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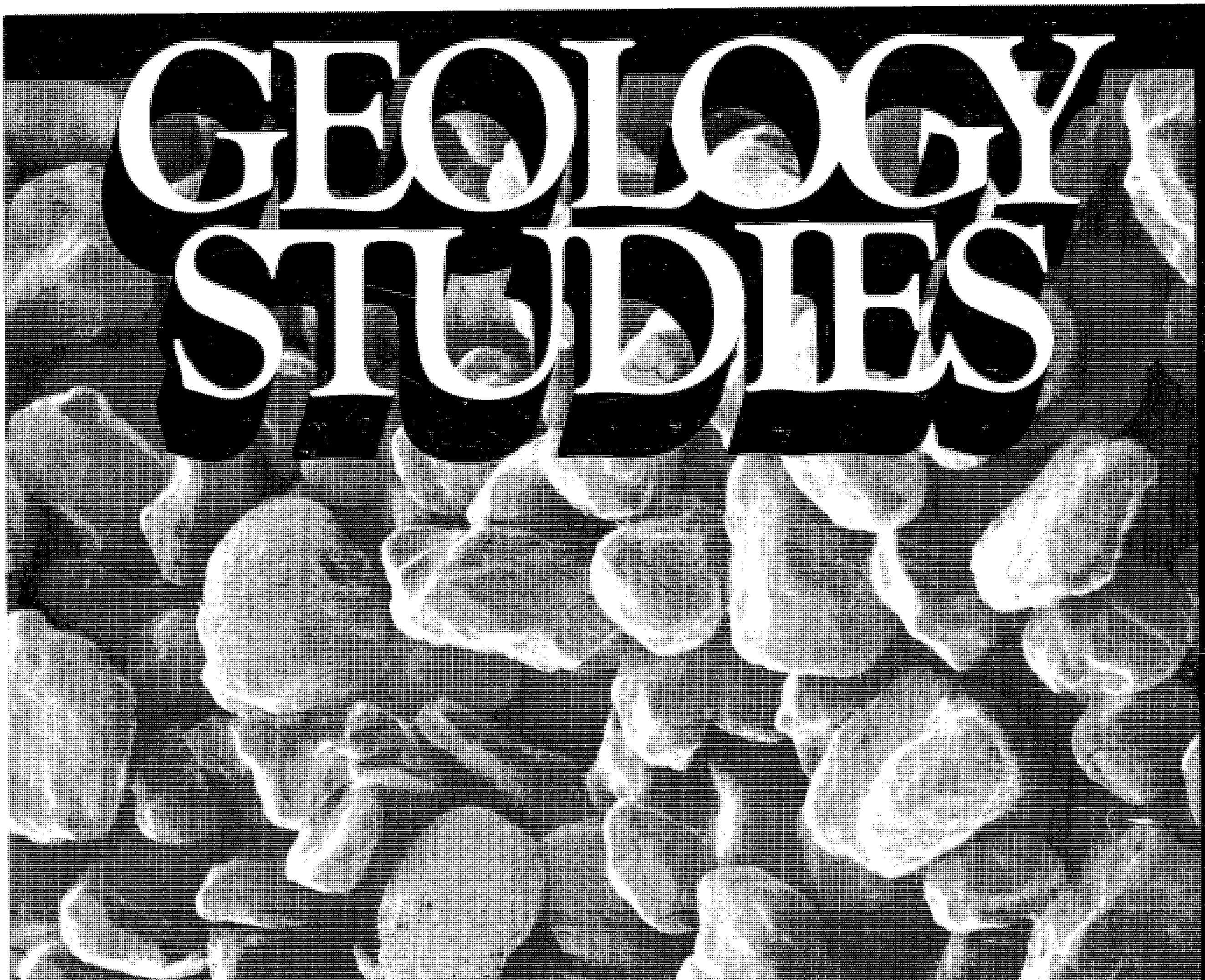
GEOLOGY STUDIES



VOL. 24 PART 2 DEC. 1977

Brigham Young University Geology Studies

Volume 24, Part 2

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THE GLORY OF GOD IS INTELLIGENCE

Cover: Sahara dune sand, X130. Photo courtesy Amoco Production Research, Tulsa, Oklahoma, contributed by Paul E. Potter, Department of Geology, University of Cincinnati, Cincinnati, Ohio 45221.

A publication of the
Department of Geology
Brigham Young University
Provo, Utah 84602

Brigham Young University Geology Studies is published semiannually by the department. *Geology Studies* consists of graduate-student and staff research in the department and occasional papers from other contributors. *Studies for Students* supplements the regular issues and is intended as a series of short papers of general interest which may serve as guides to the geology of Utah for beginning students and laymen.

ISSN 0068-1016
Distributed December 1977
Price $5.00
(Subject to change without notice)
12-77 525 28856

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Compound Faceted Spurs and Recurrent Movement in the Wasatch Fault Zone, North Central Utah*

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ABSTRACT.—Landform features of the Wasatch Range in northern Utah provide a key to interpretation of the past history of uplift in the Wasatch Fault Zone. Pediments produced during quiescent stages of recurrent uplift are found preserved as remnants on the face of the range, often occurring at the apices of successive generations of triangular facets. Observations suggest that pediments originate directly from backwearing slope retreat, with lateral corrasion by streams important only in local areas of major drainage.

Identification and correlation of these pediment remnants in a 75-km segment of the Wasatch Front in Utah Valley indicates that three main pediment levels can be observed and traced throughout the area, at approximate present elevations of 180, 420, and 900 m above the base of the range. Just as these levels represent quiescence, the areas between them represent cycles of active uplift. Each major uplift period results in nearly uniform displacement throughout the length of the range. These major cycles, however, are a cumulative effect of smaller discontinuous scissors-type movements as recorded by minor pediment remnants. If the displacement and duration of an active cycle are relatively uniform, then it appears that uplift is currently active rather than quiescent.

INTRODUCTION

The Wasatch fault system, which forms the eastern boundary of the Great Basin, has probably been active since the mid-Tertiary. Its current activity can be seen in the many scarps which displace Pleistocene Lake Bonneville sediments, moraines, and Recent alluvial fans, and in continuing seismicity. The earlier history of uplift, however, is difficult to establish because the down-thrown block is covered with alluvium so it is impossible to determine pre-Bonneville displacement. One key to this early history is apparent in the morphology of the Wasatch Range, where certain landform features have been preserved throughout much of the span of activity. These features are near-horizontal segments along the ridges of the west-facing escarpment, often occurring at the apex of large and small triangular facets. They are interpreted to be remnants of pediment surfaces, produced at the foot of the mountain block by slope retreat during quiescent periods between recurrent uplifts. They subsequently have been uplifted and perched above the base of the range where erosion has reduced them to their present form. An analysis and correlation of these features should provide a relative time-space chronology of active and quiescent episodes during much of the history of the Wasatch Fault System uplift.

Providing such a chronology is the purpose of the present study, wherein this correlation has been accomplished for a portion of the fault system. Significant results have been obtained regarding the uplift history, expected future activity, and origin and preservation of pediments. The area studied is a 75-km-long portion of the Wasatch Front in Utah Valley, from Payson Canyon on the south, the southern terminus of a main en echelon break, to the Traverse Mountains on the north, at the Utah County-Salt Lake County line (fig. 1).

Acknowledgments

I wish to thank W. Kenneth Hamblin, who inspired the project and has served as committee chairman. In addition, the comments and criticisms of Myron G. Best as committee member, James L. Baer, and Harold J. Bissell have been especially helpful. Appreciation is also due my wife, Beth, for her support and encouragement and for serving as typist.

Financial assistance has been through a faculty U.S. Geological Survey Research Grant, No. 14-08-0001-G-364, and a fellowship award from Gulf Oil Co.

PREVIOUS STUDIES

Early Work

The Wasatch Range has attracted the attention of geologists for over a century, beginning with the surveys of the 1870s under Hayden, Wheeler, and King. Bradley (1873) discussed the range, although he was concerned mostly with the section north from Ogden. Gilbert (1875), the first to recognize the block-faulted origin of the Basin and Range Province, ascribed this origin to the "Wahsatch" Range as well. Several geologists disagreed with his conclusions, and controversy over the "Basin and Range problem" began. Excellent discussions of this controversy can be found in Davis (1925), Gilbert (1928), Nolan (1943), and Thornbury (1965). The earlier interpretations of Gilbert have been well supported by subsequent study as discussed by Mackin (1960), who used datable volcanic flows to establish tilting and faulting sequence.

The first to study the internal geology and structure of the Wasatch Range in any detail was Emmons (1877). His work was followed by that of Blackwelder (1910, 1925), Loughlin (1913), Schneider (1925), and Stillman (1928). These men were mostly concerned with stratigraphy and structural history, and little was said about the Wasatch fault or the physiography of the range.

The recurrent tectonic activity of the Wasatch fault was noted by Gilbert (1890) in his monograph on Lake Bonneville, in which he described the many scarps in the Bonneville sediments, including those at American Fork Canyon, Rock Canyon, Hobble Creek Canyon, and Spanish Fork Canyon within the study area of this report. Gilbert concluded the Wasatch Range is still uplifting. In a later paper published posthumously (Gilbert 1928), he extended and amplified his observations on the Wasatch Range and concluded it is a horst with greatest displacement on the western (or Wasatch) fault. His proposed eastern fault has never been established and is probably nonexistent. He also stated that the major cross-cutting rivers such as the Provo and Weber are antecedent to the uplift.

The first detailed physiographic studies of the Wasatch fault were those of Davis (1903, 1909). He was the first to define and describe the triangular facets along the mountain front and conclude they were evidence of faulting. He discussed the origin and development of the facets, but concluded they were the primary fault surface, which has been disproved since. He believed in recurrent uplift of the moun-

*A thesis presented to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree Master of Science, August 1977: W. K. Hamblin, thesis chairman.

tain block, but did not recognize its effect on the landforms except in wineglass canyons (Davis 1925). However, in a later paper (Davis 1938), he discussed recurrent uplift of pediment surfaces and concluded that uplift is continuous rather than recurrent since "benched faces" are not observed. Nevertheless, his work remains as the most significant geomorphic study of the Wasatch Range for several decades.

General Geology

In addition to some of those mentioned above, several general studies were made previously for portions of the study area. The Traverse Mountains were studied by Marsell (1931) and Bullock (1958). The main mass of the Wasatch Range was examined by Calkins and Butler (1943); and Baker (1959) described fault patterns near Provo. Eardley (1934) studied the structure and physiography of the Wasatch Range adjacent to Juab Valley and later (Eardley 1939) presented a synthesis of structural development of most of the range. Descriptive guides were authored by Rigby (1962, 1968) and Rigby and Hintze (1968). Environmental geology was well discussed on a preliminary basis by several papers in Hilpurt (1971).

A number of master's theses have considered various segments of the area in terms of general geology or structure. Harris (1936) interpreted the structure of Rock Canyon; Gwynn (1948) studied Slate Canyon, and Mecham (1948) mapped Little Rock Canyon near Springville. Gaines (1950) studied the area from Provo Canyon to Rock Canyon, and the mouth of Spanish Fork Canyon was studied by Hodgson (1951). Perkins (1955) described the lower American Fork Canyon area, the Baldy area was discussed by Olsen (1955), and Rhodes (1955) dealt with the Buckley Mountain area. Peterson (1956) studied Loafer Mountain and Payson Canyon areas, and the Lehi quadrangle was mapped and described by Bullock (1958).

Several geologic maps are available in addition to and partly based upon the aforementioned thesis maps. Baer (1964, 1972, 1973) and Baker and Crittenden (1961) covered most of the area in quadrangle maps, and Hintze (1969b) mapped the area just east of Provo. All these maps show Wasatch Fault traces, step faults, and antithetic faults related to the system.

Peculiar features and geology of Lake Bonneville were first described by Gilbert (1890) and were later discussed and mapped in detail by Hunt, Varnes, and Thomas (1954) for northern Utah Valley, and by Bissell (1963) for southern Utah Valley.

Studies of certain other areas either adjoining or with a similar history elsewhere have provided clues to interpreting the Wasatch Range in the study area. Eardley (1934) has already been mentioned. Crittenden, Sharp, and Calkins (1952) described the rangefront east of Salt Lake Valley, and Crittenden (1964) discussed the general geology of Salt Lake County. Feth et al. (1966) briefly described compound facets near Ogden. Gilluly (1928) noted many similar features in the Oquirrh Range. In Sharp's (1939, 1940) studies of the Ruby-East Humboldt in Nevada, several significant observations were made. These studies have suggested the following: en echelon fault patterns are common and may cause termination of portions of a range, fault dips are 60° or higher and not equal to facet angles, recurrent uplift is likely, and uplift began in the mid-Tertiary.

The time of initiation of block faulting is a subject attracting attention from many workers. Davis (1903) merely said it began in the Late Tertiary, and Gilbert (1928) said it was pre-Pliocene. Later stratigraphic studies allowed more accurate dating, and as Eardley (1934) stated, the faulting must be post-Wasatch Conglomerate (early Eocene) and post-volcanics. The volcanics he mentioned in the southern Wasatch have subsequently been dated as Oligocene. Eardley (1934, 1939) however, also felt the faulting began after deposition of the Pliocene Salt Lake Formation, and cites Plio-Pleistocene initiation. Most have believed this projected age to be too young. Schneider (1925) stated it as Mid-Miocene on stratigraphic evidence. Others variously cited initiation of block faulting as Late Oligocene to Early Pliocene (Gilluly 1928, in the Oquirrh Range), Miocene (Sharp 1939, Ruby-East Humboldt Range), Early Oligocene (Nolan 1943, Basin and Range Province overall), Middle to Late Tertiary (Hunt et al. 1954), Oligocene (Bissell 1959), and Late Oligocene to

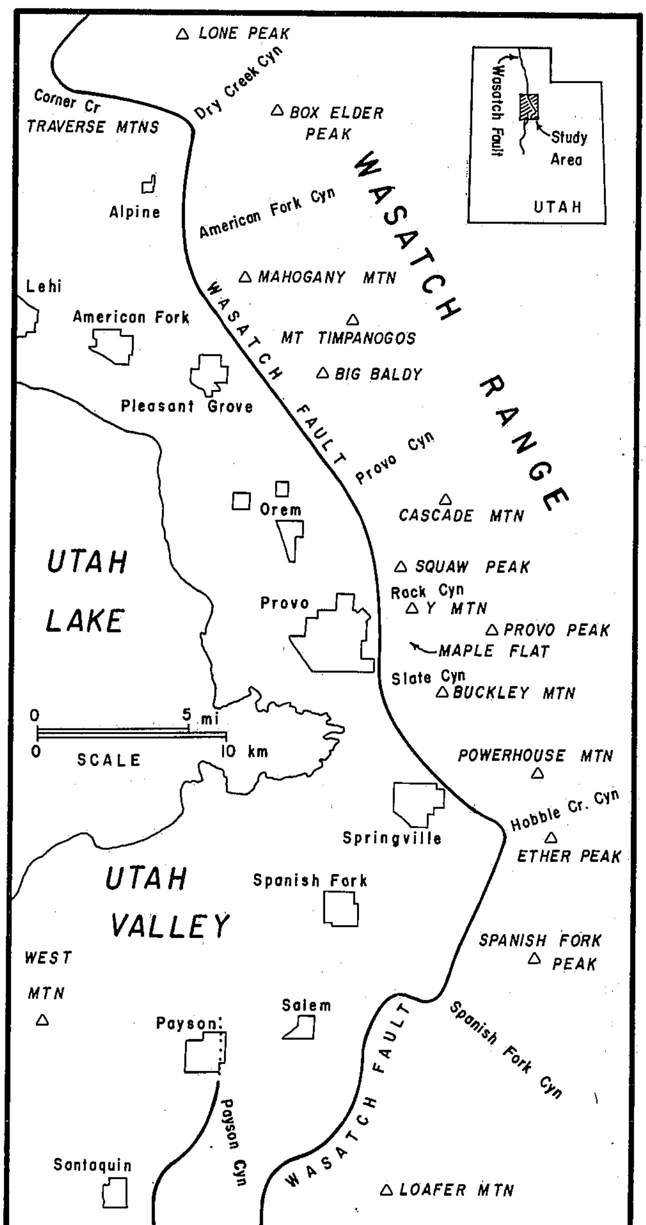


FIGURE 1.–Index map to study area and places named in text.

Early Miocene (Proffett 1977, western Nevada). Loring (1976) plotted all reported times for the entire Great Basin on maps and concluded that block faulting was contemporaneous throughout, with no net geographic migration through time. She also noted an unexplained Late Mesozoic to Early Tertiary period of extension in many areas. One recent paper by Rowley and Anderson (1972) attempted to synthesize these dates, as did Loring, and concluded that all high-angle normal faulting began during the Miocene at the latest. It appears that the safest time to place this event is in the Miocene.

Another subject of special interest to the present study is prefaulting topography. It was first described at length by Eardley (1933) when he stated that a surface with 900 m of relief existed "prior to faulting." This surface can be seen presently perched about 900 m above the valley floor and exhibits a more mature-appearing topography. He deduced this by noting a discrepancy between overall physiographic relief plus valley fill and stratigraphic displacement along the fault as measured in certain areas. The mature surface can be seen in several areas, often having hanging valleys, as noted earlier by Hayes (1926). Eardley's model also included eastward tilt of the mountain block by three or four degrees, which explains the filling in of back-valleys such as Heber Valley. Similar surfaces have been observed by Crittenden et al. (1952) east of Salt Lake City, by Gilluly (1928) in the Oquirrh Range, and by Sharp (1940) in the Ruby-East Humboldt Range.

Eardley's interpretations were challenged by Threet (1959), who said the surface was everywhere a stripped bedrock bench where the Manning Canyon Shale has been eroded. Conclusions on this subject will be made later in this paper. Support for eastward tilting, however, came from Peterson (1969), who used drainage reversals. Later, when studying stream terraces along the front, Eardley (1970) refuted his earlier conclusions about eastward tilt. Stokes (1964) suggested that the primary relief of the prefaulting surface is a result of orogenic thrusting. Eardley's (1933) conclusions were especially significant for the present study. It may be that his prefaulting topography was itself produced by an earlier stage of faulting he failed to recognize and that the mature surface represents pedimentation during a quiescent period of recurrent uplift. These speculations will be discussed in a later section.

Wasatch Fault Geometry

An understanding of the geometry of the Wasatch fault system and its several individual fault surfaces is an important foundation on which to construct a model of physiographic evolution of the scarp. That the rangefront is a true fault scarp as opposed to a fault-line scarp was established by Davis (1909), Schneider (1925), and Pack (1926) and can be proven by the criteria of Blackwelder (1928) and Johnson (1939). Cotton (1950) also discusses features of fault scarps, including "composite scarps" produced by recurrent faulting, which are, however, not synonymous with compound faceted spurs as envisioned in the present context.

The trace of the fault at the surface is of prime importance. Marsell (1964) showed a summary of historical development of the mapped trace beginning with Gilbert (1928), who mapped broad bends around various salients and no en echelon breaks. Eardley (1939) revised this to include en echelon traces in southern Utah Valley. Baker (1959) showed a more comprehensive map of all faults in the study area, and more recently Cluff, Brogan, and Glass (1973) mapped all young scarps as identified with low-sun-angle photography. The fault trace through the present study area (fig. 1) begins on the south as a major en echelon break in upper Payson Canyon, gaining greater displacement northward on the west side of Loafer Mountain (Eardley 1939, Peterson 1956, Hintze 1962, Bissell 1964), bending abruptly eastward with no en echelon break around the north end of Loafer Ridge and northward again at the mouth of Spanish Fork Canyon (Hodgson 1951, Bissell 1964), and from there it follows the base of the range with broad bends north to the Alpine area. At Dry Creek Canyon northeast of Alpine it abruptly bends nearly due west over the groin between the Traverse Mountains and Lone Peak (Marsell 1931) and abruptly trends northward again at the mouth of Corner Canyon. Crittenden et al. (1952) suggested that this west-trending segment at the Traverse Mountains coincides with the Charleston andDeer Creek faults and the three become one surface. Although Gilbert (1928) believed the Traverse Mountains were a spur bounded by faults, he did not see the evidence, and Marsell (1931) concluded there are no bounding faults other than the Wasatch. This trace, then, is seen to include bends, both gentle and abrupt, and discontinuous en echelon breaks. These same features have been noted in other areas such as the Oquirrh Range (Gilluly 1928), the Ruby-East Humboldt Range (Sharp 1939), and the Basin and Range Province in general (Nolan 1943, Rowley and Anderson 1972). One final note: because of pediment formation, slope retreat, and recurrent movement, often the recent scarp traces lie valleyward of the foot of the mountain block by a considerable distance as noted by Pack (1926) and Crittenden et al. (1952).

The main trace of the Wasatch fault system actually represents a multitude of individual breaks; in addition to this, often parallel faults can be observed within the mountain block and are presumably present on the valley side of the main trace beneath the alluvial fill. They may be termed step faults and were discussed by Gilluly (1928), Rowley and Anderson (1972), Baker (1959), and Hintze (1968, 1969a). Davis (1909) also observed them and stated that any movement along them must have ceased long ago as they exert no control on topography or facet development. This conclusion appears valid, and they probably represent older subsidiary branches of the Wasatch fault now inactive. These subsidiary faults dip nearly uniformly in the same direction as the main break at a lower angle than the frontal fault (Hintze, 1969a, 1971). An analogous "mirror-image" system was recently discussed by Proffett (1977) for an area in western Nevada. He noted successive generations of normal faults with the older systems having lower dips than the more recently active breaks. He suggested this represents progressive tilting of the upthrown block with continuing tectonism causing the younger breaks to have the same initial orientation that the older, now gentler, faults had. This may be the best explanation for the observed Wasatch features.

Proffett (1977) also discussed antithetic faults as part of the system, and they were described for the Wasatch Range by Hintze (1968, 1971). They occur in the valley alluvium, dipping toward the main break, and also within the range, where they dip into, and are truncated by, one of the main subsidiary or step faults just discussed. Their origin is a result of fault curvature at depth and related extension as discussed by Hamblin (1967, 1970) and reaffirmed by Proffett (1977).

The dip of the main Wasatch fault at the surface was often misinterpreted by early workers to be equal to the slope angle of the triangular facets (Davis 1909, Gilbert 1928, even Baker 1959). It was demonstrated early, however, by Pack (1926), Schneider (1925), and Stillman (1928) that this was untrue, and the true dip angle varied between 50° and 90°. Later studies have supported these higher values (Eardley 1934, 1939; Bissell 1959), and it appears to be the general case in other parts of the Basin and Range (Gilluly 1928, Sharp 1939, Nolan 1943, Cotton 1950). Similar values are also reported for the Hurricane fault (Hamblin 1970), which may represent the southern continuation of the Wasatch system. It is well established, then, that the facet slopes are not equal to the fault dip and are instead a product of slope retreat, and that the fault dips are quite high and tend to decrease at depth.

A final geometric property of the Wasatch fault system to consider is the displacement along it. Post-Pleistocene displacement can be well established by offset of Lake Bonneville sediments, as was early noted by Gilbert (1890, 1928), Davis (1909), Pack (1926), and Marsell (1931). These scarps of up to 30 m were discussed in detail by Hunt et al. (1954) and Bissell (1959, 1963, 1964). Bissell (1959) cites 60 m of post-Bonneville uplift. A good summary of these scarps and other evidence of Recent activity is that of Cluff, Hintze, and Brogan (1975). Total displacement prior to the Pleistocene, however, is much more speculative and variable. Early workers based their estimates on physiograhic relief alone, not knowing the fill depth in the valleys, and suggested values like 1800 to 3000 m (Davis 1909, Schneider 1925), 2100 m or more (Gilbert 1928), or 1500 m (Stillman 1928). Hintze (1962, 1971) included estimated valley fill thickness and arrived at 3000 to 4500 m of displacement. In some areas identifiable beds are exposed on both sides of the fault, and true stratigraphic displacement can be measured; using this basis, Eardley (1933, 1934, 1939) puts the value at 1500 to 1800 m at Santaquin Canyon; Hunt et al. (1954) say 1200 to 2100 m at Mt. Timpanogos; Baker (1959) cites 1800 m at Spanish Fork Canyon and 1350 meters at American Fork Canyon; and Crittenden (1964) cites 1500 m or more at the Traverse Mountains and 3000 m at the Salt Lake salient. These stratigraphic determinations may not represent total displacement inasmuch as there are often multiple fault planes, folding, and variations along the front; a good, round, average figure in 3000 m.

To summarize, the Wasatch fault is a zone of normal faults dipping steeply to the west, having an irregular main trace including en echelon offsets, step faults, and antithetic faults, and a total displacement of several thousand meters; this system is expressed physiographically as a complex fault scarp exhibiting distinctive compound faceted spurs.

Geophysics

A few geophysical surveys have been conducted along the Wasatch Front which may provide data on the thickness of valley fill, buried faults, and so forth. The valley fill thickness in Salt Lake Valley has been interpreted geophysically by Mattick (1968, 1970) and Arnow, VanHorn, and LaPray (1970). Results suggest a surface of moderate relief buried by 1000 m or more of unconsolidated alluvium. A gravity and seismic profile near Ogden (Cook and Berg 1961; Cook, Berg, and Lum 1967) suggests numerous buried step faults and a total fill depth of 2100 m. Crosby (1972) also did a seismic survey which suggested buried step faults in Juab Valley.

Current and historic seismicity of the Wasatch fault zone is discussed by Cook (1971), Smith (1971), Smith and Sbar (1974), and Cluff et al. (1975). The area is defined as part of the Intermountain Seismic Belt by Smith and Sbar (1974), which is a line of high activity, except for a seismic gap from Payson to Salt Lake City. Tectonic creep has not yet been established in this area.

Origin of Pediments

Essential to the conceptual model presented in this paper are the origin and evolution of pediments. How pediments form is a subject which has in the past incited considerable controversy. To avoid going into great depth on this subject, I refer the reader to excellent reviews by King (1953), Leopold, Wolman, and Miller (1964), and Hadley (1967), and to a bibliography by Lustig (1968). Pediments were first described by Gilbert (1877) and first named by McGee (1897); Maxson (1950) reviewed the nomenclature. From the beginning, two schools of thought developed: The first stated that lateral planation by streams was the origin of pediments and was subscribed to by Gilbert (1877), Paige (1912), Blackwelder (1929, 1931), Johnson (1932), Howard (1942), Miller (1950), Rahn (1966, 1967), and Mackin (1970); the other school held that a combination of weathering, backwearing, and transport by sheetfloods was the origin, and this group included McGee (1897), Davis (1930, 1938), Rich (1935), King (1953), and Schultz (1955). A few have maintained that both processes are active and significant, including Bryan (1923), Gilluly (1937), Sharp (1940), and Bullock (1951); they have generally favored backwearing over lateral planation, with Sharp (1940) assigning a ratio of 60 percent backwearing to 40 percent lateral planation in the Ruby-East Humboldt Range. Lustig (1969) states that drainage evolution and slope retreat are the cause and eliminates sheetfloods as a factor. Most recent observers tend to discount the effect of lateral planation by streams, while recognizing it does occur. Whatever their origin, broad pediments have been observed throughout the Wasatch Front area (Bullock 1951; Pack 1926; Marsell 1964; Crittenden et al. 1952). The importance of pediments and how they will be used and interpreted in the present study will be discussed in the next section.

CONCEPTUAL MODEL

The origin and development of compound faceted spurs and associated pediment remnants depend on a number of surficial processes all operating on a fault block experiencing recurrent uplift. Each of these processes and its effect on the system need to be understood for a viable conceptual model to be developed. The model presented here is shown by a series of diagrams in figure 2 and is an extension and modification of that suggested by Hamblin (1976). However, it differs considerably from Hamblin's model in that he did not include the concepts of erosion concurrent with uplift, uneven stream spacing, facet apices not related to pediments, or destruction of older facets. It represents the closest approximation to reality that can be envisioned at present. Before describing the sequential development as seen in figure 2, the most significant factors and their effect on the development will be discussed, including pediment formation and preservation, recurrent uplift, downcutting by streams, slope retreat, and structural control as expressed by differential erosion on alternate resistant and nonresistant strata.

Pediment Formation

As noted by King (1953), pediment formation is a universal process, occurring in all climates. It is an end product

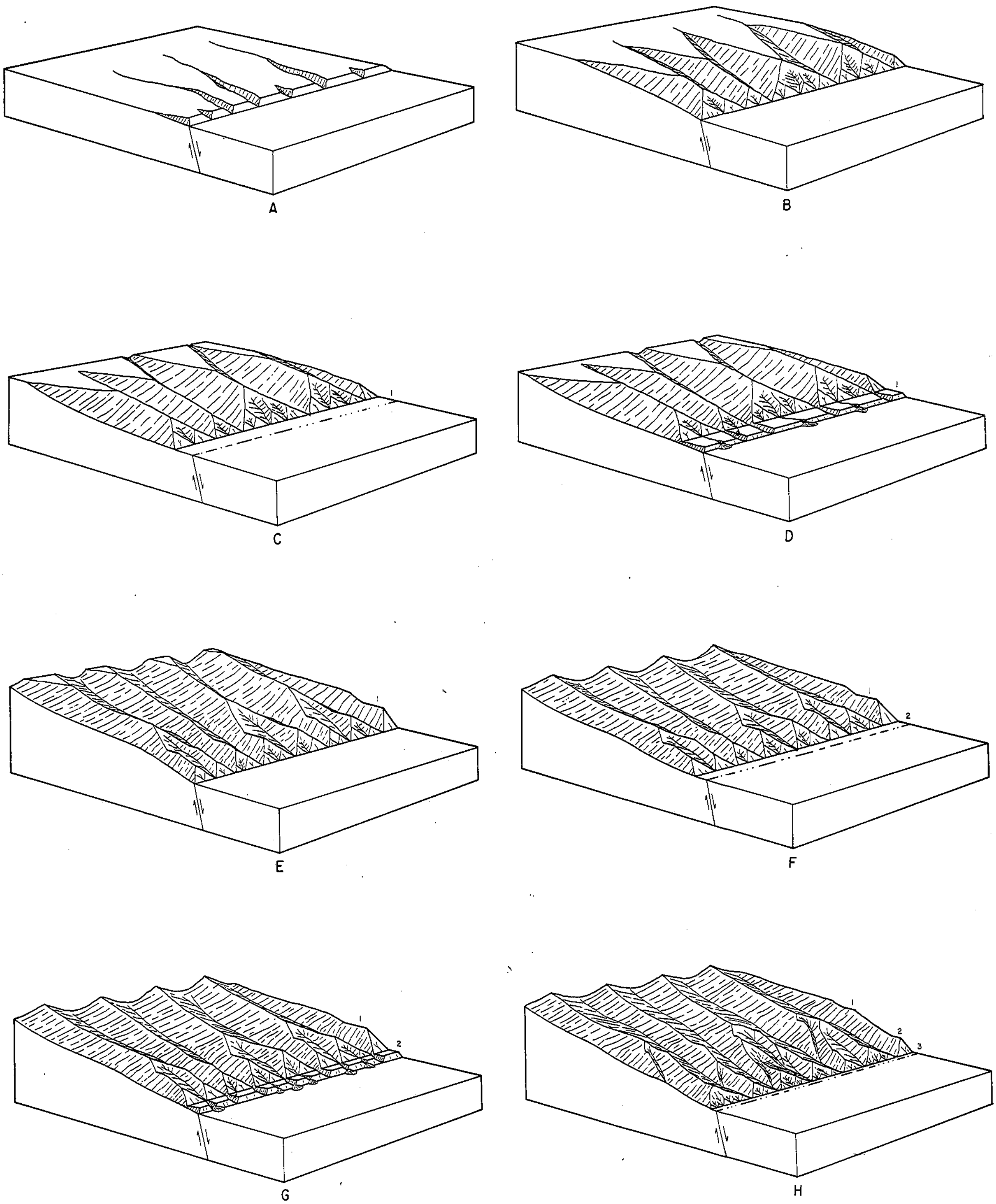


FIGURE 2.—Conceptual model of compound faceted spur development and pediment preservation. See text for full discussion. Pediment levels are numbered 1–3 for identification through sequential development. Initiation of uplift activity shown in A, with the cycle concluding in B. Quiescence indicated from B to C, and uplift resumes in D. The second active cycle ends in E, beginning another quiescent period which ends in F. A third active uplift cycle begins in G and concludes in H. Two uplifted remnant pediments are seen, with a third in the making during the next period of quiescence.

of slope retreat. The precise processes of pediment formation and their relative importance, a controversial and often discussed subject, is not an issue here if we state only that pediments do indeed form and have formed in the past. It is certain that if a mountain block is tectonically stable for a long enough period of time, a pediment will be formed at its base with a width directly proportional to the duration of stability.

Recurrent Uplift

The conclusion that uplift results from intermittent discrete events on the scale of single earthquakes with low scarps is a moot point. Few would deduce that escarpments thousands of meters high were produced in a single event; indeed, the largest scarps from historic recorded earthquakes are on the order of tens of meters high. Rather, the meaning of recurrent uplift as envisioned here is that cycles of relatively high uplift activity occur interspersed with periods of relatively low activity or quiescence. The active periods represent a series of discrete displacements and associated scarps which result in a cumulative displacement much greater than that of any single event. While short periods of erosion certainly are interspersed between the discrete events, the length of time is insufficient to allow significant pediment formation. Between these active cycles are periods of quiescence when the amount of active uplift is relatively low or nonexistent. These periods have sufficient duration to allow pediments to develop as expected. In addition to pediment generation, slope retreat modifies the range during quiescence as discussed in a later section. Recurrence is seen in the close of a quiescent period and initiation of a new active cycle. At this onset of uplift, and continuing through the active period, the pediment surface just produced is largely destroyed by downcutting, but a remnant tends to be preserved in the ridge between drainages, often at the apex of newly formed facets.

Pediment Preservation

It is assumed that pediment remnants are preserved as near-horizontal ridge segments in one of two possible ways. First, horizontal ridge segments are assumed to not migrate back but are partially removed during slope retreat. Thus the initial pediment width must be large enough that subsequent removal by slope retreat is insufficient to destroy it in the time since its formation. This possibility implies that any pediment remnants preserved higher up on the escarpment must have been initially wider than those found lower, and therefore that either the history has been one of progressively shorter quiescent periods or that older shorter quiescent periods have left no record.

Alternatively it may be proposed that horizontal ridge segments are carried back with slope retreat processes, and even though initial pediment width may be small, little is lost in backwearing. This possibility allows total flexibility in pediment width through time, and therefore duration of quiescence can take any value above the minimum needed to produce a pediment initially. It implies that backwearing as proposed by Penck (1924) is the dominant slope retreat process, and not downwearing as suggested by Davis (1922).

Although the conceptual model could adopt either of these hypotheses, the latter seems preferable to allow preservation of pediments; a conclusion from the observed data is made later to support this preference. Certainly it is perceived that if a sufficiently long erosive period occurs, features will become obscured or lost whatever the processes of preservation; and this must happen for very old events.

Downcutting

Prior to initiation of uplift, it must be assumed that a drainage system existed, and that uneven rather than ordered spacing of channels is likely. These preuplift drainages were antecedent to the faulting and exerted strong control on later landform development, especially triangular facets. Downcutting, with associated slope retreat, by these streams is the primary origin of facets, as noted by Davis (1909). However, the simplified presentation of uplift on a large scale followed by downcutting as shown by Davis (1909), Hamblin (1976), and others tends to cloud the real developmental history, as downcutting is undoubtedly concurrent with uplift. Therefore, any conceptual model—including the present one—should allow for contemporaneous uplift and erosion in facet development.

In addition to forming and modifying facets, the antecedent streams are in turn affected by recurrent uplift in two ways. During periods of quiescence these streams tend to approach a classic graded profile with the valley floor as baselevel. Recurrent uplift lowers the baselevel relative to the streams and causes entrenchment in the lower reaches of the stream as it tends to restore a graded profile to the new baselevel. The lower graded section meets the upper at a knickpoint which ultimately migrates back until it disappears. If there was insufficient time for this loss, or if the streams failed to keep pace with the faulting (Davis 1909), the knickpoint may remain. Multiple uplifts will cause multiple graded reaches and knickpoints, some or all of which may be preserved. Besides the multiple graded profiles, a second effect of recurrent uplift is formation of wineglass canyons and hanging valleys by the aforementioned entrenchment and reentrenchment, as noted by Hayes (1926) and Eardley (1933).

Downcutting and associated slope retreat by streams with a different origin is also an important process. These are the streams which form on the face of the facets because of the slope of the new surface, and are thus best termed consequent streams. They modify the larger facets in the manner noted by Davis (1909, p. 746):

> The moderate dissection of the large facet by small ravines results in the development of several little basal facets along the fault line, where they form the truncating terminals of several little spurs.

Davis considered this effect to be the sole origin of compound faceted spurs as he did not recognize the effects of recurrent uplift on facets (although he did recognize that recurrent uplift is likely). While compound facets have an additional origin in recurrent movement as discussed here and by Hamblin (1976), the effect of consequent streams is an important part of the model. Inasmuch as these consequent streams, like the antecedent ones, are unevenly distributed, the small basal facets so produced will be of varying sizes. Since these basal facets have no genetic relation to the uplifted pediment surface and their apex elevations will vary, they would not be expected to correlate as an indication of most recent uplift. If, however, basal facets are present which have a preserved pediment remnant at or near their apex, and these remnants correlate well, it is likely that these facets are not merely a result of consequent stream development. Both types are apparently seen in reality, and both types are expected in the model.

Recurrent uplift and renewed downcutting will modify both consequent streams and facets. The consequent streams may continue across the pediment, cut through it, and remain as a larger extended system still on the face of a now larger facet; or they may be diverted into another drainage and eventually lost, while new consequent streams are intitiated on the newly formed facets. As large facets are uplifted, they tend to recede and lose character but may be preserved. However, the small basal facets which form from consequent streams are generally lost during recurrent uplift owing to more vigorous downcutting and "sidewearing" by the larger antecedent streams. A consideration of these and previous conclusions suggests that through cycles of recurrent uplift, preserved pediment remnants should dominate over preserved facets in later stages.

Slope Retreat

Slope retreat is a pervasive process involved in all the foregoing discussions; certain specific effects, however, need mention. Two mechanisms of slope retreat, or a combination of the two, may be involved: backwearing (Penck 1924), or the near-parallel retreat of scarps, and downwearing (Davis 1922), or the reduction of a surface to a peneplain. The best concept for purposes of this model is stated thus: slope retreat causes a near-parallel backwearing of the escarpment with a reduction in slope angle with time. The result of this is that the longer a feature, slope, ridge, or facet has been exposed to weathering and erosion, the more gentle its slope angle will become.

One significant deduction is therefore that the surface of triangular facets is a result of slope retreat to a stable slope angle and does not reflect the actual fault surface, which usually dips more than 60°. This relation, discussed in a prior section, has been observed by many workers, notably Gilluly (1928, p.116), who stated:

> It seems wholly improbable that any scarp characterized by 'faceted spurs' of physiographically greater age should have retained the dip of its bounding fault.

Nevertheless, for a unique active uplift period, the facet slope angles will be similar. Most basal facet angles range between 20° and 40° as recorded by Davis (1909), Gilbert (1928), Gilluly (1928), Baker (1959), and others; with 35° a good average figure. Compound facets above the basal facets, interpreted to be older, dip about 25° (Davis 1909).

Structural Control

One significant controlling parameter not expressed in the model of figure 2 is geologic structure. Where contrasting resistance to erosion is seen in the lithologies making up the mountain block, it should be expected that differential erosion may in time cause less resistant units to be stripped off of more resistant units forming a stripped surface bench. These surfaces could be misinterpreted as uplifted remnant pediments if their true origin were unknown; however, they can usually be identified as such in this region.

It is important not to totally disregard any true stripped benches for the following reason: since geologic structure here is not that of uniformly horizontal beds (Baker 1964, 1972, 1973), there will arise cases in which structural trends cross remnant pediment levels. These pediment surfaces may coincide with stripped bedrock surfaces at those points; indeed, they may be more broad there than normal because of the lithology contrast. They can still be considered valid pediment remnants if the overall correlation of pediments does not directly follow the structural trends. However, it must also be expected that in some areas structural control is so dominant that valid correlations of ambiguous data is impossible.

Sequential Development

Each of these geologic controls has been considered in the preparation of the model shown in figure 2. The onset of uplift activity on a block with preexistent drainage is seen in A, with the active cycle concluding in B. Only a low scarp signals the initiation of activity, and downcutting begins at the same time. Downcutting is concurrent with uplift from A to B, and the triangular facets produced by this are not all the same size as a result of uneven spacing of the preexistent streams. The facet between closely spaced streams is much smaller as required by slope retreat, and the apex of that facet connects with the undissected surface in a ridgeline rather than meeting it directly. B also represents the beginning of a quiescent phase, which concludes in C with the formation of a broad pediment, compound facets, and a graded stream profile. Note that none of these facets are directly related to pedimentation. A new active cycle begins in D and concludes in E, with corresponding modifications of drainage, valley form, facets, and ridges. Some of the original consequent streams have been diverted and uplifted facets lost while others remain. The pediment is preserved at an accordant level, though not always at a facet apex. Incipient wineglass canyons and doubly graded drainage with a knickpoint are evident. A quiescent period then begins, and ends in F with a new pediment produced. The remnant uplifted pediment is preserved, and the antecedent streams are still doubly graded with knickpoint. Another active phase begins in G and concludes in H, with two remnant pediments uplifted and preserved and a third in the making. Forms become more complex, as facets are created and destroyed, and antecedent streams now have three separately graded segments. Wineglass canyons are prominent. Some of the initial large facets remain in compound systems, while others have been lost leaving only most-recent-stage facets at the end of a long ridge. Multiple basal facets are unrelated to pediment uplift, resulting instead from consequent stream dissection of larger facets which are related to a pediment. The cycle can continue through successive generations, pediment remants tending to be preserved and facet forms lost or modified. A comparison of the "final stage" seen in figure 2H with the features of Spanish Fork Peak (fig. 3) reveals many similarities and supports the observations of the preceding discussion.

METHODS

The prime objective of the study was to correlate the remnant pediment surfaces and construct a history of displacement. The first step, then, was to identify these features and observe their characteristics so they could be mapped on a topographic base and projected to a profile ready for correlation. The triangular facets have been well described by several workers, from the first identification by Davis (1909), to later work by Gilbert (1928), Gilluly (1928), Sharp (1939, 1940), and others studying areal geology. Some have described the compound nature of the facets, such as Bissell (1964), Rigby (1962), Feth et al. (1966), and Rigby and Hintze (1968); but the pediment remnants have been essen-

FIGURE 3.–Oblique aerial photograph of Spanish Fork Peak.

FIGURE 4.–Oblique aerial photograph of selected facets on Spanish Fork Peak. See figure 6 for a topographic map of this area.

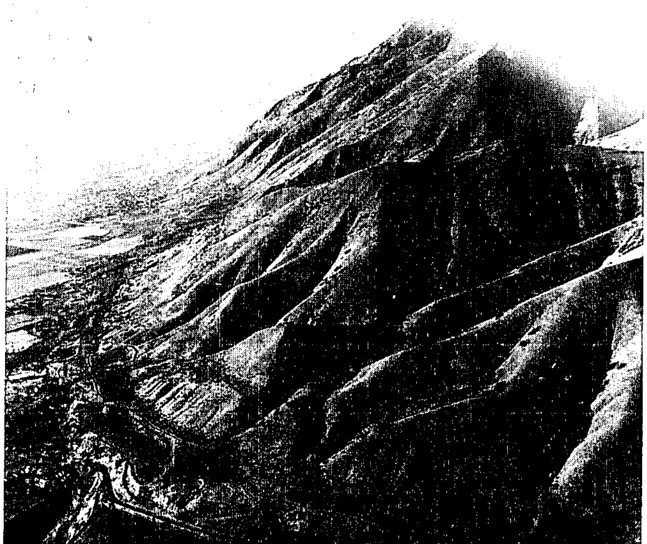


FIGURE 5.–Oblique aerial photograph of area just north of Hobble Creek Canyon.

tially undescribed. Davis (1909) expected recurrent uplift but did not recognize any features produced by it, and Sharp (1939, 1940) noticed horizontal ridge segments or "treads," but did not describe these definitively as remnant pediments. It was not until the work of Hamblin (1976) that the pediments were described and tentatively correlated.

The remnant pediments consist of near-horizontal ridge segments often beginning at the apex of triangular facets as can be seen in figures 4 and 5. They usually dip towards the fault a few degrees, but occasionally have a backward dip as seen in figure 5, which may indicate eastward tilt on the mountain block (as suggested by Eardley 1933 and Peterson 1969). The width of the pediment surface, as expressed by the length of the ridge segment, varies from zero up to 1200 m, with the minimum identifiable size being about 30 m. They are best observed with vertical stereo aerial photos in conjunction with oblique aerial photos. As a planimetric plot was desired for correlation, the method consisted of identification by aerial photography followed by mapping on a topographic base.

Aerial Photography

Proper identification of both facets and pediment remnants requires critical lighting to enhance shadow detail and emphasize form. This is best done with low-sun-angle photography, as described by Cluff and Slemmons (1971) and Cluff et al. (1973) in a project involving Recent scarp recognition for the Wasatch fault zone. The vertical photography they shot was examined for the study area of this report and found to be quite helpful. Their coverage, however, did not include much of the mountain front, and so additional vertical aerial photography was obtained at two scales (about 1:60,000 and 1:28,000) to cover the study area. Fortunately, much of this additional photography was taken at a low enough sun angle for the features to be well modeled. These vertical aerial photos were then viewed stereoscopically to aid in identification of facets and pediments, with the low-altitude coverage being most helpful.

Oblique aerial photography also proved to be essential in feature identification. Three flights were taken to provide optimum lighting conditions, one in late afternoon and two in the morning. It was found that the southern third of the study area, from Springville south, was best photographed in the late afternoon; the Timpanogos and south Provo areas required early to midmorning light; and the central Provo and Alpine areas did not receive proper light until late morning. This oblique aerial photography included both black-and-white prints and color transparencies, with the color slides proving to be most useful in observation and identification of pediments.

Pediment Mapping

With identification of the landforms from the photographs, the next step was mapping, or plotting, these features on the topographic quadrangle maps. Nearly the entire study area is covered by maps at a scale of 1:24,000, the exception being the extreme southern end near Payson Canyon, which has been mapped at 1:62,500 only. The facets and pediments are usually well expressed in the topographic contours, and there was little difficulty in locating positions and elevations to the nearest contour. A segment of the Spanish Fork Peak quadrangle which includes the same area seen in the photograph of figure 4 is shown in figure 6. The three prominent basal facets and pediments at their apices are easily recognized in the contour map. For mapping purposes thin lines represent facet outlines and ridgelines, and heavy lines represent remnant pediments, shown for this same area in figure 7. As the minimum identifiable pediment width was about 30 m, this was plotted as a heavy dot. Also plotted as dots were all facet apices which did not already have a distinct pediment remnant.

After features were plotted in this manner on each of the quadrangle maps, the information from the separate quadrangles was transferred to a large acetate overlay, including elevation values for all the pediment remnants and facet apices. The southern portion at the smaller scale was enlarged to match the rest of the area. In all, 1275 data points (pediment remnants and/or facet apices) were identified and plotted, ready now for projection to a frontal profile.

Profile Projection

Since the purpose of this study was to accurately identify and correlate the pediment remnants, an orthographic projection of each point out to a mountain-front profile was desired. Inasmuch as the Wasatch fault is highly curved in some areas, a baseline was laid out on the acetate overlay to follow the main trend of the most recent breaks of the system. This baseline represents the intersection of the ground surface at the foot of the range with a vertical plane which curves to follow the generalized trace of the fault. This plane when "straightened out" becomes the desired frontal profile, free of perspective effects. The baseline began at the Utah County-Salt Lake County line at the summit of the Traverse Mountains, which was chosen as the zero point. It then followed the fault zone south to the limits of the study area and was graduated in hundreds of meters of horizontal distance along the line, with the total length being 75.7 km. This scale would then serve to locate each data point horizontally, and the elevation value would locate each point vertically.

In practice, each point was orthographically projected out to the baseline and tabulated according to four parameters: the horizontal distance south of the starting point, the elevation of the pediment remnant, the distance back from the baseline, and the width of the surface remnant. The tabulated data was then plotted on graph paper with a horizontal scale of 1:24,000 to match the base map, and a two-times vertical exaggeration. The horizontal distance became the abscissa, the elevation became the ordinate, and the pediment width was expressed symbolically as follows: widths less than 30 m as a heavy dot, widths from 30 to 120 m as a circle, widths from 120 to 240 m as a triangle, and widths over 240 m as a square. The distance back from the baseline was unplotted, and did not enter into later correlation. The result is a planar frontal profile on which correlation of the data is possible. This profile is printed at reduced scale in sections, including the correlations, in figure 8.

Correlation

Correlation of the pediment remnants was done visually using the elevations, widths, trends, and sequence. Inasmuch as total removal from the reality of the photographs was undesirable, certain key points were also plotted back on a series of oblique photos, and the physical character of each surface as seen on them examined to assist correlation. The correlations made were also checked against the photos for credibility. The best-fit lines for the available data usually did not take the form of constant-elevation horizontal lines, but rose and fell gently to suggest hinge- or scissor-type movement. Strongly inclined correlations, however, were deemed unlikely and not allowed in the process. Pediment width data assisted the correlation, but was not a controlling factor, as the initial widths and degree of preservation were probably

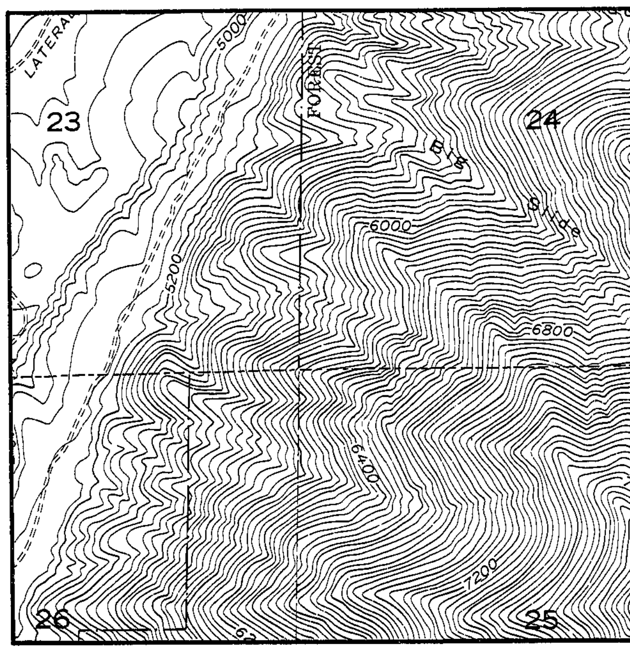


FIGURE 6.–Section of Spanish Fork Peak Quadrangle topographic map to show typical appearance of facets and pediment remnants as expressed by topographic contours. Scale 1:24,000; contour interval is 40 feet. Area shown is same as that in figure 4.

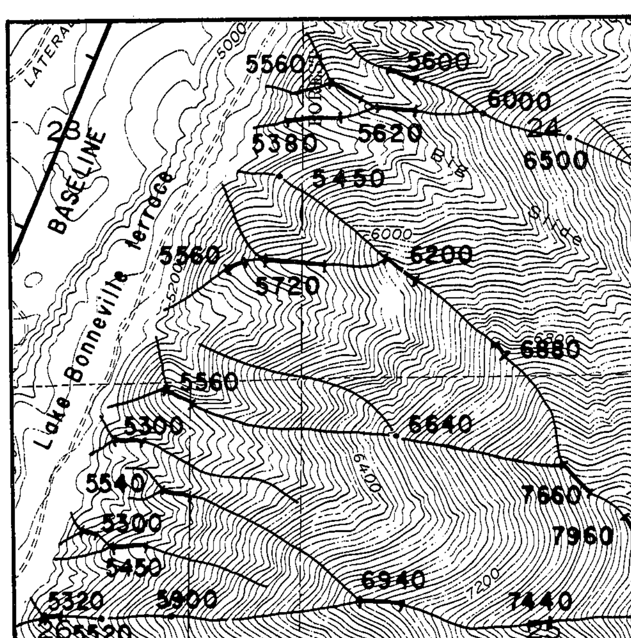


FIGURE 7.–Same map as figure 6 with facets and pediments identified by thin and heavy lines, respectively. Pediment elevations are in feet. Part of the baseline which was used for projection and plotting is seen.

variable resulting in variations in remnant width for a given surface. Many data points were left uninvolved in the correlation, and they are assumed to be either structurally controlled surfaces or poorly preserved remnant pediments which did not justify lateral correlation. Solid lines were used for good correlations, dashed lines for inferred connections which may be disputed, and dotted lines where no potential data could exist as in canyons. The results of this correlation procedure is shown in figure 8.

A future possibility lies in correlation by computer. As mentioned, the data exist in tabulated form and could easily be keypunched as a data deck. An algorithm to correlate by using the parameters and criteria listed above could conceivably be developed and may be superior to strictly visual cor-

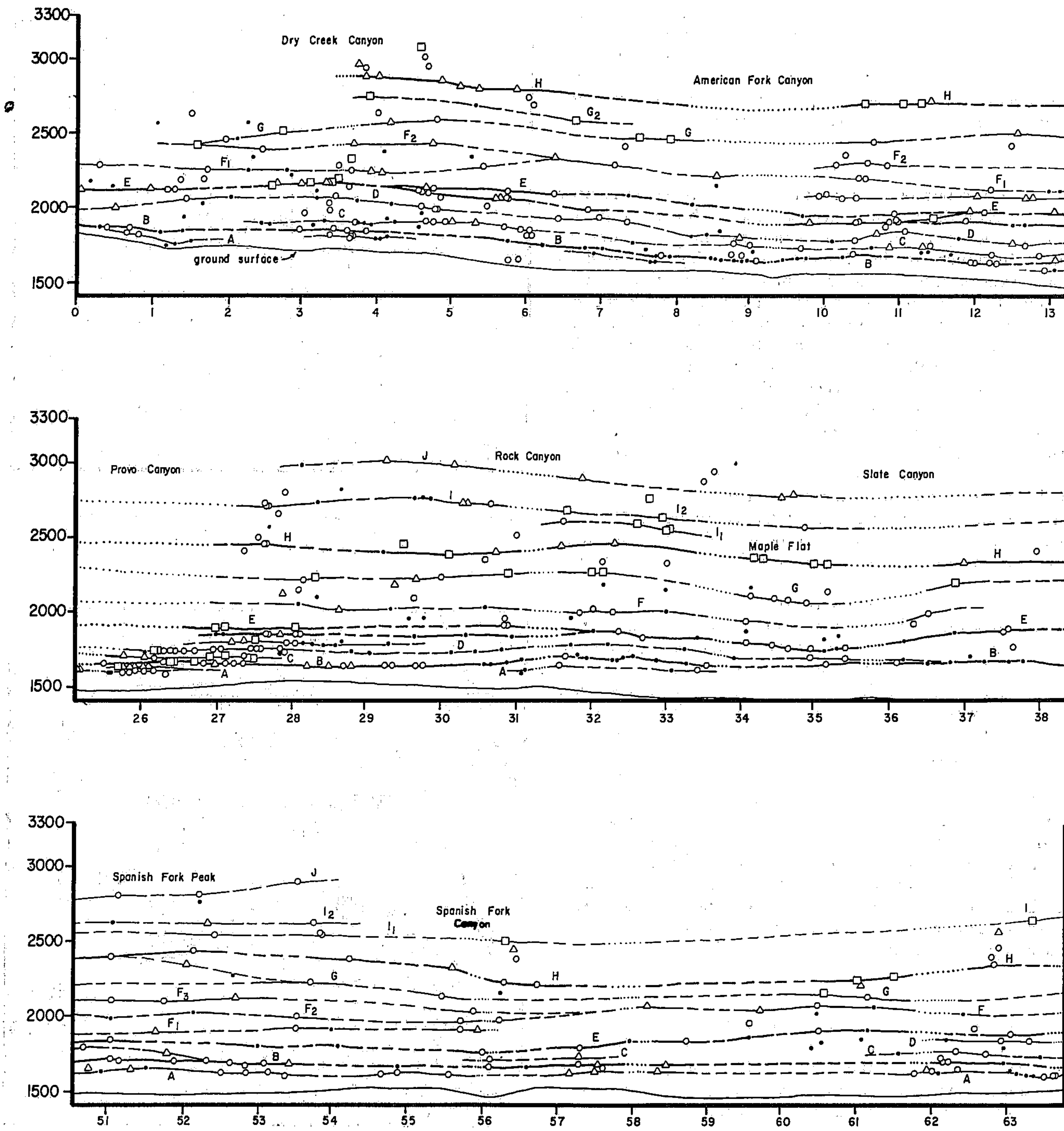
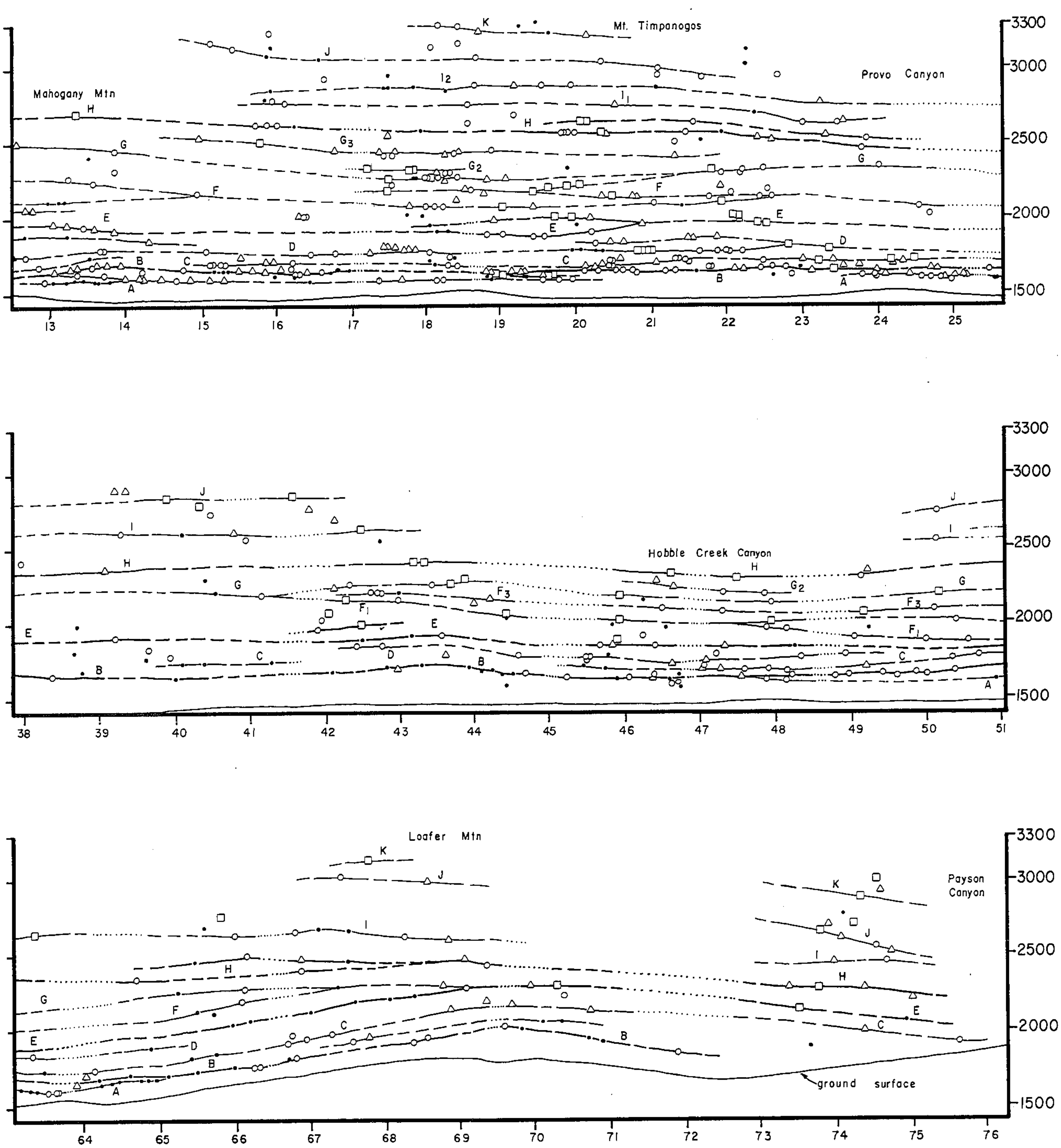


FIGURE 8.—Profile of rangefront with plotted data points and correlations. The vertical scale is exaggerated two times relative to the horizontal. The vertical scale is elevation in meters above sea level, and the horizontal scale is distance in thousands of meters south of datum point along the baseline (see text for full discussion of method). Dots represent facet apices and remnant pediments up to 30 m in width; circles are pediments 30 to 120 m wide,

relation. However, some skepticism is justified, and this procedure was not attempted for the present study.

RESULTS

The results of the correlation procedure (fig. 8) indicate that some remnant pediments are distinguishable throughout the entire length of the study area, and others are preserved only in local areas and correlation of these is quite subjective. The correlated levels were named alphabetically from lowest to highest and possible scissors branches and related close levels were given subscripts to simplify identification. Three major surfaces are ubiquitous and are printed with bold lines; using the nomenclature adopted for figure 8, these are levels B, E, and H. The other named levels (A, C, D, F, G, I, J



triangles represent widths of 120 to 240 m, and squares are remnant pediments over 240 m wide. Main correlations of levels B, E, and H are shown with a heavy line, and correlations of all other levels with a thin line. Dashed lines are inferred correlations, and dotted lines represent areas of no data such as major canyons.

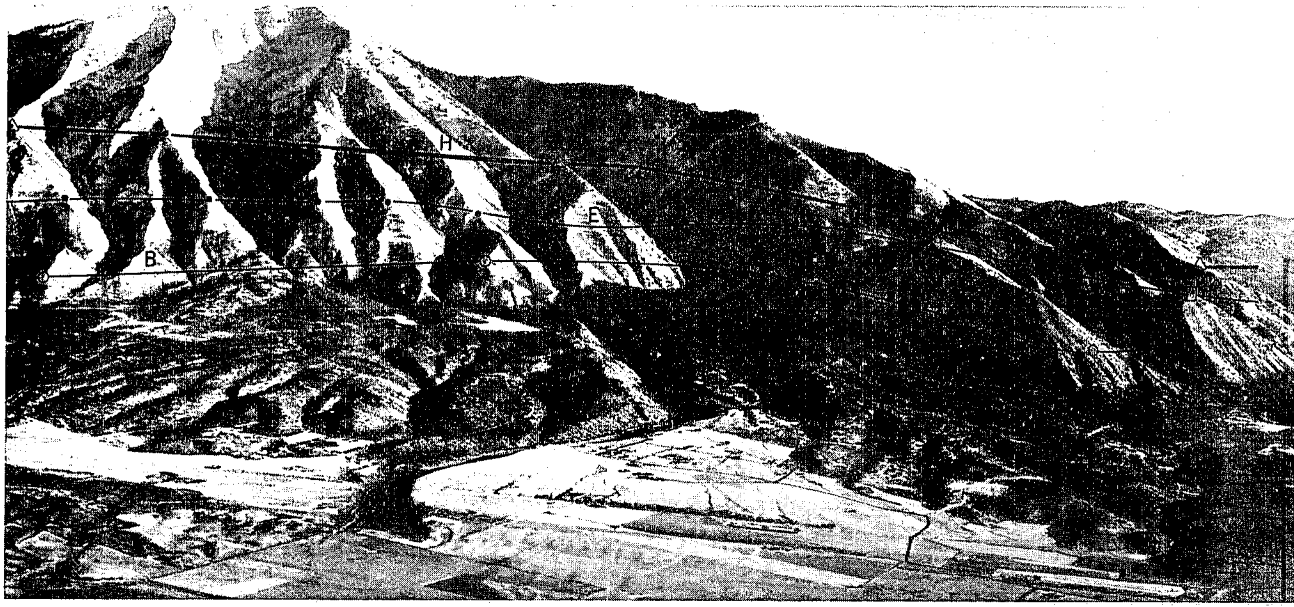


FIGURE 9.—Oblique aerial photograph of Loafer Mountain area including key pediment correlations of levels B, E, and H.

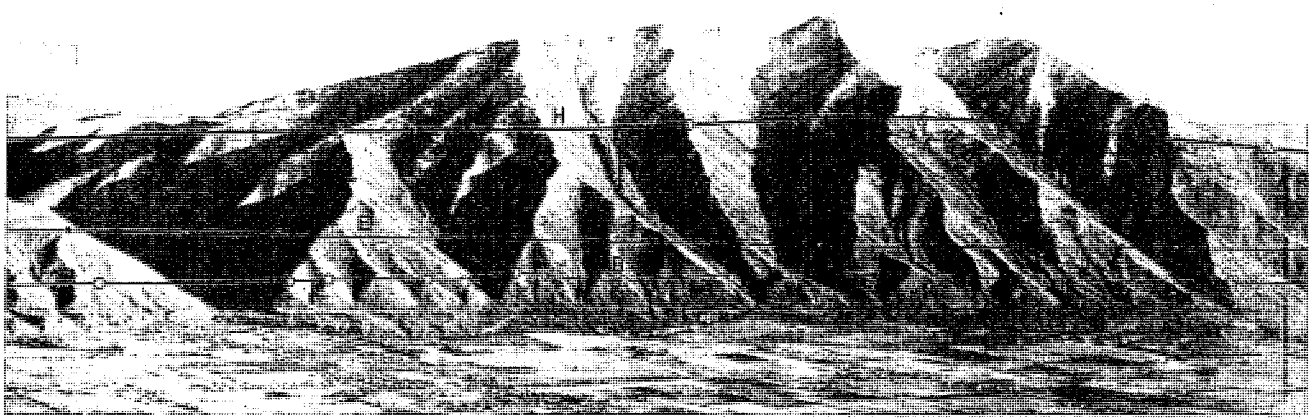


FIGURE 10.—Oblique aerial photograph of Spanish Fork Peak area including key pediment correlations of levels B, E, and H.

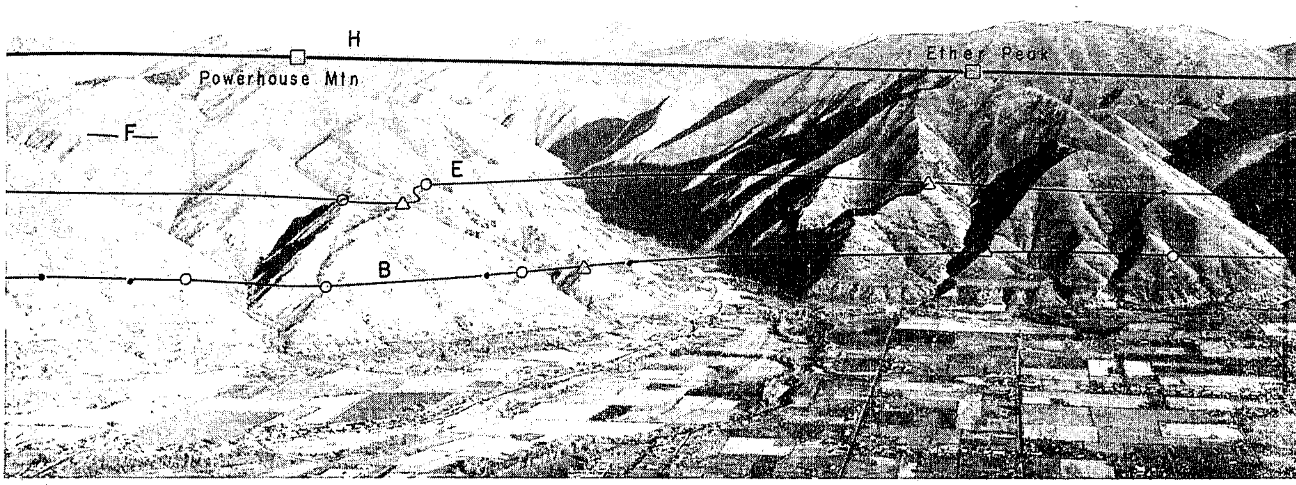


FIGURE 11.—Oblique aerial photographs of Hobble Creek area including key pediment correlations of levels B, E, and H.

and K) do not extend throughout the area, but still may be distinct and valid pediment remnants in local segments, especially if the width is large.

The B level represents the most recent uplifted pediment which usually occurs at the apices of basal facets. The A level below it may represent a pause during uplift of the B level pediment, but owing to its narrowness and appearance only locally it is possibly a false correlation of facet apices which formed by consequent drainage evolution. Level E is the next highest prominent surface, with others present between B and E in local zones. Above E level are some more pediment remnants preserved only locally (though sometimes extensively). These are more likely to represent valid pediments than level A since higher, older facets tend to be lost and pediment remnants preserved, as discussed in the conceptual model section. Another dominant surface above those is level H. It is the best preserved and broadest uplifted pediment and can be distinguished practically everywhere by its size and position. This corresponds to the maturely developed surface observed and discussed by Eardley (1933). Above it are three more levels which are preserved only locally because of their age. The H level represents a long stage of quiescence during which erosion and slope retreat probably removed or obscured remnants from earlier cycles. Even so, the I, J, and K levels represent valid correlations in some local spots where there is an abundance of data. In other areas these correlations are admittedly speculative where data are sparse.

These observations are best discussed on an area-by-area basis and will be considered from south to north, referring to figure 8, in order to discuss early the features of Spanish Fork Peak, which clearly has the best preserved record.

Payson Canyon to Spanish Fork Canyon

This segment of the Wasatch fault is the eastern portion of an en echelon pattern which presumably dies out southward and picks up again offset to the west (fig. 1). The correlations in this segment have been interpreted using this assumption and could be interpreted differently because of the scarce data. The H level is well developed, however, and is seen as a broad upland above the prominent scarp (fig. 9). The J level is also present at the apices of two prominent facets perched quite high, and this development is quite similar to that seen east of Salt Lake City (Hamblin 1976). While the B and E levels are missing or pinched out at the extreme southern end, they appear and are well preserved on the west face of Loafer Mountain (fig. 9). Northward from there, the B level remnants disappear for a stretch as the fault trace bends eastward but are preserved closer to the mouth of Spanish Fork Canyon. Another level (A) below B is seen, which may be a pediment remnant, but more likely represents accordant basal facet apices not directly related to pediment generation, as discussed in the conceptual model section.

FIGURE 12.–Oblique aerial photographs of Maple Flat area including key pediment correlations of levels B, E, and H.

Spanish Fork Canyon to Springville

This area has been called by Davis (1909) the type area for faceted spurs. It undoubtedly has the best preserved pediment remnants and compound facets of any area (figs. 10 and 11), and the record there is clearly one of relatively uniform cumulative uplift composed of individual scissors or hinge movements. The reason for this preservation may be that the mountain front throughout this segment is composed only of the Oquirrh Formation, and structural control is minimal. The basal facets and associated B level are well-preserved, and the H level is quite well developed on the face of Spanish Fork Peak (fig. 10), at the summit of Ether Peak (fig. 11), and at the summit of Powerhouse Mountain (fig. 11). Several of the pediment remnants just north of Hobble Creek Canyon (fig.5) indicate by their attitude possible eastward tilt of the block. A section of A level continues in from the south, again probably related to consequent stream dissection rather than pediment generation (fig. 2). Data points in this segment are frequent enough to justify correlations involving scissors movements, a point discussed in the conclusions.

Springville to Provo Canyon

This segment begins an area of potentially greater structural control due to the complex stratigraphy. It is interesting to note that many more data points are present from this point north than in the southern areas, probably not because of better preservation, but because of greater frequency of non-pediment-related surfaces such as structural benches. Nevertheless, good correlations are found, as expressed in figure 8. The H level is especially apparent on the face of Buckley Mountain, at Maple Flat (fig. 12), and behind Squaw Peak. Maple Flat is especially critical, as it is a broad surface carved on the resistant Humbug Formation (J. L. Baer pers. comm.). The E, G, and H levels are all well expressed in figure 12, as well as the Lake Bonneville levels. Lower-level surfaces are particularly well preserved at the mouth of Provo Canyon, probably because of the availability of lateral planation by the Provo River during pediment formation, a point discussed in the conclusions.

Provo Canyon to American Fork Canyon

Mt. Timpanogos exhibits a wealth of potential remnant pediments, but it is important not to end up following structural trends, as several surfaces exist where the Manning Canyon Shale has been stripped off the resistant Great Blue Limestone. An examination of fig. 8 will show that correlations generally do not follow the structure, which has an apparent dip to the south on the profile. Many levels are seen, including scissors movement lines, and occasionally a pediment level crosses and coincides with a structural bench. The H level is again very prominent (fig. 13) and coincides with the wide ridge behind Big Baldy and with the summit of Mahogany Mountain. While classic facets are scarce, the B level is also well represented by the data. Whether or not uplifted pediment remnants are preserved on the face of Mt. Timpanogos above the H level is somewhat speculative, but the data appears to strongly support the I_2 level, as shown (fig. 8), and the others may be valid as well.

American Fork Canyon to the Traverse Mountains

In this final segment, the B level is well established, usually at the apices of basal facets. A strong C level can be seen just south of Dry Creek Canyon (fig. 14), and the E level is well preserved throughout. The H level is present below Box Elder Peak, but is not obvious on the south face of Lone Peak, perhaps because of extensive glaciation and obliteration of the remnants. A look at the west face of Lone Peak from the Salt Lake Valley strongly suggests that this level is present to the north as well. North of the summit of the Tra-

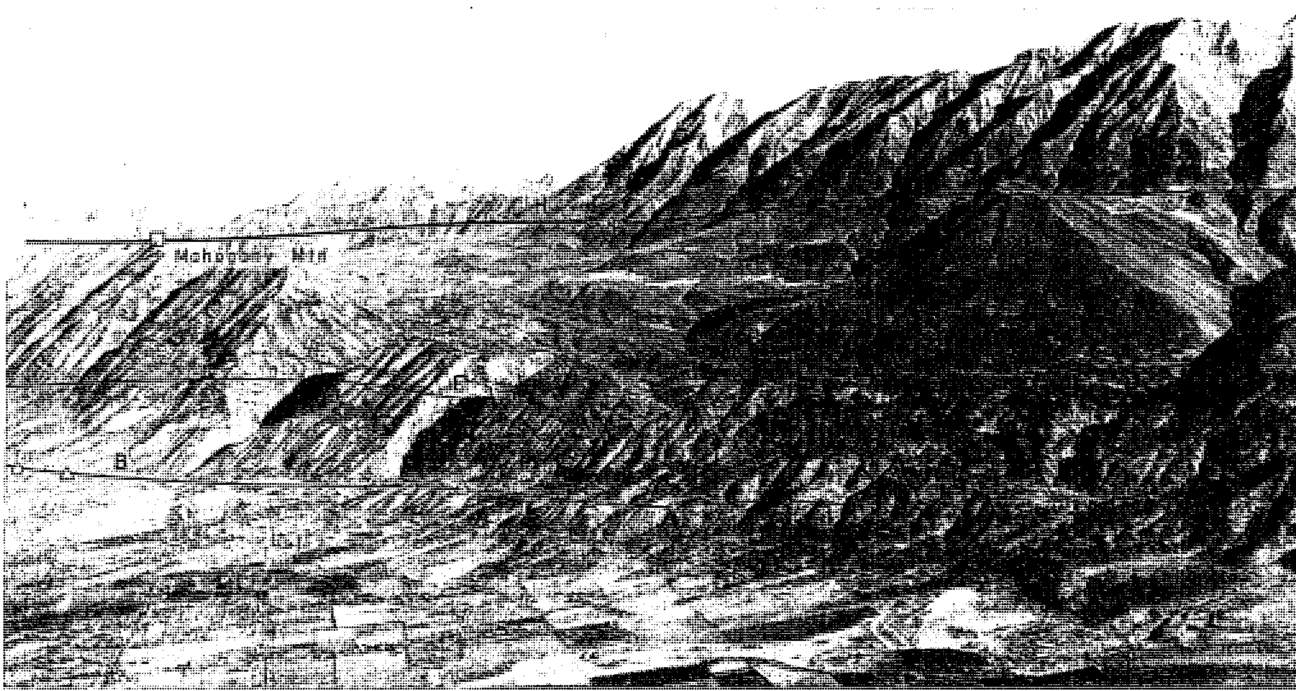


FIGURE 13.–Oblique aerial photographs of Mount Timpanogos area including key pediment correlations of levels B, E, and H.

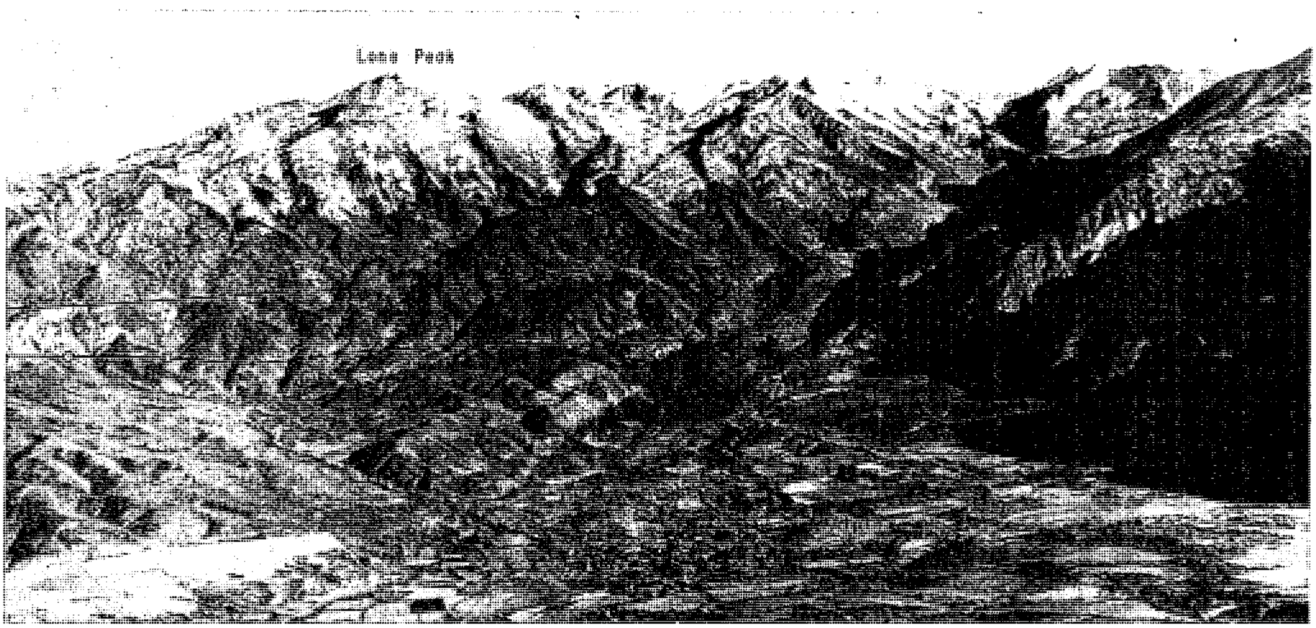


FIGURE 14.–Oblique aerial photographs of Alpine area, including key pediment correlations of levels B and E. H may be present, but is obscured by extensive glaciation of Lone Peak.

verse Mountains, and therefore beyond the limits of this study, are four streams perched on the side of Lone Peak which do not flow down the regional slope of the mountain face (fig. 15). They were noted by Gilbert (1928) and Bullock (1958) and interpreted by Gilbert to be former segments of Corner Creek which were entrenched into the mountain block and uplifted by recurrent movements. This interpretation is significant in that it implies quiescence during recurrence to allow entrenchment. A preliminary plot of the elevations of these streams above the present course of Corner Creek indicates that the lowest correlates with level B, the second correlates with level D, the third correlates with level E, and the highest possibly correlates with level F. This area should certainly be examined in greater detail.

A much more generalized summary of the results shown in figure 8 appears in figure 16 at a greatly reduced scale and with more vertical exaggeration. On this only the very prominent surfaces are plotted for the purpose of allowing a regional synthesis of the uplift history of the entire study area. Each of the three main pediment levels (B, E, and H) represents a period of quiescence with duration proportional to the width of pediment produced. The duration of level-B quiescence is short, but it is important since it represents the most recent quiescent period. Level-E quiescence was longer, but not as lengthy as that represented by level H, which endured so long that not only was a very broad pediment produced and mature topography formed, but many older remnant features were destroyed (absolute dating is discussed in the conclusion). A generalized historical development is suggested in figure 17, which may be viewed forwards or backwards in time. View a is a perspective oblique sketch of the present-day physiography of the Spanish Fork Peak area, and view b is what this area probably looked like just before Lake Bonneville entered the valley. View c restores the uplift back to the period of quiescence recorded by level B, and view d is how the range likely appeared when level E was at the valley level. Finally, view e shows the possible appearance at the close of level H quiescence. Any earlier stages would be too speculative to attempt to reconstruct; it is a subjective interpretation already.

Though not directly part of the pediment correlation, a few significant statements need to be made relative to the observed features as compared with the conceptual model. Several of the accompanying photographs (figs. 3-5, 9-14) show the presence of wineglass canyons and facets due solely to consequent stream development. A preliminary plotting of 16 stream profiles within the study area indicates numerous knickpoints and graded segments which project out to establish pediment levels, as expected in the conceptual model. Finally, high-level pediment remnants, often with strong correlations, have apparently been preserved even though high-level triangular facets are rare; certainly, many older features which were initially small have been lost, but many initially wider pediments have been preserved.

CONCLUSIONS

Pediment Formation and Slope Retreat

The observation that even high-level pediment remnants are preserved as distinct entities beyond their probable initial positions implies that near-parallel backwearing is the dominant method of slope retreat, as suspected earlier. It also seems probable that pediments originate directly from this slope retreat with the pediment level controlled by the valley floor level, below which slope retreat is inoperative. While this concept relegates lateral planation by streams to a subsidiary process, it is also apparent from the study that lateral planation is very significant in local areas such as at the mouths of major canyons, where pediment remnants tend to be more numerous, wider, and better correlated.

Uplift and Quiescence

Not only is recurrent uplift with interspersed quiescence established, but the form of discrete events is suggested. The post-Bonneville scarps tend to swell and die; so too do the older events in that scissors or hinge-type faulting is apparent. Thus one area may be active over a distance of a few kilometers for a time, then it will cease and an adjacent seg-

FIGURE 15.–Oblique aerial photograph of stranded streams at Corner Creek area. View looks southeast, with the Traverse Mountains on the right and Lone Peak to the left.

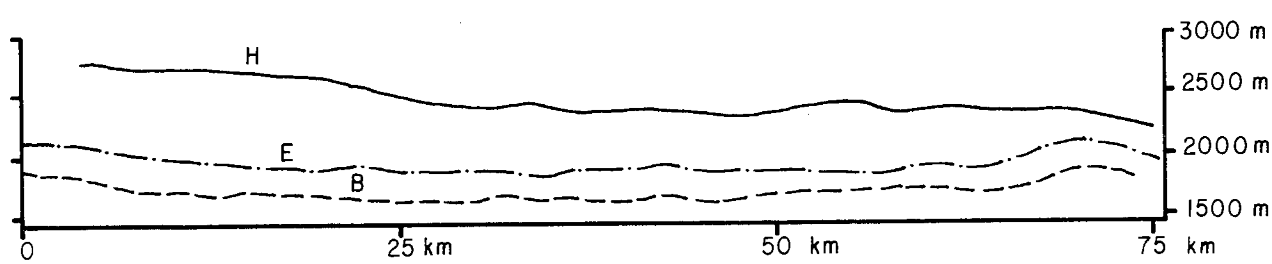


FIGURE 16.–Generalized profile of the range in the study area showing main correlations of levels B, E, and H as seen in figure 8, but at greatly reduced scale and with more vertical exaggeration (8 times).

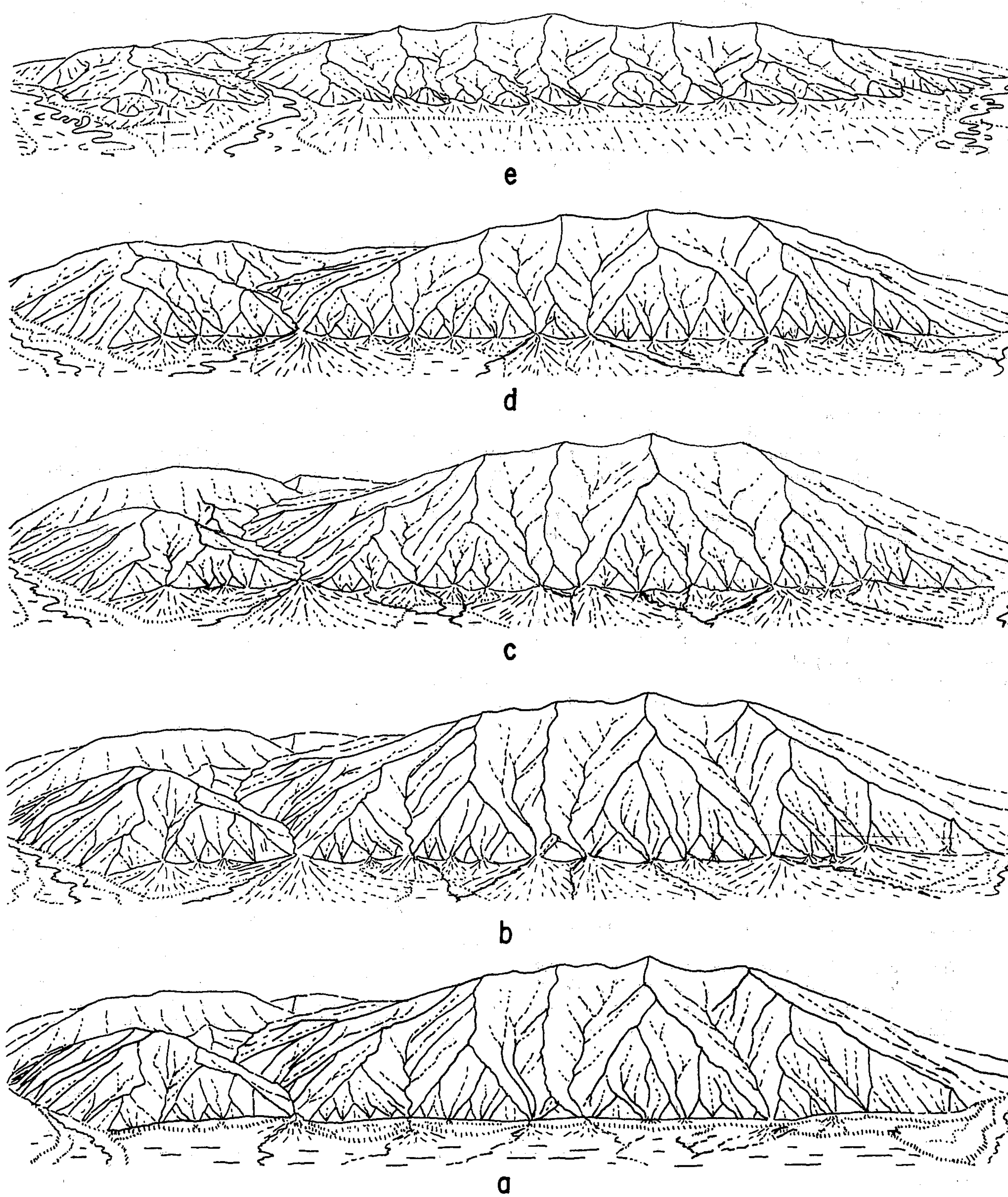


FIGURE 17.–Series of oblique perspective sketches of Spanish Fork Peak area showing probable historical development. View a shows present-day physiography. View b represents the area just before Lake Bonneville entered the valley. View c is a restoration of the uplift back to when level B was at valley floor level. View d is how the range likely appeared when level E was at valley floor level. View e shows the possible appearance at the close of level H quiescence.

ment of the fault will break and be active. A long enough sequence of these individual scissors breaks results in a cumulative displacement which is nearly uniform along the fault length. On the short-time scale, this is the type of activity seen in many seismic belts, and explains the seismic gaps along an active fault (Cluff et al. 1975). The current state of seismicity in this area is one of quiet, but a look at the low elevation of the B-level surface suggests that we are not now at the beginning of a long quiescent period but are instead in the middle of an active cycle. Values of earthquake recurrence intervals cannot be obtained from this study unless absolute dates can be assigned to each level, as discussed later.

Quiescent periods, although variable in duration, seem to be quite stable while they last. Pediments produced during them are generally planar rather than stepped, indicating a total cessation of activity for a time. The longest indicated quiescent period was that which resulted in level H; movement and quiescence prior to that are suggested but vague.

Absolute Dating

No possibility for absolute dating was observed in the study area. In other areas it may be possible if datable volcanics, for example, lie on a remnant pediment surface. If the time of initiation of faulting were known precisely and if a bona fide remnant of the prefaulting surface were observed, absolute dating could also be done; both are unclear, however. If we assume that faulting began 20 million years ago (Mid-Miocene), a consideration of the total physiographic relief and elevation of level H suggests that the H-level surface was at the valley floor level and undergoing pedimentation about 10 million years ago (Pliocene). This fact suggests that only about half the total history of uplift is documented by remnant pediments, with a few older vestiges present locally.

Tilt

As suggested by Eardley (1933) and supported by Peterson (1969), the uplift of the mountain block has probably included an eastward tilt or rotation of a few degrees along an axis about 20 km east of the front. Though by no means conclusive, several of the remnant pediment surfaces observed dip eastward a few degrees. Notable among these are some at the mouth of Hobble Creek Canyon (fig. 5) and the major one forming the ridge behind Big Baldy. This represents agreement with an earlier interpretation, but not proof of that interpretation. Many pediment remnants dip westward a few degrees; the initial pediment surface during formation, of course, would have that attitude, and any eastward tilt may only reduce the angle, but not change the direction.

Regional Geodynamics

The Wasatch fault forms the eastern boundary of the Basin and Range Province in Utah and has been established as a normal fault produced by tensional tectonics. Atwater (1970) ascribed this tension and the entire origin of the Basin and Range to changing plate boundary conditions in California when a subducting boundary changed to a right-lateral transform. Many have balked at this interpretation, and some such as Suppe, Powell, and Berry (1975) and Smith and Sbar (1974) have proposed one or more spreading centers beneath the Basin and Range with associated microplates and transform faults.

Clearly, definitive answers are unknown. All that the results of the present study can offer toward a solution is support for the interpretation of the Wasatch fault as a normal fault resulting from tension, since the observed features are unlikely as a result of faulting with any other geometry. Also well supported, even established, is the concept of recurrent movement within that fault zone. Perhaps if the sequential history developed herein could be tied to some absolute dates, something more significant could be said related to Basin and Range tectonic initiation and development.

Suggested Further Studies

The most obvious extension on this work would be to apply the method and conceptual model to other segments of the Wasatch fault and throughout the Basin and Range Province where the features are observed (thus far, they appear pervasive). This may bring out some areas where absolute dating is possible, and even interrange correlations may be attempted. A great deal about the history of Cenozoic tectonism in this province certainly remains to be discovered.

As hinted at in the section on methods, correlation by computer may prove to be possible, perhaps even preferable. This area should certainly be explored. Also suggested is further study on drainage modifications and the effect of recurrent uplift on stream profiles and patterns, which would likely complement and support pediment studies. Finally, an understanding of stratigraphic displacement would certainly be enhanced by the results of drilling a few holes through the valley fill alluvium into the buried block. The hypothesis of Wasatch fault curvature at depth could be substantiated if the fault were penetrated by the drill a considerable distance out from the front.

If the model presented here is correct, and the observations are interpreted credibly, many ramifications of these results and conclusions can be envisioned and several intriguing studies proposed.

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