# New Data on the Isostatic Deformation of Lake Bonneville

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# CONTENTS



# ILLUSTRATIONS



# TABLE

# NEW DATA ON THE ISOTATIC DEFORMATION OF LAKE BONNEVILLE

By Max D. Crittenden, Jr.


## ABSTRACT

Domical upwarping of the area formerly occupied by Pleistocene Lake Bonneville is verified by 75 new measurements of elevation on the Bonneville shoreline. Gilbert's conclusion that this uplift was an isostatic response to the removal of load is confirmed by maps which show that the deformation is closely correlated with the former distribution and average depth of water. The area of maximum uplift is west of Great Salt Lake, where the Bonneville shoreline reaches an elevation of 5,300 feet, compared with 5,090 feet at the south end near Lund and 5,085 feet at the former outlet in Red Rock Pass in southern Idaho. The 210-foot difference is about 75 percent of that theoretically possible if the lake had reached complete isostatic compensation.

Isostatic movements accompanying and following changes in the depth of water would explain the observed differences in elevation between the first and second stands at the Provo shoreline, the recent tilting of the basin floor, and several other features of lake history.

According to the most recent of several chronologies for Lake Bonneville, the anomaly created by removal of the lake water was reduced to $\frac{1}{e}$ of its initial value in somewhere between 4,000 and 10,000 years. On this basis, the calculated viscosity of the subcrust in this area is $10^{21}$ poises, compared with $10^{22}$ poises in Scandinavia.

Recent displacements on the Wasatch fault are normal—that is, down on the west; this is opposite in direction to the effects of isostatic unloading, which tend to elevate the valley block relative to the mountains. It is inferred that the two types of deformation are independent, one operating within the crust and the other mainly within the subcrust.


## INTRODUCTION

In the first monograph of the U.S. Geological Survey, G. K. Gilbert (1890) recorded in remarkable detail the widespread traces left by Lake Bonneville, the largest of the Pleistocene lakes of the Great Basin. He showed that the lake at its maximum was some 325 miles long, 125 miles wide, and had a surface area of about 20,000 square miles—nearly a quarter as large as the State of Utah (fig. 1). It extended from the site of Lund, near the southwest corner of the State, to Red Rock Pass in southern Idaho, and from the front of the Wasatch Range, where it flooded the sites of Logan, Ogden, Salt Lake City, and Provo, to the Toana Range, 10 miles west of the Utah-Nevada State line. Its maximum depth was a little more than 1,100 feet in the main northern body near the west edge of the present Great Salt Lake. To the south, the lake extended through passes between the ranges into what is now the Sevier Desert, where its average depth was about 500 feet.

Although Gilbert's study (1890, p. 363) consisted primarily of examining the bars, spits, and beach deposits that formed within the ancient lake, he soon perceived that the water surfaces delineated by these ancient features were no longer level. More than 50 islands and mountain headlands stood above the surface of the ancient lake, and on each of these a record of the ancient water surfaces was carved. Many shore features were close to the present Great Salt Lake, so that by using its surface as a plane of reference Gilbert was able to show (1890, pl. 46) that the ancient shorelines had been warped upward as much as 180 feet and that the uplift had been greatest near the west edge of the present lake where the water of the ancient lake was deepest. Gilbert inferred from this that the earth's crust had been domed upward in response to removal of load as the water evaporated.[1] But because he did not measure the elevations of any points around the west and southwest sides of the basin and because the absence of geodetic control forced him to rely on barometric measurements for elevations in the southern part of the basin, the impression has grown in recent years that many of his elevations were unreliable and that the evidence for isostatic readjustment was inconclusive (Eardley and others, 1957, p. 1164). At the same time, the extent of actual shoreline deformation has been further obscured because most modern studies of Lake Bonneville have

[1] It has recently been pointed out to me by Frank Calkins that though the word "isostasy" appears in the index to Monograph 1, it is followed by only a single page reference; but the word is not used on that page, nor apparently on any other. Indeed, "isostasy" had first been clearly defined only 10 years before Gilbert's work was finished (1890), and the principle still was not widely accepted in this country. Gilbert's attention to shoreline elevations in the field and his awareness of their significance therefore seem all the more remarkable.

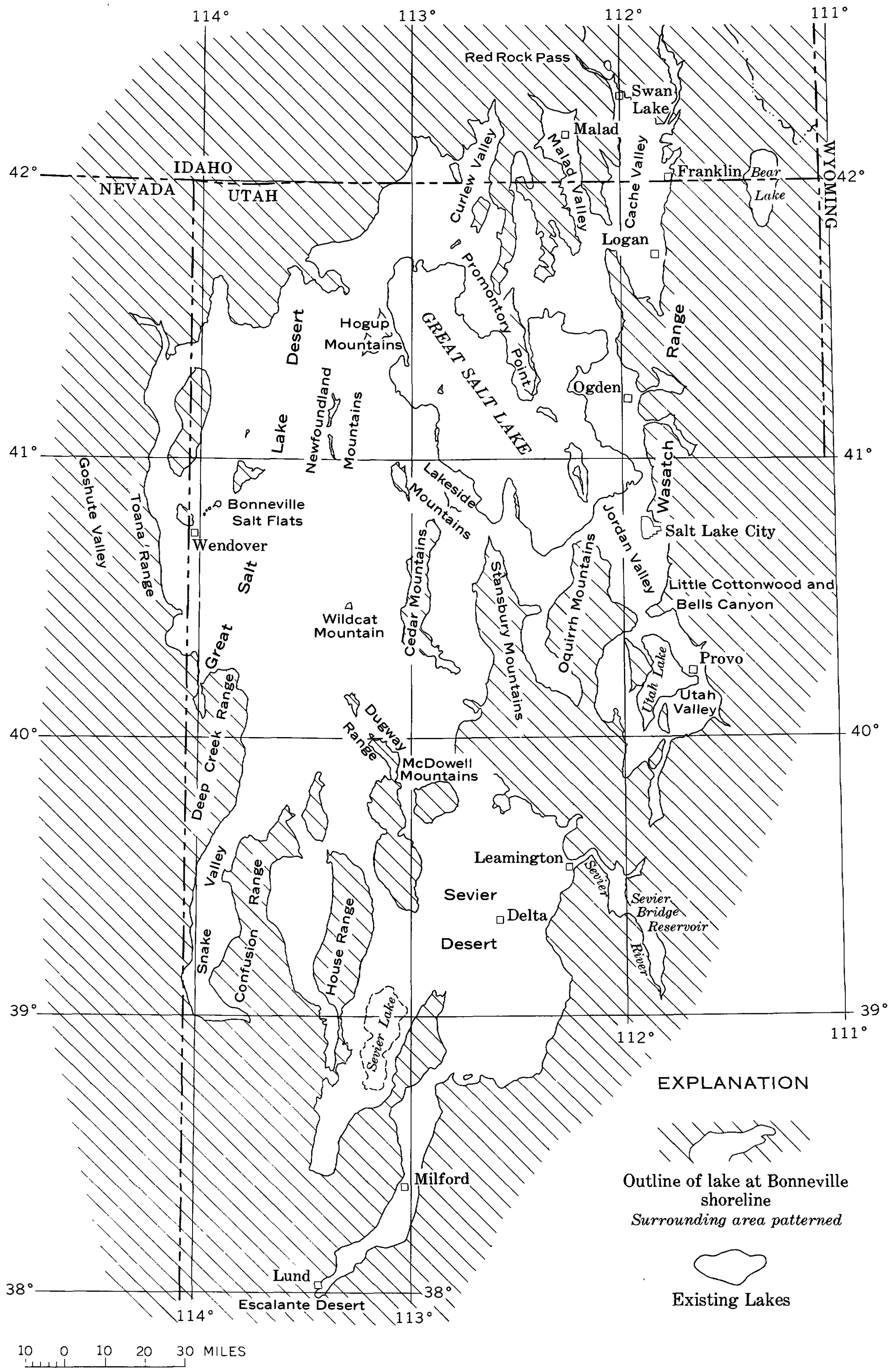


**FIGURE 1.**—Map of Lake Bonneville.

been restricted to small areas along the Wasatch Range front, where the shorelines are comparatively uniform in elevation. One result is that the figure 5,135 feet has been somewhat loosely used as representing the approximate elevation of the entire Bonneville shoreline.

Today, however, when the topography of this region has been delineated by an abundance of aerial photographs and a rapidly increasing number of large-scale topographic maps, it is possible to establish the elevation of shoreline features in many parts of the basin. The results fully confirm Gilbert's inferences regarding isostatic response to unloading; they indicate, in fact, that it was somewhat greater than he supposed. They also indicate that broad epeirogenic movements, though probably not negligible, were small compared with deformation of other types. They clearly record local deformation due to post-Bonneville faulting; and, together with the depositional record, they throw much light not only upon the history of Lake Bonneville but upon some broader problems concerning the character of the earth's crust.

## ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance of Robert C. Bright, W. J. Carr, Leonard Izett, Robert Maurer, H. T. Morris, Roger Morrison, G. I. Smith, M. H. Staatz, Peter B. Stifel, and D. J. Varnes, who have supplied shoreline elevations and other information used in this paper. I am deeply indebted also to A. H. Lachenbruch and D. R. Mabey for constructive and patient discussion of the problems of earth deformation, and to Mabey, Morrison, Varnes, and F. C. Calkins for critical review of the manuscript.

## PURPOSE AND METHODS

The present reexamination of Bonneville shoreline elevations was undertaken primarily to determine whether the shoreline, despite the fact that it had been warped by isostatic movements, might not be of use in establishing the absolute direction of the most recent movement on the Wasatch fault.

As the data accumulated, the desirability of reevaluating Gilbert's evidence for isostatic deformation became evident, and this in turn led to the consideration of broader geologic and geophysical problems. The method used was to obtain aerial photographs from parties engaged in geologic or topographic mapping and to locate salient lakeshore features on them by photogeology. For present purposes, only those on the highest shoreline (Bonneville) have been used. These features were then transferred to a topographic base by Kail plotter, by projection, or by inspection, depending on the accuracy of the base available. The best results were obtained by using 1:20,000 photographs and base maps at 1:24,000. Where such work has been checked in the field, as it has been along the front of the Wasatch Range and in parts of the Confusion Range, the results proved to be nearly as accurate as any that could have been obtained by trigonometric measurement of elevations. In some places where the shorelines are very faintly marked they can be located not only with greater ease but with more accuracy from photographs than on the ground. Even in such places, however, determination of the ancient water level involves some judgment, which Gilbert (1890, p. 125, 365), with characteristic frankness, expressed as a probable error of ±2½ to 3 feet under the most ideal conditions; he increased this to ±35 feet where further uncertainty was caused by his having to depend on barometric leveling. The best determinations made during the present work are regarded as subject to errors of ±5 feet arising from uncertainty of geologic interpretation. Those made from high-altitude photographs and 1:24,000 maps are subject to errors of ±10 feet. Only 10 of the 90 points depend entirely on 1:250,000 scale maps; for these, the shorelines were tied to spot elevations rather than to contours wherever possible, but in spite of this they are probably subject to errors of ±20 to 30 feet.

All the elevations available, together with information about their exact location and how each was obtained, are listed in table 1. Of the 90 localities, 9 are taken directly from Gilbert without modification, 4 use Gilbert's spirit-level measurements corrected by being tied to new bench-mark elevations, 10 depend entirely on 1:250,000 maps, and 18 are obtained from various published and unpublished sources. The remaining 49 are determined from aerial photographs and from quadrangle maps that are mostly on a scale of 1:24,000.

## EXTENT OF LAKE

The outline of Lake Bonneville at its highest level, together with all the shoreline elevations now available, was first plotted on base maps at a scale of 1:250,000. These outlines, further reduced by projection, are shown in figure 1.

TABLE 1.—*Bonneville shoreline elevations*

| No. | Name | Township and Range, Salt Lake base line meridian (except as noted) | Source | Elevation in feet | Notes |
|---|---|---|---|---|---|
| 1 | Red Rock Pass, Idaho | T. 12 S., R. 38 E. (Boise meridian). | Gilbert (spirit level) and USC&GS BM at Swan Lake. | 5, 085 | |
| 2 | Franklin, Idaho | T. 16 S., R. 40 E. (Boise meridian). | Gilbert (spirit level) and USC&GS BM at Franklin Station. | 5, 131 | |
| 3 | Logan | T. 12 N., R. 1 E | Gilbert (spirit level) and USGS BM at old Logan Station. | 5, 142 | |
| 4 | Blacksmith Fork | NE¼ sec. 11, T. 10 N., R. 1 E. | 1:20,000 photographs and 7½-minute Paradise quadrangle. | 5, 160 | Leonard Izett and Tom Mullens (written communication, 1960). |
| 5 | Baxter Ridge | S½ sec. 19, T. 10 N., R. 1 E. | do | 5, 180 | Do. |
| 6 | Willard | T. 8 N., R. 2 W | Gilbert (hand level) from lake surface. | 5, 184 | |
| 7 | Huntsville | T. 6 N., R. 2 E | Lofgren (1955, p. 83) | 5, 150 | |
| 8 | Ogden | T. 6 N., R. 1 W | Gilbert (hand level) from Ogden Station (4303). | 5, 179 | |
| 9 | Weber Canyon | N½ sec. 25, T. 5 N., R. 1 E. | Ogden 7½-minute quadrangle | 5, 200 | |
| 10 | Hobbs Canyon | Sec. 12, T. 4 N., R. 1 W | Kaysville 7½-minute quadrangle | 5, 160 | |
| 11 | Bountiful (Ward Canyon). | Sec. 21, T. 2 N., R. 1 E | Bountiful 7½-minute quadrangle | 5, 180 | |
| 12 | Salt Lake salient | Sec. 13, T. 1 N., R. 1 W | Aerial photographs and Salt Lake City North 7½-minute quadrangle. | 5, 220 | |
| 13 | Fort Douglas | | 1:20,000 photographs; Fort Douglas 7½-minute quadrangle; and Gilbert (spirit level). | 5, 180 | |
| 14 | Bells Canyon | Sec. 14, T. 3 S., R. 1 W | Draper 7½-minute quadrangle on ground. | 5, 140 | Downthrown block of Wasatch fault. |
| 15 | Draper | Sec. 34, T. 3 S., R. 1 E | do | 5, 180 | Upthrown block of Wasatch fault. |
| 16 | Corner Canyon | Sec. 4, T. 4 S., R. 1 E | Lehi 7½-minute quadrangle on ground. | 5, 160 | Downthrown block of Wasatch fault. |
| 17 | Point of Mountain | Sec. 24, T. 4 S., R. 1 W | Jordan Narrows quadrangle; Gilbert (spirit level) | 5, 160 | |
| 18 | American Fork | NW¼ sec. 32, T. 4 S., R. 2 E. | Lehi 7½-minute quadrangle on ground. | 5, 190 | Upthrown block of Wasatch fault. |
| 19 | do | do | do | 5, 140 | Downthrown block of Wasatch fault. |
| 20 | Spanish Fork | Sec. 23, T. 8 S., R. 3 E | Spanish Fork 7½-minute quadrangle. | 5, 120 | |
| 21 | do | Sec. 3, T. 9 S., R. 3 E | do | 5, 125 | Bar west of canyon mouth. |
| 22 | Loafer Canyon | Sec. 23, T. 9 S., R. 2 E | Spanish Fork Peak 7½-minute quadrangle. | 5, 090 | |
| 23 | West Mountain | Sec. 15, T. 9 S., R. 1 E | West Mountain 7½-minute quadrangle. | 5, 125 | Bar. |
| 24 | Santaquin | | Gilbert (spirit level) | 5, 107 | |
| 25 | Tintic Mountain | Secs. 13–14, T. 11 S., R. 2 W. | Tintic Mountain 7½-minute quadrangle on ground. | 5, 120 | H. T. Morris (written communication, 1960). |
| 26 | Allens Ranch | Sec. 5, T. 9 S., R. 2 W | Fivemile Pass 7½-minute quadrangle on ground. | 5, 150 | Do. |
| 27 | Butterfield Canyon | T. 3 S., R. 2 W | Eardley and others (1957, fig. 7). | 5, 165 | |
| 28 | Garfield | Sec. 31, T. 1 S., R. 2 W | do | 5, 195 | |
| 29 | Black Rock | Sec. 19, T. 1 S., R. 3 W | Gilbert (spirit level) checked on ground with Garfield 7½-minute quadrangle. | 5, 208 | |
| 30 | Antelope Island | Sec. 9, T. 2 N., R. 3 W | Antelope Island 7½-minute quadrangle. | 5, 250 | Bar. |
| 31 | Stockton | Sec. 24, T. 4 S., R. 4 W | 1:20,000 aerial photographs and Stockton 15-minute quadrangle. | 5, 250 | |
| 32 | Fivemile Pass | SE¼ sec. 7, T. 7 S., R. 3 W | 1:62,000 photographs and Fivemile Pass 7½-minute quadrangle. | 5, 185 | |
| 33 | South Mountain | Sec. 12, T. 4 S., R. 6 W | 1:20,000 photographs and Grantsville 7½-minute quadrangle. | 5, 255 | |
| 34 | Grantsville | Sec. 5, T. 3 S., R. 6 W | 1:37,680 photographs and Timpie 15-minute quadrangle. | 5, 274 | USGS bench mark on shoreline. |
| 35 | Kimball Canyon | Secs. 1–2, T. 2 S., R. 7 W | do | 5, 280 | |
| 36 | North end Stansbury Mountains. | NW¼ sec. 28, T. 1 S., R. 7 W. | 1:31,000 photographs and Timpie 15-minute quadrangle. Gilbert (spirit level, mean of two determinations). | 5, 300<br>5, 271 | |
| 37 | Delle Ranch | Secs. 12–13, T. 3 S., R. 8 W. | 1:37,000 photographs and Timpie 15-minute quadrangle. | 5, 290 | |

TABLE 1.—*Bonneville shoreline elevations*—Continued

| No. | Name | Township and Range, Salt Lake base line meridian (except as noted) | Source | Elevation in feet | Notes |
|---|---|---|---|---|---|
| 38 | Antelope Canyon | Sec. 25, T. 4 S., R. 8 W. | 1:37,000 photographs and Deseret Peak 15-minute quadrangle. | 5, 270 | |
| 39 | Dry Canyon | Sec. 7, T. 5 S., R. 8 W. | do | 5, 260 | |
| 40 | Davis Knolls | Sec. 21, T. 7 S., R. 7 W. | 1:23,300 photographs and Davis Knolls 7½-minute quadrangle | 5, 230 | |
| 41 | Davis Mountain | Sec. 19, T. 8 S., R. 7 W. | 1:23,300 photographs and Indian Peaks 7½-minute quadrangle. | 5, 230 | Bar. |
| 42 | Little Davis Mountain. | NE¼ sec 32, T. 7 S., R., 8 W. | 1:23,300 photographs and Camels Back Ridge NE 7½-minute quad quadrangle. | 5, 250 | Bar. |
| 43 | Tabby Mountain | T. 4 S., R. 10 W. | Tabby Mountain 7½-minute quadrangle on ground. | 5, 270 | Robert Maurer, Univ. of Utah (written communication, 1959). |
| 44 | North of Browns Spring. | Sec. 7, T. 4 S., R. 10 W. | 1:33,300 photographs and Wig Mountain NE 7½-minute quadrangle. | 5, 300 | Well-formed bar. |
| 45 | Cedar Spring | Sec. 36, T. 4 S., R. 11 W. | do | 5, 285 | |
| 46 | Wig Mountain | Sec. 1, T. 6 S., R. 11 W. | Wig Mountain 7½-minute quadrangle. | 5, 255 | |
| 47 | Wildcat Mountain | T. 4 S., R. 13 W. | 1:33,300 photographs and Wig Mountain NE 7½-minute quadrangle. | 5, 300 | |
| 48 | Granite Mountain | T. 8 S., R. 13 W. | 1:23,700 photographs and Granite Peak 7½-minute quadrangle. | 5, 220 | |
| 49 | Cannon Mine | Sec. 5, T. 10 S., R. 12 W. | Dugway Range 7½-minute quadrangle on ground. | 5, 210 | M. H. Staatz and W. J. Carr (written communication, 1958). |
| 50 | Cup Butte | N. edge sec. 3, T. 11 S., R. 9 W. | Hand level from BM on Coyote Springs 7½-minute quadrangle. | 5, 221 | Roger Morrison (written communication, 1961). |
| 51 | Thomas Pass | NW¼ sec. 12, T. 13 S., R. 11 W. | Topaz Mountain 7½-minute quadrangle on ground. | 5, 205 | Bar. M. H. Staatz and W. J. Carr (written communication, 1958). |
| 52 | Drum Mountains | T. 14 S., R. 10 W. | 1:31,000 photographs and Delta sheet at 1:250,000. | 5, 200 | |
| 53 | Desert Mountain | T. 12 S., R. 6W. | Delta sheet at 1:250,000 on ground. | 5, 210 | Bar. |
| 54 | Leamington | | Gilbert (spirit level), and USC&GS BM at Leamington. | 5, 115 | |
| 55 | Leamington Canyon of the Sevier River. | T. 14 S., R. 3 W. | Three barometric traverses from USGS BM F45. | 5, 110 | Inner edge of rock-cut bench in quartzite on south side of canyon (D. F. Varnes, written communication, 1961). |
| 56 | Sevier Bridge Reservoir. | NE¼ sec. 5, T. 17 S., R. 1 W. | Controlled barometric traverse | 5, 090 | Cut bench on ridge of volcanic rock, east shore of reservoir (D. F. Varnes, written communication, 1961). |
| 57 | Oak City quadrangle | NE¼ sec. 17, T. 16 S., R. 4 W. | Controlled barometric traverse between bench marks. | 5, 126 | Break in slope, inner edge of bench cut on southwest corner of ridge of conglomerate (D. F. Varnes, written communication, 1961). |
| 58 | do | Near center sec. 2, T. 18 S., R. 5 W. | USGS BM elev. 5149 | 5, 150 | Bench mark is on outer edge of rock-cut bench on nose of conglomerate (D. F. Varnes, written communication, 1961). |
| 59 | Fillmore | | Gilbert (barometric) | 5, 145 | |
| 60 | Southeast of Milford | Sec. 4, T. 29 S., R. 10 W. | 1:37,000 photographs and Cave Canyon 7½-minute quadrangle Dennis (1944, p. 123). | 5, 110<br>5, 107 | |
| 61 | Lund | NE¼ sec. 30, T. 32 S., R. 14 W. | 1:37,000 photographs and Avon NW 7½-minute quadrangle. | 5, 090 | |
| 62 | Milford Flat | Sec. 25, T. 28 S., R. 11 W. | 1:20,000 photographs and Milford Flat 7½-minute quadrangle. | 5, 105 | |
| 63 | Black Rock | T. 24 S., R. 11 W. | 1:63,360 photographs and Preuss Valley 4 NE 7½-minute quadrangle. | 5, 150 | |
| 64 | Cricket Mountains | T. 21 S., R. 10 W. | 1:63,360 photographs and Richfield sheet at 1:250,000. | 5, 220 | Elevation believed too high—point ignored in contouring fig. 3. |
| 65 | Lakeview Reservoir | T. 25 S., R. 12 W. | 1:63,360 photographs and Preuss Valley 4 NW 7½-minute quadrangle. | 5, 135 | |

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TABLE 1.—*Bonneville shoreline elevations*—Continued

| No. | Name | Township and Range, Salt Lake base line meridian (except as noted) | Source | Elevation in feet | Notes |
|---|---|---|---|---|---|
| 66 | South of Newhouse | N½ sec. 34, T. 27 S., R. 14 W. | 1:63,360 photographs and Lund 2 NW 7½-minute quadrangle. | 5,100 | |
| 67 | Wah Wah Mountains | T. 25 S., R. 14 W | 1:63,360 photographs and Preuss Valley 3 NW 7½-minute quadrangle. | 5,115 | |
| 68 | Taylors Canyon | Sec. 1, T. 20 S., R. 14 W | 1:63,360 photographs and Antelope Mountain 7½-minute quadrangle. | 5,140 | |
| 69 | Kings Canyon | T. 20 S., R. 18 W | 1:20,000 photographs and Confusion Range 4 SE 7½-minute quadrangle. | 5,125 | |
| 70 | Cowboy Pass East | T. 17 N., R. 16 W | 1:20,000 photographs and Confusion Range 1 SW 7½-minute quadrangle. | 5,150 | |
| 71 | Confusion Hills | T. 15 S., R. 16 W | 1:20,000 photographs and Confusion Range 1 NW 7½-minute quadrangle. | 5,175 | |
| 72 | Foute Ranch | T. 16 N., R. 18 W | 1:20,000 photographs and Confusion Range 2 NE 7½-minute quadrangle. | 5,155 | |
| 73 | Cowboy Pass West | T. 17–18 S., R. 17 W | 1:20,000 photographs and Confusion Range 2 SE 7½-minute quadrangle. | 5,120 | |
| 74 | Conger Range | T. 20 S., R. 18 W | 1:20,000 photographs and Confusion Range 2 SW 7½-minute quadrangle. | 5,120 | |
| 75 | Gold Hill | Sec. 7, T. 7 S., R. 17 W | Nolan (1935, pl. 2, and p. 54) | 5,205 | |
| 76 | Wendover Beacon, Nev. | T. 32 N., R. 70 E. Mount Diablo Meridian. | 1:63,360 photographs and Elko sheet at 1:250,000. | 5,200 | |
| 77 | Wendover, Nev | T. 33 N., R. 70 E. Mount Diablo Meridian. | Altimeter traverse from point on Elko sheet at 1:250,000. | 5,200 | |
| 78 | Leppy Pass | T. 1 N., R. 19 W | Schaeffer (1960, p. 112) | 5,204 | |
| 79 | Silver Zone Pass East, Nevada. | T. 34 N., R. 68 E. Mount Diablo Meridian. | 1:63,360 photographs and Elko sheet at 1:250,000. | 5,190 | |
| 80 | Pilot Range East | T. 5 N., R. 19 W | 1:63,360 photographs and Wells sheet at 1:250,000. | 5,200 | |
| 81 | Pilot Range North (Tecoma). | T. 7 N., R. 19 W | Gilbert (spirit level) | 5,182 | |
| 82 | Loray, Nev | Sec. 3, T. 38 N., R. 68 E. Mount Diablo Meridian. | 1:63,360 photographs and USC&GS level line along Southern Pacific Railroad. | 5,167 | |
| 83 | Muddy Creek | Sec. 2, T. 10 N., R. 15 W | 1:63,360 photographs and Brigham City sheet at 1:250,000. | 5,200 | |
| 84 | Hogup Mountains North. | Sec. 6, T. 9 N., R. 11 W | Barometer traverse from USC&GS BM. | 5,250 | Peter B. Stifel, Univ. of Utah (written communication, 1961). |
| 85 | Hogup Mountains Southeast. | Sec. 3, T. 8 N., R. 11 W | 1:63,360 photographs and Brigham City sheet at 1:250,000. | 5,300 | Elevation believed too high—point ignored in contouring on fig. 3. |
| 86 | Peplin Mountain | T. 11 N., R. 12 W | Gilbert (spirit level) | 5,232 | |
| 87 | Morris Ranch | Sec. 32, T. 13 N., R. 12 W | 1:62,500 photographs and Kelton Pass 15-minute quadrangle. | 5,210 | |
| 88 | Summer Ranch Mountains. | Sec. 36, T. 13 N., R. 8 W | 1:62,000 photographs and Brigham City sheet at 1:250,000. | 5,180 | |
| 89 | Mount Tarpey | T. 9 N., R. 6 W | Gilbert (spirit level) | 5,252 | |
| 90 | Little Mountain | Secs. 13 and 24, T. 10 N., R. 4 W. | 1:33,200 photographs and Bear River City 7½-minute quadrangle. | 5,220 | |

The outline of the lake is drawn largely on the basis of the contouring on the 1:250,000 maps, combined with the shoreline data obtained from all sources for each area. With one exception, the outline as thus determined agrees well with that shown by Gilbert's map on a scale of 1:800,000 (1890, in pocket). Gilbert's Escalante Bay, however, at the extreme south end of the lake, is now known to be in error. This was recognized independently by P. E. Dennis (1944) and by C. L. Hubbs (written communication, 1961) and is confirmed by the present study. It is of some interest to note that Gilbert himself did not have an opportunity to examine the supposed shorelines south of Lund (fig. 3), and he was clearly somewhat doubtful regarding both the shorelines and the elevations in that area. Of the former, he notes (1890, p. 369):

A comparative study of these systems of bars showed that the oscillations had been essentially the same at all localities, and it is thus known that throughout the area of their occurrence the shoreline belongs to the same high-water stage. The demonstration applies to the entire main body of the lake and its principal dependencies, and to the Sevier body and Preuss Bay, *but it does not apply to Escalante Bay.* [Italic mine.]

He noted, moreover, that the shoreline record was reported by his assistants Howell and Webster to be "* * * faint and difficult of determination" (Gilbert, 1890, p. 370).

Part of the reason for the difficulty that the early workers had in tracing these shorelines is to be found on the aerial photographs. Well-marked strandlines can be traced on the photographs from the vicinity of Milford southward along both sides of the valley to a point about 1 mile southwest of Lund, but there they become lost in an expanse of patchy ground that must formerly have been a marsh. Farther southwest, a series of low discontinuous scarps can be traced at least 5 miles into the Escalante Desert; careful study of the photographs reveals, however, that these features split and branch and cut across topography in such a way as to show that they are fault scarps rather than shorelines. Recognition of this fact clears up the doubts that Gilbert clearly felt regarding this area and which presumably led him to conclude with these words the discussion quoted in part above (Gilbert, 1890, p. 370):

In view of these conclusions the Escalante data will be disregarded in the subsequent discussion of the deformation of the Bonneville shore.

## NOMENCLATURE OF LAKE BONNEVILLE EVENTS

Because the chronology of Lake Bonneville is still in a state of flux, the names applied to the various stillstands and to the deposits formed during each of them are subject to disagreement. It is therefore necessary to define the terms that will be applied to the salient events in the history of the lake throughout this report.

Lake Bonneville is defined as the body of water that occupied the Bonneville basin after the formation of the thick, mature pre-Bonneville soil of Hunt (in Hunt and others, 1953, p. 15, 43); any bodies of water that may have occupied the basin earlier are referred to as pre-Bonneville lakes.

The lake deposits younger than that soil in the northern Utah Valley are believed by Hunt (in Hunt and others, 1953, p. 17) to contain a record of two high stands that he called the Alpine and the Bonneville, and of two lower stands that he called the Provo and the Stansbury. These correspond respectively to what Gilbert (1890, p. 90–152) referred to as the Intermediate, Bonneville, Provo, and Stansbury "Stages." A similar sequence of events has been inferred by Eardley and others (1957, fig. 20), who were the first to attempt to construct an absolute time scale, in years, for part of the sequence. Recent work in the area of the Sevier River delta by Varnes and Van Horn (1961) has led them to conclude that deposits equivalent to Hunt's Alpine Formation record as many as three lake maxima, and still other modifications and refinements of Hunt's chronology are likely to be made as work is extended into other areas.

As the controversial aspects of chronology and stratigraphy are outside the scope of this paper, the following nomenclature is selected somewhat arbitrarily for the present purpose and is not urged for more general use. The basic unit of lake history (fig. 2) is termed a "cycle"; it consists of a major rise and fall, whether or not the lake returned to the starting level. The earliest major rise is designated the Alpine cycle; it is regarded by some as having occurred entirely within a single cycle and by others as forming parts of more than one cycle. The culminating event in the history of the lake was the Bonneville cycle during which the lake overflowed at Red Rock Pass and initiated the downcutting of the outlet to the level of the Provo shoreline. The latter part of the Bonneville cycle is therefore denoted the Provo I stillstand. A subsequent rise to this same level is designated the Provo II stillstand. A later cycle culminated at the Stansbury shoreline, and others probably at still lower levels, but no attempt has been made to name each of them here.

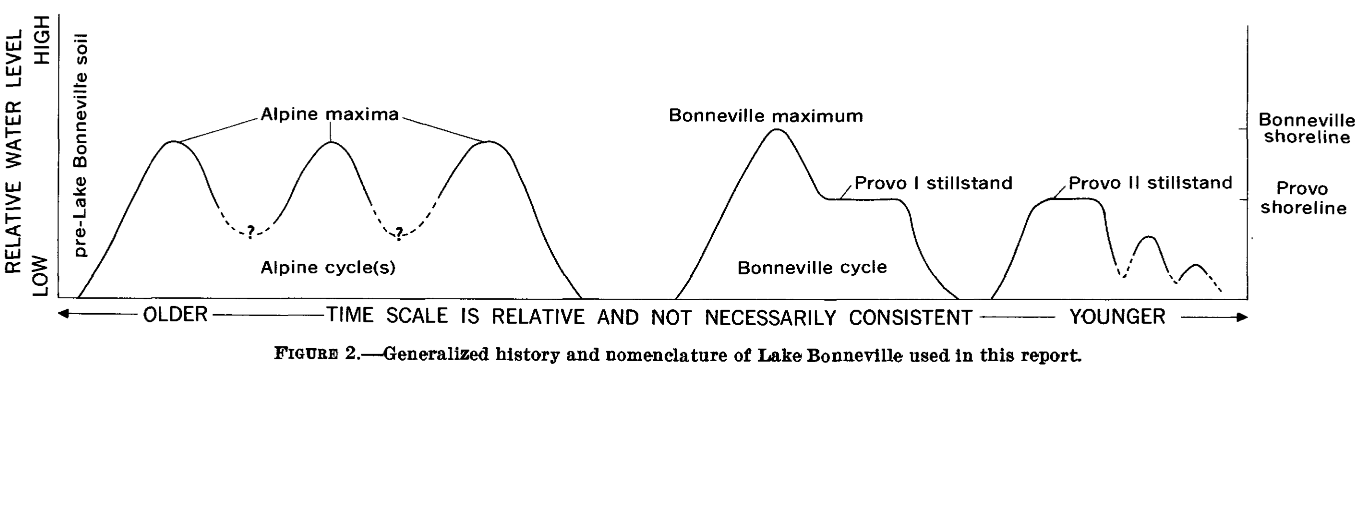


FIGURE 2.—Generalized history and nomenclature of Lake Bonneville used in this report.

## IDENTITY OF THE HIGHEST SHORELINE

Gilbert gave the name "Bonneville shoreline" to the highest strand of the ancient lake. The question of whether this shoreline is everywhere of the same age was discussed by Gilbert (1890, p. 369) and was answered in the affirmative because he believed he could recognize a similar series of shoreline embankments at all the places he examined. It seems probable that Gilbert was correct, but the matter cannot be settled with certainty until detailed stratigraphic studies have been completed in all parts of the basin. In any case, even though some uncertainty must remain for shoreline elevations determined entirely by photogeologic methods, all the newly determined elevations are here assigned to the Bonneville shoreline.

## OBSERVED DEFORMATION

The present configuration of the highest shoreline of Lake Bonneville is shown by means of contours in figure 3. As already noted, the shore features delineating the ancient water surface, originally level, now exhibit a broad domical uplift that reaches a maximum height of a little more than 200 feet. This amount is some 20 feet greater than Gilbert estimated, but the pattern of uplift he showed in the northern part of the lake is remarkably close to the one that has now been worked out with the help of much fuller data. The points of minimum deformation are at the extremities of the lake, near Lund at the south and Red Rock Pass at the north. The area of maximum uplift lies somewhere near the center of what Gilbert referred to as the main body—the large expanse of deep water that occupied the present area of Great Salt Lake and extended across the Great Salt Lake Desert.

Both the precision and the completeness of the data regarding shoreline elevations are still deficient in many places because of the absence of accurate topographic maps and vertical geodetic control. These deficiencies are particularly serious in the area around Lakeside, Newfoundland, and Hogup Mountains, where the only bench marks available are along the railroads; the elevations of U.S. Coast and Geodetic Survey triangulation stations within the ranges have not been established.

## WATER LOAD

In order to analyze the history of observed deformation of the shorelines in the Bonneville basin in quantitive terms, it is necessary to know the load that was there placed upon the earth's crust and subsequently removed. In this respect Lake Bonneville is one of the most satisfactory of Nature's experiments with isostasy. The large number of islands and headlands that projected above the surface and their wide distribution over all parts of the lake make it possible to reconstruct the outline and the depth of the ancient lake with much greater accuracy than is possible for the Fennoscandian ice sheet, for example, whose center lay so close to the Baltic Sea that its maximum thickness can never be determined accurately.

The present estimates of load were prepared by determining the difference in elevation between the existing surface of land or water, as shown on the 1:250,000 AMS sheets, and the original water surface when the lake stood at the Bonneville shoreline, as determined from figure 3. To allow for small irregularities in the lake bottom and shoreline, average depths over squares 6 miles on a side were estimated from the map by inspection, and these values were plotted at each township corner throughout the basin. The results indicate that the water of Lake Bonneville, when it was full, weighed $10^{13}$ tons. The effect of this load, however, depended not only on its magnitude but on the fact that it was distributed unevenly over a total area of about 35,000 square miles. To allow for the irregularities of area and depth, two diagrams are included that show the average depth of water over circles of different radius; in figure 4 the radius is 25 miles, and in figure 5 the radius is 40 miles. To prepare these diagrams, the depths at each township corner were transferred to a 1:1,000,000-scale base; a circle of the chosen radius was then centered successively over every fourth township corner, the average depth within the circle at each point was calculated, and the resulting values were contoured. In order to provide closer control near the edge of the lake where the values are changing rapidly, averages were calculated for every township corner along two east-west lines. The 100-foot contour interval selected for these maps results in a spacing approximately equal to that of the 20-foot contours of the observed deformation, an aid to visual comparison. A series of profiles (fig. 6) based on figures 3, 4, and 5 affords still another means of comparison.

## POSSIBLE CAUSES OF DEFORMATION

### SUPERFICIAL VERSUS DEEP-SEATED EFFECTS

Inasmuch as the surface of Lake Bonneville at its highest level stood some 500 to 1,000 feet above the floors of the present intermontane valleys, the Bonneville shoreline is generally high on the piedmont or mountain slopes and is therefore cut into or close to bedrock. As a result, the differences in elevation shown in figure 3 cannot be ascribed to slumping in areas of deep sediment fill, to local compaction, or to any other super-

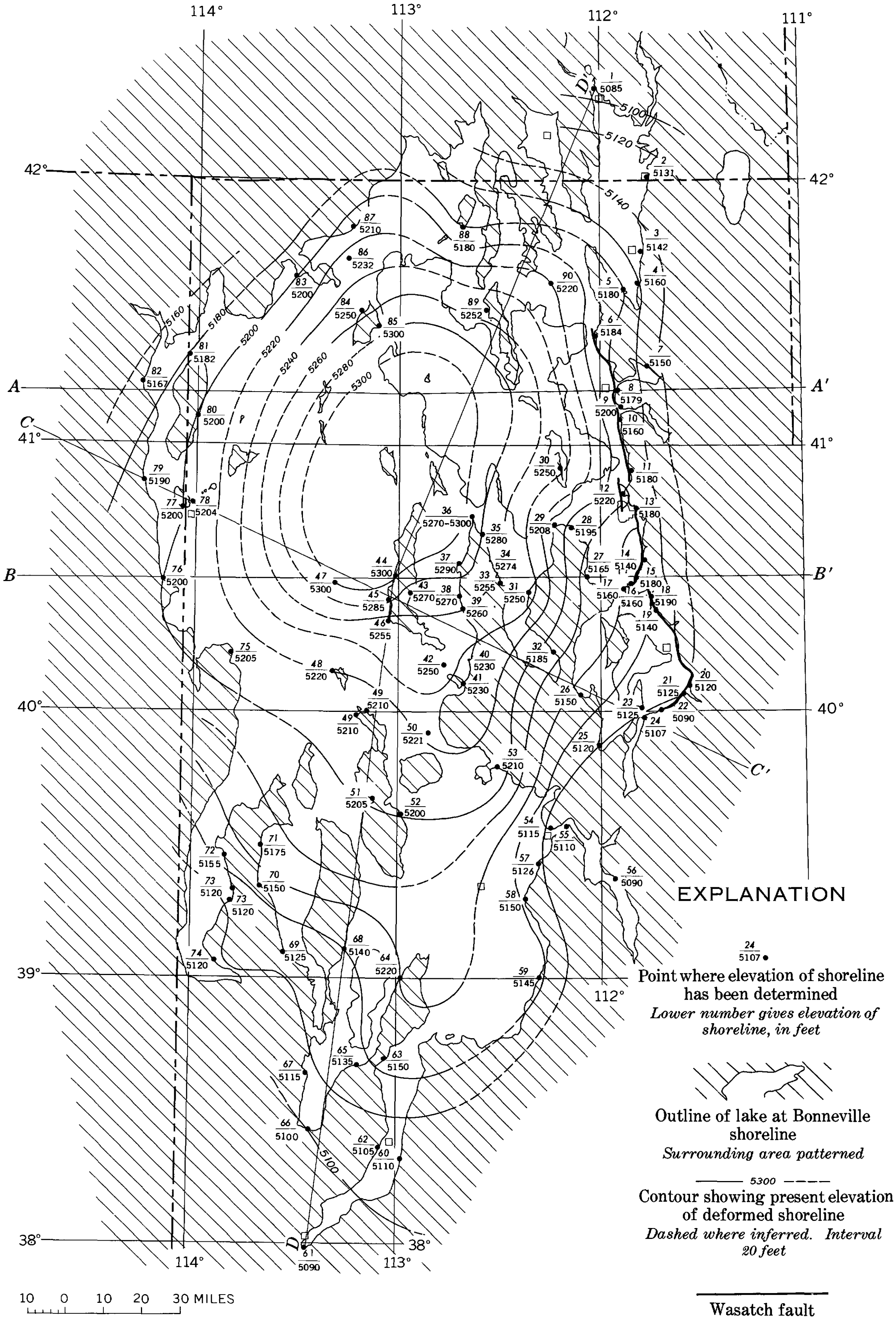


FIGURE 3.—Map showing deformation of the Bonneville shoreline.

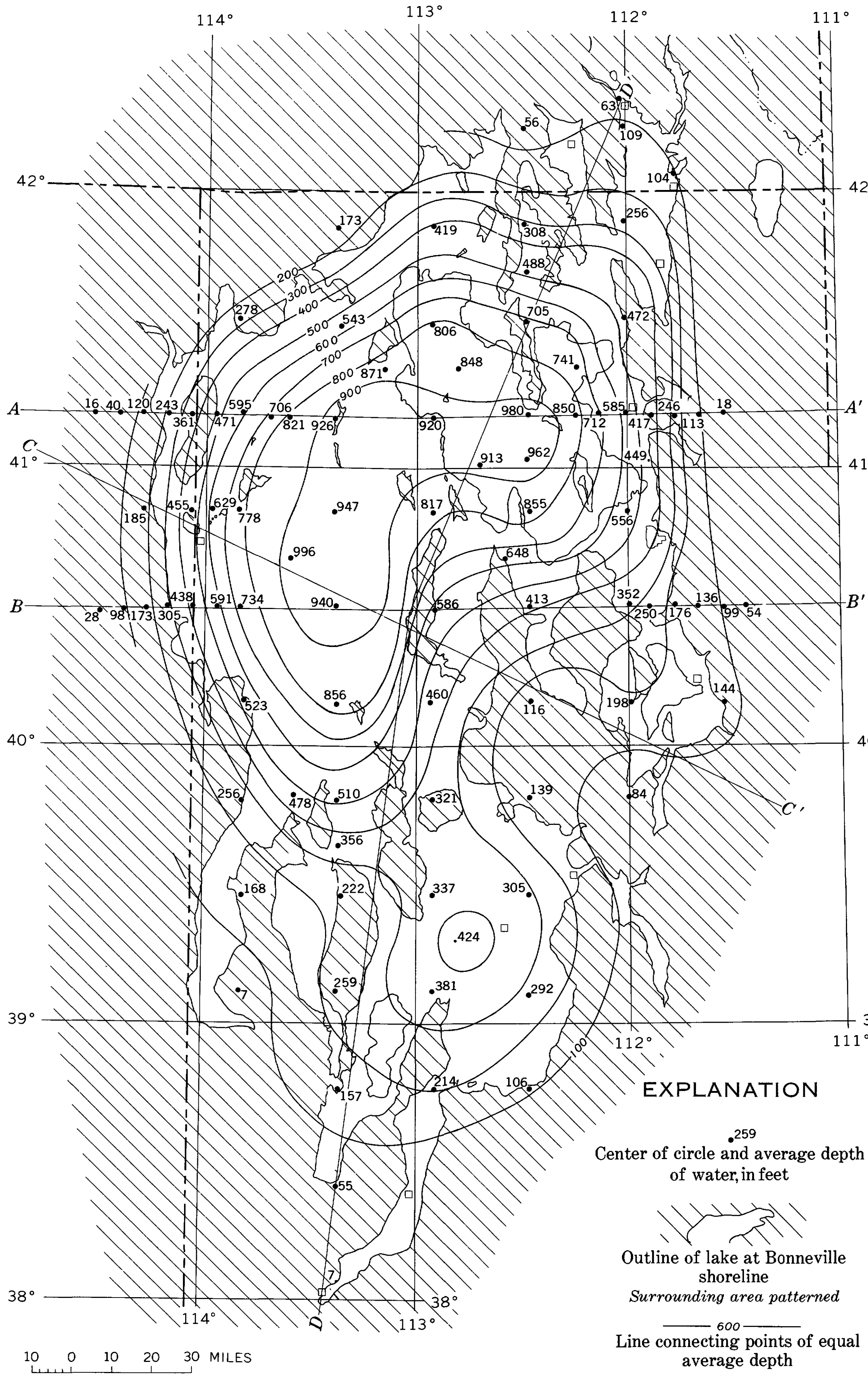


**Figure 4.**—Map showing depth of water averaged over circles of 25-mile radius.

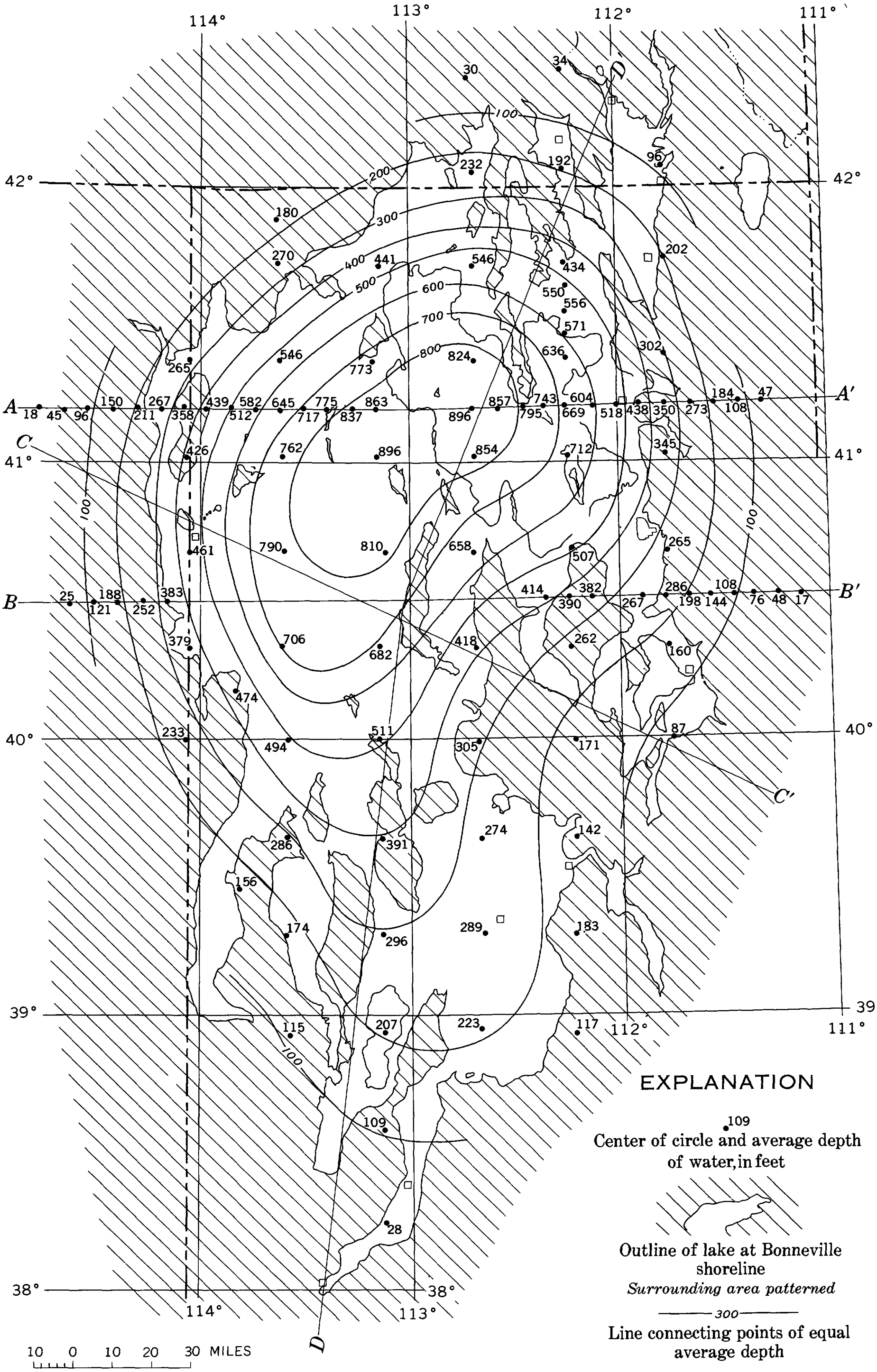


FIGURE 5.—Map showing depth of water averaged over circles of 40-mile radius.

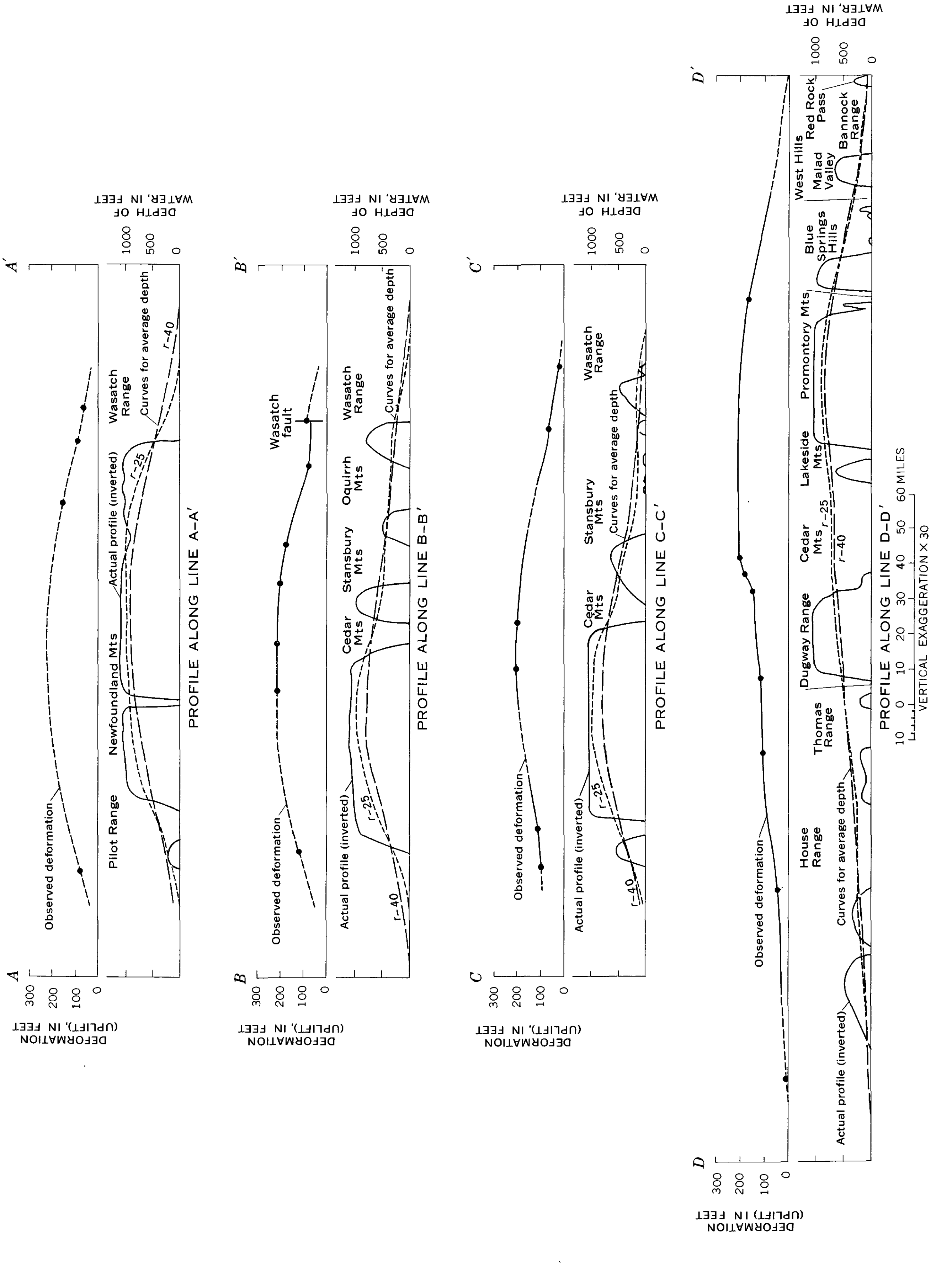


**Figure 6.—Profiles showing observed deformation and average depth of water.**

ficial effects. Although this conclusion is evident from the magnitude and great lateral extent of the deformation alone, it is reinforced by the fact that shorelines extend in many places from one range to another across areas of deep fill without appreciable deviation. Moreover, the observed deformation requires first subsidence, then uplift, a sequence of events that could never be produced by local surficial means. Because the deformation has affected the crust of the earth over an area of more than 35,000 square miles, the processes by which this deformation took place must have operated at great depth—probably below the crust. The possible causes to be examined include (a) elastic compression of the crust, (b) epeirogenic movements unrelated to Lake Bonneville such as tilting, warping, and arching, and (c) isostatic response brought about by plastic flow beneath the crust or by some other mechanism.

### ELASTIC COMPRESSION OF THE CRUST

The first and most rapid mode by which the earth responds to a load like that of Lake Bonneville is by elastic compression of the crust. That this response requires only a few years is shown by the fact that Lake Mead has depressed the crust in some places as much as 7 inches in 15 years, an amount close to that predicted by theory (Raphael, 1954, p. 1). To calculate the elastic compression caused by Lake Bonneville it will be assumed that a load ($\sigma_z$) of 1,000 feet of water is placed on a column of crust 50 km thick, for which Young's modulus ($E$) is approximately $7\times10^{11}$ dynes per cm$^2$ and Poisson's ratio ($\nu$) is 0.25. For simplicity it will be assumed that the load is of infinite horizontal extent, and that deformation of the column in the horizontal plane is zero. Under these conditions, $\epsilon_z$, the unit shortening in the vertical direction becomes

$$\epsilon_z=\frac{\sigma_z}{E}\left[\frac{(1+\nu)(1-2\nu)}{1-\nu}\right],$$

and the total shortening, $\Delta Z=\epsilon_z Z$. Substituting the values given above, $\Delta Z=178$ cm or approximately 6 feet.

A more sophisticated treatment of elastic deformation involving the earth as a whole was presented recently by Slichter and Caputo (1960), who show that for an ice load 900 km in diameter, the elastic deflection would be 3 percent of the ice thickness. But because this percentage decreases as the load decreases in diameter, a load the size of Lake Bonneville (200 km in diameter) would result, by extrapolation of the values Slichter and Caputo have given, in elastic deflection in the center of the load of only about 0.5 percent, or for 900 feet of water, 4.5 feet. This is the same order of magnitude as that obtained earlier.

Since both values are within the limits of error in many of the shoreline elevations, it is obvious that elastic compression is not the principal mechanism involved; its effects will therefore be ignored, for the present, in dealing with the isostatic deformation.

### EPEIROGENIC DEFORMATION

It has been argued (for example, Heylmun, 1960) that the observed deformation of Lake Bonneville shorelines could have resulted entirely from secular movements that had nothing to do with the presence of the lake; the coincidence of the load with the pattern of deformation being either fortuitous or due to long-continued deep-seated secular movements that gave rise to both the basin and the deformation. Such movements might, in theory at least, involve almost any combination of (a) tilting on a regional scale, (b) doming or subsidence of the entire basin, or (c) local uplift or warping within the basin. Let us examine the evidence for and against each of these.

#### REGIONAL TILTING

Tilting on a large scale is eliminated as the principal causative factor by the symmetrical character of the domical uplift that affected the shorelines of Lake Bonneville. It is nevertheless desirable to consider the possibility that tilting on a smaller scale has occurred but is partly concealed by some larger phenomenon. This can be done by comparing the elevations of the shorelines at the extremities of the lake.

The places least subject to effects related to the lake itself are at the ends of long shallow arms that extended well away from large areas of deep water. The site of Lund, near the south end of the lake, lay at the end of such an arm—a narrow one that extended to a point 30 miles south of Milford, with an average depth of less than 50 feet. The elevation of the Bonneville shoreline decreases gradually from 5,105 and 5,110 feet near Milford (fig. 3) to 5,090 feet at the extreme south end of this arm. It is 5,100 feet at the extreme south end of the adjoining Sevier Lake arm and 5,120 feet at the south end of the Snake Valley arm, farther northwest. Since neither of these localities was so far from deep water as the arm near Lund, 5,090 feet may be regarded as the normal elevation for this end of the lake. This figure is confirmed by Varnes' determination of 5,090 feet on a similar narrow arm that extended up the Sevier River to the site of the Sevier Bridge Reservoir.

At the north end of the lake, in southern Idaho, there is, unfortunately, no topographic control in Curlew Valley (fig. 1) or in the valley near Malad. In Cache Valley, however, along the north end of the Wasatch Range, the Bonneville shoreline gradually descends northward, being 5,142 feet at Logan, 5,131 feet at Franklin, and 5,085 feet at Red Rock Pass. The last figure is 23 feet less than Gilbert's, which was 5,108 feet (1890, p. 412, table 23), and about 60 feet less than the estimate of Williams (1952). It was obtained by using Gilbert's spirit-level measurement of 303 feet for the difference in elevation between the Bonneville shoreline and the Swan Lake station and adding this amount to the elevation of the USC&GS bench mark Y–261 on the railroad at Swan Lake; it was further checked in the field by locating the shoreline along the north edge of Poverty Flats (T. 13 S., R. 39 E.), a few miles to the southeast, where it consistently falls below the 5,100 contour on the map of the Preston quadrangle. As the elevation of the shoreline at Red Rock Pass, according to the newest figures, is only 5 feet less than it is near Lund, there cannot have been any appreciable tilting of the basin as a whole in a north-south direction.

Tilting or warping in an east-west direction is more difficult to measure because the lake is mainly bounded on the sides by relatively steep linear mountain slopes along which deep water reached almost to the shore. On the west side, where there are no deep reentrants, the effects of loading extend well beyond the limits of the old shoreline. The problem is further complicated on this side by the fact that there was a high-level lake in the adjoining basin of Goshute Valley. This lake contributed to the load, but because it was not connected with Lake Bonneville its shorelines do not aid in measuring the deformation.

Conditions on the east side are somewhat better, because the lake entered two of the deep river canyons near Ogden and flooded the back valleys behind the Wasatch Range. Unfortunately, however, the usefulness of this fact is reduced because of uncertainty regarding the extent of the post-Bonneville faulting along the mountain front. Although the amount and direction of fault displacement can be measured at the range front, the extent to which these movements affected the elevations of the shorelines in the back valleys cannot be determined independently. The only means, therefore, of estimating east-west tilt is to compare the average water levels on the east and west sides along shores of equal steepness and depth. It is evident from figure 3 that the distribution of islands and of open water along the two sides of the lake was so unequal that precise comparisons cannot be made without detailed computation of loads, and this cannot be made until we have reliable shoreline elevations at many more points along the west side of the basin than we do now. In general, however, the elevations along the west side average about 5,200 feet; whereas those along the east side, in places where there has been little or no faulting, average about 5,175 feet. This suggests a possible uplift on the west side of from 20 to 30 feet.

### REGIONAL DOMING

Heylmun (1960, fig. 1) noted that the pattern of uplift shown on Gilbert's map (1890, pl. 46) resembles that postulated by Harris (1959, p. 2639) for a Mesozoic uplift in western Utah and eastern Nevada, and he therefore concludes:

> As outlined by Harris, the Sevier Arch has a configuration very similar to the contouring shown on figure 1, so it is suggestive, if not positively proved, that the warping is, in fact, the result of the continued influence of the Sevier Arch.

This conclusion is untenable for the following reasons:

1. The supposed resemblance between the two patterns of deformation depends on Gilbert's incomplete data in the central part of the lake and on his erroneous data regarding Escalante Bay.
2. It ignores the fact that the central part of the Bonneville basin contains the lowest point in the eastern Great Basin, a condition that could not have resulted from doming.
3. It requires a belated rebirth within this limited area of an uplift that was formed early in the Laramide orogenic activity and that extended over all of easternmost Nevada and the western part of Utah. This uplift, moreover, has been thoroughly broken up by the block faulting that characterizes the Basin and Range province.

Viewed broadly, the evidence recorded by the old shorelines of Lake Bonneville is inconsistent with any hypothesis involving prolonged secular changes. As will be shown later in discussing chronology, the part of the Bonneville sedimentary record already deciphered reveals as many as three high stands prior to that at the Bonneville shoreline. But both Gilbert's pioneer work and the recent more detailed studies show that whereas the whole system of shorelines has been domed upward some 200 feet in the center, there is not enough divergence in many places between the early strandlines and later ones to be detectable without detailed study. This would not be so if the basin or any large part of it had undergone continuous tilting. If it had, the younger shorelines would have become progressively higher on one side of the lake and lower on the other. At present there is no evidence that they do.

Secular upwarping or subsidence that fortuitously coincided with the lake basin would have had a similar effect, but the difference of elevation would have been concentrated in the center of movement; any given strandline would in the first instance be lower than all its predecessors, whereas in the latter instance it would be higher. This result, too, is out of accord with the known facts.

The history of Lake Bonneville is so complex that the effects of relatively slow secular movements could well be obscured by the differences in elevation between the thresholds that controlled the major cycles. Nevertheless, it is clear that the amount of secular movement that took place between the Alpine and Bonneville cycles is very small compared with the movement that has taken place since. Present evidence indicates that there is only one way in which the observed shoreline deformation could have been produced by purely fortuitous means. The lake basin would have had to remain virtually stationary during all of the Alpine cycle and the early part of the Bonneville cycle, so that the Alpine and Bonneville shorelines would be, at most, only a few tens of feet apart. Upwarping must then have begun and proceeded at the rate required for isostatic adjustment, but it must now have almost if not wholly stopped. The uplift must, moreover, have been domical in outline and must have affected an area just large enough to include all of Lake Bonneville. The amount of coincidence required by this explanation makes it hard to accept.

#### LOCAL WARPING

In spite of the lack of evidence for large-scale secular movements, certain minor irregularities in the shorelines suggest that local warping has occurred at some places within the basin. It is evident from figure 3 that the normal slope characterizing the domical upwarp in the northern part of the lake, whatever its cause, is 2 to 2½ feet per mile. On the southwest side of the Cedar Mountains, however, the surface rises northward at a rate of 4½ feet per mile between stations 44 and 46 but flattens abruptly to the south between stations 46 and 49. (See also section D–D′, fig. 6.) As no recent faulting is known to have occurred along the Cedar Mountains, these irregularities seem to be best explained by local warping. Similar irregularities are evident in the profile across the Stansbury and Oquirrh Mountains (profile B–B′, fig. 6), though it is possible that these are due to faulting.

Recent data from D. J. Varnes (written communication, 1961) show similar anomalies along the southeast edge of the basin near Leamington; three stations spaced at intervals of about 2 miles along the Bonneville shoreline beginning 3½ miles northeast of station 57 (fig. 3), show a continuous decrease in elevation from 5,126 feet at that point through 5,125, 5,100 and 5,090 feet, yet the shoreline rises again to 5,110 feet at the next station (Leamington, 55). Other local irregularities will perhaps be revealed as more accurate elevation data accumulate.

## ISOSTATIC DEFORMATION

### MODE OF RESPONSE

Because of the inadequacy of the preceding alternative explanations, I am forced to conclude, as Gilbert did, that the principal cause of the observed doming of the earth's crust in the Lake Bonneville area was an isostatic response to removal of the load of water. It is desirable to state explicitly just how that response is believed to have taken place.

When subjected to a load whose magnitude has been estimated, the earth's surface is presumed to have been bent downward by an amount proportional to the load and at a rate determined by the physical properties of the crust and the material beneath it. If time were sufficient for this process to reach its conclusion, the amount of deflection would be exactly that required to restore isostatic balance. It is further assumed that while the earth was thus depressed, the water of the lake formed beaches and rock-cut terraces that recorded the exact position of the shoreline both on the margins of the lake and on islands and headlands near the center. Finally, when the water evaporated and the load was removed, the earth again sought to return to a condition of equilibrium. As a result, the once-level shorelines were bowed upward; and if time permitted, they would rise by an amount theoretically equal to the initial downward deflection.

Obviously this picture is vastly oversimplified. In practice it is unlikely that any surface load, particularly one of small extent, would be fully compensated, or that recovery would be complete when the load was removed. It is evident also that inasmuch as the only measure of the amount of initial downwarping is the present upward doming, any extent to which the earth has failed to return to its original position will further reduce the apparent degree of compensation. What is more important, the process depicted above as relatively static and consisting of a single cycle actually consisted of a continuous response to a constantly varying load. In the following pages, some but not all of the simplifying assumptions are discussed and evaluated.

Theoretical examination of the mechanical and hydrodynamic processes within the earth that give rise to this surface response has been carried out by Daly (1934), Haskell (1935), Gutenberg (1941), Niskanen (1948), Vening Meinesz (1937), and many others. Although the individual treatment of the problem varies, it is generally agreed that the basic mechanism is an essentially hydrostatic response of a floating crust supported by a highly viscous but fluid substratum. The crust is presumed to act as an elastic plate sufficiently strong to resist the shear stresses caused by the load. This shear strength is assumed to affect the configuration of the response by acting to distribute a point load over a finite area; but otherwise, the crust will be assumed to be essentially inert and to follow more or less closely the plastic movement of the subcrust. Analysis of the isostatic phenomenon is therefore concerned almost exclusively with the viscous response of the substratum.

Some writers have dealt with the resulting movements within the substratum in terms of spherical harmonics, as if they involved virtually the entire globe (Niskanen, 1948); others have dealt with harmonic loading in a two-dimensional model in which the curvature of the earth is neglected (Heiskanen and Vening Meinesz, 1958, p. 361). Both groups, however, have reached the following conclusions regarding the essential nature of the process:

1. A central depression is developed beneath the load by outward flow of material in the subcrust.
2. A peripheral bulge due to the presence of this outward-moving material should, at least in theory, form around the initial depression.
3. The time required to attain a given degree of isostatic adjustment, or recovery, will vary directly as the viscosity of the substratum and inversely as the diameter of the load but is essentially independent of its magnitude.

Another mechanism, that of phase changes, has been widely discussed recently as a possible explanation of both the Mohorovicic discontinuity itself (hereafter referred to as the Moho) (Kennedy, 1959) and of smaller discontinuities at much deep levels (see for example, Birch, 1951). In either case, however, though phase changes may modify the rate of movement, they are incapable of accounting for both such movements and isostatic adjustment. MacDonald and Ness (1960, p. 2180) also discussed the long-term changes in surface elevation as related to phase changes at the Moho, but in every example they ascribed the isostatic adjustment to some unrelated, more deep-seated, and much more rapid mechanism. Similarly, Vening Meinesz (Heiskanen and Vening Meinesz, 1958, p. 369) took deep-seated phase changes into account in deriving an effective value for the viscosity of the subcrust from the data for Fennoscandia, but he believed the principal mechanism to be viscous flow. The phase-change mechanism was examined most recently by Broecker (1962), who concluded that for probable values of the geothermal gradient and of the heats of transformation, phase changes at the Moho are insufficient to account for more than ⅓ to ⅕ of the rebound observed at Lake Bonneville.

## CRUSTAL MODEL

To evaluate the significance of isostasy as a mechanism of crustal response, it is necessary to establish a model of the sort of crust to which a load is being applied. A very simple model will suffice, in which the following parameters are assumed:

| | *Crust* | *Mantle* |
|---|---|---|
| Thickness | 50 km | ---- |
| Mean density | 2.80 | 3.25 |
| Bulk modulus | $10^{12}$ dynes per $cm^2$ | ---- |

The thickness of the crust in this area includes part of the intermediate layer with a compressional-wave velocity of 7.59 km per sec as determined by Berg and others (1960, p. 529) by seismic methods. The mean density of the crust is determined by combining their velocity model with Woollard's relation between velocity and crustal density (1959, fig. 7). Although the value of 50 km assumed for the thickness of the crust in this area is larger than that obtained by a more recent seismic study (L. C. Pakiser, written communication, 1962), it is not unreasonable when dealing with problems of isostatic compensation. D. R. Mabey (written communication, 1960) analyzed isostatic anomalies for 12 pendulum stations in the Basin and Range province and found that Pratt-Hayford anomalies are smallest for a depth of compensation of 56.9 km. Hayford's (1910, p. 58) observation of deflections of the vertical over another area of similar extent indicate a probable depth of compensation of 66 km.

## COINCIDENCE OF UPLIFT AND LOAD

The most obvious method of determining whether isostasy is a significant cause of the observed uplift of Lake Bonneville is to compare the uplift with the load. A remarkable coincidence between the pattern of uplift (fig. 3) and that of the load represented by the ancient lake (figs. 4, 5) can be seen almost at a glance. The greatest uplift occurred over the deepest water, between the present west shore of Great Salt Lake and the Bonneville Salt Flats. A secondary lobe of uplift extended southward over the area of deep water that occupied what is now the Sevier Desert. Smaller lobes correspond in position with the arms that occupied Cache Valley and Malad Valley. Examination of the 5,200-foot contour shows that except for the possibility of a small secular eastward tilt, noted earlier, the configuration is nearly symmetrical with respect to the outline of the lake.

The highest shorelines observed stand at an elevation of 5,300 feet in the area of the Cedar Mountains, on Wildcat Mountain, and in the Hogup Mountains. The distribution of these points with respect to deep water suggests that equal or perhaps slightly greater elevations may be found in the Newfoundland or Lakeside Mountains. In any case, the maximum height now known (5,300 feet) indicates uplift of some 210 feet above the elevations of the shorelines at the south end of the lake and above its outlet at the north end. Excluding Gilbert's dubious points in the Escalante Desert, this figure is about a fourth larger than the range of 177 feet observed by Gilbert between the lowest point and that at the north end of the Stansbury Mountains (Gilbert, 1890, p. 366–367). In spite of these differences, the results derived from the newest information show such close correlation between doming and load as to fully confirm Gilbert's conclusions that the deformation was caused by isostatic response to unloading.

### DEGREE OF ISOSTATIC COMPENSATION

Knowing both the load that has been applied to a segment of the earth's crust and the amount of deflection that has resulted, it should theoretically be a simple matter to calculate the extent to which isostatic balance has been reached. Let us assume that a load is placed on a floating crust supported by a viscous substratum with a density of 3.25. In this theoretical model, both the strength of the crust and the viscosity of the subcrust will be neglected, and isostatic compensation is therefore assumed to be complete. The result of loading under these conditions will be to depress the crust until the weight of the subcrustal material displaced is equal to the load. On this basis, the deflection ($w$) produced by a given load would be inversely proportional to the ratio between the density of the load ($\rho$) and that of the substratum ($\rho'$). Because the load is water with a density of 1, $w=\frac{h}{\rho'}$, where $h$ is the depth of the water. The 1,100 feet of water in the central part of the basin would thus be theoretically capable of depressing the crust 340 feet. But this figure was the maximum spot depth whereas islands and other irregularities in the floor of the basin make the average depth considerably less. As shown by figure 4, the maximum depth of water in the central part of the basin over a circle of 25-miles radius was about 980 feet, a little south of the tip of Promontory Point. This amount of water would have been capable of depressing the crust about 306 feet, so that the observed uplift of Bonneville shoreline, 20 feet, indicates that isostatic compensation is 68 percent complete. On this same basis, 70 percent compensation is indicated for the northern Stansbury Mountains, and 59 percent is indicated for the northern Dugway Range. Similar estimates for other parts of the basin would seem to indicate that the maximum observed uplift is on the order of 70 percent of the theoretical maximum.

This figure, however, is probably too low, for each attempt to evaluate one of the original simplifying assumptions brings the actual isostatic response more nearly into agreement with that required by theory. For example, because the shear strength of the crust is not zero, the point loads applied at the surface may be effectively distributed over an area materially larger than the 25-mile radius used to derive the original figure of 68 percent compensation. A simple empirical means of allowing for this factor is to increase the size of the circles over which the depth of water is averaged until the slope of the resulting curve (fig. 7) matches that of the deflection observed at the edge of the load. By interpolating between the curves for 25 and 40 miles, it seems likely that a value of 35 miles would produce a reasonable match. At that value the greatest average depth of water is about 925 feet, which would make the calculated deflection about 285 feet if the assumed crustal density is 3.25. On this basis, the degree of isostatic adjustment represented by an uplift of 210 feet would be increased from 68 percent to about 73 percent.

Another factor open to question is the density assumed for the material displaced from beneath the load. The value 3.25 used here is in good agreement with the value obtained by applying the compressional-wave velocity of 7.97 km per sec determined by Berg and others (1960, p. 530) for material below a depth of 72 km in the vicinity of Great Salt Lake to the curves given by Woollard (1959, p. 1530, fig. 7) for the relation of velocity to density. But this value holds good only if compensation is effected entirely by movement of material immediately below the crust. Daly (1934, p. 138), recognizing this problem, calculated what might be called the effective density of the material displaced beneath the Fennoscandian ice cap, as follows:

> If, as seems probable, the ice cap was full-bodied for a time longer than the Post-Glacial epoch, the Fennoscandian crust was basined almost or quite to the limit demanded for equilibrium with the rest of the earth. If the assumption is correct, we can secure an estimate of the density of the material that was displaced horizontally when the crust was basined. The thickness of the ice cap at its center was probably at least 3,000 meters. In order that the central non-elastic deepening of the basin should be 550 meters, the mean density of the material horizontally displaced, beneath the crust, was about 4.9. If the thickness of the ice at the center was 3,500 meters, the mean density of the material so displaced was about 5.7

Unfortunately, Daly does not explain how these values were obtained; but as $\frac{3,000}{550} = 5.4$ and $\frac{3,500}{550} = 6.3$, it seems probable the smaller values included some allowance for the fact that the loads are of finite rather than of infinite horizontal extent.

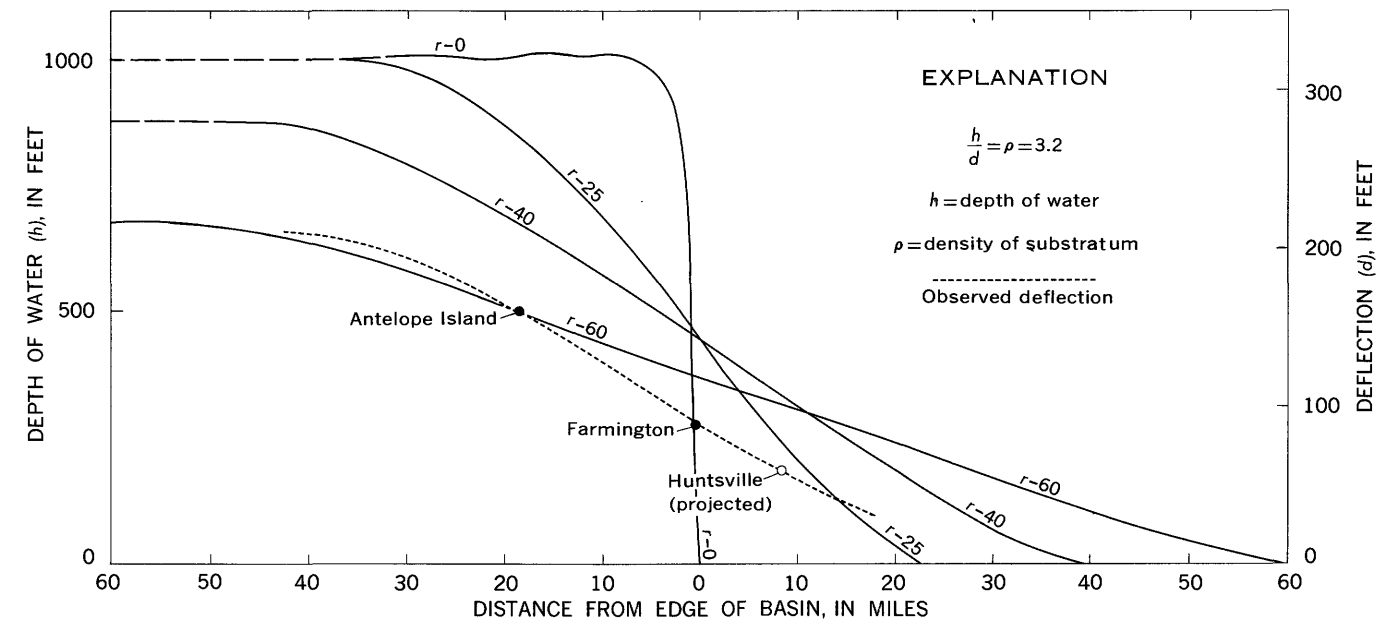


FIGURE 7.—Comparison of observed deflection with depth of water averaged over various radii.

Later, however, Daly (1940, p. 320) abandoned the idea of deep flow in favor of movement concentrated at the base of the lithosphere. Gutenberg (1941, p. 757), however, apparently still favored the theory, for he says:

> * * * the conclusion seems inevitable that the movements extend to many hundreds of kilometers downward with scarcely decreasing amplitudes.

However this may be, if even the smaller of Daly's effective values for Fennoscandia were used for Bonneville, the maximum theoretical uplift would be reduced to $\frac{1{,}000}{4.9} = 204$ feet, which would indicate that isostatic adjustment was more than 100 percent.

Actually Daly's figures may have quite another significance. They are based, as indicated by his words "* * * almost or quite to the limit demanded by equilibrium * * *," on the assumption that isostatic adjustment under the given load was complete, a condition that is inherently improbable. And as any failure to attain complete compensation would serve to increase the effective value of the density, the surprisingly high values Daly found may indicate a lack of isostatic adjustment rather than a high density. If, for example, the 550 meters of nonelastic deflection of the crust recorded by Daly represented only 75 percent isostatic compensation, the amount of movement that should have taken place would be $\frac{550}{0.75} = 747$ meters. The resulting density would then be reduced from 4.9 to 3.6, a value that seems much more reasonable. At any rate, because the thickness of the ice cap, which Daly gave as 3,000 meters, has been estimated by others (Charlesworth, 1957, p. 42) as ranging from 1,000 to 4,000 meters, the evidence from Fennoscandia does not seem capable of yielding reliable information about either the degree of compensation or the density of the material displaced.

As applied to Lake Bonneville, this conclusion indicates that the density of 3.25 provisionally used must assuredly be a minimum, for if any large part of the outflow of material from beneath the crust was significantly deeper than 75 km, the assumed density would have to be increased, and the apparent degree of compensation would consequently be even greater than the 75 percent already calculated.

A still more effective means of evaluating the overall degree of compensation is to compare the total load of water, obtained from figures 4 or 5, with the weight of material displaced, as derived from figure 3. To do so, the contours on each figure were first completed around the margins of the lake by projection using a spacing comparable with that within the lake where some control is available. The area within each contour was determined by planimeter, and the volume between each contour was calculated by the formula $V = \frac{1}{3}(A_m + A_n + \sqrt{A_m A_n})(m-n)$, where $m$ and $n$ are given contours, and $A_m$ and $A_n$ are the areas within those contours, respectively. The total volume displaced, determined by this method, was found to be $1.0 \times 10^{14}$ cu. ft. Using a density of 3.25, this represents $1.03 \times 10^{13}$ tons. Because of the lack of control beyond the margin of the lake, this value is not significant beyond the first figure.

The corresponding value for the weight of water, obtained from figure 5 by an identical method, is $1.15 \times 10^{13}$ tons. The agreement between these figures suggests that compensation during the high stand of the Bonneville cycle may well have been essentially complete, but the error involved in extending the contours on figure 3 and errors due to lack of geodetic control in parts of the lake may affect the volume displaced by as much as 10 or 20 percent. The coincidence should, therefore, be regarded only as verifying that the degree of compensation is high; probably in excess of the 75 percent already calculated.

### RATE OF RESPONSE

Evidence has been presented that the high shorelines of Lake Bonneville have been domed upward by an amount equivalent to at least 75 percent of that required for complete isostatic adjustment. It is desirable now to consider the evidence available from geology regarding the rates at which this response has taken place.

#### GEOLOGIC CHRONOLOGY

Estimates vary widely for both the duration and the timing of the salient events in the history of Lake Bonneville. Only a few radiocarbon dates have been obtained from woody material, and still fewer have been well tied to the geologic record. Many dates have been obtained from tufa and shell material, but the evidence they provide is in conflict with that obtained by ordinary geologic methods and hence is of uncertain value. The graphs in figure 8 illustrate the present range of opinion on the lake history and chronology.

The first three graphs are based on studies of the sediments of Lake Bonneville and associated glacial deposits and soils. Eardley and others (1957, fig. 20; adapted here as fig. 8*A*) regarded the Alpine "Stage" as possibly equivalent to the Kansan glaciation of the midcontinent area and suggested a later history that does not include any long interglacial intervals.

Morrison (1961a, 1961b, and written communication, 1961) studied the stratigraphy of the lake deposits in the Jordan Valley south of Salt Lake City where these deposits intertongue with glacial sediments at the mouths of Little Cottonwood and Bells Canyons. Figure 8*B* illustrates his interpretation of the lake history. He subdivided and correlated the deposits mainly on the basis of soils formed during interglacial intervals. The oldest soil, a very strongly developed one referred to by Hunt and others (1953, p. 43) as the pre-Lake Bonneville soil, is directly overlain by sediments of the Alpine cycle and also by glacial deposits that Morrison correlated with the earlier of two stades of the Bull Lake Glaciation in the Rocky Mountain region. A second soil, somewhat less strongly developed, which he called the mid-Lake Bonneville soil, was formed on deposits as young as those of the Bonneville cycle and also on the deposits of the later stade of Bull Lake Glaciation. Morrison therefore correlated these early lake cycles with the Bull Lake and Tahoe Glaciations of early Wisconsin (Iowan) age. The youngest soil (moderately developed) formed on the youngest Lake Bonneville sediments and on glacial deposits that Morrison correlated with the Pinedale Glaciation. This glaciation is now commonly believed, from radiocarbon dating, to have begun about 26,000 years ago and to have ended between 6,500 and 7,500 years ago. The absolute age of the Alpine and Bonneville cycles, however, can only be estimated by extrapolation beyond the range of radiocarbon dating.[2]

Varnes and Van Horn (1961) made a stratigraphic study of the deposits of Lake Bonneville along the Sevier River between Leamington and Delta, Utah. The sequence of events recorded there seems to be more complicated, and presumably more complete, than that recorded elsewhere. The time interval that Gilbert originally ascribed to the deposition of the yellow clay (Alpine) is now believed to include three periods of high water separated by two recessions, one of which may be equal in duration to that which separated the Alpine from the Bonneville. The only evidence for the absolute age of these deposits is carbon-14 dates for inorganic carbonate and shells from the white marl that yielded ages of 15,000 to 19,000 years B.P. As with other carbon-14 dates on marl and shells, these are much younger than the dates obtained on woody material associated with glacial deposits of apparently comparable age.

Broecker and Orr (1958) obtained carbon-14 dates as young as 16,000 years B.P. from tufa carbonate at the Bonneville shoreline. Their chronology (fig. 8*C*) therefore agrees with that of Varnes and Van Horn rather than that of Eardley (fig. 8*A*) or Morrison (fig. 8*B*).

A chronology assigning a greater age to some Lake Bonneville features is that of figure 8*D*, which I have developed by analogy with a record prepared by Smith (1958, and written communication, 1960) from the subsurface deposits of Searles Lake, Calif. These deposits

[2] Recent work in the Little Cottonwood area by Richmond and Morrison (written communication, 1962) has revealed the existence of a well-developed soil believed to be the mid-Lake Bonneville soil between the moraines formed during the late stade of Bull Lake Glaciation and gravel deposits formed during the rise of the Bonneville shoreline. On this basis, plus evidence from other parts of the basin, Morrison now believes that the Bonneville overflow took place during the early stade of the Pinedale Glaciation, probably about 20,000 years ago. Only the Alpine cycles are now believed to correlate with the Bull Lake and Tahoe Glaciations, and to be older than 40,000 years.

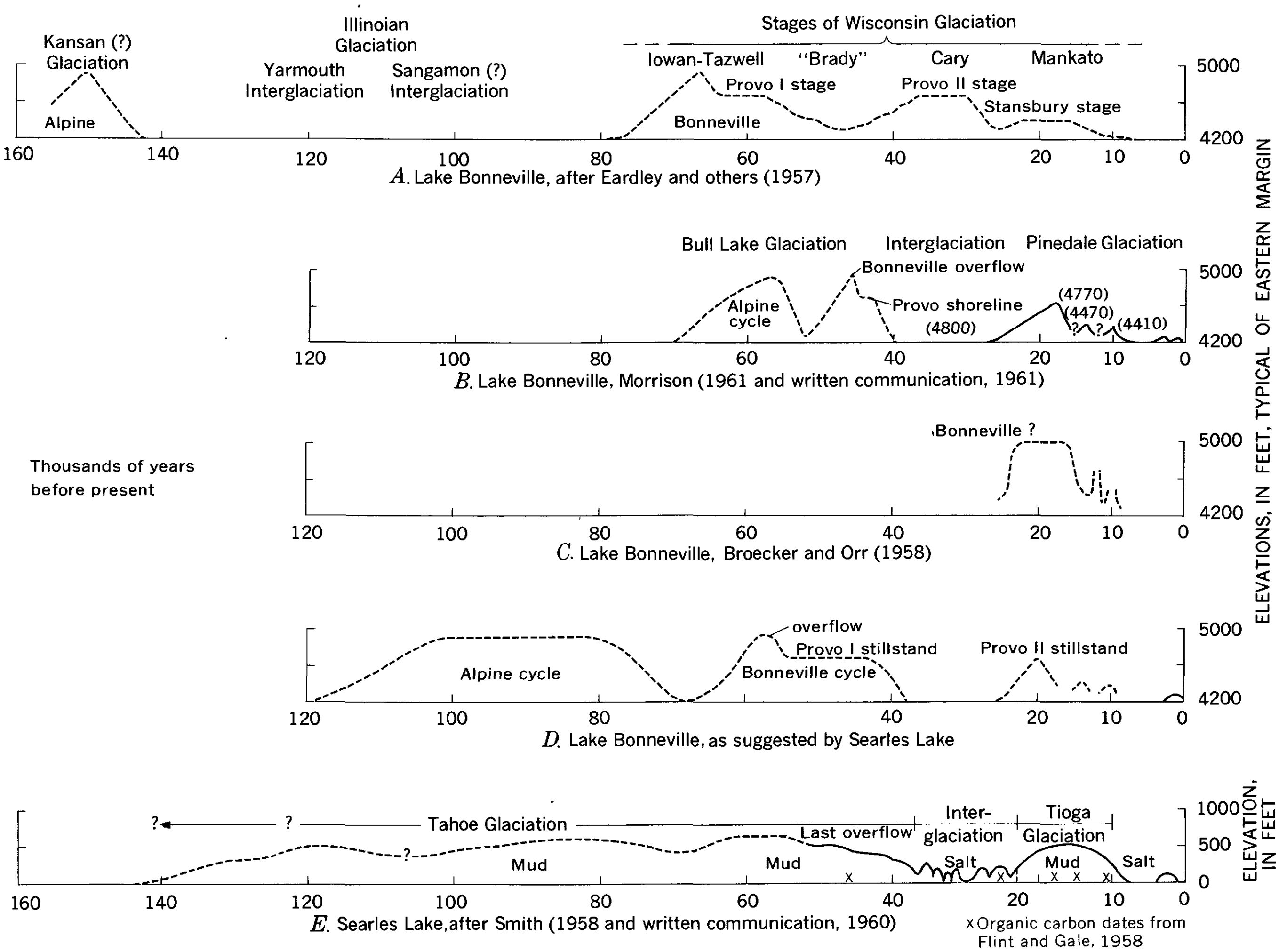


**FIGURE 8.—Graphs showing interpretations of Lake Bonneville history.**

consist of alternate layers of mud formed during glacial maxima and salt formed during the intervening periods of relative desiccation. A series of dates ranging from 8,000 years to as much as 45,000 years has been obtained on the organic-carbon fractions from this sequence (Flint and Gale, 1958, p. 707); the age of the deposits older than 45,000 years is estimated by extrapolating the sedimentation rate measured in the more fully dated upper part. Correlation between this sequence and that of Lake Bonneville hinges on the assumption that the deposits laid down in Searles Lake during the time interval between the Tahoe and Tioga Glaciations are of the same age as the soil formed on deposits of Lake Bonneville during the time interval between the Bull Lake and Pinedale Glaciations (fig. 8*B*). It also presumes that the Alpine and Bonneville cycles (figs. 2, 8*D*) together are equivalent to the whole of the Bull Lake Glaciation in the Wasatch Range and that this in turn is equivalent to all of the Tahoe Glaciation in the Sierras. This correlation is supported by the stratigraphic and soil records of Lake Lahontan, in western Nevada (Morrison, 1961a), which, like Searles Lake, received its principal water supply from the Sierra Nevada. In both the Lahontan and Bonneville records the best-developed soil is that which precedes the deposits correlated with the Bull Lake and Tahoe Glaciations. A less well-developed soil was formed at each place during the time interval between these glaciations and the younger Pinedale and Tioga Glaciations. In view of the great thickness of salt formed during this latter time interval, characterized in the Lake Bonneville area by only moderately developed soils, it seems improbable that the earlier, more strongly developed soils are to be correlated with either of the weakly recorded minima of the Searles Lake record (fig. 8*E*, 70,000 or 105,000 years B.P.). As a result, the chronology derived from Searles Lake, which agrees well with that of Morrison (fig. 8*B*) after about 40,000 years B.P., makes the Alpine and Bonneville cycles about twice as long as Morrison estimated. Not enough evidence is now available to determine which of these chronologies is the most nearly correct.

### RELATION BETWEEN GEOLOGIC CHRONOLOGY AND ISOSTATIC DEFORMATION

Graphs that relate depth of water to time (fig. 8) form a convenient basis from which to calculate the rate of isostatic response if the relation between depth and load is known. Fortunately, the northern part of the lake, where the deflection was greatest, has an unusually flat floor and steep sides (profiles, fig. 6), and the curve relating depth to volume is approximately linear (Eardley and others, 1957, p. 1145, table 1, and fig. 2). For such a body, the curves of figure 8, which show variations in depth of water or elevation of lake surface, may be used directly as an expression of load. Before attempting to deal with the effects of such continuously varying loads, however, it is desirable to examine the way in which the earth responds to a load that is applied (or removed) instantaneously. This is conveniently expressed by an equation that relates the fraction ($d$) of the ultimate response to the time ($t$), in years, since the application (or removal) of the load.

$$d=1-e^{-\frac{t}{T_r}}$$

The term "$T_r$" (called the relaxation time by Heiskanen and Vening Meinesz, 1958, p. 369) is the time, in years, during which the deviation from isostasy diminishes to $\frac{1}{e}$ of its initial value.[3] In terms of the deflection, ($d$), this is equivalent to $1-\frac{1}{e}$, or 0.63212 of its ultimate value. Accordingly, the deflection resulting from a given load will amount to 63 percent of its final value at the end of $T_r$ years, will attain 63 percent of the remainder during the next $T_r$ years, and so on. This relation is expressed graphically for $T_r$ of 5,000, 10,000, and 40,000 years in figure 9*C*. The more rapidly the earth responds to a given load, the smaller the value of $T_r$.

To apply these relations to a continuously changing load, such as that of Lake Bonneville, it is necessary to integrate the effects of each increment of load over the period of time extending from its application to the present. This has been done for Morrison's chronology in steps of 2,000 years, and the result for $T_r$ values of 5,000 and 10,000 years forms figure 9*B*. A similar calculation based on the chronology derived from Searles Lake is shown in figure 10. Both graphs involve an assumption as to the initial isostatic condition of the basin. For present purposes, isostatic equilibrium is assumed to have been complete at the beginning of the Alpine cycle; the deflection curves of figures 9*B* and 10*B* therefore begin at zero. This assumption, though apparently arbitrary, is not unreasonable. Although the basin was undoubtedly loaded and unloaded repeatedly during earlier parts of the Pleistocene, it seems theoretically probable that the intervals of time that separated the major divisions of the Pleistocene were longer than those that separated individual glaciations. This is further supported by the fact that the only deposits that have been observed beneath the deposits of Lake Bonneville along the Wasatch Range are alluvial fans; lake deposits, if they existed, are buried so deeply as to be concealed.

Comparison of these curves with the deformation observed during each cycle is a powerful tool for analyzing the extent of isostatic adjustment and the significance of different geologic chronologies. It is evident that increasing the value of $T_r$ causes a decrease in the total deflection resulting from a given lake cycle and a time delay in both warping and recovery. The maximum deflection resulting from the Alpine cycle, for example, is reduced from the theoretical maximum of 290 feet ($T_r=0$) to 220 and 160 feet for values of $T_r$ of 5,000 and 10,000 years, respectively. The effect is also delayed some 2,000 to 3,000 years. Actually, the elevation at a given high stand must be determined not in terms of the maximum deflection but by the deflection at the time when that particular stand occurred. On that basis, the calculated deflection during Morrison's Alpine maximum is reduced from 220 feet for $T_r=0$, to a little less than 200 feet for $T_r=5{,}000$ years. Other geologically significant relations to be obtained from these graphs will be discussed later.

### VALUE OF $T_r$ FOR LAKE BONNEVILLE

In spite of the uncertainties regarding the absolute chronology of Lake Bonneville, it is possible to use the graphs of calculated response to set certain limits on the value of $T_r$.

Examining first the curve derived from Searles Lake (fig. 10*B*), it is evident that even on this extended time scale a $T_r$ of 40,000 years would produce a downwarping at the end of the Alpine cycle (placed at 82,000 years B.P. on this time scale) of 140 feet. But inasmuch as the deflection observed is measured by upwarping, this must be reduced by the 75 feet of uplift that would still remain to take place at $t=0$ (present). Hence, the maximum uplift of the Alpine deposits for

[3] The fraction $\frac{1}{e}=\frac{1}{2.718}$ was used by Vening Meinesz and will be used here; any other fraction could be used, with the appropriate modification of $T_r$.

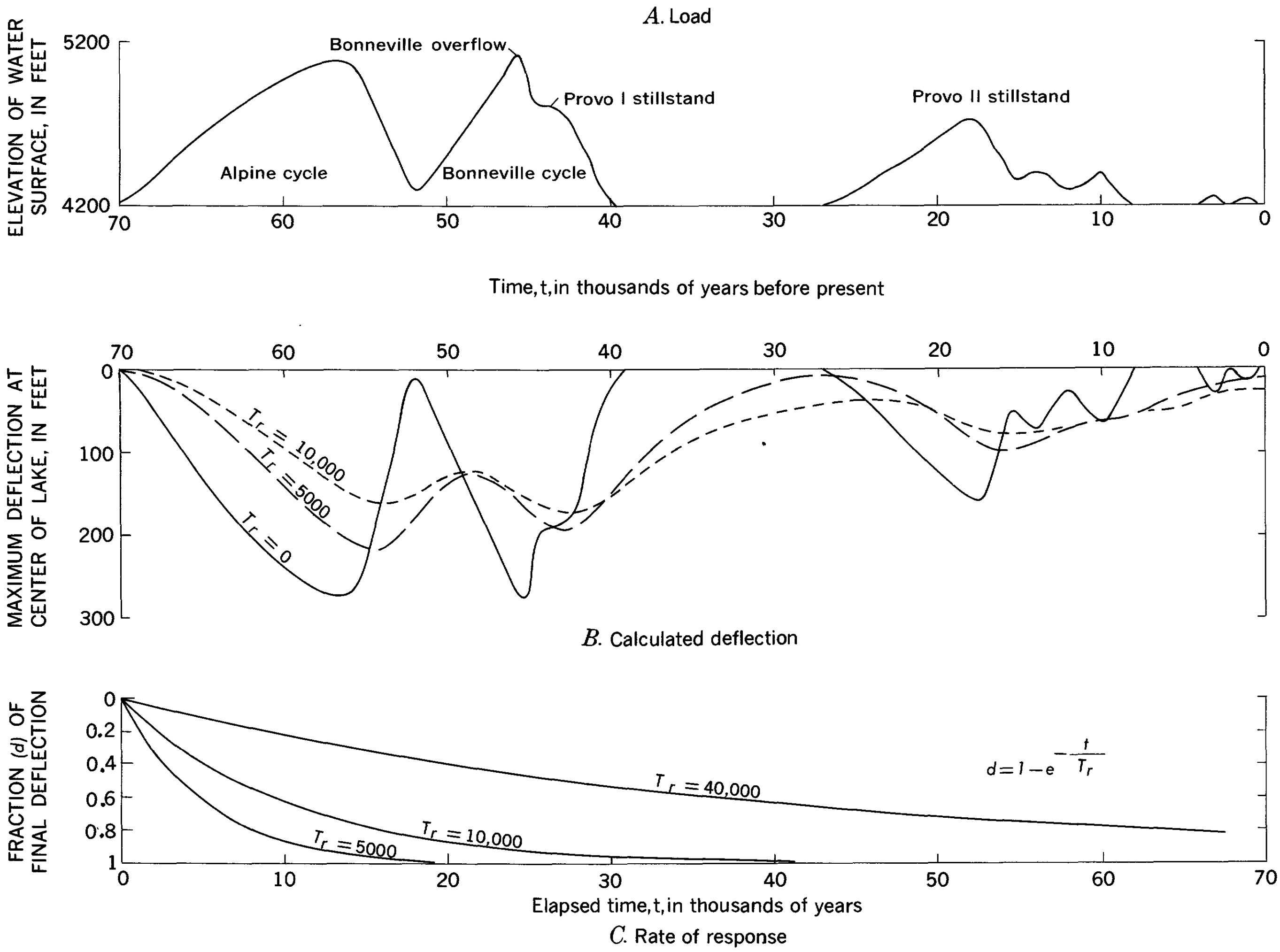


FIGURE 9.—Calculated deflection based on Morrison's curves. *A*, Load expressed as variations in elevation of lake surface; *B*, calculated deflection at center of basin for various values of $T_r$, assuming a linear relation between water depth and load and a subcrustal density of 3.25; *C*, fraction of final deflection, at a given time, for various values of $T_r$.

$T_r$=40,000 years would be 140 less 75, or 65 feet—only a third of that observed. The corresponding deflection of the Bonneville shoreline (57,500 years B.P.) would be 130 feet less 75, or 55 feet. From this disagreement between the calculated and observed deflection it is clear that $T_r$ for Lake Bonneville cannot have been as great as 40,000 years.

The curve (fig. 10*B*) based on a $T_r$ of 10,000 years yields a deflection for the Alpine cycle (84,000 years B.P.) of 260 feet, which, after allowing 30 feet for the residual uplift, reduces to 230 feet, a figure not too far from that observed (210 feet). On this same basis, however, the maximum water load in the Bonneville cycle caused a deflection of only 150 less 30, or 120 feet. This value is much too low; moreover, as far as is known, there is no such difference in elevation between the high deposits of the Alpine and Bonneville cycles near the center of the basin (p. E26). Further downward adjustment of $T_r$ will only increase the discrepancy at the Alpine cycle, however; and therefore, in spite of the poor match, it seems that a value of 10,000 years for Lake Bonneville is a reasonable compromise. Because it is based on the extended time scale inferred from Searles Lake, it represents a maximum for Lake Bonneville.

Considering now the more restricted time scale of Morrison (fig. 9), it is evident that a $T_r$ of 5,000 years yields a deflection at the Alpine maximum (placed by Morrison at 56,000 years B.P.) of 200 less 10, or 190 feet, which is very close to the value observed. The Bonneville maximum (45,000 years B.P.) yields a somewhat less satisfactory result (160 less 10, or 150 feet), but the difference depends in large part on the configuration of the curves, which is highly subjective. By interpolation, a value of $T_r$ of about 4,000 years seems to be the best that can be obtained from Mor-

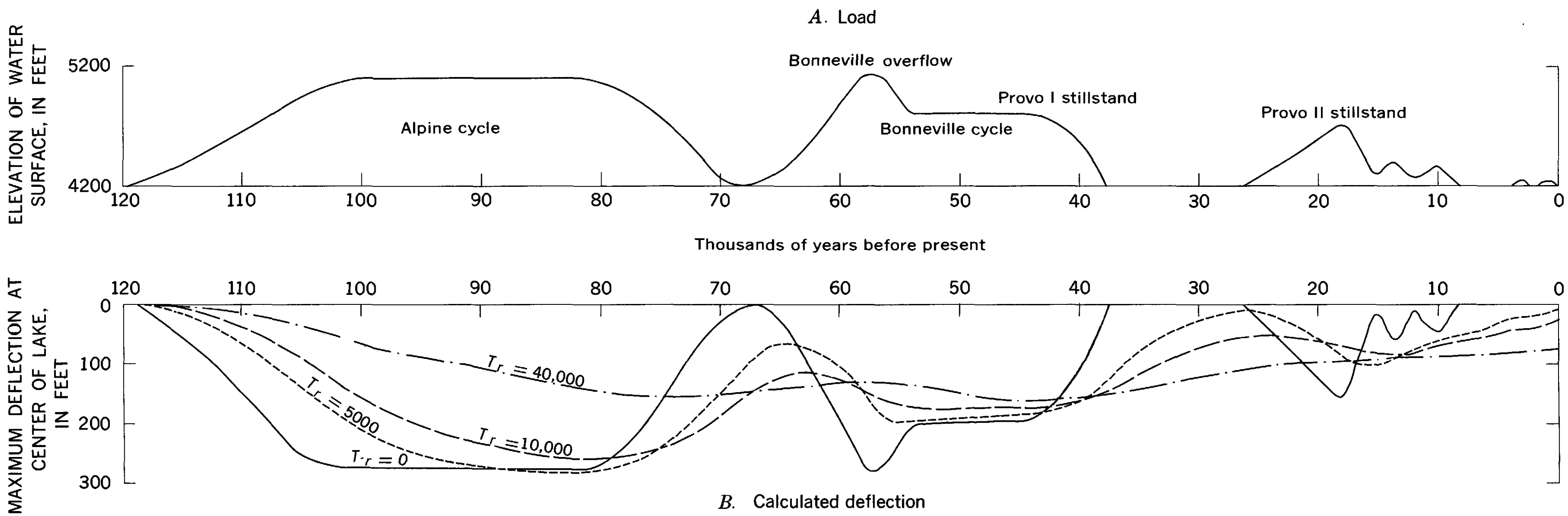


FIGURE 10.—Calculated deflection based on chronology of Searles Lake. Curves of part *B* show the calculated deflection in the center of the basin, assuming a linear relation between water depth and load and a density for subcrustal material displaced of 3.25.

rison's curves; and though this is not the shortest of the time scales, it seems to represent the most reasonable minimum value for Lake Bonneville.

The above values of 4,000 and 10,000 years for $T_r$ are based on the shortest and longest time scales and therefore represent the limiting values that are reasonable for Lake Bonneville.[4]

### PRESENT RATE OF UPLIFT

It is evident that estimates of the rate of uplift based on existing geologic chronology are none too satisfactory; at best they yield only a range of possible values. Another method of determining the rate is the direct geodetic measurement that has been used so successfully in Scandinavia. But because the total amount of uplift in this area is only an eighth of that in Scandinavia, the rate and amount of movement is so low that it can be detected only by precise leveling repeated at widely separated times. Unfortunately, such releveling has not been carried out on any of the lines that cross the center of the basin, where the uplift was greatest. A line of first-order levels was established, however, by the U.S. Coast and Geodetic Survey in 1911 along the route of the old Central Pacific Railroad across the northern rim of the basin, and this line was releveled between 1953 and 1958. Comparison of these two sets of levels, which extended well beyond the edge of the basin, reveals (fig. 11) that there is a systematic difference between the two, recorded on this graph as a more or less continuous slope. Although the slope appears large, the actual difference in elevation between one end of the line and the other is only 470 mm (1.544 feet) in a horizontal distance of 843 km (523.8 miles)—a ratio of 1:2,000,000. According to the Coast and Geodetic Survey (written communication, 1960), discrepancies of this order of magnitude may be the result of an unusually large accumulation of the small errors inherent in all physical measurements and probably do not represent actual changes in elevation. Yet apart from this systematic difference there is a marked upward deflection of the curve between Valley Pass, Nev., and Corrinne, Utah, of exactly the character that would be expected if this area were responding slowly to residual isostatic forces. The maximum upward deflection amounts to 100 mm in a horizontal distance of 34 km, a ratio of 1:360,000—some six times greater than the average for the line as a whole. This coincidence, though highly suggestive, is still not conclusive, and verification of actual continuing isostatic adjustment must await releveling of some of the lines that extend across the center of the basin.

[4] After this manuscript was prepared, Morrison concluded (written communication, 1962) that his correlation of the Bonneville overflow event with the late stade of Bull Lake Glaciation was in error; he now believes the lake rose to the Bonneville shoreline during the early stade of the Pinedale Glaciation, or about 20,000 years ago. This revision reduces by half the shortest time scale here considered (fig. 9) and suggests that the value of $T_r$ for Lake Bonneville is at or near the lower limit of the range given—that is, approximately 4,000 years.

In order to give some idea of the differences in elevation that are likely to result from continuing isostatic adjustment, calculated values of the amount of residual uplift and the rate of uplift corresponding to three values of $T_r$ have been taken from the tables on which figures 9 and 10 were based and are shown below.

*Calculated amount and rate of residual uplift*

| $T_r$ (*yr*) | *Amount of residual uplift (ft)* | *Rate of uplift mm per yr* |
|---|---|---|
| 5,000 | 10 | 0.6 |
| 10,000 | 25 | .9 |
| 40,000 | 75 | .4 |

### COMPARISON WITH SCANDINAVIA

Although the uncertainties as to the absolute timing of the Lake Bonneville events make it impossible to establish the value of $T_r$ more closely than somewhere between 4,000 and 10,000 years, it is of considerable interest to compare this result with those obtained in Scandinavia. Gutenberg (1941, p. 760) estimated that the anomaly in Scandinavia was reduced to $\frac{1}{e}$ of its initial value in about 14,000 years. Vening Meinesz (Heiskanen and Vening Meinesz, 1958, p. 369), after correcting the rate of observed uplift for elastic response and phase changes, derived a value of 5,280 years. These values, though widely discordant, are of the same order of magnitude as those obtained for Lake Bonneville despite the fact that the Scandinavian ice sheet was 10 times the diameter of Lake Bonneville and therefore, according to the papers cited above by both Gutenberg and Vening Meinesz, should have responded 10 times more rapidly.

The relation between dimension of load and rate of response was expressed by Vening Meinesz as a simple equation: $T_rL=k$, in which $k$ is a constant; $T_r$ the relaxation time, here in thousands of years; and $L$ the width, in thousands of kilometers, of a load of infinite length. According to this equation, Gutenberg's figure of 14,000 years for the relaxation time in Scandinavia yields a value of 16.8 for the constant, whereas Vening Meinesz's figure of 5,280 years yields the value 6.3. It must be noted, however, that in Vening Meinesz's original calculation the ice load in Scandinavia was approximated by a strip of width $L$ and of infinite length. For a load with the finite dimensions $LM$, in thousands of kilometers, Vening Meinesz gave the formula

$$T_r \frac{LM}{\sqrt{L^2+M^2}}=k.$$

For Lake Bonneville, which can be reasonably approximated by a load 200 km square, this reduces to $T_r\times 0.1445=k$. With this modification, the constant 16.8 corresponding with Gutenberg's figure of 14,000 years for $T_r$ in Scandinavia would give a relaxation time of about 100,000 years for Lake Bonneville. This is more than twice the largest estimate for the time since the lake last stood at the spill point and almost 10 times the smallest estimate. The constant 6.3, corresponding with Vening Meinesz's figure of 5,280 years, on the other hand, yields a relaxation time of about 45,000 years for a load the size of Lake Bonneville.

Although Vening Meinesz warned that the formulas given above for the relation between the dimensions of the load and the rate of response are only approximate, it still seems surprising to find that the values of $T_r$ derived by extrapolation from Scandinavia (45,000 and 100,000 years) differ by an order of magnitude from those based on observation at Lake Bonneville (4,000 to 10,000 years).

The difference may represent an actual difference in viscosity. On the other hand, it could be accounted for by other means: the basic theory of viscous flow may not be correctly applied, or the present geologic interpretations, particularly in regard to chronology of Lake Bonneville, may be in need of revision.

The effective viscosity for the subcrust beneath Lake Bonneville can be calculated from the limiting values of $T_r$ already derived from the existing geologic chronologies. The necessary equation was given by Vening Meinesz (Heiskanen and Vening Meinesz, 1958, p. 364) as $k=\frac{\rho g}{2\eta f}$, in which $k$ is an expression of time equal to $\frac{1}{T_r}$, in seconds, $\rho=3.27$, $g=980$ d per sq cm, $\eta=$the dynamic viscosity of the substratum, and $f$ is a function of the horizontal dimensions $LM$, in centimeters, being equal to $\frac{\pi}{\frac{LM}{\sqrt{L^2+M^2}}}$. For a load 200 km square, this becomes $\frac{\pi}{1.4\times 10^7}$ or $2.2\times 10^{-7}$ Transposing and solving for $\eta$, we find it to range from $0.9\times 10^{21}$ poises

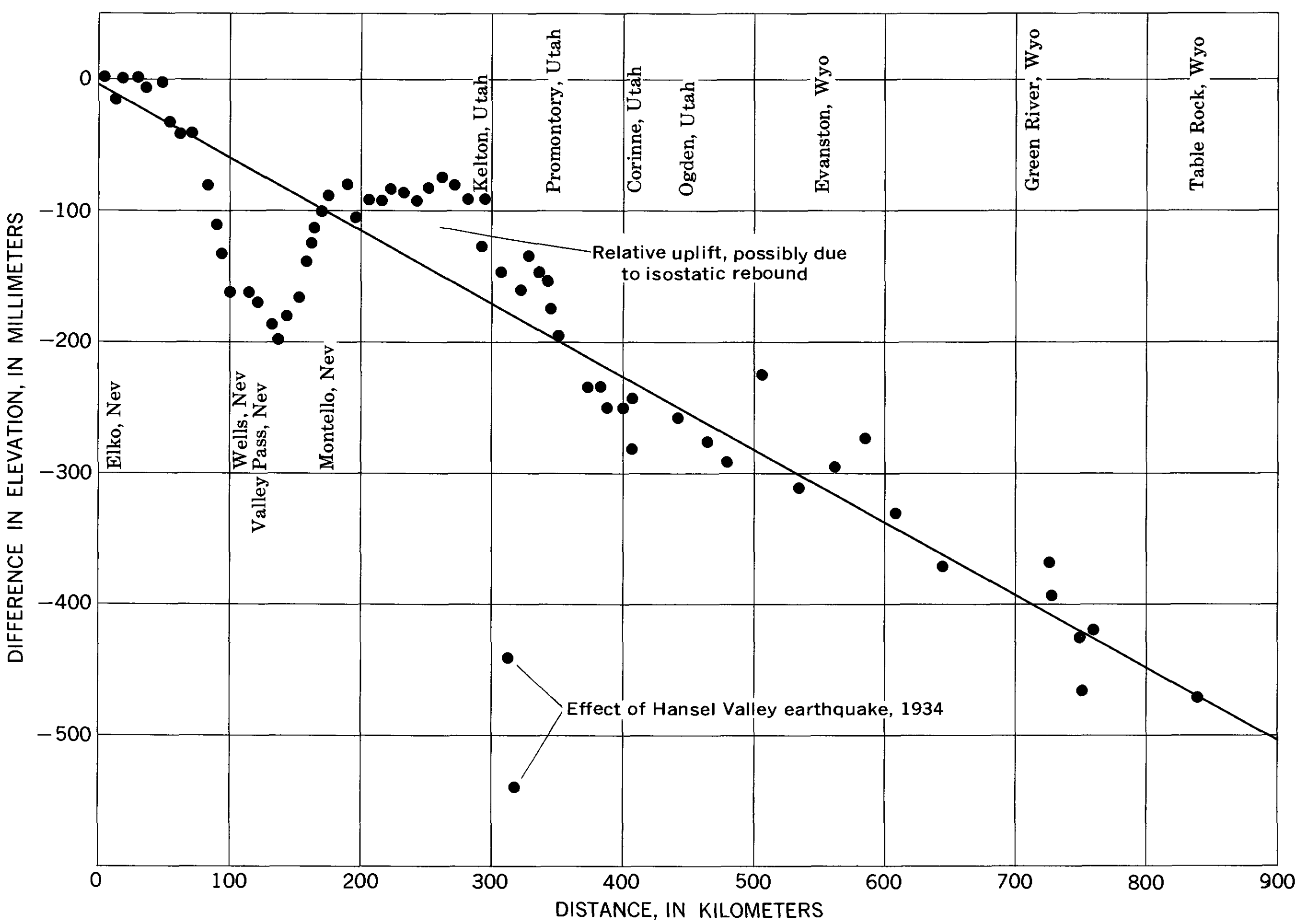


FIGURE 11.—Graph showing difference between first-order levels across part of the Bonneville basin in 1911 and 1958.

to $2 \times 10^{21}$ poises. This value, in round numbers, $10^{21}$ poises, is one order of magnitude less than the value of $10^{22}$ poises calculated by Vening Meinesz for Scandinavia.

Although it seems intuitively reasonable that the Basin and Range province should be more mobile than the Fennoscandian shield, the indicated difference in apparent viscosity is surprisingly large. Daly (1940, p. 394) and others suggested that the low viscosity under the Great Basin implies an abnormally thin crust, perhaps underlain by a gigantic batholith, still partly liquid. The character of the crustal warping under Lake Bonneville, together with its independence of the faulting that is an inherent part of the Basin and Range framework, are such as to permit Daly's conclusion regarding the subcrust, but they do not contribute directly to information regarding the thickness of the crust.

There has been much discussion recently of the significance of phase changes as an explanation for the discontinuity at the Moho. This mechanism offers attractive features, particularly in regard to the relation of rate of response to horizontal dimension of load. If, for example, the phase changes, and hence the amount of uplift, depend essentially on upward flow of heat, the rate should exhibit the same independence of horizontal dimension that is suggested by the fact that the value of $T_r$ obtained above (p. E24) for Lake Bonneville is nearly identical with that obtained by Vening Meinesz for the much larger area in Scandinavia. It is obvious, of course, that the phase-change theory as now applied to the problems of geosynclinal history (MacDonald and Ness, 1960, p. 2189) is not adapted to the present problem, but further study of this and related mechanisms may, nevertheless prove fruitful (Broecker, 1962).

Another avenue of approach is through modifications of the viscous-flow hypothesis, perhaps in terms of the depth at which the flow takes place. It is to be hoped that ultimately it will be possible to obtain enough precise information about the nature of the response under Lake Bonneville to suggest ways in which the theory should be modified.

The third alternative is to look for major errors in the chronology of Lake Bonneville. There is, in fact, a pressing need for more and better information about almost all aspects of Lake Bonneville history. Additional detailed stratigraphic studies are needed to establish a stratigraphic sequence applicable to all parts of the basin. These should be widely distributed over the lake basin rather than concentrated along one edge in order to establish the relative heights of the various lake deposits in the center and along the west and north edges, where data are virtually lacking at present. Correlation by means of soil stratigraphy, combined with radiocarbon or potassium-argon dating, should be applied as fully as possible to establish a more complete series of absolute dates. In spite of the inadequacy of present data, it seems unlikely that revisions of Lake Bonneville chronology can account for the order-of-magnitude difference between the figures obtained in this area and in Scandinavia.

## GEOLOGIC CONSEQUENCES

Lake Bonneville at least twice remained full long enough for the basin to reach a high degree of isostatic compensation, and this fact points to some conclusions of considerable geologic interest.

### VERTICAL SPACING OF ALPINE AND BONNEVILLE SHORELINES

Isostatic theory suggests, on the basis of the curves (figs. 9, 10), that within certain limits a marked difference in the duration of Alpine and Bonneville cycles would result in a difference in the elevation of their shorelines in the center of the basin even though they might have had the same threshold. If, therefore, the Alpine cycle lasted appreciably longer than the Bonneville as Gilbert supposed, the Alpine shorelines would probably have reached a correspondingly greater degree of compensation and, having originally been farther depressed, would now appear higher in relation to those of the Bonneville cycle in the center of the basin than they do at the edge. Although there are only a few places where the elevations of the Bonneville and Alpine shorelines can be compared in adjacent exposures, this idea has received some support. Roger Morrison (written communication, 1961) supplied the following information based on his detailed work near Little Cottonwood Canyon and on brief reconnaissance at Cup Butte, just northeast of McDowell Mountains:

> At Cup Butte, near the mid-point of the western side of the Old River Bed (Coyote Springs 7½-minute quadrangle) the highest shoreline is at an altitude of 5,221±2 feet. Here, unfortunately, I cannot separate the Alpine from the Bonneville deposits with assurance. A coarse angular (blocky) iron- and manganese-stained gravel makes up most of the spit complex at Cup Butte. This is overlain by finer gravel, made up of fairly well-rounded pebbles scantily coated with desert varnish; this gravel appears to range from a foot to rarely more than 10 feet in thickness. The lower, blocky unit, to judge from its bulk and stratigraphic position, probably belongs to the Alpine Formation of Hunt (in Hunt and others, 1953, p. 17), and the upper pebbly unit could well be his Bonneville Formation. The upper gravel coarsens toward the rocky crag (5,241 feet) into which the high shoreline is carved, and there I was not sure of being able to distinguish between the two gravels.

It is evidently uncertain whether the deposits of the Alpine and Bonneville cycles at Cup Butte are in their normal relation or are reversed. Morrison's data suggest, however, that the deposits of the Alpine cycle have been warped upward at least 30 feet more in this part of the basin than those of the Bonneville cycle; if the deposits should prove to be reversed, this amount would be increased to 50 feet. Only a detailed study of the stratigraphic relations over much wider areas will make it possible to determine whether this effect is actually the one predicted by isostatic theory.

The few available data bearing on this question are tabulated below:

*Relative elevation of Bonneville and Alpine shorelines*

| | *Central part of basin (Cup Butte, near Old River Bed)* | *East edge of basin (Below mouth of Little Cottonwood Canyon)* | *Difference* |
|---|---|---|---|
| Bonneville cycle | 5, 221 | 5, 140 | 80 |
| Alpine cycle | 5, 200 | 5, 100 | 110 |

Inadequate as they are, the above data have suggested a further working hypothesis regarding a possible threshold during the Alpine cycle. If the deposits of the Alpine cycle were arched upward isostatically, the fact that they coincide closely with the Bonneville shoreline near the center of the basin but are some 40 feet below it along the east edge leads one to expect that they will be still lower near the extremities of the basin. The Alpine deposits in northern Cache Valley may thus prove to be as low as 5,000 or 5,025 feet; and the threshold, if one existed, would have been correspondingly low.

## VERTICAL SPACING OF PROVO SHORELINE

A second possible effect of the isostatic readjustment of the lake during loading and unloading is that as the water receded rapidly from its high stand at the Bonneville shoreline to that at the Provo shoreline the central part of the basin, and to some extent its steep sides also, would have been overcompensated (fig. 9*B*, 53,000 years B.P.). If that were so, the shorelines cut during the ensuing stillstand (Provo I) should now be higher than the threshold. When, after a long period of dessication, the lake again rose to the Provo shoreline, most if not all of the compensatory uplift should have taken place; and the lake, in its newly filled condition, should have been undercompensated (fig. 9*B*, 18,000 years B.P.). The new strand deposits should therefore be correspondingly lower than the old ones and should coincide more closely with the elevation of the threshold. Lake deposits along the east side seem to record just such a history (fig. 8*B*). According to Eardley and others (1957), the deposits associated with the Provo I stillstand have an average elevation of about 4,800 feet; whereas according to Morrison (written communication, 1961), the younger deposits, formed during the Provo II stillstand, have an elevation of about 4,770 feet.

A further and closely related consequence of a high degree of isostatic compensation depends on the fact that isostatic movements were greater and more rapid in the center of the basin than on its sides. One would therefore expect the beaches formed during a general stillstand to have a wider vertical distribution—to be more "smeared out"—near the center of the lake than at its margins. Such an effect has, in fact, been observed by Eardley and others (1957, p. 1163, fig. 10), who recorded a vertical spread of as much as 50 feet in a group of beaches near the middle of the lake that corresponds to a single well-marked shoreline on the rim.

## RECENT WARPING OF BASIN

The surface of the Bonneville Salt Flat has been shown by Eardley and others (1957, p. 1156, and fig. 1) to slope gently westward from the Cedar Mountains, where its elevation is about 4,230 feet, to Wendover on the Utah-Nevada State line, where its elevation is 4,211 to 4,214 feet. They conclude,

> * * * the basin of the Great Salt Lake Desert has a closure of 7 to 10 feet below the 4,221-foot contour, and presents an ideal example of the bar theory of salt formation.

In view of other evidence of uplift near the center of the basin, Don R. Mabey suggested (oral communication, 1960) that much of the closure noted above and much of the westward slope of the salt flats may be a direct result of the last increments of isostatic readjustment.

What is probably a similar effect was noted by Varnes (written communication, 1961) on the east side of the Sevier Desert, where delta deposits of the Sevier River have been backtilted to such an extent that the coarse gravels of the Provo II stillstand no longer have sufficient gradient to account for their having been transported westward. Varnes attributed this effect to isostatic warping of the Sevier arm of the lake (fig. 3).

## ABSOLUTE MOVEMENT ON THE WASATCH FAULT

Both the recent displacements on the Wasatch fault and the total movement over long periods have consisted of normal faulting in which the mountain block has apparently always moved upward relative to the adjoining valley block. It is nevertheless of geologic interest in examining a given increment of this displacement, such as that resulting in the fresh post-Bonneville scarps, to determine if possible the dominant direction of movement relative to some fixed datum. The hope that the shorelines of Lake Bonneville might provide such a datum was, in fact, the original motive for making this study.

If no isostatic adjustment had occurred in this region, it would be an easy matter to establish the elevation of some shoreline, such as the Bonneville, over a large area and to use this value as a datum from which to measure the displacement on any fault that cut this shoreline. The actual problem, however, is by no means so simple; there is no single elevation that can be regarded as the normal level for the Bonneville shoreline; moreover, the total difference in elevation due to isostatic changes is, on the average, 5 or 10 times the amount of recent displacement on any of the faults along the Wasatch front. It is therefore necessary to compare the observed elevations not with a well-established datum but with a hypothetical datum based on inferences regarding the character and extent of isostatic adjustment. Figure 12 shows a typical example of the relation between faulting and isostatic deformation along the east margin of the basin. The solid line indicates the present position of the deformed Bonneville shoreline, and the dots indicate the location of the points at which it was determined. The base of the diagram is close to the original position of the shoreline, as indicated by its elevation at the south end of the lake and at the northern outlet. In order to analyze the throw of the faults, the projected position of the shoreline is also shown for two assumptions: (a) that only the mountain block was active, and (b) that only the valley block was active.

In the first instance, the projected position of the shoreline would reach the base line at a point marked *A*, some 10 miles east of the mountain front, and the elevation of the Bonneville shoreline at the front before the faulting would have been about 5,135 feet. Absolute uplift of the range is opposed by two lines of reasoning. (a) The curves for isostatic deformation should, in theory, approach either the maximum or minimum values asymptotically, a requirement met by the pattern of deflection in the two places where the curve can be observed as it approaches zero. If all the fault displacement were up on the east, the resulting curve would be carried at its maximum slope to within a mile or two of the point where it intersects the base line. (b) Because the wavelength of the deformation (profile fig 5) does not exceed the width of the load (200 km), the water in a relatively flat-floored basin such as that of Lake Bonneville would be similar in effect to that on a plate, and the deflection would therefore be approximately symmetrical across its margins. The elevation of the Bonneville shoreline along an unfaulted edge of the lake should therefore be about midway between the maximum and the minimum, or just under 5,200 feet. The western margin, along which there has not been any recent faulting, supports this hypothesis reasonably well; although, as indicated earlier, the shoreline is in general a little higher on this margin than on the eastern margin. This reasoning suggests that the normal elevation along the steeper parts of the shoreline, for example between Salt Lake City and Ogden, should be more nearly that now observed on the mountain block—namely 5,160 to 5,180 feet—and also supports the conclusion that the greater part of the movement was down on the west.

This conclusion conflicts with that of Bissell (1959), who states, "* * * the footwall has been the most active element * * *" and "Sediments of the Lake Bonneville

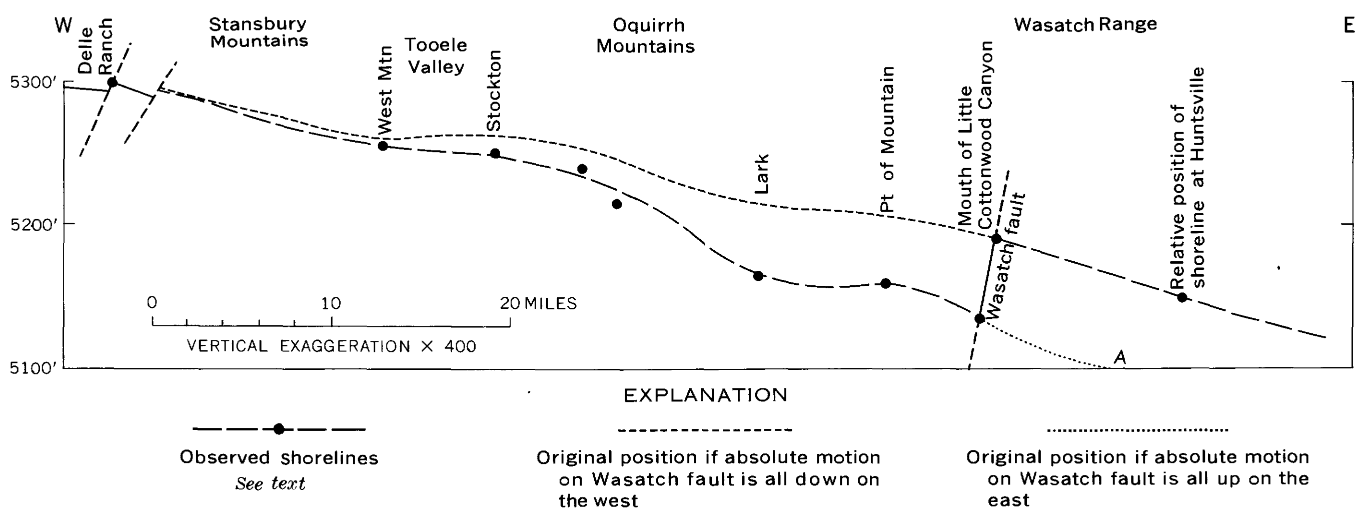


**FIGURE 12.—Diagrammatic profile showing Wasatch fault displacement at the eastern margin of Lake Bonneville.**

group, in some localities, have been carried up on the footwall as much as 200 feet above the elevation at which they were deposited." This statement is open to some question, because unless allowance is made for the effects of isostatic deformation, it is impossible to determine the level at which a given set of shoreline sediments was deposited. The conclusion may nevertheless be essentially correct for the Provo area, because the amount of isostatic uplift should be considerably less in the deep reentrant now occupied by Utah Lake than on the open shorelines north of Salt Lake City, and the elevation before the faulting should there have been correspondingly lower. There is no reason, moreover, why the footwall may not have been the active block along one segment of the fault while the hanging wall was active along another. In any case, regardless of the movement during recent faulting, the long-term displacement must have involved both blocks, for the top of the range now stands at nearly 12,000 feet above sea level, and the base of the fill in parts of the basin has sunk below sea level (Cook and Berg, 1961, p. 82).

## RELATION OF ISOSTATIC UPLIFT TO BASIN AND RANGE STRUCTURES

One of the most challenging aspects of the isostatic deformation of the Bonneville basin is its apparent total independence from the areally coincident phenomena of Basin-and-Range faulting. Owing to the steepness of the mountain slopes, the waters of Lake Bonneville were supported almost entirely by the floors of the intermontane basins, on which they exerted, over large areas, as much pressure as a blanket of sediments 400 feet thick. Such loads adjoined major normal faults not only along the full length of the Wasatch Range but in other areas nearby—for example, along the west sides of the Oquirrh, Stansbury, and House Ranges and along the east sides of the Deep Creek and Fish Springs Ranges. These faults are major features of the earth's crust, the Wasatch fault having a length of as much as 150 miles and a displacement of as much as 15,000 feet. Some of the faults have given rise to earthquakes in recent times. Post-Bonneville faulting has occurred on many of the range fronts in this region, and the Wasatch fault has undergone a 20- to 80-foot displacement for much of its length since the disappearance of Lake Bonneville. Although this displacement took place at a time when the center of the basin was still unloading—that is, when the forces of isostasy would have tended to make the valley block move upward—the throw was invariably down on the valley side. The movement has thus been in the direction opposite to that which would be expected if it were in any way related to the isostatic response to unloading.

It seems probable that this independence is due to fundamental differences in both the mechanism and the site of operation of the two phenomena. The active element in the isostatic process is believed to be the subcrust, whereas the faults that characterize the Basin and Range province must be essentially features of the crust. This conclusion has rather paradoxical consequences: the normal faults, which are the shallower of the two sets of features, are the older, the more persistent, and the more widespread; but the forces leading to the more deep-seated isostatic response have been transmitted through the crust, apparently without effect on the normal faults. The movement on the faults is always downward on the valley side, whereas it would be upward if it constituted a direct response to isostatic unloading. These facts pose a problem that cannot be solved without a thoroughgoing analysis of the forces involved in isostatic adjustment on the one hand and normal faulting on the other. (For further discussion, see Crittenden, 1963.)

One further comment is in order. The relatively delicate state of isostatic balance of this area of the earth's crust, as revealed by its ready response to the rise and fall of Lake Bonneville, brings into sharp focus the unanswered questions regarding the origin of the Basin Ranges. It has often been said rather casually that erosion of material from the tops of ranges and deposition in the adjoining basins provides an adequate mechanism for the formation, or at least for the continued development of these structures. From the point of view of isostasy, this is unlikely; the valley blocks, now covered by as much as 10,000 feet of unconsolidated sediments, are not heavy, as their depressed position would imply, but are already too light; the adjoining mountain blocks, composed of solid rocks, are already too heavy; yet the valleys continue to subside, and the ranges continue to rise, maintaining all the while a delicate regional isostatic balance. The origin of the local driving forces within the crust that give rise to this process have yet to be clearly explained.

## CONCLUSIONS

1. A review of deformation of the high shoreline of Lake Bonneville, made with the help of photogeology and utilizing modern geodesy where available, fully confirms G. K. Gilbert's belief that the earth has responded isostatically to the fluctuations of Lake Bonneville. The maximum elevation of the highest shoreline in the central part of the basin is 5,300 feet. This is at least 210 feet higher than its elevation at the south end of the lake and at its former northern outlet in Red Rock Pass.

2. These facts indicate that isostatic recovery has reached at least 75 percent of the theoretical maximum, as calculated on the assumption that it took place in a segment of relatively weak crust floating on a substratum of negligible viscosity and a density of 3.25.

3. The effects of isostatic adjustment and recovery may account for several geologic features of the Bonneville area. Among these are differences in elevation of the two Provo stillstands, westward tilting and closure of the Bonneville Salt Flats near Wendover, eastward tilting of the Sevier River delta, and possible differential uplift of deposits of the Bonneville and Alpine cycles.

4. Post-Bonneville displacements on the Wasatch fault are opposite in direction to those that would be expected to result from isostatic movements caused by the dwindling of Lake Bonneville. This indicates that the two processes operate independently and by different mechanisms—Basin-and-Range faulting within the crust, isostatic compensation within the subcrust. Details of the mechanisms of these processes are still imperfectly understood and offer an outstanding regional problem for future work.

5. Existing chronologies for Lake Bonneville differ widely, especially for the time prior to the Bonneville overflow. The estimates best supported by organic-carbon dating (Morrison, 1961a, 1961b) and one derived from Searles Lake (Smith, 1958) indicate that the relaxation time, $T_r$ (the time required for an anomaly to be reduced to $\frac{1}{e}$ of its initial value), for Lake Bonneville is between 4,000 and 10,000 years.

6. Based on this range for $T_r$, it is calculated that the apparent dynamic viscosity of the subcrust in the Bonneville area is $10^{21}$ poises, compared with $10^{22}$ poises calculated for Scandinavia by Niskanen, Gutenberg, Vening Meinesz, and others.

7. Because both the load and the isostatic response can be measured precisely, Lake Bonneville is one of the most ideal of Nature's experiments in isostasy. To take advantage of this precision, however, more accurate and widespread information is needed on (a) shoreline elevations in the western and northwestern part of the basin, (b) stratigraphy of lake deposits, particularly in the central and western parts of the basin, (c) the ages of these deposits, and (d) the rate of present uplift, if any. When satisfactory data on these points have been obtained, it should be possible to determine the apparent viscosity of the subcrust more accurately than has yet been done, and by combining these results with seismic data, to evaluate the rigidity of the crust in this segment of the Basin and Range province.

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