A Geophysical Characterization of the Soda Butte Creek Drainage, Yellowstone National Park

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Executive Summary

At the invitation of Dr. Wayne Hamilton (Yellowstone National Park), Dr. William Sill and Dr. Marvin Speece met in the spring of 1995 to discuss the use of geophysical investigations at sites along the Soda Butte Creek drainage. The proposed project involved a graduate student, Eric Nyberg, and equipment from the Geophysical Engineering Department at Montana Tech. Summer employment for the graduate student, field assistance, and supervision were provided by Dr. Hamilton.

The geophysical characterization of the Soda Butte Creek drainage was performed in order to obtain knowledge about the area's subsurface. Subsurface information was acquired by performing both seismic refraction and electrical resistivity measurements. The determination of the valley fill thickness, its composition, the thickness of the local aquifer, and the identification of bedrock were key objectives for this project.

The results of the study indicate that both the maximum valley fill thickness and aquifer thickness are in the neighborhood of 100 ft; furthermore, the fill consists primarily of sands and gravels. The lack of clay layers suggests that the aquifer may be highly permeable. Finally, the bedrock unit which underlies the valley fill is most likely the Flathead Sandstone, a Cambrian-age unit which exhibits a low effective porosity under laboratory studies. Field measurements, however, suggest that the sandstone has a higher porosity which is probably due to fractures. Thus, groundwater flow occurs predominantly through the valley fill, but fracture flow through the bedrock may also exist.

In the body of this report, seismic cross-sections are presented for three profiles across the Soda Butte Creek drainage. These cross-sections show the depth to the water table and the depth to bedrock. Seven electrical resistivity soundings are also presented, and these indicate not only the absence of clay layers within the valley fill, but also the presence of bedrock. The report closes with a discussion of seismic velocity and electrical resistivity measurements on a sample of the Flathead Sandstone.

INTRODUCTION

Geophysical techniques were used to help characterize the subsurface of the Soda Butte Creek drainage. Both seismic refraction surveys and vertical electrical soundings (VES) were performed in an attempt to better understand the characteristics of the local aquifer. The study site is located near the northeastern boundary of Yellowstone National Park, and it is approximately three miles from the community of Cooke City, Montana. Soda Butte Creek is a major tributary of the Lamar River, which in turn is a major tributary of the Yellowstone River; thus, this investigation will assist the National Park Service in decisions concerning future development along the Park's northeastern boundary.

Three seismic refraction surveys and seven soundings have been used to define the following parameters associated with the valley's subsurface:

- thickness of the valley fill,
- composition of the valley fill sediments,
- saturated thickness of the local aquifer, and
- identification of bedrock.

By obtaining this information through geophysical means, important insights pertaining to the area's hydrogeology can be developed. Since no previous hydrogeologic studies (i.e., pumping tests) have been performed in this environmentally sensitive location--due, in part, to the costs and impacts associated with drilling water wells--the use of cost effective, low-impact geophysical methods is a viable approach for obtaining subsurface information.

The seismic refraction method is a high-resolution technique used for locating the water table and depth to bedrock. Seismic refraction studies utilize acoustical energy which travels at different velocities through different materials. As the energy propagates through a layered subsurface whose acoustical velocities increase with depth, part of the energy will refract upon encountering an interface between different media. The layers must be of sufficient thickness to be detectable. Furthermore, because the velocities must increase with depth, a low velocity layer underlying a relatively higher velocity layer will not be detected. This phenomenon is known as the hidden layer problem, and it can lead to interpretation errors.

To minimize the environmental impacts of the study, the refraction method was performed by generating seismic waves with a sledge hammer. The refraction measurements were made with a 24-channel BISON 9000 seismograph and a 15 ft spacing between detectors (i.e., geophones). A seismic wave's travel-time from the ground surface source to a refracting layer, along this layer, and back to ground surface geophones was precisely measured. Subsurface layer velocities and thicknesses have been calculated from the time-distance relationships between the geophones and each source.

The VES method is an electrical resistivity technique that is used to characterize vertical changes in subsurface electrical properties. While VES has a lower resolution for determining depths compared to the seismic refraction method, it can be used to indicate clay layers and other electrically distinct layers. In order to measure vertical changes in the resistivity of subsurface strata, an electrical current is introduced directly into the ground through a pair of electrodes. The resulting voltage difference is then measured between another pair of electrodes, and the subsurface's apparent resistivity is then calculated. A series of resistivity measurements are then made at various electrode spacings centered on a common point; thus, sampling depth is increased by increasing the electrode spacing. An R-Plus direct current system and the Schlumberger VES array were used for this study, whereby the voltage electrodes were set at a fixed distance about a central point while the current electrode spacing was varied logarithmically from this distance. By using the resistivity soundings in conjunction with the seismic refraction surveys, any potential hidden layers can hopefully be identified since low electrical resistivities generally correspond to low seismic velocities.

In addition to collecting the field data by the two geophysical methods, laboratory measurements were made on a sample of the Cambrian-age Flathead Sandstone (C_f). Both acoustical and electrical properties were obtained in an effort to identify this rock type as possibly being the bedrock unit which underlies the valley fill.

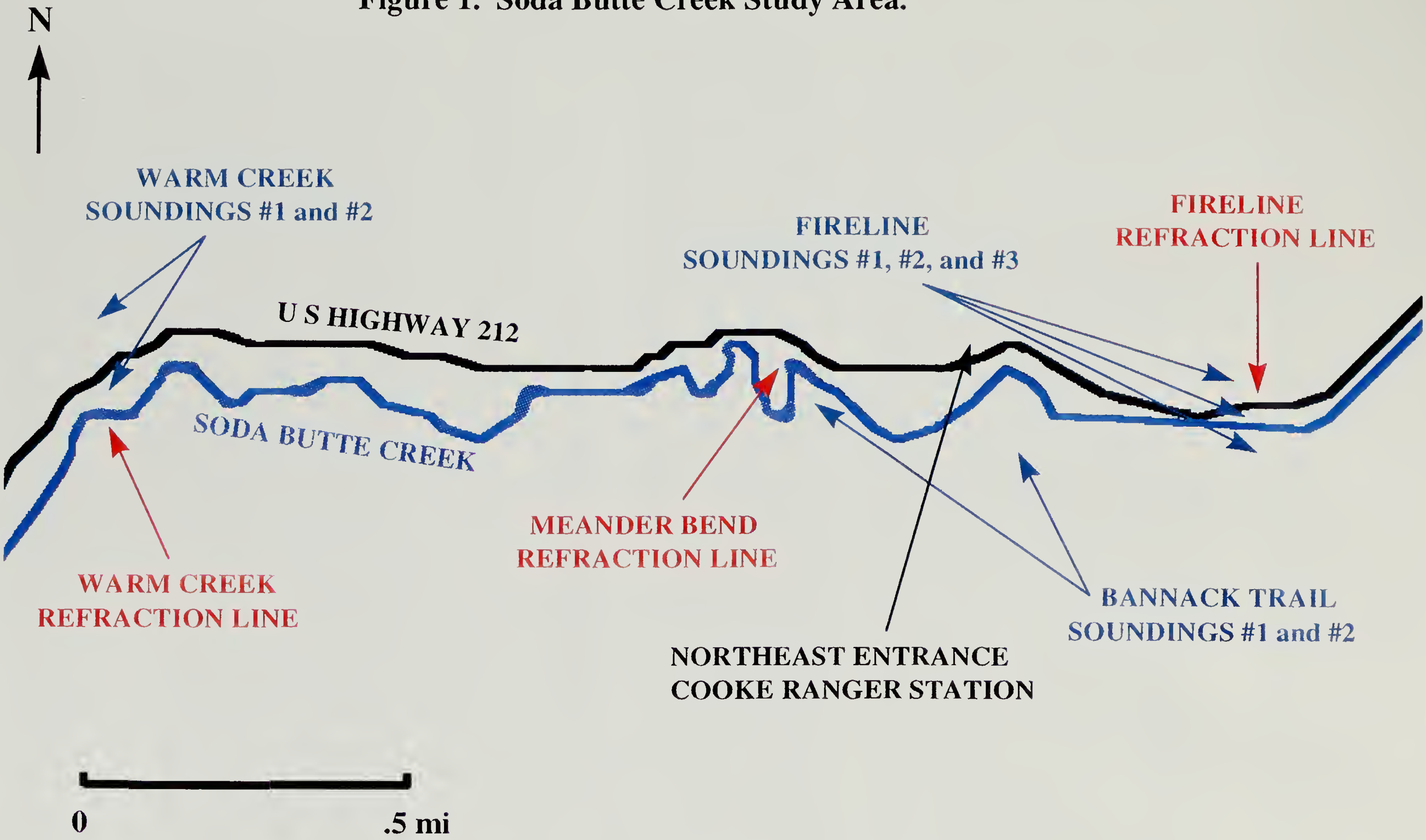
LOCATION and GEOLOGIC BACKGROUND

The Soda Butte Creek drainage characterization site is in close proximity to the Northeast Entrance of Yellowstone National Park (See Figure 1). Soda Butte Creek is located in a Pleistocene-age, glacially carved valley within the Beartooth Mountains. During the Pleistocene, great icecaps covered most of the Park; furthermore, these icecaps existed during the following periods of glaciation which have been categorized from oldest to youngest: 1) pre-Bull Lake, 2) Bull Lake, and 3) Pinedale (Pierce, 1974). The inception of glacial activity began roughly 130,000 years ago, and it ended approximately 10,000 years ago (Alt and Hyndman, 1986).

The valley fill associated with the Soda Butte Creek drainage is comprised of glacial deposits, stream deposits (i.e., alluvium), and landslide debris. The predominant glacial material includes till and--to a lesser degree--kame deposits, while the alluvium is comprised chiefly of stratified sandy gravel with minor interbeds of sand and silt. The landslide deposits generally consist of nonsorted debris in a clayey matrix (Pierce, 1974). The valley fill is bounded laterally and underlain by Cambrian-age sedimentary bedrock which includes limestone, shale, and sandstone members. The total thickness of these rocks is approximately 1100 ft within the study area (Elliott, 1979). Mapping performed by Hamilton (1995) near Warm Creek indicates that the Flathead Sandstone (C_f) underlies the valley fill. The width of the valley is close to one mile.

Water well logs for the Cooke City area indicate that the valley fill is on the order of 100-150 ft thick. While claybound sands and gravels are the major constituents mentioned in the well logs, thin clay layers are also present. The wells typically produce at approximately 30 gpm, and this

Figure 1. Soda Butte Creek Study Area.



suggests that the local aquifer may be highly permeable. The Tucker well (SW 1/4, NE 1/4 of S33, T9S, R14E) was drilled to a depth of 120 ft. At this depth, claybound gravels exist and bedrock was not encountered.

In a further attempt to identify the underlying bedrock formation, a cross section (Figure 2) has been constructed in close proximity to the Tucker well from the Geologic Map of the Southwest Part of the Cooke City Quadrangle, Montana and Wyoming (Elliott, 1979). The cross section extends from the top of the Cambrian-age Pilgrim Limestone (C_{pi}) which outcrops north of Soda Butte Creek to the top of an outcrop of the same formation south of the creek. The cross section is one mile long, and the outcrops are at elevations of 8240 ft and 7800 ft, respectively; consequently, the apparent dip of C_{pi} is 4.7^0 SE. Approximately 0.35 mile from the northern outcrop, the top of the valley fill is at an elevation of 7740 ft. Thus, simple trigonometric calculations indicate that the top of C_{pi} would have once existed roughly 645 ft above the present location of the valley fill--presuming no geologic structure exists within the bedrock. By concluding that the valley fill is close to 150 ft thick at this locale, the present-day bedrock underlying the valley fill would be nearly 795 ft below the top of the once-existing C_{pi}.

The stratigraphic column for the Cooke City area shows the following Cambrian-age formations and their respective approximate thicknesses: 1) Snowy Range Formation (C_s)--230 ft, 2) Pilgrim Limestone (C_{pi})--245 ft, 3) Park Shale (C_p)--245 ft, 4) Meagher Limestone (C_m)--100 ft, 5) Wolsey Shale (C_w)--180 ft, and 6) Flathead Sandstone (C_f)--100 ft (Elliott, 1979). The total thickness for C_{pi} through C_w is about 770 ft. By comparing this value to the 795 ft calculated previously, this would suggest that the valley fill extends 25 ft into C_f, and that it is underlain by approximately 75 ft of the sandstone.

DATA COLLECTION and MODELING

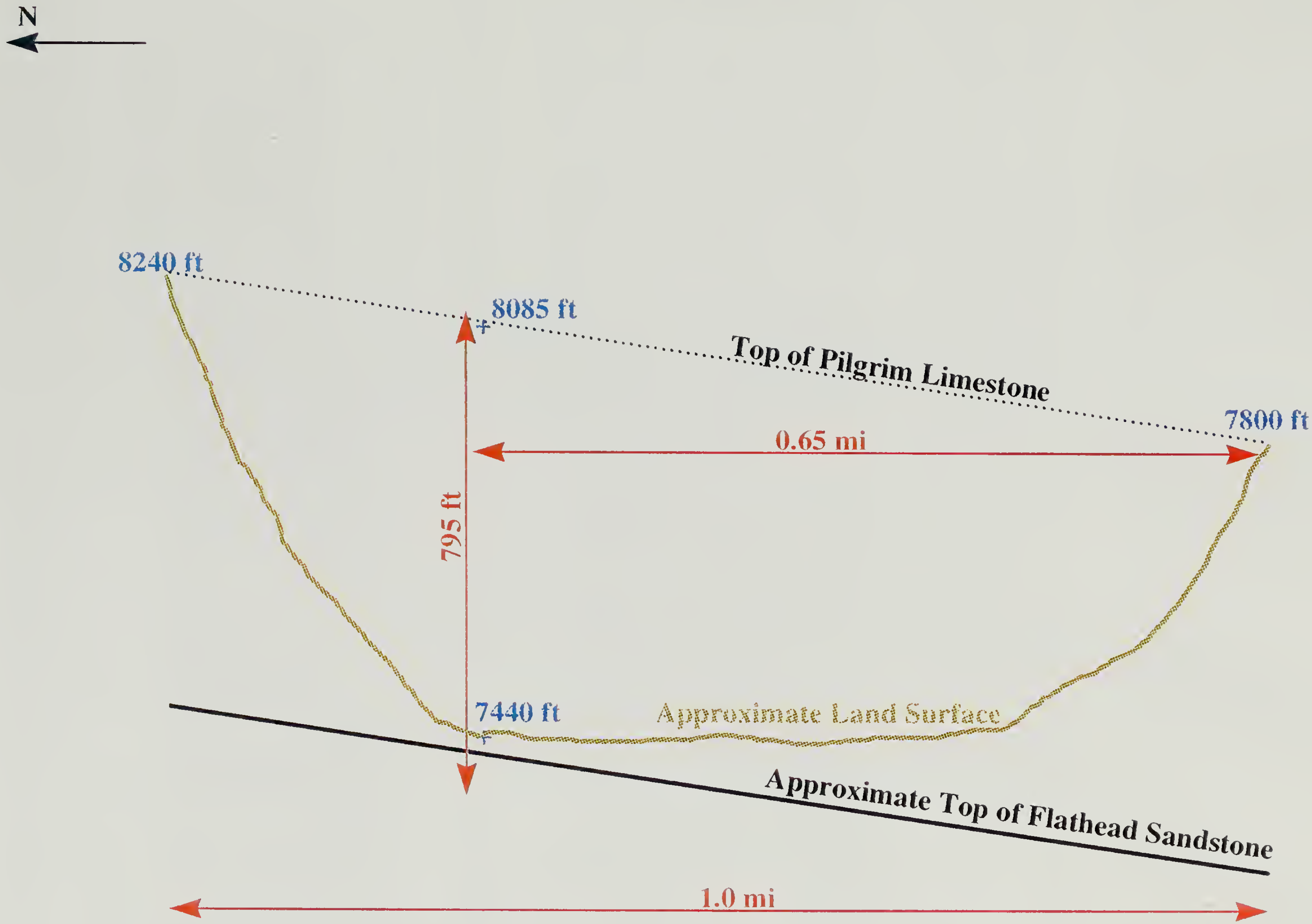
SEISMIC REFRACTION SURVEYS

Refraction surveys were performed to locate the water table and to map the valley fill/bedrock contact. Three seismic lines were created within a two mile section along Soda Butte Creek. The locations of the lines were chosen in consultation with Dr. Hamilton such that the surveys could be performed in an efficient manner. Thus, open areas near U.S. Highway 212 were used since the transportation of the equipment was rather arduous. These open areas included meadows and the 1988 fireline. The seismic lines are shown in Figure 1, and they are denoted as the Warm Creek, Meander Bend, and Fireline refraction lines. The seismic data has been interpreted by using a PC-based version of the SIPT2 V-4.0 modeling software (Rimrock Geophysics, 1993). The software algorithm is based on the delay-time method, and it includes a ray-tracing scheme for model verification (Haeni, et al, 1987).

The Warm Creek refraction line is located southwest of the Warm Creek picnic area, and is south of Soda Butte Creek. The line trends north-south for 780 ft and its north end is less than 5 ft from Soda Butte Creek. The land surface in this area consists of a marshy floodplain. A depth

Figure 2. Cross Section Through the Cambrian Formations Near the Tucker Well.

(Not to Scale)



model (Figure 3) illustrates a two-layer case: 1) saturated valley fill--v_p = 6000 ft/s and 2) sedimentary bedrock--v_p = 9400 ft/s. V_P is defined as the velocity at which a compressional acoustic wave travels through a material, and thus variations in velocity indicate different strata within the subsurface. The valley fill is presumably alluvial in nature since the work by Pierce (1974) shows surficial deposits in this area to be comprised of sands and gravels. The central depression within the bedrock could possibly have been formed by a paleochannel which cut down into the bedrock. While the thickness of the valley fill has been determined for this refraction line--as well as the others--it must be noted that the thickness of the bedrock layer is unknown. No data has been obtained which would indicate the bedrock thickness, so the bedrock is presumed to be an infinite half-space.

The Meander Bend refraction line trends north-south for 574 ft, and it is located on a sand and gravel meander bend of Soda Butte Creek. The southern end of the line is approximately 150 ft from the creek. A depth model (Figure 4) portrays a three layer profile: 1) thin vadose (unsaturated) zone--v_p = 1100 ft/s, 2) saturated valley fill--v_p = 6100 ft/s, and 3) sedimentary bedrock--v_p = 11000 ft/s. The valley fill is again presumed to be alluvial deposits.

The Fireline refraction profile consists of two lines--one located north and the other south of Soda Butte Creek. The line is located just east of the Park boundary, and it trends north-south for 1359 ft along the fireline which was cut through heavy timber during the historic wildfire season of 1988. The northern half of the line is located on landslide debris while the southern half is located on a gravelly kame deposit (Pierce, 1974). The depth model (Figure 5) represents a three layer profile: 1) vadose zone--v_p = 1100-1200 ft/s, 2) saturated valley fill--v_p = 6000-6900 ft/s, and 3) sedimentary bedrock--v_p = 10900-11900 ft/s. The origin point (i.e., 0 ft) defines the southern extent of the north line; consequently, subsurface features in the creek's vicinity have been interpolated from the north and south lines. The high compressional wave velocity for the saturated fill was obtained from the north half of the model, and thus it is indicative of the landslide debris. The gravelly kame deposits have a compressional wave velocity which is consistent with those of the saturated alluvium.

Data from each refraction model is shown in TABLE I. The minimum, maximum, and average thickness values for the valley fill's unsaturated and saturated zones are listed.

	UNSATURATED FILL THICKNESSES (ft)			SATURATED FILL THICKNESSES (ft)		
REFRACTION LINE	min	max	avg	min	max	avg
Warm Creek	-----	-----	-----	55.6	196.6	109
Meander Bend	3.7	13.4	9	66.5	129.3	98
Fireline	0.0	19.6	12	108.0	166.2	137

TABLE I. Thickness Values.

While quite a range of values exists between minimum and maximum saturated thicknesses, a majority of the thicknesses are over 100 ft. Additionally, the smaller values tend to be located

Figure 3. Warm Creek Refraction Profile.

(Vertical Exaggeration = 1.5 X)

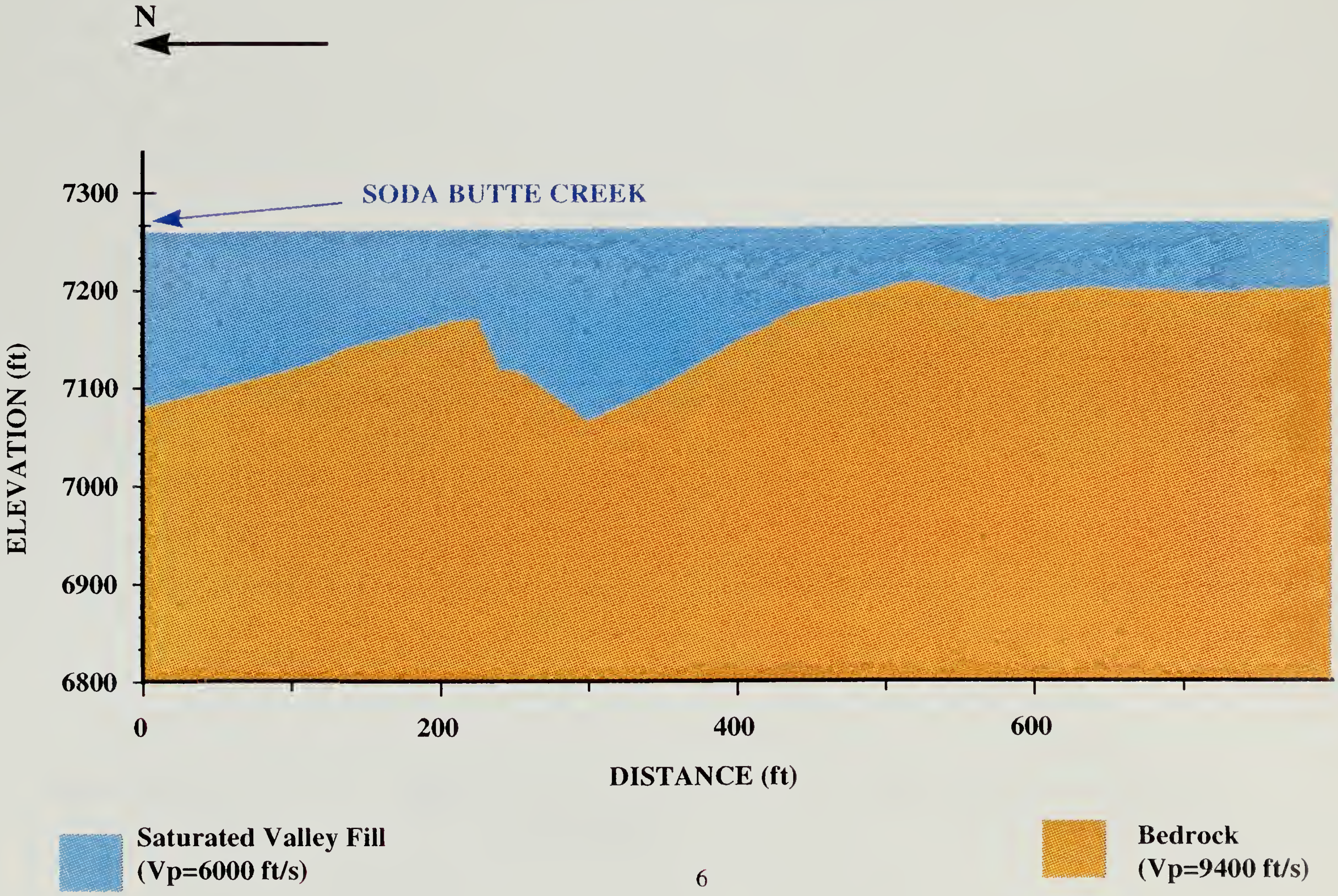


Figure 4. Meander Bend Refraction Profile.

(Vertical Exaggeration = 1.3 X)

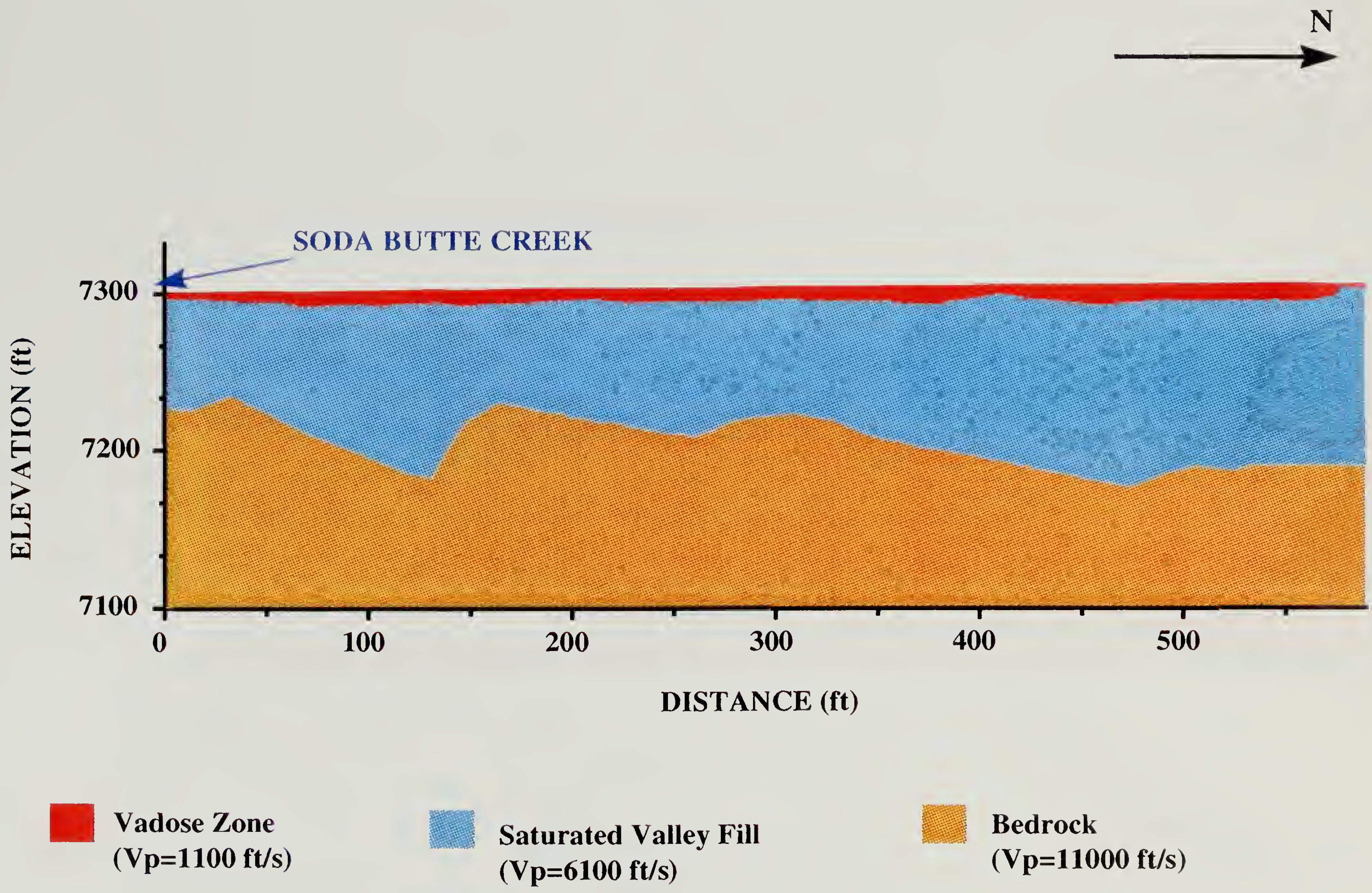
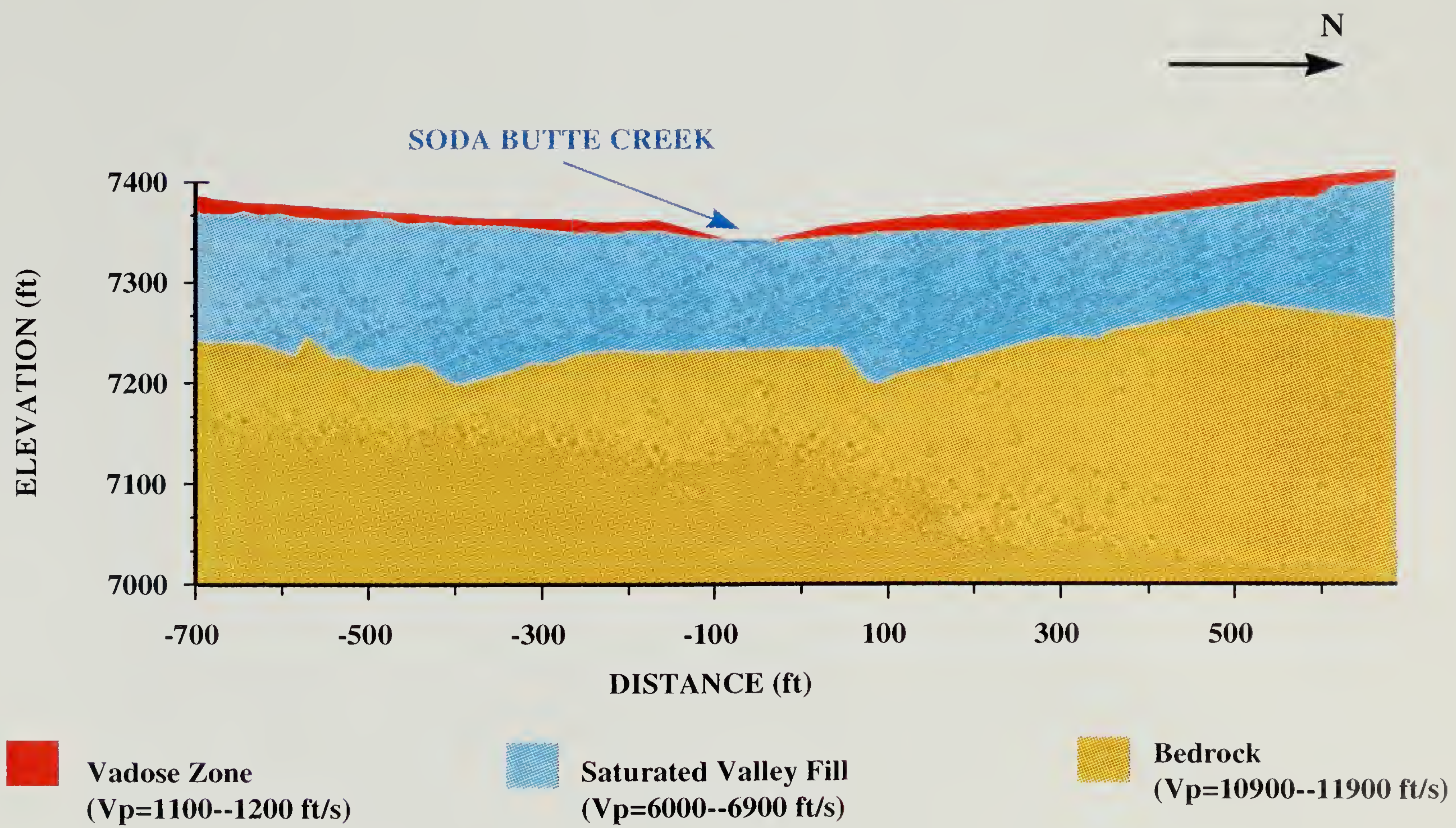


Figure 5. Fireline Refraction Profile.

(Vertical Exaggeration = 1.2 X)



near the ends of the profiles, and thus suggests that the underlying bedrock is closer to the land surface at these locations. This observation fits the concept of a glaciated valley whose maximum valley fill thickness is located near the center of the valley.

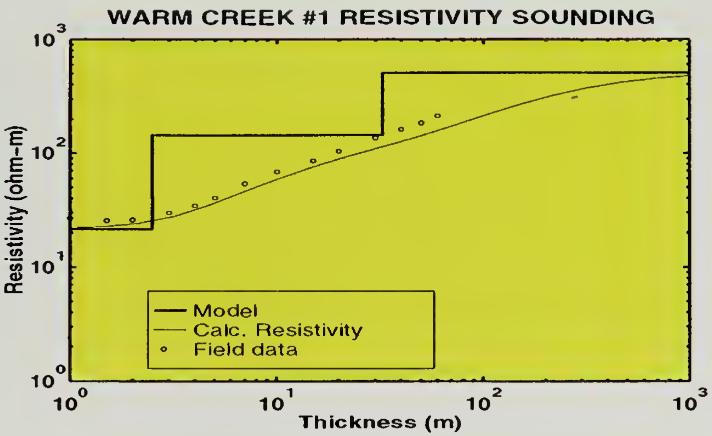
RESISTIVITY SOUNDINGS

Schlumberger resistivity soundings were used to determine not only the thickness of the valley fill, but also to indicate any significant clay deposits within the saturated sediments. The existence of clay lenses below the water table could imply that confining layers are present within the local aquifer; moreover, any clay layers could potentially be hidden layers in the seismic interpretation. The seven sounding sites are shown in Figure 1. Warm Creek soundings #1 and #2 were conducted north of Soda Butte Creek near the Warm Creek picnic area, Fireline soundings #1, #2, and #3 were performed along the fireline, and Bannack Trail soundings #1 and #2 were done along the Bannack Trail south of Soda Butte Creek.

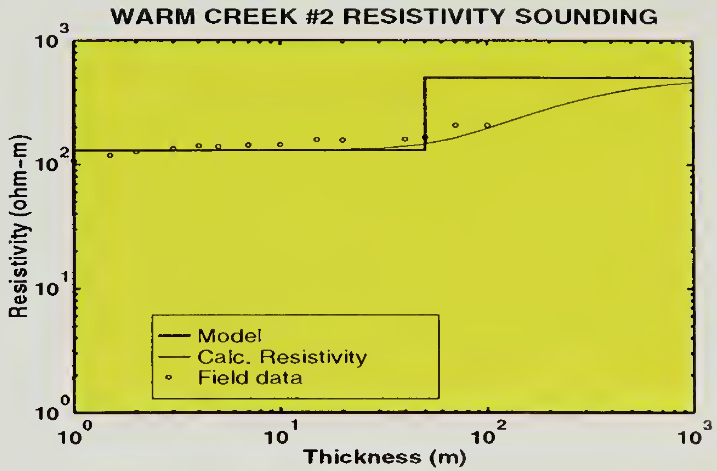
One-dimensional models (Sill, 1996) were used to interpret the apparent resistivity data (i.e., field measurements). Initially, forward models were generated in an attempt to match each model's output with the apparent resistivity data. Inversions were then applied to the results of the forward models. Figures 6 and 7 illustrate the depth models that have been generated from the inversion results. The apparent resistivity field data have been plotted against their relative spread positions--one-half the total sounding spread length. The approximate thicknesses and corresponding resistivities of subsurface layers are denoted by the 'steps' on each graph.

Each model shows a trend of increasing resistivity with depth. This suggests that a relatively higher resistivity unit--bedrock--underlies the valley fill. Additionally, none of the models indicate the presence of clay layers within the saturated subsurface since low resistivity layers do not exist at depth. The low apparent resistivities associated with Warm Creek soundings #1 and #2 are the result of prominent soil horizons which are developed in marshy areas. While Fireline soundings #1 and #2 do show a decrease in resistivity at depth to some degree, these models imply that the valley fill's vadose zone is more resistive than the saturated fill.

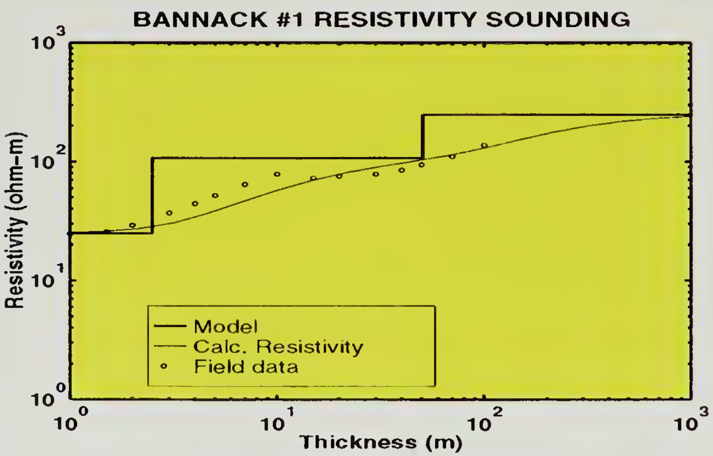
The models generated from the Warm Creek data indicate that the saturated valley fill consists of relatively clean sand and gravel. The 164 ft fill thickness shown in sounding #2 compares well with the 180 ft thickness from the north end of the Warm Creek refraction profile. The Bannack Trail models portray the valley fill as having a thickness on the order of 150 ft. This value is nearly twice the thickness given for the south end of the Meander Bend refraction profile; however, this conspicuous discrepancy may actually suggest that the valley fill rapidly thickens south of the Meander Bend area. The Fireline models indicate that the valley fill thickness is also on the order of 150 ft at their respective locations. These values correlate well with the Fireline refraction profile. Since the results of the resistivity models support those of the refraction models, the existence of hidden layers is unlikely.



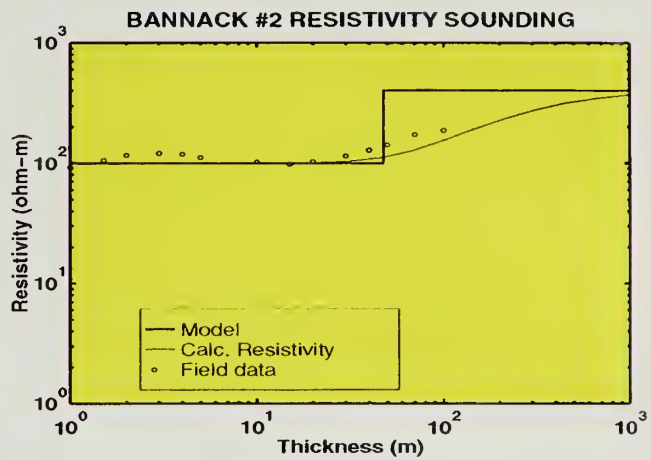
LAYER	RESISTIVITY (ohm-m)	THICKNESS
1	22	2.5 m (8.2 ft)
2	144	30.0 m (98.4 ft)
3	510	--------



LAYER	RESISTIVITY (ohm-m)	THICKNESS
1	130	50 m (164 ft)
2	500	--------

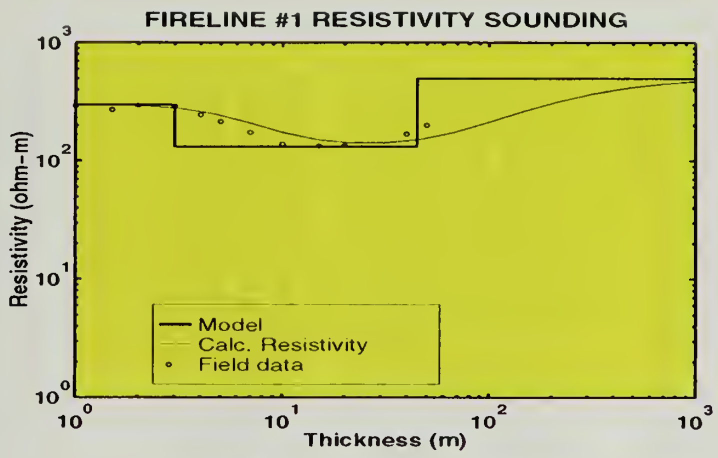


LAYER	RESISTIVITY (ohm-m)	THICKNESS
1	25	2.5 m (8.2 ft)
2	110	48 m (157.4 ft)
3	250	-------

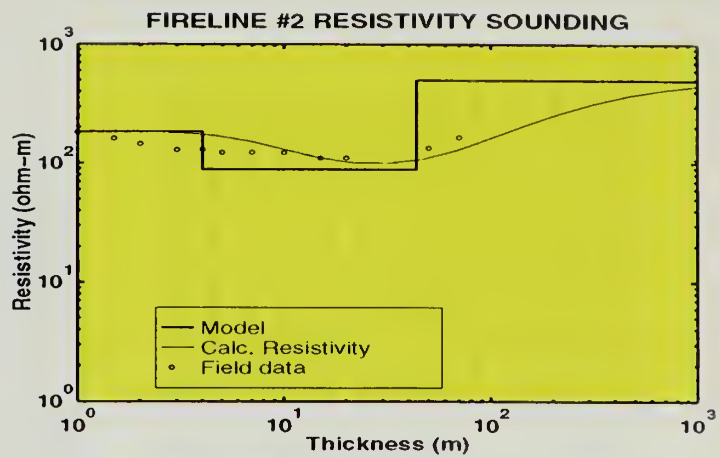


LAYER	RESISTIVITY (ohm-m)	THICKNESS
1	100	47.6 m (156.1 ft)
2	400	-------

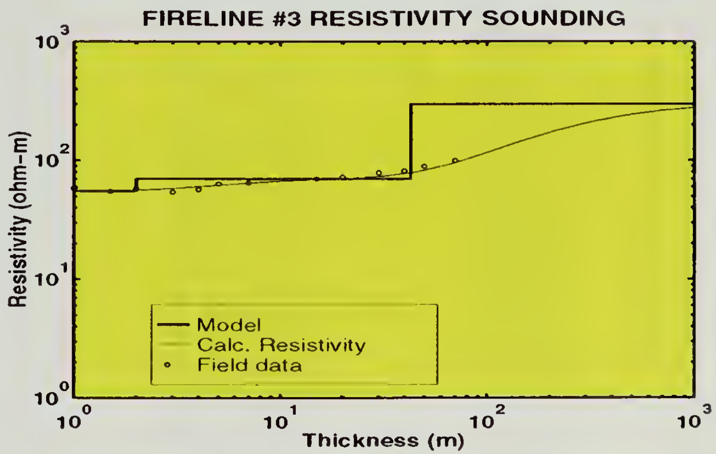
Figure 6. Schlumberger Soundings.



LAYER	RESISTIVITY (ohm-m)	THICKNESS
1	300	3 m (9.8 ft)
2	132	42 m (137.8 ft)
3	500	-------



LAYER	RESISTIVITY (ohm-m)	THICKNESS
1	185	4 m (13.1 ft)
2	90	39.5 m (129.6 ft)
3	500	--------



LAYER	RESISTIVITY (ohm-m)	THICKNESS
1	55	2 m (6.6 ft)
2	70	41 m (134.5 ft)
3	300	-------

Figure 7. Schlumberger Soundings.

LABORATORY MEASUREMENTS

Density, porosity, and acoustical and electrical properties were determined for a sample of the Flathead Sandstone (C_f) in an attempt to identify this rock type as possibly being the bedrock unit which underlies Soda Butte Creek's valley fill. The sample of C_f was collected from an outcrop which is located 0.5 mile northeast of Cooke City, MT. The sample consists of cemented quartz grains, and it lacks an abundance of other minerals that would suggest the existence of possible conductive material (i.e., clays). In order to estimate the acoustical and electrical properties similar to those associated with the in situ bedrock, the sample was saturated with tap water that had a resistivity of 10 ohm-m. Tap water was used because the resistivity of the groundwater was not known. The sample was saturated for a three month period. During this time, no significant changes in water resistivity were observed, and thus any potential conductors have not diffused out of the rock sample. TABLE II summarizes the results of the laboratory measurements, and Figure 8 shows the electrical properties as functions of frequency. The low effective porosity of C_f suggests that it is rather impermeable.

DENSITY	POROSITY	V_P	RESISTIVITY	ABSOLUTE PHASE
2.65 g/cc	3 %	14000 ft/s	2800--3600 ohm-m	0.03--0.2 rad

TABLE II. Properties of C_f Rock Sample.

The density, porosity, and compressional wave velocity of C_f are rather straightforward parameters to interpret. The absolute phase in TABLE II is the absolute value of the phase difference between an input or primary voltage and the corresponding induced or secondary voltage. Thus, relatively large phase differences would imply that conductive materials are being polarized.

By observing Figure 8, one can clearly see that higher input frequencies correspond to resistivity decreases and phase increases; however, the effect is exaggerated since the large phase increases between 100 Hz and 1000 Hz are most likely due to the polarization of a calibrating resistor which is used in the laboratory measurements. The effect of the higher frequencies was less dramatic on the resistivity values since no changes in magnitude have been observed. In fact, these values are on the order of 3000 ohm-m.

Once the rock sample properties had been determined, a theoretical resistivity value based on Archie's Law was calculated and compared to the measured results. The law assumes that a rock consists of silicates and pores. Furthermore, these pores are interconnected, and pore water is the only conductor within a rock. Archie's Law is formulated as follows:

$$\rho_r = \rho_w \phi^{-m}, \tag{1}$$

whereby ρ_r is a rock's resistivity, ρ_w is the pore water resistivity, ϕ is a rock's porosity, and m is the tortuosity. Tortuosity is defined as the inverse ratio of the length of a rock specimen to the

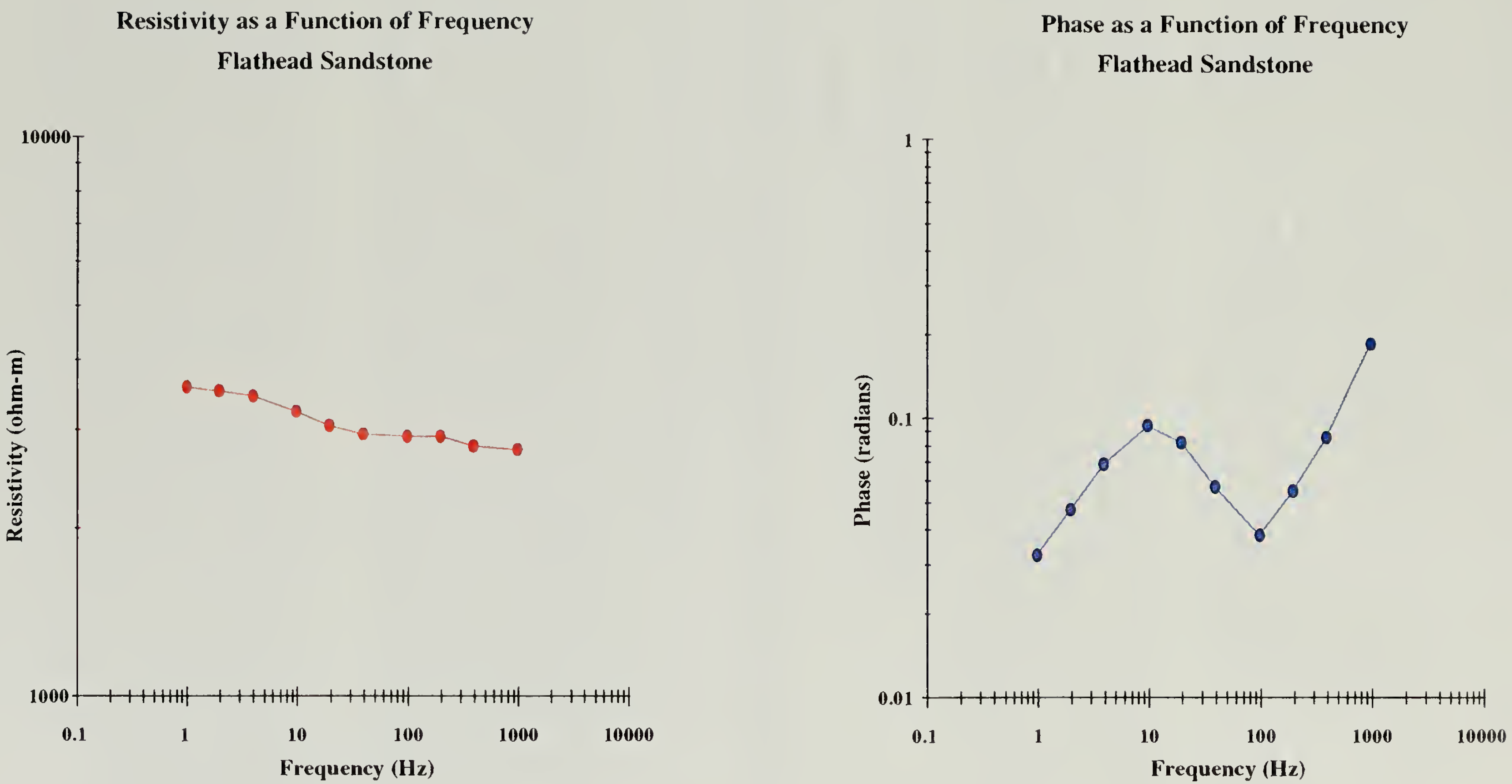


Figure 8. Electrical Properties of the C_f Rock Sample.

length of the equivalent path of electrolyte within it (Bates and Jackson, 1984). The values range from 1.2 to 2.7. By estimating $m = 2$ for the C_f rock sample, Archie's Law yields a resistivity of approximately 11100 ohm-m. For tortuosities approaching 1.2 and 2.7, resistivities decrease by two orders of magnitude and increase by one magnitude, respectively. The calculated resistivity--with $m = 2$--is roughly a magnitude larger than the measured resistivities. The disparity in these results suggests one of two things: 1) the rock sample exhibits a lower resistivity because it actually does contain conductors other than the pore water, or 2) the sample displays the effects of surface conduction which exists along the interfaces between the pore water and the pore walls. Since few minerals other than quartz were observable in the rock sample, surface conduction is most likely causing the lower resistivities.

As previously shown, the in situ bedrock exhibits resistivities on the order of 500 ohm-m. These values are at least one magnitude smaller than the theoretical values. Supposing that the bedrock is indeed C_f, the discrepancy in resistivities must result from the bedrock having 1) a higher porosity due to fractures, 2) conductive materials in the rock's pores, or 3) a combination of both. If clay is presumed to be the additional conductor besides the pore water, then the Waxman-Smits method can be used to quantify the properties associated with clay conduction.

The Waxman-Smits method is defined by the following formula:

$$\rho_r = [\rho_w + B(Q_v)]\phi^{-m}, \tag{2}$$

whereby B is the mobility of clay and Q_v is the number of equivalents of cations per liter of a solution. B and Q_v can be determined as follows:

$$B = 3.8(1-.83e^{-0.5\rho w}) \text{ and } Q_v = [.01(CEC)(w_c)\rho_{rock}]/\phi, \tag{3}$$

where CEC is the cation exchange capacity, w_c is the weight fraction of clay in a rock, and ρ_{rock} is the rock's saturated density. Figure 9 illustrates Sill's (1996) modeling program of resistivity as a function of porosity for the C_f bedrock. The following parameters were used:
1) $\rho_w = 100$ ohm-m, 2) $w_c = 2\%$, 3) CEC = 50 meq/100 g, 4) $\rho_{rock} = 2.71$ g/cm^3, and 5) m=2. Archie's Law yields a resistivity of 500 ohm-m at a porosity of 45% while Waxman-Smits gives a similar value at 11%. The pore water resistivity was chosen at 100 ohm-m since this is a typical value for aquifers in Southwest Montana (Sill, 1996); furthermore, the CEC is a mid-range value.

In order to estimate the amount of clay present in the valley fill, the previous model was modified such that $w_c = 8\%$ and $\rho_{rock} = 2$ g/cm^3--a typical value for unconsolidated sediments. Figure 10 shows the model results. Archie's Law yields a resistivity of approximately 100 ohm-m at a porosity of 90% while Waxman-Smits gives a similar value for a porosity of 18%. While Archie's Law produces an unrealistic porosity, the value obtained by the Waxman-Smits method is indicative of a fairly porous medium. The percentage of clay that was used in the model suggests that the valley fill may contain claybound materials. However, w_c at 8% would not be considered significant enough to describe the valley fill as being impermeable.

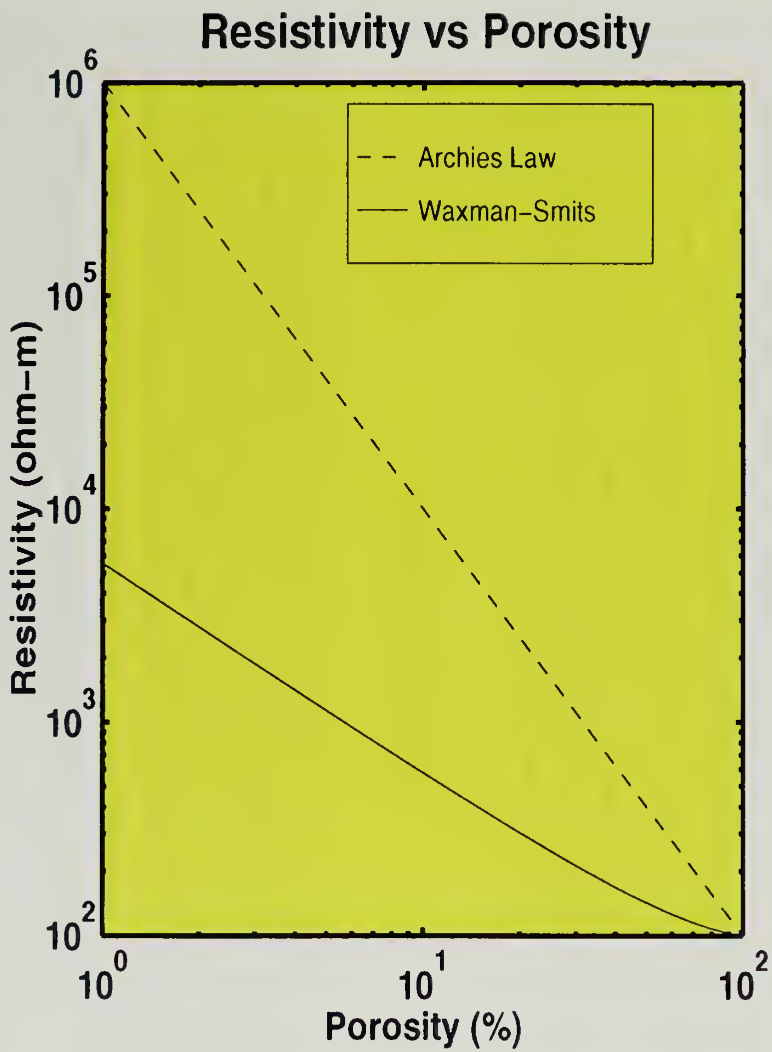


Figure 9. Resistivity Model for the C_f Bedrock.

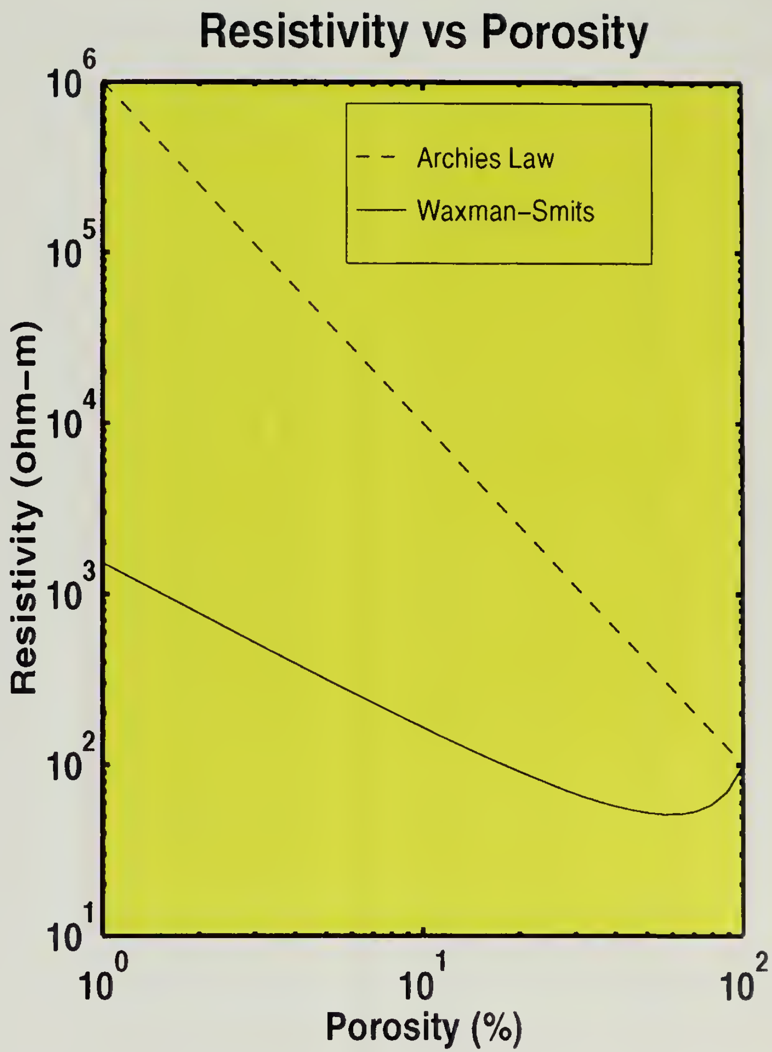


Figure 10. Resistivity Model for the Valley Fill.

Conclusions and Recommendations

The results of the Soda Butte Creek drainage characterization study suggest the following:

- the maximum thickness of the local aquifer is in the neighborhood of 100 ft,
- the valley fill consists primarily of sands and gravels; thus, the lack of clay layers indicate that the aquifer is unconfined and it may be highly permeable, and
- the bedrock unit underlying the valley fill is most likely the Flathead Sandstone (C_f).

Since the in situ bedrock exhibits resistivities on the order of 500 ohm-m--and theoretical values are magnitudes higher--the bedrock is probably fractured and contains some clays. Similarly, the in situ bedrock's compressional velocities are on the order of 10000 ft/s. Laboratory measurements on a sample of C_f show that the velocity is 14000 ft/s. Again, the differences may be due to fractures, or possibly because the bedrock varies from one location to another. Consequently, the drainage's groundwater flow is primarily through the valley fill, but fracture flow through the bedrock may exist as well.

Recommendations for further field work at the site include performing additional seismic refraction surveys north of the Warm Creek site and south of the Meander Bend site. A refraction survey was originally done north of the Warm Creek site, but the data was not interpreted due to poor signal quality. An investigation south of the Meander Bend would give insight as to whether the valley fill is indeed as thick as the resistivity soundings suggest. Also, additional resistivity soundings must be performed at the Warm Creek and Meander Bend refraction sites. The original measurements were not reproducible, and they led to the construction of unrealistic depth models. This problem was most likely due to inhomogeneities within the shallow subsurface (Telford, et al, 1990). The Geophysical Engineering Department at Montana Tech has recently purchased a time-domain electromagnetic system. Additional resistivity values obtained with this instrument would lead to an increased knowledge of the site's subsurface. The additional field work has been planned for late July or early August, 1996.

Acknowledgments

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