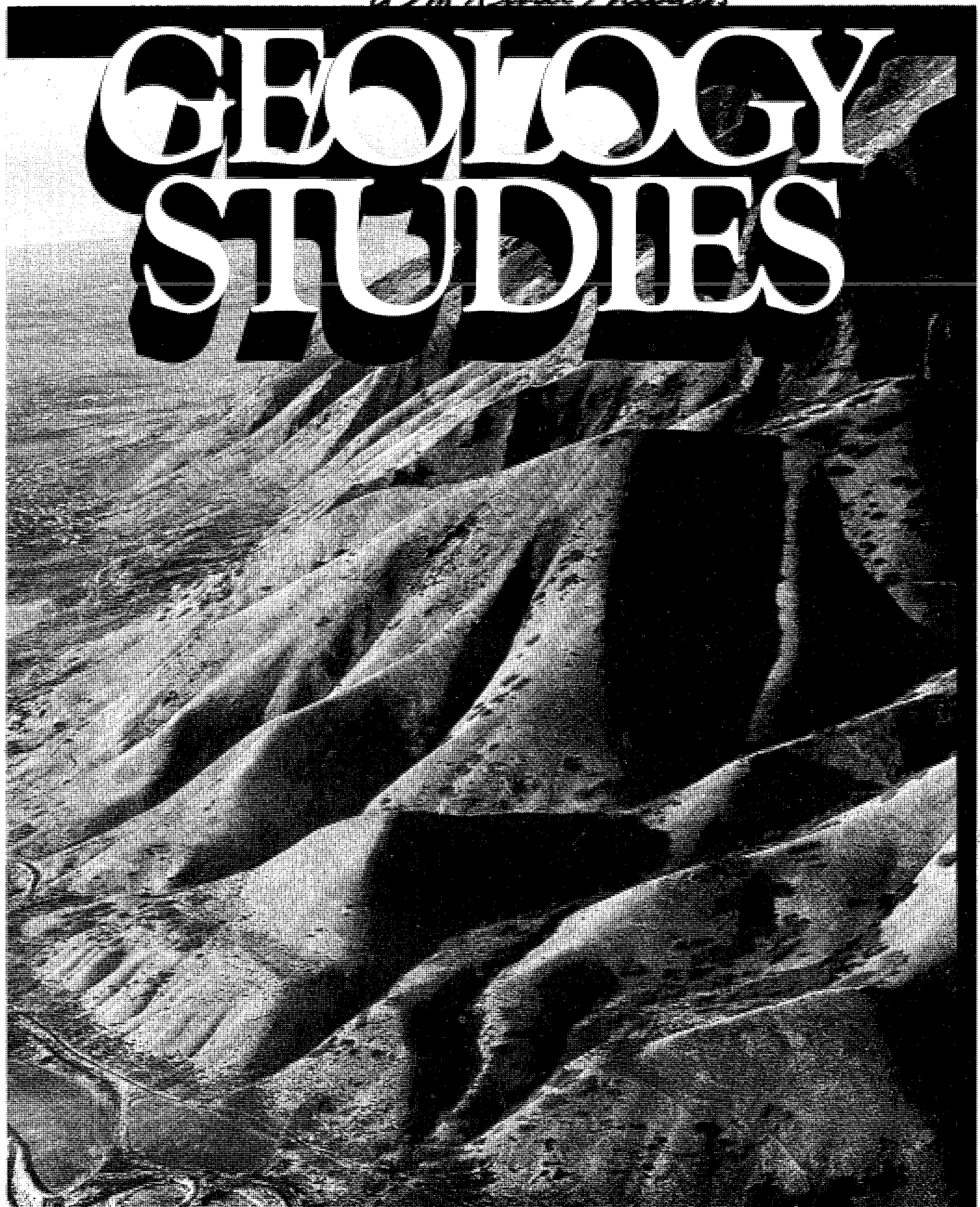
BRIGHAM YOUNG UNIVERSITY

GEOLOGY STUDIES



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THE GLORY OF GOD IS INTELLIGENCE

Cover: Compound faceted spurs along the Wasatch Mountains indicate alternating periods of fault displacement and tectonic stability.

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Late Cenozoic Movement on the Central Wasatch Fault, Utah*

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ABSTRACT.—Geomorphic features which develop as a fault block is uplifted give an indication of the history of displacement and style of movement of the fault. During periods of movement fault scarps are produced. Subsequent tectonic stability results in dissection of the scarp into compound faceted spurs by the major cross-cutting streams. Slope retreat of the fault scarp develops narrow pediments. When uplift is resumed, these pediments remain but are dissected into narrow ridges. Faceted spurs indicate periods of rapid uplift whereas remnant pediments suggest tectonic quiescence. Dissection of the faceted spurs and remnant pediments is dependent upon the nature and amount of movement, lithology, and prefault drainage.

The portion of the Wasatch range at Ogden Canyon, Utah, displays six major periods of uplift separated by short periods of tectonic stability. Southward the number of periods of displacement that are preserved in the mountain front decrease, and at the Salt Lake salient only one period of uplift is seen. This suggests a scissor type of movement during all major periods of tectonic activity with greater displacement being to the north.

INTRODUCTION

Approximately 75 percent of Utah's total population live at the base of the Wasatch Mountains. Located along the foot of this range are several centers of population concentrated into about 2 percent of Utah's total surface area. Understanding geologic hazards which might affect the welfare of these centers is therefore very important.

The Wasatch Mountains were formed as the result of uplift along the Wasatch fault. Recent seismic studies and observations of faulted Lake Bonneville sediments indicate that the area is still seismically active. The close proximity of a dense population to a potential hazard has been a cause for general concern. Many people have studied the fault by mapping its surface trace and monitoring its movement. Efforts have also been directed toward predicting future movement and associated earthquakes.

Emphasis in this study was placed on the geologic history of displacement and on an interpretation of the history of uplift because such information would be important in attempting to understand present-day seismicity and to predict how and where the fault may move in the future.

A record of Pleistocene uplift is found in the scarps that cut the Lake Bonneville shoreline and the Pleistocene glacial moraine deposits. Older movement is recorded in the distinct geomorphic features eroded in the mountains as the block was uplifted. Features which are helpful include the compound faceted spurs and the remnant pediments. The purpose of this study is to examine and understand these geomorphic features and identify the geological history of the Wasatch fault. From this study it was also possible to reconstruct prefault topography and describe the fault-block development.

Location of the Study Area

Between Nephi, Utah, in the south and Brigham City, Utah, in the north, a distance of 150 km, the Wasatch Mountains exist as a continuous range. A portion of the range between the Salt Lake salient and Ogden Canyon was chosen to study in detail (fig. 1). Access to the area is made possible by Interstate 15 and U.S. Highway 91, both of which run parallel to and within a few miles of the mountain front. Secondary roads provide additional routes in the area for detailed study. All the cities along the range from Nephi to Brigham City are in Utah.

Regional Setting

The mountains of the Wasatch Range represent an important regional geologic and topographic junction. They form the eastern border of the Basin and Range Province and the western margin ot the east-west trending Uintas of the Rocky Mountain Province. The Wasatch Front is part of the major global feature known as the Intermountain Seismic Belt (Smith and Sbar, 1974) which extends from Montana to Nevada, passing through Idaho, Wyoming, and Utah, with a branch in Arizona.

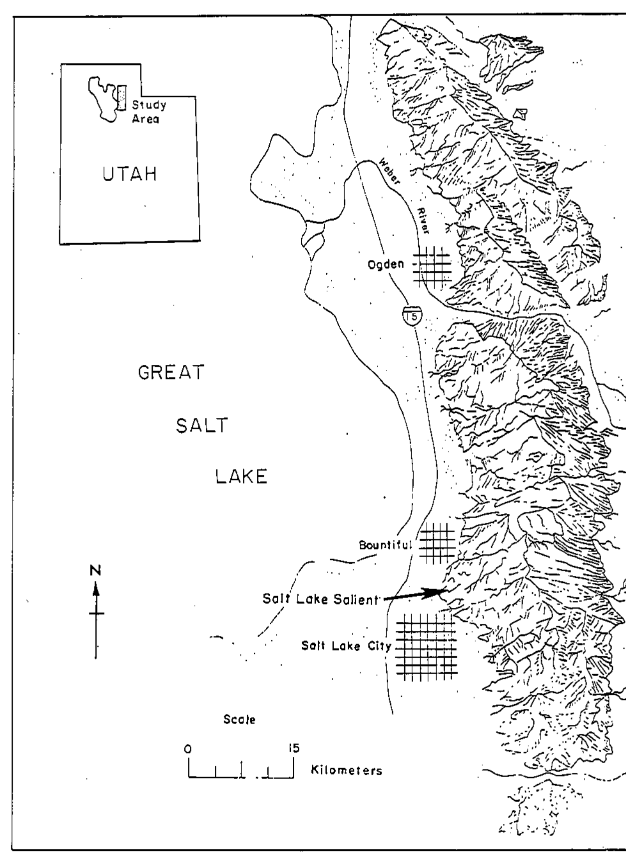

FIGURE 1.—Index map showing location of study area.

*A thesis presented to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree Master of Science, February 1978. Thesis chairman, W. Kenneth Hamblin.

There is a general pattern in the morphology of the Wasatch Mountains. Typically the range is divided into a series of north-south trending arcuate sections interrupted by narrow east-west projections or salients. These arcuate sections or reentrants are approximately 60 kms in length, and the salients are 8 to 10 kms wide. From the valley floor the mountains are seen to have low elevations at each of the salients, and this elevation increases toward the centers of each of the reentrants. Although the Wasatch Range is relatively narrow, it reaches elevations of over 3,600 m. One of these reentrants composes the study area, bounded on the south by the Salt Lake salient and on the north by the Pleasant View salient.

Previous Work

First studies of the Wasatch Range were carried out by the geological surveys in the 1870s. Bradley (1873) discussed the northern section of the range. When Gilbert (1875) proposed that the Basin and Range Province was controlled by block faulting, it began a long controversy which was summarized by Nolan (1943). Gradually it became accepted that the Basin and Range Province, including the Wasatch Mountains, was indeed a product of faulting. Evidence for the fault origin of the mountains was thought to be seen in the geomorphic features of the range.

Some of the geomorphic features found on the Wasatch Front predate fault movement. Gilbert (1928) describe "old graded slopes running down from the ridge crests to the tops of the frontal facets" and believed them to be erosion surfaces formed prior to uplift. Eardley (1944) described two erosion surfaces which predate movement in the north central Wasatch area. The highest erosion surface, found between elevations of 2,550 m and 2,750 m, was called the Herd Mountain surface and was believed to be Miocene in age. A lower erosion surface, the Weber Valley erosion surface, is claimed by Eardley to be late Pliocene or early Pleistocene in age and lies between elevations of 2,200 and 2,500 m.

The postfaulting geomorphic features have also received attention. King (1878) described the Wasatch Front as a plane of recurrent displacement. Davis (1903) also recognized the fact that a record of uplift is preserved in the features of a fault block. He described and defined triangular facets using Maple Mountain east of Spanish Fork as this type area. It was postulated by Davis that faulting was the cause for the entire relief of the range and that prior to faulting the area consisted of a large peneplain. Eardley disagreed with Davis, suggesting that the mountains of the north central Wasatch were approximately as high before faulting as after, with displacement of only 900 m at Ogden which gradually decreases toward North Salt Lake, where there is little or no uplift. His evidence was restricted to observations of the Weber Valley erosion surface.

Once the triangular facets were described by Davis, they began to receive much attention. Gilbert (1928) gave the first detailed account of the facets produced by faulting. He pointed out that facets could also result from wind, waves, or river erosion. There are, however, definite differences between facets resulting from fault movement and those formed by other means. Gilbert explains that fault-produced facets are less craggy, show fewer details of underlying structure and stratigraphy, and have a generally less convex shape when compared with other erosional facets. Gilluly (1928) described triangular facets produced by basin and range faulting in the Oquirrh Mountains, Utah. He pointed out that the facets formed earlier have lower angles of slope than those produced later, and, regardless of any large amounts of slope retreat, the facets maintain their triangular outline although that outline at some places is blurred. More recently Hintze (1962) used triangular facets to indicate the presence of the fault in the region of Provo. Bissell (1964) also discussed triangular spurs in his account of the southern Wasatch Mountains. In their account of the geology of the Weber Delta District, Feth and others (1966) include a discussion of multiple fault facets. They identify possibly three major episodes of uplift. The fault facets of each period of movement lie at flatter angles, and Feth concludes that this phenomenon may indicate a gradual eastward tilting of the fault block.

More recently remnant pediments between the facets have been studied by Hamblin (1976). He emphasized the interrelationship of faceted spurs and pediments. From his study Hamblin concluded that these features could definitely be used to determine the history of movement on the Wasatch fault. The scarps indicate periods of fairly rapid movement, and the remnant pediments represent periods of quiescence. Anderson (1977) described a portion of the front between Spanish Fork and the Traverse Mountains in detail and constructed a model to explain the development of the scarps and their subsequent dissection.

DEVELOPMENT OF SPURS AND PEDIMENTS

It was Davis who realized that an expression of fault movement could be seen in the geomorphic features of a fault block. His conclusions were drawn from observations of the mountains east of Mapleton and Spanish Fork, where the mountain front is divided into very pronounced triangular facets. Davis believed that the scarps were gradually developed as the fault block was continuously uplifted and were subsequently dissected into faceted spurs. Because the faceted spurs are well expressed in this area, it has been used by later workers to produce a conceptual model explaining how these geomorphic features develop and are modified by erosion. Hamblin (1976) believed that remnants of narrow erosional surfaces are preserved at the apices of many of the faceted spurs. These, he suggested, represent periods of quiescence and were formed as the scarps receded by erosion. Thus, movement of the fault was not continuous but was interrupted by periods of stability. In his model Hamblin described how the faceted spurs are eroded and dissected into compound faceted spurs by major cross-cutting streams and also by consequent streams which develop on the faceted spurs. He also showed how progressive slope retreat is accompanied by a decrease in slope angle of the faceted spurs.

Anderson (1977) further developed the model of recurrent uplift and applied his results to the area between Spanish Fork and the Traverse Mountains at Point of the Mountain. He recognized that the development of the triangular scarps represents a period of relatively rapid movement, whereas the pediments represent periods of quiescence. The conclusions of these previous workers have been combined with observations on the study area, and a conceptual model has been developed.

In the study area faceted spurs are the geomorphic features which characterize this landform. The sets of triangular facets occur at successively higher elevations and are separated by flat-lying remnant pediment surfaces. Stream erosion has modified the morphology of these features. The scarps have been dissected by cross-cutting and consequent streams into compound faceted spurs. It is also unusual for the pediments to be laterally continuous; rather they are eroded into narrow ridges.

As a result of variations in the rate of uplift, a fault block can develop different types of geomorphic features. During periods of relatively rapid movement, the dominant process is that of scarp development. Although there will no doubt be short periods of quiescence interspersed between movements, the total effect will be that of scarp development with little slope retreat and pediment formation. Relatively rapid movements are separated by times of quiescence characterized by different geomorphic modifications. Scarp development is naturally suppressed, and slope retreat results in the development of pediments at the base of the range.

Pediments are smooth, undissected erosion surfaces inclined at angles of from less than 1° up to 10°, found adjacent to areas of higher relief and steeper slopes. Views concerning the origin of pediments are varied. McGee (1897) suggested that they were the result of sheetwash. Blackwelder (1931) thought they were produced by lateral erosion, and Gilluly (1937) suggested a combination of the processes of back-weathering, sheetwash, and of lateral planation. Pediments in this area have now been uplifted and are preserved as remnants at different elevations in the fault block.

The model of recurrent uplift can be explained with reference to the series of figure 2. Diagram A represents the initial period of uplift, consisting of a series of discrete movements and larger displacements of several meters each. If an interval of stability followed this period of tectonic activity, significant modification would occur as a result of weathering and erosion. Cross-cutting streams would dissect the scarp into compound faceted spurs. Gradually the mountain front would recede with the formation of a pediment, and the slope angle of the scarp would decrease. Such a period of stability is represented in diagram B. Suppose the block were now tectonically reactivated. A fresh scarp, as seen in diagram C, would be produced. Dissection of this newly formed scarp, illustrated in diagram D, is caused by erosion of the original cross-cutting streams which develop on the first generation of faceted spurs. The results of a third period of tectonic uplift which produces another fault scarp is shown on diagram E. Diagram F demonstrates the third generation of faceted spurs produced during quiescence. Associated with each period of intervening stability, a generation of consequent streams forms on the fronts of the new facets.

A variation of this basic model is demonstrated in figure 3. Not all the newly formed facets will develop consequent streams with significant erosive power. Diagram A illustrates a block with two periods of movement separated by an interval of stability. The first generation of facets have not developed consequent streams, and subsequent dissection of the second generation scarp is modified (see diagram B). When one compares figures 2D and 3C, the different results are evident.

METHOD OF STUDY

The objective of the study was to interpret the history of the Wasatch fault, using faceted spurs and remnant pediments as indicators of movement. Aerial photographs were available on a scale of 1:30,000 feet. Four north-south trending mosaics, giving complete coverage of the area, were examined stereoscopically, and the geomorphic features were mapped directly. The faceted spurs were seen as triangular scarps and could be differentiated from the remnant pediments which exist as narrow east-west trending ridges running back from the apices of the spurs. Displaced Lake Bonneville sediments made it possible to map the trace of the fault clearly on the aerial photographs. Since the fault and pediments are large features and the study area was extensive, this method of mapping was very good because it provided the overall picture and the bulk of information.

Further mapping of the spurs was made on topographic sheets. Eight 1:24,000 scale topographic maps provided complete coverage of the study and adjacent areas. Pediments could easily be distinguished from scarps because of the break in slope which occurs at their junction. Information mapped on aerial photographs was transferred to the topographic sheets to facilitate correlation where elevation is an important criterion.

Information derived from aerial photographs and topographic sheets was checked and supported by field observations. Faceted spurs and remnant pediments not clearly distinguished in the laboratory study were mapped in the field. These scarps were not clearly visible on the aerial photographs or topographic sheets because they were either of a minor nature or had been considerably eroded. The work of Eardley (1944) and Bell (1952), which provided the basic structural and stratigraphic information, was supplemented by field observations. Scarps, benches, and cliffs which are structurally or stratigraphically controlled were differentiated from scarps and pediments resulting from fault movement.

Cluff and Slemmons (1971) and Cluff, Brogan, and Glass (1973) demonstrated the value of low-sun-angle photography to enhance fault-related features. Optimum light conditions are essential to properly identify facets and pediments. A maximum light-to-shadow condition can be obtained by taking photographs in the late afternoon when optimum light conditions prevail. Photographs were taken so that a mosaic of the entire area could be compiled. With all information gathered, the data were analyzed in several ways. Profiles of the Wasatch Front were constructed at twenty different locations along the study area. Scarp and pediment levels were also plotted in a frontal projection (fig. 4). The pediments were then correlated on a basis of elevation, relative position, widths, and continuity. If the pediments could be correlated clearly, they were joined with a solid line; but if there was some uncertainty, a dashed line was used.

Relationship of Geomorphic Features to Structure and Stratigraphy

In some parts of the study area the geomorphic development of the mountain front is controlled more by the underlying structure and stratigraphy than by the uplift along the fault. Breaks in slope, scarps, cliffs, and other irregular areas are often the result of geologic control other than erosion alone. These non-fault-associated features were identified largely from field work and were distinguished from relevant data provided by faceted spurs and remnant pediments. The type of lithology has an effect on spur and pediment development and preservation.

Hamblin (1976) recognized benches in the Wasatch Mountains and described them as breaks in slope resulting from differences in rock type. Benches have also been identified in the study area. Terraces resulting from geologic control not related to faults were identified:

A. Kaysville Quadrangle (111'53"W41'06"N). North of Hobbs Canyon a granulite lense is surrounded by migmatite, and a bench is produced. The granulite, which is more resistant to erosion than the migmatite, coincides with the A-level pediment. Consequently the pediment width, which is normally only 120 m wide, at this level is 245 m wide.

B. Kaysville Quadrangle (111'53"W41'02"N). A thrust with a north-south trend extends between Beaver Creek and Weber Creek. The thrust gives rise to a zone of rock which is easily eroded to form a bench. This bench coincides with the scarp at the 1,700-m level and increases the normal width of

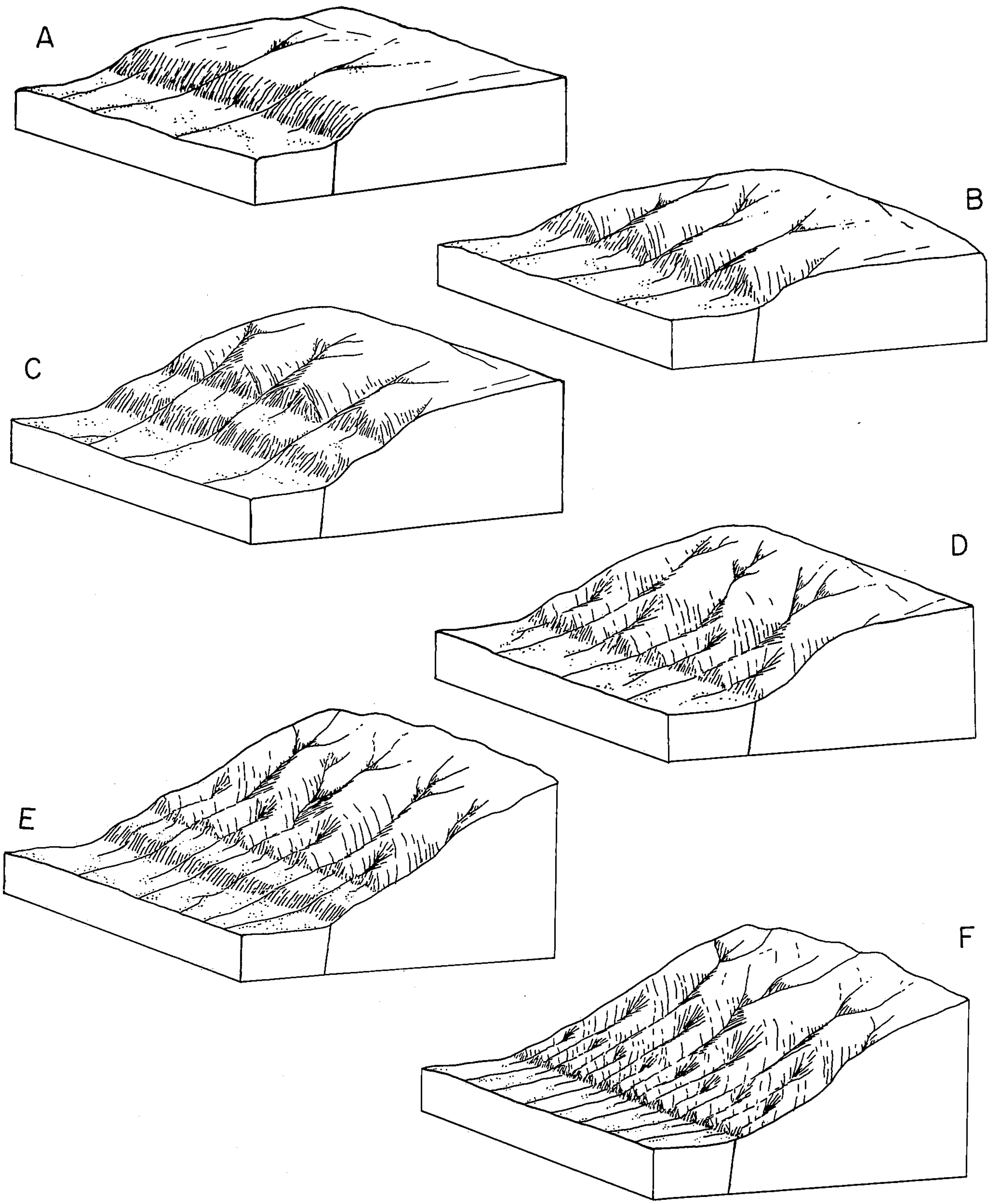

FIGURE 2.–Diagrams A–F represent a sequential series illustrating the development of a fault block undergoing periods of movement separated by intervals of quiescence. A represents initial movement, with B showing dissection by major cross-cutting streams and slope retreat of compound faceted spurs, producing a narrow pediment. Further uplift is indicated in C. Dissection by cross-cutting streams and consequent streams developed in C is shown in D. Results of further uplift are illustrated in E and F (after Hamblin 1976).

this surface from 120 to about 210 m. Again, it is the A-level pediment which is affected.

C. Bountiful Peak Quadrangle (111'51"W40'57"N). The topographic sheet indicates an area of irregular contours between Ricks Creek and Davis Creek. Field observations show that this is an area of landslide and is the cause for the apparent unusually wide pediment in this area. This same landslide has actually destroyed several of the older pediments in this particular area and causes the gap seen in figure 4 between Bountiful and Kaysville. Along the Wasatch Front in this area landslides are common and have been described by Pashley and Wiggins (1970).

The stratigraphy of the mountains controls other modifications to scarp and pediment morphology. There is a difference between Salt Lake City and North Salt Lake and the area to the north. Conglomerates and other coarse clastics of the Tertiary Knight Formation constitute the Salt Lake salient. The mountains between North Salt Lake and Ogden, however, are composed mainly of granulites and migmatites of Precambrian age. Pediments and scarps are expressed differently in these two main lithologies. Scarps developed in the Precambrian metamorphic rocks are better defined and show less dissection by streams than those on the conglomerates. In the Salt Lake salient the spurs and pediments are dissected to such an extent that they are difficult to identify. Conglomerates show features of the model shown in figure 2, and metamorphic strata possess characteristics of the model illustrated in figure 3. This may reflect a difference in lithology or perhaps a different history of uplift between the two areas. There appears to be far more uplift between Ogden and Bountiful than in the Salt Lake salient.

In the area east of Ogden, different stratigraphic conditions exist which alter the patterns of scarp and pediment development. Exposed here are Cambrian quartzites and limestones, both resistant units which tend to form cliffs. As a result, the scarp and pediment formation has been impeded and, although some recognition of the features was possible, it was nonetheless more difficult than in other areas.

Generally the pediments or erosional surfaces are inclined slightly towards the west. Ideally they have an inclination of 0–10°, but in many instances the slope is up to 30°. In some instances the pediments are inclined to the east, which may be supportive of Eardley's (1933) suggestion that the Wasatch fault block has been tilted to the east. Other examples, however, indicate that this inclination of the surface to the east is a result of coincidence of a nonresistent bed with a pediment level. In such cases the pediments are easily eroded and give only the appearance of eastward tilting and cannot be used to support Eardley's idea. An example of this is found between Centerville Creek and Parrish Creek on the Bountiful Peak Quadrangle (111'50"W40'55"N).

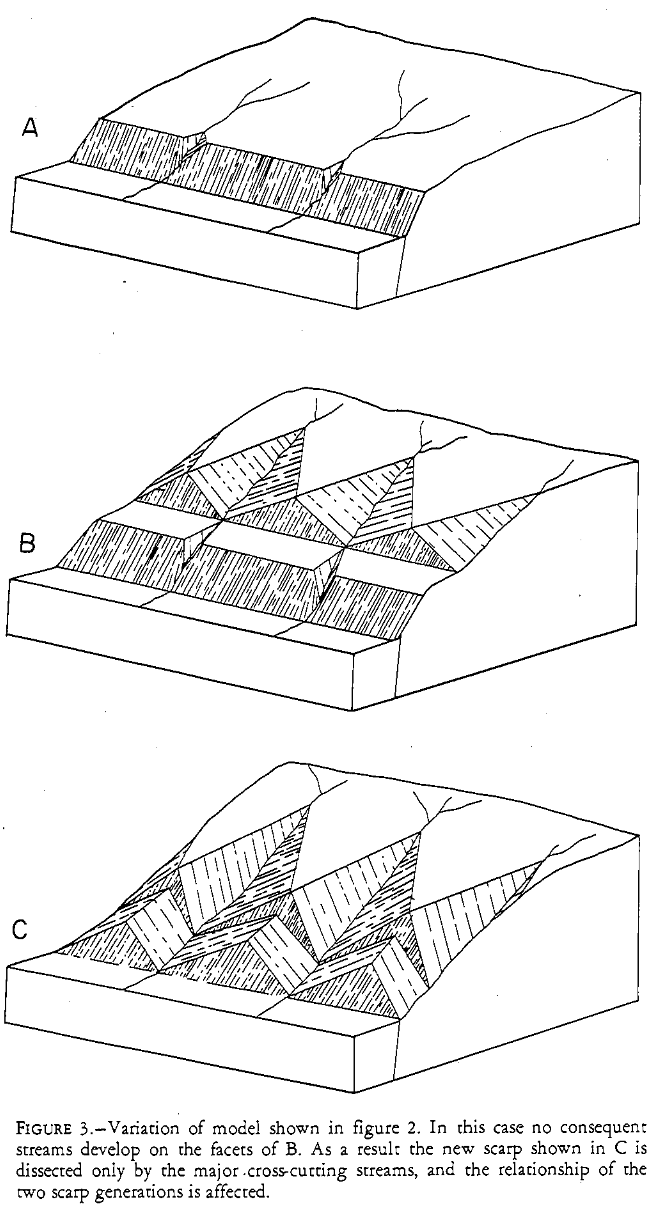

FIGURE 3.—Variation of model shown in figure 2. In this case no consequent streams develop on the facets of B. As a result the new scarp shown in C is dissected only by the major cross-cutting streams, and the relationship of the two scarp generations is affected.

OBSERVATIONS

Observations of Recorded Data

With the spurs and pediments accurately mapped, it became apparent that movement was not consistent throughout the area. The successive scarp levels were plotted graphically (fig. 4), and profiles were constructed at regular intervals (fig. 5) throughout the study area. The major pediment and spur sets often have minor levels associated with them, but they are usually only local. They represent pauses during general periods of tectonic activity during which small pediments develop and are preserved when uplift continues. These minor levels are difficult to correlate because they are local and hard to identify; therefore, only the major levels will be described in detail.

Figure 4 shows the spurs plotted and correlated according to their elevations, width, lateral continuity, and relative positions. Continuous lines represent equivalent scarps correlated with some certainty, whereas dash lines indicate tentative correlation. In the later case, correlation is made difficult mainly because of a lack of lateral continuity. There is an increase in the number of levels of faceted spurs from two in the south up to six in the north. Not all the pediment levels are persistent throughout the area. Gaps are usually explained by the presence of canyons, landslides, and occasional poor preservation.

Figure 5 shows the profiles of the mountain front looking north. Pediments in the ideal situation tilt to the west at angles between 0 and 10°. Many of the pediments, however, tilt westward with angles up to 25°. A decrease in slope angle of the faceted spurs is seen at higher levels successively. There is a difference between the northern and southern profiles, with the northern slopes being much steeper than those between Bountiful and Becks Hot Springs, north of Salt Lake City. The profiles vary considerably, but three general groupings can be made:

1. Profiles with scarps at a generally low angle with a small break in slope between the scarp face and pediment. This type of profile is most commonly seen in the southern part of the area, in the region south of Bountiful (fig. 6).

2. Profiles having faceted spurs with high slope angles separated by fairly flat-lying pediments. There are distinct breaks in the profile between spurs and pediments with the latter being fairly narrow. These profiles are found mostly in the northern section of the area between Farmington and Ogden but the best examples are farther south (fig. 7).

3. Intermediate features consisting of various combinations of steep- and gentle-faceted spurs with pediments of variable widths and inclination. This group is found between Farmington and Bountiful and represents a transition between the profiles to the north and to the south (fig. 8).

Observations of Pediment Levels

Only the earliest periods of faulting and quiescence are visibly recorded along the Wasatch Front. The earliest periods of faulting are represented by the facets which occur at the highest elevations. It is possible, and indeed probable, that a record of later events has been buried beneath the thick sediments left behind after the disappearance of Lake Bonneville. Along the entire length of the study area, the terraces of Lake Bonneville are fairly well preserved. Recent movements of the fault are evidenced in the scarps which now cut the Lake Bonneville sediments and the Pleistocene moraine deposits. In the quarries at the western end of the Salt Lake salient, the fault plane itself is exposed. This plane dips to the west at angles between 70° and 80° and is highly brecciated and shows good slickensides in some areas.

Recent fault scarps consist of a series of arcuate and en echelon features which roughly parallel the mountain front. The scarp is found immediately adjacent to the mountain front, but is normally located moderately close within the Lake Bonneville terraces. The recent picture of the Lake Bonneville sediments lying against the Wasatch Front is different from what it would have appeared in the early history of the area because the sediments are recently developed features. To describe the sediments in terms of pediment development would not be strictly accurate because it is not a true rock-floored erosion surface as would be expected.

The presence of valley fill sediments makes it difficult to determine whether we are in a period of active movement or quiescence. Recent scarps and fault traces found at some distance from the mountain front suggest pediment development and may indicate that we are in a period of quiescence. An alternative would be that the location of the scarps is merely the

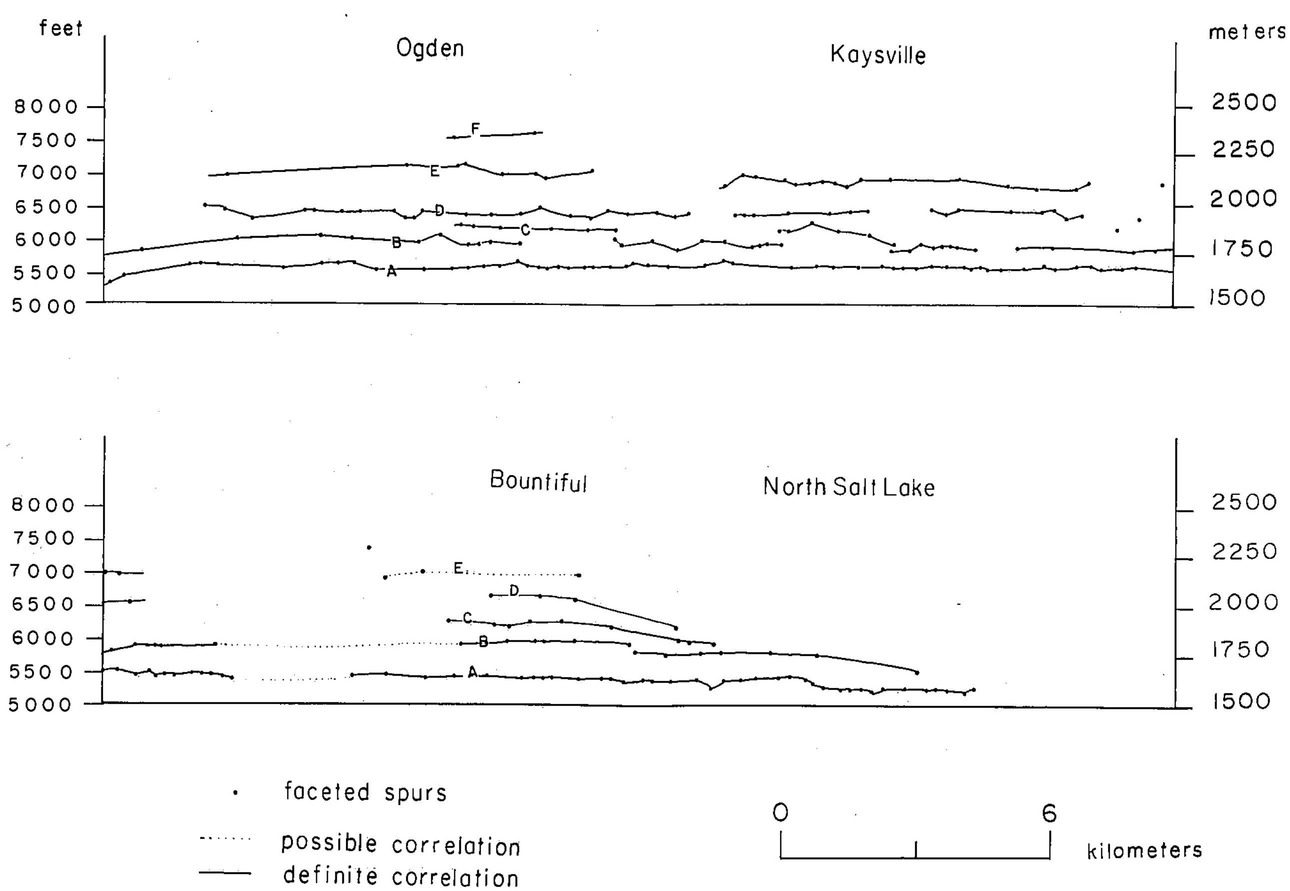

FIGURE 4.—Small dots represent facets plotted according to their elevation. The facets were correlated on the bases of elevation, lateral continuity, relative position, and width.

surface expression of the buried fault and that we are in a period of relative movement. Smith and Sbar (1974) propose that we are indeed part of a seismically active belt, but that this portion of the Wasatch now represents part of a seismic gap and lacks seismicity.

A Level

The A level is the lowest and also the youngest pediment exposed. It is possible that younger spurs and pediments were carved into the mountain front but have since been buried by Quaternary sediments. This lowest spur-pediment level is found consistently in the study area and is the most persistent and well preserved of all the levels exposed. In general, the pediment is only 120 m wide, although this varies plus or minus 30 m throughout its length. Most of the increased pediment widths are the result of control by underlying structure and stratigraphy or by landslides. For example, a large break in consistency of this level is produced by the landslide on the Bountiful Peak Quadrangle (111'51"W40'57"N). The A-level pediment is generally narrow between the towns of Ogden and Centerville but gradually increases in width between Bountiful and North Salt Lake until at the Salt Lake salient it becomes the dominant pediment level and is very extensive.

Although some of the A-level facets are inclined at shallow angles, most are steep. The apices of this set of spurs are fairly consistent at the elevation of 1,700 m. Field observations made it possible to identify a minor pediment which is quite consistent from South Ogden to Kaysville. This erosion surface occurs as a very narrow break in slope approximately midway down the major scarp face.

The fault line scarp of level A has not yet been completely eroded into compound faceted spurs, and at several locations it is undissected. A good example is seen on the Bountiful Peak Quadrangle (111'51"W40'57"N) to the north of Ricks Creek. Erosion is nevertheless quite advanced, and, as a result, most of the scarp is not expressed as compound faceted spurs. Erosion by antecedent streams is dominant with downcutting and slope retreat occurring concurrently with uplift. Consequent streams are now developing on the faces of the faceted spurs and assist in the erosion of the scarp.

Another feature observed at this level is a remnant pediment soil. The soils which Bell (1952) describe at different altitudes in the Farmington Mountains were located to the east of Farmington (111'54"W41'03"N). These soils are tan in color and contain large amounts of coarse material separated by a finer matrix. The soil exists as an uneven layer about 15 m thick on the A-level pediment surface resting against the higher scarp. These soils represent remnants of sediment which accumulated on the erosion surface as the pediment developed. No soils were located on higher levels, and, although they probably did exist, it is most likely that they have been removed by erosion following uplift and dissection.

The A-level faceted spurs indicate a period of rapid uplift disrupted by an interval of quiescence about midway in their development. The uplift was preceded by a time of quiescence during which the pediment was formed. The minimum amount of uplift during this time was 180 m. Greater amounts may be possible, but evidence of it would now be concealed beneath the Lake Bonneville sediments.

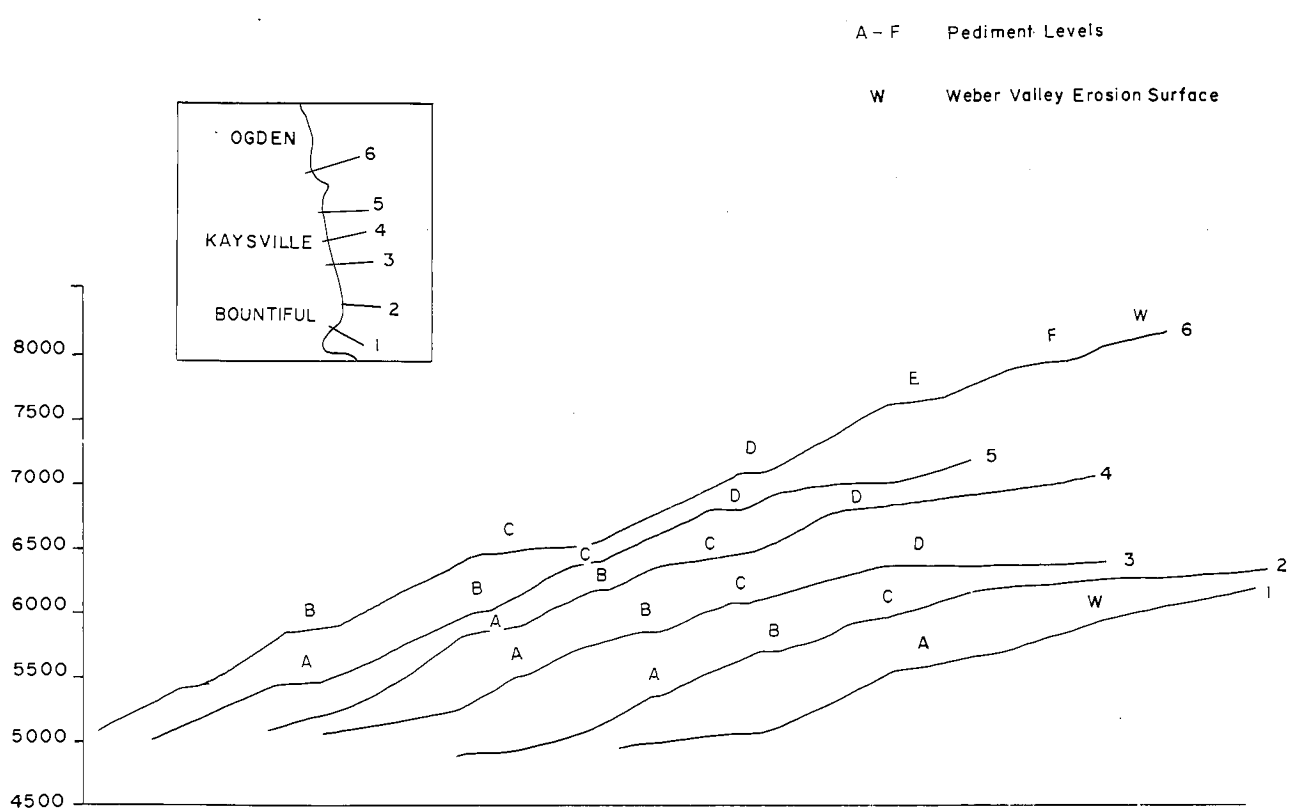

FIGURE 5.—Profiles of the mountain front drawn at representative intervals throughout the study area.

B Level

The next major level has been designated as the B level. This surface is not so consistent as the A level, but is probably better defined than the higher spurs and pediments. Inclinations of the spurs and pediments are always slightly lower than those of the A level directly below, although the inclinations do vary from area to area. Pediment widths are approximately 150 m although in some areas they may be wider. This is the result of compounding with higher erosion surfaces. Compounding of these pediments indicates a scissor type of movement on the fault as one area is uplifted while another remains stable. This concept will be expanded in the description of the C level.

At about 1,800 m the apices of the faceted spurs associated with level B can be found. Although this statement is true for the greater part of the area, variation exists between Bountiful and the Salt Lake salient, where the pediment level gradually drops in elevation until it becomes compounded with the A level at about 1,700 m, again suggesting a pivot type of movement on the fault in this region.

Major cross-cutting streams have caused advanced dissection with downcutting and slope retreat being the dominant processes. Streams formed consequently on the older facets are established and also contribute to dissection. The effect of stream erosion has been to completely break down the scarp into compound faceted spurs, with the pediments remaining only as narrow ridges.

Uplift of the B level is of a similar amount and duration to that of the A level. A fairly rapid uplift is suggested by the high angles of the facets. The lower angles of this scarp when compared with the A level scarp appear to be the result of progressive slope retreat and not the effect of different rates of movement. This contrasts with Penck's (1924) concept of parallel retreat of slopes, where the angle of slope depends mainly upon material size. A short period of quiescence is suggested by the narrow (150 m) pediment widths. The compounding of A and B pediments between Bountiful and the Salt Lake salient suggests that there was little or no fault movement in this area. As a result the spurs are poorly developed and much broader than are commonly found at this level. Uplift amounts to between 150 and 180 m for the northern part of the area.

C Level

The C level is not very consistent and forms the most in-

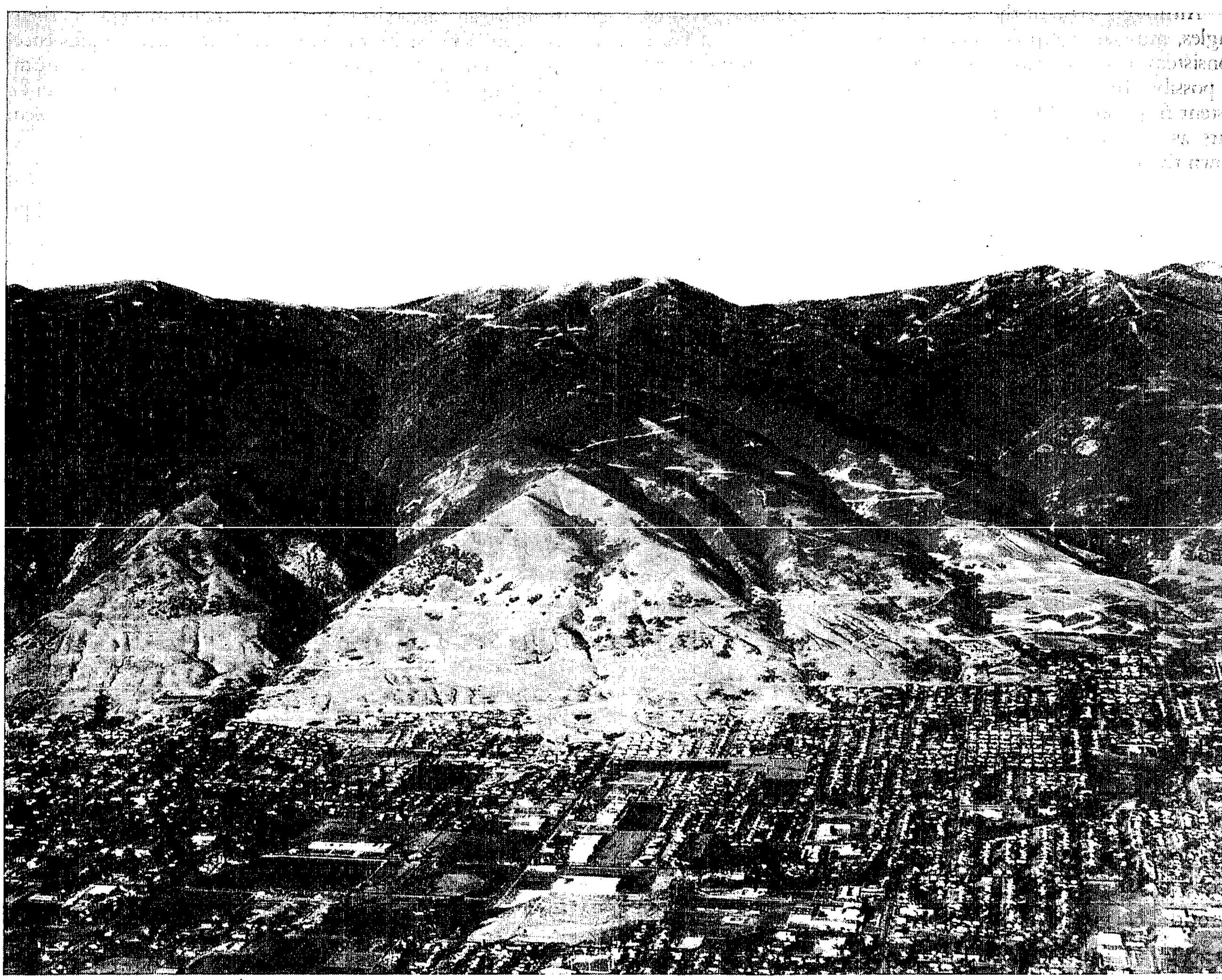

FIGURE 6.—Photo of the Wasatch Front east of Bountiful, showing small break in slope between the scarp face and pediment. Characteristics of the model illustrated in figure 3 are seen here.

complete of all major erosion surfaces. As a result of prolonged slope retreat, the angle of inclination of the spur is lower than both the A and B levels. Pediment widths vary between 150 and 180 m although compounding of the pediments has resulted in increased widths at some locations.

The incomplete nature of this level is significant in determining the overall pattern of movement of the fault. An indication of the general nature of movement was obtained by observing this level in detail. A gap in the C level is present along the front directly east of Ogden, but it was found to be lithologically controlled. Here the Tintic Quartzite and limestones of the Cambrian constitute a cliff-forming unit which has suppressed the development of the spurs and pediments. Other gaps can be explained by erosion and consequent poor preservation. The remaining majority of gaps at this level help to explain the patterns of fault movement at this horizon.

There exists a definite interrelationship among the B, C, and D levels. Where one of the levels of facets is absent, the lower pediment is wider than average. Usually it is the C-level facets which are absent and the B and C levels are found adjacent. This suggests a scissor or pivot type of movement. Figure 9 demonstrates this type of movement and shows how the compounding of the facets is modified as a result. Diagrams A through C show the sequential development of a fault block experiencing scissor motion. Because of scissor movement, facets carved are different sizes; and it is likely that smaller ones will not develop consequent streams. As a result, the erosion of younger facets is modified, and a variation of the basic model as shown in figure 3 is produced. Wider pediments are developed in areas of little or no vertical uplift.

Enlarged pediment widths and gaps in this level indicate a time of variable movement on the fault. The scissor or pivot type of uplift which is dominant during this time is significant in that it represents on a small scale the overall style of movement for the fault. The C-level pediment is also compounded with the A and B levels at the Salt Lake salient, again suggesting a large-scale pivotal movement. Preceding this time of irregular uplift, there was a period of quiescence and erosion during which the pediment was formed.

D Level

The D level is found more continuously than the under-

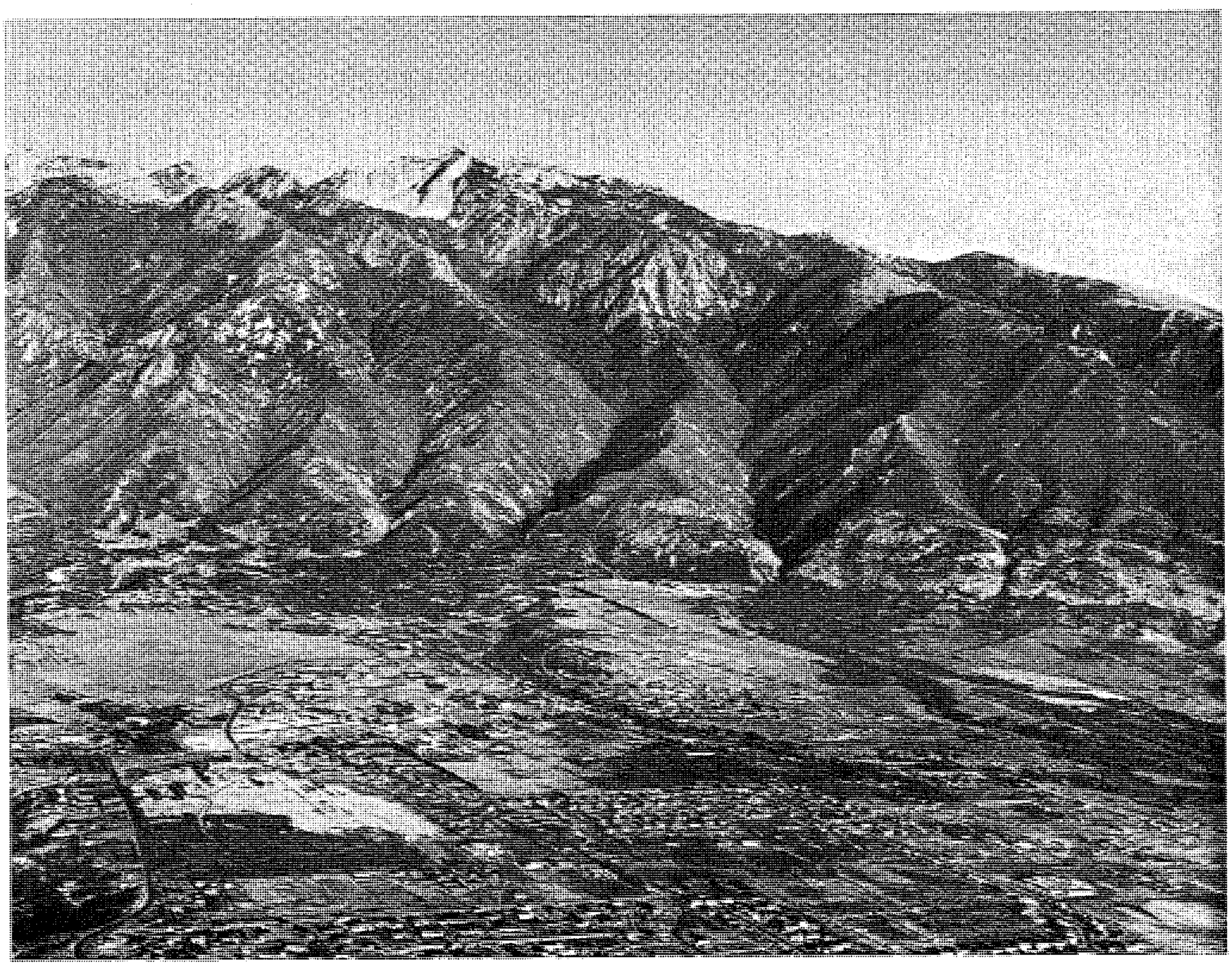

FIGURE 7.–Photo of the Wasatch Mountains south of Little Cottonwood Canyon, showing faceted spurs with high-angle slopes separated by fairly flat-lying pediments.

lying C level. This continuity supports the concept of scissor movement of the C level, for if the gaps were erosional, they would be more evident in the facets of the D level. Instead, faceted spurs of this level are much larger in surface area than those seen below, in part because they are at a lower angle and also because they have been dissected by fewer streams. Reference to figure 2 will illustrate this concept. There is an increase in pediment widths from those previously seen with ranges between 300 and 360 m.

Although moderately flat lying now because of continuous slope retreat, the scarp indicates a relatively long time of rapid movement. Wide pediments suggest that movement was preceded by a long interval of tectonic stability. Scissor movements of a minor nature are again seen, but not as extensively as in the C level. Large-scale pivotal uplift is suggested because of the compounding of pediment levels which gradually increases from north of Bountiful to the Salt Lake salient, where profiles are very low and indicate a dominance of quiescence over movement (fig. 5).

E Level

For most of the study area the E level was the first pediment surface developed, and in all areas it is the highest persistent level. The pediments are isolated, existing as wide, flat areas, although sometimes they occur as ridges. Widths of the erosion surfaces vary between 300 and 450 m. They form flat areas where headward erosion has not yet reached the higher elevations and where dissection has been only from the original major cross-cutting streams and the first generation of consequent streams. Where the E level pediments are the highest, they merge into the Weber Valley erosion surface which represents prefaulting topography. Spurs are expressed as dissected triangles which have low angles of inclination, about 30°. The triangles are now indistinct and have been rounded by continuous erosion since the time the fault block initially moved. Vertical movements amount to about 210 m.

The E-level erosion surface is more persistent in the northern half of the area, and, as it is traced southward, it becomes compounded with lower pediments. From the account of this and later formed levels, it can be seen that gross compounding occurs between Bountiful and North Salt Lake. This compounding toward the south is accompanied by a drop in elevation and, as in other levels, is due to scissor movement of the fault.

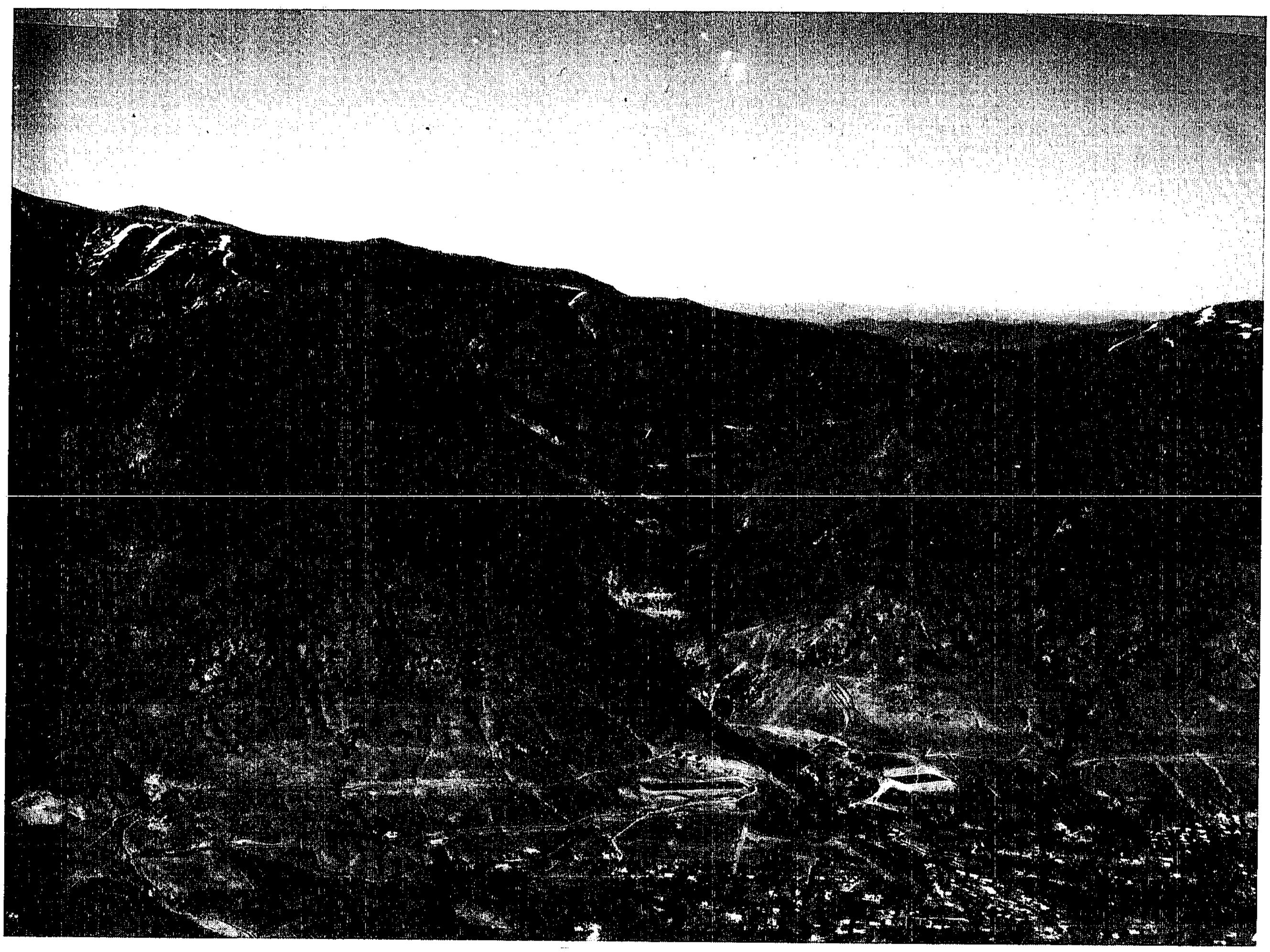

FIGURE 8.–Photo of the Wasatch Mountains northeast of Bountiful showing combinations of steep- and gentle-faceted spurs with pediments of variable width and inclination.

The E level was carved during a long period of quiescence following the initial uplift of the Wasatch fault block. The quiescence was succeeded by a long and gradual period of uplift. Gradual movement is inferred because the slope of the spur seems to be too low to be explained by slope retreat alone. A high initial angle on the scarp is anticipated because the fault plane where exposed dips between 70 and 80°. If movement was gradual, slope retreat would take place as the scarp was developing and would produce a scarp with a fairly low angle. It is assumed that this is what occurred at the E level.

F Level

About the E level are the vestiges of an earlier period of movement. Several spurs are seen which are very similar in appareance to the Weber Valley erosion surface. These facets are confined to the north of Weber Canyon, but isolated occurrences are found to the south. It is possible that this uplift was more extensive than it now appears, but evidence in the form of facets has been removed or eroded to such an extent that it is hard to recognize. This level of facets was probably carved when the Wasatch fault started its history of movement.

Weber Valley Erosion Surface

Eardley (1944) described the Weber Valley erosion surface as an ancient peneplain formed prior to movement of the Wasatch fault. It was broken by block faulting, and, as a result of uplift and rejuvenation of drainage, it is now highly dissected. The Weber Valley erosion surface can be recognized because of a change in profile from the frontal scarps to the surface. Prior to faulting, the area could be pictured as a region of low, well-rounded hills separated by broad, flat valleys which were gradually becoming filled with coarse clastic deposits thought to be Oligocene in age—a fairly mature type of topography. The dissected remnants of this early relief are now preserved above the frontal facets of the fault block. In the Ogden area, the Weber Valley erosion surface is found above 2,100 m. As it is traced southward, it decreases in elevation until at the Salt Lake salient it is found at 1,900 m. In several areas it is difficult to distinguish the surface of the Weber Valley from the topmost fault-related facets because they have been considerably eroded.

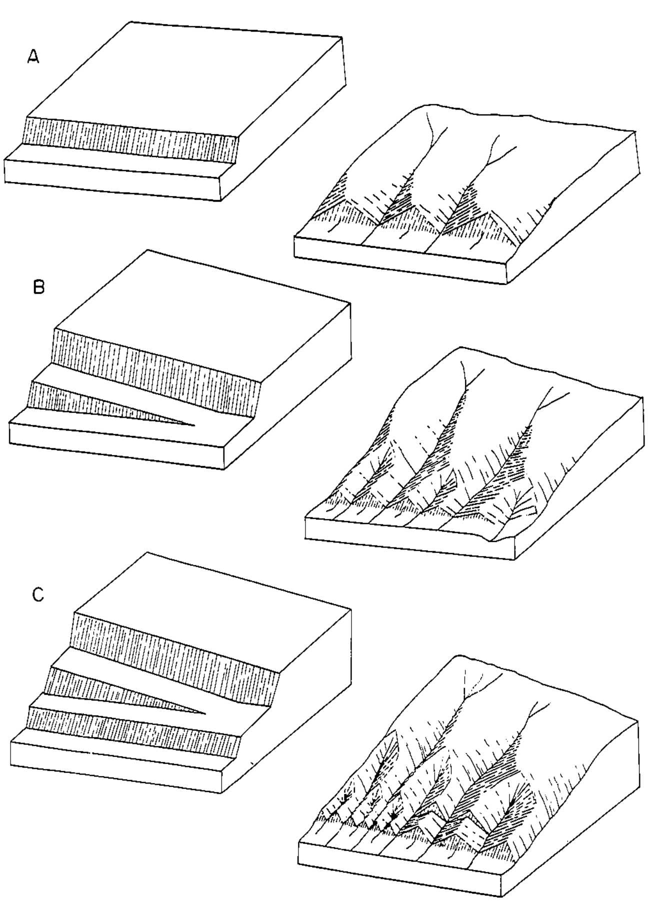

FIGURE 9.—Series of diagrams illustrating how scissor movement affects geomorphic development of fault block. Diagrams at right are dissected forms of ideal blocks at left. Note that smaller facets do not produce consequent streams.

General Features

There are several features in the study area of a general nature which cannot be described under each of the specific levels. Descriptions of each level have indicated that the erosion surfaces tend to become compounded in the southern part of the area between Bountiful and the Salt Lake salient. In addition to this compounding the pediment levels drop in elevation. For example, the A level is found consistently at 1,700 m until at south Bountiful it drops to 1,650 m. This example is representative of all the levels, although they may drop different amounts and at different locations. Accompanying the drop is a decrease in the height of the mountains (fig. 10). East of Ogden there is an average elevation of about 2,850 m, whereas in North Salt Lake it is only 2,100 m.

Another general observation is the change in profile of the front from area to area. In the south the front is not very steep, with comparatively gentle slopes running from the valley floors to the highest elevations. Farther north, however, the front becomes steeper until between Weber Canyon and Ogden Canyon it is very steep with some inclinations of up to 75° (fig. 11).

The surface area of each of the faceted spurs increases at the higher elevations, and this increase is related to the development of drainage as the fault block is uplifted. With the development of each level of facets, a new generation of consequent streams appears, and with continued uplift they become better established with a larger drainage area and a higher erosive power. As a result, the earliest formed scarp is eroded into compounded faceted spurs by only the major cross-cutting streams. In contrast, the latest formed scarp is dissected by several generations of consequent streams in addition to the major cross-cutting streams.

CONCLUSIONS

From the conceptual model and the observations of the study area, it is possible to draw some conclusions about the style and history of movement along the Wasatch fault. The faceted spurs and remnant pediments are geomorphic features produced as the fault block was uplifted. The scarps and pediments record development of the fault block: scarps indicating rapid movement and pediments forming during quiescence. These are basic assumptions from which conclusions can be drawn.

Uplift in the area has not been consistent, but has fluctuated considerably. Total visible displacement in the northern part of the area is about 670 m while in the southern part it is only 370 m. The number of periods of uplift also vary. East of Ogden there are six periods of uplift whereas east of Bountiful there are only two or sometimes only one. Between these two extremes, the number of levels varies because the movement has not been consistent. The absence of scarp levels gives an important line of evidence in determining the style of fault movement. This irregular uplift could be explained in two ways. First, it may be possible that gaps are the result of partial erosion of scarp levels. Many of the gaps, however, are not persistent vertically. For example, the C-level scarps are absent in several areas, but the overlying D level is more continuous and lacks the anticipated gaps. A second, more likely explanation, is that the Wasatch fault has experienced pivotal movements. This would certainly explain the absence of scarps between areas. Where the facets are not present, the erosion surfaces are widened because of compounding. For example, where C-level facets never developed because of lack of movement, the pediments of the B and C levels have become compounded, creating unusually wide erosion surfaces.

This scissor movement was most extensive during the period when the C level developed but was also evident during B and D level times. The A level, however, represents a time of fairly consistent uplift throughout the entire area. It is hard to determine whether there was pivotal movement of the fault at E and F levels because they are now poorly preserved. The conclusion is therefore made that there has been scissor movement along the fault of a minor nature. This type of movement is especially well developed on the C level but is seen to a lesser extent on the B and D levels.

Another interesting observation leads to a conclusion similar to that outlined above. A gradual decrease in the number of faceted surfaces and a similar drop in elevation from the north to the south requires an explanation. It is also noted that the pediment surfaces gradually become compounded between Bountiful and the Salt Lake salient. These characteristics are suggestive of scissor movement on the fault, but this time on a much larger scale. Uplift of 670 m at Ogden and only 370 m in the Salt Lake salient clearly supports this idea. This pivotal movement which rotates at the salient has maximum uplift at Ogden.

The geomorphic features displayed in the Salt Lake salient differ significantly from those in the northern part of the study area. A difference in lithology is found between the Salt Lake salient and the area to the north. The salient is composed of conglomerates and other coarse clastics which are easily eroded, with the facets becoming rounded and losing definition. Pedi-

FIGURE 10.—View of Wasatch Mountains near Kaysville showing the increase in elevation from south to north (right to left).

ments are larger here and were produced with less difficulty during periods of quiescence than in the hard metamorphic suite of rocks to the north, which are dissected less easily and better retain the faceted spurs.

There is another reason for the obvious difference between the Salt Lake salient and the portion of the study area north of Bountiful. At Millcreek the Wasatch fault splits, with the major branch passing through Millcreek and then trending at 155° to the southeast. Eventually the trace of the fault is lost in the Tertiary sediments of the salient. Smaller branches of the fault pass along the foot of the mountains. The plane can clearly be seen again at the western projection of the salient where the fault has been exposed in a gravel quarry. This major branching of the fault is probably partly responsible for the differences in topography because the salient has been uplifted only a small amount, certainly less than the area northwards.

It is probably a correct assumption that the differences in faceted spur and remnant pediment development between the areas in the north and south have been produced by a combination of factors. Gross pivotal movement, difference in lithology, and a major branching of the fault have combined to produce the pronounced differences.

It has already been noted that change in lithology between North Salt Lake and Bountiful is, in part, the cause of a difference in expression of the geomorphic features. The control of lithology on the development and erosion of the spurs and pediments is again displayed in the range east of Ogden. Here the Tintic Quartzite and limestones of the Cambrian have a tendency to form cliffs, and the development of faceted spurs and pediment surfaces is suppressed (fig. 12). These features are visible, but not so distinctly as in the adjacent Precambrian metamorphic rocks. Therefore, it is obvious that lithology is a control on the formation and subsequent erosion of the faceted spurs and remnant pediments.

Major cross-cutting streams dissect the scarp level formed into compound faceted spurs. On the faces of these spurs small consequent streams will develop. The next scarp produced is then dissected not only by the major cross-cutting streams but also by the newly formed consequent streams. With the formation of each new scarp level, consequent streams appear which aid in the dissection of later formed scarps. Resulting from this process is an increase in dissection of the younger scarps which creates smaller faceted spurs. Older generations of streams show

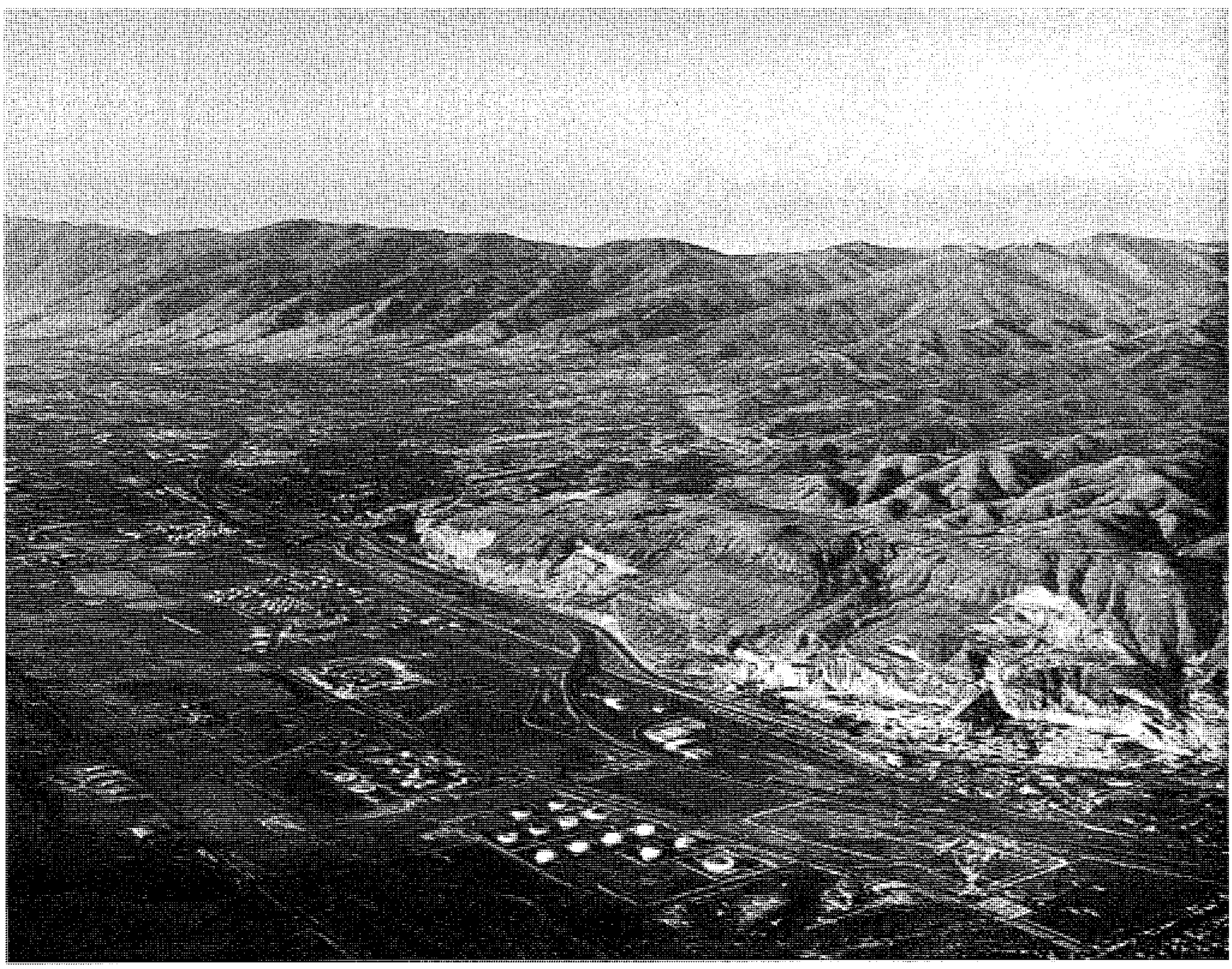

FIGURE 11.–View looking north over the western end of the Salt Lake salient, showing that the Wasatch Front becomes progressively steeper to the north.

more advanced downcutting and have longer courses than the newer.

Apparently not all the faceted spurs generate consequent streams. For example, in the Salt Lake salient not all the facets produced in the conglomerates and sandstones develop consequent streams, and the first proposed model is dominant (fig. 2). The same kind of thing is found in the northern part of the area where uplift has been greater (fig. 13). Many of these metamorphics, however, show the characteristics of the second model as seen in fig. 3, indicating that the major cross-cutting streams dominate the drainage and that generations of consequent streams have not developed so readily (fig. 7).

One reason consequent streams do not develop on the facets is illustrated in figure 9. Diagrams A through C show the sequential development of a fault block where scissor movement is present. The facets of the ramp shown in B are different sizes because of the scissor type of movement. Only the larger facets will possess enough surface area to produce consequent streams. C shows the result of further uplift and how development of consequent streams is an important factor when considering the developmental history. On the extreme right of C there has been no uplift, and compounding of the pediments occurs, producing an unusually wide pediment.

Diagram C represents a very simplified model of what actually takes place in the area. In the south elongated pediment ridges dominate. Farther north, the slope of the mountain increases, with facets being dissected only by the major streams with no consequent streams developing. Still farther north several levels of facets, each of which has developed consequent streams, cause greater dissection of younger scarps. This model is better illustrated in figure 14, a diagrammatic plan view of the study area.

History of Movement

Eardley (1944) described the Weber Valley erosion surface and claimed it to be late Pliocene or early Pleistocene in age. In the study area, however, it is not possible to assign an absolute age to movement of the fault. If volcanics are located on an erosion surface in other areas, dating may be possible, but as yet it has not been done.

The Weber Valley erosion surface represents the vestiges of the prefaulting topography. Prior to uplift it was the site of much erosion and could be envisaged as a series of well-rounded hills and sediment-filled valleys. This surface now ex-

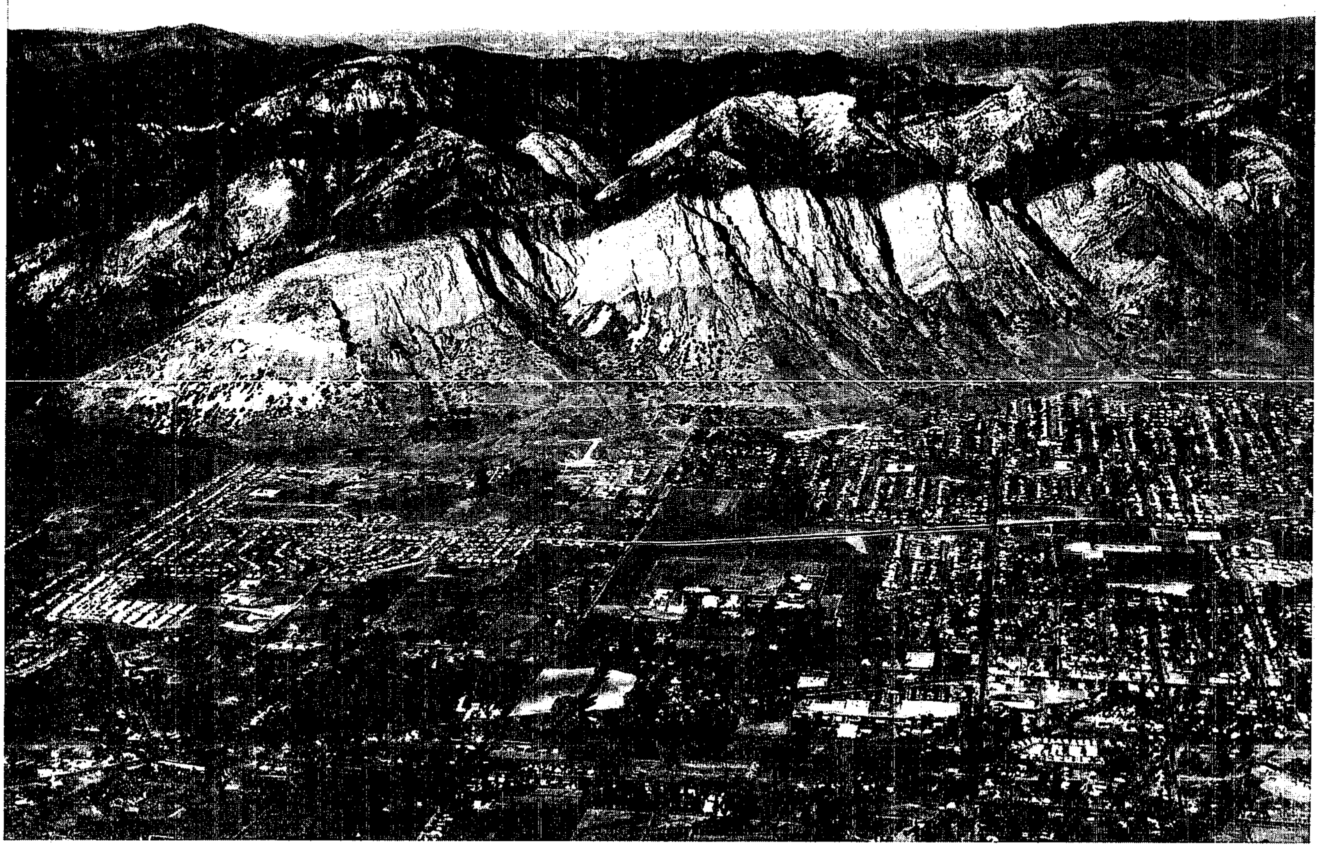

FIGURE 12.—View east of Ogden where Cambrian quartzite and limestone are cliff-forming units which tend to suppress development of faceted spurs and remnant pediments.

ists as the dissected remnants of the original pediment on the crest of the mountains in this area. It is characterized now by a rounded topography and lacks the westward facing facets typical of postfaulting topography.

At the initiation of faulting, the Weber Valley erosion surface was gradually uplifted. First movements were apparently gradual because the scarp facets are at too low an angle to be explained by slope retreat alone. Already movement was not uniform, with the northern area being uplifted more than the southern. Following this period of activity there was a time of tectonic stability during which a large pediment was produced. Slowly the mountain front withdrew from the fault line by slope retreat leaving behind a gently westward-sloping erosion surface. After this interval of quiescence, the fault became reactivated, and a new scarp, the E-level scarp, was produced by a series of small displacements. Uplift appears to have been more rapid than for the preceding F level. Stability followed, allowing the development of a new erosion surface and dissection of the scarp into compound faceted spurs by the major cross-cutting streams. Consequent streams would also have appeared on these newly formed faceted spurs.

The quiescence which allowed the pediment of the D level to form was followed by tectonism which produced the scarps of the same level. These scarps were dissected more than those of the earlier level because in addition to being dissected by the major cross-cutting streams, they were also cut by the first generation of consequent streams. On these newly formed facets, the second generation of consequent streams appeared. Not all the facets, however, equally produced consequent streams, and this discrepancy ultimately gave rise to variations in the basic model.

Tectonic stability and then activity produced the C level. Gaps in the faceted spurs in this level suggest that movement was irregular with one portion being uplifted for a period, then pausing, with an adjacent area becoming active. The C level was produced when pivot or scissor type of movement dominated.

The A and B scarps and pediments are very similar in style of uplift and duration. Following the uplift of the C level scarp, there was a short period of quiescence allowing pediment formation, dissection, and the production of the third generation of consequent streams. Along this portion of the

FIGURE 13.—View of the range north of Weber Canyon where first proposed model, illustrated in figure 2, is fairly well developed.

Wasatch Front there was a long interval of uplift responsible for the B level scarps. This interval was interrupted by a short quiescence permitting the A level erosion surface to develop. The last visible evidence of rapid uplift is seen in the scarps of the A level. This interval was interrupted halfway in its development by a short period of stability.

Evidence of recent movement can be seen in the displaced Lake Bonneville sediments throughout the area, indicating that this region is still active. Smith and Sbar (1974) suggest that portions of the Wasatch fault are temporarily inactive or represent seismic gaps. This would support the idea that the fault is in an active period but is experiencing a scissor type of movement. The moderately recent sediments of Lake Bonneville have concealed possible movements younger than the A level.

SUMMARY

It is evident that the faceted spurs and remnant pediments are the geomorphic features which were carved as the fault block was uplifted. Since the time of their formation, they have been modified by stream erosion and are now highly dissected. The scarps and pediments record the nature and history of movement: scarps indicating rapid movement, pediments forming during quiescence. Combinations of quiescence and movement produce gentle slopes, and rapid movement results in steep slopes. There are six scarps in the northern part of the area, indicating six periods of rapid movement, dwindling to only one scarp in the south. This gradual reduction in the number of scarps indicates a scissor type of movement with the pivot at the Salt Lake salient. In addition to the overall scissor type of motion, there are minor pivotal movements.

Expression of pediments and scarps is partly controlled by underlying structure and stratigraphy. Cliff-forming units tend to suppress their formation, whereas softer units tend to express the features well. False pediments and unusually wide pediments are often explained by lithologic benches, landslides, and in one case by the coincidence of a pediment with a thrust sheet.

The fault-related features are crowned by the Weber Valley erosion surface, which was the initial erosion surface developed prior to faulting. It shows advanced dissection with a well-rounded topography. This surface drops in elevation when traced southward until it finally constitutes a large portion of the Salt Lake salient.

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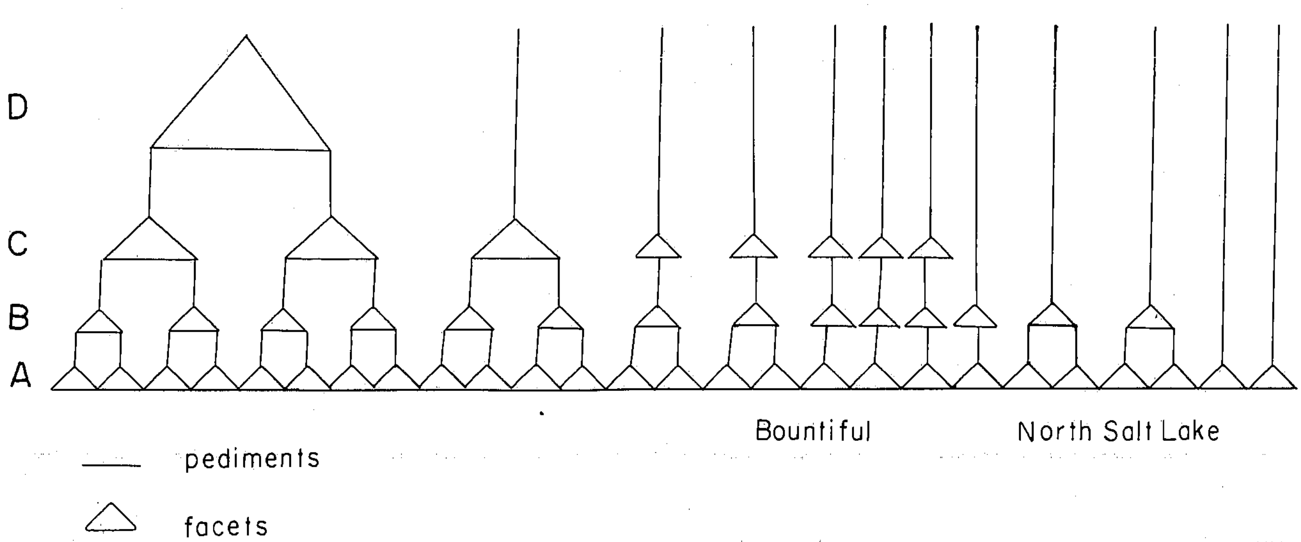

FIGURE 14.–Diagrammatic display of facets as they become compounded by scissor movement. This would be typical for the Bountiful area. A gradual reduction in the number of scarp levels is accompanied by an increase in pediment width.

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