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Geomorphic, Seismic, and Geotechnical Evaluation of Sand and Gravel Deposits in the Sheridan, Wyoming, Area

U.S. GEOLOGICAL SURVEY BULLETIN 1845

Geomorphic, Seismic, and Geotechnical Evaluation of Sand and Gravel Deposits in the Sheridan, Wyoming, Area

By JACK K. ODUM and CARTER H. MILLER

A study of the Sheridan, Wyoming, area aggregates, with emphasis on a new seismic prospecting technique and aggregate physical properties.

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By Jack K. Odum *and* Carter H. Miller

Abstract

Exploration and production of coal and other resources in the Powder River Basin, Wyoming and Montana, have resulted in a rapid increase in population and in commercial and residential construction. Some of the elements that affect the development of a community are the quantity, quality, and availability of natural building materials, such as sand and gravel. This report treats three aspects of the sand and gravel deposits in the Sheridan, Wyoming, area: the geomorphic setting, the use of seismic-refraction data to delineate buried deposits, and the geotechnical analysis of aggregate samples.

The geomorphic settings of the sand and gravel deposits are of two types: alluvial deposits that are overlain by fine-grained materials in stream valleys and alluvial deposits that cap multiple pediment surfaces. Headward erosion of gullies combined with slope wash cause further erosion of pediment caps near the mountain fronts. Coarse-grained material eroded from these upper-level caps is reworked and either incorporated into the side-slope colluvium and (or) added to the load of the current downcutting stream, eventually becoming an alluvial-fill deposit. Lithologic point counts, physical property measurements, and field observations indicate that three main rock types compose the deposits: crystalline rocks, carbonate rocks, and other sedimentary rocks. A similarity of composition and physical characteristics exists between valley samples from similar source areas and between samples from valleys and pediments in general. Based on the relative similarity of the deposits, a three-zone conceptual geologic-materials model was devised: Zone I is manifested mainly by the fine-grained Lightning and upper part of the Kaycee Formations and by colluvium, which overlies the sand and gravel in the valleys, and in places, overlies the pediment gravels. Zone II encompasses all coarse-grained material and includes the early Pleistocene pediment gravels as well as the gravels of undifferentiated Arvada (not positively identified in the study area), Ucross, and lower part of the Kaycee Formations. Zone III includes the poorly consolidated rock of the Fort Union and Wasatch Formations and its weathered regolith.

The seismic-refraction method was used to compute the configuration of the interface between the higher velocity bedrock and the overlying, lower velocity unconsolidated alluvium across five major stream valleys and three pediment sites. A seismic-interpretation technique, which involved a combination of surface-refraction and borehole velocities, was used to establish Zones I and II. The validity of this method of analysis for the valley surveys is supported by the very high coefficients of correlation ($r=0.996$ and 0.978) that were determined when the depths to Zone II, computed by this method, were compared to the depths determined by boring. The interface depths that were calculated with this technique were used to determine the ratio of the thickness of Zone I (fine-grained overburden) to Zone II (coarse-grained sand and gravel) along each valley cross section. The Big Goose Creek valley section shows the greatest ratio of sand and gravel to overburden thickness at about 3:1, and the Goose Creek valley section shows the smallest at 1.2:1.

In the analysis of sulfate soundness, in terms of percent loss, a fairly high correlation ($r=0.66$) with percent water-absorption and a very low correlation ($r=0.14$) with percent of crystalline clasts present were found. The fair correlation of water-absorption percentage versus sulfate soundness is attributed to the fact that water absorption is a good measure of a sample's overall porosity, regardless of lithologic composition. Percent of crystalline clasts present showed poor correlation with sulfate-soundness loss because most clasts were only slightly weathered, although a wide range of surface-rind weathering was found among individual clasts at any one site. In general, the degree to which a crystalline clast weathered appears to be related primarily to the percentage of biotite found within that clast. Sample loss caused by the Los Angeles abrasion test, showed a fairly high correlation ($r=0.57$) with the percent of crystalline clasts for those samples that were previously tested for sulfate soundness. The increased weakening of crystalline clast surfaces by the sulfate-soundness test is reflected as increased abrasion loss. For those samples not previously subjected to the sulfate-soundness testing, it appears that

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the clast shape may be a more important factor in determining a specific sample's abrasion loss. During testing, the thinner, tabular carbonate clasts were found to be more susceptible to splintering and breakage than the smoother, semirounded crystalline clasts.

INTRODUCTION

Exploration and production of coal and other resources in the Powder River Basin, Wyo. and Mont., has resulted in a rapid increase in population, as well as in commercial and residential construction. Some of the elements that affect the development of a community are the quantity, quality, and availability of natural building materials, such as sand and gravel. In the Sheridan, Wyo., area (fig. 1), most of the early production of sand and gravel aggregate came from quarries that were developed in the easily visible and accessible pediment deposits. The flat pediment surfaces are also desirable sites for urban and residential growth. When old gravel quarries become surrounded by the community, they cannot be expanded, and therefore, are abandoned. Sites farther from the community center are being encroached upon by new housing developments. Because few people want the traffic, noise, and dust associated with aggregate quarries near their homes, strong neighborhood support exists for zoning to prevent the development or expansion of quarries. Such zoning results in the location of quarries farther from the community, which in turn results in higher transportation costs and higher overall construction costs. The U.S. Geological Survey has undertaken engineering geology studies to aid in land-use planning during this period of expansion.

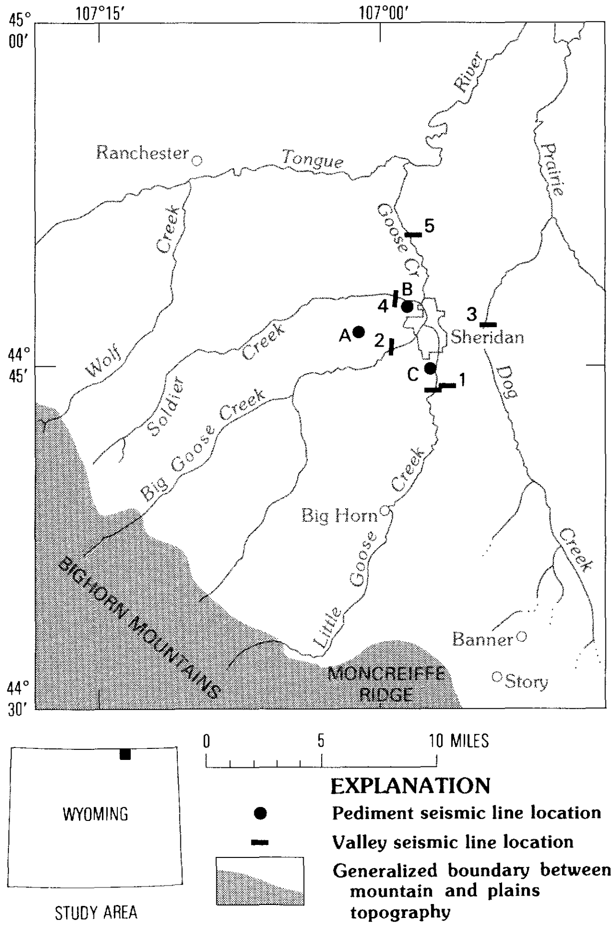


Figure 1. Index map of the Sheridan, Wyoming, area showing the location of valley and pediment seismic-refraction surveys.

Examination of the deposits, in conjunction with the review of previously published maps of the area (preliminary geologic maps of the Becton, Beaver Creek Hills, Hultz Draw, and Sheridan quadrangles (Hinrichs, 1978; 1979a, b; 1980); Big Horn quadrangle (Ebaugh, 1976); and Sheridan area, northwestern Powder River Basin, Wyo. (Kanizay, 1978)), indicates that the deposits are of two kinds: (1) Alluvial sand and gravel that are locally overlain by relatively fine grained alluvium in stream valleys and (2) alluvial deposits that cap multiple pediment surfaces. Seismic-refraction surveys indicate that the buried contact between the unconsolidated sands and gravels, and the underlying bedrock in both types of deposits can be delineated.

Geomorphology

Reconnaissance of the local Quaternary geology, from exposures along major stream valleys and their marginal terraces and pediments, indicates that the majority of the sand and gravel pits in the Sheridan, Wyo., area have apparently been developed in deposits of the Arvada(?), Ucross, and Kaycee Formations (Leopold and Miller, 1954). The objectives of the geomorphic investigation were: (1) To examine the geographic distribution of commercially accessible sand and gravel deposits, both within the major stream valleys and capping nearby pediment surfaces; and (2) to determine whether such aggregate deposits (regardless of geologic age) could be classified by composition rather than by formation names that have been adopted from other parts of the basin. The objectives were accomplished using field observations, results from seismic surveys, and geotechnical tests.

Seismic Refraction

Seismic-refraction surveys can be used to delineate the configuration of the buried contact between unconsolidated gravel, sand, and fines, and the underlying bedrock on pediment surfaces and in stream valleys. The objectives of this approach are: (1) To delineate the subsurface profile of the major stream valleys and selected pediments for the purpose of determining the thickness and lateral continuity of the unconsolidated deposits, and (2) to determine if the materials model that was developed in the geomorphic section could be applied to the geologic interpretations that were derived from the seismic-refraction surveys.

To more accurately examine the thickness and lateral continuity of the buried sand and gravel deposits, it was desirable to seismically subdivide the unconsolidated deposits into fine- and coarse-grained material zones. These zones would correspond to those previously established in the geomorphic section model. This subdivision profiling was accomplished using an interpretation technique, developed by the authors, that employs a combining of surface-to-surface seismic-refraction velocities with those from downhole-velocity surveys. Shallow (maximum of 75 ft) auger drilling was used along the surface seismic spreads to gather additional information on the extent of the sand and gravel deposits and to confirm the seismically calculated depths to the boundaries between the fine-grained material, coarse-grained material, and bedrock.

Geotechnical Characteristics

Samples of the sand and gravel units were collected, and standard tests ASTM (American Society for Testing and Materials, 1972), were done in the U.S. Geological Survey, Engineering Geology Branch, Soil Mechanics Laboratory. These tests included grain-size analysis, bulk specific gravity, water absorption, sodium sulfate soundness, and LA (Los Angeles) abrasion. In addition to these tests, a lithologic count of rock-type groups (crystalline, carbonate, and other sedimentary) that compose the gravel units was performed.

The objective of the geotechnical testing program was the gathering of data on sample composition and durability. These data were used to compare pediment samples to valley samples and to test the relationship of composition parameters (water absorption and lithology) to overall sample durability.

Acknowledgments

We wish to express our appreciation to the people who have assisted in the preparation of this document. We thank those people responsible for drilling, physical-properties testing, and technical assistance, and the clerical staff for their work in manuscript preparation, as well as the many others who provided helpful suggestions for improving the presentation of this study. N.E. Hinrichs, W.P. Hasbrouch, and P.S. Powers, U.S. Geological Survey, and R.B. Johnson, S.A. Schumm, and J.D. Nelson, Colorado State University, provided many helpful suggestions for improving the presentation of this study.

GENERAL GEOLOGY AND GEOGRAPHY

The Bighorn Mountains, an upthrust block of Precambrian rocks, lie between the downwarped Bighorn Basin to the west and the Powder River Basin to the east (fig. 2). Both the mountains and the basin are part of the Rocky Mountain foreland geomorphic province. This province, in turn, lies between the Fold-Thrust belt on the west and the Great Plains on the east.

Cenozoic Era History

Throughout the Paleocene and Eocene Epochs of the Cenozoic Era, this area underwent deformation related to the Laramide orogeny. Debris shed from uplifts filled the downwarping basins with conglomerates and clastic sediments, and coal-forming swamps were widespread. The Fort Union Formation was deposited during the Paleocene. By the end of the Paleocene, much of the overlying Paleozoic and Mesozoic rocks had been stripped away from the uplifted mountain blocks, exposing their Precambrian cores.

The Wasatch Formation, which is composed of conglomerate, fine- to coarse-grained sandstone, claystone, siltstone, and coal, records the continued tectonic activity during the Paleocene and early Eocene. Near the mountain front, the Kingsbury Conglomerate Member of the Wasatch Formation contains clasts of sedimentary rocks, mainly limestones, derived from the initial stripping of the material that overlay the uplifted basement blocks (Sharp, 1948). Moncreiffe Ridge, just south of Little Goose Creek, is one of several high piedmont spurs that extend 2–3 mi east of the mountain

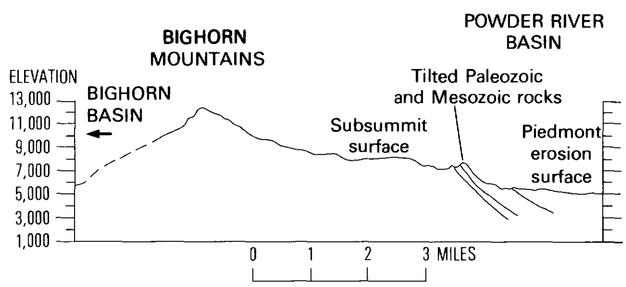


Figure 2. Generalized topographic cross section of the east side of the Bighorn Mountains near Sheridan, Wyoming (modified from Sharp, 1948).

front and have a height of about 1,500 ft above the surrounding plains. The ridge is composed of boulders (some greater than 15 ft in diameter), cobbles, pebbles, interbedded silts, and arkosic sands (Sharp, 1948). This aggregate material, called the Moncrief Member of the Wasatch Formation, consists of igneous and metamorphic rocks derived from the Precambrian core of the Bighorn Mountains (Nelson, 1968). Sharp believes that the Moncrief Member was deposited as a series of alluvial fans during the Eocene.

The Eocene was a time of renewed thrust faulting (Sharp, 1948), but the rate of movement was slow enough that drainage patterns were not appreciably disturbed. Southwest of the study area, near Buffalo, Wyo., Mapel (1959) has mapped valley-fill gravels of Oligocene age, based on fossil evidence. Love and others (1963) believed that this valley-filling cycle continued throughout the Oligocene and possibly reached the level of the subsummit surface (fig. 2) by Miocene time. McKenna and Love (1972) have reported the occurrence of Miocene mammal fossils in strata on the subsummit surface. Uplift was renewed during the late Pliocene or early Pleistocene. Rejuvenation of streams accompanied this uplift, along with the climatic changes of the Pleistocene and Holocene, and resulted in a sequence of erosion cycles, which in turn, led to the development of the pediments and cut-and-fill terraces found today.

Physiography

Exhumation of the Bighorn Mountains has resulted in the erosional stripping of vast quantities of Tertiary sediments. The cross section (fig. 2) shows peaks that make up the backbone of the range at elevations exceeding 13,000 ft. To the east of the tilted Paleozoic and Mesozoic rocks, the average elevation of the bordering plains of the western Powder River Basin is about 4,750 ft. A sequence of eroded pediment surfaces step down to the east. These surfaces may extend as far as 14 mi east of the mountain flanks and have elevations ranging from 4,000 to 6,000 ft. These steplike surfaces lie between 25 and 900 ft above present stream levels (E.N. Hinrichs, written commun., 1985).

The western two-thirds of the study area (fig. 1) is characterized by broad, flat, northeasterly sloping erosional surfaces (often mantled by sand and gravel), upturned Paleozoic and Mesozoic rocks protruding above these erosional surfaces, and intervening flat-floored alluvial valleys (fig. 3). The physiography of the eastern third of the study area, east of Little Goose and Goose Creeks, is one of irregularly dissected elongated hills, where higher surfaces are generally devoid of appreciable amounts of sand and gravel. These low hills trend northward and form the divides between broad alluvial valleys that also trend northward. Landslides in relatively thin colluvial material are common in these dissected hills (Chleborad and others, 1976; Miller and others, 1980). Resistant and variegated red clinker (baked bedrock that results from the burning of a subsurface coal seam) caps many of the hills in the eastern part of the study area, particularly along Prairie Dog Creek.

The study area is located in Sheridan County, north-central Wyoming, and is confined mainly to the river valleys and pediment surfaces within a 20-mi radius of the city of Sheridan (fig. 1). Big Goose and Little Goose Creeks have drainage basins that originate within the glaciated areas of the Bighorn Mountains. The streams flow through steep canyons cut into the Paleozoic and Mesozoic sedimentary rocks and then flow across the flatter topography of the Tertiary age sedimentary rocks. The Soldier Creek drainage basin contains a few tributaries on the Precambrian rocks of the Bighorn Mountains but is predominantly restricted to Paleozoic and Mesozoic age rocks. Little Goose Creek crosses older and harder tilted sedimentary rocks, along its eastward trend, then turns northward and flows through the city of Sheridan, where it is joined by the east-flowing Big Goose and Soldier Creeks. Little Goose and Big Goose Creeks are collectively called Goose Creek downstream from their confluence. Goose Creek flows north about 18 mi to its confluence with the northeast-trending Tongue River near the Wyoming-Montana border. All these streams receive drainage from the pediments and hills that flank the mountain front. Prairie Dog Creek (fig. 1) differs from the other three streams in that all its tributaries head in and flow over the relatively weaker sedimentary rocks of Tertiary age that underlie the foothills and plains. The source areas of these five streams, in general, determine the type, quantity, and quality of the sand and gravel found in the disassociated alluvial deposits.

GEOMORPHIC SETTING OF SAND AND GRAVEL DEPOSITS

Overview

In the Sheridan, Wyo., area, sand and gravel deposits of economic significance occur in two general geomorphic settings: (1) Alluvial caps on erosional surfaces (pediments and bedrock benches next to streams), and (2) alluvial fill in stream valleys. For simplicity of discussion in this report, bedrock benches next to the streams will be considered a part of the pediment sequence. Moncreiffe Ridge, just south of the

Figure 3. Pediments and tilted Paleozoic and Mesozoic rocks along the east flank of the Bighorn Mountains. View is southeastward from highway switchback west of Ranchester, Wyoming.

study area, contains vast amounts of gravel in the Moncrief Member. However, because of its distance from urban centers and relative inaccessibility, it is not considered as an economic resource at this time.

Previous Studies in the Sheridan, Wyoming, Area

Darton (1906) first commented on the extensive, flat, erosion surfaces found east of the Bighorn Mountains. Alden's (1932) work on physiography and glaciation in eastern Mont. and Wyo., classified two of these pediment surfaces as "No. 2 and No. 3 benches" to fit into his overall Pleistocene chronological scheme. Sharp (1948) believed that he had located a few isolated remnants of Alden's No. 1 bench and stated that only the lowest terrace appears to be alluvial fill. An age of no older than mid-Pleistocene for the high-level pediment cover has been proposed by Bullard (1967). He based his observations on pulmonate gastropods that were found in silt lenses interbedded with the pediment gravels.

Sharp (1948) used Pleistocene ventifacts that were located on various erosional surfaces as indicators of changing paleoclimatic conditions. Mears (1981) cited the occurrence of ice-wedge and sand-wedge casts in the intermontane basins of Wyoming, at elevations as low as 4,395 ft, as evidence that a dry wind-swept permafrost environment existed in this area in late Wisconsin time.

Leopold and Miller (1954), from their investigations of cut-and-fill terraces along several streams in the Powder River Basin, established a generalized chronology of Holocene sedimentation and erosion. With the addition of archaeological site data along the Bighorn Mountains and other areas of Wyoming (Haynes and Grey, 1965; Albanese and Wilson, 1974), as well as more recent stratigraphic work by D.S. Fullerton (written commun., 1977), a more complex Holocene chronology is in the process of development.

Pediments

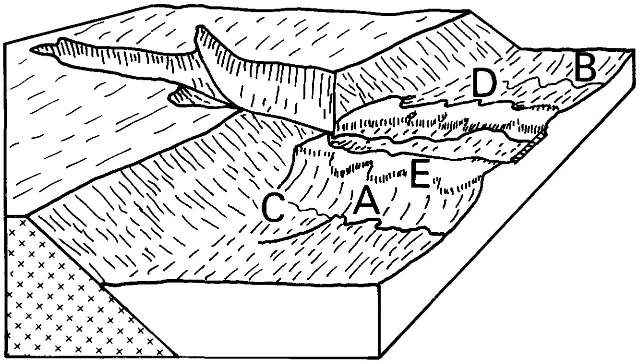
Pediments are gently inclined erosional surfaces of low relief that occur between mountain fronts and the flanking basin. These bedrock surfaces are often extensive and are generally veneered with fluvial and colluvial clay, silt, sand, and gravel. The coarser materials may be of economic value as construction (aggregate) materials. Some authors believe that pediments form in all environments but are best developed and preserved, and hence, more numerous in semiarid and arid environments. The processes and events involved in pedimentation have been a subject of debate for decades. Opinions differ as to whether unconcentrated flow accompanied by backwearing and rill wash, or lateral planation by streams in well-defined channels, is more effective in pediment formation (Leopold and others, 1964). It is recognized that all these processes are active on pediment surfaces in varying degrees for different regions. The development of multiple levels of erosional surfaces, as exist in the Sheridan, Wyo., area and their significance to the interpretation of the regional geologic history have been discussed by several authors (Rich, 1935; Hunt and others, 1953; Scott, 1965; Hadley, 1967; Ritter 1972; Schumm, 1977).

Stream Piracy and Aggregate Capping of Multiple-Level Pediment Surfaces

Figure 4 is a photograph of a wind gap in a high-pediment spur remnant. The gap identifies a stream course abandoned due to stream piracy. The stream-piracy block diagram of figure 5 (Rich, 1935) and the following selected statements by Schumm (1977, p. 287), not only demonstrate the significance of stream capture as a process in the development of multiple-pediment surfaces (stairstep) on relatively weak rocks at the base of more resistant mountain scarps, but also illustrate a mechanism by which coarse aggregate is distributed to the various levels.

> "The stream removes a coarse and large sediment load from the mountains and therefore requires a steep gradient to transport this load across the pediment zone. However, streams A and B draining only the piedmont area of soft rocks (fig. 5) have a much gentler gradient, and they have incised into and eroded the weaker rocks. The streams draining from the highlands maintain a steeper gradient and are at a significantly

Figure 4. Wind gap cutting a dissected ridge of an upper pediment surface.



EXPLANATION
A and B — Piedmont streams incised into weaker rocks
C and D — Piedmont streams in position to capture highland stream
E — Surface abandoned by capture of highland stream

Figure 5. Model for the development of multiple-pediment surfaces in response to stream capture (Rich, 1935).

> higher level near the scarp. The result is that streams C or D will capture the high-level stream, thereby leaving surface E as an abandoned pediment. Following capture, gravels are moved from the canyon *** and spread over the lower weaker rock surface to form the next lower pediment gravel cap. Another response to stream capture is a rejuvenation of the existing mountainbred stream. This rejuvenation is accompanied by a flushing of sediments, stored in the drainage basin, onto the new alluvial surfaces. After a period of sediment flushing, *** erosion of a pediment by lateral planation and backwearing of valley sides slopes is replaced by gravel deposition and lateral stream shifting." (Schumm, 1977, p. 288).

A repetition of these events could easily lead to the formation of multiple-surface pediments under the geologic situations which are present along the Bighorn Mountains.

The gravel-armored pediment surfaces are more resistant to erosion than the shale and sandstone bedrock exposed along valley walls. Therefore, most upper pediment surfaces are removed by backweathering and erosion along lateral valley walls rather than by downward erosion of the pediment surface itself.

Pediment Surfaces in the Sheridan Area

Along the Bighorn Mountains, multiple-level pediments exist and vary widely in size and height above drainages. Surficial and bedrock mapping in the Sheridan area by Ebaugh (1976) and Hinrichs (1978; 1979a, b; 1980) have identified as many as eight pediment levels. These surfaces range in elevation from 4,000 to 6,000 ft and lie anywhere from 25 to 900 ft above stream level. Near the mountain front, the upper erosional surfaces form fairly extensive slopes that are dissected only by major mountainbred streams. Figure 6 is a photograph of a pediment remnant that is dissected by Soldier Creek (fig. 1). From a distance, some surfaces appear to have alluvial-fan configurations. Figure 7 shows the gently undulating, concave-up surface geometry of the pediment shown in figure 6. The uppermost surfaces, in general, have thin soil covers and are occasionally dotted with white cobbles and boulders of carbonate rocks as much as 2.5 ft in diameter. Few other rock types are found exposed on the surface. Figure 8 is a photograph showing a cross-sectional view above Big Goose Creek of gravels that cap a pediment erosional surface cut across upturned Mesozoic strata. Headward erosion of gullies combined with slope wash result in continued erosion of these higher elevation surfaces. As distance increases away from the mountain front, the surfaces became isolated gravel-capped knobs rising above the surfaces of the lower pediments. At the lower ends, the pediment surfaces merge with the modern fluvial terraces. Sand and gravel eroded from the caps are reworked and added to the coarse-grained material freshly supplied from the mountains, and are eventually redeposited as valley-fill and side-slope colluvium.

Valley Alluvial Deposits

Leopold and Miller (1954) studied alluvial deposits and terraces in the Powder River Basin and compiled a generalized model of the postglacial stratigraphy for some of the alluvial valleys in eastern Wyoming (fig. 9*A*). They identified four deposits which, from oldest to youngest, are the Arvada, Ucross, Kaycee, and Lightning Formations. Much of their work was done in the middle and eastern parts of the Powder River Basin, as far as 70 mi from the mountain front. Field work by D.S. Fullerton (written commun., 1977), also within the Powder River Basin, showed a much more complex chronologic stratigraphy of deposition and erosion. Haynes and Grey (1965), working at the Sisters Hill archaeological site near Buffalo, Wyo., approximately 31 mi south of the study area, have also compiled a complex stratigraphic sequence of postglacial deposits (fig. 9*B*). Letters A to G on figure 9*B* indicate unnamed deposits between the Ucross and Kaycee Formations. While working in the Bighorn Quadrangle, a part of the present study area, Ebaugh (1976) compiled a more simplified sequence of depositional formations (fig. 9*C*).

A major objective of this study is to determine the thickness and configuration of coarse-grained aggregate deposits. Surface-run seismic-refraction surveys and downhole-velocity surveys were the prospecting tools used to meet this objective. Although Ebaugh's (1976) Bighorn quadrangle stratigraphic section is generally representative of the depositional sequence within the study area, formational boundaries, especially in uncon-

Figure 6. Example of a dissected pediment surface along the east flank of the Bighorn Mountains. From a distance, these surfaces may appear to be dissected alluvial fans.

solidated materials, do not necessarily correspond to seismically determined boundaries because of the lithologic and water-saturation variability found within a given formational unit. Therefore, a model that is based on three material types (fine-grained, coarse-grained, and bedrock), which are seismically identifiable on both pediments and in stream valleys, has been adopted for this study.

Conceptual Materials Model

Much of the gravel and bedrock of the pediments, and nearly all the gravel and bedrock in the valleys, is covered by fine-grained (clay, silt, and fine sand) alluvium and colluvium. Boundaries between the coarse-grained (sand and gravel) material and the overlying fine-grained material and between the coarse-grained material and the underlying bedrock, can be approximately distinguished by combining seismic data from surface and downhole surveys with supplemental borehole lithologic information. The geologic interpretation, however, must take into account the weathering at the upper surface of the bedrock, lensing in the fine-grained and coarse-grained layers, and a water table that may cut across all these boundaries. For this reason, a conceptual model (fig. 10), based on material types that can be delineated by seismic velocity measurements, was developed as follows: Zone I is mainly composed of fine-grained alluvium of the Lightning and upper part of the Kaycee Formations of Leopold and Miller (1954) and colluvium which overlie the sand and gravel in the valleys, although some thin deposits of Zone I also overlie the pediment gravels. Zone II encompasses all coarse-grained material and includes the early Pleistocene pediment gravels as well as the sands and gravels of undifferentiated sediments of the Arvada (which was not positively identified in the study area), Ucross, and lower part of the Kaycee Formations (Leopold and Miller, 1954). Zone III includes the poorly consolidated rocks of the Fort Union and Wasatch Formations and their weathered regolith.

SEISMIC INVESTIGATIONS

Introduction

Pediments and valley floors are surfaces of gently undulating relief in the Sheridan, Wyo., area. In the study

Figure 7. Typical concave slope of pediment surface, south of Soldier Creek, near the Bighorn Mountain front. The white cobbles are carbonate rocks.

area, these surfaces are usually covered by vegetation, and consequently, little indication exists as to either the underlying material or its thickness. Although the pediment cap may be exposed along ravines and in landslide scarps, no guarantee can be given that the thickness of the cap material a few feet away may be the same. In the table below are listed examples of the variability of alluvium thickness observed in 11 backhoe exploration pits within an approximately 2 acre plot:

Pit No.	1	2	3	4	5	6	7	8	9	10	11
Alluvium thickness (ft)	3.6	0.7	9.8	2.0	2.3	5.3*	2.3	2.0	4.4	3.3	3.6*

*No sand and gravel.

Sand and gravel may be present in a pediment cap in variable quantity or even missing, as indicated by the asterisked items in the above list; it can be more than 20 ft thick as observed in the exposure of a buried channel fill. The thickness of alluvial fill in valleys, and the amount of sand and gravel in the fill, may also differ greatly across, as well as up and down, the stream valley.

Most commercial exploration for sand and gravel in the Sheridan, Wyo., area has been done by randomly digging pits on the pediment surfaces. To the knowledge of the authors, very little exploration has been conducted in the valleys. For purposes of these broad studies, however, neither numerous excavations nor boreholes were feasible. Seismic-refraction techniques were, therefore, employed for exploring the thickness and configuration of both the alluvial caps on the pediments and the alluvial fill in the valleys, as well as for discerning the units of sand and gravel in the alluvium. The seismic-refraction surveys were supplemented by lithologic and downhole-velocity information from relatively few boreholes.

Refraction Surveys

The seismic-refraction technique involves the recording of travel times for both direct and refracted compressional-wave fronts as they pass known points (seismometers) along the surface of the ground. Other seismic waves are recorded, of course, but they do not pertain to this study. First arrival times (energy traveling

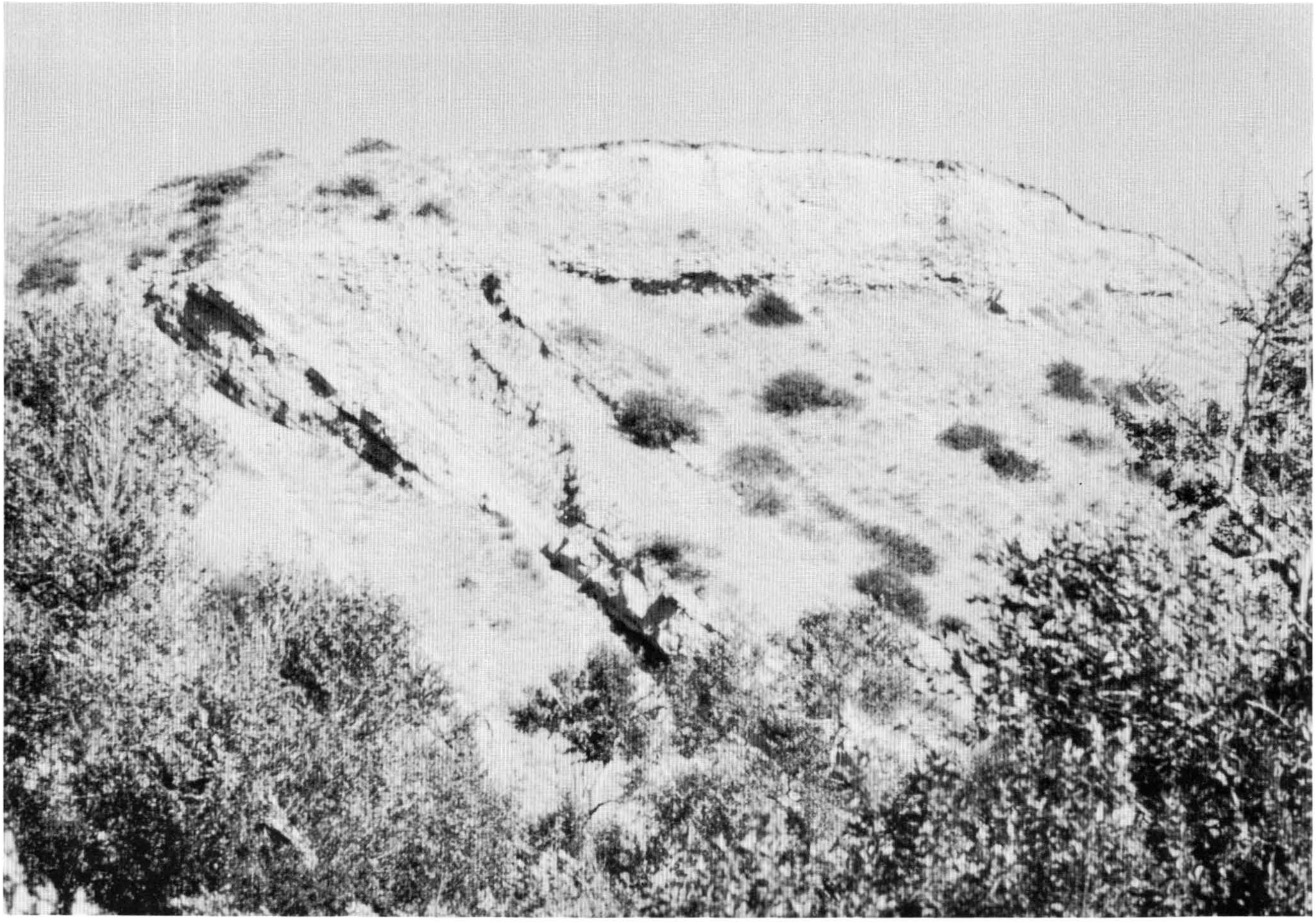


Figure 8. Gravel-capped pediment surface that truncates upturned Mesozoic sediments above Big Goose Creek.

directly through the uppermost geologic layer) are plotted on a time-distance graph. A line drawn through these points defines a slope, and the reciprocal of that slope defines the compressional-wave velocity (V_1) of that uppermost velocity layer, called the low-velocity layer and given the symbol V_1. Arrival times for the refracted compressional wave are also plotted on the same time-distance graph, and the reciprocal of the slope of the line that is drawn through these points defines the velocity (V_2) for the lower of two velocity layers. The intersection of the V_1 and V_2 lines defines the critical distance Xc, and the projection of the $1/V_2$ line to the ordinate ($t=0$) defines the intercept time, T_i. Thickness of the upper layer is calculated using the T_i (intercept time) and the Xc (critical distance), and therefore, the depth to the top of the second layer is computed. Formulas that calculate these depths are collectively called the time-intercept method (Dobrin, 1960).

Programs designed for use with the Hewlett-Packard 65, 67, and 97 hand-held calculators[1] were used for reduction of location surveys and of the raw seismic data. These programs are: Stadia-alidade traverse reductions (Miller and Odum, 1983) and Depth and configuration of a buried refraction-velocity layer (Miller and Bullard, 1978).

Drilling and Downhole Velocities

In the summer of 1981, test borings were conducted at selected sites along the valley and the pediment seismic-refraction spreads to acquire geologic and further velocity information to aid in the seismic-refraction interpretations. The holes were augered into apparent bedrock with 4.5-in.-diameter solid-stem augers. The holes were cased with 3-in. (inside diameter) plastic pipe. Sometimes the alluvium caved, particularly

[1]Any use of trade names in this report is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey. (Released in response to a Freedom of Information Act request.)

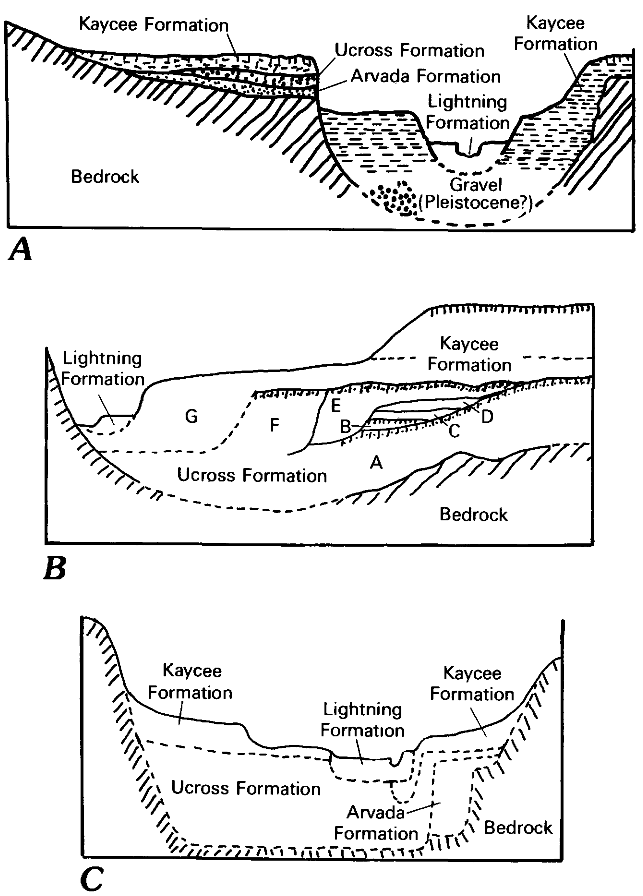
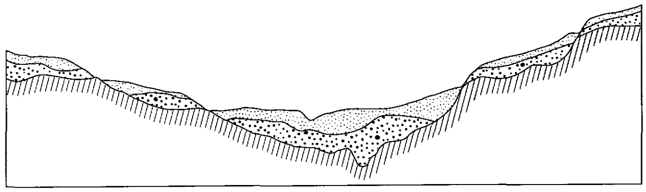


Figure 9. Conceptual models of the chronological stratigraphy of valley-fill deposits in the Powder River Basin, Wyoming. *A*, Model for eastern Wyoming (Leopold and Miller, 1954). *B*, Sister's Hill archaeological site near Buffalo, Wyoming (Haynes and Grey, 1965, courtesy of Plains Anthropologist). *C*, Generalized model for the Bighorn Quadrangle, Wyoming (Ebaugh, 1976).

below the water table, and prevented the emplacement of casing into unweathered bedrock. Consequently, much of the drilling was done with difficulty, and not all holes were cased to a desired depth, nor were a satisfactory number of holes drilled. The annulus between the borehole wall and the plastic pipe was backfilled with sand. Downhole compressional-wave velocities were measured in each hole after the backfilling was done.

Compressional waves were generated and measured, and velocities were calculated using techniques described by Gibbs and others (1975). Compressional waves were generated by vertical impacts of a sledgehammer on a 1.0-ft-square steel plate, located 3.0 ft from the borehole. A single seismometer was secured at 3.3-ft intervals within the plastic casing by inflation of a packer mounted on one side of the seismometer. The arrival times of the compressional waves were plotted versus corrected slant depths caused by an offset of the



EXPLANATION

Zone I
Fine-grained material; unconsolidated sediments including colluvium and the Lightning and upper Kaycee Formations, which are situated mainly in the valleys and cover nearly all gravel deposits

Zone II
Coarse-grained material; mainly sand and gravel of the lower Kaycee, Ucross, and Arvada (?) Formations in the valleys and of other Pleistocene deposits on the pediments

Zone III
Bedrock; poorly consolidated sedimentary rocks and regolith of the Fort Union and Wasatch Formations

Figure 10. Conceptual model of materials that can be differentiated into three main seismic zones by a combination of both surface and downhole seismic data and borehole lithologic information. The sand and gravel deposits are the object of the surveys, and the model shows their relative distribution in the two types of deposit areas—valleys, where they are nearly always buried by fine-grained deposits, and pediments, where burial is much shallower.

steel plate, and velocities of the low-velocity layer (unconsolidated alluvium and colluvium) were determined from the resulting data.

Simplified lithologic columns, on time-distance graphs, and computed downhole compressional-wave velocities (V_{d1}) for the eleven valley and three pediment boreholes are presented in figure 11. Downhole-velocity measurements were unobtainable, due to hole caving, for the borehole at Little Goose Creek site JM–2 and Big Goose Creek site SPP–1.

Seismic-Refraction Field Techniques

Seismic-refraction surveys were run perpendicular to the valley axis of Little Goose, Big Goose, Prairie Dog, Soldier, and Goose Creeks. Each survey consisted of two to seven seismic spreads along the ground surface. Each spread was normally 550 ft long, except where physical obstruction required a shorter length. Twelve seismometers were evenly spaced along each spread at 50-ft intervals, and their horizontal and vertical positions were surveyed onto a base map of each site. Shotholes were drilled to a depth of 4 ft at the ends of each spread, directly under the end seismometers where charges were implanted. The charges were equivalent to about ½ lb of 60 percent dynamite, and detonation was accomplished with no-delay seismic-electrical caps. After the alternate shooting and recording of both ends of the 550-ft spread were completed, a 165-ft spread with geophone spacing of 15 ft was situated at either end position of the 550-ft

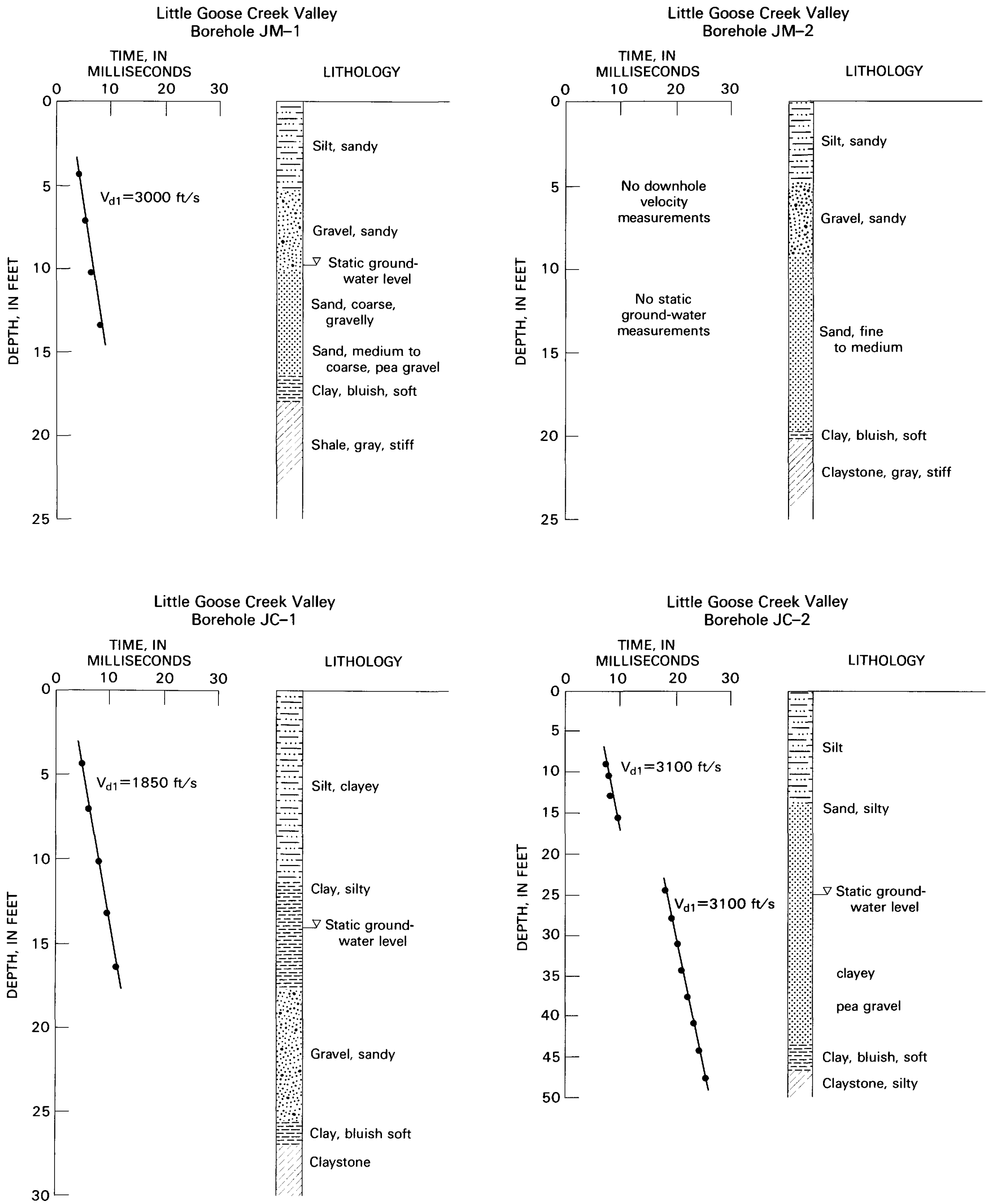
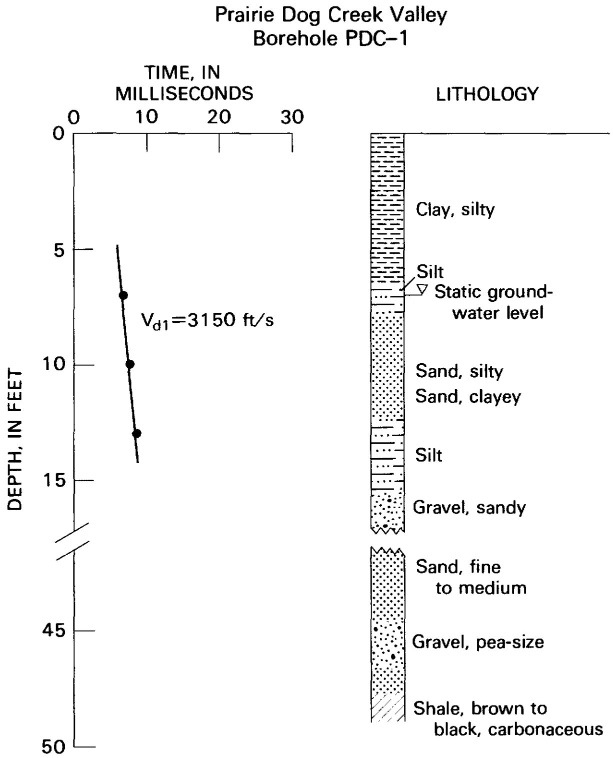
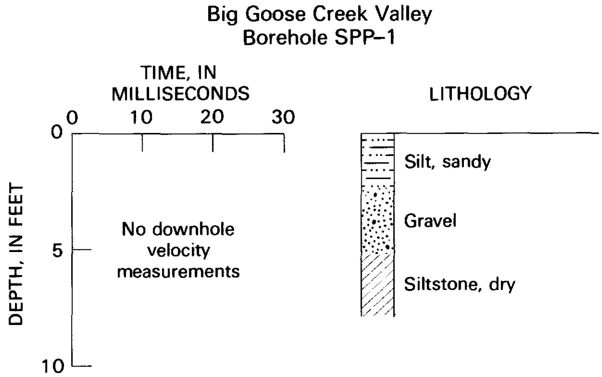
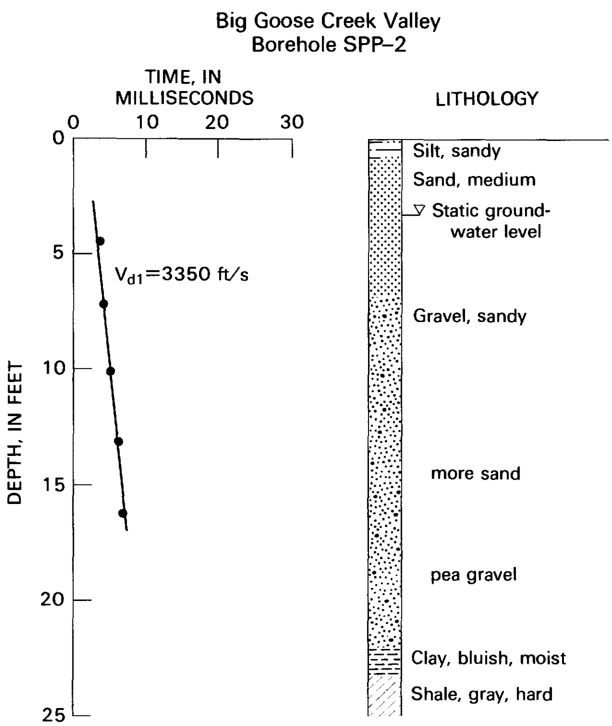
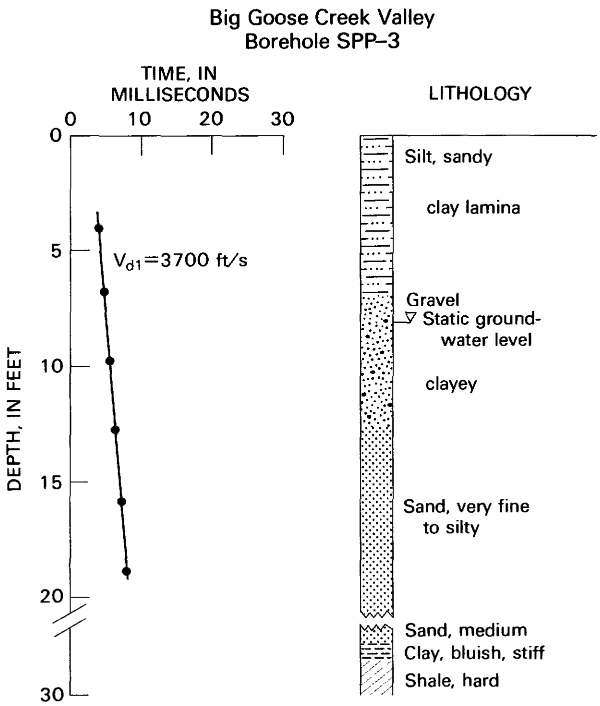


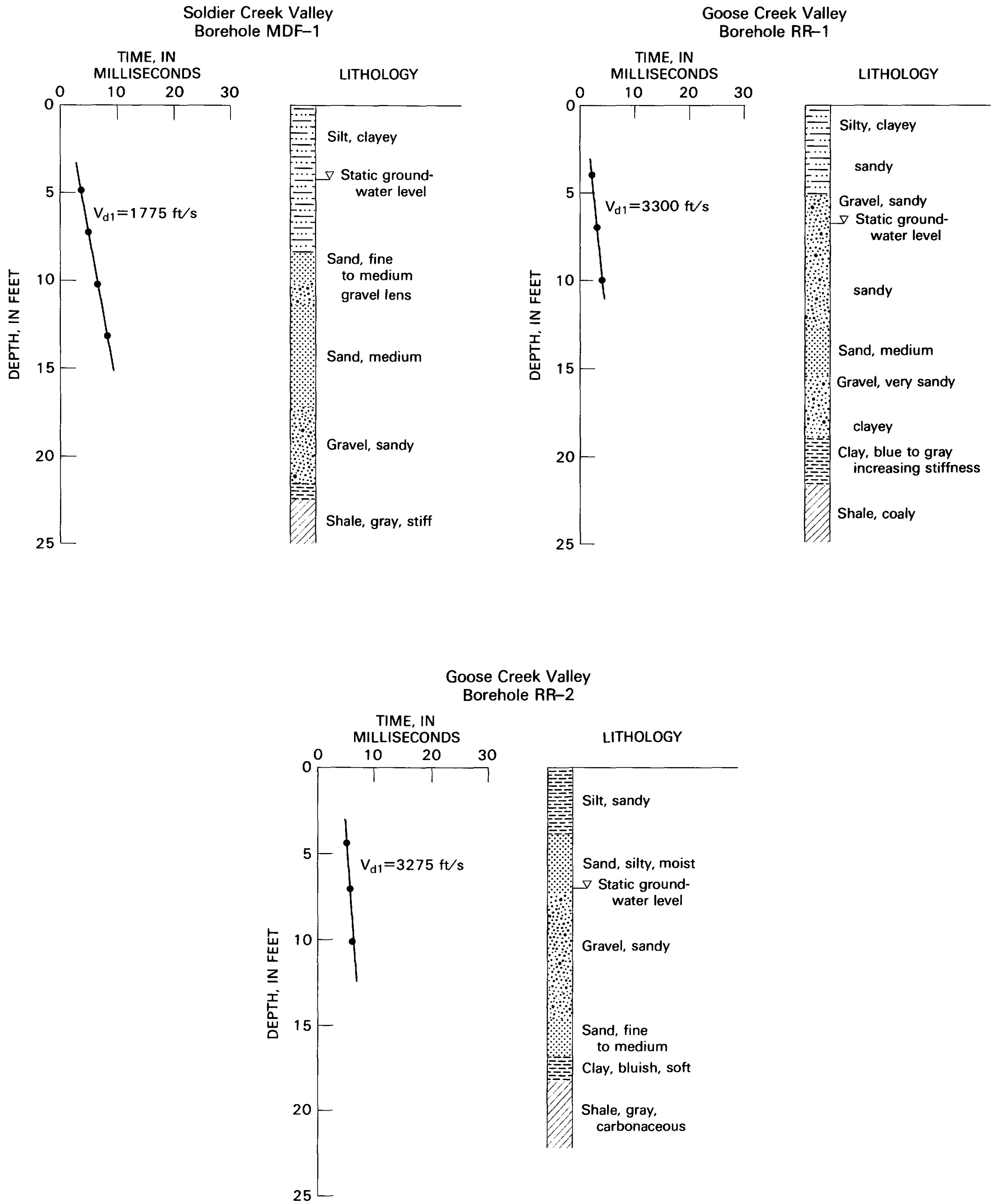
Figure 11 (above and following three pages). Simplified lithologic columns and time-distance graphs for the downhole compressional-wave velocity (V_{d1}) measurements for eleven valley and three pediment boreholes.


Prairie Dog Creek Valley
Borehole PDC-1
TIME, IN MILLISECONDS
0 10 20 30
LITHOLOGY
DEPTH, IN FEET
0
5
10
15
45
50
V_{d1}=3150 ft/s
Clay, silty
Silt
Static ground-water level
Sand, silty
Sand, clayey
Silt
Gravel, sandy
Sand, fine to medium
Gravel, pea-size
Shale, brown to black, carbonaceous


Big Goose Creek Valley
Borehole SPP-1
TIME, IN MILLISECONDS
0 10 20 30
LITHOLOGY
DEPTH, IN FEET
0
5
10
No downhole velocity measurements
Silt, sandy
Gravel
Siltstone, dry

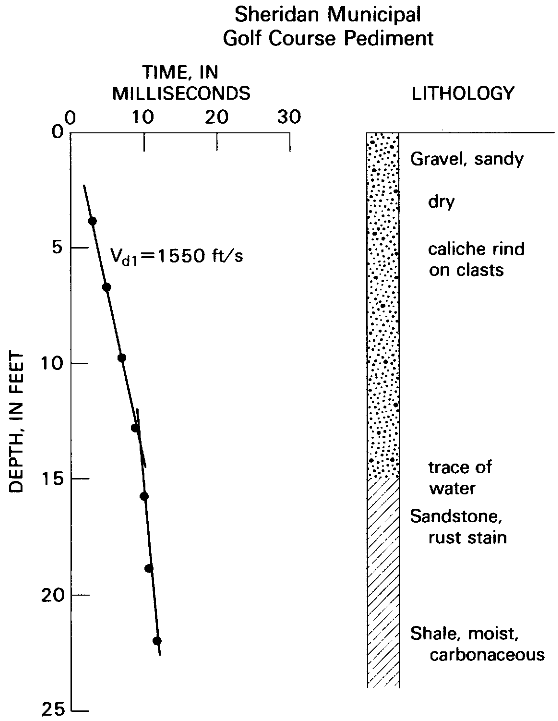

Big Goose Creek Valley
Borehole SPP-2
TIME, IN MILLISECONDS
0 10 20 30
LITHOLOGY
DEPTH, IN FEET
0
5
10
15
20
25
V_{d1}=3350 ft/s
Silt, sandy
Sand, medium
Static ground-water level
Gravel, sandy
more sand
pea gravel
Clay, bluish, moist
Shale, gray, hard

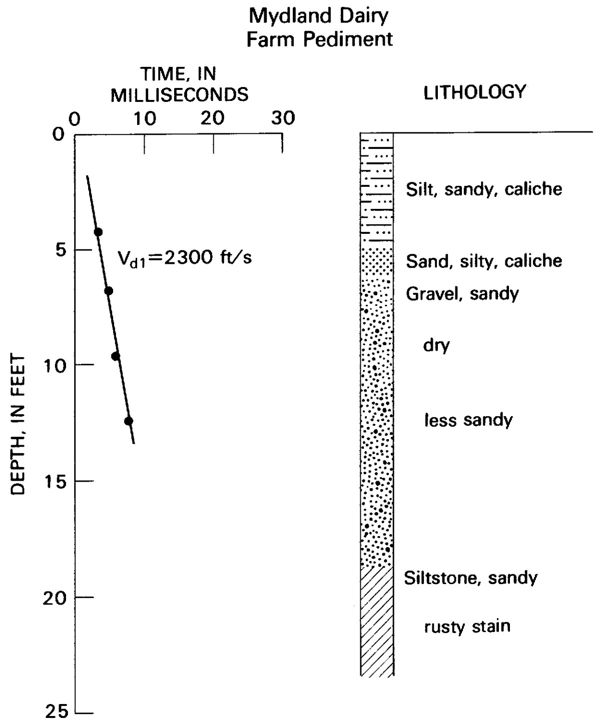

Big Goose Creek Valley
Borehole SPP-3
TIME, IN MILLISECONDS
0 10 20 30
LITHOLOGY
DEPTH, IN FEET
0
5
10
15
20
30
V_{d1}=3700 ft/s
Silt, sandy
clay lamina
Gravel
Static ground-water level
clayey
Sand, very fine to silty
Sand, medium
Clay, bluish, stiff
Shale, hard

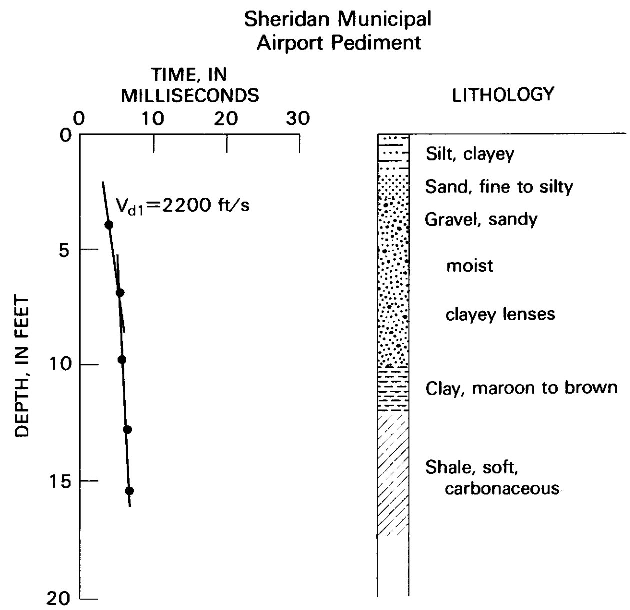


spread. Explosive charges for these shorter spreads were equivalent to ¼ lb of 60 percent dynamite and were placed at a depth of 3 ft directly beneath the end geophones of these 165-ft spreads and very near the shotholes used for the 550-ft spreads.

At each of the three pediment sites, a single 330-ft seismic-refraction spread with 30-ft spacings was run. Seismic energy for these spreads was provided by a charge equivalent to ¼ lb of 60 percent dynamite at a depth of 4 ft, directly beneath the end geophones. Shot-







hole depths were mathematically corrected by incorporating uphole times in the calculations of velocities for all spreads in the valleys and on pediment surfaces, but the time-distance graphs show only the raw data.

Seismic Interpretation Model

The average $\overline{V}_1$ for the uppermost (low-velocity) layer, indicated on the following model, and time-distance and geologic interpretation cross sections (both valleys and pediments) were corrected for uphole times derived from the 165-ft surface-run seismic spreads after shothole corrections were done and comparisons were made with any V_1 velocities discernable along the 550-ft spreads. The indicated V_2 velocities were derived from the longer 550-ft surface-run seismic spreads. Henceforth, these $\overline{V}_1$ and V_2 velocities will be identified as as surface-run $\overline{V}_1$ and V_2. Another V_1 velocity was determined using the downhole seismic surveys. This latter velocity will be hereafter referred to as the downhole velocity V_{d1}.

Seismic profiles of the buried $\overline{V}_1$–V_2 interface were computed from the surface-run seismic-refraction data by both the time-intercept and method-of-differences formulas, and were compared to the geologic interfaces logged from borehole cuttings. The $\overline{V}_1$–V_2 seismic interface proved to be the general boundary between the fine-grained material and the underlying coarse-grained alluvium, rather than the boundary between the undivided valley fill and the underlying bedrock, as previously expected. Figure 12*A* compares the thickness of fine-grained material logged from boreholes with the thickness of the $\overline{V}_1$ layer computed from surface-run seismic data. The slope of the regression line shows a near-perfect one-to-one correspondence, and the coefficient of correlation is a very high 0.996. Thus, the $\overline{V}_1$ layer determined from the surface-run seismic-refraction data defines a layer of predominantly fine grained and generally partly saturated material. This layer is called Zone I.

A second subsurface interface was also calculated using the two methods and plotted. Calculations used the surface-run V_2 velocity and the downhole V_{d1} velocity (representing undivided, unconsolidated colluvium and alluvium) determined from boreholes along the respective seismic line (fig. 11). The position of this second computed boundary was also compared to the geologic interfaces logged from borehole cuttings. The V_{d1}–V_2 seismic interface proved to be the general boundary between the undivided alluvium (including weathered bedrock) of valley fill or pediment cap and the underlying nonweathered bedrock. Figure 12*B* compares the thickness of undivided valley fill or pediment-cap material logged from boreholes, with the thickness of the V_{d1} layer computed with V_2. The slope of this regression line also shows a near-perfect one-to-one correspondence, and the coefficient of correlation is also a very high 0.978. Thus, the V_{d1} layer defines the total thickness of undivided valley fill or pediment cap. The difference in thickness of the V_{d1} and $\overline{V}_1$ (Zone I) layers is here called Zone II, and it consists mainly of coarse-grained material that underlies the fine-grained alluvium and overlies bedrock.

Whereas the uppermost, fine-grained layer is represented by the $\overline{V}_1$ velocity and the total undivided valley fill/pediment cap is defined by the V_{d1} velocities, the velocities of the V_2 layer are evidently influenced mainly by nonweathered bedrock, and to a lesser extent, by the weathered bedrock and some of the overlying and partly saturated, coarse-grained material. Zone III is here defined as mainly nonweathered bedrock that is detected by the V_2 velocities. If the bedrock beneath the

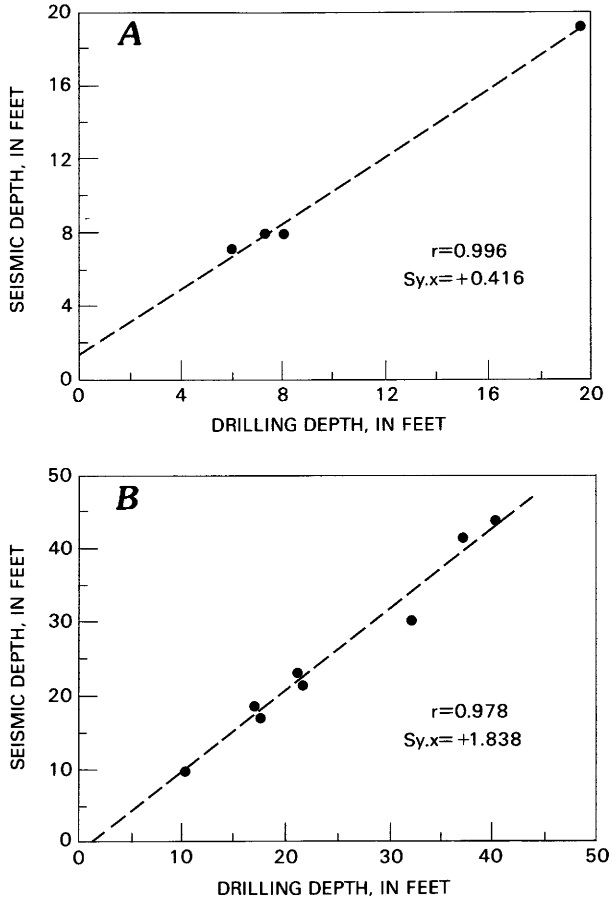


Figure 12. The thickness of a lithologic unit determined by drilling and compared to the seismically determined unit thickness. *A*, An uppermost layer of fine-grained material detected by the low velocities interpreted from surface-run seismic surveys. *B*, The total thickness of undivided valley fill or pediment cap detected by the low velocities of borehole surveys. r is the correlation coefficient, and Sy.x is the standard error of estimate.

sand and gravel was shaley, then a transition zone of bedrock that weathered to a "sticky" blue-gray clay was usually encountered. The weathered zone commonly ranges in thickness from 2 to 10 ft and becomes relatively more competent with depth.

Although the weathered sedimentary bedrock is composed predominantly of grains smaller than fine in size (mainly silt and clay sized), its characteristic velocities are more similar to the velocities of nonweathered bedrock (Zone III) than to the fine-grained material of Zone I (present in the valleys but generally absent on the pediment caps). The main reasons are that the weathered bedrock is much more compact and usually fully saturated, whereas the fine-grained material of Zone I is loosely packed and usually nonsaturated.

The velocities of the Zone III nonweathered bedrock also tend to be higher than those of the sand and gravel, thus providing a velocity contrast detectable by seismic surveys, even though both units may be saturated. The sand and gravel of Zone II on the pediment caps, for example, is clearly distinguished by seismic surveys.

The static ground-water levels encountered in the boreholes and at local streams and ponds indicate that (1) the bedrock of Zone III under the valleys, but not necessarily under pediment caps, is fully saturated; (2) the coarse-grained material of Zone II is commonly saturated under the valleys but much less so in the pediment caps; and (3) the fine-grained material of Zone I is commonly only partly saturated in the valleys, and this zone is commonly very thin to absent on the pediment caps. A fully saturated media usually increases the average velocity of the media, depending on the velocity of the media and its porosity. The depth of the ground-water table in the Sheridan area, however, did not seem to affect unduly the interpretation of the seismic model, possibly because an increasing degree of saturation down to the water table masks the water table. Typical velocities for the individual zones seemed to prevail regardless of the static ground-water level in the boreholes. Another indicator of relative noninterference by the ground-water table is that the method-of-differences interpretations never show a relatively flat, horizontal seismic interface, which they would, if local distinct ground-water tables in a porous granular medium were controlling the velocities.

A model for aiding the seismic interpretation of lithologic layering has been devised. The model is shown graphically in figure 13 and is described as follows:

Zone I—is defined by the $\overline{V}_1$ velocity data, which is obtained from the shorter surface-run seismic lines. This $\overline{V}_1$ velocity is representative of the layer of mostly fine grained, near-surface material, but which undoubtedly includes a small portion of the underlying coarse-grained material.

Zone II—is defined by the V_{d1} velocity data, which is obtained from borehole surveys. The V_{d1} layer includes the total thickness of undivided alluvium of valley fill/pediment cap, and Zone II is the difference in thickness of the V_{d1} and $\overline{V}_1$ (Zone I) layers. Zone II is mainly composed of coarse-grained material (sand and gravel) that may be partly to fully saturated. The zone may also include lesser amounts of fine-grained material at its upper boundary and weathered bedrock at its lower boundary.

Zone III—is defined by the V_2 velocity data, which is obtained from the longer surface-run spreads. Zone III is composed mainly of nonweathered bedrock that is infinitely thick for purposes of the refraction interpretation. Lesser amounts of weathered bedrock and even saturated coarse-grained material may be included at the upper boundary of this unit.

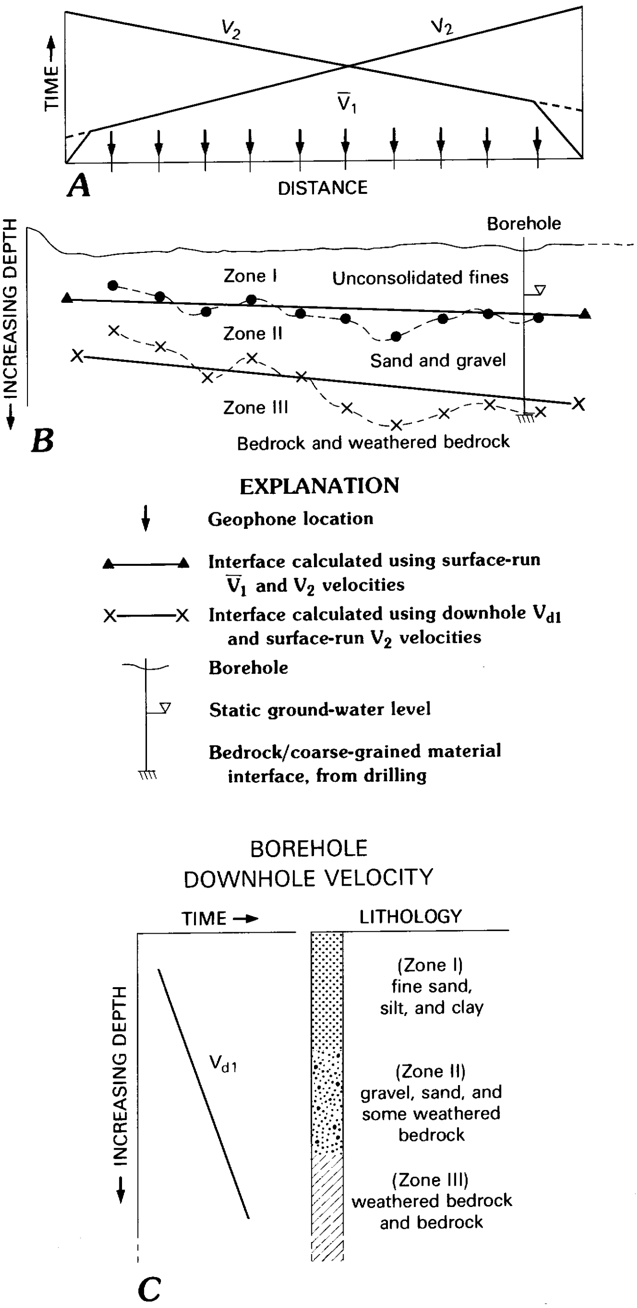


Figure 13. A model of lithologic layering used in interpreting seismic and borehole data. *A*, Surface-run spread, $\overline{V}_1$ and V_2. *B*, Boundary interfaces computed using $\overline{V}_1$–V_2 and V_{d1}–V_2. *C*. Downhole compressional-wave velocity, V_{d1}.

Thickness and Configuration of Valley Fill

Little Goose Creek Valley

Seven seismic-refraction survey lines (fig. 1, valley seismic spread 1) and the lithology and downhole velocities from four boreholes were used in the construction of the seismic and geologic cross section across Little Goose Creek valley (pl. 1, fig. *A*). Bedrock composed of fine-grained sandstone and siltstone crops out on the west side of the valley, but a fairly thick accumulation of colluvium is found on the east side. The average thickness of the unconsolidated material (Zones I and II combined) beneath seismic lines 1–5 is about 13 ft. Interpretation of seismic lines 6 and 7 will be discussed separately. Both the thinnest (5 ft) and thickest (29 ft) sequences of fill are located near the center of the valley (pl. 1, fig. *A*).

The unconsolidated material has been subdivided into Zone I (fine grained) and Zone II (coarse grained) layers by using the technique described in the seismic interpretation model. Zone I material beneath lines 1–5 (west and central portions of Little Goose Creek valley) ranges in thickness from 2.5 to 8 ft, with the average thickness being about 4 ft. The sand and gravel of Zone II beneath seismic lines 1–5, ranges in thickness from 5 to 29 ft, with the average thickness being 9 ft.

Some of the seismic cross sections at the sides of the valleys, such as those (lines 6 and 7) at the east side of Little Goose Creek valley (pl. 1, fig. *A*), show interfaces that slope away from the valley centers instead of toward them, as might be expected. The reason for these apparently reversed slopes is unclear. Those interfaces, which slope away from valley centers, always occur at the side of a valley where the topographic elevation increases and the unconsolidated (Zones I and II) low-velocity layer thickens. Boreholes JC–1 and JC–2 (fig. 11) confirm that the Zone I and Zone II materials do indeed thicken on the east side of the valley, mainly because of the accumulation of slope-wash debris and talus. Both the method-of-differences interpretations and time-intercept calculations produce an interface which slopes away from the valley center. A possible explanation for this trend as exemplified by the computed configuation of line 7, is that a relatively flat lying interface beneath an upward-sloping topographic surface would appear as an "updip" interface to refracted V_2 waves, which are traveling west toward the valley center. In the case of line 7, the configuration also could indicate the presence of an exposed gravel levee along the valley margin.

Borehole data from holes JC–1 and JC–2 indicate a decrease in grain size, from gravel in hole JC–1 to predominantly coarse sand in JC–2 at the eastern valley margin. These logs also indicate that there is still a good correlation between thicknesses that are measured from drilling and those predicted by the model method of interpretation for seismic lines 6 and 7. The range of Zone I thickness for the eastern side of Little Goose Creek valley is 12–26 ft, with an average thickness of 19 ft. Zone II ranges in thickness from 10 to 24 ft, with an average thickness of 17.3 ft.

Big Goose Creek Valley

Three seismic-refraction lines and the lithology and downhole velocities from three boreholes were used to compute the subsurface configurations of the east-trending Big Goose Creek valley (fig. 1, valley seismic spread 2). Figure *B* of plate 1 depicts the geologic and seismic cross section for this valley. The southern valley wall is a near-vertical cliff of sedimentary bedrock. The northern valley side is a moderate slope with a covering of colluvial slope wash. Some outcrops of bedrock can be found along the north side of the valley.

The fine-grained (Zone I) layer is fairly uniform across the valley and ranges in thickness from 3 ft near the stream to 11 ft near the center of the valley with an average thickness of 8 ft.

As observed from the seismic data, the coarse-grained (Zone II)-bedrock (Zone III) contact in this valley is quite irregular. Consequently, the thickness of the Zone II deposit is difficult to determine, particularly in the vicinity of SPP–1. Based on the central portion of the valley, the coarse-grained (Zone II) deposits range in thickness from 14 to 29 ft, with an average thickness of 25.4 ft.

The seismically calculated depth to bedrock (Zone III) beneath the south end of line 3 has a relatively poor correlation with the depth determined by borehole SPP–1. Borehole SPP–1 penetrated 3 ft of fine-grained (Zone I) material and 3 ft of coarse-grained (Zone II) material before encountering bedrock at a depth slightly below stream level. Downhole V_{d1} velocity measurements were not taken on this hole, and the short (165 ft) seismic line did not record a refraction of the compressional waves corresponding to the thin layer of unconsolidated material at the south end of the seismic line. Consequently, the Zone I–Zone II interface was calculated using the surface-run $\overline{V}_1$ velocity determined from the short lines associated with seismic line 2, and the Zone II–Zone III interface, below seismic line 3, was calculated using the V_{d1} from borehole SPP–2. Although there is considerable disagreement between the depth to bedrock determined by drilling versus seismic measurements, notice that the bedrock outcrops have relatively steep topographic slopes and that this trend may continue where the slopes are buried. We may, therefore, surmise that the first two data points on the south simply do not detect the steeply sloping buried interface or that V_{d1} is incorrect.

Borehole SPP–2 lies between seismic lines 2 and 3, and a projection of the general trend of the method-of-differences interpretations (dashed lines) would indicate that the seismically determined interfaces are relatively close to those determined by drilling. The Zone II–Zone III seismic interface beneath line 1 is 3 ft below the contact depth picked from drilling information.

Prairie Dog Creek Valley

Three seismic-refraction lines and the lithology and downhole velocity from one borehole were used in compiling the subsurface configuration of the northeast-trending Prairie Dog Creek valley. Of the four river valleys surveyed, the Prairie Dog Creek valley (fig. 1, valley seismic spread 3) is the only one that does not have a present-day drainage basin originating in the Bighorn Mountains. Figure *C* of plate 1 shows a profile of the surface topography and the subsurface interface configurations derived from the seismic-refraction and downhole-velocity data. Fine-grained sandstone and siltstone crop out adjacent to the canal on the west side of the valley. Relatively thick colluvium and slope-wash material have accumulated along the east side of the valley.

As in the Little Goose Creek valley cross section, the calculated Zone II–Zone III seismic interface on the east slopes away from the valley center rather than toward it. The probable explanations for the anomalous slope direction presented for Little Goose Creek valley apply to this valley as well. Thicknesses of Zones I and II beneath the easternmost survey, therefore, are not used in the thickness-averaging analysis.

The disagreement between the depth to bedrock determined by drilling versus seismic interpretation seen at the west end of line 1 is similar to that found at the south side of Big Goose valley. We also surmise that a steeply sloping buried bedrock surface exists on the west side of Prairie Dog Creek valley.

The range of thickness of Zone I, fine-grained silt and clay, for the west and central portions of the valley is 9–18 ft with an average thickness of 14 ft. Zone II, coarse-grained sand and gravel, ranges in thickness from 14 to 24 ft, with an average thickness of 19.3 ft. A rancher's well, located about 300 ft northeast of borehole PDC–1, was reported to have been drilled through 75 ft of soil, sand, and gravel before "blue clay" was encountered.

Soldier Creek Valley

The data from two seismic-refraction lines, along with lithologic and downhole seismic information from one borehole, were used to delineate the subsurface interface configurations across east-trending Soldier Creek (fig. 1, valley seismic spread 4). Soldier Creek parallels Big Goose Creek and they have a common pediment divide, but Soldier Creek valley is not as wide and its base level is higher.

Plate 1, figure *D*, shows the topographic cross section and the subsurface interfaces that were calculated from borehole and seismic data. Bedrock crops out on both sides of the valley. The surface-run $\overline{V}_1$ is approximately the same as V_{d1}, which indicates that the sand and gravel of Zone II may be present in limited quantities. The borehole lithologic log shows that the unconsolidated material is predominantly clay, silt, and fine to medium sand. The upper 8 ft of the hole is made up of silty clay, and the log indicates that there is about 2 ft of sand and gravel above the blue clay of weathered bedrock. The absence of sand and gravel of Zone II across the valley is also supported by the interpreted seismic data of plate 1, figure *D*. Average thickness of the Zone I material along the seismic lines is about 17 ft with the thickest section being on the north side of the valley and under the present-day stream channel near the center of the valley.

Goose Creek Valley

The Goose Creek survey is 3.3 mi north of Sheridan, Wyo., and below the confluence of Big Goose and Little Goose Creeks (fig. 1, valley seismic spread 5). The data from four seismic-refraction lines, along with the lithologic and downhole-velocity information from two boreholes, were used to determine the subsurface boundary configurations across the north-trending Goose Creek valley. Plate 1, figure *E*, shows the computed subsurface configurations. Bedrock consisting of siltstone and sandstone crops out on both sides of the valley. The west side of the valley is gently sloping, and most bedrock is buried beneath colluvial slope wash and talus. The east side of the valley is steeper and has many bedrock exposures. Fine-grained (Zone I) material is fairly uniform in thickness across the valley floor but thickens along the valley margins as a result of colluvium accumulation. Zone I ranges in thickness from 8 to 13 ft, with an average thickness of 11.5 ft. The thickest accumulation of coarse-grained (Zone II) material is under seismic line 2 (pl. 1, fig. *E*) and is about 20 ft. The depth to the bedrock surface calculated by the method-of-differences interpretation is comparable with the data obtained from borehole RR–1 on the west end of line 2, and apparently projects to a reasonable comparison of bedrock depth with RR–2 to the west. The seismic depths at the west end of line 2, however, do not match the adjacent seismic depths on the east end of line 3. The reasons are unclear but may simply be a relatively rapid steepening of 15 ft or so at the junction (which is a bend-in-line) of the two lines.

About 200 ft south of line 3 is an abandoned gravel pit, and the sand and gravel is within a few feet of the ground surface. A stream cut on the west side of Goose Creek, and in line with the seismic survey, exposes 5 ft of sand and gravel above the present stream level under an 8-ft covering of fine-grained (Zone I) material. The interface between the fine- and coarse-grained material in the outcrop is very distinct.

Thickness and Configuration of Pediment Caps

Seismic-refraction surveys, borehole investigations, and grab-sample analysis of the sand and gravel deposits, which cap the pediments, were conducted at the following three pediment sites (fig. 1): (A) Sheridan Municipal Golf Course—located west of the city limits and midway between the Big Goose and Soldier Creek valleys; (B) above Soldier Creek on the Mydland Dairy Farm, which is about 2 mi northwest of Sheridan; and (C) above Little Goose Creek near the Sheridan Municipal Airport. Time-distance graphs and geologic cross-section interpretations for these three pediment sites are presented in plate 1, figure *F*.

Unlike the valley sites, the fine-grained (Zone I) material on the pediments is a very thin, sandy silt layer, generally less than 3 ft thick, which grades into the underlying coarse-grained material of Zone II. Because of the thinness of the Zone I layer and the wider spacing of the seismometers on the 330-ft seismic lines on the pediments (the valley surveys used 165 ft surface-run lines to define the $\overline{V}_1$ velocity of the fine-grained, Zone I layer), the Zone I layer is seismically nondeterminable. The $\overline{V}_1$ velocity determined from the one 330-ft surface-run seismic line is, therefore, predominantly representative of the coarse-grained (Zone II) material with but minor influence from the thin, fine-grained (Zone I) material and weathered bedrock. The downhole V_{d1} velocity represents all the unconsolidated, undivided Zone I and II material as in the valley surveys.

Plate 1, figures *F–A*, *F–B*, and *F–C* show the seismic time-distance graphs and calculated interfaces between the undivided fine-grained (Zone I) - coarse-grained (Zone II) layers and the bedrock (Zone III) for each site, using the seismic interpretation model that was employed for the valley surveys.

Sheridan Municipal Golf Course Pediment

The Sheridan Municipal Golf Course site is located on the drainage divide between Big Goose and Soldier Creeks (fig. 1, dot A). This site is about 360 ft above Big Goose Creek and about 310 ft above Soldier Creek. Two views of the site are shown by the photographs of figures 14 and 15. Figure 14 shows the gentle rolling surface of the sand and gravel cap, and figure 15 shows sand and gravel (Zone II) material exposed in an abandoned gravel pit.

Soldier Creek Pediment

The Soldier Creek pediment site is on the north flank of the divide between Big Goose and Soldier Creeks (fig. 1, dot B). The site is about 120 ft above the Soldier Creek valley investigation site and about 150 ft below the golf course site.

The shot holes at either end of the seismic line and the exploratory borehole (dry) encountered about 3 ft of fine-grained material (Zone I), which is too thin to be seismically detected. The bedrock is composed of slightly weathered silty sandstone.

One 330-ft seismic-refraction line was run southeast-northwest across the gently undulating pediment surface. The coarse-grained (Zone II)-bedrock (Zone III) interface was calculated by using both $\overline{V}_1$ from the surface-run spread as well as the downhole V_{d1} measurement, in conjunction with the surface-run V_2. The two calculated interfaces straddle the Zone II-Zone III interface that was determined by boring.

Sheridan Municipal Airport Pediment

This site is south of the Sheridan Municipal Airport and about 150 ft above Little Goose Creek (fig. 1, dot C). The exploratory borehole and shot holes penetrated only a 1-ft-thick layer of fine-grained (Zone I) surficial material above sand and gravel (Zone II). Below the sand and gravel is a brownish-maroon clay that is transitional with the underlying soft, silty carbonaceous shale of Zone III. Static ground-water level was about 1.5 ft below ground surface. Because the unconsolidated material that overlies the bedrock is relatively thin at the airport site, as it is at all the pediment sites, the surface-run $\overline{V}_1$ segment of the time-distance graph for the airport pediment is relatively short, and consequently, was determined only with difficulty. The coarse-grained (Zone II)-bedrock (Zone III) interface that was calculated using the surface-run $\overline{V}_1$ does not, therefore, correlate well with the interface determined by boring. Calculations using the downhole V_{d1} velocity and the surface-run $\overline{V}_1$ velocity, however, produce an interface that has a relatively good correlation with the depth determined by boring.

GEOTECHNICAL CHARACTERISTICS

Introduction

The quality of a gravel deposit, and therefore, its usefulness as a construction aggregate, is dependent on physical characteristics such as composition, texture, grain-size distribution, porosity, and durability. These characteristics are inherent but may be modified by the environment.

The testing program for aggregates in the Sheridan, Wyo., area was designed to measure the physical characteristics and durability of deposits, and was focused primarily on gravel-sized clasts (those that pass a

Figure 14. Photograph, looking west, of gently rolling pediment and abandoned-gravel-pit surface west of the Sheridan Municipal Golf Course. This surface forms the divide between Big Goose and Soldier Creeks.

3.0-in. sieve but are retained on a 3/16-in. sieve). For this study, durability is defined as an aggregate's ability to resist chemical as well as mechanical breakdown, and is determined by the sodium sulfate soundness and Los Angeles abrasion tests. Other tests that were used to characterize deposits include lithologic pebble·count, grain-size distribution, bulk specific gravity, and water absorption. Once a sample was characterized, it was compared to other samples from a similar geomorphic setting (valley or pediment). Samples that showed anomalous values in either composition or durability, when compared to the calculated "norm", were analyzed to determine what geologic and (or) environmental factors influenced the sample site. Additionally, the relationship of the composition of a sample to its durability, regardless of geomorphic setting, was evaluated.

Field Sampling and Testing Parameters

Twenty-four samples of coarse-grained (Zone II) material were collected from stream valleys and 19 from pediment caps. The location of all stream-valley samples, except for the one Ucross Formation sample (taken from Leopold and Miller's (1954) type section), is shown in figure 16*A*. Test results are summarized in table 1. The location of pediment samples is shown in figure 16*B*, and test results are summarized in table 2. The tables also include location coordinates of the samples to the nearest quarter section.

Stream samples were taken from sand and gravel bars. Samples appear similar to those of the lower Kaycee and Ucross Formations as described by Leopold and Miller (1954) and Ebaugh (1976). The pediment samples were collected from both operating and abandoned aggregate quarries, landslide scarps, and road cuts. The samples were a composite from an entire exposure rather than from a "gravel-rich" section. Elevation of each pediment sample above present-day stream level is included in table 2.

The entire range of gravel grain sizes was not used in all tests. Lithologic counts were done on the following size ranges: 3–1½ in., 1½–1 in., and 1–½ in. In several sample splits, there were less than 10 clasts in the 3–1½ in. size range. Percentages determined for each size

Figure 15. Close-up of gravel bank in abandoned gravel pit, west of the Sheridan Municipal Golf Course. Notebook is 8.5 in. long.

range of a specific sample were added together and an average percentage value representing the range of 3–½ in. was determined. Grain-size distribution tests, which were done to calculate percentages of gravel, sand, and fines, used the following ASTM sieve numbers: 3, 2, 1½, 1, ¾, ½, ⅜, 4, 10, 16, 30, 50, 100, and 200, which represents a range of 3.0–0.003 in. No samples of a diameter greater than 3 in. were collected. Instead, the percentages of the cobbles larger than 3 in. were estimated at the outcrop and recorded in tables 1 and 2. Bulk-specific-gravity (dry) and water-absorption values were determined for the following size ranges: 1½–¾ in., ¾–⅜ in., and ⅜–3/16 in. Sulfate-soundness tests were done on the same grain-size ranges as the bulk-specific-gravity and water-absorption tests, except for six samples (noted in tables 1 and 2), which were tested using a size range of 1½–¾ in. All but two of the Los Angeles abrasion tests were run on the ASTM designated "A" grading grain-size range of 1½–⅜ in. Two abrasion-test samples required "B" grading with a grain-size range of ¾–⅜ in.

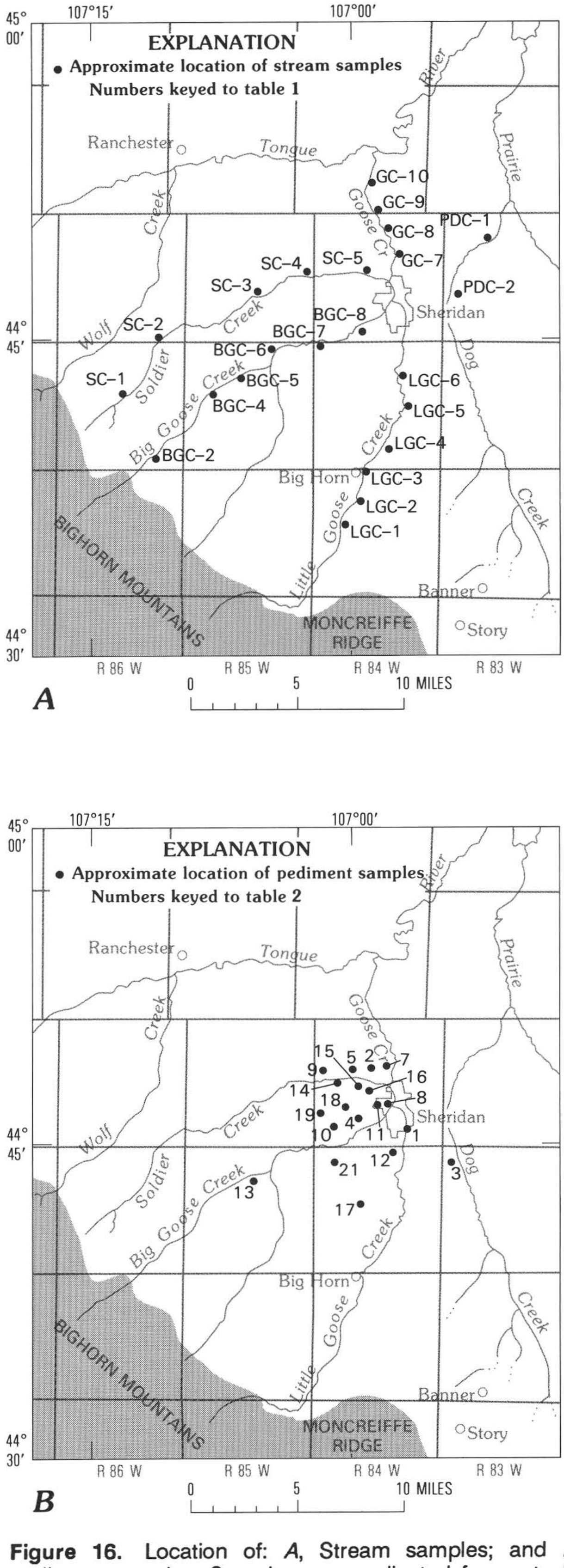


Figure 16. Location of: *A*, Stream samples; and *B*, pediment samples. Samples were collected for geotechnical and physical-properties tests.

Table 1. Geotechnical properties of valley samples

[BGC, Big Goose Creek; LGC, Little Goose Creek; GC, Goose Creek; PDC, Prairie Dog Creek; SC, Soldier Creek; --- indicate no data available]

Sample No./ name	Location				[2]Grain-size wt. distribution (%)			Number of pebbles	Lithologic pebble count (%)			[3]Bulk specific gravity (dry)	[3]Water absorption (wt. gain, %)	[4]Sulfate soundness (wt. loss, %)	[5]Abrasion (wt. loss/ 500 revolutions, %)	Depositional environment, % of clasts greater than 3-in. diameter
		Sec.	T.	R.	Gravel (76.2-4.76 mm)	Sand (4.76-0.075 mm)	Fines (<0.075 mm)		Crystalline	Carbonate	Other sedimentary					
BGC-2	SW1/4NW1/4	35	55 N.	86 W.	69	26	5	166	49	46	5	2.59	2.31	---	24.86	Gravel bar, 55.
BGC-4	NW1/4NW1/4	8	55 N.	85 W.	60	33	7	85	49	43	8	2.51	2.23	---	---	Gravel bar, 30.
BGC-5	NE1/4NE1/4	10	55 N.	85 W.	75	18	7	121	35	60	5	2.59	3.20	21.00	26.96	Gravel bar, 25.
BGC-6	SE1/4NE1/4	2	55 N.	85 W.	58	39	3	30	48	46	6	2.62	2.25	---	26.93	Low-level terrace, 13.
BGC-7	NW1/4NW1/4	6	55 N.	84 W.	63	35	2	76	49	49	2	2.54	3.27(?)	---	---	Gravel bar, 10.
BGC-8	NW1/4SW1/4	33	56 N.	84 W.	60	36	4	90	48	48	4	2.63	1.34	18.01	---	Bedrock exposed, 20.
LGC-1	SW1/4SW1/4	9	54 N.	84 W.	59	39	2	120	54	43	3	2.60	2.44	---	23.56	Low-level terrace, 55.
LGC-2	SE1/4NW1/4	4	54 N.	84 W.	53	45	2	77	52	44	4	2.62	1.05	---	---	Gravel bar, 45.
LGC-3	NW1/4NW1/4	34	55 N.	84 W.	74	25	1	81	51	39	10	2.55	2.15	---	25.44	Gravel bar, 55.
LGC-4	NW1/4NW1/4	23	55 N.	84 W.	60	37	3	271	54	40	6	2.60	2.19	---	---	Gravel bar, 35.
LGC-5	NW1/4NE1/4	15	55 N.	84 W.	66	31	3	185	42	51	7	2.64	1.44	---	---	Low-level terrace, 25.
LGC-6	NE1/4NE1/4	10	55 N.	84 W.	74	26	0	114	39	55	6	2.61	1.71	---	27.24	Stream cut, 25.
GC-7	SE1/4SE1/4	10	56 N.	84 W.	69	22	9	13	46	46	8	2.53	3.99	131.67	33.65	Stream cut, 25.
GC-8	NW1/4SE1/4	3	56 N.	84 W.	62	35	3	116	52	37	11	---	---	---	---	Gravel bar, 15.
GC-9	SW1/4SE1/4	34	57 N.	84 W.	57	37	6	60	43	50	7	2.55	2.16	---	24.04	Stream cut, 15.
GC-10	NE1/4SE1/4	28	57 N.	84 W.	58	36	6	230	52	43	5	2.57	2.18	11.20	27.33	Low-level terrace, 15.
SC-1	NE1/4SW1/4	15	55 N.	86 W.	87	9	4	109	2	88	10	2.61	1.55	---	---	Dry stream channel, 60.
SC-2	SE1/4SE1/4	2	55 N.	86 W.	74	21	5	45	0	100	0	-----	---	---	---	3 ft below pediment level, 20.
SC-3	SE1/4SW1/4	22	56 N.	85 W.	63	24	13	180	16	66	18	2.57	3.78	19.60	22.56	Gravel/sand bar, 5.
SC-4	SW1/4SE1/4	13	56 N.	85 W.	51	40	9	31	6	84	10	-----	---	---	---	Stream cut, 5.
SC-5	SE1/4NW1/4	16	56 N.	84 W.	28	40	32	19	56	36	8	2.39(?)	3.32(?)	20.28	---	Abandoned channel, 1.
PDC-1	SW1/4NE1/4	8	56 N.	83 W.	2	95	3	---	---	---	---	---	---	---	---	Sand bar.
PDC-2	NW1/4NW1/4	30	56 N.	83 W.	12	68	20	---	---	---	---	---	---	---	---	Sand bar.
Ucross, Wyo.	---				56	39	5	190	56	39	5	2.58	2.10	11.69	26.82	Low-level terrace.

[1]Sodium sulfate-soundness test on grain-size range from 1.5 to 0.75 in.

[2]Run according to ASTM method D 422-63.

[3]Run according to ASTM method C 127.

[4]Run according to ASTM method C 88-71a.

[5]Run according to ASTM method C 131-69.

Table 2. Geotechnical properties of pediment samples

[--- indicate no data available]

Sample No.	Location				Elevation above stream level	[3]Grain-size wt. distribution (%)			Number of clasts	Lithologic pebble count (%)			[4]Bulk specific gravity (dry)	[4]Water absorption (wt. gain, %)	[5]Sulfate soundness (wt. loss, %)	[6]Abrasion (wt. loss/500 revolutions, %)	Depositional environment, % of clasts greater than 3-in. diameter
		Sec.	T.	R.		Gravel (76.2-4.76 mm)	Sand (4.76-0.075 mm)	Fines (<0.075 mm)		Crystalline	Carbonate	Other sedimentary					
PT-1	NW1/4NW1/4	35	56 N.	84 W.	20	64	30	6	189	75	21	4	2.62	1.22	---	24.39	First bedrock terrace, Little Goose Creek.
PT-2	SE1/4SE1/4	16	56 N.	84 W.	50	76	22	2	155	56	39	5	2.48	3.46	---	32.50	Abandoned quarry, Big Goose Creek.
PT-3	NE1/4SW1/4	6	56 N.	83 W.	50	84	13	3	106	64	28	8	2.54	2.39	---	---	Hill cap quarry, Prairie Dog Creek.
PT-4	SE1/4NE1/4	32	56 N.	84 W.	60	73	23	4	103	43	51	6	2.57	2.63	---	20.92	Landslide scarp, Big Goose Creek.
PT-5	SW1/4NE1/4	17	56 N.	84 W.	60	85	13	2	90	37	57	6	2.65	2.73	---	19.39	Abandoned quarry, Soldier Creek.
PT-7	SW1/4NW1/4	15	56 N.	84 W.	70	62	28	10	181	55	42	3	2.61	1.68	11.82	23.51	Operating quarry, Goose Creek.
PT-8	NW1/4SE1/4	27	56 N.	84 W.	70	72	25	3	59	78	19	3	2.56	2.46	[1]15.11	29.54	Stream cut, City Park, Big Goose Creek.
PT-9	NW1/4NW1/4	17	56 N.	84 W.	70	66	27	7	152	43	56	1	2.58	3.11	14.30	---	Clast >3-in. diameter = 5.
PT-10	NW1/4NW1/4	33	56 N.	84 W.	90	66	31	3	62	37	60	3	2.52	2.84	---	---	Operating quarry.
PT-11	SE1/4SE1/4	21	56 N.	84 W.	90	78	13	9	147	50	30	20	2.57	2.38	---	---	Landslide scarp in pediment drainage.
PT-12	NE1/4NE1/4	3	55 N.	84 W.	90	72	22	6	105	84	11	5	2.55	1.42	13.23	35.44	Clast >3-in. diameter = 2.
PT-13	SW1/4SW1/4	10	55 N.	85 W.	115	69	25	6	158	50	36	14	2.54	2.80	16.20	29.99	Clast >3-in. diameter = 25.
PT-14	SE1/4NW1/4	20	56 N.	84 W.	120	74	21	5	87	37	59	4	2.61	2.51	12.20	16.96	Near Soldier Creek seismic line.
PT-15	NW1/4SW1/4	20	56 N.	84 W.	120	71	26	3	82	35	62	3	2.55	2.33	---	---	Hill cap quarry, Big Goose Creek.
PT-16	SE1/4NE1/4	21	56 N.	84 W.	140	56	31	13	180	41	54	5	2.55	[2]---	[1]21.57	30.02	Operating quarry.
PT-17	SW1/4NW1/4	21	55 N.	84 W.	160	64	28	8	110	71	28	1	2.60	2.31	[1]15.33	25.78	Gentle surface west of Little Goose Creek.
PT-18	NW1/4SE1/4	29	56 N.	84 W.	170	72	20	8	71	30	69	1	2.61	3.69	6.85	---	Landslide scarp, Hanna Draw.
PT-19	NW1/4SE1/4	30	56 N.	84 W.	360	63	33	4	82	32	51	17	2.57	2.12	[1]10.67	22.84	Golf course pediment seismic site.
PT-21	NW1/4NW1/4	8	55 N.	84 W.	380	64	28	8	55	40	56	4	2.60	1.27	13.80	20.59	Prospect pits, upper pediment surface.

[1]Sodium sulfate-soundness tests on grain-size range from 1.5 to 0.75 in.
[2]Insufficient data to determine representative water-absorption value.
[3]Run according to ASTM method D 422-63.
[4]Run according to ASTM method C 127.
[5]Run according to ASTM method C 88-71a.
[6]Run according to ASTM method C 131-69.

Test results of the Ucross Formation type section sample were not used in the following linear-regression analysis or any of the other analyses, because it came from outside the study area. However, test results for this sample are presented in table 1 and are plotted on the following graphs for comparative purposes.

Test Results and Analyses of Geotechnical Properties

Lithologic Count

Lithologic pebble counts were done on samples to determine compositional percentages of the following lithologic groups: (1) Crystalline rocks (undifferentiated igneous and metamorphic), (2) carbonate rocks (limestone and dolomite), and (3) other sedimentary rocks. Lithologic pebble-count data are reported as an average percentage value for the grain-size range of 3–½ in.

The crystalline group of clasts is composed mainly of Precambrian age rocks of felsic composition that range in texture from gneissic to granitic. Biotite is common in some clasts and plays an important role in the durability of the crystalline rock group. Foliated metamorphics and diabase dike rocks make up the majority of the other lithologies found in the crystalline group.

The carbonate group is composed of limestone and dolomite clasts, mainly from the Bighorn Dolomite and Madison Limestone, although some carbonate material is also derived from other rocks of Paleozoic and Mesozoic age. In general, the carbonate clasts are tabular with subrounded edges and appear to be relatively unweathered.

The third lithologic group is composed of a variety of noncalcareous sedimentary rocks that usually compose less than 10 percent of the total sample. Most of the clasts in this group are sandstone and quartzite pebbles and irregular-shaped concretions of chert, flint, limonite, and clinker.

Valley Deposits

We generally assume that the lithologic composition of a gravel sample will depend on three principal factors: (1) The distance of the sample site from the source area of a specific lithology (for this study, crystalline rocks from the mountain core and carbonate and other sedimentary rocks from the uplifted flanking sediments), (2) the quantity of material supplied from each source area, and (3) the durability of each lithology during transport. All valley samples (fig. 16A) were selected from localities plainward of the crystalline, carbonate, and other sedimentary source areas for Little Goose, Big Goose, and Goose Creeks. Table 1 (valley samples) lists the percentages of the various lithologic groups found at each site. Percentage ranges and averages for each lithologic group for the combined valley deposits are as follows:

Lithologic group	Range (percent)	Average (percent)
Crystalline	35–56	48.2
Carbonate	36–60	45.7
Other sedimentary	2–11	6.1

The percentage ranges and averages do not include the high-carbonate-group percentages of samples SC–1 to SC–4 (table 2) from Soldier Creek, because these samples, which are from a single source area, are a special case that is discussed later. Based on the above table, it appears that the crystalline and carbonate groups dominate, and that the valley gravels are composed roughly of equal amounts of each group. The mixing of these two lithologic groups apparently occurs quickly after the stream has passed through both source areas so that the transport distance within the study area is of insufficient length to segregate a particular lithology based on durability, size, and shape.

A sample of Leopold and Miller's (1954) Ucross Formation was taken near its type locality on Clear Creek, about 23 mi from the mountain front, for comparison with samples from within the study area. Clear Creek has a geomorphic setting and aggregate source areas very similar to Little Goose Creek, Big Goose Creek, and their composite stream, Goose Creek, but the transport distance is nearly twice that of an average sample within the study area. The lithologic-group percentages determined for the Ucross Formation sample were as follows: crystalline (56), carbonate (39), and other sedimentary (5). All percentages that were determined for this sample fall within the range determined for the valley samples that were collected within the study area.

Soldier Creek heads within Paleozoic and Mesozoic carbonate rocks. The high percentages of the carbonate group (66–100) in samples SC–1 through SC–4 reflect the overwhelming influence of a single lithologic-type source area. Sample SC–5, from near the junction of Soldier Creek with Goose Creek, however, shows a lithologic group mixture similar to samples of the areas of Little Goose, Big Goose, and Goose Creeks. We suspect that the source area for the crystalline-group clasts found in sample SC–5 is from the higher pediment surfaces that border both sides of the valley. As the pediment slopes erode and retreat, the gravel-cap material is spilled downslope and is eventually incorporated into the stream-bed load. Lithologic compositions of some of the pediment samples in the surrounding area are also similar to that of sample SC–5. Not only is it evident that at least part of a valley's gravel deposit is derived from the reworking of material originally deposited on higher pediment surfaces, it is also fairly certain that this reworking of gravel-cap material occurs repeatedly during the development of each successively lower pediment (stream floor) surface. The percentage of valley gravel that is either reworked or "freshly" derived from the lithologic source areas is not known.

Present-day Prairie Dog Creek drains an area occupied by only fine-grained Tertiary sedimentary rocks, therefore, very little gravel-size material is found in its upper surficial deposits. The small amount of sand and gravel that is found in the bed and on flanking terraces is probably derived from the erosion of the small pediment remnants to the west of the stream.

Pediment Deposits

The results of lithologic pebble counts on samples that were taken from 19 bedrock terrace and pediment sites (fig. 16*B*) are presented in table 2. Combined percentage ranges and averages for all sites for each group are displayed below.

Lithologic group	Range (percent)	Average (percent)
Crystalline	30–84	50.4
Carbonate	11–69	43.6
Other sedimentary	1–20	6.0

Although the pediment samples have wider ranges for lithologic groups than do valley samples from Little Goose, Big Goose, and Goose Creeks, the average percentage for each lithologic group is not appreciably different from those calculated for the 17 valley samples. The sample sites are not spread far enough apart geographically to evaluate variation in lithologic composition with either surface elevation or distance from the mountain front.

A rough correlation appears to exist between a higher percentage of crystalline clasts and the first major pediment slope immediately west of Little Goose and Goose Creeks. Among the pediment samples, the highest percentages of crystalline clasts recorded (84, 78, 75, and 71) are from samples PT–12, PT–8, PT–1, and PT–17, respectively (fig. 16*B*), all of which occur at various elevations on the broad and gently sloping pediment just above and west of Little Goose and Goose Creeks. Crystalline clasts in this area appear to have been concentrated by deposition and (or) accumulation through reworking on the gently sloping pediment surface as the stream migrated eastward along the regional dip direction.

Bulk Specific Gravity and Water Absorption

Bulk specific gravity (saturated surface dry) is the ratio of the weight of solids in the aggregate to the weight of an equal volume of distilled water at its maximum density, at 39.2 °F. The water-absorption test measures the maximum amount of water that can enter the pore spaces. Bulk-specific-gravity and water-absorption results, which are reported in tables 1 and 2, represent the grain-size range of 1½–3⁄16 in. and are the computed average values of tests that were run on the three grain-size ranges discussed in the introductory portion of this geotechnical section.

Bulk Specific Gravity

Griffith (1937), in his paper on the physical properties of typical American rocks, listed the following apparent-specific-gravity (specific gravity obtained from a mixture of minerals composing a rock specimen) ranges and averages for granite, limestone, and dolomitic limestone.

Rock	Range (g/cm^3)	Average (g/cm^3)
Granite	2.53–2.67	2.60
Limestone	2.54–2.72	2.67
Dolomitic limestone	1.65–2.73	2.69

The bulk-specific-gravity (saturated surface dry) results that were reported in tables 1 and 2 represent the specific gravity of the material when all permeable surface voids are filled. Bulk-specific-gravity values are normally less than those determined for apparent specific gravity.

Figure 17 is a plot of bulk-specific-gravity values versus frequency of sample occurrence for pediment samples (fig. 17*A*) and valley samples (fig. 17*B*). Ranges and average values for the pediment and valley samples are listed below.

Geomorphic setting	Range (g/cm^3)	Average (g/cm^3)
Pediment	2.48–2.65	2.573
Valley	2.51–2.64	2.584

Not included in the valley-sample averaging is the 2.39-g/cm^3(?) value for sample SC–5. When the 2.48-g/cm^3 value for pediment sample PT–2 is also not included, the average bulk-specific-gravity value of the pediments is 2.578 g/cm^3. If the average values for the

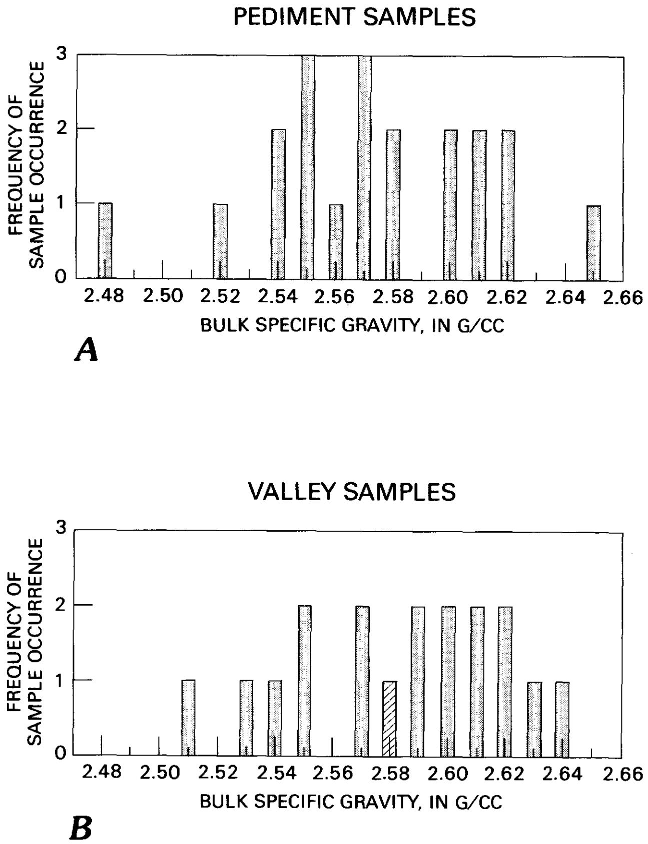


Figure 17. Graphs showing the frequency of sample occurrence of bulk-specific-gravity values for: *A*, Pediment samples; and *B*, Valley samples. Hachured area represents Ucross Formation value.

pediment and valley samples are then rounded to two decimal places, they would be the same. The bulk-specific-gravity value of 2.580 g/cm^3 for the Ucross Formation sample is very close to the valley-sample mean of 2.584 g/cm^3.

Water Absorption

Water-absorption tests were done on the same samples as the bulk-specific-gravity tests. Range and average values for each grain-size fraction tested are listed in table 3. Also listed are the range and average values for a composite of all three grain-size fractions (1½–3⁄16 in.). These average water-absorption values are listed in tables 1 and 2 and are used in later linear-regression correlations.

Valley samples generally show a wider range of water-absorption values but overall have a lower average value than do pediment samples. At least some of the higher water-absorption values for stream samples can be attributed to individual site characteristics. The high degree of weathering associated with site SC–7 and the high percentage of "other sedimentary group" clasts (mainly weakly cemented sandstone) at site SC–3 are good examples of site characteristics, rather than area characteristics, which lead to higher water-absorption values. From table 1, there appears to be no pattern of increasing or decreasing water-absorption values with respect to the distance of a sample site from the source area. Possibly an exception to the above statement is for samples along Soldier Creek; however, there are insufficient data for an objective analysis of this drainage.

The coefficient of correlation (r) that was determined for a linear regression analysis of average percent of water absorption versus elevation of a pediment sample above present-day stream level is a low 0.24. Higher pediment surfaces with older deposits show both high and low water-absorption values. Comparison of water-absorption percentages to the percent of crystalline clasts in a sample showed an extremely random scattering of points and a coefficient of correlation of less than 0.002. This near-zero correlation value reflects the field observation that a sample site may contain coarse-grained, semirounded crystalline clasts with thin weathered rinds and (or) biotite-rich clasts which weather easily and disintegrate when touched. Therefore, with respect to water-absorption data collected within the study area, very local environmental conditions and clast composition tended to overshadow regional weathering effects.

Sulfate Soundness and Los Angeles Abrasion

The overall durability of an aggregate sample, when tested for resistance to freeze-thaw and abrasion degradation, can be related to the lithologic composition and clast shape and texture. West and others (1970), in their work to develop procedures to predict the amount and effect of aggregate degradation on samples of grouped lithologies, made extensive use of petrographic analysis to determine textural and grain-size characteristics of individual clasts. Kazi and Al-Mansour (1980) examined samples of igneous rocks of differing crystal sizes and found that grain size was a major factor influencing a sample's soundness and abrasive behavior, as West and others (1970) had found previously. Kazi and Al-Mansour (1980) also noted a wide range of test results from the average values within each group of fine- to coarse-grained rocks, even though each sample was composed of one lithologic rock type. The deviation of test results within a grain-size group appears to be controlled by factors such as degree of weathering, texture, and clast shape. It is assumed that for samples of the same size, shape, and lithologic composition, with the same total volume of pores, the fine-grained rocks will, in general, be more durable than coarse-grained rocks.

Table 3. Water-absorption and sulfate-soundness comparison

[--- indicate no range of samples; * indicates no correlation]

Sample type	Water absorption (percent gain) Range	Average	Sulfate soundness (percent loss) Range	Average	Coefficient of correlation (r)
			Grain-size range (inches)		
			1 1/2 - 3/4		
Valley	0.40-2.31	1.17[1]	7.02-17.48	11.69[1]	0.72
Pediment	0.56-4.03	1.72	3.80-21.57	11.38	0.32
All samples	0.40-4.03	1.45[1]	3.80-21.57	10.80[1]	0.62
Ucross Formation .	---	1.37	---	9.88	---
			3/4 - 3/8		
Valley	1.06-3.71	2.01[1]	11.13-22.27	17.44[1]	0.41
Pediment	1.40-3.36	2.21	9.71-17.96	13.35	0.0003*
All samples	1.06-3.71	2.11[1]	9.71-22.27	15.40[1]	0.41
Ucross Formation .	---	2.12	---	12.21	---
			3/8 - 3/16		
Valley	1.17-6.22	3.34[1]	14.95-33.60	26.66[1]	0.98
Pediment	1.77-5.97	3.83	11.60-27.34	18.38	0.95
All samples	1.17-6.22	3.58[1]	11.60-33.60	22.52[1]	0.95
Ucross Formation .	---	2.81	---	13.08	---
			1 1/2 - 3/16		
Valley	1.05-3.99[1]	2.36	11.79-20.70[1]	16.19	0.37
Pediment	1.22-3.69	2.51	3.80-21.57	12.40	0.66
All samples	1.05-3.99[1]	2.44	3.80-21.57[1]	14.30	0.66
Ucross Formation .	---	2.10	---	11.69	---

[1]Absorption and sulfate-soundness data for samples GC-7 and Ucross are not included in compilation of table.

The naturally occurring gravel deposits in this area, which are typically the aggregate borrow sites for construction purposes (fill, asphalt, concrete, and so forth), are mixtures of fine-grained, tabular carbonate clasts, medium- to coarse-grained, semirounded crystalline clasts, and a small amount of other clastic and concretionary sedimentary clasts. For this report, gravel sample durability was analyzed by comparing the results of sodium sulfate-soundness and Los Angeles abrasion tests, to the percent of water absorption and the percent of crystalline clasts present within the sample. However, data points on figures 18 and 19 are plotted using dots to represent stream samples and X's to represent pediment samples so that general geomorphic setting trends may be observed.

Sulfate Soundness

The aggregate-soundness test evaluates the durability of an aggregate under an accelerated freeze-thaw weathering environment that was simulated by wetting with sodium sulfate (Na_2SO_4) and then drying. The sulfate-soundness test results are reported in terms of percent of total weight loss.

Listed in table 3 are the ranges and averages for sulfate-soundness tests performed on the same grain-size increments that were used for bulk-specific-gravity and water-absorption tests. Water-absorption (water gain) and sulfate-soundness (decreasing durability) values both show an increase as grain-size range decreases. The table shows that average water-absorption values are higher for pediments than for valleys. For sulfate-soundness values, the trend is reversed with the valleys having the higher average values. Also shown on table 3, are the coefficients of correlation of each grain-size increment for a comparison of water absorption to sulfate soundness. The best correlation between water absorption and sulfate soundness is for the smallest grain-size range. Figure 18 is the graph of average water-absorption versus average sulfate-soundness values for a grain-size range of 1½–3/16 in. The correlation coefficient for all samples (6 valley and 10 pediment) tested is a fairly high 0.58. Linear regression analysis of the percent of coarse-grained crystalline clasts versus percent weight loss from a five-cycle sulfate-soundness test showed a very poor correlation of 0.07.

Los Angeles Abrasion

Aggregate abrasion, measured by means of the Los Angeles abrasion test on the same grain-size ranges as those used for sodium sulfate-soundness testing, determines a sample's relative resistance to mechanical breakdown. After 500 revolutions of the testing apparatus, the sample is screened through a No. 12 sieve and results are reported in terms of percent of sample weight loss.

Figure 19 is a graph comparing the percent of crystalline clasts present to the percent of weight loss for 24 samples (11 valley and 13 pediment). Fourteen of the 24 test samples were composed of material which had previously been subjected to sulfate-soundness testing. Data points for these 14 samples, dots for valleys and X's for pediments, are circled. The remaining 10 samples were composed of "natural," untested material. The dashed linear- regression line, which represents only the samples that had previously undergone sodium sulfate-soundness testing, has a fairly high coefficient of correlation of 0.57. The solid linear-regression line, which represents the "natural," untested samples, has a lower coefficient of correlation of 0.30. A comparison of weight loss during Los Angeles abrasion testing (for samples not previously subjected to sulfate-soundness testing) versus percent of water-absorption showed a low coefficient of correlation of 0.22.

Hartley (1974) reported a good correlation between increasing abrasion (decreasing durability) with increasing porosity. Generally, this increase in porosity varies with chemical decomposition, particularly if there is a high degree of surface alteration (weathering), because cements and intergranular bonds are destroyed and there is an overall increase in effective surface area. The steeper slope of the dashed linear-regression line (representing samples subjected to sodium sulfate-soundness testing before abrasion testing) shows a fairly high correlation of increasing abrasion loss with increasing percentages of crystalline clasts present. We believe that the original "porous" nature of the crystalline clasts and their differing degrees of weathered surface rinds make these clasts susceptable to increased weakening as a result of the freeze-thaw weathering effects of the sodium sulfate-soundness testing. This increased weakening then leads to increased abrasion losses. However, a low correlation exists overall between

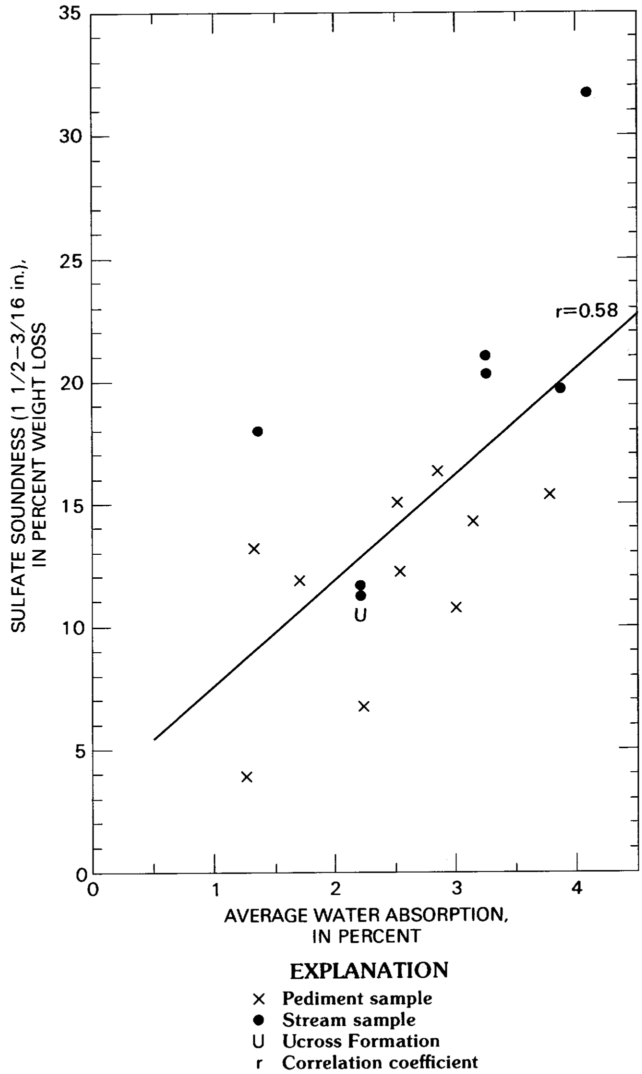


Figure 18. Graph showing weight loss during a five-cycle sodium sulfate-soundness test of samples composed of a mixture of predominantly crystalline and carbonate clasts (small percentage of other sedimentary-type clasts included) as a function of the percentage of average water absorption.

the percentage of water absorption and the percentage of crystalline clasts. A possible explanation for this is that one or two large weathered crystalline clasts that were weakened by sulfate-soundness testing might totally disintegrate during abrasion tests, which would then tend to obscure the more competent nature of the majority of the crystalline clasts in the sample.

Where samples have not been previously subjected to additional weakening by sodium sulfate-soundness tests (as is indicated by the solid regression line of fig. 19), clast shape appears to be a more important factor than lithology in determining a sample-abrasion loss. The thinner, more tabular shape of the carbonate clasts is more susceptable to splintering and breakage during testing than the smoother, semirounded shape of the crystalline clasts.

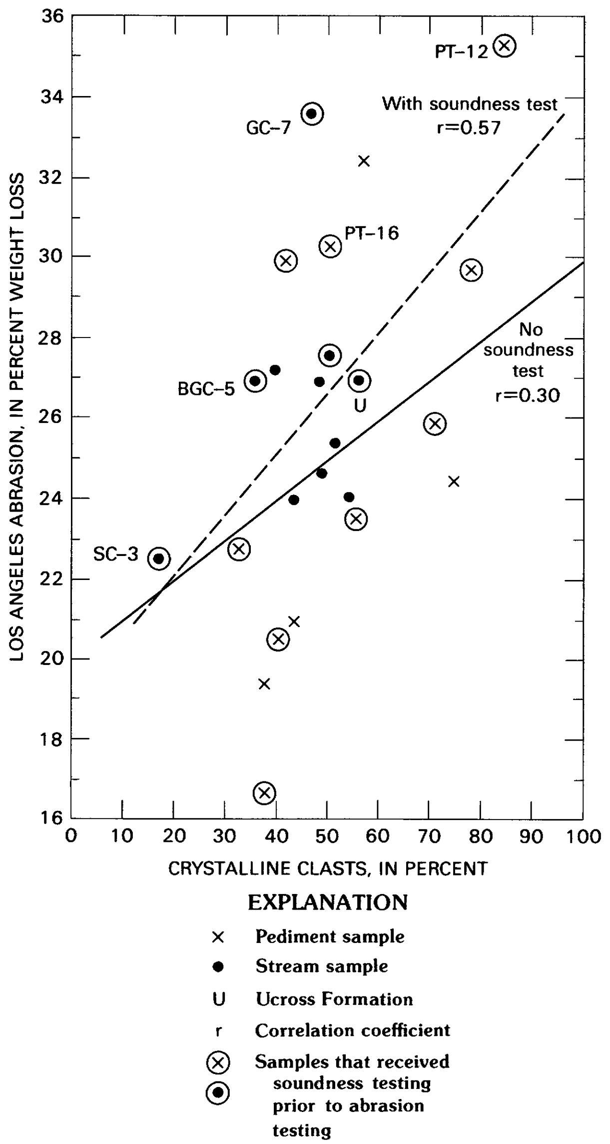


Figure 19. Graph showing weight loss during a 500-revolution Los Angeles abrasion test of samples composed of a mixture of predominantly crystalline and carbonate clasts (small percentage of other sedimentary-type clasts included) as a function of the percentage of crystalline clasts.

SUMMARY

The geotechnical results from lithologic count, bulk-specific-gravity tests, and field observations indicate that a similarity of composition and physical characteristics exists among valley samples with similar source areas and between valley samples and lower-pediment-surface samples. Additionally, very little difference was found among all geotechnical test results on valley and pediment samples and the sample of the Ucross Formation, which was taken from its type locality southeast of the study area. Weathering of deposits, predominantly reflected in the breakdown of biotite-rich granitic clasts, appears to be random and does not correlate well with either the distance of a deposit along a stream course or the elevation of the sample above the present-day stream.

Sulfate-soundness loss correlates fairly well with percentage of water absorption and shows a very low correlation with percentage of crystalline clasts present. The fair correlation of water-absorption percentage versus sulfate-soundness loss is attributed to the fact that water absorption is a good measure of a sample's overall porosity, regardless of lithologic composition. The greater a sample's porosity, the more susceptible that sample is to particle loss that results from the freeze-thaw weathering effects of sulfate-soundness testing. Percentage of crystalline clasts present showed a very low correlation with sulfate-soundness loss because of the wide range of surface-rind weathering found among individual clasts at any one site. The degree to which a crystalline clast weathered appears to be primarily related to the percentage of biotite found within that clast.

For Los Angeles abrasion loss, it was found that samples previously subjected to sulfate-soundness testing showed a fairly high correlation with percentage of crystalline clasts. We believe that the original "porous" nature of the crystalline clasts and their differing degrees of weathered surface rinds make these clasts susceptible to increased weakening as a result of the mechanical weathering effects that result from the simulated freeze-thaw action of the sulfate-soundness test. This increased weakening of crystalline clast surfaces then leads to increased abrasion loss. On the other hand, where samples have not been previously subjected to additional weakening by sulfate-soundness tests (as is indicated by the solid regression line of fig. 19), clast shape may be a more important factor than lithology in determining a sample's abrasion loss. The thinner, more tabular shape of the carbonate clasts is more susceptible to splintering and breakage during testing than the smoother, semi-rounded shape of the crystalline clasts.

An empirical seismic-interpretation model, keyed to specific geologic material zones, was developed to subdivide the unconsolidated valley fill and pediment capping deposits. The validity of this method of analysis for the valley surveys is supported by the high correlation coefficients determined when the depths to an interface (either the fine-grained/coarse-grained boundary or the coarse-grained/bedrock boundary) that were computed seismically by the method-of-differences interpretations are compared to the depths that were determined by boring. Even in areas where boreholes did not intersect computed boundary interfaces, projected trends of nearby interfaces indicate a relatively high correlation.

Using the interfaces that were calculated by the method-of-differences interpretations, the ratio of the thickness of fine-grained (Zone I: fine sand, silt, and clay) to coarse-grained (Zone II: sand, gravel, and some weathered bedrock) material was computed, over about 200-ft spacings, for each valley except Soldier Creek. Listed below are the range and average of these Zone I to Zone II ratios:

Ratio of Zone I thickness to Zone II thickness		
Creek	Range	Average
Goose	0.67–1.63	1.18
Prairie Dog	0.83–4.0	1.81
Little Goose	0.78–5.0	2.25
Big Goose	2.25–4.83	2.93

Based on a single seismic cross section, Big Goose Creek valley appears to have the best ratio of sand and gravel to overlying fine-grained material. However, Big Goose Creek valley is fairly narrow in comparison to the Little Goose Creek and Goose Creek valleys. Sizeable amounts of sand and gravel fill in deep bedrock channels are indicated for all valleys. In addition, sand and gravel deposits in Little Goose Creek and Goose Creek valleys, although thinner, are more accessible due to thinner overburden. The deposits in Prairie Dog Creek valley are composed predominantly of coarse sand and are covered by thick accumulations of fine-grained material.

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