A Geophysical Study in Grand Teton National Park and Vicinity, Teton County Wyoming

GEOLOGICAL SURVEY PROFESSIONAL PAPER 516-E

A Geophysical Study in Grand Teton National Park and Vicinity, Teton County Wyoming

By JOHN C. BEHRENDT *and* BENTON L. TIBBETTS, U.S. GEOLOGICAL SURVEY, WILLIAM E. BONINI, PRINCETON UNIVERSITY, *and* PETER M. LAVIN, PENNSYLVANIA STATE UNIVERSITY

With sections on

STRATIGRAPHY AND STRUCTURE, *by* J. D. LOVE, U.S. GEOLOGICAL SURVEY *and* PRECAMBRIAN ROCKS, *by* JOHN C. REED, JR., U.S. GEOLOGICAL SURVEY

GEOPHYSICAL FIELD INVESTIGATIONS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 516-E

Seismic refraction, gravity, and aeromagnetic studies provide new data on the structural geology of a famous area

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1968

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, ***Secretary***

GEOLOGICAL SURVEY

William T. Pecora, ***Director***

For sale by the Superintendent of Documents, U.S. Government Printing Office

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By JOHN C. BEHRENDT, BENTON L. TIBBETTS, WILLIAM E. BONINI, and PETER M. LAVIN

ABSTRACT

An integrated geophysical study—comprising gravity, seismic refraction, and aeromagnetic surveys—was made of a 4,600-km^2 area in Grand Teton National Park and vicinity, Wyoming, for the purpose of obtaining a better understanding of the structural relationships in the region. The Teton range is largely comprised of Precambrian crystalline rocks and layered metasedimentary gneiss, but it also includes granitic gneiss, bornblende-plagioclase gneiss, granodiorite, and pegmatite and diabase dikes. Elsewhere, the sedimentary section is thick. The presence of each system except Silurian provides a chronological history of most structures. Uplift of the Teton-Gros Ventre area began in the Late Cretaceous; most of the uplift occurred after middle Eocene time. Additional uplift of the Teton Range and downfaulting of Jackson Hole began in the late Pliocene and continues to the present.

Bouguer anomalies range from −185 mgal over Precambrian rocks of the Teton Range to −240 mgal over low-density Tertiary and Cretaceous sedimentary rocks of Jackson Hole. The Teton fault (at the west edge of Jackson Hole), as shown by steep gravity gradients and seismic-refraction data, trends north-northeast away from the front of the Teton Range in the area of Jackson Lake. The Teton fault either is shallowly inclined in the Jenny Lake area, or it consists of a series of fault steps in the fault zone; it is approximately vertical in the Arizona Creek area.

Seismic-refraction data can be fitted well by a three-layer gravity model with velocities of 2.45 km per sec for the Tertiary and Cretaceous rocks above the Cloverly Formation, 3.9 km per sec for the lower Mesozoic rocks, and 6.1 km per sec for the Paleozoic (limestone and dolomite) and Precambrian rocks. Gravity models computed along two seismic profiles are in good agreement ($\sigma = \pm$ 2 mgal) if density contrasts with the assumed 2.67 g per cm^3 Paleozoic and Precambrian rocks are assumed to be −0.35 and −0.10 g per cm^3 for the 2.45 and 3.9 km per sec velocity layers, respectively. The Teton Range has a maximum vertical uplift of about 7 km, as inferred from the maximum depth to basement of about 5 km.

Aeromagnetic data show a 400γ positive anomaly in the Gros Ventre Range, which trends out of the surveyed area at the east edge. Exposed Precambrian rocks contain concentrations of magnetite and hematite. A prominent anomaly of about 100γ is associated with the Gros Ventre Range, and 100γ anomalies are associated with the layered gneiss of the Teton Range. On this basis the unmapped Precambrian rocks of the Gross Ventre Range are interpreted as layered gneiss. The sources of the magnetic anomalies, as indicated by depth determination, are at the surface of the Precambrian rocks. A model fitted to a profile across the Gros Ventre Range gives a depth to the Precambrian surface and a susceptibility of 0.0004 emu (electromagnetic units) for the source, which is consistent with modal analyses of the layered gneisses. A residual magnetic map shows that the granitic rocks and layered gneiss probably continue beneath the floor of Jackson Hole east of the Teton fault. The location of aeromagnetic anomalies is consistent with the interpretation that the Teton fault diverges from the front of the Teton Range.

INTRODUCTION

The area covered in this report consists of 4,600 km^2 (square kilometers), in Teton County, Wyo. (fig. 1), between lat 43°15′ to 44°08′ N. and long 110°23′ to 111°00′ W., and includes Grand Teton National Park and parts of Teton National Forest. The Teton Range forms the west border of Jackson Hole, a downfaulted basin containing a thick section of sedimentary rock. The Gros Ventre Range trends into the area from the southeast. The Mount Leidy and Pinyon Peak highlands form the east and northeast borders of Jackson Hole.

Geologic work by Love (1956a) suggested a great thickness of Tertiary and Cretaceous sedimentary rocks in Jackson Hole. The Teton fault of post-middle Pliocene age generally has been considered to be a steeply dipping normal fault (Love, 1956b). Geophysical work was undertaken to obtain as much information as possible on the structural relationships and the subsurface geology of the region.

Present investigation and acknowledgments.—The text, except the sections by Love and Reed, was prepared by Behrendt. The 1964 seismic data were interpreted by Behrendt and Tibbetts. The original gravity survey was made in 1955 by Bonini and Lavin, of Princeton University; their work was partly supported by the National Science Foundation.

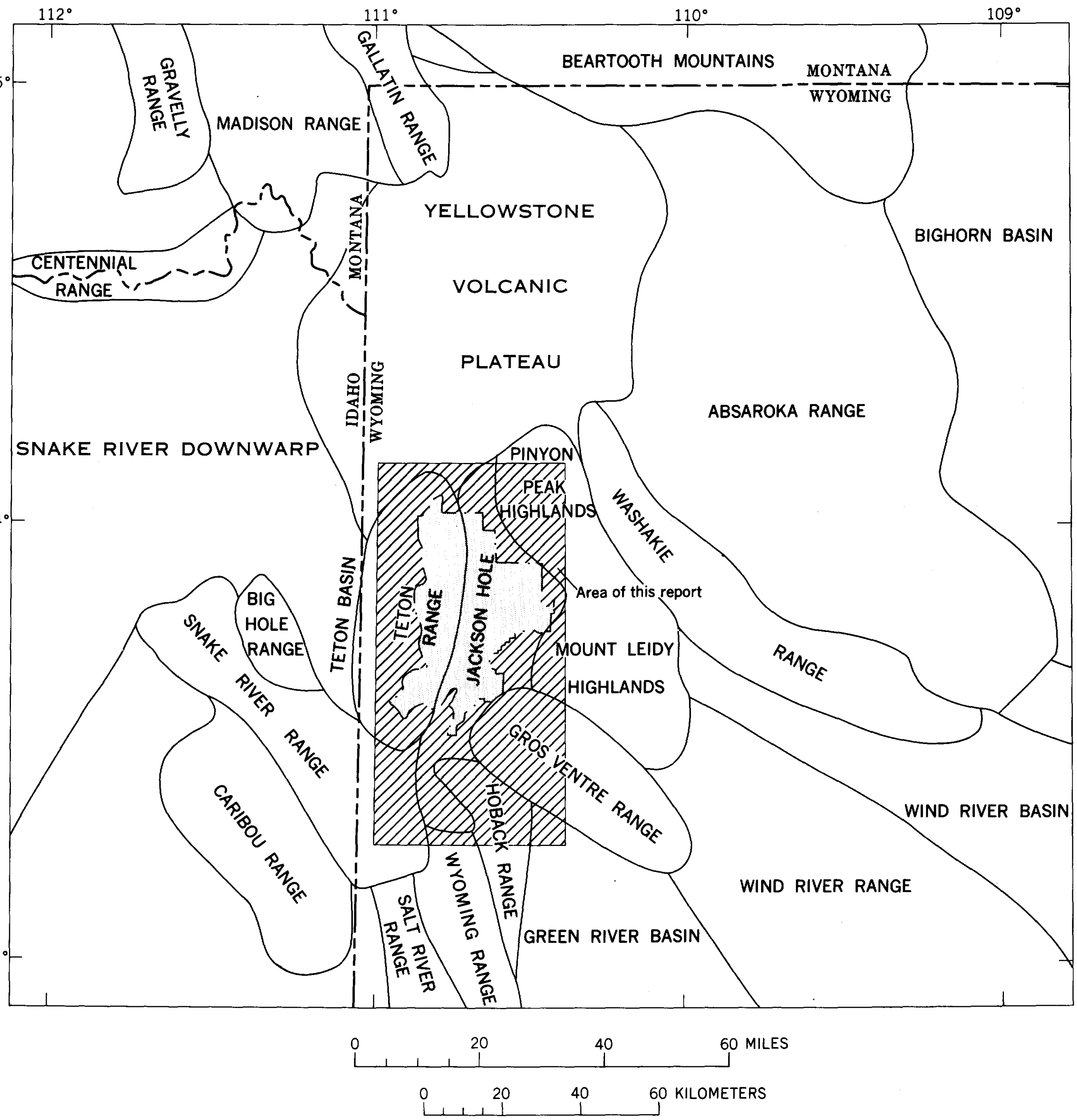

FIGURE 1.—Index map of northwestern Wyoming and adjacent parts of Idaho and Montana showing area of this report (striped). Shaded area is Grand Teton National Park.

The seismic measurements were made with the assistance of L. C. Pakiser, R. E. Warrick, W. H. Jackson, G. I. Evenden, and D. B. Hoover, all members of the U.S. Geological Survey. We appreciate the support of the National Park Service personnel at Grand Teton National Park, particularly H. J. Estey, W. E. Dilley, R. A. Mebane, and G. F. Wagner.

STRATIGRAPHY AND STRUCTURE—A SUMMARY

By J. D. Love

The area discussed in this report is of unusually great interest because (1) Jackson Hole was downfaulted in late Cenozoic time, thereby preserving a part of the geologic record that has been lost elsewhere in Wyoming; (2) it includes mountain ranges of different ages and origins; (3) its crustal disturbances are undoubtedly related to volcanism in the adjoining Yellowstone National Park area; (4) the thick stratigraphic section includes all systems except the Silurian; (5) strata of all Cenozoic epochs are thick, fossiliferous, and well exposed; and (6) the completeness of the stratigraphic record enables us to demonstrate the chronologic development of most structures.

The relation of Jackson Hole to upfolded and faulted mountains and to downwarps is shown in figure 1; the distribution of major rock units and significant structural features is shown on plate 1. The recognized sedimentary and volcanic rock units and their relation to tectonic events are shown in table 1. Details of stratigraphy, structure, petrography, geologic history, and paleontology of Jackson Hole and adjacent areas are given in reports listed in "References Cited."

TABLE 1.—*Summary description of sedimentary and volcanic rocks and of tectonic events in the Grand Teton National Park and vicinity*

Age	Sedimentary rocks		Thickness (meters)	Volcanic rocks	Tectonic events
	Formation	Description			
Recent	Modern stream deposits and alluvial fans.	Quartzite gravel along streams; fans composed of Paleozoic, Mesozoic and Cenozoic rocks, all of which are on east side of Jackson Hole.	0–120		Minor faults break alluvial fans along east base of Teton Range and offset surfaces in National Elk Refuge.
Pleistocene	Pinedale glacial deposits and associated outwash.	Moraines, largely from Precambrian core of Teton Range and quartzite gravel outwash spread out to south.	0–60	White ash from undetermined source. White ash, probably from Yellowstone National Park.	Outwash plains tilted west because of recurrent movement on Teton fault; Flat Creek Valley was downdropped about 60 m. Floor of Jackson Hole tilted west; some faulting may have accompanied tilting.
	Loess	Silt, light-gray, poorly bedded, soft.	3–20	Rhyolite extruded in Pitchstone area of Yellowstone National Park; age uncertain.	Minor faults developed in National Elk Refuge.
	Bull Lake glacial deposits and associated outwash.	Moraines, largely from Precambrian core of Teton Range and from a few areas on the east side of Jackson Hole; associated quartzite outwash gravel, chiefly in southern part of Jackson Hole.	0–120		

TABLE 1.—*Summary description of sedimentary and volcanic rocks and of tectonic events in the Grand Teton National Park and vicinity*—Continued

Age	Sedimentary rocks		Thickness (meters)	Volcanic rocks	Tectonic events
	Formation	Description			
Pleistocene	Oldest glacial deposits.	Remnants of morainal debris composed of many rock types, at high and low elevations in Jackson Hole.	0–60?		
	Upper lake sequence.	Shale, brown-gray; very soft gray sandstone and locally derived conglomerate.	0–150		Jackson Hole sagged; tilting of floor raised the lower lake sequence on the east side 300 m above remnants in central part; extensive faulting occurred near Gros Ventre Buttes in southern Jackson Hole. New lake basin was created in central Jackson Hole and in it the upper lake sequence was deposited.
	Lower lake sequence.	Shale, claystone, siltstone, and sandstone, red, green, gray, and black; lower part deposited in deep water.	0–60	Probably some volcanic activity in adjacent areas contributed pyroclastic debris to sediments. Red and black andesite extruded; 300 m thick in places. Light-gray glassy porphyry bodies intruded. Gray basalt extruded; 150 m thick in places. Pink and gray pumice breccia; 10 m thick.	Southern Jackson Hole sagged and thereby created a lake basin in which the lower lake sequence was deposited. Hoback normal fault developed in southern Jackson Hole; east edge of west block dropped 3,000 m or more. Central part of Jackson Hole tilted west by continued downdropping of valley block along Teton fault.
Pleistocene or Pliocene.	Bivouac Formation.	Conglomerate of Tertiary igneous rocks, quartzite boulders, and granite; purplish-gray rhyolite welded tuff in upper part.	0–300	Purplish-gray rhyolite welded tuff.	

TABLE 1.—*Summary description of sedimentary and volcanic rocks and of tectonic events in the Grand Teton National Park and vicinity*—Continued

Age	Sedimentary rocks		Thickness (meters)	Volcanic rocks	Tectonic events
	Formation	Description			
Pliocene				Basalt flows on east side of Jackson Hole.	Major movement (3,000 m or more) took place along Teton fault, west block up, east block down. The fault cut nearly at right angles across the ancestral Teton-Gros Ventre uplift, and the east block hinged down. Middle Pliocene rocks on southwest side of Snake River Range were overridden by Cambrian limestone.
	Teewinot Formation.	Limestone, tuff, and claystone, with white soft conglomerate at base.	0–1, 800	Rhyolite flows and welded tuff interbedded with pyroclastic rocks in northern part of Jackson Hole.	East-trending normal fault developed across Jackson Hole at north margin of Gros Ventre Buttes and caused formation of Teewinot lake basin.
	Camp Davis Formation.	Conglomerate, red and gray; white tuff, diatomite, limestone, and red and green claystone in lower part.	0–1, 700	Rhyolite tuff, probably derived from Yellowstone National Park area.	Southwest margin of Gros Ventre Range was thrust over some lower Pliocene rocks and others were deposited on thrust blocks. This fault (Cache thrust) extends through Jackson and west-northwest across Teton Pass and on into Idaho. Some movement may have been earlier. Sharp north-trending folds developed at north end of Teton Range.
Miocene	Colter Formation__	Volcanic conglomerate, tuff, and sandstone, white to greenish-brown; contains locally derived basalt and andesite rock fragments.	0–2, 100	Pyroxene andesite and basalt extruded from large vents in northern and eastern parts of Jackson Hole.	Floor of northern part of Jackson Hole sagged several thousand meters. Ancestral Teton-Gros Ventre uplift and area to east raised and partly stripped of Cenozoic rocks.
Oligocene	Wiggins Formation.	Volcanic conglomerate, gray to brown, with white tuff layers.	0–1, 000	Andesite and basalt vents along northeastern margin of Jackson Hole extruded large quantities of agglomerate and ash.	

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TABLE 1.—*Summary description of sedimentary and volcanic rocks and of tectonic events in the Grand Teton National Park and vicinity*—Continued

Age	Sedimentary rocks		Thickness (meters)	Volcanic rocks	Tectonic events
	Formation	Description			
Eocene	Tepee Trail Formation.	Volcanic conglomerate, tuff, and claystone, bright-green to olive-drab.	0–300	Pyroxene andesite and basalt were extruded from vents along east margin of Jackson Hole.	
	Aycross Formation.	Claystone, siltstone, and sandstone, brightly variegated to green and white, soft, bentonitic; quartzite conglomerate lenses.	0–150	Rhyolite and andesite tuff of intermediate composition, probably derived from vents in the Absaroka Range.	Uplift of south-central Jackson Hole caused extensive stripping of Pinyon Conglomerate; 600 m of this debris was redeposited on south side of ancestral Gros Ventre Range.
	Wind River and Indian Meadows Formations.	Claystone, siltstone, and sandstone, brightly variegated; drab coal-bearing zone 30–90 m thick in middle.	0–1, 000	Hornblende andesite tuff present in easternmost sections.	Northwest-trending Tripod Peak fault developed in northeastern part of Jackson Hole; east side was raised and stripped of 2,600 m of strata. Salt River, Wyoming, Hoback, and Snake River Ranges moved northeast along low-angle thrust faults and overrode conglomerates of late Paleocene age.
Paleocene	Sandstone and claystone sequence and Pinyon Conglomerate.	Sandstone and claystone, greenish-gray and brown; underlain by light-brown conglomerate composed of highly rounded quartzite rock fragments. Coal and gray shale at base.	0–1, 200		Ancestral Gros Ventre uplift rose in late Paleocene time and was folded with gentle northeast flank and steep southwest flank. This caused deposition of thick locally derived conglomerates along southwest margin. Targhee uplift northwest of ancestral Teton Range reached maximum size and provided several hundred cu km of quartzite debris to Pinyon Conglomerate in Jackson Hole. Asymmetric northwest-trending folds, with thrust faults on their southwest flanks, extended obliquely northwest from the ancestral Gros Ventre uplift. The Washakie Range rose and was thrust southwestward.

TABLE 1.—*Summary description of sedimentary and volcanic rocks and of tectonic events in the Grand Teton National Park and vicinity*—Continued

Age	Sedimentary rocks		Thickness (meters)	Volcanic rocks	Tectonic events
	Formation	Description			
Cretaceous	Harebell Formation.	Sandstone, olive-drab, silty; drab siltstone and dark-gray shale; thick beds of quartzite conglomerate in upper part; chalky white sandstones in southernmost sections.	0–1, 500		The ancestral Teton-Gros Ventre uplift rose as a broad gentle arch with the Targhee uplift at its northwest end. Another gentle fold marked the first movement of the Wind River Mountains.
	Meeteetse Formation.	Sandstone, gray to chalky white; blue-green to gray biotitic siltstone; thin coal; and green to yellow bentonite.	0–200		
	Mesaverde Formation.	Sandstone, white, massive, soft; thin gray shale; sparse coal.	0–300		
	Lenticular sandstone, shale, and coal sequence.	Sandstone and shale, gray to brown; abundant coal in lower 600 m.	1, 100±		
	Bacon Ridge Sandstone.	Sandstone, light-gray, massive, marine; gray shale; many coal beds.	280–370		
	Cody Shale	Shale, gray, soft; thin glauconitic sandstone; some bentonite; marine.	400–670		
	Frontier Formation.	Sandstone, gray, and black to gray shale; marine; many persistent white bentonite beds in lower part.	300		
	Mowry Shale	Shale, silvery-gray, hard, siliceous; contains many fish scales; thin bentonite beds; marine.	200		
	Thermopolis Shale	Shale, black, soft, fissile; persistent sandstone at top; marine.	50–60		

TABLE 1.—*Summary description of sedimentary and volcanic rocks and of tectonic events in the Grand Teton National Park and vicinity*—Continued

Age	Sedimentary rocks: Formation	Sedimentary rocks: Description	Thickness (meters)	Volcanic rocks	Tectonic events
Cretaceous and Jurassic.	Cloverly and Morrison(?) Formations.	Sandstone, light-gray, sparkly; rusty near top; underlain by variegated soft claystone; basal part is silty dully variegated sandstone and claystone.	200		
Jurassic	Sundance Formation.	Sandstone, green; underlain by soft gray shale and thin highly fossiliferous limestone; marine.	150–200		
	Gypsum Spring Formation.	Gypsum, white; interbedded with red shale and gray dolomite; partly marine.	240–300		
Jurassic(?) and Triassic(?).	Nugget Sandstone.	Sandstone, salmon-red, hard, fine-grained.	0–110		Regional tilting southward caused Nugget Sandstone to be stripped from north half of Jackson Hole.
Triassic	Chugwater Formation.	Siltstone and shale, red, thin-bedded; one thin marine limestone in upper third.	300–500		
	Dinwoody Formation.	Siltstone, brown, hard, thin-bedded; marine.	60–120		
Permian	Phosphoria Formation and stratigraphic equivalents.	Dolomite, gray, cherty; black shale and phosphate beds; gray-brown sandstone; marine.	50–75		
Pennsylvanian	Tensleep Sandstone and Amsden Formation.	Sandstone, light-gray, hard; underlain by red shale; basal part is red sandstone; marine.	200–500		
Mississippian	Madison Limestone.	Limestone, blue-gray, hard, fossiliferous; thin red shale in places near top; marine.	300–370		
Devonian	Darby Formation.	Dolomite, dark-gray to brown, fetid, hard; brown, black, and yellow shale; marine.	60–150		

TABLE 1.—*Summary description of sedimentary and volcanic rocks and of tectonic events in the Grand Teton National Park and vicinity*—Continued

Age	Sedimentary rocks		Thickness (meters)	Volcanic rocks	Tectonic events
	Formation	Description			
Ordovician	Bighorn Dolomite	Dolomite, light-gray, siliceous, very hard; white dense very fine grained dolomite at top; marine.	90–150		
Cambrian	Gallatin Limestone.	Limestone, blue-gray, hard, thin-bedded; marine.	55–90		
	Gros Ventre Formation.	Shale, green, flaky; about 100 m of hard cliff-forming limestone in middle; marine.	180–240		
	Flathead Sandstone.	Sandstone, reddish-brown, very hard, brittle; partly marine.	50–60		
Precambrian					Regional unconformity cuts across all Precambrian rocks.

DOWNWARPS

JACKSON HOLE

Jackson Hole is a complexly folded and faulted downwarp and within it are several structurally deep areas. One is an elongate trough adjacent and parallel to the west margin of Jackson Hole. Within it, at shotpoint 4.1, the top of the Precambrian is about 3 km below sea level (fig. 10), whereas on top of Mount Moran to the west the same horizon is about 4 km above sea level. The present structural configuration of this trough was caused by dropping in late Cenozoic time of the western part of Jackson Hole along the Teton fault and by sagging of the floor in the northeastern and southeastern sections, perhaps under the weight of a thick section of Miocene and Pliocene rocks in addition to the older strata (table 1).

A second deep area, which is also broad, lies between the Whetstone anticline and the Buffalo Fork thrust fault. Here, the top of the Precambrian is estimated to be 3.4 km below sea level. A third deep area, perhaps the deepest of all, is east of the north end of the Bacon Ridge anticline where the Precambrian surface is estimated to be at least 4.5 km below sea level.

GREEN RIVER BASIN

The Green River topographic basin lies southeast of Jackson Hole and is separated from it, but the two structural basins are connected by a narrow gooseneck-shaped enormously deep syncline that has been overridden by both the Hoback and Gros Ventre Ranges (fig. 2). Precambrian rocks at the bottom of this syncline are estimated to be at a depth of more than 9 km (Love and Keefer, 1965).

MOUNTAINS

Bordering Jackson Hole are four types of mountains: (1) a horstlike upfaulted block (Teton Range), (2) intricately folded and faulted mountains of sedimentary rocks underlain by low-angle thrust faults rather than by a Precambrian core (Snake River and Hoback Ranges), (3) folded asymmetric anticlinal uplifts with Precambrian cores and thrust or reverse faults along the steep flanks (Gros Ventre and Washakie Ranges), and (4) mountains that are remnants of thick piles of nearly horizontal pyroclastic rocks (Absaroka Range and Yellowstone Volcanic Plateau).

TETON RANGE

The Teton Range is a north-trending uplifted block of Precambrian and Paleozoic rocks about 60 km long and 15–25 km wide. It is bounded on the east by the Teton normal fault (pl. 1; cross section, fig. 7) and on the west by another, virtually parallel normal fault (unnamed and incompletely known; not shown in fig. 2) along the Wyoming-Idaho State line. This fault is not exposed but is inferred because a sharp linear topographic break in alluvial deposits coincides with steepened west dips in Paleozoic rocks of the Teton Range at the east margin of Teton Basin (fig. 1). If this interpretation is correct, the Teton Range is a horst between the two downfaulted blocks, Teton Basin and

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Jackson Hole. The core of the mountain is largely granite and metamorphic rocks (Reed, p. E12 of this report) overlain by west-dipping Paleozoic rocks on the west side; these are faulted off on the east side.

The Teton Range was formed in two stages. During Late Cretaceous and early Tertiary times it was the northwestern part of a broad northwest-trending fold continuous with the Gros Ventre Range. Later in Cenozoic time this uplift was thrust southwest. Then the overriding block was broken by a series of faults, the largest of which is the Teton fault. The area of downfaulted blocks became the southern part of Jackson Hole, and thereby separated the uplift into two very different segments. The Teton Range continued to rise, whereas the Gros Ventre Range did not.

SNAKE RIVER AND HOBACK RANGES

The Snake River and Hoback Ranges are composed entirely of Paleozoic and Mesozoic sedimentary rocks that are intricately folded, overturned in places, and faulted. No Precambrian rocks are exposed. The ranges are piles of overlapping thrust sheets emplaced along low-angle thrust faults, such as the Jackson, Darby, Absaroka, St. John, Game Creek, and Bear Creek (fig. 2). Dominant movement was to the northeast, and the amount of displacement probably was many kilometers. The thrust sheets were apparently emplaced during early Eocene time, but some thrusting or gravity faulting occurred much later and in the opposite direction. For example, southwest of the mapped area, overturned Cambrian limestones along the southwest margin of the Snake River Range moved southwestward onto middle Pliocene rocks.

The Snake River and Hoback Ranges are structurally separated, but they are genetically related; both are composed of low-angle thrust sheets of about the same age, and, on their northern margins, both are underlain and bounded by the Jackson thrust. The trace of the Jackson fault curls around the east side of the Hoback Range where Paleozoic and Mesozoic rocks have been shoved onto conglomerates of latest Paleocene age.

GROS VENTRE RANGE

The Gros Ventre Range is an asymmetric anticlinal uplift that has Precambrian rocks in the core. The northeast flank is a broad area of gently dipping Paleozoic and Mesozoic strata. The steep southwest flank overrides the Green River basin along the Cache thrust (fig. 2). Vertical displacement on top of the Precambrian from the crest of the mountains to the bottom of the underlying basin is estimated to be more than 12 km. Maximum horizontal displacement is about 13 km.

The range was a broad gentle uplift as far back in time as latest Cretaceous. Major thrusting after middle Eocene time peeled back the north edge of the previously emplaced Jackson thrust block. Thrust masses (Love, 1956b), which were preserved because they were dropped by movement along the Hoback normal fault, 8 km southwest of the Gros Ventre Range (fig. 2), probably were emplaced during early Pliocene time as a result of rise of the mountain arch and movement on the Cache thrust. The separation of this uplift from the Teton Range by normal faulting during late Cenozoic time has been noted above.

WASHAKIE RANGE

The Washakie Range, like the Gros Ventre Range, is an asymmetric anticline that has a Precambrian core, a gentle northeast flank, and a steep thrust-faulted southwest flank. In several places the fault along the southwest side, the Buffalo Fork thrust, steepens and becomes a high-angle reverse fault. The throw on the Precambrian rocks between the top of the uplift and the bottom of the overridden syncline to the southwest is 6 km or more. During latest Cretaceous time the range was a broad low fold that subsequently rose and probably was thrust faulted during the Paleocene. At that time it may have been the dominant mountain range in the area. Post-Oligocene normal faulting near the south boundary of Yellowstone National Park lowered this part of the range by at least 300 m (meters).

ABSAROKA RANGE

The Absaroka Range is different from all other mountains in the region because it is not a structural uplift but an erosional remnant of a formerly vast nearly horizontal pyroclastic deposit several hundred meters thick that buried the adjacent folded mountains during Eocene and Oligocene time. The source of this debris was the Yellowstone-Absaroka volcanic area northeast and east of Jackson Hole. During middle and late Cenozoic time this was a relatively stable area affected by only minor warping and faulting in most places. Thus, it contrasts markedly with the spectacularly unstable major part of the Teton-Jackson Hole area only 30 km to the southwest.

Late Cenozoic erosion reexcavated the adjacent basins, exhumed the older folded mountains, and left the Absaroka Range as a series of high sharp drainage divides and steep-sided remnants of the original plateau. The underlying Washakie Range has been partly exhumed, and one type of mountain range can be seen overlapping the other.

YELLOWSTONE VOLCANIC PLATEAU

The Yellowstone Volcanic Plateau is not strictly a mountain range but is a broad rolling upland of more than 5,000 km^2, interrupted by a few peaks and ridges of volcanic rocks and by sharp steep-sided canyons. The rocks are chiefly andesite and basalt of Eocene and

Oligocene age in the eastern part, rhyolite of Pliocene and Pleistocene age in the middle part, and rhyolite and basalt of similar age in the western part. These rocks have been warped and faulted in some places, but they are commonly nearly horizontal.

ANTICLINES

Many large anticlines 15–30 km long and with 1,500–3,000 m amplitude, which range in age from pre-middle Paleocene to Pleistocene, are present in the Jackson Hole area (pl 3). Most of these folds have thrust or reverse faults on their southwest sides, and at least two were monoclines until Pliocene time. A few of the anticlines are described in order to show the variety present.

The Spread Creek anticline, which is 30 km long and has at least 2,000 m of closure, is bounded on the southwest by a thrust fault (crossed in one deep oil well). The anticline involves Paleozoic rocks (penetrated in two oil wells) and was formed before deposition of the Paleocene Pinyon Conglomerate. The Bacon Ridge anticline, which is more than 30 km long and has only a small amount of closure, plunges to the northwest and is bounded on the southwest by a small thrust fault. This anticline involves Paleozoic rocks, and is in part older than the Pinyon Conglomerate and in part younger. The Whetstone anticline is a broad open southeastward-plunging fold formed in post-Paleocene time.

The Red Hills anticline is a sharp fold involving Paleozoic rocks but is older than the Pinyon Conglomerate. The adjoining Ramshorn anticline to the northwest, however, was apparently a northeast-dipping monocline until post-middle Pliocene subsidence of the western part of Jackson Hole. At that time, westward tilting was sufficient to produce the west limb of the fold. The Munger anticline south of Jackson Hole was formed likewise; it was a southwest-dipping monocline until the Hoback normal fault became active in Pliocene time. Movement along this fault caused the rocks to the west to hinge down in such a way that the northeast flank of the anticline was created. This fold is one of several caused by tension rather than compression.

The Little Granite anticline, east of the Munger, was formed after Paleocene time, for it involves youngest Paleocene rocks, but before emplacement, along the Jackson thrust, of the Hoback Range which, moving northeastward, completely overrode the anticline in places (fig. 2). Subsequently, the north flank of this anticline was overridden by the Gros Ventre Range block, which moved southwestward along the Cache thrust.

THRUST FAULTS

Three types of thrust faults are present in the mapped area. (1) The low-angle type which involves both competent and incompetent sedimentary beds but no mountain cores of Precambrian rocks, as in the Snake River and Hoback Ranges, and which commonly have many kilometers of horizontal displacement. (2) The steeper type, which involves Precambrian cores of the mountain uplifts and which have only a few kilometers of horizontal displacement, such as the Cache and Buffalo Fork thrusts. These faults grade from thrust to reverse in many places. (3) Thrust faults which involve incompetent beds on anticlines and whose displacement is less than 2 km, such as the Spread Creek and Bacon Ridge thrusts. In places along the crest of the Bacon Ridge anticline, some of the bentonitic Cretaceous rocks are so incompetent that they were squeezed into recumbent folds before breaking.

NORMAL FAULTS

Three normal faults are especially important in the structural development of Jackson Hole. (1) The Teton normal fault, which is 80 km long and has a maximum vertical displacement of about 7 km with the east block down, is responsible in part for the uplift of the Teton Range as we know it today; it originated within the last 10 million years and is still active. (2) The Hoback normal fault, which is 40 km long and has at least 3 km displacement, with the west block down, probably began slightly later than the Teton fault and it also continues to be active. (3) The Warm Spring fault, cutting across the southern part of Jackson Hole, is about 19 km long and has at least 2 km of displacement, with the north block down; it is of Pliocene age. Subsidence of the north block during middle Pliocene time probably was responsible for impounding Teewinot lake in which 2 km of sediment accumulated. The fault has been inactive since late Pleistocene time.

CHRONOLOGY OF TECTONIC EVENTS AND THEIR RELATION TO VOLCANISM

The chronology of tectonic events in Grand Teton National Park and vicinity is summarized in table 1. The Teton Range apparently rose at the time the valley floor to the east subsided, but the volume of the lifted block is considerably less than that of the dropped block. This discrepancy still requires explanation.

Volcanism began in the Yellowstone-Absaroka area in early Eocene time and continued to the Pleistocene. Considerably more than 4×10^4 km^3 (cubic kilometers) of debris were blown out and spread to the east by wind and water. Jackson Hole did not subside during the first 20 million years of volcanism in the adjacent Yellowstone-Absaroka area despite the extrusion of an enormous volume of debris. However, from Miocene time to the Pleistocene, large-scale subsidence of Jackson Hole was coincident with extensive volcanic activity, not only in the sinking area (for the first time) but to a much greater extent in the Yellowstone-Absaroka area which did not subside. This relation suggests that Jackson Hole sank as subcrustal material moved laterally into the area of greatest volcanism.

PRECAMBRIAN ROCKS

By John C. Reed, Jr.

Precambrian rocks are extensively exposed in the core of the Teton Range and in several small areas in the Gros Ventre Range east and southeast of Jackson. The Precambrian rocks in Grand Teton National Park on the east flank of the Teton Range are being studied by the author. The geologic map (pl. 1) of this part of the Precambrian complex and the following descriptions are based largely on his unpublished data and on brief published descriptions by Horberg and Fryxell (1942), Bradley (1956), and Reed (1963). The Precambrian rocks in the Gros Ventre Range and on the western slope of the Teton Range have never been mapped or studied in detail, but presumably, they are similar to those in the eastern part of the Teton Range.

LAYERED GNEISS

The oldest and most widely exposed Precambrian rocks in the Teton Range in Grand Teton National Park are layered metasedimentary gneiss of medium high metamorphic grade. These rocks, designated layered gneiss on plate 1, comprise a heterogeneous array of biotite gneiss, biotite-hornblende gneiss, quartz-plagioclase gneiss, hornblende gneiss, and amphibolite. Thin layers of mica schist, amphibole schist, amphibole-cordierite schist, and calc-silicate rocks are commonly interleaved with the gneiss, and locally, the sequence contains thin layers of iron formation and pods and irregular masses of metagabbro and ultramafic rocks.

Individual layers range in thickness from fractions of a centimeter to tens of meters, and some can be traced for several hundred meters. Most layers, however, are less continuous, and many display boudinage structure and sheared-out isoclinical noses. Later folds with diverse axial trends are superimposed on the isoclines, which indicates that the layered gneiss sequence has undergone at least two episodes of folding (Reed, 1963).

Light- to medium-gray fine- to medium-grained biotite gneiss comprises the bulk of the layered sequence in most areas. The biotite gneiss is generally even grained, strongly foliated, and conspicuously layered. Locally, it displays conspicuous augen of plagioclase, garnet, and magnetite. It is interlayered on all scales with dark-gray fine- to medium-grained biotite hornblende gneiss, light-gray to white quartz-plagioclase gneiss, and dark-green to black hornblende amphibolite.

Average modes of these rock types, which together comprise more than 95 percent of the layered gneiss, are given in table 2.

It is difficult to estimate the proportions of these rocks in the layered gneiss unit, but the number of specimens counted to determine the average modes (table 2) is a crude index of their volumetric proportions.

Table 2.—*Average modes, in volume percent, of principal rock types in the layered gneiss of the Teton Range* [1]

	Biotite gneiss	Quartz-plagioclase gneiss	Amphibole gneiss	Amphibolite
Number of specimens	27	10	15	19
Quartz	40.9	36.2	16.3	7.8
Potassium feldspar	3.9	7.6		
Plagioclase	35.8	47.6	37.1	21.2
Biotite	16.2	2.4	5.8	.3
Hornblende			33.2	70.5
Muscovite	.7	2.8		
Chlorite	1.6		2.6	.2
Garnet	.9	.6	1.3	Trace
Epidote	1.4	2.6	1.5	.4
Leucoxene, Sphene	Trace	Trace	.7	.1
Magnetite, Ilmenite	Trace	Trace	1.1	.1

[1] Determined by counting 50 random grains in standard thin sections of randomly selected specimens representative of each rock type.

GRANITIC GNEISSES

North of Leigh Canyon, granitic gneisses of two types are major components in the Precambrian complex in the Teton Range. Hornblende-quartz monzonite gneiss (pl. 1) forms a large elongate body that extends from near the mouth of Webb Canyon southward to the upper reaches of Moran Canyon. Similar gneiss crops out north and west of Lake Solitude and in several smaller pods and sill-like bodies between Leigh Canyon and Doane Peak. Biotite granodiorite gneiss forms several irregular discontinuous bodies on the east flank of the range north of the mouth of Leigh Canyon. Average modes of these rocks are given in table 3.

The hornblende-quartz monzonite gneiss is a medium-grained light-gray to pink rock. It is not layered, but displays conspicuous foliation and lineation defined by strongly alined dark clots of fine-grained hornblende and biotite. Contacts with the layered gneiss are sharp or transitional over a few tens of meters and are parallel to layering in the enclosing rocks. Foliation in the quartz monzonite gneiss is generally parallel to the contacts. Nowhere do contact relations suggest that the quartz monzonite is intrusive. In several areas the quartz monzonite contains continuous layers of dark hornblende amphibolite a few meters to several hundred meters thick. Some of these can be traced for as much as 5 km. They are parallel to foliation in the quartz monzonite

TABLE 3.—*Average modes, in volume percent, of granitic gneisses in the Teton Range* [1]

	Hornblende-quartz monzonite gneiss	Biotite granodiorite gneiss
Number of specimens	13	10
Quartz	39.2	43.5
Potassium feldspar	18.5	11.6
Plagioclase	36.6	33.4
Hornblende	3.7	1.4
Biotite	1.4	8.1
Muscovite		.8
Chlorite		1.0
Epidote	.6	.2
Sphene, Leucoxene	Trace	.2
Magnetite, Ilmenite		Trace

[1] Determined by counting 50 random grains in standard thin sections of randomly selected specimens representative of each rock type.

gneiss and to layering in the enclosing layered gneisses. They are similar in composition to the amphibolite layers in the layered gneisses (table 2).

The biotite granodiorite gneiss is a medium- to dark-gray strongly foliated rock. Commonly, it displays ovoid augen of gray potassium feldspar as much as 3 cm long. In many places it is rudely layered. Layering and foliation are parallel to layering in the enclosing rocks, and contacts with the layered gneiss are gradational over several hundred meters.

The patterns of mineral lineations and of the axes of minor folds in the granitic gneisses are similar to those in the layered gneisses, which shows that all these rocks were deformed during at least the last episode of folding and regional metamorphism (Reed, 1963).

HORNBLENDE-PLAGIOCLASE GNEISS

Coarse-grained nonlayered weakly foliated hornblende-plagioclase gneiss comprises the bulk of the exposed Precambrian rocks in the Teton Range southeast of the Open Canyon fault (pls. 1, 3). Similar gneiss also occurs as thin layers and small pods in the layered gneisses at least as far north as Cascade Creek.

The rock consists of irregular equidimensional blotches of dark-green hornblende 1.2–5 cm across set in a matrix of milky-white altered plagioclase. Hornblende comprises 20–40 percent of the rock; plagioclase, 40–80 percent; quartz, 0–5 percent; and epidote, 0–10 percent. Magnetite and ilmenite are absent. The mineralogy and texture suggest that the rock may be a metamorphosed diorite.

GRANODIORITE AND PEGMATITE

The high peaks of the Teton Range between Buck Mountain and Cascade Creek are carved in an irregular mass of fine-grained light-colored granodiorite and coarse-grained muscovite and biotite pegmatite that extends northward into Leigh Canyon. Large bodies of similar rocks also occur north of Moran Canyon and near the head of Death Canyon. All the enclosing gneisses are laced with networks of discordant dikes of granodiorite and pegmatite ranging in thickness from several centimeters to more than 30 m. These dikes and small irregular intrusive bodies comprise as much as half of the country rock near the large intrusive masses; but they decrease in abundance away from these masses, and south of Granite Canyon and north of Webb Canyon only a few small dikes are present.

The intrusive bodies contain abundant tabular inclusions of the wallrocks. Contacts of the dikes and of the individual inclusions are knife sharp, but it is difficult to map the contacts of the larger granodiorite and pegmatite bodies because of their complex geometry and the transition between intrusive rocks containing abundant large inclusions and country rocks cut by networks of anastomosing dikes. The dikes cut cleanly across all structures in the enclosing rocks, and inclusions in the intrusive rocks have minor folds and mineral lineations that must have formed before the granodiorite and pegmatite were emplaced. These relations show that the granitic rocks invaded the surrounding gneisses after the last episode of folding and regional metamorphism.

The average modal composition of the granodiorite is given in table 4. No modal analyses of the pegmatite are available, but its bulk composition is probably similar to that of the granodiorite.

TABLE 4.—*Average mode, in volume percent, of granodiorite in the Teton Range* [1]

Quartz	35.8	Muscovite	3.3
Potassium feldspar	27.3	Chlorite	.8
Plagioclase	29.6	Epidote	Trace
Biotite	3.0		

[1] Determined by counting 50 random grains in each of 12 standard thin sections of randomly selected typical specimens.

DIABASE

Scattered dikes of dark-green to black diabase and basalt cut all the other Precambrian rocks in the Teton Range. The dikes trend N. 70°–85° W. and are nearly vertical. The largest of these dikes is 40–50 m thick, and has been traced for more than 11 km from near Leigh Lake to the head of Moran Canyon. The other dikes range in thickness from 1 to 20 m.

The dike rocks are composed principally of plagioclase and pyroxene. Some are holocrystalline and have ophitic or subophitic textures; others consist of phenocrysts set in a dark microcrystalline matrix. Some sensibly attract a hand magnet. No modal analyses are available, but chemical analyses suggest that the dike rocks are typical tholeitic basalts.

The dikes are clearly Precambrian, for they are unconformably overlain by Flathead Sandstone of Cambrian age on the summit of Mount Moran and on peaks on the ridge north of Moran Canyon. Post-Cambrian fault movement along some of the dikes in the south fork of Cascade Creek has sheared the dike rocks and displaced the overlying Paleozoic rocks.

GEOPHYSICAL STUDY

FIELD MEASUREMENTS

Some gravity survey work was done in the mapped area in 1955 by Lavin and Bonini (1957), of Princeton University. From their base station, which was tied to gravity station GW35 at Billings, Mont. (Behrendt and Woollard, 1961), they established 280 field stations. In 1964–65, Behrendt, during the present investigation by the U.S. Geological Survey, established 430 additional stations. The survey was tied to the North American gravity-control network by means of LaCoste and Romberg geodetic gravimeter G–8. A base station at Jackson Airport was tied to station WU7 at the Colorado School of Mines, Golden, Colo. (Behrendt and Woollard, 1961). Reoccupations by the Geological Survey of the earlier Princeton University base station showed a difference of only 0.1 mgal (milligal) between the two surveys. Because the data were contoured at a 5-mgal interval, this difference was neglected. Worden gravimeters W226, W177, WE134, and W57 were used for the survey; W57 was calibrated against a portion of the North American calibration range, and for the other gravimeters the manufacturer's calibration was used. Elevations were obtained from bench-mark data, spot elevations on topographic maps, and barometric altimetry. The elevations are accurate to 1–2 m in the areas of low relief, for which modern maps were available; but they may be in error by as much as 10–20 m in areas of high relief, such as the Teton Range, for which modern maps were not available. These greater errors correspond to 2- to 4-mgal errors in the Bouguer anomalies. On Jackson Lake, stations were observed on ice, and water depths were obtained by echo sounding and from an unpublished bathymetric map of the National Park Service. Terrain corrections were made out to Hammer Zone M, except for the highest stations for which corrections were carried out to a distance where they became negligible. A density of 2.67 g per cm^3 (grams per cubic centimeter) was used in the Bouguer reduction. The gravity results are shown on plate 1, which also shows the generalized geology by Love (1956c) and John C. Reed, Jr. (unpub. data). Love's (1956b) tectonic map of Teton County is shown in figure 2. Other gravity surveys in adjacent areas have been published by Bonini (1963) and by Pakiser and Baldwin (1961).

Four seismic refraction experiments were made in 1964 and 1965 to study the seismic velocity structure in Jackson Hole. The objective was to correlate the information thus obtained with the gravity and geologic data and thereby gain an understanding of structural relationships in the region. The locations of the four profiles are shown on plate 1. Each array in 1964 consisted of six geophones located at 0.5-km intervals. The one array used in the 1965 experiment consisted of 12 geophones spaced 0.2 km apart. In places where the configuration was not in a straight line (pl. 1), lateral homogeneity was assumed. Charge size ranged from 3 to 300 kg (kilograms). Arrival times are accurate to ± 0.01 sec (second), and distances are accurate to ± 100 m. Elevation corrections were not made for lines 1–3, which cover terrain whose maximum relief was about ± 30 m (about ± 0.01 sec). Elevation corrections were made for traveltimes on line 4, where relief was as much as 130 m.

An aeromagnetic survey was flown at a constant barometric elevation of 3,700 m, except that the elevation was 4,300 m over the high peaks of the Teton Range. The north-south flight lines were spaced 1.6 km apart. The results of the survey are shown on plate 2, together with part of an unpublished aeromagnetic survey of Yellowstone National Park. A residual map, constructed by removing the earth's field linearly as shown by the total intensity map of the United States for 1965 (U.S. Coast and Geod. Survey, 1965), is shown on plate 3. All estimates of depth to sources of magnetic anomalies were calculated by the method of Vacquier, Steenland, Henderson, and Zietz (1951) with the observed profiles. The exclusive use of this method is justified by the ruggedness of the topography, which would make more sophisticated computations unrealistic.

GRAVITY SURVEY

The Bouguer anomaly map (pl. 1) shows several interesting features. The most apparent is the −240-mgal negative anomaly over Jackson Hole compared with −185 mgal over the Teton Range. A steep gradient, clearly associated with the Teton fault near the south end of the range, broadens northward near Jenny Lake and trends north-northeast across the lake. The gradient steepens considerably below the northeastern part of Jackson Lake, reaching a maximum of 15 mgal per km (milligals per kilometer) near Arizona Creek. The Teton fault (pl. 1; fig. 2) was drawn to conform to the steep gravity gradient. The 55-mgal anomaly results

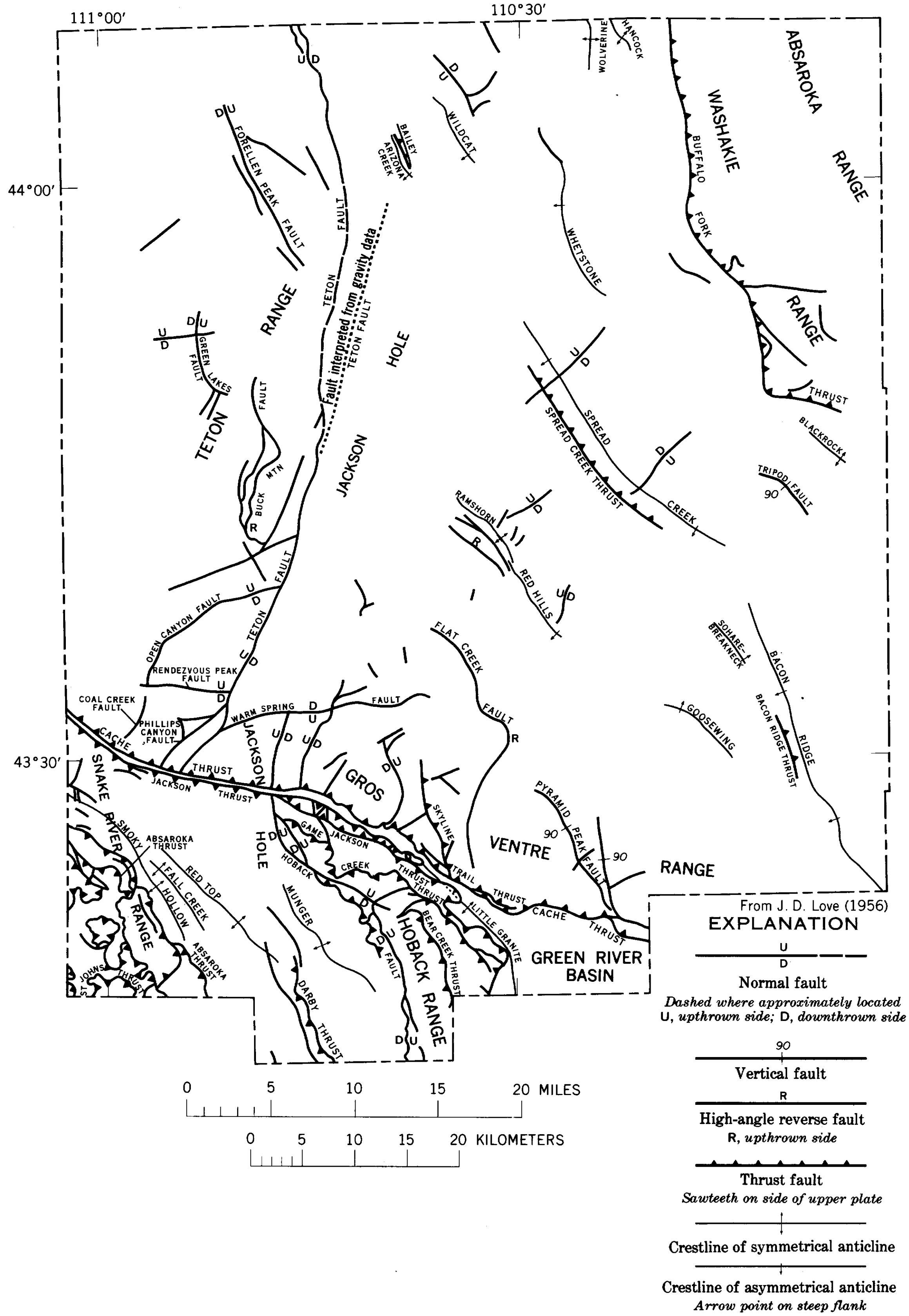

FIGURE 2.—Tectonic map of Teton County, Wyo.

from contrast between low-density sedimentary rock in the basin and relatively high-density Precambrian crystalline rock of the Teton Range.

The most negative parts of the Bouguer anomaly map coincide with the area of thickest low-density Tertiary and upper Mesozoic sedimentary deposits, which is near the east edge of Jackson Lake. Thick low-density deposits also occur just north and south of Blacktail Butte and south of Jackson.

The west-northwest trend of the Gros Ventre Range, which is reflected on the gravity map, appears to influence the gravity contours in the southern part of the Teton Range, as might be expected from the relative ages of the two uplifts (table 1). Blacktail Butte is associated with a 10-mgl positive anomaly caused by the density contrast between the relatively dense Paleozoic rocks and the less dense Tertiary sedimentary rocks.

The saddle between the −225-mgal contours between shotpoints 2.2 and 2.3 indicates a relatively broad anticline as discussed on page E19.

The extrusive volcanic rocks in the northern part of the area do not seem to have a great effect on the Bouguer anomalies, a condition that suggests that the rocks are of low density contrast or that they are thin; probably they are both.

Because of uncertainties about elevation, the significance of anomaly closures shown within the Teton Range is difficult to evaluate. The contours at the north end of the range show 20 mgal of relief and reflect northerly anticlinal plunge of the crystalline core of the range.

SEISMIC-REFRACTION SURVEY

PROFILES 1–3

SLOPING LAYER ANALYSIS

The seismic velocity structure within the sedimentary rock and crystalline basement underlying Jackson Hole was studied by refraction methods. Three observed profiles are located on plate 1, and data on their traveltimes are shown in figures 3–5. Lines 1 and 2, as planned, gave maximum structural control, and line 3, which was laid out along the strike of the gravity minimum, gave the best velocity information. Note the early arrival data from the 6.1-km per sec (kilometers per second) apparent velocity at the west end of line 2 (fig. 4); there the line crosses the Teton fault area (pl. 1). A three-layer model (fig. 6), based on the apparent velocities shown in figures 3–5 and using a critical distance analysis for sloping layers, gives a good fit to these data. This model, because it was constructed on the basis of the apparent velocity lines (figs. 3–5), does not show that the Teton fault crosses the profile east of 2–1, whereas the traveltime curve (fig. 4) and the gravity data (pl. 1) indicate that it does.

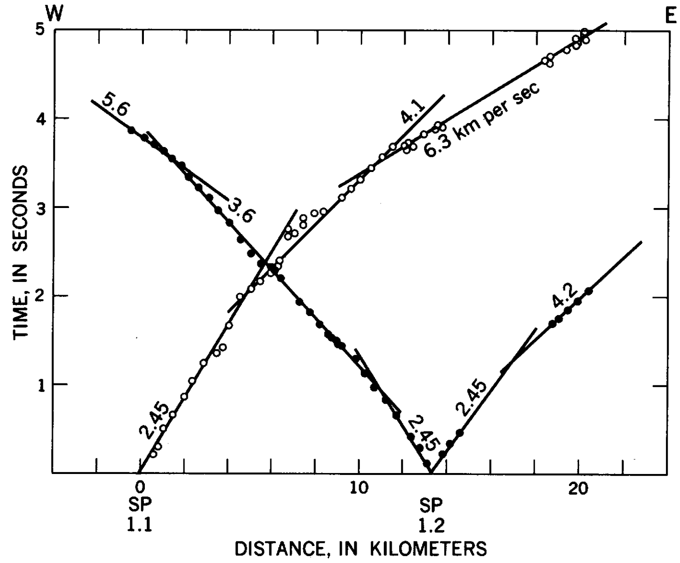

FIGURE 3.—Seismic traveltime graph for line 1. Apparent velocities, in kilometers per second, are shown. SP, shotpoint.

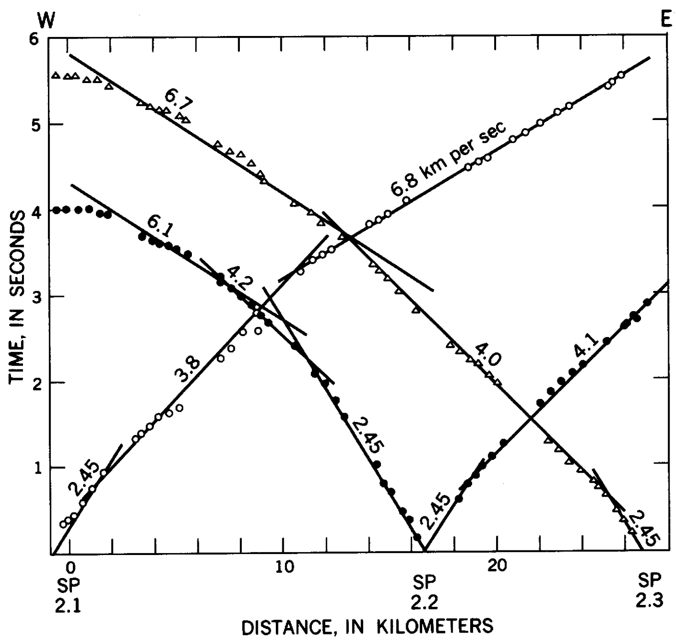

FIGURE 4.—Seismic traveltime graph for line 2. Apparent velocities, in kilometers per second, are shown. SP, shotpoint.

The thickest parts of the 2.45 km per sec layer are at shotpoints 1.1 and 2.2–3.3, where gravity values are lowest. Model depths to the 3.9 layer are 1.5 and 1.4 km, and depths to 6.1 are 3.2 and 2.7 km, at shotpoints 1.1 and 2.2–3.3, respectively.

DELAY TIME ANALYSIS

The traveltime data show considerable scatter from the apparent velocities shown in figures 3–5, which is

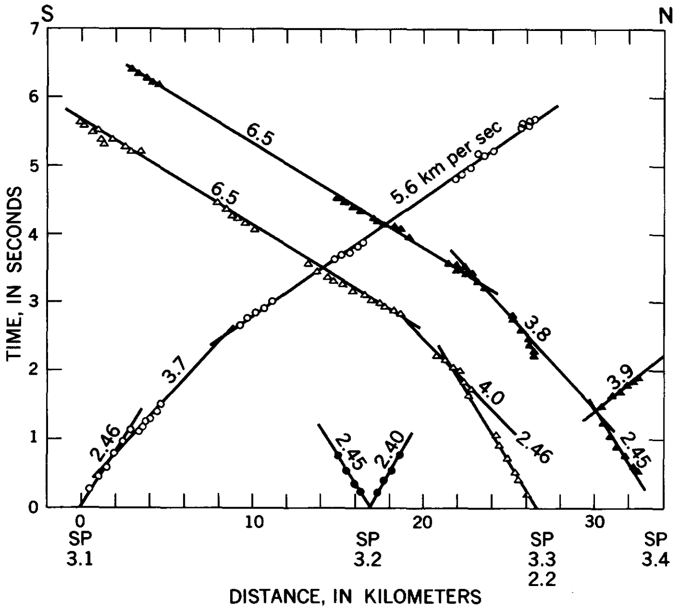

FIGURE 5.—Seismic traveltime graph for line 3. Apparent velocities, in kilometers per second, are shown. Shot at 3.2 had insufficient energy. SP, shotpoint.

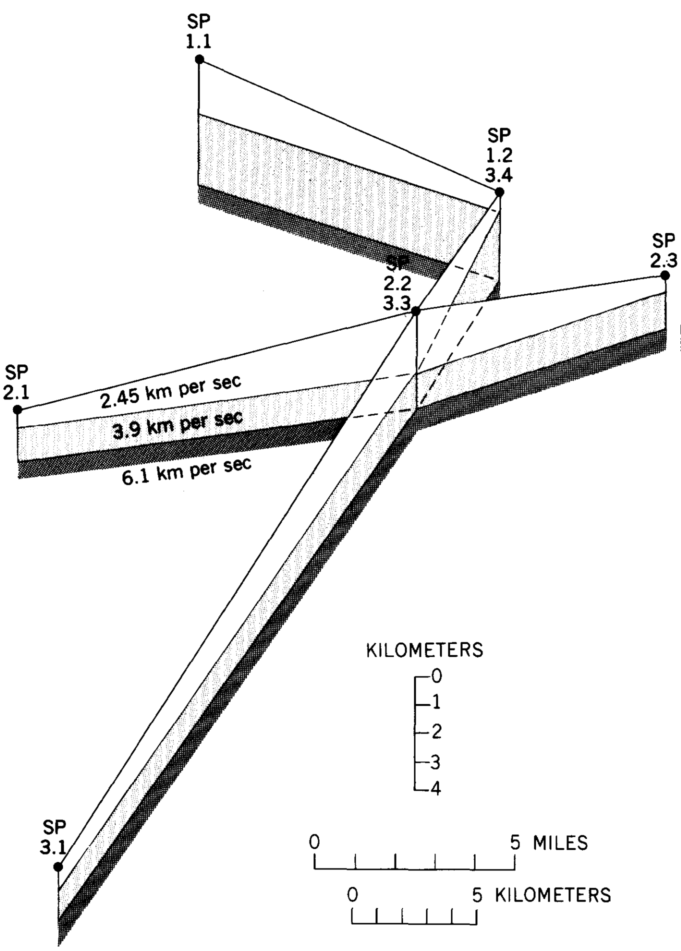

FIGURE 6.—Sloping layer model fitted to traveltimes for seismic lines 1–3. SP, shotpoint.

the result of departures from the uniform velocity-planar interface assumption of the model shown in figure 6. On the assumption that the scatter is the result of variations in the thickness of the layers, and that the three velocities of the sloping layer model are real, a delay time analysis was made of line 2 using the method of Pakiser and Black (1957). The interface calculated at the base of the 2.45-km per sec layer and the scatter are shown in figure 7. The analysis for the 3.9- to 6.1-km per sec interface, because of cumulative errors, was much poorer than that for the 2.45-km per sec interface (fig. 7). The estimate of the uncertainty of this surface is represented by the error bar shown in figure 7. The depth at shotpoint 2.2–3.3 was used as a tie point for the base of the 2.45-km per sec layer, and the depths at 2.2–3.3 and 2.3 were used for the contact between the 3.9- and 6.1-km per sec layers.

The well shown in figure 7 is about 100 m north of line 2. This well penetrates the Cloverly Formation (Lower Cretaceous), in which the 3.9-km per sec refractor is interpreted to occur. The exposed Cloverly nearby is quartzitic (Love, 1956a), and it may be the top of the 3.9-km per sec refractor. Commercial seismic companies use this formation or its equivalent as a reflection marker horizon throughout Wyoming (Berg, 1961; Peters, 1960). A good reflecting surface suggests, although it does not prove, the presence of a good refractor. A velocity of 3.9 km per sec might be expected in Cretaceous sedimentary rocks (Blundun, 1956).

The 6.1-km per sec layer is interpreted to include both Paleozoic and Precambrian rocks (fig. 7). Because the Paleozoic section consists primarily of limestone and dolomite (table 1), a velocity of 6.1 km per sec is not improbably high; Blundun (1956) reported a Mississippian limestone in Alberta whose velocity was 6.4 km per sec.

The obvious alternative to this interpretation would be to accept the 6.1-km per sec refractor as the crystalline basement; however, this would leave no place for the Paleozoic rocks, for a kilometer of carbonates could not be accommodated in the 3.9-km per sec layer. It is unlikely that the Paleozoic rocks are absent in Jackson Hole, for they crop out in the surrounding mountains and in Blacktail Butte. Contact between the 3.9- and 6.1-km per sec layers, therefore, is placed at the top of the Paleozoic rocks.

The depth shown at the well (fig. 7) to the top of the Paleozoic rocks is interpreted from two wells in the Spread Creek area about 6 km to the south (Love and others, 1951); the extrapolated thickness of the Lower Cretaceous section probably does not vary more than about 100 m in this distance. The contact between the Paleozoic rocks and the Precambrian basement was not

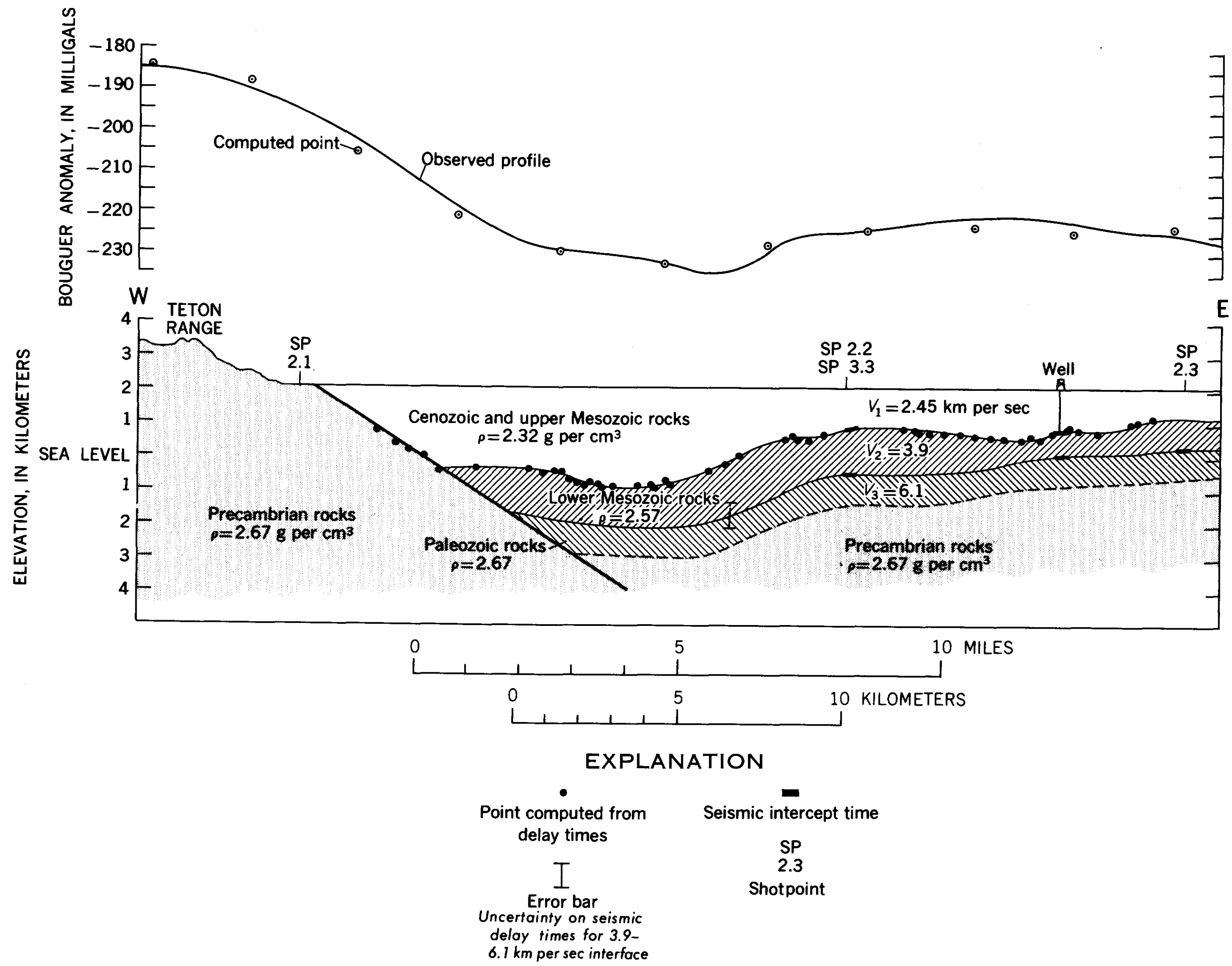

FIGURE 7.—Seismic delay-time model for seismic line 2. Bouguer gravity-anomaly curve is compared with theoretical (computed) points computed from seismic model by the two-dimensional line integral method using densities shown and a regional slope of —0.72 mgal per km to the east. Standard deviation of computed points is ±2.0 mgal.

recognized in the refraction data, owing to the low velocity contrast (possibly even a reversal). Undoubtedly, the later arrivals on lines 2 and 3 are sufficiently distant from the shotpoints to have been refracted through a higher velocity at the Paleozoic-Precambrian contact, if one exists. In figure 7, the depth shown to this contact, at the well, is based on the thickness of the Paleozoic section in the Spread Creek area, and the dashed contact was drawn assuming constant thickness along the profile.

GRAVITY ANALYSIS ALONG LINE 2 PROFILE

The gravity analysis along the line 2 profile was based on a theoretical gravity profile of the seismic model which was calculated by use of the two-dimensional line integral method compared with the observed data (fig. 7). Density contrasts -0.35 and -0.1 g per cm³ for the 2.45- and 3.9-km per sec layers, respectively, relative to the 6.1-km per sec layer, with a regional gradient of -0.72 mgal per km to the east, gave the best fit to the observed data. The standard deviation of the computed points relative to the observed profile is ±2.0 mgal. The 2.45-km per sec layer, on which seismic control is the best, is the major influence on gravity variation in this profile as well as on the Bouger anomaly map (pl. 1). Another gravity model calculated for the seismic model of figure 7, assuming only a density contrast of 0.4 g per cm³ between the 2.45- and 6.1-km per sec layers, gave nearly as good a fit with standard deviation ±3.1 mgal. This second calculation illustrates the degree to which the upper layer controls the gravity variations, but it is less plausible geologically than the model shown in figure 7.

The Teton fault is shown in figure 7 as an east-dipping normal fault. The shape of the contact between the Precambrian crystalline rocks of the Teton Range and the younger sedimentary rocks, calculated from the seismic data, does not indicate a steeply dipping fault. The computed gravity values are in agreement with the observed data, and even suggest that a slightly lower angle might give a better fit. The fault may be a single break of rather low dip, as shown in figure 7, or it may consist of several closely spaced more steeply dipping faults arranged steplike to the average slope. The main constraint in any such steplike arrangement is that the contact between the 2.45- and the 3.9-km per sec layers must remain nearly as shown in figure 7. The geophysical data do not discriminate between these possibilities, but the latter is favored as being more reasonable geologically. This analysis supports Love's (1956b) interpretation that the Teton fault is a normal fault.

The anticline mentioned previously (p. E16) as observed on the gravity map (pl. 1) is not shown in figure 2; but it is reflected in the contact between the 2.45- and 3.9-km per sec layers, and its axis appears to be near shotpoint 2.2–3.3 (pl. 1; fig. 7). In the area of the profile this anticline is more prominent than the Spread Creek anticline (Strickland, 1956), and the two are separated by a syncline. The Spread Creek anticline in the vicinity of the well (fig. 7) is barely recognizable in the seismic data, and its gravity effect is negligible.

PROFILE 4

The steep gravity gradient observed along the northeast shore of Jackson Lake suggested that a branch of the Teton fault trends through this area and is steeper than along line 2. The seismic refraction experiment carried out along line 4 in 1965 (pl. 1) tested these inferences. The traveltime plot is shown in figure 8. The velocities determined for lines 1–3 were used, and traveltime variations due to structure were assumed. The arrivals from six shots were recorded at one location (pl. 1) consisting of a 12-geophone spread. Apparent velocities fitted to the data by the method of least squares were used to identify the arrivals. Thus, shot 4.6 was refracted through only the first layer, shots 4.5, 4.4, and 4.3 penetrated the second layer, and shots 4.2 and 4.1 reached the third layer. Good second arrivals through the second layer were also recorded from shot 4.1. The time-depth method of Hawkins (1961) was used to determine the depth of the 2.45- 3.9-km per sec contact for shots 4.3–4.6 and, using the second arrival, for shot 4.1. A critical distance analysis was made for the depth to the 6.1-km per sec layer based on the apparent velocity of 4.78 km per sec obtained from the line connecting the means of the first arrival times and distances of shots 4.1 and 4.2. The model thus obtained is shown in figure 9.

A two-dimensional gravity analysis along profile 4 is shown in figure 10. The densities were held the same as in the analysis of profile 2, and a regional gradient of −0.64 mgal per km to the southeast gave the best fit. The standard deviation of the computed points from the observed profile is ±1.6 mgal.

The most striking feature of this model is the vertical step between shotpoints 4.3 and 4.2, which presumably

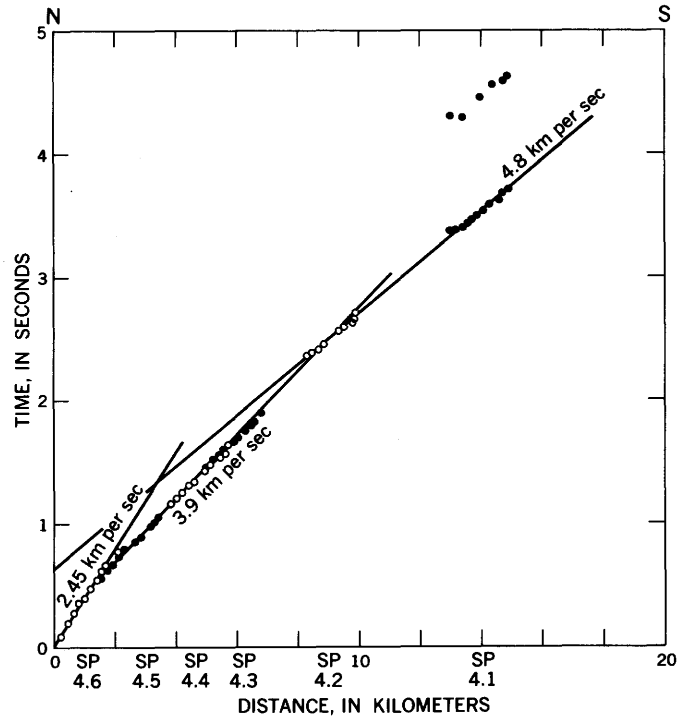

FIGURE 8.—Seismic traveltime graph for seismic line 4. Geophone spread was fixed; distances of shots to geophones are shown. Second arrivals from shot 4.1 are refracted along the top of the 3.9-km per sec layer. SP, shotpoint.

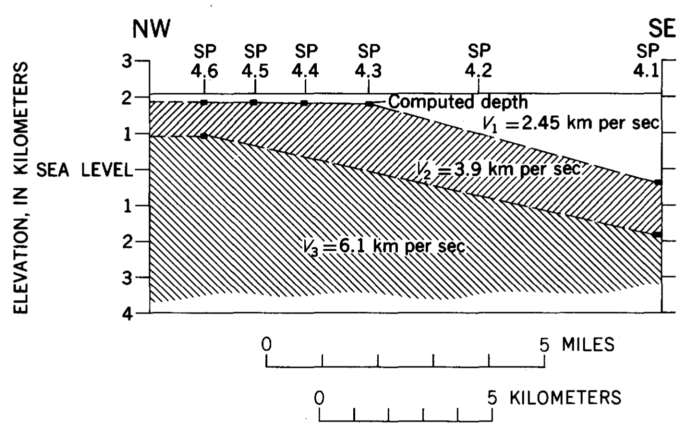

FIGURE 9.—Model fitted to traveltime data of seismic line 4 using time-depth method and assumed velocities shown in figure 6. SP, shotpoint.

is produced by the steeply dipping or vertical Teton fault. Other models with lower dips do not fit the data nearly so well. Therefore, even though the two-dimensional assumption is violated in the southern part of the profile (see pl. 1), the Teton fault or fault zone, which dips low where it crosses line 2, is possibly vertical where it crosses line 4. The Bouguer anomaly map (pl. 1) suggests that the fault or fault zone also is steeper in southern Jackson Hole, particularly opposite Blacktail Butte.

North of Jenny Lake the Teton fault is inferred from the gravity and seismic data (pl. 1). The gravity contours indicate that the low-density fill in Jackson Hole, which largely accounts for the gravity anomaly, thins to the north and east of line 4. This thinning, together with the scarcity of data and the lack of good elevation control here, makes it difficult to trace the possible continuation of the fault to the northeast.

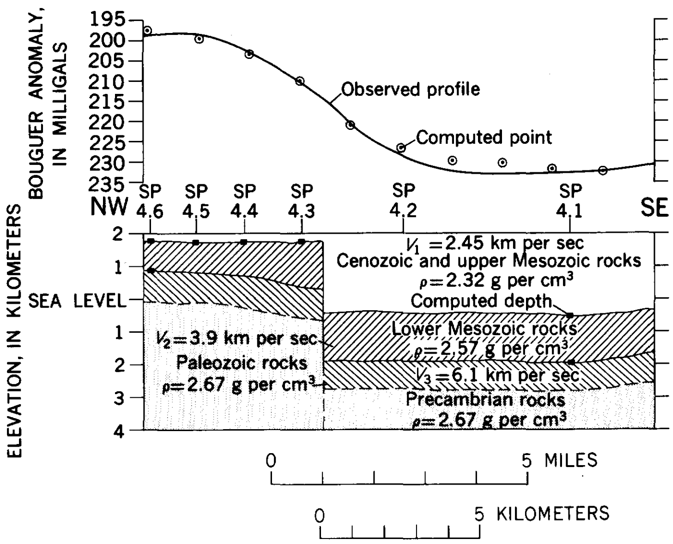

FIGURE 10.—Bouguer-anomaly curve and theoretical two-dimensional line integral gravity model for seismic line 4 based on model of figure 9; densities shown with a −0.64 mgal per km regional gravity gradient to the southeast. The standard deviation of computed points is ±1.6 mgal. SP, shotpoint.

It is difficult to explain the volume deficiency on the upthrown side of the fault between Arizona Creek and the front of the Teton Range without another fault bordering the range. To avoid this explanation, several cubic kilometers of Precambrian rocks between the fault trace under Jackson Lake and the present mountain front would have to be removed by water or ice after middle Pliocene time. There is little evidence that either accomplished this amount of selective erosion—it would have to be selective, for otherwise the mountain front would not have remained intact. Plate 1 therefore shows an inferred fault along the mountain front in this area. There is no geophysical evidence to support the presence of such a fault, but none would be expected if the area between the two faults is underlain at a shallow depth by dense high-velocity rock (as shown in fig. 10). The Teton fault and the inferred fault are shown to merge in the Jenny Lake area. The fault trending north-northeast through Jackson Lake (pl. 1; fig. 2) probably originated during the Late Cretaceous to early Tertiary orogeny, and its topographic expression probably was destroyed by later events.

The steep gravity gradients associated with the northern and southern parts of the Teton fault trend north-northeast and are separated by the broader gradient which trends north, as previously noted. The dip is steep or vertical at the north end, and presumably it is the same along the steep gradient in the south. The central part, as mentioned previously, is probably a fault zone or a series of step faults. Reed has mapped two faults (pl. 1) that are parallel to the north-northeast trend. This configuration is virtually an en echelon pattern and suggests that horizontal as well as vertical stresses may have been involved in the fault movement.

The northeastern branch of the Teton fault diverges where the gross lithology of the Precambrian rocks changes (pl. 1), an observation supported by the magnetic anomalies associated with the layered gneiss. Steep gravity gradients are in the areas of the magnetic anomalies, which suggests that the Precambrian rock controls the nature of the faulting. The layered gneisses apparently fault at a steeper angle or along one or more closely spaced fractures relative to the granitic rock.

The greatest depth to basement observed is 5 km, at shotpoint 4.1 (fig. 10). The summit of the Grand Teton is about 2.1 km above the valley floor. The base of the Paleozoic before erosion could not have been much higher, because Flathead Sandstone is still preserved on the summit of Mount Moran. The sum of 7 km therefore gives a reasonably accurate estimate of maximum vertical displacement between the Teton Range and the floor of Jackson Hole.

WARM SPRING FAULT GRAVITY ANALYSIS

Just north of the Gros Ventre Buttes, in the southwestern part of Jackson Hole, the gravity contours strike approximately east, a trend which reflects the Warm Spring fault (pl. 1; fig. 2). The vertical displacement of the fault was estimated on the basis of the difference of 20 mgal between the Paleozoic rocks outcropping on the Gros Ventre Buttes and the minimum value within the −225-mgal contour just north of this fault. Along profile 2 (fig. 7) the 3 km of 2.45-km per sec rock produces a 50-mgal difference in Bouguer anomaly, if one uses an infinite slab calculation. Because the previous work indicated that the gravity difference can be approximately accounted for by this rock layer, we obtain by the infinite slab assumption an estimated thickness of 0.9 km for the 2.45-km per sec layer in the Warm Spring fault area. If the thickness of the 3.9-km per sec layer is about the same in this area as it is to the north along profile 2—~1.2 km—the vertical relief on the fault is approximately 2.1 km. This compares favorably with the minimum displacement of 2 km reported by Love (p. E11) from his geologic mapping.

AEROMAGNETIC SURVEY

The total magnetic intensity map (pl. 1) shows a very conspicuous anomaly, about 100γ in amplitude, over the Gros Ventre Range and the southern Teton Range. The source of this anomaly is in the basement rock. The Precambrian rocks have not been studied in detail in the Gros Ventre Range, but they were mapped, by Reed (p. E12), in the Teton Range. The magnetic anomaly in the southern Teton Range is over outcropping layered gneiss (table 2), which is probably the source of the anomaly. Neither the granitic rocks nor the hornblende-plagioclase gneiss of the Teton Range has an associated magnetic anomaly, whereas the layered gneisses in the northern Teton Range do. These observations suggest that the Precambrian rock of the Gros Ventre Range is similar to the magnetic rocks of the Teton Range.

A profile across the Gros Ventre Range (pl. 2, *A–A′*), from which the regional field has been removed, is shown in figure 11. The computed model is a combination of models A69 and A70 (Vacquier and others, 1951); the standard deviation of the computed points is ±4γ. The computed body is oversimplified; but because of the ruggedness of the topography, a more detailed model would be impractical. The apparent volume susceptibility contrast for this model is 0.0004 emu, assuming induced magnetization only. The calculated source is 1.2 km below the flight elevation, or 2.5 km. This elevation is about 300 m below the contact between the Mesozoic and Paleozoic rocks (pl. 1), which indicates that the anomaly source is at the top of the Precambrian rock. (See table 1.) The susceptibility is appropriate for the layered gneisses, assuming negligible susceptibility for the granite and granite gneisses, and it suggests a magnetite content of 0.05–0.10 percent (Lindsley and others, 1966). This amount is consistent with Reed's modal analyses (tables 2–4 of this report).

Depth estimates show the source of the Gros Ventre Range anomaly east of the computed profile to be virtually at the bedrock surface, which indicates that the Paleozoic rocks there must be thin. Depth estimates in the Teton Range indicate that the source is at the surface, which implies that the contacts between the magnetic and nonmagnetic rocks are fairly steep.

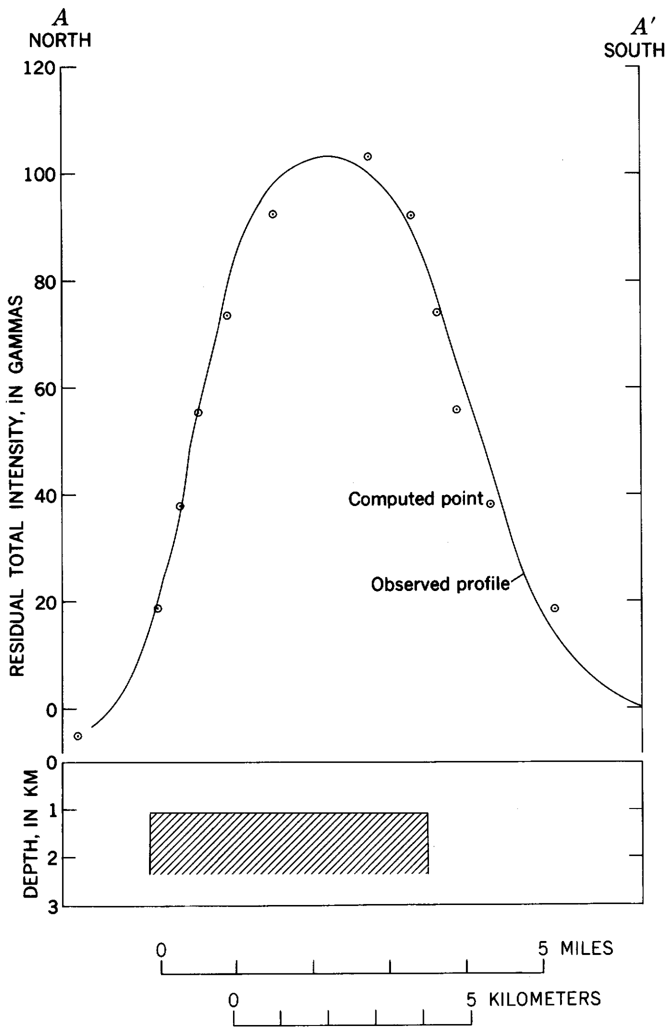

FIGURE 11.—Observed residual total magnetic intensity profile over Gros Ventre Range anomaly compared with theoretically computed points of model (shaded) shown. Body extends to infinite depth. $\Delta K_a = 0.0004$ emu, and is the apparent susceptibility contrast. Depth below flight-line elevation is shown. Standard deviation of computed points is ±4γ. *A–A′* is shown on plate 2.

In the northern Teton Range the magnetic contours associated with the layered gneiss extend over Jackson Lake, which indicates a fairly shallow depth to the layered gneiss and supports the seismic and gravity interpretation of the location of the Teton fault.

The total magnetic intensity map (pl. 2) shows a large anomaly of 400γ in the Gros Ventre Range trending off the east edge of the mapped area. This anomaly is not complete enough for a thorough analysis, but it can be associated with a basement feature. At the southern steep gradient, the depth to the crystalline source is estimated to be 300 m.

Precambrian rocks occur at the surface at the extreme edge of the mapped area (pl. 1). A preliminary field check of the area by J. D. Love shows that these rocks are chiefly granite and granite gneiss, and that they surround many bodies of mafic rocks and are cut by others. Local concentrations of magnetite and hematite were observed within this complex. In addition, the Flathead Sandstone (Cambrian) directly overlying the Precambrian rocks has several beds containing moderate amounts of hematite.

The diabase dikes, with one exception, are not shown on the magnetic maps because flight elevations were too high for the effects of these thin bodies to be recorded. The prominent dike on Mount Moran, which was crossed by one flight line only 580 m above the surface, showed a residual anomaly of about 30γ. A depth calculation showed that the source is at the surface, as would be expected for a dike. A ground traverse across this dike showed an anomaly of only 700γ; so it is not surprising that the effect is negligible on the aeromagnetic profiles.

The residual magnetic map (pl. 3) shows a low (centered near Slide Lake) to the south of the gravity minimum (centered near the east end of Jackson Lake), which would not be expected if the magnetic low were the result of the thickest part of the sedimentary section. This negative anomaly is probably the result of lithologic contrasts within the Precambrian basement. The contrasts, perhaps, are caused by the continuation, east of the Teton fault, of the relatively nonmagnetic granitic rock which is bounded on the north and south by layered gneiss. Depth estimates, based on the observed profiles, were made about 6 km south of seismic line 2. These estimates gave a depth of 4,300 m below the surface, which is slightly shallower than the depth to basement along line 2 (fig. 7) but which is within the error of the method. The origin of this gradient is probably the contact between the granitic rocks and the more magnetic layered gneiss to the north, which continues beneath Jackson Hole east of the Teton fault.

The volcanic rock in the area, with three exceptions, appears to be virtually nonmagnetic, as would be expected because most of this rock is very silicic (Carey, 1956). Two 40γ to 60γ positive anomalies near the north edge of the area are associated with rhyolite flows (Love, 1956c). A 20γ anomaly is associated with andesite porphyry (Scopel, 1956) of East Gros Ventre Butte. No anomaly was mapped over West Gros Ventre Butte, which contains the same rock, because the flight lines did not cross this area.

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U.S. GOVERNMENT PRINTNG OFFICE: 1968 O—297-153