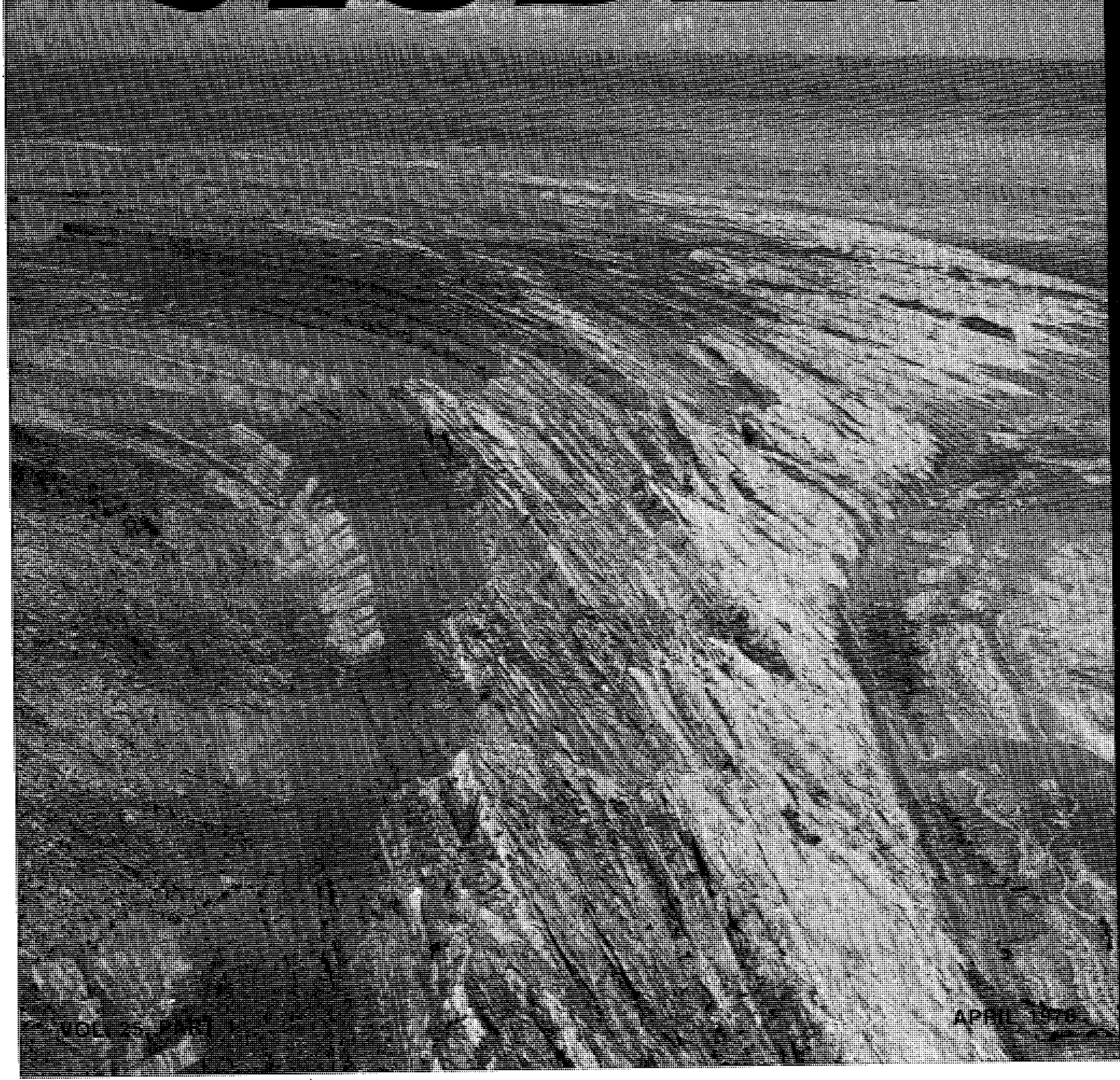
BRIGHAM YOUNG UNIVERSITY

GEOLOGY STUDIES



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Papers reviewing geology of field trip areas, 31st annual meeting, Rocky Mountain Section, Geological Society of America, April 28-29, 1978, at Brigham Young University, Provo, Utah.

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THE GLORY OF GOD IS INTELLIGENCE

Cover: East flank of San Rafael Swell, Emery County, Utah; looking north. Photo by W. K. Hamblin.

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Quaternary Tectonics along the Intermountain Seismic Belt South of Provo, Utah

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Abstract.—The historic record of seismicity in the Intermountain West shows that earthquakes are unevenly distributed in space and time. Areas where they are spatially concentrated tend to follow major structural-physiographic province boundaries. South of Provo, Utah, the seismic areas are superposed on important structural zones: the intermountain seismic belt on the structural transition zone between the Basin and Range and Colorado Plateaus provinces; and the southern Nevada seismic zone on a structural corridor within which the effects of intense late Cenozoic deformation trend transverse to the structure in the Basin and Range province. There is abundant documentation of Quaternary deformation, including widespread normal faulting, in and adjacent to the southwestern High Plateaus of Utah (fig. 1). The distribution and mechanism of earthquakes and Quaternary faults together with their proximity to major province boundaries and other important geophysical and geothermal anomalies provide a basis for published interpretations of the seismotectonics of the area in terms of subplates that are bounded by active tectonic zones.

Currently, a multifaceted program on earthquake hazards and earthquake risk evaluation includes earthquake recording and analysis, studies of crustal structure, studies of ground response, mapping of engineering characteristics of surficial deposits, stratigraphic studies of the eastern Bonneville basin, detailed site studies of fault recurrence and the geophysical expression of selected faults, regional mapping of late Quaternary faults, and regional studies of the geomorphic characteristics of active faults. A primary goal of the geologic studies within the program is to accurately date fault events at selected sites and apply that knowledge to local and regional assessments of earthquake potential.

INTRODUCTION

The historic record of seismicity and the need to understand that record in terms of its regional and local geologic and geophysical settings are important in evaluating seismic hazard and seismic risk. Geologic (including geomorphic) and geodetic evidence that could qualitatively extend the record of seismicity back in time from the historic is also potentially useful, though successful examples of such application are few.

In this report, an attempt is made to outline the regional geologic and geophysical settings of seismicity in southwest Utah, to summarize current understanding of the Quaternary tectonics of the area, and to outline the trend of recent and current earthquake hazard research in the area.

ACKNOWLEDGMENTS

I thank Robert Bucknam who has provided much help by sharing unpublished data and participating in many valuable discussions. I thank William Spence and Kenneth Sargent for very helpful technical reviews.

SEISMIC AREAS IN SOUTHWESTERN UTAH

The intermountain seismic belt (ISB) was defined by Smith and Sbar (1974) as a zone of pronounced earthquake activity extending northerly from Arizona through Utah, eastern Idaho, and western Wyoming, and terminating in northwestern Montana. In Utah, the ISB follows the eastern boundary of the Basin and Range province; most epicenters are located within about 20 km eastward of that boundary (figs. 2, 3). In the vicinity of Cedar City, the ISB is joined by an easterly trending zone of seismicity that extends across southern Nevada and is referred to here as the southern Nevada seismic zone (SNZ). These seismic areas are defined on the basis of a brief period of recorded seismicity between 1961 and 1970 (Smith and Sbar 1974). A similar seismicity pattern is indicated by maps of more complete historic epicentral data (Smith 1978). The magnitudes of located earthquakes in Utah south of Provo range from about 3 to 6, and no reported surface rupturing has been associated with any of them. Two earthquakes with approximate magnitudes of 6.7 and 6.1 occurred in the Richfield area on November 14, 1901, and September 29, 1921, respectively, and a third earthquake with an approximate magnitude of 6.1 occurred northwest of St. George on November 17, 1902 (Cook and Smith 1967).

In general, epicentral locations are not accurate enough to assign individual earthquake events to mapped faults although a spatial coincidence can be recognized for some of the larger structures of western Utah. For several years, the University of Utah has continuously monitored earthquakes on regional and local scales along the Wasatch Front and determined their location, magnitude, and source mechanisms (Smith and Sbar 1974, Smith 1978). Epicentral locations based on these continuing studies show preferential distributions along some of the major fault zones such as the Wasatch fault zone. Of possible special interest is a lack of significant earthquake activity from 1962 to 1976 along the Wasatch fault zone for 70 km north from Provo to Salt Lake City and along a second segment extending from north of Salt Lake City 70 km north to Brigham City (Smith 1978). Earthquakes were recorded in the ISB in that area, but their epicenters do not fall close to the trace of the main Wasatch fault. To explain this relative seismic quiescence along a segment of the Wasatch fault zone that contains abundant and locally spectacular geomorphic and geologic evidence of young displacement, Smith (1978) made an analogy from plate tectonics where active plate boundaries are known to be in continuous motion. Averaged over a century or more, movement can be expected at all points along the plate boundaries. Gaps in the seismic activity could be developed along a boundary as a result of the past occurrence of a large earthquake, but eventually these gaps will be filled in by future earthquakes. Using this interpretation, areas of unusually low seismicity and areas of previous faulting, such as along parts of the central Wasatch Front, might be regarded as having a higher probability for future large earthquakes. Other interpretations are possible, as outlined by Smith (1978).

Some earthquake activity in the ISB occurs as swarms of events closely spaced in time and space but with no distinct main shock. An example of swarm activity occurred near Cedar City in late 1971. The largest event in a series of hundreds of small events had a magnitude 4.5 (Smith and Sbar 1974).

STRUCTURAL SETTING OF THE SEISMIC AREAS

The spatial coincidence of the ISB with the eastern boundary of the Basin and Range province suggests a genetic association. Smith and Sbar (1974) made a comparison with plate tectonics by suggesting that the seismicity in the intermountain region is related to tectonism at subplate boundaries. They augmented their suggestion with relative motions indicated by fault plane solutions and with supporting geologic evidence. In Utah, three subplates are involved, Basin and Range, middle Rocky Mountains, and Colorado Plateaus (fig. 2). In its northern part, the Basin and Range subplate

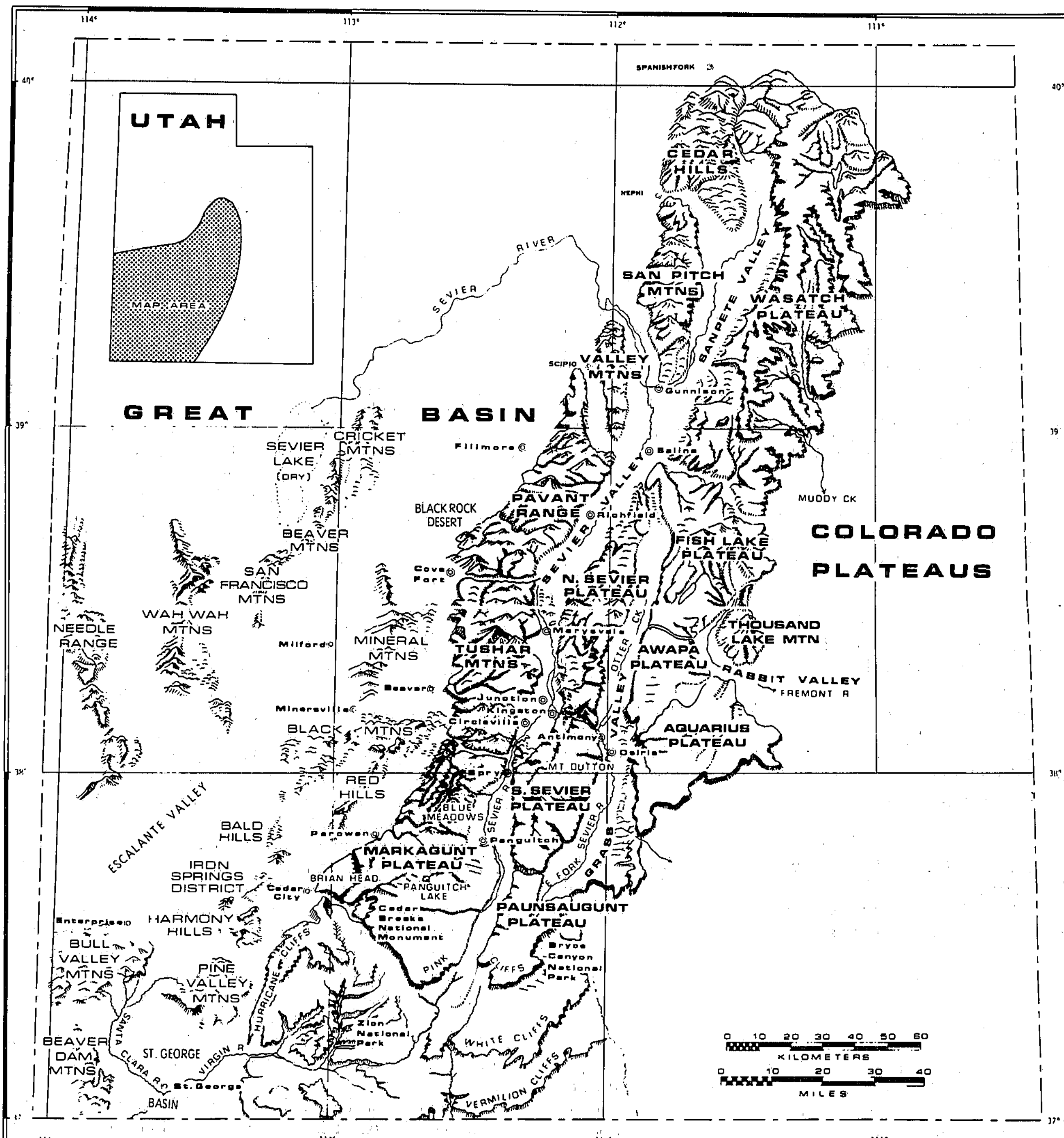

FIGURE 1.– Index map of southwestern Utah showing the High Plateaus and several of the mountain masses of the adjacent Great Basin; from J. J. Anderson et al. (1975).

is east-bounded against the middle Rocky Mountains, and in Utah that physiographic boundary is sharply defined by the Wasatch front and its structural entity—the Wasatch fault zone. To the south, in Utah and Arizona, the Basin and Range subplate is east-bounded against the Colorado Plateaus. The Wasatch fault zone defines the northern part of that boundary, but the southern part is not sharply defined by any single physiographic or structural feature, and its location is in places somewhat arbitrary (fig. 2).

Provo is situated near the northern limit of the boundary between the Basin and Range and Colorado Plateaus provinces. Within the subject area of this report, the ISB follows the Basin and Range–Colorado Plateaus boundary at least as far south as Cedar City. East of the boundary is a structurally elevated broad area of dissected plateaus (fig. 1) in which mostly horizontal to gently tilted Cenozoic strata are cut by late Cenozoic normal faults that are generally more

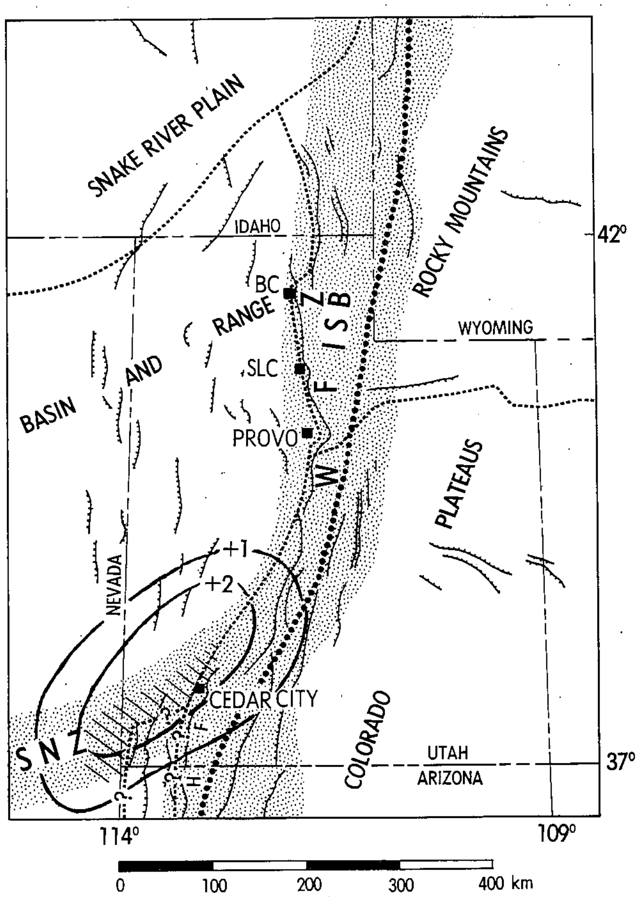

FIGURE 2.—Index map showing the area of concentrated earthquake epicenters in Utah and adjacent states (stipple) with respect to the boundaries between the major physiographic-structural provinces (short-dashed lines, queried in southwest part where locations are uncertain). Light-hachured lines mark traces of some of the large faults; hachures are shown on downthrown side. Heavy solid lines are contours based on teleseismic P-wave residuals, in seconds. Heavy dotted line marks boundary between area to west with relatively high heat flow (>1.5 HFU) and to east with more normal heat flow (<1.5 HFU). Cross-ruled area indicates corridor of complex late Cenozoic structure that trends transverse to the trend of Basin-Range structures. ISB–intermountain seismic belt, SNZ–southern Nevada seismic zone, BC–Brigham City, SLC–Salt Lake City, WFZ–Wasatch Fault Zone, HF–Hurricane Fault. Modified from Smith et al. (1975), Braile et al. (1974), and Keller et al. (1975).

widely spaced and of smaller displacement than those of the adjacent highly deformed Basin and Range province (Hintze 1963). This faulted plateau country is commonly referred to as a structural transition zone between the Basin and Range and the Colorado Plateaus provinces, and it roughly coincides with the ISB in that area. The transition zone is approximately 60 km wide east of Nephi but widens south-southwestward to twice that width at the Utah–Arizona border. Focal mechanisms for three earthquakes within the transition zone indicate high-angle normal faulting with extension axes oriented east to east-northeast (Smith and Sbar 1974, table 1). High-angle normal faulting toward the northeast was also indicated a short distance north of the structural transition zone by a composite focal mechanism solution determined from 19 aftershocks of the October 1, 1972, Heber City earthquake 40 km northeast of Provo (C. J. Langer written comm. 1978).

Smith and Sbar (1974) considered the easterly trending zone of seismicity in southern Nevada and southwest Utah as separate from the ISB which was depicted as extending southward into Arizona. More recently, Smith (1978) abandoned that interpretation and suggested instead that the seismicity in Arizona may be related to strain release around the Colorado Plateaus whereas the ISB turns southwest near Cedar City and includes the zone of seismicity that extends across southern Nevada (SNZ of fig. 2). Available data appear to be inadequate to provide a strong preference for one or the other of these interpretations. The separation of the seismicity into two belts is preferred on geologic grounds because the southerly trending zone of seismicity (ISB of fig. 2) follows a zone of good structural continuity from Utah into Arizona evidenced by the southerly trending late Cenozoic fault system of the structural transition zone. The easterly trending seismic belt in southwest Utah (SNZ of fig. 2) follows a major structural corridor that transects the northerly trending structural grain and is characterized by intense late Tertiary deformation and widespread plutonism (Mackin 1954, 1960). Its structural history and style is different from that of the structural transition zone associated with the ISB. A fault plane solution from adjacent Nevada indicates strike-slip motion with either left slip on an easterly trending plane or right slip on a northerly trending plane (Smith and Sbar 1974, fig. 6).

The inclusion of the southern Nevada seismicity in the ISB probably is preferred on geophysical grounds. Geophysically, the Basin and Range–Colorado Plateaus boundary is a transition zone between thin crust (~30 km) to the west and a thicker crust (~43 km) to the east. The transition is marked by a low P_n velocity of ~7.5 km/sec, a thinner crust (~25 km) than beneath the adjacent provinces, and an upper crustal low-velocity layer between 8 km and 15 km deep (fig. 4). These features overlie a north-trending mantle upwarp that extends at least 300 km north-south along the southern Wasatch fault. The mantle upwarp apparently extends about 200 km into the Basin and Range province, but it also extends eastward beneath the structural transition zone and ISB (Braile et al. 1974; Keller et al. 1975; Smith et al. 1975). Smith, Braile, and Keller (1975) suggested that travel time residuals from earthquakes in the Nevada–Utah border area as well as teleseismic residuals reflect a mantle upwarp in southwestern Utah and adjacent Nevada roughly coincident with the zone of seismicity in that area (fig. 2). There is, thus, a similarity in the deep crustal structure between the ISB and eastern SNZ that may favor the assignment of seismicity in the two zones to a single seismic belt.

In summary, the ISB between Provo and Cedar City coincides with a major crustal transition that is manifested at the surface by a major physiographic-structural boundary between provinces (subplates) and by an eastward decrease in the intensity of late Cenozoic normal fault deformation. At depth, the transition from the thicker crust of the Colorado Plateaus to the thin crust of the Basin and Range province is marked by a mantle upwarp and related thermal effects (fig. 2). Southward from Cedar City, sparse earthquake activity is scattered over the broad structural transition zone ex-

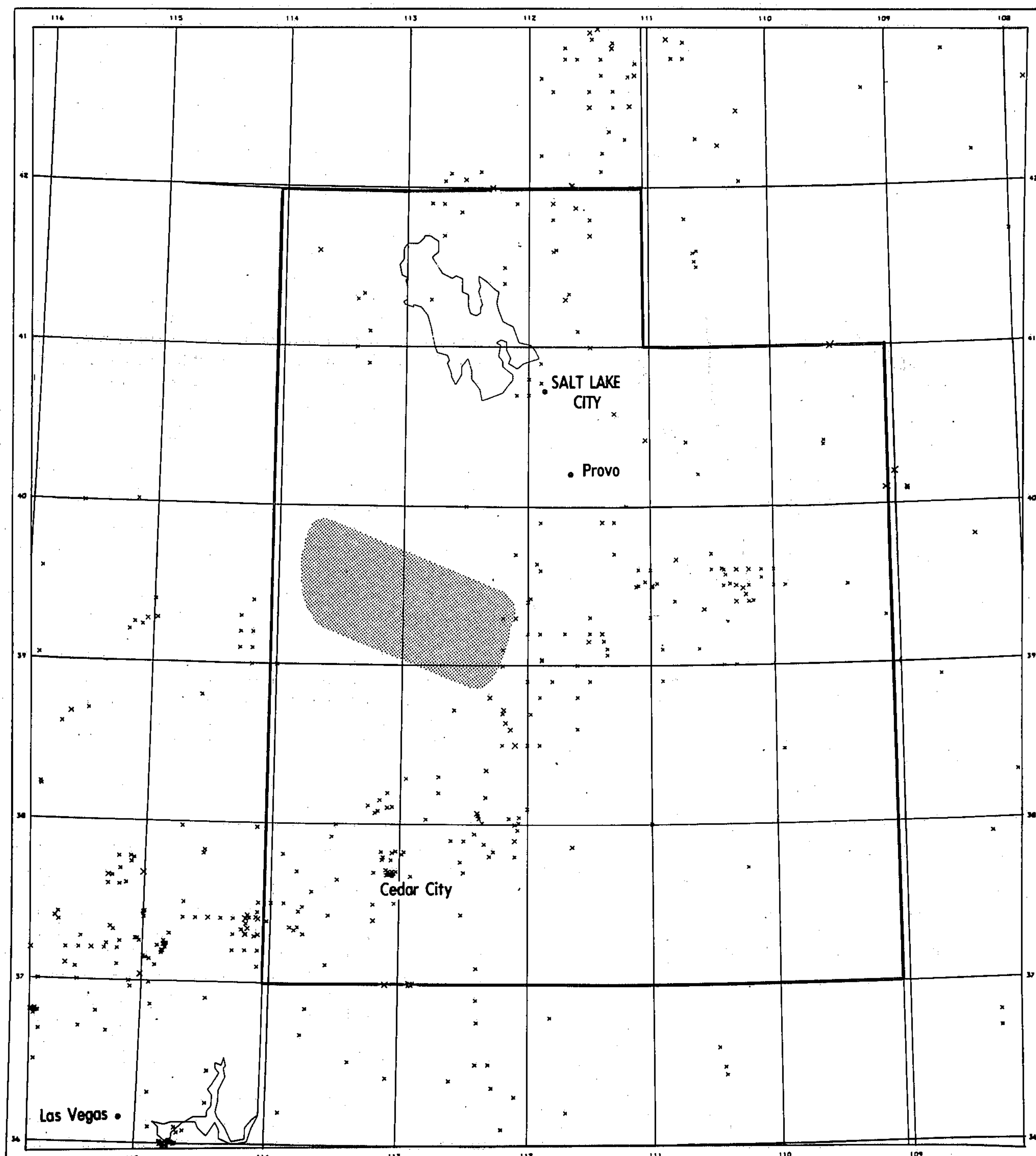

FIGURE 3.– Map showing earthquake epicenters in Utah and adjacent areas for the period 1961 through 1974; from the files of the National Earthquake Information Service, U.S. Geological Survey, Denver, Colorado. Corridor within which Holocene fault scarps are found is indicated by shading (from R. C. Bucknam, written comm. 1977).

tending south into the Grand Canyon region. The eastern margin of the Basin and Range province is not well defined south or west of Cedar City so the seismicity there bears a questionable relationship to province or subplate boundaries. The main concentration of earthquakes appears to turn westward at Cedar City and follow a major structural corridor, within which intense late Tertiary deformation occurred along trends that strike at a high angle to the northerly trending structure in the Basin and Range province.

QUATERNARY FAULTING

In western Utah, research in structural geology traditionally has focused on: (1) orogenic events such as the pulse of east-directed compressional tectonics that swept across the area in Late Cretaceous time (Sevier orogeny); (2) mid-Tertiary volcano-tectonic events such as the formation of calderas in Juab County, the deposition of more than 3 km of volcanic strata in the Marysvale area from extrusive centers in the Tushar Mountains, or the intrusive and extrusive events in the Iron Springs district in the southwest corner of Utah; (3) the development of the Basin and Range province by extensional tectonics; or (4) some combination of these. Quaternary tectonics has received brief attention in some of this research, especially in studies of faulting in the Basin and Range province which has long been recognized as extending into the Quaternary and, in some places, throughout the Quaternary.

At widespread localities throughout the eastern Basin and Range province the middle-Tertiary geologic record contains evidence of strong normal faulting, but mountain ranges produced during these times have been largely destroyed by erosion or by superposition of younger structures such as downfaulted basins. (For examples, see Gilluly 1928, Christiansen 1952.) Existing ranges produced during the late Tertiary by block faulting are generally highly modified by erosion and tend to be flanked by pediments. Existing block-faulted ranges that are bounded on one or more sides by conspicuous fault scarps are probably mostly latest Pliocene and Quaternary in age (Louderback 1924, Nolan 1943). Along many of them, such as the Oquirrh Range southwest of Salt Lake City, there is evidence for young faulting (Gilluly 1932). In some cases, the Pliocene and Quaternary faults that produced the existing ranges represent reactivation of older faults.

A late Pliocene and Quaternary age for normal faulting in the High Plateaus of Utah contemporaneous with extensional deformation in the Basin and Range province has been recognized since the early work of Dutton (1880). J. J. Anderson (1965) noted that the present structural pattern of the northern Markagunt Plateau northeast of Cedar City is the result of Pliocene(?) and Quaternary faulting along a conjugate set of faults, the major set trending about N 35° E, the subsidiary set, about north-south. Recent studies by Anderson (1978) indicate Holocene faulting at the edge of the Markagunt Plateau about 10 km northeast of Cedar City. As evidence of young faulting high on the Wasatch Plateau northeast of Salina, Spieker (1949) noted that erosion surfaces including glacial features are offset by northerly trending normal faults that have produced scarps against which small natural lakes are impounded. Not only are the high plateaus fragmented by Quaternary faults but their uplift by warping (Spieker 1949) and displacements on western marginal normal faults are in large part Quaternary in age with an estimated 600 m of relative uplift at the province boundary during the Pleistocene (Hunt 1956). Quaternary displacements of similar magnitude and direction have been reported for the Hurricane fault near Cedar City (Averitt 1964) and near St. George (Hamblin 1970a).

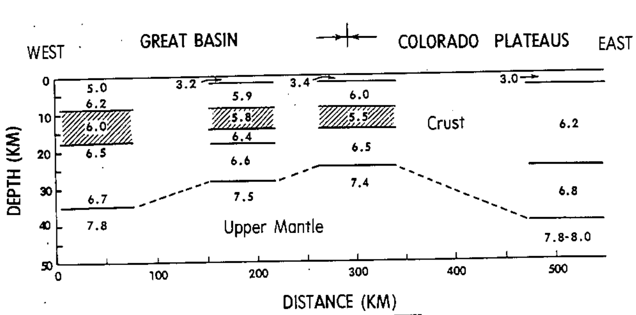

FIGURE 4.–Sections of crust and upper mantle P-wave velocity structure (in km/sec) at about lat. 39° N. These sections span the Basin and Range-Colorado Plateaus transition zone; cross-ruled areas indicate a crustal low-velocity layer (data from Smith et al. 1975).

Because no historic surface fault rupture has been reported in southwest Utah, we must rely on the geologic record for an understanding of young faulting in that area. Three of the principal subjects of Quaternary research in western Utah have been (1) the geomorphic evolution of fault scarps, (2) Lake Bonneville history and its correlation with glacial deposits and soil stratigraphy, and (3) the stratigraphy of Quaternary extrusive rocks and their classification on the basis of their geomorphic expression. Each of these has contributed significantly to our understanding of Quaternary tectonics along the seismic belts in southwestern Utah, and they are considered in turn.

Geomorphic Evolution of Fault Scarps

Davis (1903) recognized that faceted spurs found above the base of block-faulted mountain fronts in the Basin and Range province and along the Wasatch Front reflect long-continued displacements on the frontal faults. One of the classic examples that involves several sets of faceted spurs each having different inclinations toward the valley is found at the west front of the Wasatch Range in the Spanish Fork area south of Provo. More recently, Hamblin (1976) suggested that the size and spacing of pediment remnants preserved at the apices of successive generations of faceted spurs can be used as a guide to understanding the displacement history on a frontal fault. Hamblin's detailed study of the Spanish Fork area indicates eight periods of nearly continuous fault movement separated by relatively short periods of stability during which pediments were cut. Displacements during episodes of recurrent movement are about 200–300 m. No absolute time scale has been applied to the displacement histories developed from geomorphic studies of bedrock mountain fronts.

On the basis of a study of the geomorphic characteristics of young fault scarps formed on unconsolidated alluvium in the Basin and Range province of north central Nevada, Wallace (1977) showed that selected geomorphic parameters can be used as a key to the ages of fault displacements. The relationship to age of one of these parameters, the principal slope angle, is shown in figure 5. Bucknam and Anderson (1978) made studies of fault scarps in the eastern Basin and Range province of Utah and found that the relationships developed by Wallace (1977) apply there also. Further, they found that scarp height can be an extremely important variable if slope angle is used to estimate absolute or relative ages of fault scarps. Current research of the morphology of fault scarps preserved on unconsolidated alluvial deposits of the eastern Basin and Range province is considered in a subsequent section on recent and current research.

Lake Bonneville History

One of the most conspicuous features of the arid to semiarid landscape of western Utah is the widespread occurrence of well-developed shorelines and beach forms produced by late Quaternary Lake Bonneville. These features and sediments associated with the lake provide important references for dating late Quaternary fault events.

The earliest comprehensive study of the lake history was that of Gilbert (1890), who proposed two high stands of the lake with nearly complete evaporation between the two stages. Modern studies, summarized by Morrison (1965), suggest a far more complex history. A simplified version of the currently understood stratigraphic relationships is given in figure 6. The main stratigraphic unit of lacustrine sediments of the lake is the Lake Bonneville Group. The lowest and thickest part of the unit is the Alpine Formation, equivalent to the "yellow clay" of Gilbert (1890). Morrison (1965) reported the existence of shorelines, locally higher than the prominent Bonneville shoreline, that he believed to be of Alpine age and which he associated with a lake level that resulted in overflow of the lake at Red Rock Pass, Idaho. That overflow is believed to have produced a catastrophic flood along the Snake River plain.

The Alpine Formation is overlain by the Bonneville Formation, which is composed of two members, a lower white marl member and an upper member associated with the highest shoreline (Bonneville shoreline) of the last lake cycle that also resulted in an overflow of the lake at Red Rock Pass. In many areas, there is a prominent shoreline (Provo shoreline) representing a stillstand in the recession from the Bonneville shoreline. The uppermost member of the Lake Bonneville Group is the Draper Formation, and two stillstands associated with lake stages of this age, the Provo II and Stansbury shorelines, are widely recognized. Soils and subaerial deposits within the major stratigraphic units record a complex series of fluctuations of the lake within the framework described above.

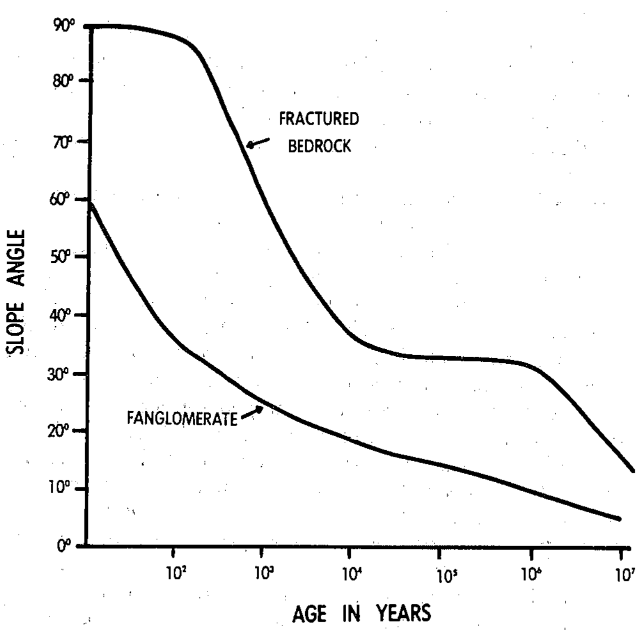

FIGURE 5.–Postulated curves for principal slope angles against age. The curves are intended to circumscribe the major field of scarp slopes of various ages and in various materials ranging from unconsolidated fanglomerate to fractured bedrock; from Wallace 1977.

Crittenden (1963) made a detailed study of the elevation of the highest shoreline of the lake which he correlated with the Bonneville shoreline. That shoreline, originally cut at a constant elevation, now defines a broad domical uplift with a maximum closure of about 65 m. The uplift formed as a result of isostatic rebound. Shoreline elevations given in figure 6 are for the vicinity of Provo.

Radiocarbon determinations of the Lake Bonneville chronology, taken as a whole, show inconsistencies and preclude presentation of a definitive history. Morrison and Frye (1965) evaluated the radiocarbon chronology of Lake Bonneville and chose several "landmark" dates to outline the major events in its history. Among those dates are 20,700 years for the transgression of the white marl lake cycle; 15,400 years for the transgression of the later lake cycle of Bonneville Formation time (the cycle that rose to the Bonneville shoreline); and 11,800 years for the recession between the last cycle of Bonneville Formation time and the first cycle of Draper age (fig. 6).

An additional date pertaining to lake chronology is provided by studies of flood deposits associated with the overflow of Lake Bonneville at Red Rock Pass, Idaho. Molluscan fossils from gravels of a terrace cut on flood deposits have been dated 29,700 ± 1,000 years (Trimble and Carr 1961, p. 1746, sample W-731). The terrace is interpreted by them to be closely associated with erosion during the waning stages of the flood; the overflow, therefore, occurred in Alpine time about 30,000 years ago.

Applications of the time-stratigraphic relationships of Lake Bonneville to fault histories have been made mainly along the Wasatch front. Much of the formation of the Wasatch Front by faulting took place before the first rise of Lake Bonneville but probably during Quaternary time (Morrison 1965). In the vicinity of Provo, Hunt, Varnes, and Thomas (1962) reported displacements of more than 100 m in pre-Lake Bonneville Pleistocene deposits, whereas deposits formed during the Bonneville shoreline maximum (estimated to be no older than 15,400 years, fig. 6) are locally offset 18 m; and at one locality, they have been displaced above their original shoreline level. To the north, in the Jordan Valley area near Salt Lake City, Morrison (1965) estimated about 15 m of displacement on the Wasatch fault zone since the Bonneville shoreline maximum and stated that individual faults show lesser displacements. According to Morrison, all faults in the main Wasatch fault zone in the Jordan Valley area have been active since the time of the Bonneville shoreline maximum, and most have been active since the Graniteville Soil formed (estimated to be about 11,800 years ago, fig. 6).

At several localities in the Basin and Range west of the Wasatch Front and west of the ISB, faults displace deposits or surfaces that were formed in or by Lake Bonneville. Recent studies by R. C. Bucknam (pers. comm. 1977) of fault histories at those localities indicate probable Holocene displacements in Rush Valley in eastern Tooele County; on the east flank of the Fish Springs Range, Juab County; and east of the Drum Mountains, Millard County.

Stratigraphy of Quaternary Extrusive Rocks and Basin-Fill Sediments

From the standpoint of Quaternary fault studies, the seismic areas south of Provo can be divided into two parts, (1) the basin of Lake Bonneville and its directly adjoining hills and mountains where determinations of fault histories rest primarily on the application of the chronology established from the stratigraphic and geomorphic lake record to tectonic events, and (2) the remainder of the area which is mostly above and beyond the limits of Lake Bonneville and where the hope of determining displacement histories rests in dating offset Quaternary materials such as lavas or basin-fill sediments or offset surfaces such as stream terraces or pediments. Substantial portions of the seismic areas in southwest Utah and adjacent Arizona are underlain by alkalic basaltic lavas that were erupted concurrently with major northerly trending normal faulting and regional uplift (Best and Brimhall 1974). In many areas, the faulted lavas are known or can be inferred to be of Quaternary age. Examples in Utah are in the Cove Fort–Black Rock Desert areas, at the margins of the St. George basin, and in the Markagunt Plateau. In some cases, such as the Black Rock Desert, lavas were erupted into Lake Bonneville. Substantial portions of the seismic areas are also underlain by alluvial deposits that are known or inferred to be of Quaternary age (Hintze 1963). Examples are in the Escalante, Cedar City, Parowan, Sevier, and Sanpete valleys.

Volcanism in the Black Rock Desert area was reported on recently by Hoover (1974) and in the Cove Fort area by Clark (1977). K–Ar data indicate that mafic volcanism began in those areas about 2 million years ago. In the Black Rock Desert area, it continued into the period of Lake Bonneville occupation so that age estimates for the younger of the extrusive rocks can be inferred from correlations to Lake Bonneville history. In general, eruptions took place from northerly trending fault-controlled fissures, and successively older eruptive products record progressively greater amounts of fault displacement ranging from 67 m in 1-million-year-old lavas to about 6 m in lavas that are inferred to be a few thousand years old (Hoover 1974). Some of these displacements, especially the young ones, may be of volcano-tectonic origin, because nearby shorelines that are probably pre-Holocene in age are not displaced by faults that strike parallel to those that offset the Holocene(?) lavas. Alternatively, the ages inferred for the lavas may be too young. For the Cove Fort area, Clark (1977) calculated east-west horizontal extensional strain of approximately 7.5 m per kilometer within the past 1 million years.

A sophisticated scheme has been developed for the classification and assignment of relative ages to volcanic rocks in southwestern Utah and adjacent Arizona on the basis of the nature of the surface upon which they were erupted and the extent to which they have been modified by posteruptive erosion and soil development (Hamblin 1970b, which includes a brief review of earlier classifications). Those who have developed the classifications have avoided attaching absolute time scales to them. Age approximations have been made in a few cases but only for rocks that fall into the very youngest categories. Nevertheless, in areas where lithologic

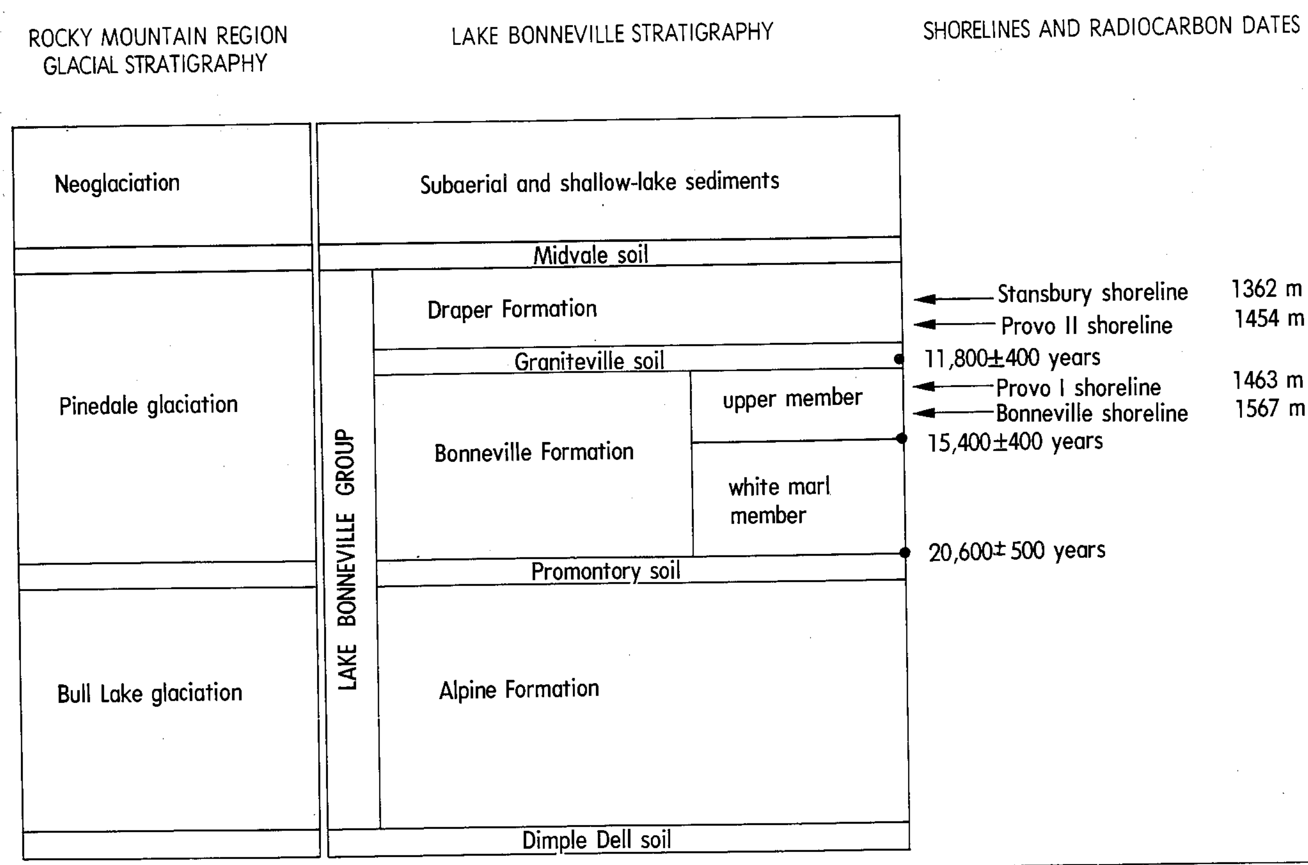

FIGURE 6.– Diagram showing the relationship between selected aspects of Lake Bonneville stratigraphy (including major episodes of soil development) and (1) glacial stratigraphy of the Rocky Mountain region, (2) elevations of selected Lake Bonneville shorelines, and (3) three radiocarbon dates (dots) chosen by Morrison and Frye (1965) as "landmark" dates that establish main tiepoints for the framework of the radiocarbon chronology of Lake Bonneville. Shoreline elevations are for the Provo area (Bissell 1963) except for Stansbury shoreline elevation, which is for the Salt Lake City area (Morrison 1965).

distinctions between flows are difficult or uncertain, relative ages assigned to sequences of flows on a geomorphic basis are an aid to understanding local fault histories; and where relative ages are augmented by scattered isotopic ages, they provide a chronological basis for mapping and for understanding regional structural history. Such is the case in the Utah–Arizona border area and the western Grand Canyon area of the structural transition zone, where displacements on the major northerly trending faults, such as the Hurricane, Sevier, Toroweap, and Grand Wash, have been interspersed with eruptions of late Cenozoic lavas that have crossed the faults. Recurrent movement along the faults can be determined quantitatively in some areas and qualitatively in many (Hamblin 1970a). On the southern part of the Hurricane fault, for example, four periods of late Cenozoic movement are documented, and three of those represent offsets of about 600, 60, and 15 m that occurred at successively younger times during the Quaternary (Hamblin 1970a). On the northern part of the Hurricane fault, Averitt (1964) reported four periods of Quaternary movement, the first two producing 300–400 m of displacement, the third 60–90 m, and the fourth, 12 m. Huntoon (1977) reported Holocene displacement on the Toroweap and Hurricane faults, but the evidence is not convincing.

There has been no report of a systematic effort to date Quaternary terrace, pediment, or fan surfaces or Quaternary basin-fill deposits in the seismic areas south of Provo. In numerous places old Quaternary alluvial materials or surfaces are offset by northerly trending normal faults more than successively younger ones, and if ages were available, they would greatly expand our knowledge of the history of young faulting. Examples are found in the valleys of Scipio and Beaver and at scattered localities along the valley of the Sevier River from Panguitch to Richfield.

In summary, the widespread documentation of Quaternary normal faulting on northerly trends along the trace of the seismic areas in Utah aids considerably in understanding the seismotectonics. Together with geophysical and geothermal data, it provides a basis for interpreting the contemporary tectonics of that part of the intermountain region in terms of subplates that are bounded by active tectonic zones (Smith and Sbar 1974, Smith 1978). Nevertheless, for the purpose of seismic hazards and seismic risk evaluations within the region, a growing need exists for specific data on the ages of young fault events that are generally not found in existing reports. Compilations that show faults only as Quaternary in age have been utilized as indicators of the seismic potential of a region, but they are generally not adequate for that purpose.

RECENT AND CURRENT RESEARCH OF EARTHQUAKE HAZARDS IN UTAH

One of the most active areas of recent and current earth science research in the Intermountain West is focused on earthquake hazards and earthquake risk evaluation. In Utah, the 1976–77 state legislature commissioned the Utah Geological and Mineral Survey to conduct zone mapping of seismic risk thoughout the state. The 95th Congress of the United States passed an Earthquake Hazards Reduction Act, and an important part of the implementation of that act is focused on research along the Wasatch Front, which is being coordinated by and funded through the U.S. Geological Survey (USGS). The concern that has led to these legislative enactments is based on seismologic and geologic data, namely, the concentration of historic earthquake activity along the Wasatch fault zone which embraces abundant evidence of young-looking fault scarps, some of which suggest displacements of several meters (Smith and Sbar 1974; Cluff et al. 1970, 1973; Cook 1972; Morisawa 1972). Approximately 85 percent of the population of Utah and virtually all of the major industrial centers of Utah are located along or within 20 km of the Wasatch fault zone. This juxtaposition of population along a major fault greatly increases the possibility of catastrophe in the event of a large earthquake (Cluff 1975).

An important part of earthquake hazards and risk evaluation in the Wasatch Front urban corridor involves current mapping of surficial materials and monitoring of ground response to seismic shaking. The results of these USGS studies are being combined to show the areal potential for strong ground shaking and/or ground failure should an earthquake strongly affect the main urban area. Present plans also call for geophysical studies by the USGS of the geometry of selected faults in the Wasatch fault zone.

Clearly, the need exists to identify potentially "active" faults within and adjacent to the Wasatch fault zone and to accumulate data on their frequency of movement (recurrence) and maximum expectable magnitude of displacement, in order that probabilistic estimates of the potential for specific fault movement can be made. A subject of special interest related to this need is the definition of "active faults." The term has a variety of definitions (both informal and legal), and many of them require information on the age of last movement. Some examples are the following:

1. The Alquist-Priola Act of California establishes that active faults are those which have had surface displacement within Holocene time (about the last 10,000 years).
2. According to G. J. Lensen (cited as 1976 written comm. by Slemmons and McKinney 1977) the New Zealand Geological Survey has established three classifications of active faults. A *Class I Active Fault* is either a fault that has shown repeated movement over the last 5,000 years, or with a single movement over that period and repeated movement in the last 50,000 years. A *Class II Active Fault* is less active, exhibiting either repeated movement over the last 50,000 years, or one single movement in the last 5,000 years and repeated movement in the period of 50,000 to 500,000 years. A *Class III Active Fault* is the least active, exhibiting either a single movement over the last 50,000 years or repeated movement during the 50,000–500,000-year period.
3. The Nuclear Regulatory Commission definition of "capable fault" includes faults that have had displacement within the last 35,000 years or recurrent movement within the past 500,000 years.

Clearly, a dating capability ranging from historic to about 500,000 years is needed to encompass commonly used definitions of active faults. The age range is also that of most interest to the majority of risk and hazards studies.

Considerable amounts of data—data difficult to acquire—are needed to establish the history of fault recurrence and the lengths of fault rupture within the critical time framework. Woodward–Clyde Consultants (written comm. 1975) conducted a study of young-looking displacements along the Wasatch fault zone and selected several sites where needed data on fault recurrence might be acquired. Detailed investigations are underway by Woodward–Clyde Consultants under contract to USGS for fault recurrence studies at two sites—Bells Canyon near Salt Lake City and Hobble Creek near Provo. Stratigraphic studies of Quaternary lacustrine, colluvial, and glacial sediments of the eastern Bonneville basin are underway by the USGS, and those studies will interface closely with the fault recurrence studies.

It is not realistic to expect that accurate dating of the late Quaternary history of faulting will be achieved at more than a very few localities. It is hoped that displacement histories can be determined at a few localities and that the resulting data will be applicable to the region. Because most faults in the region have a vertical component of displacement, which tends to produce conspicuous scarps, the greatest potential for widespread application of dated relationships rests in the geomorphic expresson of fault scarps, especially those formed on unconsolidated to weakly consolidated materials such as the widespread basin-fill alluvium. Easily measured geomorphic parameters such as principal slope angle of the scarp and width of its crest have been shown by Wallace (1977) to vary with age of the scarp. Early results of related studies by Bucknam and Anderson (1978) indicate that scarp height is an important variable that should be considered if relative ages are to be assigned to fault scarps. The effect of scarp height on principal slope angle for several sets of fault scarps, each believed to represent a single episode of faulting, is depicted schematically in figure 7. If time lines could be superposed on a quantitative plot similar to that shown in figure 7, an approximate age could be assigned to any scarp of variable height or set of scarps of variable height that formed during a single episode of faulting. This is a prime goal of current research.

Another goal of current research is to compile maps of western Utah on which fault scarps formed on alluvium are categorized according to their age, or approximate age, of last movement. Such compilations would show only faults that are known or inferred to have been active in the last 500,000 years, and, as such, they would be maps of active faults in the broadest sense. The recognition of patterns in the distribution of active faults is important because it is known from geologic studies (Slemmons 1967) and earthquake studies (Ryall 1977, Smith 1978) that large-magnitude earthquakes that produce surface rupturing in the Basin and Range province migrate from place to place with time. Early results of current studies in Utah show an irregular distribution of scarps of known or inferred Holocene age that does not everywhere match the distribution pattern of historic seismicity. Large parts of the seismic areas apparently lack Holocene scarps, and, conversely, they are found over at least one large area outside the seismic belts (fig. 3). If the time frame is increased to include all scarps of probable late Quaternary

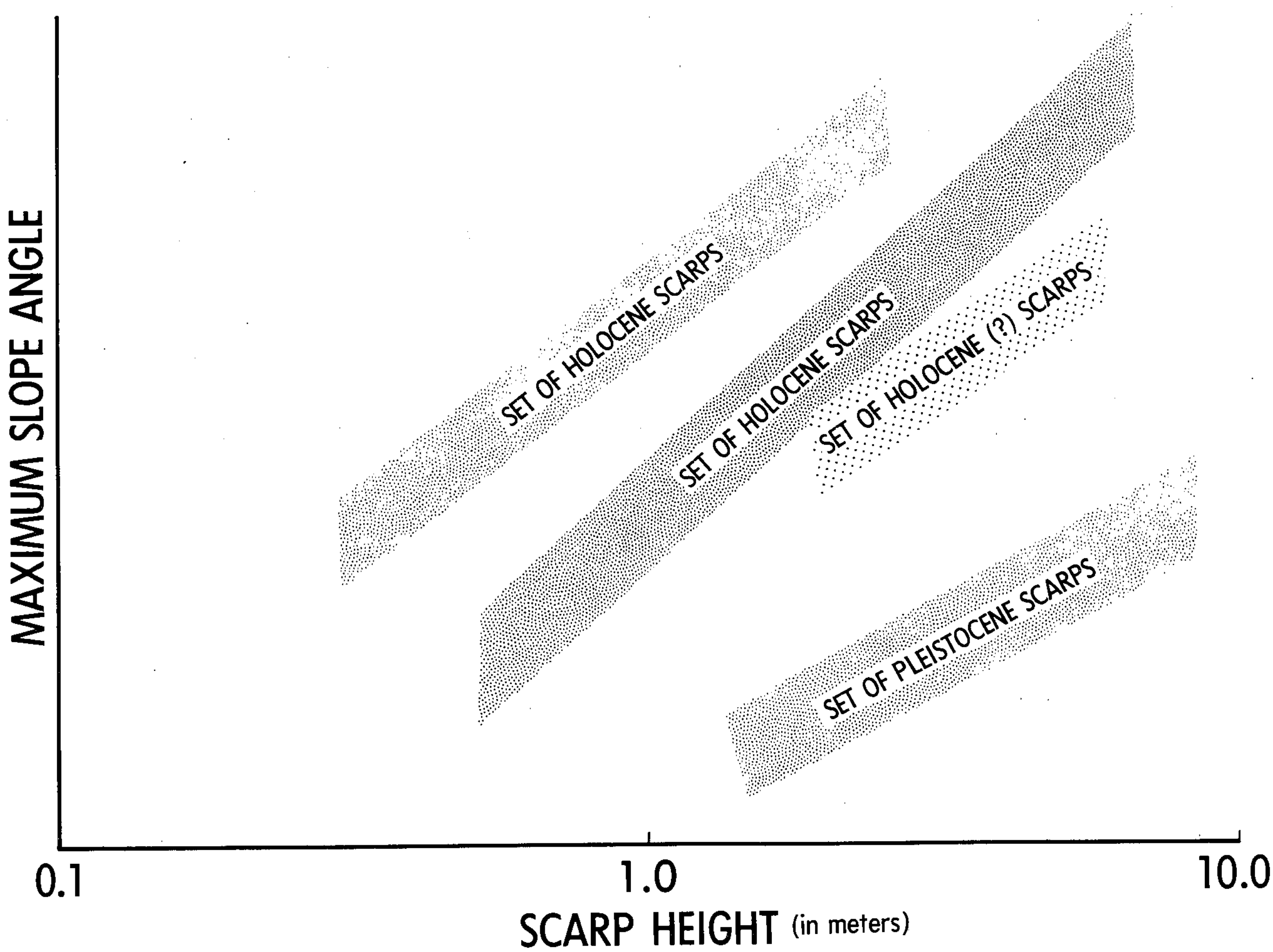

FIGURE 7.– Schematic diagram of maximum slope angle plotted against scarp height, showing fields within which data points representing fault scarps that formed on alluvium at four different times might tend to fall.

age (<500,000 years), there is a somewhat better match in distribution with that of the historic seismicity. These observations indicate migration of high-energy seismic events with time. As noted by Smith (1978), the migrations demonstrate that seismic zoning based solely on evidence of Holocene faulting or historic seismicity could lead to erroneous results.

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