Paleochannel aquifer potential at Montana State University : a test of hypotheses

by David Allen Donohue

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
Groundwater resources in the Gallatin Valley of southwestern Montana are controlled by several factors. These include depositional controls on the Bozeman alluvial fan, tectonic activity in the block-faulted valley and erosional activity due to base level changes within the basin during the geologic past. The purpose of this study is to evaluate the presence of a postulated paleochannel within the Bozeman alluvial fan interpreted from a seismic refraction survey by Brown and others (1983). To test this hypothesis, a conceptual groundwater exploration model for the southeastern end of the Gallatin Valley was developed. Field studies included drilling of a well within the trend of the proposed paleochannel, an earth resistivity survey and shallow seismic refraction survey across the paleochannel on the campus of Montana State University.

The Roskie well is drilled to a total depth of 56 m (184 ft). Aquifer analysis indicates that the well is drilled into material that hydraulically compares with Tertiary material throughout the valley. The earth resistivity survey included resistivity profiling at the 9 m (30 ft) and 30 m (100 ft) a-spacings in order to intercept the postulated paleochannel at a relatively shallow and a relatively deep level. Interpretation of the data suggests no deep paleochannel cut into fine-grained Tertiary material and filled with a thick sequence of Quaternary gravels is present.

The seismic refraction survey utilized a 12-channel seismic recorder and did not repeat the results of the study by Brown and others (1983). Seismic results indicate material with velocities greater than 2000 m/s (6500 ft/s) are located within 3 m (10 ft) of the surface throughout the study area. The discrepancy between the results of the two studies appears to be due to the mis-interpretation of the first arrival seismic wave with the single channel recorder used in the 1983 study.

The results of this study indicate that the study area is not underlain by Quaternary Bozeman alluvial fan material. A Tertiary pediment surface underlies the area and material with seismic velocities characteristic of Tertiary sediments is found to a depth greater that 56 m (184 ft). Future wells drilled into this area cannot expect yields to be greater than 378 lpm (100 gpm) due to the hydraulic properties of the Tertiary material.

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APPROVAL

of a thesis submitted by

David A. Donohue

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

17 May 89

Date

Chairperson, Graduate Committee

Approved for the Major Department

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Date

Head, Major Department

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Henry L. Parsons

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ABSTRACT

Groundwater resources in the Gallatin Valley of southwestern Montana are controlled by several factors. These include depositional controls on the Bozeman alluvial fan, tectonic activity in the block-faulted valley and erosional activity due to base level changes within the basin during the geologic past. The purpose of this study is to evaluate the presence of a postulated paleochannel within the Bozeman alluvial fan interpreted from a seismic refraction survey by Brown and others (1983). To test this hypothesis, a conceptual groundwater exploration model for the southeastern end of the Gallatin Valley was developed. Field studies included drilling of a well within the trend of the proposed paleochannel, an earth resistivity survey and shallow seismic refraction survey across the paleochannel on the campus of Montana State University.

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INTRODUCTION

Problem

Alluvial fan deposits are the principal groundwater reservoir for many areas of the western U.S. (Bull, 1972). These deposits are economically important to farmers, ranchers, and the general public who depend upon them as a source for water. The alluvial fans and their streams control much of the groundwater recharge in the adjacent groundwater basins (Bull, 1972; Cehrs, 1979). In the block-fault basins of southwestern Montana alluvial fans are an integral part of the groundwater system. An important source of groundwater in the Gallatin Valley is the Bozeman alluvial fan located at the base of the Gallatin Range (Hackett and others, 1960). Groundwater within the alluvial fan is withdrawn for both domestic and irrigation use. Understanding groundwater controls on the Bozeman alluvial fan as well as locating optimal sites for groundwater withdrawal can have considerable benefits for local groundwater users.

Previous scientific investigations regarding the availability of groundwater from the Bozeman alluvial fan began with Hazen (1942) who examined the Gallatin River basin on a reconnaissance basis. Wantland (1953) ran several refraction seismic and resistivity surveys across the alluvial fan and other parts of the Gallatin Valley to support the groundwater resource investigation by Hackett and others (1960).

Wantland was concerned with locating the depth to Precambrian bedrock in the valley and determining the extent of valley fill. Hackett and others (1960) explored recharge on the alluvial fan and recognized that irrigation, stream loss and rainfall were important. Brustkern (1977) modeled the impact of land use change on groundwater resources of the Bozeman area, in particular the Bozeman alluvial fan. His model was concerned with how the aquifer would respond to various land use changes but was limited by the availability of geohydrological and geophysical data. Much more complete information regarding inflow, outflow, recharge, discharge and the details of the geology are needed. Dunn (1978) examined changes in groundwater levels and groundwater chemistry in the Gallatin Valley to determine if any changes in the groundwater had occurred since the study by Hackett and others (1960). His findings indicate no significant changes in water availability and water chemistry have occurred.

Purpose

Groundwater is needed on the Montana State University campus to supply chlorine-free water for research purposes and to supplement the present water supply. The primary concern was the report that Precambrian gneiss had been encountered in building foundations near the site where the wells were planned. Water wells drilled into such material would be expensive and would potentially yield little water. Brown and others (1983) used refraction seismic techniques to assess the distribution of this near-surface bedrock feature. They found that a 4500 m/s (15000 ft/s) velocity, suggestive of Precambrian bedrock, is present under parts of the MSU campus, but the seismic energy sources used could not detect this feature on all parts of the campus. During this study, preliminary interpretations suggested that a 60 m (200 ft) deep channel might exist near Roskie Dormitory at the west end of campus. The channel interpretation was based on time-velocity plots and their relations to a topographic depression in the area. Such a channel or channels might serve as an important groundwater resource on the fan. The difficulty with the interpretation was the sparse data and potential alternative interpretations of the geophysical data. Additional work is needed. The purpose of this investigation is to further test these ideas. Several questions need to be addressed.

1. Do additional hydrologic investigations confirm or deny the presence, size, extent and trend of the postulated channel?

2. Do additional geophysical studies confirm or deny the postulated channel, and if the channel is confirmed, can it be better delineated?

3. Can an understanding of the alluvial fan setting postulated by Hackett and others (1960) be refined to better understand the groundwater potential on the west side of the MSU campus based on the hydrologic and geophysical data?

Location

The Bozeman alluvial fan was mapped on the basis of surface morphology by Hackett and others (1960). They found a Quaternary alluvial fan with an apex at the mouth of Hyalite (Middle) Creek at the north end of the Gallatin Range, Montana. The alluvial fan was mapped with an elongate shape and is approximately 18 km (11 mi) long and 10 km (6 mi) wide at its widest section (Figure 1). The alluvial fan is bounded on the east by Sourdough Creek, on the west by South Dry Creek, on the south by the Gallatin Range, on the northeast by the floodplain of the East Gallatin River, and on the northwest by the West Gallatin River. The city of Bozeman straddles the east-central portion of the fan.

The specific area on the Bozeman alluvial fan chosen to test the presence of the paleochannel interpreted by Brown and others (1983) is located on the property of Montana State University (Figure 2). The site extends across Roskie field, bound on the east by Roskie Dormitory, on the west by Marsh Laboratory field, on the south by Lincoln Avenue and on the north by Garfield Street. This area was chosen because Brown and others (1983) had mapped the trend of the buried paleochannel through this area. Only a minor amount of development has occurred here previous to this study so that geophysical lines could be run. This site is also located where Montana State University was interested in drilling an exploratory irrigation well to test the model proposed by Brown and others (1983).

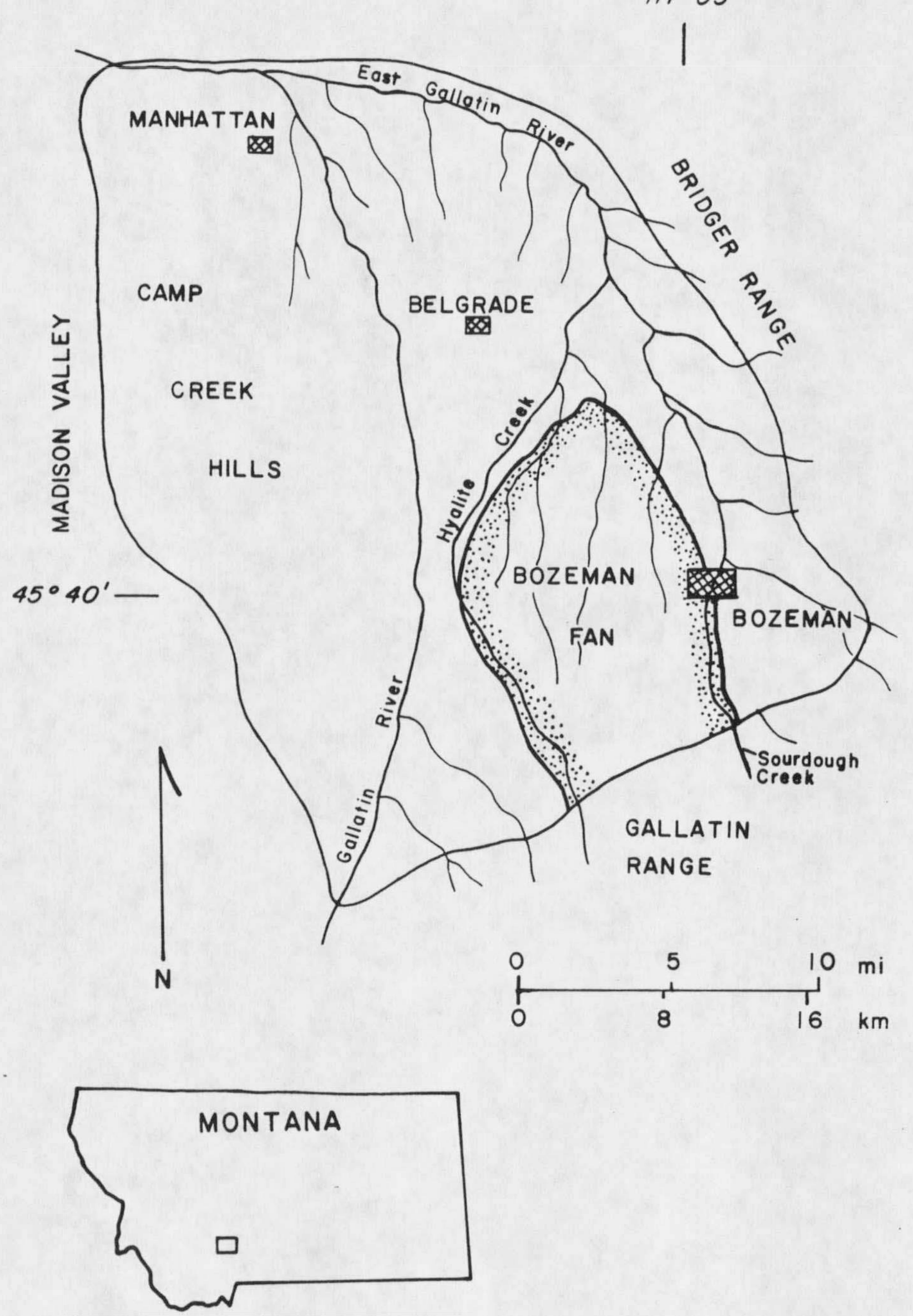


Figure 1: General location of the Bozeman alluvial fan and the Gallatin Valley, Montana (modified from Hackett, 1960).

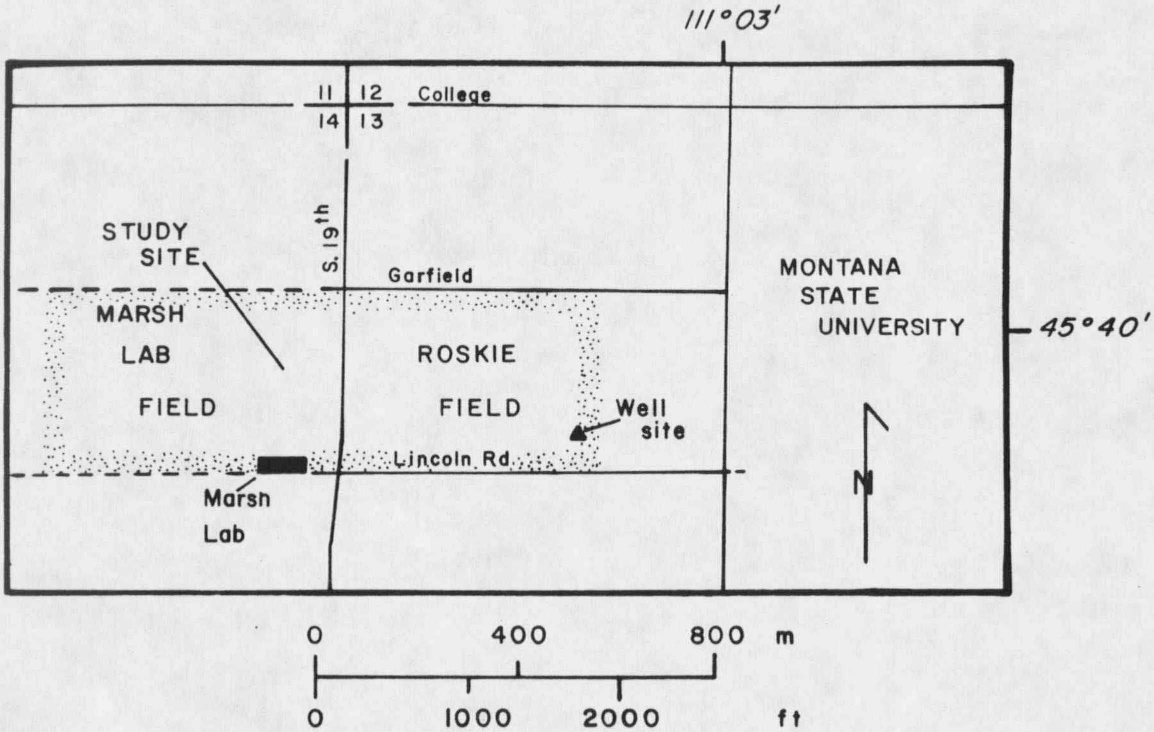


Figure 2: Study site index map, Montana State University. The intersection of South 19th and College is a section corner with numbers indicating the sections in T 2 S, R 5 E.

Geologic Setting

The Bozeman alluvial fan is in a block-faulted basin characterized by basin and range style faulting in southwestern Montana (Davis and others, 1965; Reynolds, 1979) (Figure 3). Large thicknesses of alluvium are generally considered to fill these valleys. Complex faulting and extended periods of erosion complicate these deposits. A review of the geologic history that led to the formation of the Gallatin Valley is necessary in order to understand the structural and depositional controls governing the hydrogeology of the Bozeman alluvial fan.

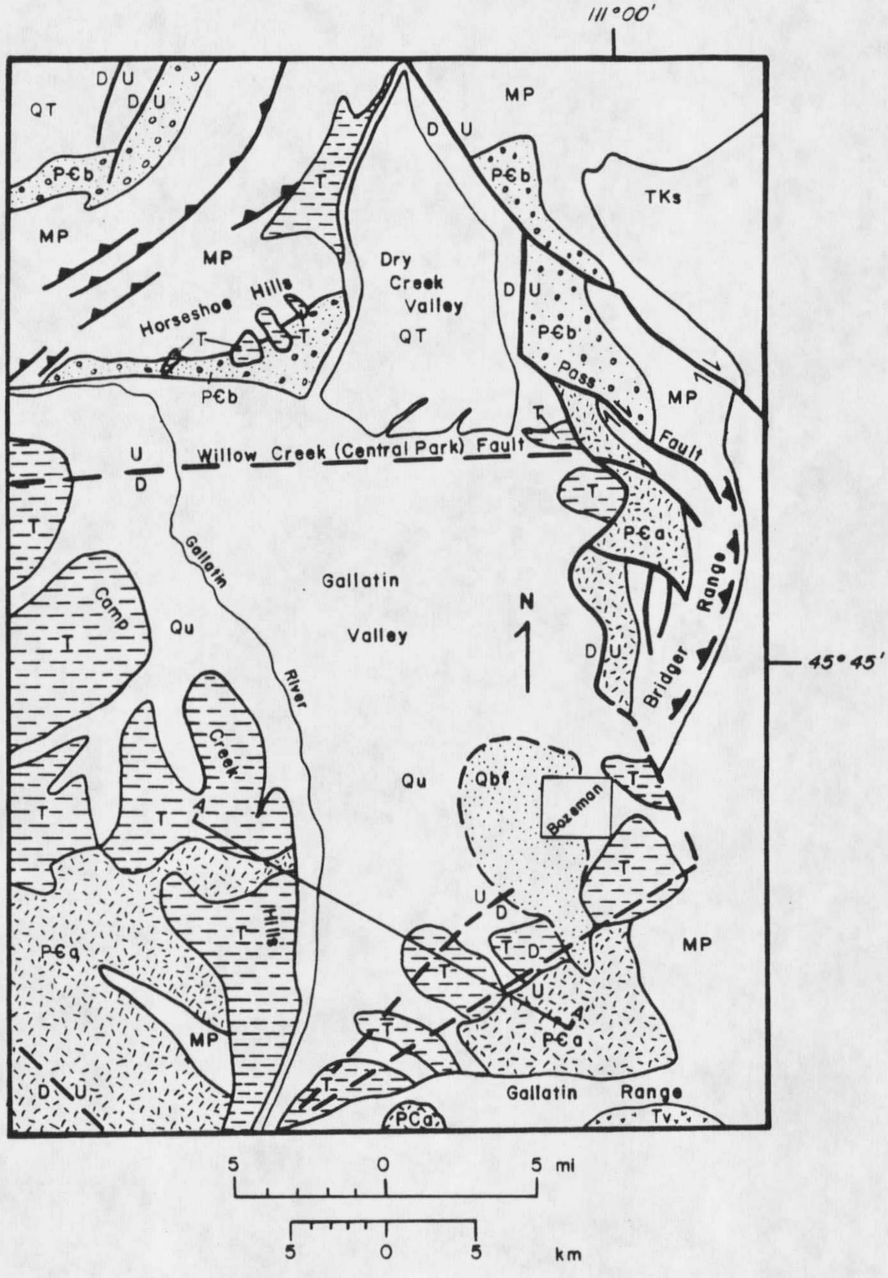


Figure 3: General tectonic map of the Gallatin Valley area. Qbf = Bozeman alluvial fan; Qu = Quaternary-age basin fill; QT = older Quaternary-Tertiary sediments; T = Tertiary sediments; Tv = Tertiary volcanics; TKs = Tertiary - Cretaceous-age sediments; MP = Mesozoic-Paleozoic rocks; PЄb = Precambrian Belt Supergroup; PЄa = Precambrian Archean rocks (modified from Hackett and others, 1960; Hughes, 1980; Lageson, 1989).

Pre-Tertiary Rocks

Development of the geologic architecture of the Gallatin Valley began in early Precambrian time. Archean basement gneissic rocks underlie the valley and cropout along the valley margins (Robinson, 1963; Zim and Lageson, 1984; Craiglow, 1986). During Proterozoic time a major east-west trending fault cut the Archean metamorphic rocks (Harrison and others, 1974). While this fault was active, the southern Dillon Block consisting of Archean metamorphic rocks was uplifted relative to the northern block. The uplift shed coarse-grained conglomeratic sediments northward into the Belt Basin (Harrison and others, 1974). Proterozoic Belt Supergroup strata are found along the northeastern margin of the Gallatin Valley. Deposition of the Belt sediments was controlled by this major east-west trending normal fault called the Willow Creek (Central Park) Fault (Harrison, 1974).

Paleozoic and Mesozoic sediments flank the Gallatin Valley and underlie the basin (Robinson, 1961; Davis and others, 1965). Deposition of these sediments took place on a relatively stable craton which developed after faulting ceased on the Willow Creek trend. The Paleozoic rocks are dominantly epicontinental marine muds and carbonate deposits with a thickness of about 1500 m (5000 ft). The Mesozoic sediments, approximately 1500 m (5000 ft) thick, consist dominantly of marine shales and sandstones (Robinson, 1963). Periods of erosional activity are seen as unconformities within the stratigraphic section.

Late Cretaceous Elkhorn Mountain volcanic rocks are present along the northern margin of the basin (Robinson, 1961; Chadwick, 1981). These late Cretaceous volcanic rocks underlie the source area for much of the early Paleocene stream-laid volcaniclastic sediments (Robinson, 1961). Intrusive stocks, most probably offshoots of the Boulder Batholith which lies to the west of the area, underlie the northwest and southwest portion of the basin.

Eocene-Paleocene volcanic rocks are found to the south of the Gallatin Basin in the Gallatin Range. Composition ranges from andesitic to dacitic flows, flow breccias, mudflow breccias and conglomerates (Chadwick, 1981). These provided additional source material for stream-laid Tertiary deposits in the Gallatin Valley.

Tertiary Sediments

Although the valley is postulated to have been formed in the Oligocene, rocks of this age are not recognized. Two Tertiary stratigraphic units are recognized in the Gallatin Valley: the early middle Eocene to early Miocene Renova Formation and the middle to late Miocene Sixmile Creek Formation (Hughes, 1980). An erosional unconformity separates the two formations (Figure 4). Each of these units produce differing amounts of groundwater and are important to identify when searching for water supplies.

Prior to deposition of the Renova Formation, most sediments shed from the uplifted mountains were transported eastward out of the basin by through-flowing streams (Robinson, 1963; Glancy, 1965). Dissection of the landscape in early Eocene time left an erosional topography on which the Renova formation was deposited (Robinson, 1963; Hughes, 1980; Thompson and others, 1982). The late Eocene saw a shift to a drier climate, development of internal drainage, and deposition of the Renova Formation.

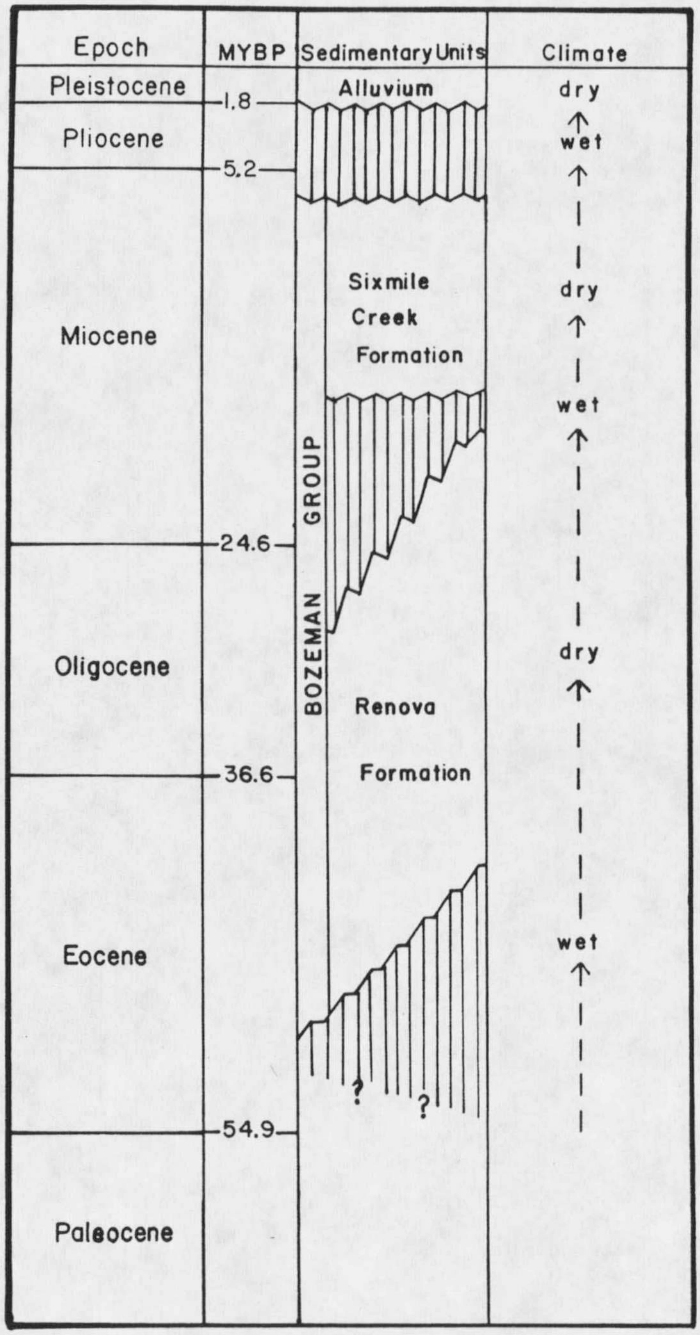


Figure 4: Generalized Tertiary stratigraphic section for southwestern Montana and the Gallatin Valley, showing depositional and erosional cycles and their relation to climate (modified from Thompson and others, 1982).

The Renova Formation is divided into a lower and an upper part. The lower part consists dominantly of fine-grained lacustrine and floodplain sediments, derived mostly from volcanic ash. Some coarse clastic materials derived from local sources are present as minor scattered lenses. Deposition of Renova sediments probably occurred in low-gradient streams (Hughes, 1980; Fields and others, 1985). The upper part of the Renova Formation is dominated by large quantities of volcaniclastic rocks and montmorillonitic mudstones. Minor scattered lenses of coarse clastic sediments, arkose, and conglomerate are present within this unit (Fields and others, 1985). Deposition of both members of the Renova formation was controlled by internal drainage into what would become the Gallatin Valley basin.

Renova Formation deposition occurred until early Miocene time when a shift to a more humid climate occurred (Thompson and others, 1982). Through-flowing drainage systems redeveloped and allowed removal of an unknown quantity of Renova sediments from the basin. A dissected erosional topography developed and produced an unconformity (Hughes, 1980). This moister climate continued until early middle Miocene time when a more arid climate developed.

Deposition of the Sixmile Creek Formation began following the climatic change from moist to dry during the early middle Miocene time. Basin filling resumed and gradually buried the erosional surface formed during post-Renova time (Hughes, 1980; Thompson and others, 1982). The Sixmile Creek Formation is composed of a sequence of gravelly sediments derived from developing fault-block mountains (Hughes, 1980; Fields and others, 1985). The coarse clastic sediments were deposited as fans, mudflows, debris flows, ephemeral stream deposits and some large channel fills. Volcaniclastic sediments comprise the majority of the deposits. (Hughes, 1980; Fields and others, 1985). These sediments were deposited under high-gradient flow conditions such as those found today in the arid southwestern United States. The coarser grained Sixmile Creek Formation rests upon Precambrian through Paleozoic rocks in other parts of the Gallatin Valley where dissection has cut into pre-Tertiary bedrock (Hughes, 1980).

Deposition of the Sixmile Creek Formation continued through late Miocene time until a climatic shift from a dry to wet environment occurred. The basin filling with Sixmile Creek Formation sediments ended by middle or late Pliocene time. This moist climate brought on the development of through-flowing streams which cut into the Sixmile Creek Formation. Some coarse-grained sediments were transported across this late Tertiary surface. These sediments are represented by the Quaternary-Tertiary older alluvium surface (Hackett and others, 1960; Hughes, 1980). The time of deposition of these sediments is not clear.

Late Tertiary - Early Quaternary

Pediment surfaces developed in the basins of southwestern Montana during the extensive erosion of the Sixmile Creek Formation (Fields and others, 1985). Up to late Tertiary or early Quaternary time paleodrainage direction is thought to have been in an easterly direction when not internal (Robinson, 1963; Glancy, 1965; Hughes, 1980). But during late Tertiary-early Quaternary time, a regional uplift to the south tilted most of the Gallatin Valley northward and formed the ancestral Missouri drainage (Robinson, 1961). The Gallatin

River cut through the bedrock at the eastern end of the valley and assumed its present drainage direction to the northwest. This new drainage direction along with a climatic change to a relatively warm, wet climate most likely contributed to the progressive downcutting of the streams into the late Tertiary sediments, leading to the development of the pediment surfaces. Downcutting was not restricted to the Tertiary sediments but excavated some underlying Mesozoic, Paleozoic and Precambrian rock units as seen in the Dry Creek and Horseshoe Hills area (Hughes, 1980).

Quaternary Deposits

In the basins of southwestern Montana, Quaternary sediments from locally derived sources overly the Tertiary pediment surfaces and fill dissected portions of the pediments (Fields and others, 1985). Glaciation during the Pleistocene in the Gallatin Range to the south contributed sediments which were transported northward into the southern end of the Gallatin basin (Weber, 1965). These sediments are superimposed over the Tertiary pediment surfaces as alluvial fans in the valley (Hackett and others, 1960).

The Quaternary alluvial fan deposits are composed of a heterogeneous mixture of coarse- and fine-grained sediments. Stringers and lenses of relatively clean sand and gravel deposited by the distributaries that built the alluvial fans are found throughout the deposits (Hackett and others, 1960). If this material filled pre-Quaternary erosional channels, as implied by Brown and others (1983), the potential for large water-bearing zones exists.

Basin Tectonics

The basins of western Montana, which include the Gallatin Valley, have a structural origin similar to that found in the Basin and Range Province of the western U.S. (Fields and others, 1985). Reactivation along the Willow Creek Fault (Central Park Fault) and other faults during late Precambrian, late Cretaceous and Cenozoic time contributed to the present structure of the Gallatin Valley (Robinson, 1963; Zim and Lageson, 1985).

Two dominant and significant tectonic regimes are responsible for the structural development of the Gallatin Valley: 1) Laramide fold and thrust faulting and block uplift, and 2) post-Laramide extension.

Laramide Regime

At the onset of the Laramide Orogeny, northeast-southwest compressive forces deformed and uplifted the pre-basin rocks. Extensive erosion of the uplifts occurred. Numerous northwest-trending oblique slip faults in southwestern Montana developed as a result of these compressive forces. These faults contain a left-lateral component of motion and dip steeply to the northeast (Schmidt and Garihan, 1983; Zim and Lageson, 1985). They cut both Archean and Phanerozoic rocks, as seen in the southwestern part of the Gallatin Valley, and probably extend beneath the basin sediments. Hughes (1980) observed several small northward-trending left-lateral strike slip faults in the Dry Creek Valley at the north end of the Gallatin Valley. These faults cut most of the lower Paleozoic section in this area. A study of these faults by Lageson and Zim (1984) suggests that they are reactivated Proterozoic normal faults that were folded in the early-Eocene by uplift of the Archean core of the Bridger Range.

In addition to these northwest-trending faults there is a system of northeast-trending thrust faults involving Archean, Proterozoic and Phanerozoic rocks. Major folds overturned to the east resulted from this thrusting episode. Overall direction for the compression was west to east resulting in a shortening of the crust by several tens of kilometers (Schmidt and Garihan, 1983).

Several high-angle reverse faults with a general east-west trend cut through the Bridger Range bordering the eastern margin of the basin proper. The Pass Fault is interpreted to be an extension of the Precambrian Willow Creek Fault zone located in the central part of the Gallatin Valley Basin (McMannis, 1955; Craiglow, 1986). Reactivation during Laramide compression first caused strike-slip motion on this fault, followed by later underthrusting of the Archean block to the south (Craiglow, 1985). This Archean block is concealed beneath younger deposits at the southern end of the Bridger Range and is interpreted from gravity data as a narrow gravity high (Davis and others, 1965) (Figure 5).

Post - Laramide Regime

The second tectonic regime responsible for the structural development of the Gallatin Valley is post-Laramide extension (Reynolds, 1979). The intermontane basins resulting from this tensional stress became catchment basins for clastic material shed from the surrounding mountains. Basin structures suggest faulting to be contemporaneous with sedimentation (Fields and others, 1985). The

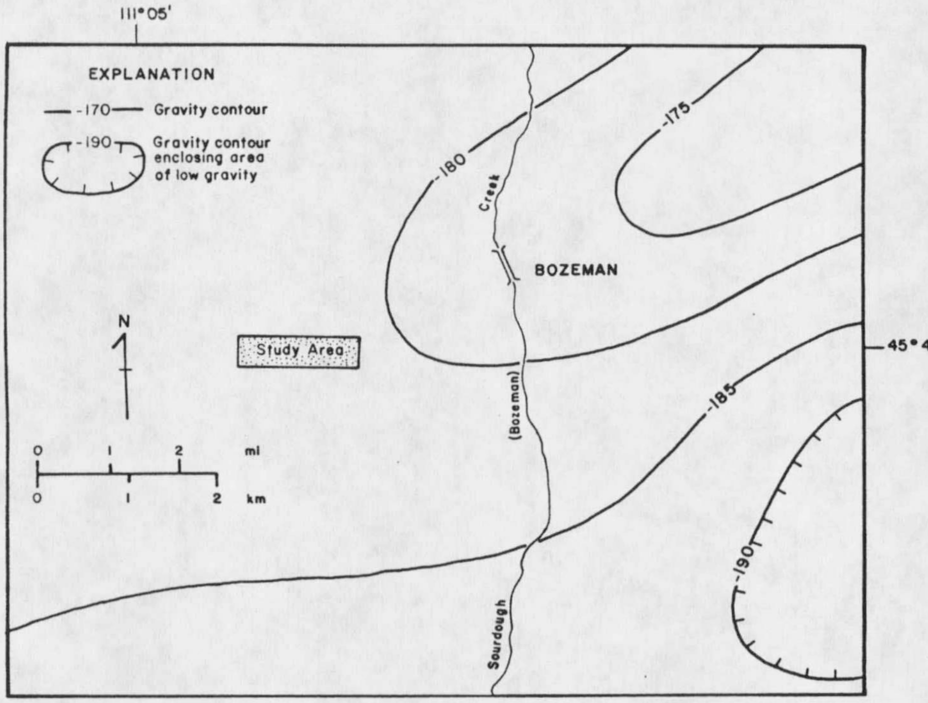


Figure 5: Bouguer gravity map of the Bozeman area. Contour interval 5 milligals (modified from Davis and others, 1965)

present stress field for the region responsible for this faulting appears to be east-west extension (Zoback and Zoback, 1980).

Structural development of the present Gallatin Basin area probably began during Miocene time (Lageson, 1989). Extensional tectonics were responsible for early basin development and controls most of Cenozoic basin geometry. Range-front faults became active during this time. Early basin shapes were much broader and shallower than present basins (Robinson, 1963; Fields and others, 1985). Normal faulting occurred along the eastern and southern margins of the Gallatin Valley through late Tertiary time. Faulting has offset Tertiary sediments but no offset of overlying Quaternary alluvium has been documented (Hackett and others, 1960; Hughes, 1980). Tertiary strata in the eastern part of the basin, where exposed, dip into the mountain front. This observation suggests a listric geometry for the basin margin structure and has important implications for any groundwater exploration model for the Gallatin Valley. Dips of Tertiary strata in the southern part of the valley are inferred to have a listric geometry as well but are not well enough exposed to document. This inference is supported by gravity data. Along the Gallatin Range front, Tertiary strata are disturbed but the Quaternary alluvial fan deposits are apparently not affected (Hackett and others, 1960). This suggests latest movement along the fault to be of late Miocene or early Pliocene time (Tysdal, 1966).

Geophysical data supports the interpretation of two northeast-southwest trending normal faults at the southern end of the Bozeman alluvial fan. This system of inferred Gallatin Range Front faults separates the Gallatin Valley from the foothills of the Gallatin Range (Figure 6). Gravity data along the southern margin of the Gallatin Valley suggests a bedrock trough underlying Quaternary sediments (Davis and others, 1965). This trough is estimated to be approximately 2 km deep and 3 km wide in the vicinity of South Cottonwood Creek. The trough is bounded on the southern and northern margins by concealed step fault zones (Davis and others, 1965). The southern fault extends approximately from the mouth of the Gallatin Canyon eastward along the range front. The fault which bounds the north margin of the structural trough appears to have more than 600 m (2000 ft) of vertical displacement (Davis and others, 1965). Gravity data suggests that the bedrock surface below the Tertiary-age sediments gradually rises from the south to the north where Precambrian crystalline rock lies just below the surface. In some areas of the valley, such as the Camp Creek Hills, Precambrian crystalline rock crops out at the surface. The location of near-surface Precambrian bedrock is a major consideration when searching for groundwater in the valley since such gneiss should form very poor aquifers (Hackett and others, 1960) and may influence the geomorphic history and geohydrologic conditions of the area.

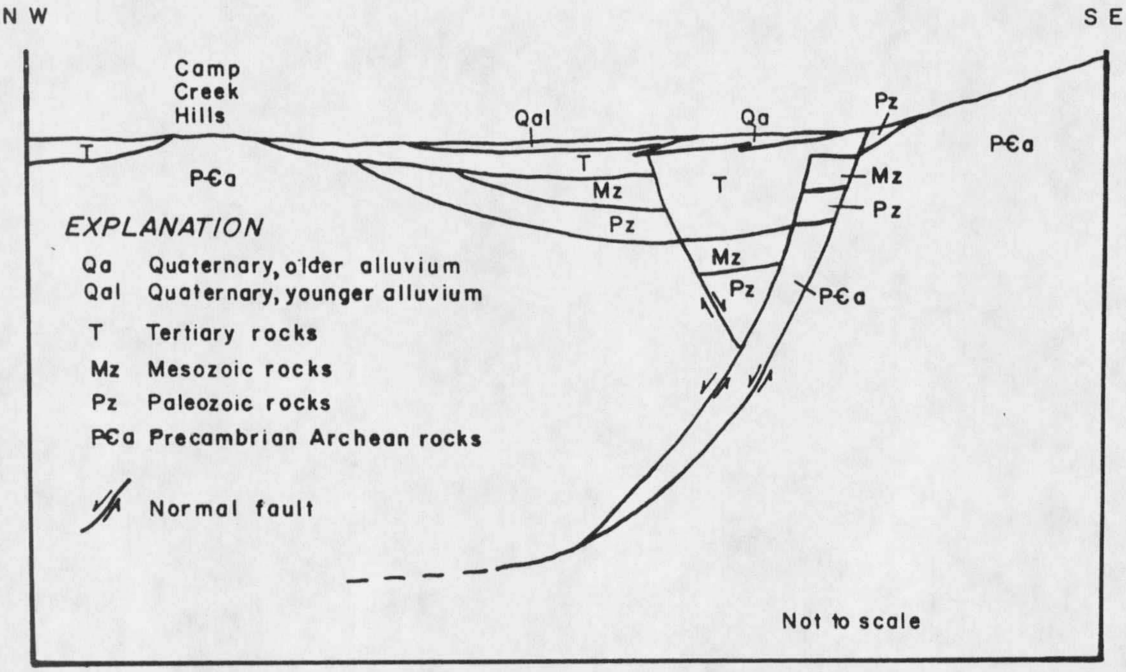


Figure 6: Schematic structural cross-section across the southern end of the Gallatin Valley near South Cottonwood Creek. Note the relationship between the Gallatin Range Front Fault and the structural trough of Davis and others (1960). See Figure 3 for line of cross-section.

Bozeman Alluvial Fan

Groundwater exploration in alluvial fan environments requires an understanding of processes controlling past and present depositional and erosional periods (Cehrs, 1979). Structural controls commonly associated with such fans in fault-block valleys also influence the hydrologic system (Dutcher and Garrett, 1963; Fetter, 1980). A testable structural-depositional model is useful when attempting to understand the groundwater potential of a system such as the Bozeman alluvial fan.

Alluvial fans can be generally thought of, from the standpoint of groundwater exploration, as alternating vertical and lateral sequences of aquifers and aquicludes (Cehrs, 1979). These variations primarily result from controlling factors such as tectonic activity (Bull, 1972, 1984; Heward, 1982; Nilsen, 1982), source rock lithologies (Hooke, 1967; Rust, 1979; Harvey, 1984), climatic variations (Bull, 1972; Boothroyd and Ashley, 1975; Blissenbach, 1980; Westcott and Ethridge, 1980; Kochel and Johnson, 1984; Ritter and TenBrink, 1986) and drainage basin size (Nilsen, 1982; Harvey, 1984). These factors are complicated by local geologic historical influences unique to a particular alluvial fan.

An alluvial fan can be divided into three main zones: 1) proximal (coarse-grained), 2) mid-fan, and 3) distal (fine-grained) areas. Figure 7 diagrammatically shows these alluvial fan zones and the gradation that exists between them. The intersection point on an alluvial fan is the point where the alluvial fan stream emerges from its channel and spreads out across the fan surface (Hooke, 1967). Downstream from this intersection point is where modern deposition of proximal sediment occurs. The Bozeman alluvial fan may display these features, but due to the lack of detailed sedimentological data, separating out the three sections is not currently possible.

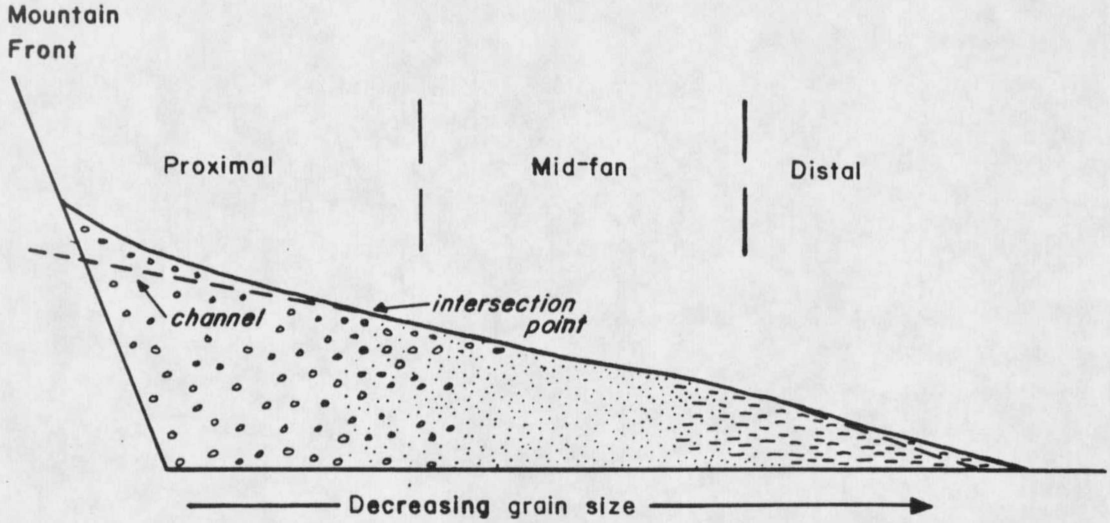


Figure 7: Schematic longitudinal cross-section of a general alluvial fan facies model (modified from Rust, 1979).

Proximal Zone

The proximal zone of an alluvial fan is dominated by coarse-grained sediments usually transported only a relatively short distance past the mouth of the canyon (Bull, 1972). In other regions, debris flow (or mudflow) deposits are also found in this area of the alluvial fan. Debris flows are caused by steep slopes, lack of vegetation, short periods of abundant water supply and a source of debris with mud-rich matrix (Johnson, 1970; Bull, 1977).

The sediments in the proximal zone of the Bozeman alluvial fan and observed in well logs consist of coarser-grained boulders and cobbles intermixed with finer grained gravels and sand (Hackett and others, 1960). Sediment sorting is poor in this zone. A deep, broad, single channel represented by present day Hyalite (Middle) Creek is present in the proximal zone of the Bozeman alluvial fan and is characteristic of fans in general (Bull, 1964, 1968). Hyalite (Middle) Creek is presently incised at the head of the Bozeman alluvial fan.

Mid-fan Zone

The boundary between the proximal and mid-fan zone on an alluvial fan is difficult to ascertain unless sub-surface exposure is available, so only approximate limits can be made. The extent of the proximal zone will vary for each individual alluvial fan (Nilsen, 1982). Sediment size within the mid-fan zone is expected to consist of coarse- to medium-grained sediments (cobbles, gravel and sand), finer-grained than those found in the proximal zone since sediment size decreases downfan (McGowan, 1979). Relatively shallow, discontinuous distributary channels radiating outward from the main stream channel of the proximal zone are often present in this zone (Nilsen, 1982). These shallow channels develop by avulsion as the channels fill and clog with sediment. Although the channels are usually braided, anastomosing or straight channels may also be present depending upon fan gradient, sediment type, sediment supply and climatic effects (Bull, 1968; McGowan, 1979; Nilsen, 1982).

The boundary between the proximal and mid-fan zone of the Bozeman alluvial fan is difficult to ascertain since very few cuts expose the material. Lithologic logs from wells drilled in the alluvial fan may show this boundary but variations in driller's descriptive logs may make identification of this boundary difficult. Because of this lack of outcrop, the shift from poorly sorted coarser-grained deposits characteristic of the proximal zone to the better sorted medium-grained stream-laid deposits of the mid-fan zone has not been identified.

The upper part of the mid-fan zone of the Bozeman alluvial fan may be complicated by the structural trough inferred from the gravity survey data (Davis and others, 1965), located at the southern end of the Gallatin Valley. A thick sequence of Cenozoic sediments is confined within this trough and thins northward. Whether or not this trough had an effect on depositional controls of the alluvial fan material is uncertain.

Distal Zone

Finer-grained, sheet-like sand, silt and clay transported by unconfined low velocity stream flow processes often characterize the distal zone of an alluvial fan (Nilsen, 1982). These deposits may interfinger with floodplain sediments near the farthest limits of the alluvial fan. Due to the lack of subsurface exposure, the boundary between the mid-fan and distal zones has not been identified on the Bozeman alluvial fan. Based upon the work of Hackett and others (1960), the Bozeman alluvial fan distal zone would tend to be similar to that characterized by alluvial fans in general.

Paleochannel Hypotheses

An interesting feature of the Bozeman alluvial fan and the main problem in this study is the postulated presence of a deep buried paleochannel inferred from seismic refraction data (Brown and others, 1983). The occurrence of such a channel does not fit most reported models of alluvial fans. The general model for the mid-fan area usually includes braided stream channels only of the magnitude of about 3 m deep (10 ft) (Bull, 1968). But local geologic history and structural controls in the Gallatin Valley basin allow for the feasibility of such a paleochannel.

A similar condition exists in the upper Madison Valley in southwestern Montana. Ruby Creek flows westward from the tectonically active Madison Range. The creek has cut a deep channel into the alluvial fan and the bedrock beneath the alluvial fan as it flows into the Madison River (B. Locke, Montana State University, personal communication, 1989). The presence of this geomorphological feature helps support the feasibility of such a condition to exist beneath the Bozeman alluvial fan.

Several hypotheses can be proposed to explain the existence of such a paleochannel on the Bozeman alluvial fan:

1) A thick sequence of Cenozoic sediments are downwarped and dip northward beneath the Belgrade plain (Hackett and others, 1960) (Figure 8). If the tectonic subsidence rate periodically exceeded the filling rate of the downwarped trough south of the Central Park Fault, a new lowered local baselevel might cause downcutting on the Tertiary strata beneath the present day Bozeman alluvial fan. Although downcutting would more likely be confined to the distal zone, the proximity of the study area to the toe of the fan could allow for some downcutting in the study area as well. As filling rates increased, renewed deposition on the Tertiary sediments would occur. Deposition of coarser-grained

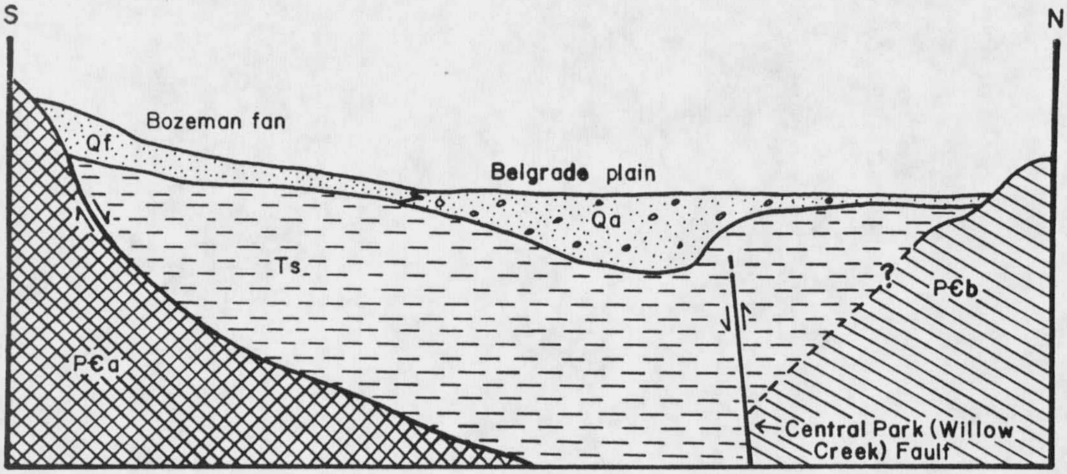


Figure 8: Schematic cross-section of the Gallatin Valley near Belgrade. Note the relationship between the Bozeman alluvial fan, Belgrade plain (Gallatin Valley floodplain) and the Central Park fault (modified from Hackett and others, 1960).

sediments during the most recent development of the Bozeman alluvial fan could have been concentrated within this channel. Once the channel filled, continued deposition on the alluvial fan surface would have occurred.

2) The Precambrian bedrock ridge buried just below the surface in the eastern central part of the Bozeman alluvial fan could also have been a factor in development of a paleochannel. The raised bedrock may have caused the stream flow in this section of the valley to be constricted as it flowed around this obstruction. A straighter stream course could cause additional downcutting as the local baselevel fluctuated. A concentration of coarse-grained lag gravels might also have been confined within such a channel during the depositional period.

3) A change in baselevel might result as the drainage direction changed from east to west during the late-Tertiary to early-Quaternary

time. As the Gallatin River cut through bedrock at the western end of the valley and drained into the Missouri River, a downcutting period would most likely have occurred on the Tertiary surface as the basin adjusted to this new drainage direction. Hughes (1980) has noted the dissection of the Tertiary surfaces at the northeast end of the Gallatin Valley, and it is reasonable to assume dissection was not confined to that part of the valley. The Tertiary paleotopography cut on Tertiary material then filled with late-Tertiary to early-Quaternary age sediments as erosion of the uplifted Gallatin Range continued.

Paleochannel Model

With these hypotheses in mind, a paleochannel could exist beneath the Bozeman alluvial fan and a thick sequence of Quaternary sediments could be confined within it. The proposed conceptual model for this study of the Bozeman alluvial fan consists of a thick sequence of Quaternary, Tertiary, Paleozoic and Mesozoic sediments present in the fault-bounded basin at the south end of the Gallatin Valley (Figure 9). The sediments thin to the north as the underlying Precambrian metamorphic rocks rise to just below the surface beneath Montana State University.

The study site is located within what is interpreted to be the lower mid-fan zone. This interpretation is based solely on the well log interpretations and geologic mapping of Hackett and others (1960). Structural complications in this area are caused by a near-surface Precambrian bedrock ridge located beneath the campus of Montana State University and inferred by gravity data (Davis and others, 1965) and

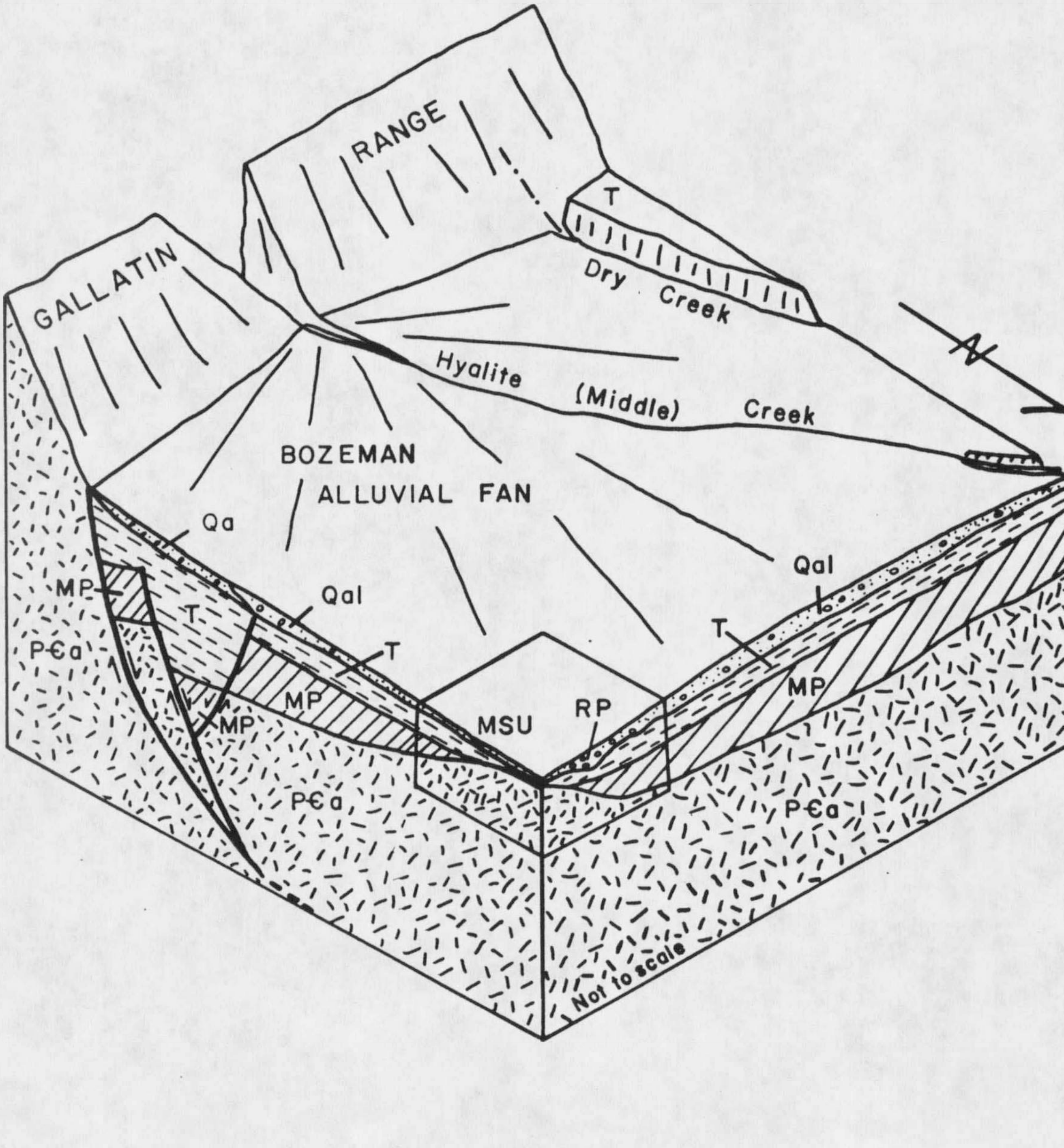


Figure 9: Block diagram of the conceptual exploration model for the Bozeman alluvial fan, southwestern Montana. MSU = Montana State University; RP = postulated Roskie paleochannel; Qa = older Quaternary alluvium; Qal = younger Quaternary alluvium; T = Tertiary sediments; MP = Mesozoic-Paleozoic rocks; PЄa = Precambrian Archean rocks. Inset Figure 10.

seismic refraction data (Brown and others, 1983). Weathered metamorphic rocks were also observed in building site excavations on campus (C. Bradley, personal communication, 1989). Since the bedrock is apparently close to the surface, a thin Quaternary and Tertiary layer would be expected in this area overlying the Precambrian bedrock. The potential for groundwater withdrawal would be severely limited in the area, but thicker Cenozoic deposits are suspected further to the west beneath Roskie field. Gravity data suggests that the near-surface bedrock ridge slopes to the west beneath the Bozeman alluvial fan (Davis and others, 1965). This may allow for thicker accumulations of water-bearing units to be found west of this bedrock ridge, in the Roskie study site.

Brown and others (1983) proposed the location of a paleochannel beneath Roskie field (Figure 10). Based on their hypothesis, the channel is proposed to be cut in Tertiary sediments and filled with a thick sequence of Quaternary gravels. A subtle topographic depression is postulated to represent a surface expression of this paleochannel. Examination of the subsurface by drilling, seismic refraction and earth resistivity surveys are necessary to determine if the model is correct and if the paleochannel does exist.

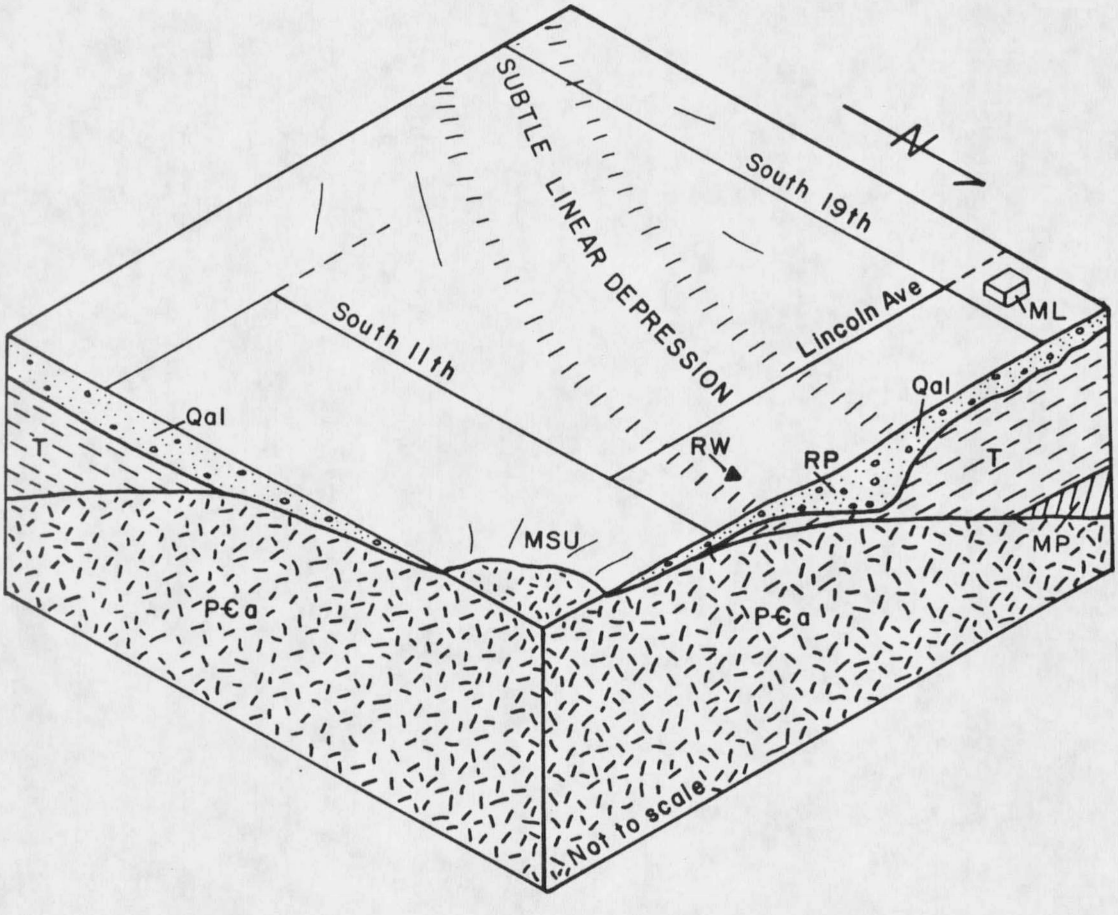


Figure 10: Block diagram of hypothesis to be tested in Roskie study area and vicinity. MSU = Montana State University; RP = postulated Roskie paleochannel; RW = Roskie well site; ML = Marsh Lab; Qal = younger Quaternary alluvium; T = Tertiary sediments; MP = Mesozoic-Paleozoic rocks; PЄa = Precambrian Archean rocks.

METHODS OF STUDY

Very little subsurface exposure is available on the Bozeman alluvial fan. Several geological exploration methods were utilized in an attempt to locate the present boundaries of the proposed paleochannel at the western end of Montana State University campus. These methods included air photo interpretation, well data interpretation, and earth resistivity and seismic refraction geophysical techniques.

Air Photo and Geomorphology

Air photos taken in the years 1937, 1965, and 1971 were examined in order to search for any surface expression that might suggest the subsurface geology in the study area. The early photos were chosen to reduce the effects of human disturbance on the alluvial fan surface which would mask any surface expression of the subsurface features. Brown and others (1983) had suggested that the postulated paleochannel could be traced as a topographic expression on the surface. Air photos were also examined to identify variations in the vegetation pattern which might suggest variations within the water table. These patterns could be confined to the trend of the paleochannel.

Drilling and Well Development

The postulated paleochannel was further tested by drilling a water well near Roskie Dormitory. The location was selected based on geophysical data and interpretations made by Brown and others (1983). A cable tool rig was used to drill a 0.15 m (0.5 ft) diameter well to a total depth of 56.4 m (184 ft). Rock chip samples were collected at 3 m (10 ft) intervals or whenever the well was bailed. A standard size 0.5 l (2 cup) sample was sieved through a screen in order to estimate the percent gravel in the field. This allowed for a crude estimate of the average size, type and amount of cementation of the sediments drilled over the sampled section. A drill log was then made.

The well is fully cased from the surface to the screened section. A plastic screen was originally installed in the well but the driller was unable to control the screen during development. The screen floated up into the casing and its location could not be determined in the well. The plastic screen was removed and replaced with a 3 m (10 ft) long, # 15 slot, 0.038 cm (0.015 in) Johnson stainless steel screen with a 1.52 m (5 ft) tail pipe section. The screen size was determined by sediment size analysis performed in the laboratory and verified by the screen manufacturer. The well was deepened from 53 m (175 ft) to 56 m (184 ft) when the steel screen was installed. Upon installation of the screen, the well was developed using a flap-valve bailer attached to the bottom of the drill stem. This surge method is easily adapted to a cable tool rig (Todd, 1980). The purpose of well development is to remove the finer grained material surrounding the screened section and to concentrate coarser grained material outside of the screen. Ultimately specific capacity is increased, sanding in of the well is eliminated and maximum economic well life is obtained (Todd, 1980).

A four hour pump test with a constant pumpage rate of 227 l/m (60 gpm) was used to determine the hydraulic parameters controlling the system. Discharge was measured by recording the time needed to fill a 208 l (55 gal) drum. Since no observation wells were available the recovery test method based on the Cooper-Jacob method described in Todd (1980) was used to analyze the data.

Several slug tests were conducted on the Roskie well in order to estimate the hydraulic conductivity of the aquifer system. The slug tests were conducted at various times in order to test for changes in the well hydraulics after development. The Hvorslev method of data analysis was used (Hvorslev, 1951).

Resistivity

A resistivity survey was performed using a Bison 2350 direct current earth resistivity meter. A Wenner array, as described in Zohdy and others, (1974), was used to determine how resistivity values varied in map view for different depths. Four electrodes are placed equal distance apart in a straight line at the ground surface (Figure 11). The resistivity of the earth material is a function of depth probed, subsurface material and the single-distance variable, a. A resistivity profile map of the subsurface was made using an a-spacing of 9 m (30 ft) and 30 m (100 ft). The two a-spacings were chosen in order to give

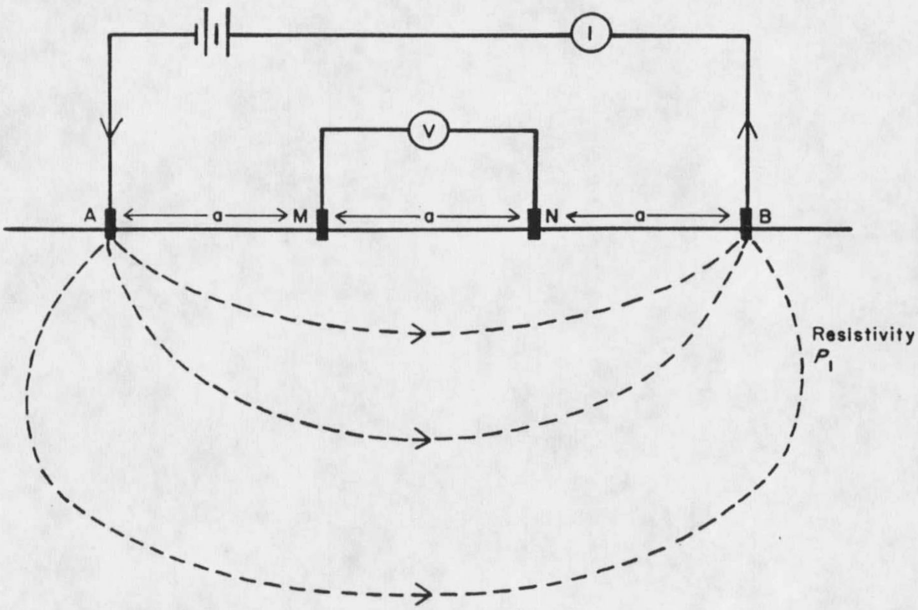


Figure 11: Wenner electrode array. A and B are current electrodes, M and N are potential electrodes; a is electrode spacing. AM = MN = NB = a. I = current meter; V = voltage meter; arrows indicate direction of current flow (modified from Mooney, 1980).

a picture of the resistance of the subsurface material and to intersect the postulated paleochannel at a relatively shallow and a relatively deep depth. Probed depth is difficult to estimate in environments with heterogeneous and anisotropic stratigraphy. A first approximation of exploration depth is often taken to be 2/3 the a-spacing (Zohdy and others, 1974; Dobrin, 1976). For example, an a-spacing of 30 m (100 ft) probes a depth of approximately 20 m (67 ft). An a-spacing of 30 m (100 ft) appears to be the limit of reliable probing depth in this study area. The depth probed was a function of the limits of the equipment due to the relatively small current source and the relatively low electrical conductivity of the heterogeneous unconsolidated alluvial material. Apparent resistivity values were recorded in the field and plotted on a base map. A profile map was made for corrected depths of approximately 6 m (20 ft) and 20 m (67 ft).

In addition to the Wenner profile, several vertical electrical soundings were completed in selected areas to determine how resistivity varies with depth beneath one point. Electrical sounding is performed by expanding the electrode spread about a single central point (Mooney, 1980). The technique is useful for determining a layering sequence of high and low resistivity zones through a subsurface section, such as gravels between clays. A plot of the apparent resistivity was made on log-log paper.

Seismic Refraction

A shallow seismic refraction survey was completed in the study area in order to further test the results of Brown and others (1983) regarding the depth to the boundaries low and high velocity material and the shape of such contacts. The seismic survey was also used to verify the results of the seismic survey previously done in the area by Brown and others (1983). A Geometrics 12-channel signal enhancement seismic recorder was used in the survey. The seismic lines had a length of 145 m (475 ft). This allowed for a depth of investigation to be approximately 50 m (160 ft) beneath the study area (Mooney, 1980). The energy source used was a 136 kg (300 lb) weight dropped from a height of 3 m (10 ft). A forward and reverse velocity-distance profile was performed for each seismic line. The energy source was offset 3 to 5 m (10 to 15 ft) at a right angle to the geophone cable. This offset distance "normally provides a direct arrival through the surface layer and allows a determination of its velocity" (Redpath, 1973). The slant distances from shot point to geophone were computed for the first three geophones. First arrivals were interpreted from waveforms recorded on the seismic screen. All 12 channels were displayed at the same time, allowing for accurate visible first-arrival picks to be made. A time-distance plot of the data was made in the field in order to visually assess potential problems and data validity. If problems were found with the time-distance plot, the line was re-done at that time. A paper copy of the seismic waveform was then made in order to analyze the seismic data in the office.

RESULTS AND DISCUSSION

Air Photo Interpretation

No obvious vegetation patterns in the study area were recognized from the air photos examined from the years 1937, 1965, and 1971. The close proximity of this area to the city of Bozeman, along with farming and grazing activity in the area could have resulted in an alteration of the vegetation pattern by human disturbance. A slight topographic depression suggesting the trend of a buried stream channel was recognized on both the air photos and the Bozeman topographic quadrangle. Upon further research it was found that this trend is a near surface morphological feature that has been altered by construction fill in the Roskie study area. Further discussion of this fill will be presented in the seismic refraction section.

Drilling and Well Development

A well was drilled on the eastern edge of Roskie field in a area hypothesized by Brown and others (1983) to contain greater than 60 m (200 ft) of coarse-grained alluvial material (see Figure 10). Such a well is expected to yield a large amount of water. Although the best location for the well based on seismic evidence is in the center of the field, the well was drilled on the eastern edge of the hypothesized paleochannel because placement at the preferred location would prove hazardous during recreational activities on the field. The results of the drilling allowed a more detailed first-hand examination and analysis of the subsurface material within the hypothesized paleochannel. The well also allowed for a comparison of the drill log and the electrical resistivity and seismic refraction data.

One other deep well was drilled in 1960 at the site of the Marsh Laboratory near the western edge of the study area and outside the postulated channel boundary. Only a very generalized well log is available for this well. The drill log reports relatively coarse-grained sediment throughout the well. The driller reported that a constant flow of 1900 l/m (500 gpm) was produced for the duration of the four hour pump test.

Drill Data and Interpretation

A lithologic log of the subsurface material encountered in the well at Roskie field suggests a general fining downward sequence (Table 1). Based on the estimated percent gravels in the sample, gravels are more abundant near the surface and decrease in thickness and frequency with depth. The sediments at depth are dominantly fine-grained sand, silt and clay with minor amounts of gravel. Clay lenses are abundant in this lower zone. Cemented sandstone fragments were identified in cuttings from the lowest 12 m (40 ft) of drilled section.

Prior to drilling there was hope that Tertiary material might be differentiated from Quaternary material. Both units were suspected of having a similar fluvial depositional history - stream channel, overbank and alluvial fan deposits. Cementation may have been the key to separating the two formations but the cable tool drilling method

Table 1: Lithologic log of Roskie well, Roskie field study area, Montana State University, Bozeman. Data from 53.3 - 56.0 m (175 - 184 ft) was supplied from driller. No samples were taken. Screened interval at 51.5 - 54.6 m (169 - 175 ft).

Depth m (ft)	Thickness m (ft)	Gravel %	Lithology summary
0-2.4 (0-8)	2.4 (8)		clay and silt; no water
2.4-3.7 (8-12)	1.2 (4)		gravel (large cobbles) uncemented
3.7-8.2 (12-27)	4.6 (15)	40	clay-bound gravels
8.2-8.9 (27-29)	0.6 (2)	30	clay and sand; water est. at 37.9 l/m (10 gpm)
8.9-10.4 (29-34)	1.5 (5)		clay-bound gravels
10.4-11.9 (34-39)	1.5 (5)	40-60	gravel, water at 11.9 m (39 ft), 7.5-11.4 l/m (2-3 gpm)
11.9-12.5 (39-41)	0.6 (2)	25	saturated sand
12.5-14.0 (41-46)	1.5 (5)	30	mixed clay-sand-gravel; saturated
14.2-20.1 (46-66)	6.1 (20)	20-25	mixed clay-sand-gravels; saturated; clay-bound gravels; clayballs
20.1-20.4 (66-67)	0.3 (1)	40	quicksand; mixed clay-sand-gravel; minor clayballs
20.4-21.3 (67-70)	0.9 (3)	50	clay-bound gravels
21.3-24.1 (70-79)	2.7 (9)	10	sandy clay; clay-bound gravels
24.1-25.3 (79-83)	1.2 (4)	10	clay; minor gravels
25.3-28.4 (83-93)	3.0 (10)	20	clay-bound gravels; sand and clay; water between 26.2-28.4 m (86-93 ft)
28.4-29.0 (93-95)	0.6 (2)	25	quicksand; clay and sand
29.0-36.0 (95-118)	7.0 (23)	<10	fine-grained sand and clay; quicksand; clayballs
36.0-40.8 (118-134)	4.9 (16)	<10	water saturated clay and fine-grained sand
40.8-44.2 (134-145)	3.4 (11)	<15	fine-grained sand and clay; cemented sandstone
44.2-53.3 (145-175)	9.1 (30)	1-10	fine-grained sand and clay; minor cemented fragments; silica or clay cement
53.3-54.8 (175-180)	1.5 (5)		gravelly sand?
54.8-56.0 (180-184)	1.2 (4)		consolidated sand?

breaks the consolidated sediment into small particles, making this distinction difficult. Some evidence of cementation was noted at a depth of about 41 m (134 ft) although it could have been missed in samples higher in the drill hole. But cementation cannot be relied upon as a distinction between the two formations. The Tertiary unit in parts of the valley is very poorly consolidated and easily eroded.

Lithologic differences between the Tertiary and Quaternary formations are not obvious in drilled materials because both units have the Gallatin Range to the south as their source area. Hackett and others (1960) used the increase in clay content noted in well logs as the boundary between Tertiary and Quaternary material. Much clay was present throughout the total depth of the Roskie drill hole, making it difficult to determine if a boundary was present between the two units.

Water Level Measurements

Static water level in the Roskie well was 3.87 m (12.7 ft) below ground level on January 6, 1985 (Table 2). This level has varied very little. No seasonal fluctuations are evident in the Roskie well. The near constant water level in the well suggests the well is completed in a confined or semi-confined aquifer system. The geologic log further supports this hypothesis since the numerous clay zones present in the well probably confine this system from water-bearing aquifers above and below (see Table 1).

Aquifer Analysis

Pump test. The well was pumped for four hours at 227 l/m (60 gpm) (Figure 12). A fairly good estimate of the hydraulic characteristics

Table 2: Water level measurements in the Roskie well. bgl = below ground level).

Date	Static Water Level (bgl) ft	m
1/6/85	12.7	3.87
5/22/85	11.8	3.58
6/20/85	11.7	3.55
8/9/85	11.0	3.35
9/5/85	10.6	3.22
10/18/85	10.7	3.26
1/14/86	11.4	3.47
3/18/86	11.3	3.44
4/29/86	11.5	3.51
10/23/87	11.1	3.39
6/10/88	10.8	3.29
10/14/88	10.8	3.29

of the subsurface materials at the screen was made. A 380 l/m (100 gpm) pumpage rate was preferred to test the well properties but the driller could not provide a pump for this purpose. The static water level prior to pumping was 3.58 m (11.75 ft) below ground level (bgl). During the pump test, water levels were measured with an echo depth sounder and cross checked with an electric tape. Both types of measurements compared well. After a rapid initial drop in water level at the start of the pump test, the water level stabilized at 22.91 m (75.15 ft) to 23.21 m (76.15 ft) bgl and remained at this level for the last 2 hours of the pump test. The 0.3 m (1.0 ft) fluctuation in water level may have resulted from slight variations in the pumping rate during the four hour pump test or from minor measurement errors. Recovery levels were measured after the pump test was terminated.

The recovery method described in Todd (1980) was used to analyze the pump test data and estimate transmissivity in the Roskie sediments.

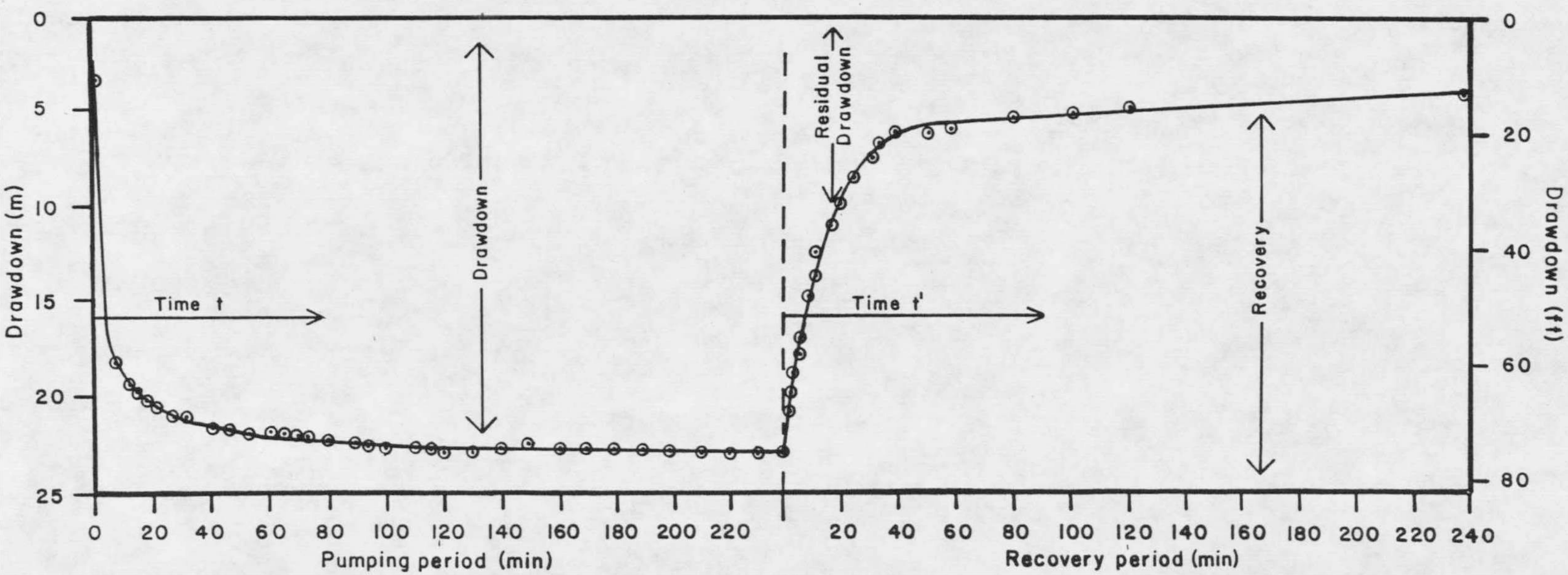


Figure 12: Drawdown and recovery data, Roskie well, May 25, 1985. (t is total elapsed time since start of test, continuing without interruption through the recovery period; t' is the elapsed time since the pump is turned off).

The advantages of this method is that no observation well was needed and aquifer thickness is not a factor in calculating transmissivity. Another advantage of this method of aquifer analysis is that uncontrolled variations in the pumping rate are not important. The recovery data can be more useful than the actual drawdown data (Fetter, 1980). This recovery method is based on the principles of the Cooper-Jacob straight line method which is rooted in the non-equilibrium (Theis) equation. Several underlying assumptions are inherent in the method (Todd, 1980). The aquifer is assumed to be fully penetrated by the screened section so that horizontal flow is everywhere equal within the aquifer. Since the aquifer thickness is relatively small and the thickness can be approximated from the drill log, this assumption is valid (Hantush, 1961). If a well is pumped for a period of time and then turned off, the rate of recharge (Q) into the well during the recovery period is assumed to be equal to the original pumpage rate. One can assume that a hypothetical recharge well with the same rate of flow was superimposed on the pumped well as soon as the pump is shut down (Todd, 1980). Based on this principle,

$$T = \frac{2.30\ Q}{4\pi \Delta s'}$$

where T = transmissivity, Q = rate of recharge, $\Delta s'$ = change in residual drawdown per log cycle during recovery period . (Residual drawdown (s') is a measurement of drawdown below the original static water level, during the recovery period). Figure 13 is a plot of the data used to determine transmissivity with the Cooper-Jacob method. Appendix A contains the pump test data.

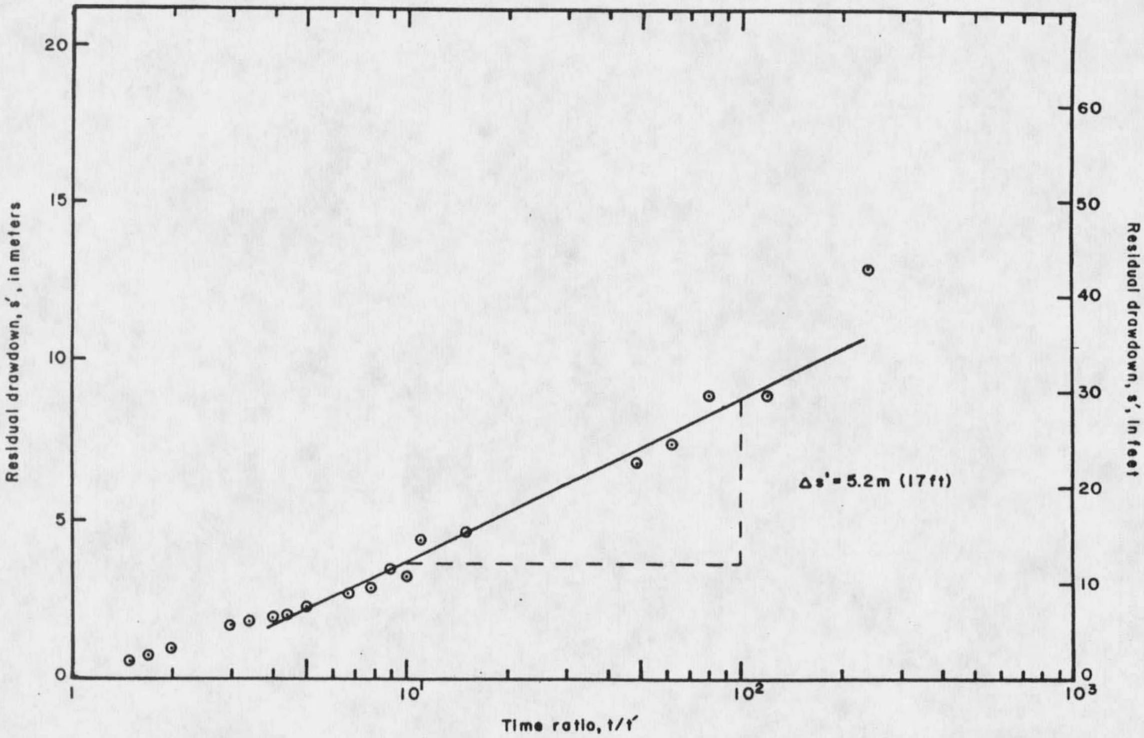


Figure 13: Cooper-Jacob semi-log plot of recovery data used to estimate transmissivity for the Roskie well.

The calculated transmissivity values from the recovery method was 12 m^2/day (930 gpd/ft). The calculated transmissivity values correspond well with the published values for the Tertiary sediments in the valley. Hackett and others (1960) report transmissivity values for the finer-grained Tertiary sediments in the range from 3.7 m^2/day (300 gpd/ft) to 75 m^2/day (6000gpd/ft). Coarser-grained Quaternary sediments on the other hand, are reported to have transmissivity values ranging from 320 to 810 m^2/day (26000 to 65000 gpd/ft) and averaging about 600 m^2/day (48000 gpd/ft).

<u>Slug tests</u>. Several slug tests were also conducted on the Roskie well to independently estimate hydraulic conductivity. Hydraulic

conductivity (K) is a coefficient of proportionality which describes the rate at which water can move through a permeable medium (Fetter, 1980). The Hvorslev method of data analysis was chosen to estimate the hydraulic conductivity of the confined system from the slug test data. This method was chosen because it is not restricted to conditions of a confined aquifer or fully penetrating screen. This is important because the well appears to be in a confined system, but full penetration of the screen is not certain since the boundaries of the confining aquifer could only be approximated by the drilling method. The driller failed to notify Montana State University when the steel screen was installed. Because of this oversight, the last 3 m (9 ft) of the drill hole was not logged (see Table 1). This amounts to 1.5 m (5 ft) of tail pipe section and 1.2 m (4 ft) of screened section. The screened section extends from 52 m to 55 m (169 to 179 ft). This zone contains an upper 1.8 m (6 ft) of fine-grained sand and clay, which was logged, and a lower 1.2 m (4 ft) of gravelly sand, as reported by the driller. Since the screened section does not fully penetrate the upper fine-grained zone nor the lower gravelly sand zone, the Hvorslev method was chosen to analyze the data and provide an independent check of transmissivity as determined by the recovery method.

The equation used in determining K with the Hvorslev method is

$$K = \frac{r^2 \ln (L/R)}{2 L T_0}$$

where r=casing radius, L=length of intake, R=radius of intake, and T_0 =time lag for one log cycle. The calculated hydraulic conductivity from a representative slug test for the Roskie well aquifer is 2.8×10^{-5} m/s (9.15×10^{-5} ft/s). This is equivalent to 2.1 m/day (52.5

gpd/ft^2). These values correspond with the range of accepted values for silty sands and fine sands (Fetter, 1980). This sediment type dominates the lithology in the drill hole and is in agreement with the sediment-size analysis performed when the proper screen size was determined. Appendix A contains the slug test data.

The hydraulic conductivity value calculated from the Hvorslev method can be used to estimate transmissivity since T = Kb where T = transmissivity, K = hydraulic conductivity, and b = aquifer thickness. The calculated transmissivity value can then be compared to the value calculated from the recovery method. Since the true aquifer thickness is not known for certain, an upper and lower end was used to estimate transmissivity values. Based on an estimate from the drill log data, the minimum aquifer thickness is 1.5 m (5 ft) and the maximum aquifer thickness is 10.7 m (35 ft). Transmissivity values were calculated to be 3.2 m^2/day (263 gpd/ft) for the minimum aquifer thickness and 22 m^2/day (1838 gpd/ft) for the maximum aquifer thickness. The average transmissivity is 13 m^2/day (1050 gpd/ft) and compares very well with the transmissivity value of 12 m^2/day (930 gpd/ft) calculated using the recovery method, considering the inadvertent problems with the drill data. The results also indicate that the Hvorslev method of data analysis was an acceptable method to use to interpret the aquifer conditions of the Roskie well.

Discussion

The data from the Roskie well can only be used to estimate transmissivity and hydraulic conductivity. A second well drilled to this depth in the aquifer and utilized as an observation well would allow for determination of the coefficient of storage. During the pump test, the maximum amount of water capable of being withdrawn from the system was not reached. A constant pump rate of 227 l/m (60 gpm) sustained over a 4 hour period only caused the water level in the well to drop about 20 m (65 ft) below ground level. This depth to water fluctuated only 0.3 m (1 ft) during the last two hours. Approximately 29 m (95 ft) of water still remained in the well during the duration of the pump test. This suggests that the aquifer could sustain a higher pumpage rate before total drawdown is reached. A pump test designed to determine the sustained yield is desirable to test the aquifer capacity but a larger pump is needed. The pumpage rate could be approximated using the method described in Driscoll (1986). But since various assumptions were used when estimating transmissivity and hydraulic conductivity, additional estimates will only compound the problem and should not be considered until these uncertainties can be eliminated.

Tertiary strata are generally thought of as yielding water sufficient for only domestic or livestock use (Hackett and others, 1960). Enough water for irrigation or other large-scale use are generally not believed to be present due to the hydraulic properties of the sediment. Whether or not this is the case for the Roskie well remains to be determined. The calculated transmissivity and hydraulic conductivity values of the Roskie well compare well with other values for the Tertiary units elsewhere in the Gallatin Valley. Further drilling and hydrologic analysis of Tertiary sediments throughout the Gallatin Valley may change this interpretation.

The Roskie well does not appear to be located within the postulated paleochannel. The nature of the fine-grained sand and clay present in the well suggests that either the well was drilled outside the channel margin while attempting to stay off of the playing field or the channel does not exist. No extensive section of coarse-grained sediments, the target of this study, was encountered in the drill hole. Further exploration is needed to fully evaluate the paleochannel presence.

Earth Resistivity Survey

Electrical resistivity was used in this study to independently test the presence of the postulated paleochannel using another exploration technique. Much fine-grained sediment was encountered in the Roskie drill hole located at the east end of the study area. The presence of this fine-grained sediment suggested that the channel was not present or the well was located on the edge of the channel. In either case it was assumed that materials of low electrical resistance were present.

A range of resistivity values was expected to be encountered during this survey. Sand and gravel saturated with fresh water have resistivity values ranging between approximately 15 ohm-m (50 ohm-ft) to 610 ohm-m (2000 ohm-ft) (Zohdy and others, 1974). Unsaturated alluvium and sands have resistivity values ranging between 9 to 800 ohm-m (30 to 2600 ohm-ft), while clays range between 1 and 100 ohm-m (3 to 330 ohm-ft). Moist clay contains both water and exchangeable ions and should thus be a good electrical conductor. The wide range in published values suggests that exact determinations of material and material thickness with apparent resistivity values would be difficult in a heterogeneous, anisotropic environment such as the Roskie study area. Even with such problems, the distribution of high resistivity material might be approximated to test the channel hypothesis. For the purpose of this study, resistivity values were used to estimate the potential for high resistivity water-bearing sediments and not to determine the exact composition of the material associated with the observed resistivity.

The presence of water in the pore space will also affect the resistivity values in a groundwater environment as well (Huntley, 1986). The seasonal variations associated with groundwater levels in unconfined aquifers will affect resistivity values. Water is a good conductor of electric current. If the water table is high, the resistivity values may be low since the sediment has become saturated. On the other hand, as the water table drops, resistivity values might increase since the conductor has been removed. If data is gathered over a short period of time so that water levels are relatively constant, this problem can be minimized. To avoid this problem, the earth resistivity survey was completed over a four week period when the weather was consistently dry and hot.

High amounts of total dissolved solids (TDS) in the water will also decrease the apparent resistivity values. Groundwater TDS was assumed to be relatively constant in the study area since the sedimentary units were similar and the range of TDS values reported by Hackett and others (1960) and Dunn (1977) at these depths was relatively uniform, approximately 229 parts per million. Water quality was expected to be good since no reports of poor water from residential houses near the study area have been made. Given the above conditions, the factor controlling resistivity values in the study area is probably the grainsize of the subsurface material.

Previous Resistivity Work

Only one published earth resistivity study has been done in the Gallatin Valley previous to this study. Wantland (1953) attempted to determine the depth to gneissic bedrock at a number of points in the valley and to determine the thickness of potential saturated alluvial material. Based on the results from this study, a few generalizations regarding resistivity values can be made. Wantland (1953) found three unconsolidated or poorly consolidated valley fill units in various areas in the Gallatin Valley. The surficial material generally consisted of permeable sands and gravels with an average resistivity value of 259 ohm-m (850 ohm-ft). Two underlying units interpreted by Wantland to be Tertiary sediments had average resistivity values of 73 ohm-m (240 ohm-ft) and 23 ohm-m (75 ohm-ft), respectively. His study also concluded that relatively high resistivities could be related to greater thicknesses of sand and gravel. Likewise the presence of more clay and/or silt size material resulted in relatively lower resistivity values. These results are consistent with data obtained during the present study. The resistivity values determined by Wantland (1953) for the Gallatin Valley were used as a reference in this study.

Data and Discussion

Eighteen horizontal resistivity profile lines and fourteen vertical soundings were completed as part of the Roskie study during the 1985 field season (Figure 14). The results of these investigations provide a much clearer picture of the underlying valley fill and generalized depositional environment. An isoresistivity map was contoured for each a-spacing. At an a-spacing of 9 m (30 ft), higher resistivity values correspond with more permeable sands and possible gravel lenses that might be suitable as an aquifer (Figure 15). The presence of such materials in close proximity to the surface could be a problem since groundwater contamination would be easier at a shallow depth. Water level fluctuations could also be large in such shallow units during the year. Some of the anomalously high resistivity zones with values >183 ohm-m (600 ohm-ft) in this survey may be associated with man-made surface disturbances. This is due to the fact that the study area is in a populated area where activity causing surface disturbance has occurred in the past. Fill has been added to some areas of the Roskie field in the past (C. Roloff, MSU, personal communication, 1988). The higher resistivity values would be a result of averaging near surface fill having a high resistivity value with lower resistivity material at depth. Since no surface expression of this condition exists, caution must be used before an interpretation can be made. Appendix B contains complete earth resistivity data.

A test of deeper materials is desirable to assess the potential for better aquifers. Figure 16 is a contour map of apparent resistivities at an a-spacing of 30 m (100 ft). There is a general

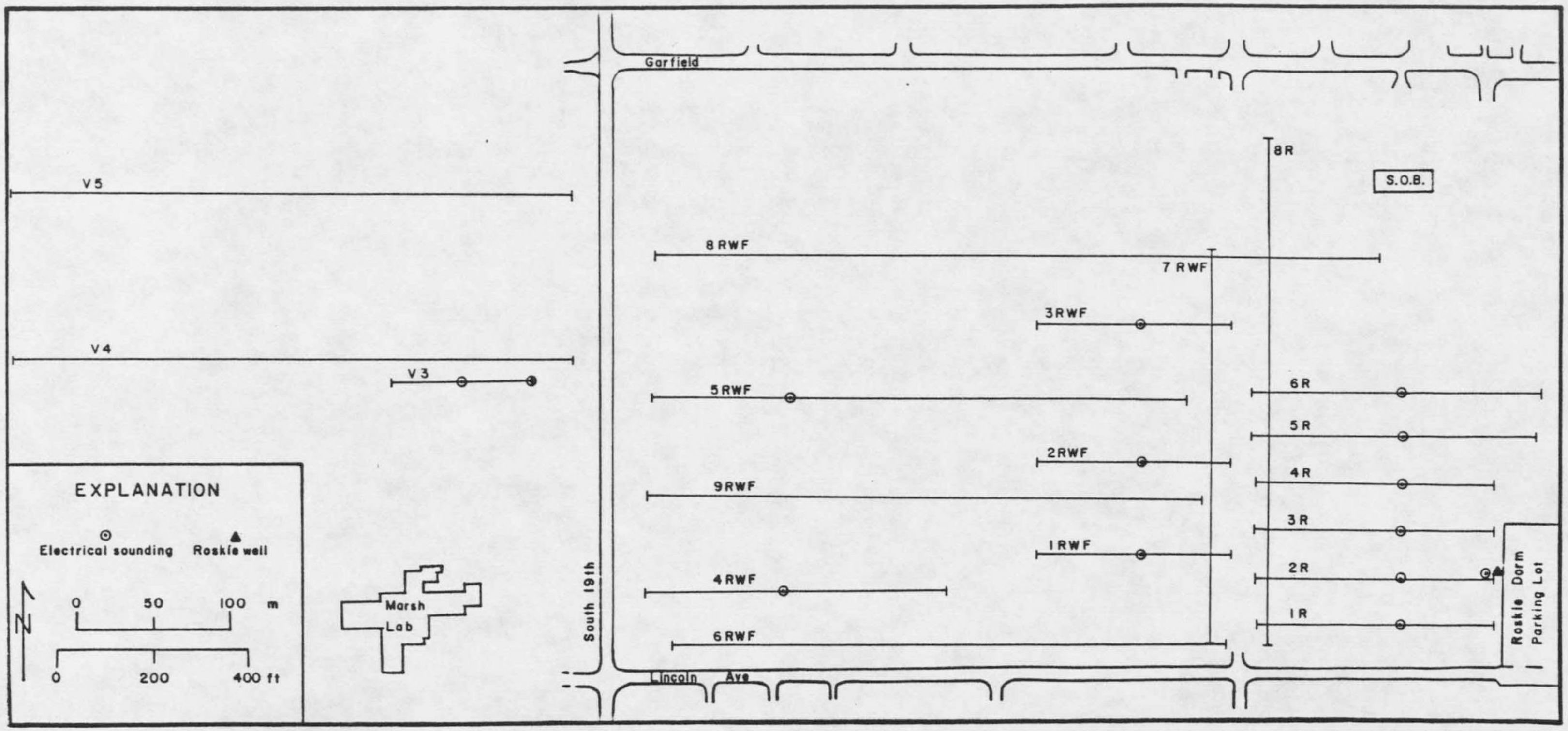


Figure 14: Location of earth resistivity survey lines, Roskie channel study area, Montana State University, Bozeman. Letters indentify locations of survey lines. R = Roskie field; RWF = Roskie west field; V = Marsh Lab (Vet Sciences) field.

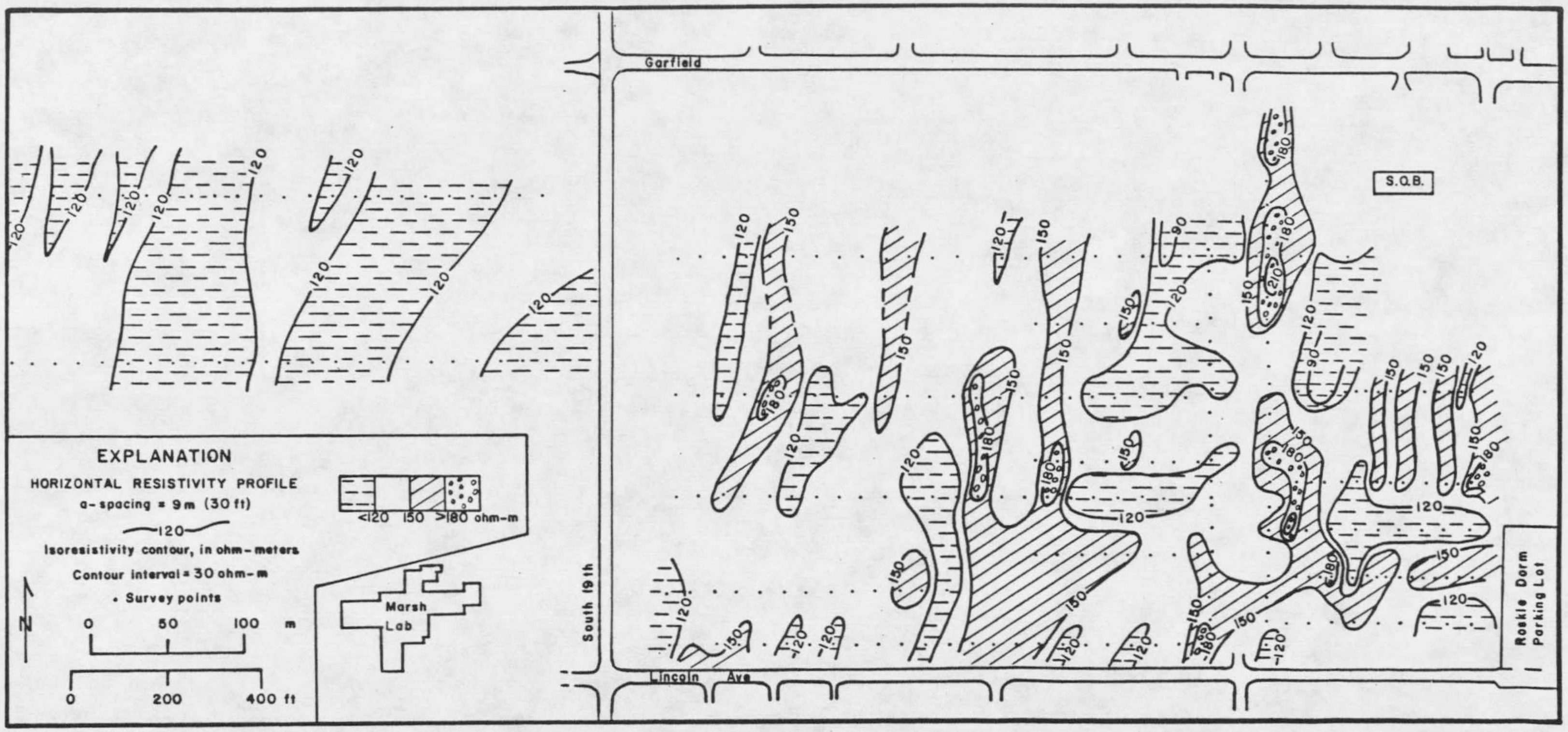


Figure 15: Map of apparent resistivity with a - spacing = 9 m (30 ft).

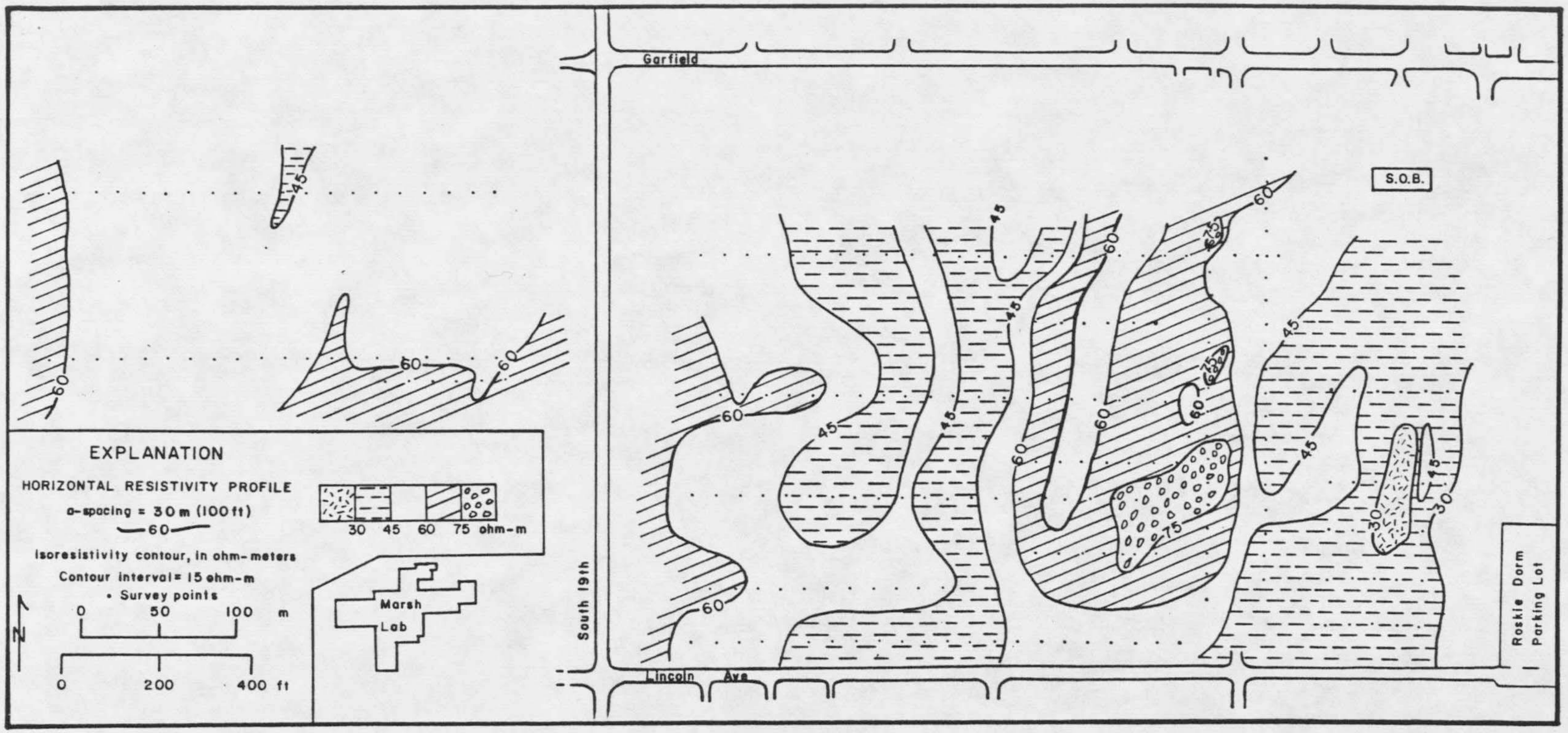


Figure 16: Map of apparent resistivity with a-spacing = 30 m (100 ft).

decrease in resistivity values at depth. This results from the drop in voltage through heterogeneous sediments as the distance between the electrodes increases (Mooney, 1980). Therefore the resistivity values for the profile with a = 9 m (30 ft) must be viewed separately from the profile with a = 30 m (100 ft). Each resistivity value must be considered in relationship to its respective profile. In other words, a 180 ohm-m (600 ohm-ft) resistivity value at an a-spacing of 9 m (30 ft) may be obtained from similar sediment with a 90 ohm-m (300 ohm-ft) value but at an a-spacing of 30 m (100 ft). In such a heterogeneous and anisotropic environment as an alluvial fan deposit, the interbedded and interfingering nature of the sediments complicate the data and prevent a simple layered model solution to be used.

Several zones of moderate resistivity sediments $\geq$ 76 ohm-m (250 ohm-ft) are present at an approximate depth of 20 m (70 ft). Near the center of Roskie field both a-spacings contain a relatively high localized resistivity zone when compared with surrounding resistivity values. The overlying high resistance areas suggest the presence of a possible continuous zone of higher resistivity sediments from the surface to at least a depth of 21 m (70 ft). Although the data does not suggest a large deep buried stream channel filled in with coarse grained material, the site appears to have the most potential for groundwater development in a gravelly (higher resistance) zone. The small stringers of higher resistive material (>180 ohm-m) may be possible targets for groundwater, but the discontinuous nature of the high resistivity zones may pose a problem since storage could be limited. The absence of any lateral and vertical continuity of these zones suggests that no paleochannel is present in the Roskie study area. Additional resistivity profiles at various a-spacings would improve upon our understanding of the subsurface in this area. A drill hole in this area could determine the extent of the porous subsurface material suitable for groundwater withdrawal.

Both isoresistivity maps seem to suggest a distinctive contour pattern (see Figures 15 and 16). The pattern appears to demonstrate an interfingering, lense-shaped depositional pattern of sediments with high and low resistivity values. This pattern is consistent with deposition of the sediments by laterally shifting braided streams such as would be expected on an alluvial fan surface downstream of the intersection point or other similar fluvial depositional environment.

The drill data from the Roskie well allowed a comparison between a vertical electrical sounding and the subsurface stratigraphy (Figure 17). In general, the sediment size interpreted from the well log decreased from about 2.4 m (8 ft) below the surface to the total depth of the well at 56.0 m (185 ft). Resistivity values from the vertical sounding suggest this pattern as well. Some scatter of points exist on the sounding curve and would normally decrease the certainty of an interpretation (Zohdy, 1965). When correlated with a well log, the uncertainty is minimized. Although normal decrease in resistivity is expected in this type of heterogenous environment, the decrease in resistivity (and increase in conductivity) corresponds well with the increase in fine-grained sediments with depth. The scatter in the sounding curve appears to be a result of thin zones of higher resistivity (coarser-grained) material layered between lower resistivity (finer-grained) material.

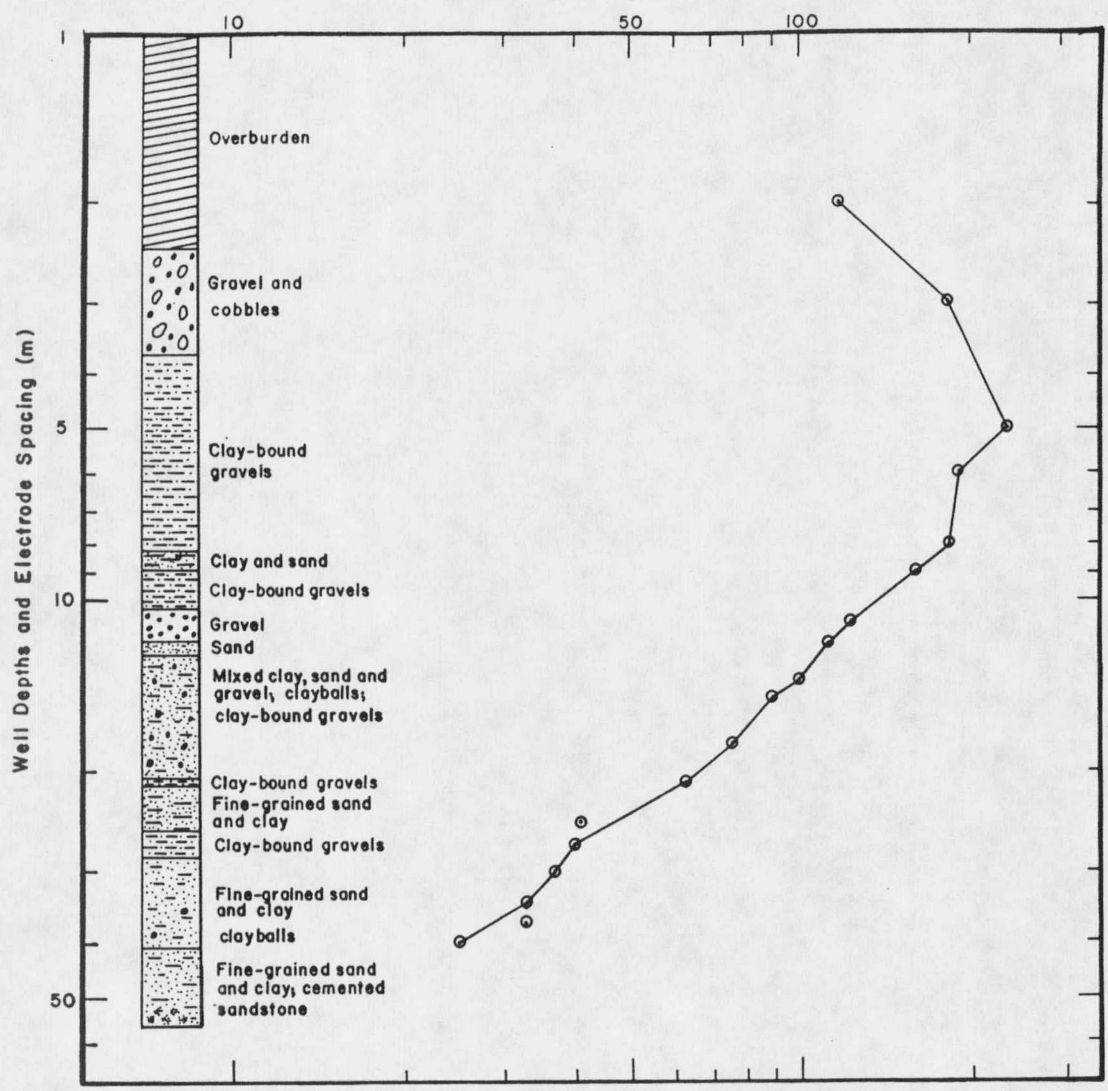


Figure 17: Comparison of vertical electrical sounding and drill log, Roskie well. (Sounding located approximately 8 m (27 ft) west of drill hole).

Seismic Refraction Survey

Since neither the drilling nor resistivity exploration techniques found evidence to support the location of the postulated paleochannel, additional seismic work was needed in the area. The reader is directed to Redpath (1973), Dobrin (1976), Mooney (1984), and Haeni (1985) for additional information concerning refraction seismic techniques and their problems.

Previous Seismic Investigations

Wantland (1951) conducted a reconnaissance refraction seismic survey in the Gallatin Valley in conjunction with the U.S. Geological Survey groundwater studies in the area. His study involved 600-900 m long (2000-3000 ft) seismic lines in order to determine the depth to basement rocks and the thickness of unconsolidated valley fill. Two seismic lines from that study are within 3.2 km (2 mi) of the Roskie study area. One seismic line encountered upper (layer 1) velocities of 1500 m/s (4900 ft/s). The second seismic line found layer 1 velocities to be 2200 m/s (7200 ft/s). No second layer velocities were encountered in either of Wantlands' seismic lines suggesting a depth to layer 2 greater than 300 m (1000 ft) (Wantland, 1951).

Brown and others (1983) completed a refraction seismic survey across most of the Montana State University campus. Their study included several seismic lines in the Roskie study area. Their hypothesis of a buried paleochannel was based on these lines along with what appeared to be a topographic expression of a subsurface channel. Interpretation of data from their study indicates near-surface

Quaternary alluvium across most of the study area and filling a paleochannel with a depth greater than 60 m (200 ft). Further discussion of the interpretations made by Brown and others (1983), will be presented after the results from this study.

Data and Interpretation

Sixteen forward and reverse refraction seismic lines were completed during the summer of 1985 in order to determine the depth to Tertiary sediments in the Roskie study area and to attempt to more definitely test the existence and location of the hypothesized buried stream channel (Figure 18). A computer program modified from Mooney (1977) was then used to calculate depths and thicknesses of individual layers from each seismic line. Interpretation of seismic data was based on expected velocities for material type, geologic age and depth of burial in the literature (Table 3). Brown and others (1983) measured seismic velocities on visually identifiable outcrops of the Quaternary, Tertiary and Precambrian units in the Gallatin Valley. Based on their measurements, seismic velocities of the Quaternary sediments ranged from 300 m/s (1000 ft/s) to 1800 m/s (6000 ft/s), Tertiary sediments ranged from 1800 m/s (6000 ft/s) to 4500 m/s (14000 ft/s) and the Precambrian crystalline bedrock seismic velocities were >4580 m/s (15000 ft/s).

The actual seismic velocities encountered in the field as a result of this study are presented in Figure 19. Velocities of less than 400 m/s (1200 ft/s) are interpreted to correspond with materials representative of modern alluvium (Table 4). These velocities are too

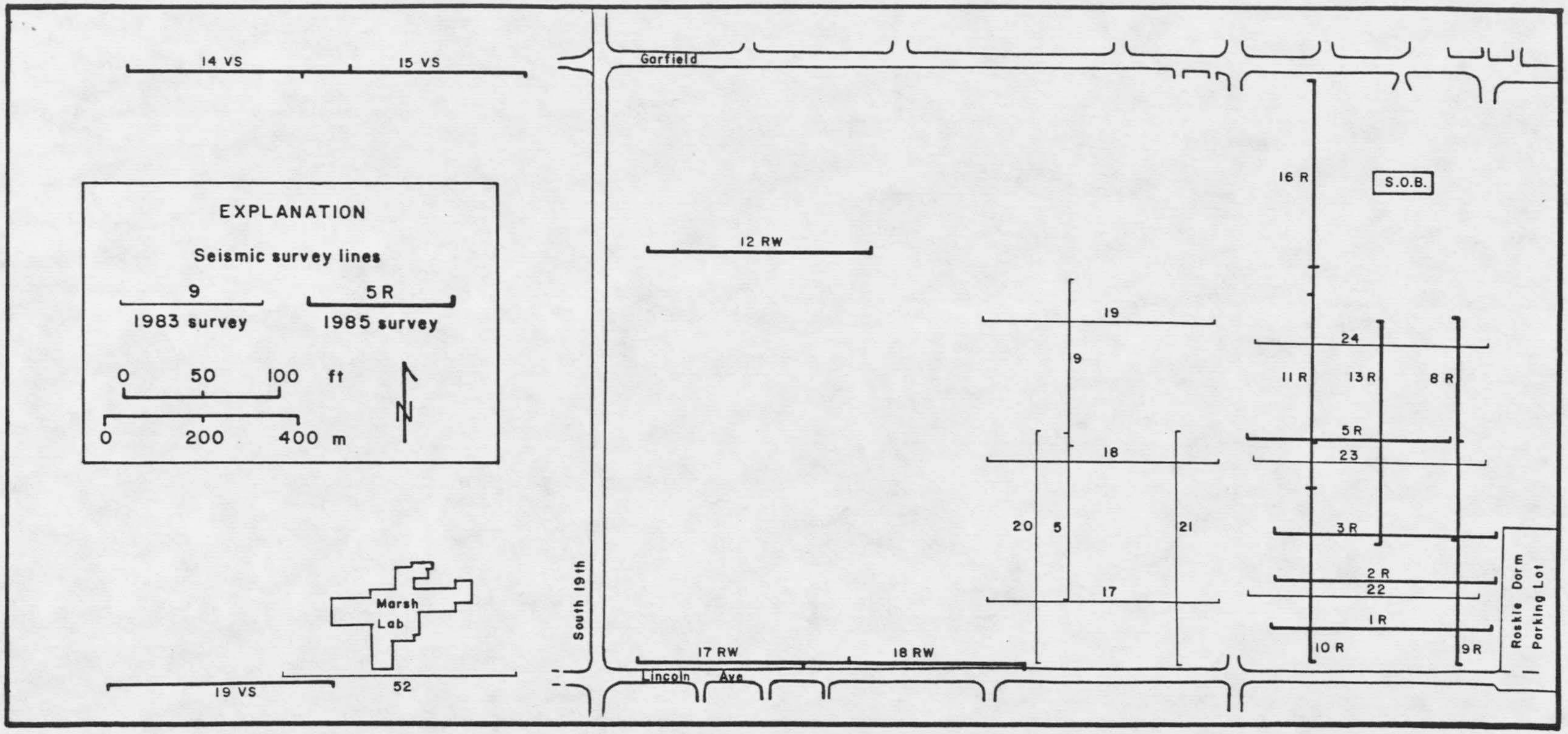


Figure 18: Location of refraction seismic survey lines, Roskie channel study area, Montana State University, Bozeman. Survey line numbers with letters identify 1985 survey lines, numbers alone identify the survey lines of Brown and others (1983).

Table 3: Average seismic velocities for various compositions, geologic ages, and burial depths (Press, 1966; Mooney, 1984; Locke, 1987).

	Velocity m\s	Velocity ft\s
Composition		
modern alluvium	350-400	1200-1300
soil	430-440	1400-1450
gravel, rubble or sand (dry)	460-910	1500-3000
sand (wet)	610-830	2000-6000
clay	910-2740	3000-9000
water	1450-1700	4700-5500
crystalline metamorphic rocks	3050-7010	10000-23000
Geologic age		
Quaternary	300-2300	1000-7500
Tertiary (consolidated)	1500-4300	5000-14000
Precambrian Archean	3800-7000	12500-23000
Burial Depth (0-610 m; 0-2000 ft)		
Pleistocene to Oligocene	2000	6500
Eocene	2200	7100

low to represent Quaternary gravel material, although they may represent near-surface, unconsolidated slow velocity sediments or fill. No intermediate velocities characteristic of thick sequences of Quaternary material were found as reported by Brown and others (1983).

A range of values exist for the higher velocity material located beneath the upper modern alluvium layer. Seismic velocities of 2150 m/s (7000 ft/s) to 2450 m/s (8000 ft/s) found in this study are interpreted as corresponding to dry Tertiary sediments. Velocities greater than 2450 m/s (8000 ft/s) are interpreted as corresponding to wet Tertiary sediments and/or more consolidated or clay-rich deposits. Appendix C contains the seismic survey data.

Thirty two depth-to-Tertiary measurements were calculated from

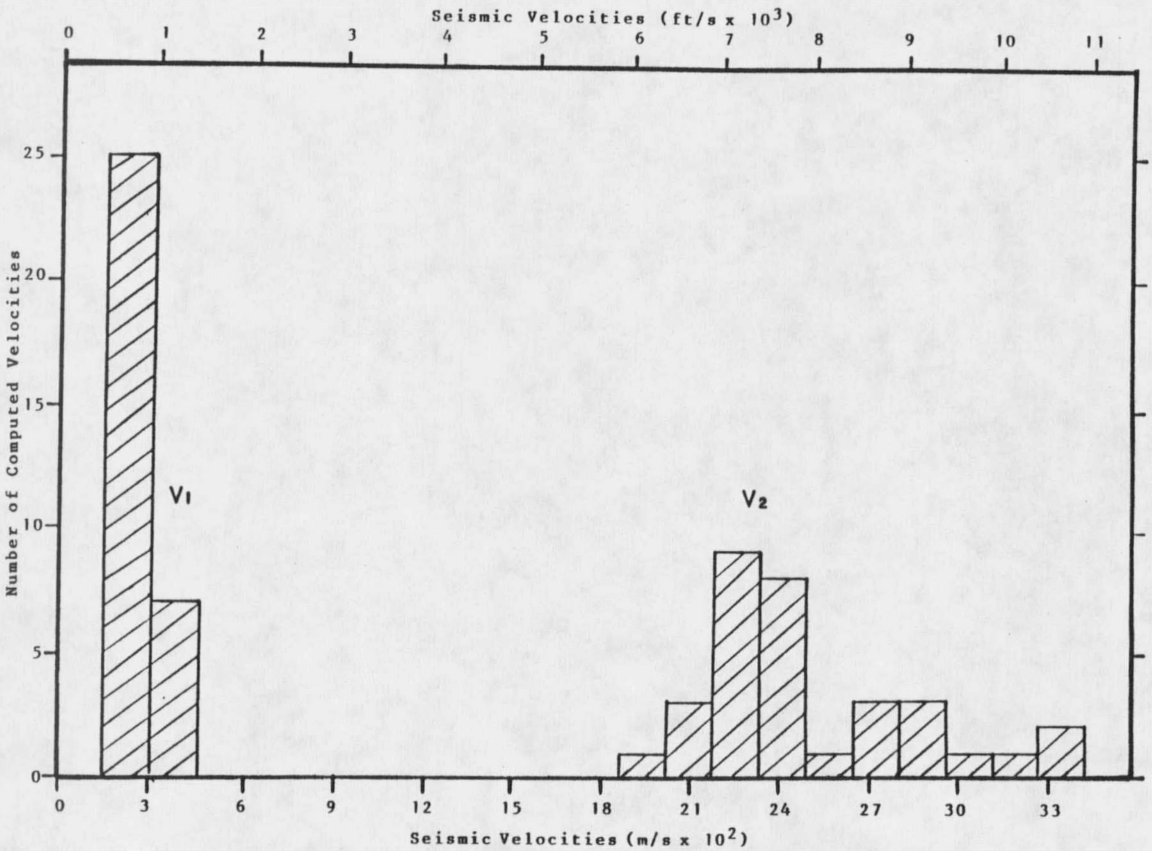


Figure 19: Histogram of recorded seismic velocities, Roskie study area, Montana State University, Bozeman.

Table 4: Observed seismic velocities of material found in Roskie study area and interpreted geologic age.

Velocity m\s	ft\s	Material
150-300	500-1000	Modern alluvium; topsoil
2000-2400	6500-8000	Tertiary (dry)
2600-3400	8500-11000	Tertiary (wet)

the seismic data. The depth to Tertiary throughout most of the study area was found to be less than 3 m (10 ft) (Table 5). The average thickness of the overlying near-surface layer is 2.0 m (6.4 ft).

Table 5: Calculated depths to top of material with velocities characteristic of Tertiary - age materials in the Roskie study area. R = Roskie field, RW = Roskie west field, VS = Vet Sciences.

East - west seismic spread perpendicular to proposed channel					North - south seismic spread parallel to proposed channel				
Line	west		east		Line	north		south	
	m	ft	m	ft		m	ft	m	ft
1R	2.7	8.9	2.5	8.2	8R	2.1	6.8	2.2	7.1
2R	2.3	7.6	2.4	8.0	9R	1.7	5.6	1.9	6.2
3R	1.4	4.7	1.4	4.6	10R	2.3	7.7	1.4	4.7
5R	1.3	4.2	1.7	5.7	11R	1.6	5.4	1.7	5.5
12RW	2.5	8.2	1.3	4.2	13R	2.1	6.9	1.7	5.5
17RW	3.8	12.5	3.1	10.2	16R	2.1	6.8	2.1	6.8
18RW	1.1	3.6	1.3	4.4					
14VS	1.7	5.7	1.3	4.3					
15VS	1.4	4.5	1.4	4.5					
19VS	3.0	9.7	2.2	7.2					

Discussion

The seismic survey did not locate a deep channel filled with thick Quaternary gravels as postulated by Brown and others (1983). Materials with velocities expected to characterize Tertiary deposits were found within 4 m (12 ft) of the surface throughout the study area. No velocities suggesting a thick gravel deposit or characteristic of a thick sequence of Quaternary sediments were found. A resurvey of seismic lines from the 1983 study also found no low velocities. There appears to be error in the interpretation of the data from the 1983 survey.

Figure 20 shows a comparison of seismic velocities from two lines surveyed during the 1983 study and this study. Line 2R was completed during the 1985 study and is located adjacent and parallel to line 22 from the 1983 study. The data from 1985 indicates that a thin layer of

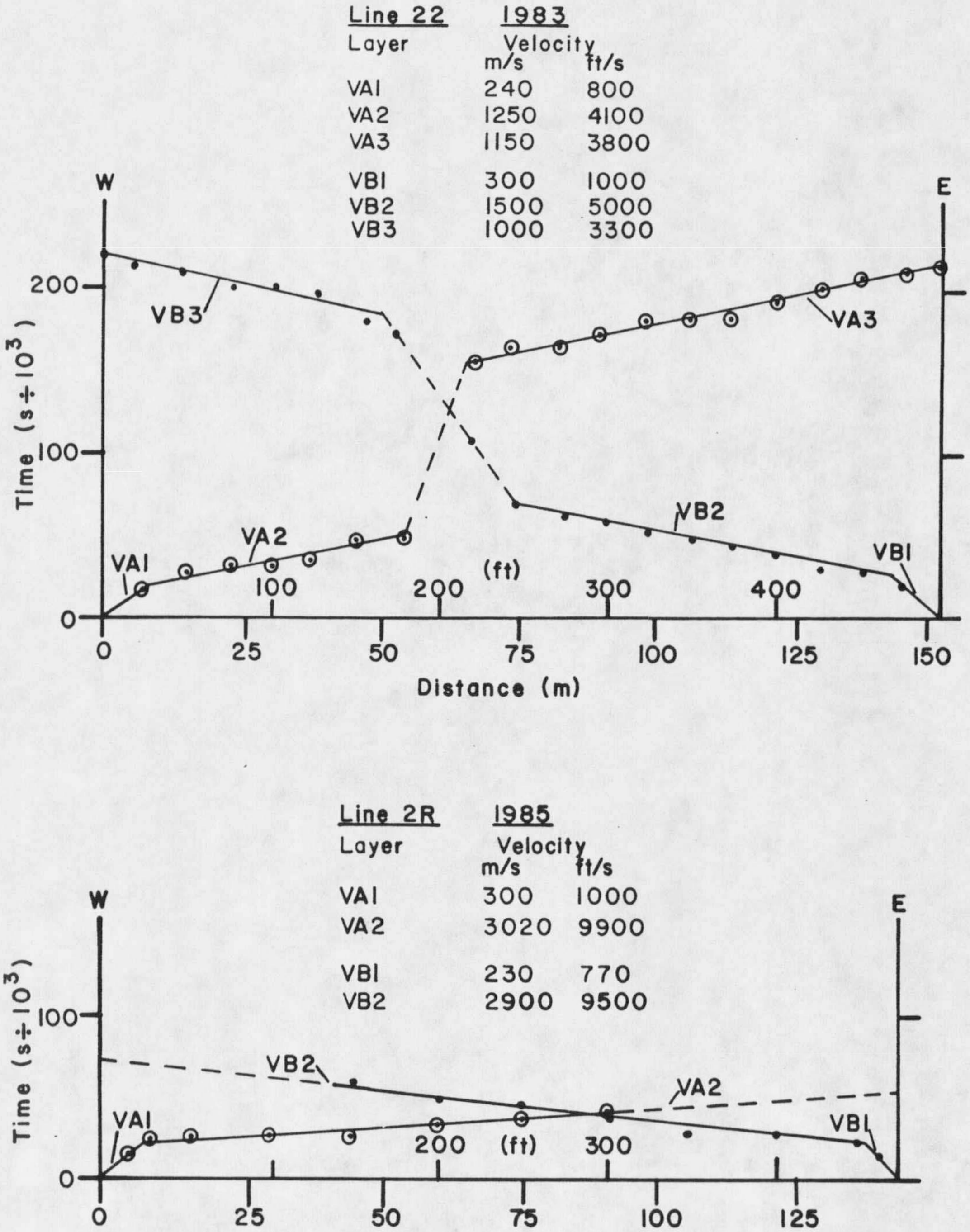


Figure 20: Comparison of seismic line 22 from 1982 survey and seismic line 2R from 1985 survey. Dashed area indicates zone of uncertain seismic data.

low velocity material directly overlies higher velocity sediments. No thick sequences of material with velocities representative of Quaternary gravels are present along this or any other line in this study. Examination of the two time-distance graphs from the same area indicate very different geologic conditions if both sets of data are correct. Upon examination of the graphs, the following discrepancies arise:

1) Line 22 contains an apparent jump in the curve while Line 2R lacks this jump.

2) Seismic velocities from layer V2 from the two surveys do not represent the same material.

The dashed area located near the center of both forward and reverse shots of the 1983 line (line 22) indicates a very low velocity area. During the 1985 study, it was found that gravel fill was spread in the area of Roskie field during construction of nearby campus buildings to cover a poorly drained area and to smooth over the field. This gravel fill would result in an extensive area with a low seismic velocity. Layers VA3 and VB3 from the 1983 study probably indicate a different seismic wave from layers VA2 and VB2 instead of a new first arrival from a third layer. This problem is common with single channel recorders (Lankston, 1986). Such a recorder was used during the 1983 survey.

The construction fill may also explain the problem of not being able to determine velocities for the full length of seismic line 2R. As seen by the dashed lines in the time-distance graph of line 2R, seismic energy was not clearly received at the geophones after a certain distance from the shot point. In 1985, a 12-channel seismic recorder was used which visually displayed all 12 geophone records at the same time. This allowed for accurate timing of the first arrivals in the field and elimination of potential errors in the data. A printout of the seismic record was also made. The single channel seismic recorder used in the 1983 study used an oscilloscope screen for each geophone record so data from all 12 geophones could not be compared at the same time. As the seismic waves entered the lower velocity construction fill, the waves were refracted away from the surface. Seismic lines traversing this area in both a north-south and east-west direction encountered this lower velocity zone. This zone appears to be localized and not to extend to any great depth. Earth resistivity data located this zone within 6 m (20 ft) of the surface, but did not detect it on the deeper 30 m (100 ft) profile line. The 1985 survey observed this phenomena but the 1983 data appears to have introduced a different seismic wave arrival time into its record.

The second problem that exists concerns velocities found in the study area. Data from 1983 indicates near-surface Quaternary velocities ranging from 1200 m/s (4000 ft/s) to 1500 m/s (5000 ft/s) are present and extensive throughout the study area. The results from the 1985 study indicate the presence of material with velocities ranging between 1980 and 3350 m/s (6500 and 11000 ft/s) located less than 3 m (10 ft) beneath the surface throughout the Roskie study area. Such velocities are interpreted to represent Tertiary sediments. Low velocities representative of modern alluvium were found directly above the Tertiary velocities. A third seismic experiment at line 2R and line

22 completed during the summer of 1987, independent of this study, also showed no velocities suggestive of a thick gravel sequence or Quaternary material. Velocities of 2350 m/s (7700ft/s) interpreted to represent Tertiary sediments were found within 3 m (10 ft) of the surface (Terry Nichols, Montana Tech, personal communication, 1987).

Why the discrepancy between the 1983 and 1985 data? As alluded to earlier, the problem may be due to difficulties associated with using a single channel seismic recorder. Lankston (1986, p.45) notes that "single channel instruments with no hard copy capability are notorious for allowing scatter to be introduced into the data because of reading inconsistencies on the part of the seismograph operator". If field work occurs in noisy or weak signal environments additional difficulty in timing of the first arrivals will result. In 1983 a single channel seismograph recorder was all that was available to Brown and others. There may well have been unrecognizable data problems.

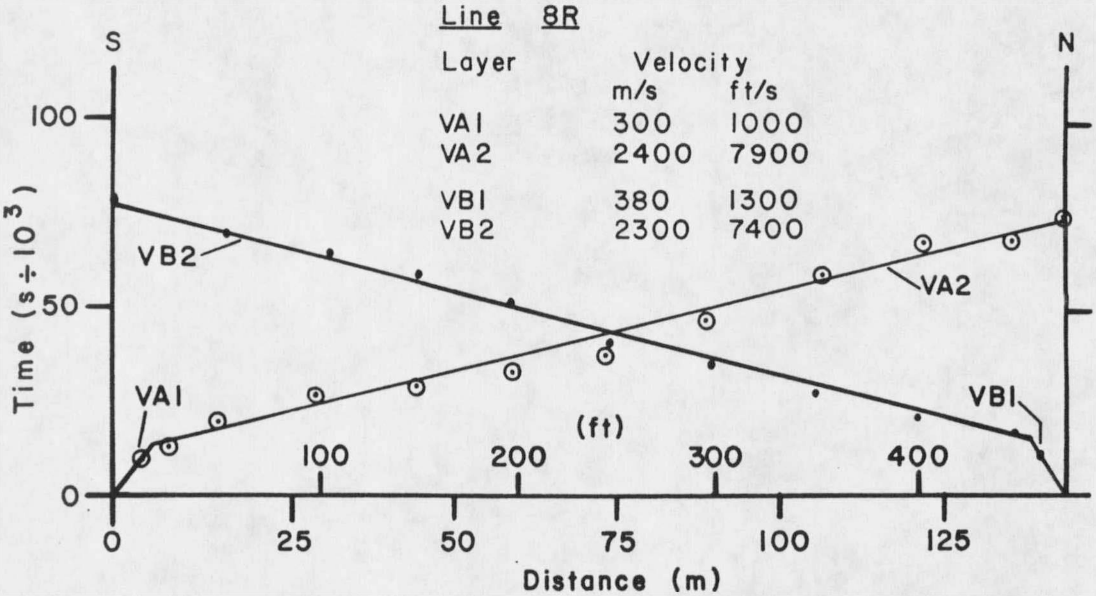
The Roskie study area can be considered a weak signal environment due to the nature of the unconsolidated or semi-consolidated sediments. Signal enhancement was necessary on all lines surveyed in order to pick an accurate first arrival time for the distant geophones.

A second difference between the 1983 and 1985 data may be the moisture content in the area at the time of survey. In wet areas, it may be difficult to generate clear compressive waves (Sverdrup, 1986). This problem may create weak or unclear signals when trying to complete a long line and using a single channel recorder. Whether or not soil moisture is the reason for the discrepancies between the two studies is hard to assess.

The single channel instrument may have introduced inadvertent data errors which were not recorded and are not reproducible. Perhaps the use of a 12 channel recorder in 1983 would have produced data more compatible with the results obtained from the 1985 study.

Additional seismic lines surveyed in the Roskie study area in 1985 produced data which consistently indicated a thin low velocity material overlying higher velocity sediments. Time-distance plots of seismic lines 8R and 9R are shown in Figure 21 and are typical of the results obtained from other seismic profiles in this study. Near surface velocities of 300 to 380 m/s (1000 to 1250 ft/s) are found along these two lines. These higher than normal V1 velocities may be due to compaction of near surface material in a heavily used area.

Velocities characteristic of Tertiary material were found on lines 8R and 9R at a depth of 1.5 to 2.0 m (5 to 7 ft) beneath the surface. Velocities ranged from 2160 to 2410 m/s (7090 to 7920 ft/s). On other seismic profiles completed during this study, Tertiary age materials were found to have higher velocities in the range of 2740 to 3350 m/s (9000 to 11000 ft/s) (see Figure 19). A range of velocities for this lower layer is present. The higher end of the velocity range may indicate zones of either water saturated materials, zones of increased clay content or areas of increased compaction. Localized water saturated materials may be a result of a perched water table or differences in the amount of irrigated land. The lower end of the range in velocities may indicate increased gravel content, lack of moisture or decreased compaction.



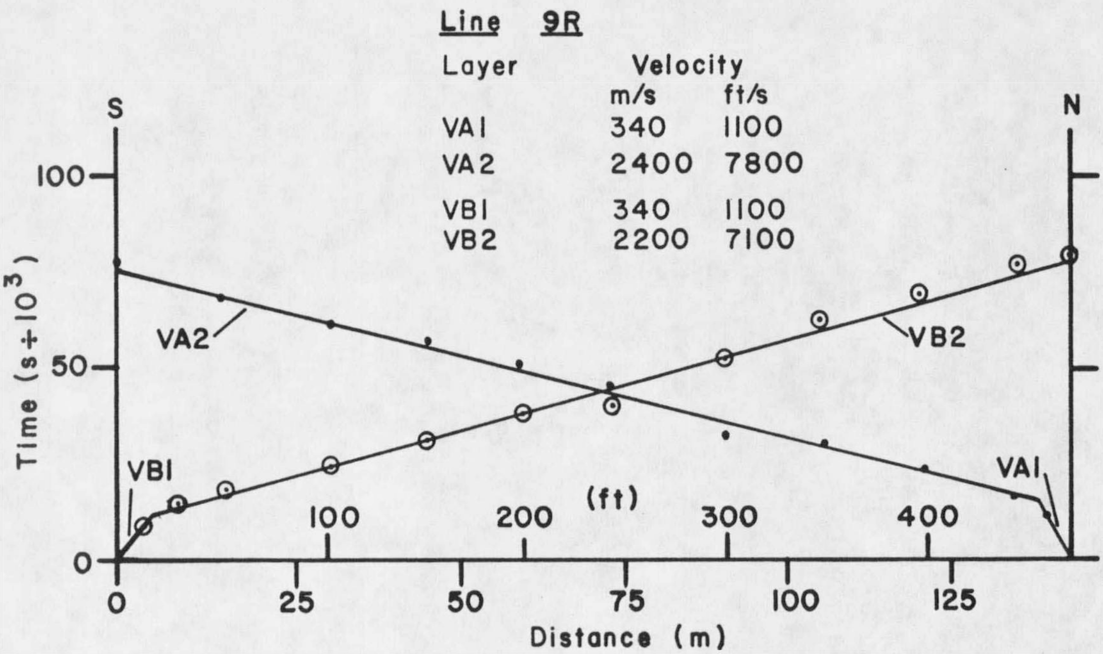


Figure 21: Time - distance plots of seismic lines 8R and 9R across Roskie field and the hypothesized paleochannel, Montana State University, Bozeman.

In groundwater exploration using refraction seismic methods, low velocities usually indicate areas of porous and permeable zones suitable for groundwater withdrawal. But higher velocities must not be ignored as potential groundwater zones. Water filling in pore spaces will increase the velocity of the material by several hundreds of m/s (Zohdy and others, 1974), so higher velocities may not indicate low porosity material. This demonstrates the need to consider information from other sources, such as geology, earth resistivity surveys, or drill logs, before a conclusion about the groundwater potential can be made.

CONCLUSIONS

Alternative Model

The results from this study indicate that the paleochannel hypothesis proposed by Brown and others (1983) should be rejected for several reasons. No thick sequences of Quaternary gravels were found in the study site. Drill hole data demonstrated the presence of relatively fine-grained sediments interlayered with coarser-grained sand and gravel lenses. Aquifer tests indicate that properties of hydraulic conductivity and transmissivity from the Roskie well correlate with values for the Tertiary aquifers elsewhere in the Gallatin Valley. Earth resistivity data does not support the channel hypothesis nor the presence of a thick gravel zone. Small zones of higher resistive material is present interfingering with lower resistive sediments. Refraction seismic work found relatively high (Tertiary) velocities within 3 m (10 ft) of the surface and no thick gravel channel fills. These facts suggest that Brown and others (1983) misinterpreted seismic wave forms and first-arrival times as they surveyed the area. This misinterpretation may have resulted from the areas of construction fill found in Roskie field. The coincidence of the location of the subtle linear depression at the surface and traced through the study area may have biased their interpretation towards a deep buried paleochannel.

Based on the results from this study, an alternative conceptual model can be proposed for the Roskie study area (compare Figure 10 and Figure 22). The Archean metamorphic rocks rise from the south to the near-surface beneath Montana State University. The extension of the fault at the northern margin of the fault-bounded trough at the southern end of the Gallatin Valley may be the structural control for this near-surface bedrock feature. The Archean metamorphic rock dips steeply to the west beneath Roskie field. A steep erosional surface or fault is suspected. The bedrock was not located by geophysical methods nor encountered in the Roskie drill hole, which suggests a depth to bedrock greater than 50 m (160 ft) beneath Roskie field.

In the revised model the Tertiary sediments overly the Archean bedrock and are present within 3 m (10 ft) of the surface (Figure 10). Determining whether the sediments are Tertiary or Quaternary units is complicated by the lack of paleontological control. Whether the Renova or the Sixmile Creek Formation is represented by these sediments is difficult to ascertain directly. Due to the presence of coarser-grained lenses and stringers observed in the drill hole and interpreted from the resistivity data, the depositional history characteristic of the Sixmile Creek Formation best fits the model. The near-surface layer may represent a Tertiary pediment surface similar to the pediments on the flanks of the Gallatin Valley (Glancy, 1964; Hughes, 1980). The higher elevations of the pediment surfaces adjacent to the Bozeman "alluvial fan" surface suggest a different geologic, erosional and/or tectonic history than the lower area where Hackett and others (1960) mapped the Bozeman "alluvial fan".

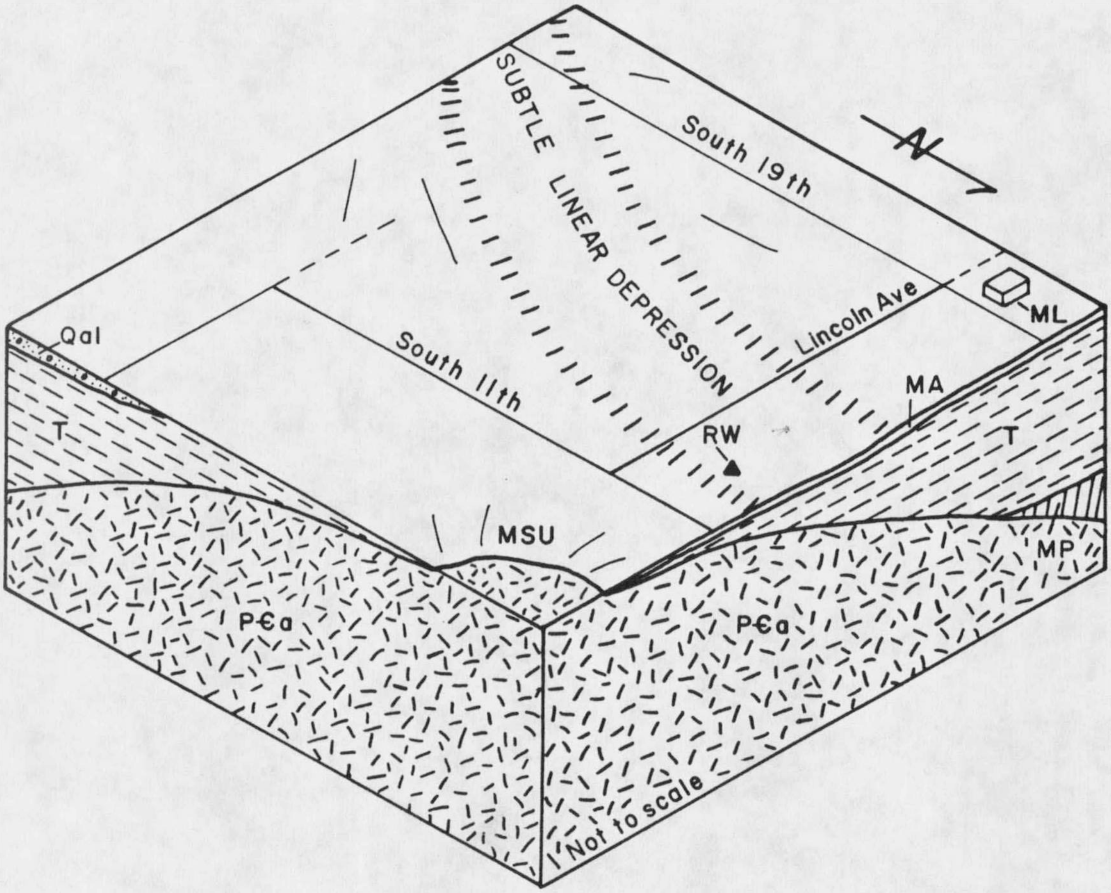


Figure 22: Block diagram of proposed alternative model for the Roskie study area. MA = modern alluvium; Qal = younger Quaternary alluvium; T = Tertiary sediments; MP = Mesozoic-Paleozoic rocks; PЄa = Precambrian Archean rocks. MSU = Montana State University; RW = Roskie well site; ML = Marsh Lab.

The Quaternary material within the study area consists of a thin sheet of alluvium, topsoil and organic material overlying the Tertiary sediments. The lack of an extensive and thick zone of gravels in this area has led to a rejection of the paleochannel hypothesis as well as to a rejection of the previously accepted thoughts of an alluvial fan depositional environment held by Hackett and others (1960).

Groundwater allocation models and land-use models derived for the Bozeman "alluvial fan" need to be revised in light of this new study.

Future Considerations

The extensive variability in the aquifer, as seen from the drill hole and resistivity data, demonstrates the changing nature of the depositional environment. Aquifer characteristics are controlled by the addition of less permeable silts and clays, both horizontally and vertically, as the streams migrated back and forth across the surface. The permeability, porosity and hydraulic conductivity of the aquifer sediments is generally reduced with the addition of these clay zones. The amount of vertical water movement may be reduced and water movement could be directed more horizontally (down slope). Thus stratification in the sediments resulting from the controlling Tertiary depositional environment appears responsible for the characteristics of the Roskie area aquifer.

The presence of Tertiary material within 3 m (10 ft) of the surface throughout the study area suggests that a high yield well is not a realistic target since the Tertiary has not been found to be a major water producer in most of the eastern part of the Gallatin Valley (Hackett, 1960). But the hydrologic studies on the Roskie well suggests that at least 379 lpm (100 gpm) may be a viable target for the aquifer. Whether this yield can be sustained or not has yet to be tested. Lateral flow through the deep aquifer may be increased by the constriction of flow resulting from the Precambrian bedrock barrier. This situation, along with the increase in fine-grained material at depth in the Tertiary units, may be responsible for an increase in horizontal water flow at this site and an increase in the amount of water available for withdrawal. Proper well development could increase the potential from the Tertiary sediments in this area. Well casing perforated at several water- bearing zones would increase well production. The well located at Marsh Laboratory was perforated in a 33 m (107 ft) zone and has a substantial 1900 lpm (500 gpm) yield. Further pump tests are necessary to determine the aquifer characteristics and the effects high pumpage rates might have on the aquifer as well as surrounding shallow domestic wells near the Roskie study area.

REFERENCES CITED

Blissenbach, E., 1954, Geology of alluvial fans in semiarid regions: Geological Society of America Bulletin, v. 65, p.175-190.

Boothroyd, J.C., and Ashley, G.M., 1975, Processes, bar morphology, and sedimentary structures on braided outwash fans, northeastern Gulf of Alaska, in Jopling, A.V. and McDonald, B.C., eds., Glaciofluvial and glaciolacustrine sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 23, p. 193-222.

Boyd, W.D., 1968, Simulation via time-partitioned linear programming: a ground and surface water allocation model for the Gallatin Valley of Montana: PhD thesis, Montana State University, Bozeman, Montana.

Brown, V.W., Erickson, R.T., Mohl, G.B., and Custer, S.G., 1983, Evidence for Precambrian control of groundwater availability in the interior of a block fault valley, Gallatin County, Montana: unpublished report, Earth Science Department, Montana State University, Bozeman, Montana, 25 p.

Brustkern, R.L., 1977, The impact of land use change on the groundwater resources of the Bozeman, Montana area: Montana University Joint Water Resources Research Center Report 88, 35 p.

Bull, W.B., 1963, Alluvial fan deposits in western Fresno County, California: Journal of Geology, v.71, p. 243-251.

-----1964, Alluvial fans and near-surface subsidence in western Fresno County, California: U.S. Geological Survey Professional Paper 437-A, p. A1-A71.

-----1968, Alluvial fans: Journal of Geologic Education, v. 16, no. 3, p. 101-106.

-----1972, Recogination of alluvial-fan deposits in the stratigraphic record, in Rigby, J.K., and Hamblin, W.K., eds., Recognition of ancient sedimentary environments: Society of Economic Paleontologists and Mineralogists Special Publication 16, p. 63-83.

-----1977, The alluvial fan environment: Progresses in Physical Geography, v.1, p. 222-270.

-----1984, Tectonic geomorphology: Journal of Geological Education, v.32, p. 310-324.

Cehrs, D., 1979, Depositional control of aquifer characteristics in alluvial fans, Fresno County, California: Geological Society of America Bulletin, v. 90, no.8, pt. I, p. 709-711; pt II, p. 1282-1309.

Chadwick, R.A., 1981, Chronology and structural setting of volcanism in southwest and central Montana: Montana Geological Society Field Conference and Symposium Guidebook, p. 301-310.

Craiglow, C.J., 1986, Tectonic significance of the Pass Fault, Central Bridger Range, Southwest Montana: Master's thesis, Montana State University, Bozeman, 37 p.

Davis, W.E., Kinoshita, W.T., and Robinson, G.D., 1965, Bouguer gravity, aeromagnetic, and generalized geologic map of the eastern part of the Three Forks basin, Broadwater, Madison, and Gallatin Counties, Montana: U.S. Geological Survey Geophysical Investigation Map GP-498.

Dobrin, M.B., 1976, Introduction to geophysical prospecting: McGraw-Hill, Inc., N.Y., 630 p.

Driscoll, F.G., 1986, Groundwater and wells: St. Paul, Minnesota, Johnson Well Division, 1089 p.

Dunn, D.E., 1977, Groundwater levels and groundwater chemistry, Gallatin Valley, Montana: Blue Ribbons of the Big Sky Areawide Planning Organization report, 62 p.

Dutcher, L.C., and Garrett, A.A., 1963, Geological and hydrological features of the San Bernardino area, California: U.S. Geological Survey Water Supply Paper, 1419, 114 p.

Fetter, C.W., Jr., 1980, Applied Hydrogeology: Ohio, C.E. Merril Co. 488 p.

Fields, R.W., Tabrum, A.R., Rasmussen, D.L., and Nichols, R., 1985, Cenozoic rocks of the intermontane basins of western Montana and eastern Idaho, in Flores, R.M. and Kaplan, S.S., eds., Cenozoic paleogeography of the west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Paleogeography Symposium 3, p. 9-36.

Glancy, P.A., 1964, Cenozoic geology of the southern part of the Gallatin Valley, Montana: Master's thesis, Montana State University, Bozeman, Montana, 66 p.

Hackett, O.M., Visher, F.N., McMurtrey, R.G., and Steinhulber, W.L., 1960, Geology and groundwater resources of the Gallatin Valley, Gallatin County, Montana: U.S. Geological Survey Water Supply Paper 1482, 282 p.

Haeni, F.P., 1986, Application of seismic refraction methods in groundwater modeling studies in New England: Geophysics, v. 51, no. 2, p. 236-249.

Hantush, M.S., 1961, Aquifer tests on partially penetrating wells: Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division, vol. 87, p. 171-195.

Harrison, J., Griggs, A.B., and Wells, J.D., 1974, Tectonic features of the Precambrian Belt Basin and their influence on post-Belt structures: U.S. Geological Survey Professional Paper 866, 15 p.

Harvey, A.M., 1984, Debris flows and fluvial deposits in Spanish Quaternary alluvial fans: implications for fan morphology, in Koster, E.H., and Steel, R.J., eds., Sedimentology of gravels and conglomerates: Canadian Society of Petroleum Geologists Memoir 10, p. 123-132.

Hazen, C.S., 1942, Reconnaissance report on Gallatin River basin, sub-basin report no. 9, upper Missouri River basin investigations, Montana: U.S. Department of the Interior, Bureau of Reclamation, 70 p.

Heward, A.P., 1982, Alluvial fan sequence and megasequence models, with examples from Westphalian D - Stephanian B coalfields, Northern Spain: Canadian Society of Petroleum Geologists Memoir 5, p. 669-702.

Hooke, R.L., 1967, Processes on arid region alluvial fans: Journal of Geology, v. 75, p. 438-460.

Hughes, G.C., 1980, Cenozoic geology and geomorphology of the Dry Creek Valley, Gallatin County, Montana: Master's thesis, Montana State University, Bozeman, Montana, 147 p.

Huntley, D., 1986, Relations between permeability and electrical resistivity in granular aquifers: Groundwater, v. 24, no. 4, p. 466-474.

Hvorslev, M.J., 1951, Time lag and soil permeability in groundwater observations: U.S. Army Corps. Engrs. Waterways Expt. Station Bulletin 36, Vicksburg, Miss, 50 p.

Johnson, A.M., 1970, Physical processes in geology: San Francisco, Freeman Press, 575 p.

Kochel, R.C., and Johnson, R.A., 1984, Geomorphology and sedimentology of humid-temperate alluvial fans, central Virginia, in Koster, E.H., and Steel, R.J., eds., Sedimentology of gravels and conglomerates: Canadian Society of Petroleum Geologists Memoir 10, p. 109-122.

Lageson, D.R., and Zim, J., 1984, Superimposed styles of deformation in the Bridger Range, southwestern Montana: in Abstracts with Programs, 97th annual meeting, Geological Society of America, v. 16, n. 6, p. 567.

Lageson, D.R., 1989, Reactivation of a Proterozoic continental margin, Bridger Range, southwest Montana: Geological Society of America, in review.

Lankston, R.W., 1986, Discussion on shallow seismic refraction survey of near-surface groundwater flow by Keith Sverdrup: Groundwater Monitoring Review, v. 6, no. 2, p. 45-46.

Locke, W.W., 1987, Low-energy seismic survey of Quaternary materials, Rocky Mountain National Park, Colorado: Mountain Geologist, v. 24, no. 2, p. 44-49.

Mcgowen, J.H., 1979, Alluvial fan systems, in Galloway, W.E., Kreitler, C.W., and Mcgowen, J.H., eds., Depositional and groundwater flow systems in the exploration for uranium: Bureau of Economic Geology, Texas.

McMannis, W.J., 1955, Geology of the Bridger Range, Montana: Geological Society of America Bulletin v. 66, p. 1385-1430.

Miller, E.W.B., 1987, Laramide basement deformation in the northern Gallatin Range and the southern Bridger Range, Southwest Montana: Master's thesis, Montana State University, Bozeman, Montana, 78 p.

Mooney, H.M., 1977, Handbook of engineering geophysics: Minneapolis, Minnesota, Bison Instruments Inc.

-----1980, Handbook of engineering geophysics, volume 2, electrical resistivity: Minneapolis, Minnesota, Bison Instruments Inc, 40 p.

-----1984, Handbook of engineering geophysics, volume 1,seismic: Minneapolis, Minnesota, Bison Instruments Inc, 100 p.

Nilsen, T., 1982, Alluvial fan deposits, in Scholle, P.A., and Spearing, D., eds., Sandstone depositional environments: American Association of Petroleum Geologists Memoir 31, p. 49-86.

Press, F., 1966, Seismic velocities, in Handbook of physical constants: Geological Society of America Memoir 97, p. 195-218.

Redpath, B.B., 1973, Seismic refraction exploration for engineering site investigations: U.S. Army Engineer Waterways Expt. Station, California, Technical Report E-73-4, 51 p.

Reynolds, M.W., 1979, Character and extent of Basin-Range faulting, western Montana and east-central Idaho: RMAG-UGA Basin and Range Symposium, p. 185-193.

Ritter, D.F., and TenBrink, N.W., 1986, Alluvial fan development and the glacial-glaciofluvial cycle, Nenana Valley, Alaska: Journal of Geology, v. 94, no. 4, p. 613-625.

Robinson, G.D., 1961, Origin and development of the Three Forks basin, Montana: Geological Society of America Bulletin, v. 72, p. 1003-1014.

-----1963, Geology of the Three Forks quadrangle, Montana: U.S. Geological Survey Professional Paper 370, 143 p.

Rust, B., 1979, Coarse alluvial deposits, in Facies models, Walker, R.G., ed., Geoscience Canada Science Reprint Series 1: Geological Association of Canada, p. 9-21.

Schmidt, C.J., and Garihan, J.M., 1983, Laramide tectonic development of the Rocky Mountain foreland of southwestern Montana, in Lowell, J.D., and Gries, R., eds., Rocky Mountain Forelands and Uplifts: Rocky Mountain Association of Geologists, Denver, Colorado, p. 271-294.

Schumm, S.A., 1968, Speculation concerning paleohydrologic controls of terrestrial sedimentation: Geological Society of America Bulletin, v. 79, p. 1573-1588.

Sverdrup, K.A., 1986, Shallow seismic refraction survey of near-surface ground water flow: Ground Water Monitoring Review, v. 6, no. 1, p. 80-83.

Thompson, G.R., R.W. Fields, and D. Alt, 1982, Land-based evidence for Tertiary variations, Northern Rockies: Geology, v. 10, no. 8, p. 413-417.

Todd, D.K., 1980, Groundwater hydrology: New York, John Wiley and Sons, 535 p.

Tysdal, R.G., 1966, Geology of part of the north end of the Gallatin Range, Gallatin County, Montana: Master's thesis, Montana State University, Bozeman, Montana, 95 p.

Wantland, D., 1951, Seismic investigations in connection with USGS groundwater studies in the Gallatin River Valley, Montana: U.S. Bureau of Reclamation Geology Report no. G-115, 8 p.

-----1953, Second phase of geophysical investigations in connection with USGS groundwater studies in the Gallatin River Valley, Montana: U.S. Bureau of Reclamation Geology Report no. G-121, 59 p.

Weber, M.W., 1965, General geology and geomorphology of the Middle Creek area, Gallatin County, Montana: Master's thesis, Montana State University, Bozeman, Montana, 86 p.

Westcott, W.A., and Ethridge, F.G., 1980, Fan-delta sedimentology and tectonic setting, Yallahs fan delta, southeast Jamaica: American Association of Petroleum Geologists Bulletin, v. 69, p. 374-399.

Young, K.B., 1971, Optimal use of groundwater and surface water in the Gallatin Valley, Montana: PhD thesis, Montana State University, Bozeman, Montana, 189 p.

Zim, J.C., and Lageson, D.R., 1985, Neotectonics and seismicity of the eastern Three Forks Basin, Montana: in Abstracts with programs, 38th annual meeting, Rocky Mountain Section, GSA, v. 17, n.4, p.273.

Zoback, M.L., and Zoback, M., 1980, State of stress in the conterminous United States: Journal of Geophysical Research, v. 85, n. B11, p. 6113-6156.

Zohdy, A.A.R., 1965, Geoelectrical and seismic refraction investigations near San Jose, California: Groundwater, v. 3, n. 3, p. 41-48.

Zohdy, A.A.R., Eaton, G.P. and Mabey, D.R., 1974, Application of surface geophysics to groundwater investigations: Techniques of Water Resources Investigations of the U.S. Geological Survey, Chapter D1, Book 2, Collection of Environmental Data, 116 p.

APPENDICES

APPENDIX A

ROSKIE WELL AQUIFER TEST DATA

Table 6: Roskie well pump test and recovery data, May 1985. All measurements from ground level.

Time (min)	Drawdown (ft)	Time (min)	Drawdown (ft)
0	11.75	190.0	75.15
1.0	42.85	200.0	75.15
1.5	53.55	210.0	76.15
4.0	58.15	220.0	76.15
5.0	61.15	230.0	76.15
5.6	62.15	240.0	76.15
6.0	62.15	Pump off	
7.0	63.15		
7.3	64.15	Time	Recovery
8.0	65.15	(min)	(ft)
9.0	65.15	0	76.15
10.0	65.15	0.25	60.15
11.0	66.15	0.50	55.15
12.0	66.15	0.75	52.15
13.0	67.15	1.0	49.15
14.0	67.15	1.2	47.15
16.0	68.15	1.3	44.15
18.0	68.15	2.0	41.15
20.0	69.15	2.5	41.15
25.0	70.15	3.0	41.15
30.0	70.15	4.0	36.15
35.0	71.15	4.5	35.15
40.0	72.15	5.0	34.15
45.0	72.15	17.0	27.15
50.0	72.15	22.0	26.15
55.0	73.15	26.5	22.15
60.0	72.15	30.0	23.15
65.0	72.65	35.0	21.10
70.0	73.15	42.0	20.65
75.0	73.15	55.0	19.15
80.0	74.15	60.0	19.05
85.0	74.15	70.0	18.35
90.0	74.15	80.0	17.85
95.0	75.15	100.0	17.55
100.0	75.15	120.0	17.25
105.0	75.15	240.0	14.75
110.0	75.15	360.0	13.95
115.0	75.15	460.0	13.45
120.0	76.15	795.0	12.70
130.0	76.15	960.0	12.50
140.0	75.15	1440.0	12.20
150.0	74.15	2820.0	11.95
160.0	75.15	4140.0	11.85
170.0	75.15	5520.0	11.85
180.0	75.15	6840.0	11.75

Table 7: Aquifer analysis using recovery method. Discharge = 60 gallons per minute. Static water level = 11.75 ft below ground level. (t'= time since pump was shut off, t = time since beginning of pump test, s'= residual drawdown).

t' (min)	t (min)	t/t'	s' (ft)
1.0	241	241	42.7
2.0	242	121	29.4
3.0	243	81	29.4
4.0	244	61	24.4
5.0	245	49	22.4
17.0	257	15.1	15.4
22.0	262	11.9	14.4
26.5	266	10.1	10.4
30.0	270	9.0	11.4
35.0	275	7.9	9.4
42.0	282	6.7	8.9
55.0	295	5.4	7.4
60.0	300	5.0	7.3
70.0	310	4.4	6.6
80.0	320	4.0	6.1
100.0	340	3.4	5.8
120.0	360	3.0	5.5
240.0	480	2.0	3.0
360.0	600	1.7	2.2
460.0	700	1.5	1.7

Table 8: Slug test data, June 1985. All measurements from below top of casing. (t = time in seconds, h = recovery height at later readings, H = initial static water level = 14.5 ft, Ho = height at first reading).

t (sec)	h (ft)	H-h (ft)	H-h/H-Ho
5.0	10.5	4.0	
13.0	11.9	2.6	0.65
35.0	12.5	2.0	0.50
44.0	12.6	1.9	0.48
55.0	12.9	1.6	0.40
73.0	13.3	1.2	0.30
84.0	13.5	1.0	0.25
93.0	13.5	1.0	0.25
104.0	13.6	0.9	0.23
125.0	13.7	0.8	0.20
134.0	13.8	0.7	0.18
144.0	13.9	0.6	0.15
173.0	14.0	0.5	0.13
197.0	14.1	0.4	0.10
208.0	14.2	0.3	0.08
243.0	14.2	0.3	0.08
273.0	14.3	0.2	0.05
306.0	14.3	0.2	0.05
317.0	14.4	0.1	0.03
357.0	14.4	0.1	0.03
399.0	14.4	0.1	0.03
509.0	14.4	0.1	0.03
582.0	14.4	0.1	0.03
761.0	14.5	0.0	0.00
932.0	14.5	0.0	0.00

APPENDIX B

EARTH RESISTIVITY DATA

Table 9: Resistivity profile data, 1985. All distances from east end of line unless otherwise noted. Resistivity = ohm-ft; a = electrode profile spacing in feet.

Line	Distance	a = 30	a = 100	Line	Distance	a = 30	a = 100
1R	0	399		4R	0	66	
	50	348			25	429	
	100	372	137		50	510	121
	150	441	148		75	495	
	200	492	130		100	474	153
	250	528	127		125	522	
	300	495	147		150	507	95
	350	480			175	474	
	400	472			200	510	100
					225	258	
2R	0	537			250	321	152
	25	522			275	480	
	50	501			300	441	192
	75	537			325	375	
	100	549	130		350	543	
	125	501			375	612	
	150	462	103				
	175	516		6R	0	537	
	200	585	120		25	360	
	225	510			50	546	116
	250	375	131		75	510	
	275	579			100	447	148
	300	633	132		125	582	
	325	357			150	522	116
	350	555			175	462	
	375	588			200	531	128
					225	429	
3R	0	351			250	420	172
	50	351			275	399	
	100	369	106		300	273	141
	150	372	93		325	300	
	200	387	96		350	255	
	250	321	116		375	351	
	300	363	132				
	350	555					
	400	408					

Table 9: Continued.

Line	Distance	a = 30	a = 100	Line	Distance	a = 30	a = 100
8R *	0	399		3RWF	0	456	
	50	495			50	420	
	100	510			100	348	207
	150	453	138		150	528	224
	200	483	135		200	432	151
	250	552	138		250	474	159
	300	459	156		300	534	210
	350	585	142		350	426	242
	400	636	117				
	450	561	144	4RWF	0	393	165
	500	552	142		50	516	187
	550		131		100	504	160
	600	492	149		150	453	156
	650	450	166		200	462	158
	700	699	160		250	495	160
	750	699	171		300	459	193
	800	705	198		350	459	191
	850	672	190		400	450	189
	900	606	157		450	441	209
	950	588	172		500	465	242
	1000	486	201		550	420	
	1050	603	208		600	390	
	1100	645					
1RWF	0	543	218	5RWF	0	492	139
	50	498	289		50	423	150
	65		287		100	411	152
	100	462			150	549	136
	115		242		200	396	167
	150	528			250	420	158
	165		243		300	399	207
	200	516			350	510	244
	215		211		400	621	234
	250	576			450	453	200
	265		225		500	384	240
	300	567			550	495	
	350	531			600	420	
2RWF	0	543					
	50	498	245				
	100	462	240				
	150	528	225				
	200	516	237				
	250	576	190				
	300	567	193				
	350	531	240				

* = distances from south end of line.

Table 9: Continued.

Line	Distance	a = 30	a = 100	Line	Distance	a = 30	a = 100
6RWF	0	618	185	8RWF	0	441	
	50	498	180		50	438	
	100	474	175		100	429	190
	150	375	171		150	381	159
	200	444	173		200	504	179
	250	402	180		250	495	180
	300	369	182		300	462	145
	350	507	161		350	408	127
	400	564	148		400	477	131
	450	552	137		450	522	135
	500	528	128		500	510	132
	550	432	140		550	477	159
	600	399	146		600	462	151
	650	423	134		650		108
	700	474	141		700	345	120
	750	411	139		750	435	178
	800	384	138		800	537	162
	850	417	150		850	546	131
	900	396	160		900	450	156
	950	432	185		950	429	210
	1000	525	183		1000	447	174
	1050	435	173		1050	282	173
	1100	507			1100	318	220
	1150	384			1150	357	214
					1200	345	152
7RWF*	0	411			1250	588	167
	50	549			1300	558	161
	100	531	170		1350	585	169
	150	567	214		1400	300	
	200	426	244		1450	477	
	250	432	223				
	300	429	256				
	350	453	296				
	400	372	267				
	450	420	220				
	500	414	238				
	550	375	249				
	600	354	255				
	650	408	225				
	700	411	210				
	750	408	161				
	800	423	180				
	850	372	263				

* = distances from south end of line.

Table 9: Continued.

Line	Distance	a = 30	a = 100	Line	Distance	a = 30	a = 100
9RWF	0	414		V4	0	372	
	50	435			50	339	
	100	540	172		100	399	196
	150	589	171		150	448	189
	200	450	165		200	429	164
	250	360	157		250	450	156
	300	435	146		300	402	188
	350	402	141		350	309	192
	400	423	146		400	318	184
	450	417	142		450	339	217
	500	381	146		500	396	162
	550	375	156		550	345	162
	600	390	140		600	405	173
	650	603	140		650	372	167
	700	447	147		700	339	171
	750	432	192		750	339	168
	800	663	218		800	354	173
	850	378	194		850	342	170
	900	360	195		900	396	180
	950	345	228		950	423	184
	1000	333	273		1000	405	197
	1050	336	254		1050	453	202
	1100	357			1100	492	
	1150	453			1150	435	
V3	0	234					
	50	198					
	100	205					
	150	220					
	200	223					
	250	213					

Table 9: Continued.

Line	Distance	a = 30	a = 100
V5	0	450	
	50	438	
	100	387	169
	150	321	166
	200	372	157
	250	366	158
	300	375	168
	350	360	157
	400	414	162
	450	378	175
	500	408	167
	550	495	140
	600	429	162
	650	315	160
	700	312	173
	750	354	160
	800	399	150
	850	408	167
	900	357	190
	950	411	167
	1000	390	159
	1050	387	204
	1100	402	
	1150	360	

Table 10: Vertical electrical sounding data, 1985. Resistivity = ohm-ft. All electrode spreads are east-west unless otherwise noted.

Distance from center (ft)	1R	2R	3R	4R	5R	6R
5	580	399	585	545	331	870
10	714	650	668	811	609	859
20	710	678	580	706	596	604
40	309	337	424	416	452	404
60	276	230	268	327	305	316
80	197	179	192	201	174	190
100	145	110	98	101	96	132
120	120	116	84	100	101	107

Distance from center (ft)	1RWF	2RWF	3RWF	4RWF	5RWF	V3*
5	165	160	179	445	482	117
10	291	276	286	605	597	209
20	418	440	418	462	590	312
30	450	519	363	502	486	336
40	448	480	373	459	348	358
50	442	441	353	400	352	350
60	419	401	301	372	323	350
70	368	377	272	331	297	319
80	343	328	248	288	278	313
90	316	285	224	255	261	286
100	276	249	214	191	247	261
110	234	219	187		233	
120	194	187	158	160	220	209
130					192	
140					157	169

* = electrode spread orientated north-south from center.

Table 10: Continued.

Distance from center (ft).	Resistivity (ohm-ft)
5	388
10	599
15	762
20	628
25	595
30	528
35	406
40	372
45	329
50	295
60	249
70	207
80	134
90	131
100	121
110	108
120	109
130	83

* Sounding located 27 feet west of Roskie well. Sounding spread is orientated north-south.

APPENDIX C

SEISMIC REFRACTION DATA

Table 11: Seismic velocities, Roskie study area, 1985.

Line	Layer	Forward velocity (ft/sec)	Reverse velocity (ft/sec)	Line	Layer	Forward velocity (ft/sec)	Reverse velocity (ft/sec)
1R	V1	667	1250	19VS	V1	1818	1000
	V2	9090	11111		V2	7661	7983
2R	V1	1000	769				
	V2	9900	9500				
3R	V1	555	555				
	V2	8850	10638				
5R	V1	667	1000				
	V2	7143	8333				
8R	V1	1000	1250				
	V2	7917	7364				
9R	V1	1100	1100				
	V2	7308	6985				
13R	V1	833	1000				
	V2	9500	7787				
10R	V1	833	500				
	V2	7308	8962				
11R	V1	625	500				
	V2	8879	7540				
16R	V1	682	714				
	V2	7692	7317				
12RW	V1	667	667				
	V2	8879	6835				
17RW	V1	1136	1389				
	V2	7965	7377				
18RW	V1	625	556				
	V2	7308	7422				
14VS	V1	667	833				
	V2	6376	7197				
15VS	V1	820	555				
	V2	6884	6785				