larger than those derived below, appears to be possible from stratigraphic evidence.

The minimum displacement of the northern block is best estimated from the relations of its characteristic unmetamorphosed Precambrian sedimentary rocks. If, as suspected, Antelope Island represents the easternmost edge of the principal depositional basin, the 7,000-foot sequence of these Precambrian rocks exposed east of Ogden must have come from somewhere west of the present site of the island, a distance of at least 30 miles. Lack of information as to the rate of thickening makes it impossible to estimate how much farther west they may have originated.

Other evidence is obtained from the relative effects of the Devonian-Mississippian unconformity (fig. 335.1, p. D-130), as expressed by the thickness of beds between it and the top of the Tintic or its stratigraphic equivalent, the Brigham quartzite. The 6,000-foot isopach in the thrust block meets the Willard thrust opposite the 2,000-foot isopach in the footwall. Projecting the isopachs eastward at the same rate as those known within the allochthon suggests about 40 miles of displacement on the thrust. A similar result is obtained from the data for rocks of Mississippian age (fig. 335.2). Isopachs representing some 4,000 to 5,000 feet of beds in the overriding block meet the Willard thrust opposite the line representing some 1,800 feet of beds in the autochthon. Here, also, a movement of some 40 miles is required to restore the continuity of the two sets of isopachs.

Displacements of the Charleston-Nebo block can best be estimated by reconstruction of the general form of the Oquirrh basin (fig. 335.3). As there is no evidence for the configuration of the now-destroyed east half, its general outline and the maximum slopes have been made approximately symmetrical with the west half. On such a basis, a displacement of about 40 miles is likely. Obviously, different assumptions regarding configuration and slope would yield values ranging from half to twice this amount.

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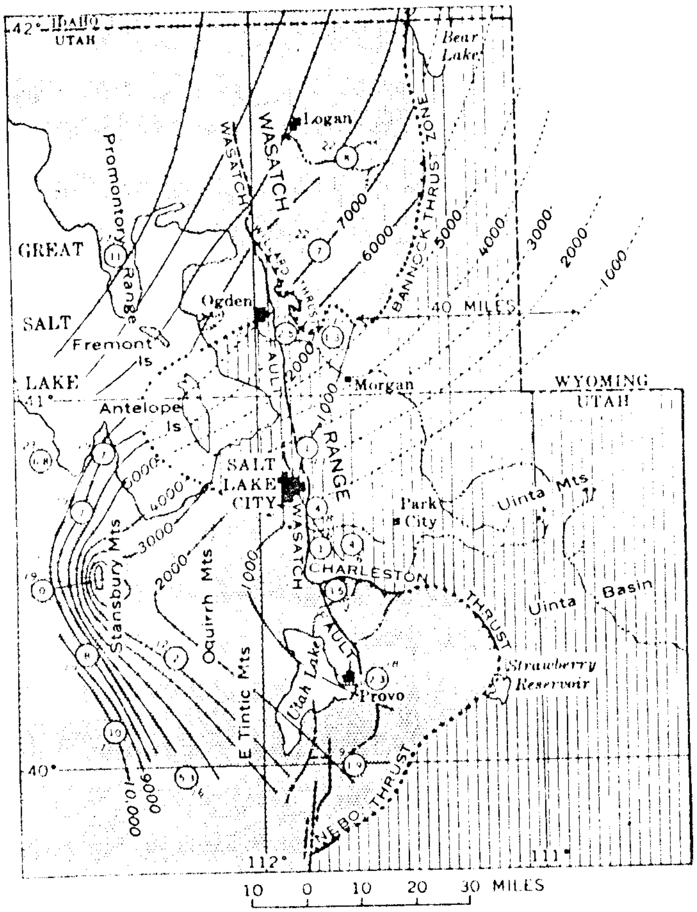


EXPLANATION

Area underlain by thick sequence
Isopach interval 1000 feet

Area underlain by thin sequence
Isopach interval 1000 feet

Steep fault
Dashed where inferred

Thrust fault
Dashed where inferred, dotted where concealed
Saw teeth on upper plate

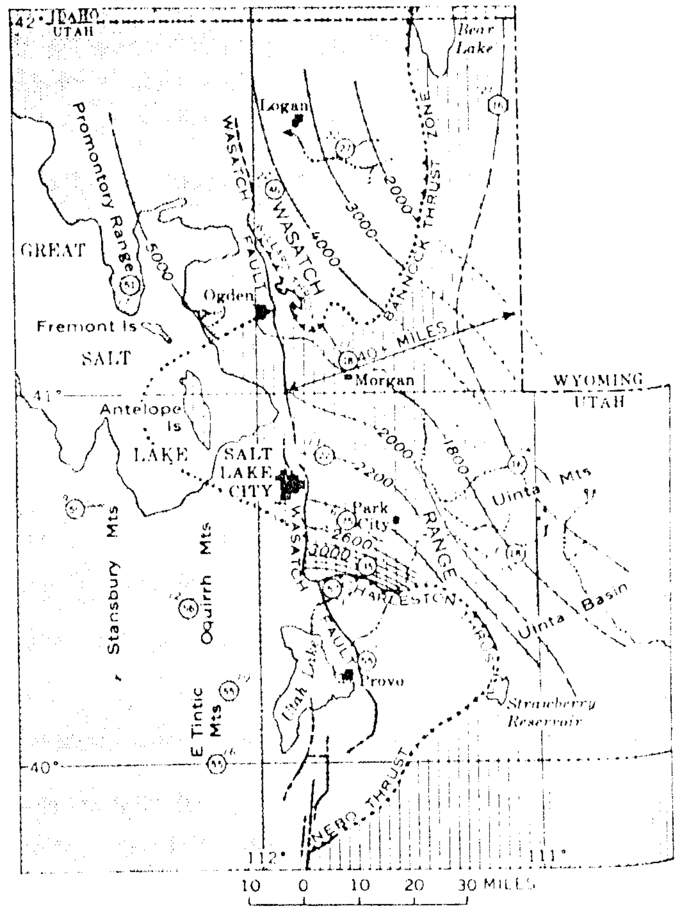
——2000 – – – ···

Isopach connecting points where rocks between Tintic quartzite and Devonian-Mississippian unconformity are of equal thickness
Dotted to show former extent across autochthon

Displacement needed to connect corresponding isopachs

Location of measured section
Outside number refers to reference listed in table; number in circle is thickness in thousands of feet

FIGURE 335.1.—Displacement on Willard and Bannock thrusts based on thickness of beds between top of Tintic quartzite and the Devonian-Mississippian unconformity.



EXPLANATION

Area underlain by thick sequence
Isopach interval 1000 feet

Area underlain by thin sequence
Isopach interval 200 feet

Steep fault
Dashed where inferred

Thrust fault
Dashed where inferred, dotted where concealed
Saw teeth on upper plate

– – – 3000 – – – – –

Isopach connecting points where Mississippian rocks are of equal thickness
Dashed where inferred, dotted to show projected position across autochthon

Displacement needed to connect corresponding isopachs

Location of measured section
Outside number refers to reference listed in table, number in circle is thickness in hundreds of feet

FIGURE 335.2.—Displacement on Willard and Bannock thrusts based on thickness of Mississippian rocks.

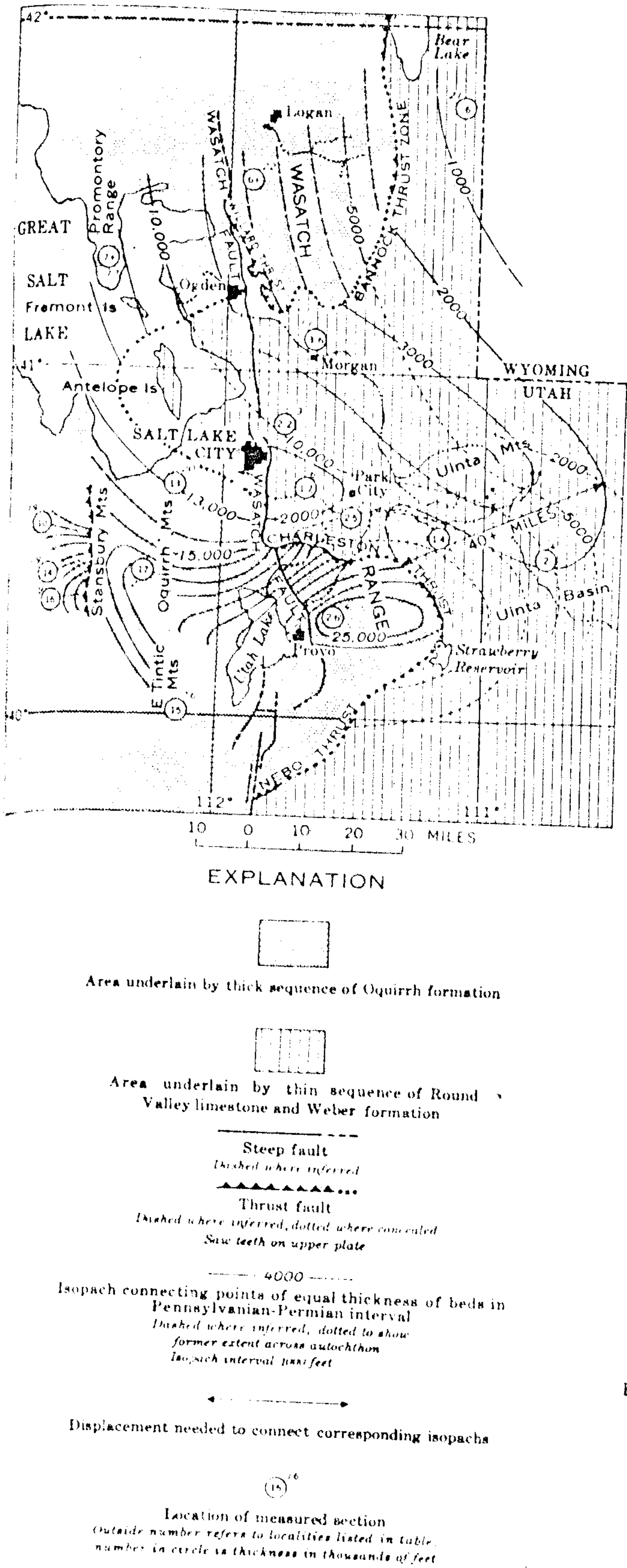


TABLE 335.1.—*References to measured section given on figures 335.1–335.3*

No. on map	Reference
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2	Unpublished data.
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FIGURE 335.3.—Displacement on Charleston and Nebo thrusts based on thickness of Pennsylvanian and Lower Permian rocks.