Regional tilt patterns of late Cenozoic basin-range fault blocks, western United States

JOHN H. STEWART *U.S. Geological Survey, Menlo Park, California 94025*

ABSTRACT

Large regions in which major late Cenozoic basin-range fault blocks are consistently tilted are recognized in the western United States. The pattern of tilt domains is characterized by transverse zones or boundaries, parallel to the extension direction, and by antiformal (tilts away from) and synformal (tilts toward) boundaries at right angles to the extension direction. Tilting of ranges averages about 15° to 20° in Nevada and Utah and indicates extension of about 20% to 30% for the entire Great Basin region, using the model proposed by Morton and Black (1975) that relates dip of beds and extension. The regional tilt pattern may be related to stress relief extending outward from antiformal boundaries that are interpreted as initial sites of rupture during late Cenozoic extension.

INTRODUCTION

Tilting of major fault blocks has long been considered a characteristic feature of basin-range structure. Recently, regional maps showing the direction of tilt of fault blocks in large parts of the western United States have been published (Rehrig and Heidrick, 1976; Stewart, 1978), and these maps, combined with new data, have been used to prepare a map showing tilt directions throughout the western United States (Fig. 1). This article describes the regional tilt pattern and discusses various aspects of the tilt pattern that

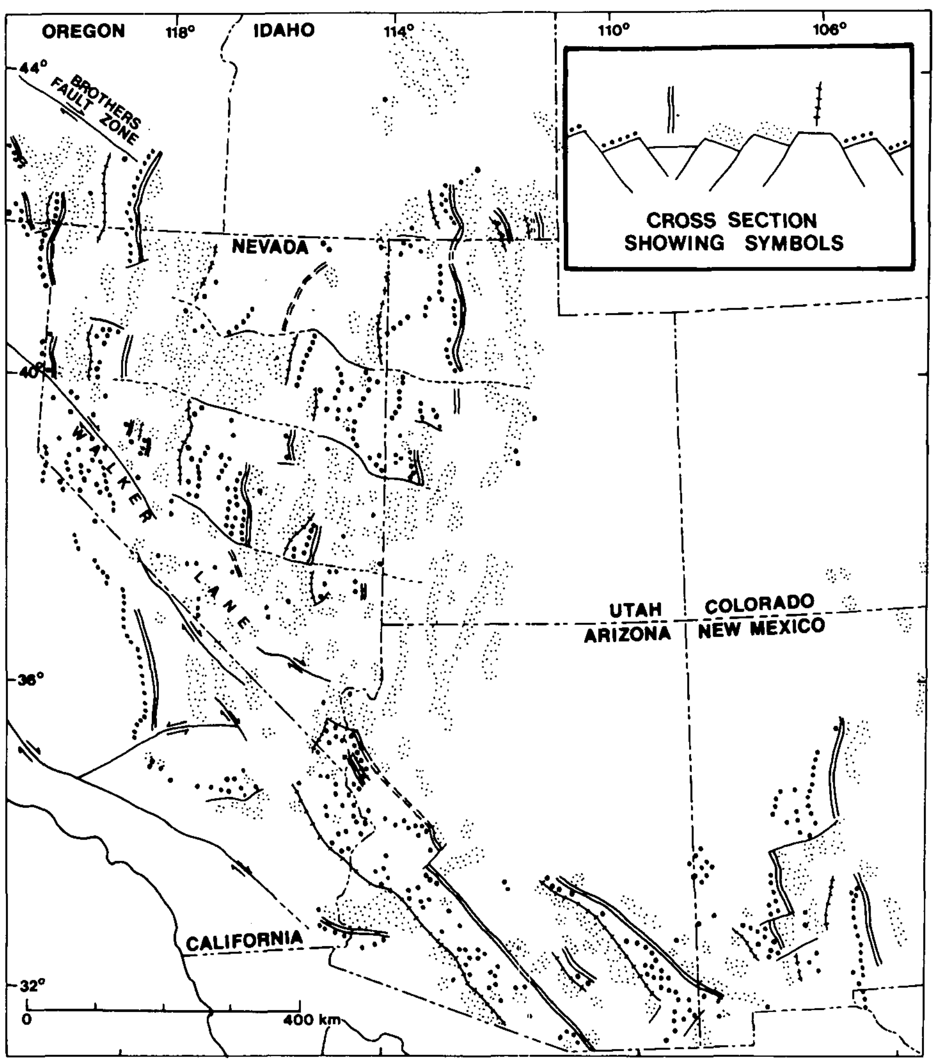

Figure 1. Tilt patterns of late Cenozoic basin-range fault blocks in the western United States (based in part on Rehrig and Heidrick, 1976, and Stewart, 1978). Light stipple, east or northeast tilt; heavy stipple, west or southwest tilt; double line, antiformal boundary, dashed where uncertain; cross-hatched line, synformal boundary, dashed where uncertain; single line, transverse zone or boundary, dashed where extended into regions of consistent tilt direction (see text for explanation); line with arrows, strike-slip fault or fault zone, arrows indicate relative movement, dashed where uncertain.

Geological Society of America Bulletin, Part I, v. 91, p. 460–464, 5 figs., August 1980, Doc. no. 00805.

provide a better understanding of basin-range structure and its origin.

CHARACTERISTICS OF TILTED BLOCKS

Three general models of basin-range structure have been proposed: horst and graben, tilted block, and listric fault (Fig. 2). At present, no general agreement exists as to which of these models is correct, and basin-range structure probably involves elements of each of the models. Tilting is most easily visualized in the tilted block and listric fault models, although moderate tilting also can be accommodated in the horst and graben model.

Tilting on many different scales is evident in the Basin and Range Province, from blocks at least as large as entire mountain ranges to relatively small blocks less than 100 m across. The tilted character of entire mountain ranges is recognized by the occurrence of major faults and steep slopes along the uptilted margin of the range (Fig. 3) and few faults and gentle slopes on the downtilted margin.

Smaller scale tilted blocks commonly occur within major blocks. In some areas, these tilted blocks appear to result from the same stresses that caused the rotation of the main block. In other areas, the small tilted blocks appears to be related to low-dipping faults that may have diverse origins (Anderson, 1971; Proffett, 1977; Davis and Coney, 1979; Eaton, 1980).

The map of regional tilt patterns (Fig. 1) includes data on both large and small tilted blocks. The tilt of large blocks is evident in many areas on the basis of the physiographic or structural features (Fig. 3). In other areas, tilt directions of both large and small fault blocks are determined only on the basis of the dip of Tertiary rocks. Dips of earliest Tertiary and older rocks are excluded because the structural attitude of these rocks could be related to tectonic events (the Late Cretaceous and earliest Tertiary Laramide orogeny, for example) unrelated to basin-range tilting.

The detailed data used in preparation of the generalized map shown here (Fig. 1) are given in Stewart and Johannesen (1979). The generalized patterns shown in Figure 1 seem fairly well defined in most areas, although new data or re-evaluation of existing data will doubtlessly lead to considerable improvements of the map. Local reversals in the direction of tilt, not all of which can be shown on Figure 1, are evident in some areas, even in areas where a consistent tilt of major blocks is well defined (Gilbert and Reynolds, 1973, Figs. 2 and 3).

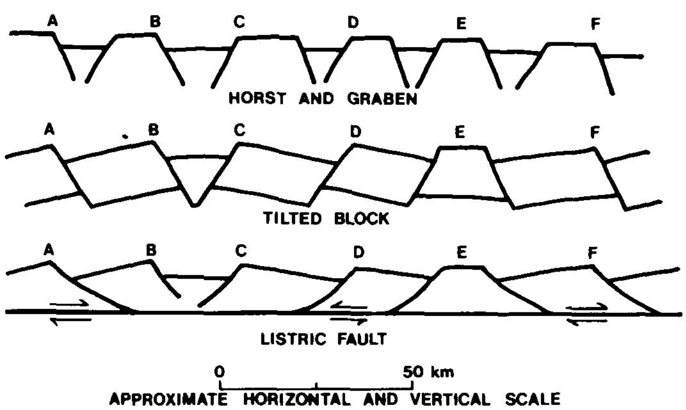

Figure 2. Generalized models of basin-range structure. Letters indicate topographically comparable parts of models. Relatively small-scale faulting and tilting within major blocks is not shown. Horst and graben model is related to downdropping of systematically spaced complex horizontal prisms (grabens) above a plastically extending substratum. Tilted block model is related to fragmentation of an upper crustal slab into buoyant blocks. Listric fault model is related to downward flattening faults that bottom along a sliding surface or thin zone of decollement.

Figure 3. High-altitude oblique photograph of Cortez Range, north-central Nevada, showing typical characteristics of basin-range tilted fault block. View southwest. Major range-bounding fault and steep slope on uptilted side of block to right; gentle slope without a major range-bounding fault on downtilted side to left. Gently sloping area of low relief on left side of range in middle-ground is developed on 14- to 16-m.y.-old basaltic andesite tilted 5° to 10° to left.

REGIONAL TILT PATTERNS

Large regions of consistent tilt directions of major late Cenozoic basin-range fault blocks are recognized in the western United States (Fig. 1). Across the strike of basin-range structure, these regions commonly extend for 50 to 250 km and include one to more than ten major mountain ranges. Parallel to strike, the regions extend for 50 to 500 km.

In Nevada and Utah, tilt directions are generally either to the east or the west. These east-tilting and west-tilting domains are bounded by three broad, west-northwest–trending transverse zones or boundaries and by north-northeast–trending boundaries at right angles to the transverse zones. The transverse zones, first recognized by Slemmons (1967), separate domains of contrasting tilt patterns. The transverse zones are extended (dashed lines on Fig. 1) into areas of consistent tilt direction where such extensions join aligned segments of transverse zones or extend the zones into areas of seemingly disrupted structure or topography on line with the transverse zones. Such extensions are problematical but are seemingly justified in that both the transverse zones and their extensions are commonly characterized by an absence of major tilted blocks, by changes in the density and pattern of young faults (Slemmons, 1967), and by changes in topographic grain. In places, the transverse zones and their extensions correspond to defined lineaments or parts of them (Ely–Black Rock lineament of Howard, 1976; part of the Blue Ribbon lineament of Rowley and others, 1978; part of the Timpahute lineament of Ekren and others, 1976), but elsewhere the zones do not follow any well-defined structural features previously recognized.

The north-northeast boundaries at right angles to the transverse zones are either synformal (tilts toward the boundary) or antiformal (tilts away from the boundary). The pattern of distribution of synformal and antiformal boundaries is different in each of the regions bounded by the transverse zones. The distribution of synformal and antiformal boundaries is crudely symmetrical with respect to a medial line extending north-northeast through the central Great Basin. This symmetry is also evident in the general eastward tilt of basin-range blocks along the eastern margin of the Great Basin and a general westward tilt along the western margin of the Great Basin, although in the Great Basin overall, about two-thirds of the blocks are tilted east and one-third tilted west (Stewart, 1978).

The pattern of tilting is inconsistent in the region of right-lateral fault slip and drag (Walker lane) in western Nevada and adjacent parts of California. In this region, tilts of fault blocks and the strike of middle Tertiary rocks are in some places oriented east-west at right angles to the general trend in Nevada and Utah.

Tilt patterns in Arizona, originally compiled by Rehrig and Heidrick (1976), and in southeastern California indicate large northwest-trending domains of consistent tilt. Synformal and antiformal boundaries between these domains trend northwest and are 45° to the trends of synformal and antiformal boundaries in Nevada and Utah. Transverse boundaries are not so evident in Arizona as in Nevada and Utah.

Antiformal and synformal boundaries in New Mexico trend north to north-northwest. A few well-defined transverse boundaries are recognized, the longest of which was first described by Chapin and others (1978).

EXTENSION DIRECTIONS

Antiformal and synformal boundaries are essentially at right angles to the extension direction, whereas the transverse boundaries are parallel to it. Evidence of this relation is clearly seen in Nevada and Utah where a general west-northwest extension direction (Zoback and Thompson, 1978) has been determined from earthquake focal mechanism, in situ stress measurements, geodetic data, alignment of volcanic vents, historic faults, and slip directions on young faults. This extension direction is at right angles to the major antiformal and synformal boundaries and parallel to the transverse boundaries. In general, the major basin-range faults and fault blocks also trend at right angles to the extension direction.

By analogy, the northwest trend of antiformal and synformal boundaries in Arizona and California indicate a southwest extension direction, and the north to north-northwest trends in New Mexico indicate a west to west-southwest extension direction.

The conspicuous change from a southwest-spreading direction in California and Arizona to a west-northwest direction in Nevada and Utah is related to an early development of basin-range extensional structures in California and Arizona, related to a southwest spreading direction, and a late development of extension structures in Nevada and Utah, related to a west-northwest spreading direction. Such a northward shift in the areas undergoing basin-range faulting and the change in the spreading direction have been described by several geologists and most recently by Christiansen and McKee (1978) and Eaton (1980). In Nevada, although most basin-range structure is related to west-northwest extension, structures related to an older west-southwest to southwest spreading direction have been described locally (Anderson and Ekren, 1977; Zoback and Thompson, 1978). The complexity of basin-range structure may be related in part to the superposition of younger structures on such older trends.

AMOUNT OF TILT AND ITS RELATION TO AMOUNT OF EXTENSION

The amount of tilt of basin-range blocks can be estimated from the dip of Tertiary rocks. Figure 4 is a histogram of dips of Tertiary rocks from widely distributed measurements throughout the main region of basin-range faulting in Nevada and Utah, based on information shown by Stewart (1978, Pl. 1). The tilt of major fault blocks is less than the dip of Tertiary rocks, because major blocks are commonly composed of smaller blocks that are tilted at a higher angle than the over-all block (Hunt and Mabey, 1966, Fig. 3). In addition, the smaller blocks may be related in part to structural events prior to the development of the major present-day basin-range fault blocks (Anderson, 1971; Proffett, 1977; G. A. Thompson and M. L. Zoback, 1979, written commun.) Nevertheless, the data in Figure 4 suggest that most ranges in the Great Basin region are tilted less than about 32°, although, locally, individual blocks are tilted at a much higher angle and, in a few places, bedding in such blocks is overturned (Anderson, 1971; Proffett, 1977).

Morton and Black (1975) have suggested a relation between the amount of crustal thinning and the amount of dip of bedding in tilted blocks. They related tilting to the rotation of large blocks (tilted block model of Fig. 2), whereby the dip of bedding gradually increases and the dip of faults gradually decreases during the progressive rotation of the blocks (Thompson, 1960, Fig. 3). A second generation of faults is developed when the original set of faults is rotated into a low-angle position (~40°) unfavorable for displace-

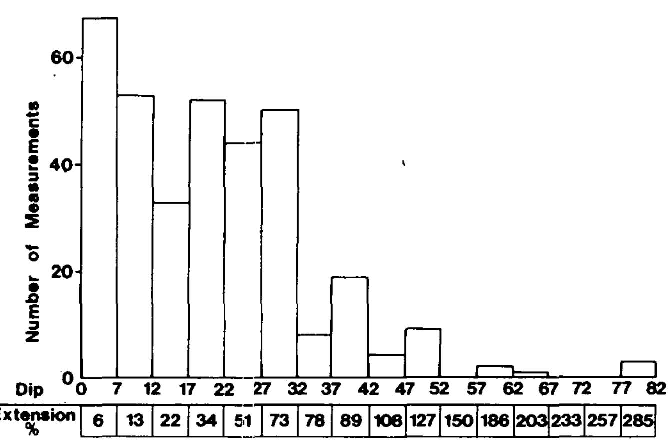

Figure 4. Histogram showing dip of Tertiary rocks, based on 345 widely distributed measurements, in the Great Basin of Nevada and Utah. Percentage of extension based on relation to dip of beds described in text.

ment in an extensional stress field. Their calculations for crustal thinning are here converted to percentage of extension; the model used assumes an initial 60° dip on fault planes. Using 15° to 20° as an average tilt of basin-range blocks, the Morton and Black model suggests extension of about 20% to 30% for the entire Great Basin region. The model also indicates, as Proffett (1977) proposed, using other data, that the amount of extension varies from area to area in the Basin and Range Province. Dips in some areas of the province average only 5° to 10°, equivalent to about 10% extension, whereas in other areas (Anderson, 1971; Proffett, 1977; Wright and Troxel, 1973) dips average more than 45°, equivalent to more than 100% extension. Contrary to Proffett's (1977) concept, however, data in the Great Basin (Stewart, 1978) do not show a consistent pattern of larger extension at the margins of the Great Basin, but rather irregular isolated areas of greater extension both within and at the margins of the Great Basin.

The quantitative relation of dip of beds to the amount of extension described above is based on the tilted block model of basin-range structure. Such a quantitative relation has not been determined for the listric fault model, but qualitatively the concept that the higher the dip, the greater the extension appears to be as true for the listric fault as it is for the tilted block model. The relation, if any, of tilting to the horst and graben model is obscure.

ORIGIN OF TILT PATTERNS

The regional tilt pattern is here related to major antiformal boundaries that may be the initial sites of rupture that led to the development of late Cenozoic extensional basin-range block faulting (Fig. 5). Stress release in response to these initial "cracks" produced master faults guided the development of basin-range structure. Tilting may in part progress sequentially from block to block outward, in places for more than 100 km, from an antiformal boundary until it meets a tilt domain progressing in the opposite direction outward from another antiformal boundary. Tilting may have been initiated by the buoyant response of the crustal blocks bounded by the master faults, as first clearly described by F. A. Vening Meinesz (summarized in Heiskanen and Vening Meinesz, 1958, p. 390–393). Sales (1976) noted that because of buoyant effects, tilt blocks form when one fault set is dominant. Continued tilting may be driven by continued extension at depth.

The development of a master set of uniformly inclined faults could also be due in part to gravitational forces related to differences in elevation. In this case, master faults would be inclined in the downslope direction. An inconsistent relation of tilt direction and present-day regional slopes, however, does not support this interpretation. Regional topography during initial development of basin-range structure could have differed from present-day topography and contributed in part to the development of regionally consistent tilt domains.

The tilt pattern does not seem to be related to a complex convection system (Proffett, 1977) directly below the fragmenting upper crust. Such a system would apparently require diverging currents at each antiformal boundary and would likely produce a major rift zone at each such boundary. Such major rift zones are not evident in the Basin and Range Province.

The transverse boundaries mark the margins of major subsystems in the fragmenting upper crust. In New Mexico, these boundaries locally follow major tectonic flaws in Precambrian crystalline basement rocks that apparently served as planes of weakness for late Cenozoic displacement (C. E. Chapin, 1978, oral commun.). In Nevada and Utah, however, the transverse boundaries do not correspond, except along certain relatively short segments, to older tectonic trends, and the transverse boundaries apparently developed largely across older tectonic features and entirely in response to the late Cenozoic stress field. Each of the transverse boundaries in Nevada and Utah may mark the northern limit of basin-range structure during a specific time period in the late Cenozoic. As mentioned above, basin-range structure apparently first developed in Arizona and California and then shifted north into Nevada and Utah, perhaps in response to the northern migration of Mendocino triple junction (Atwater, 1970). This northward shift may have occurred in discrete jumps with each transverse boundary marking the progressive northward shift in the province.

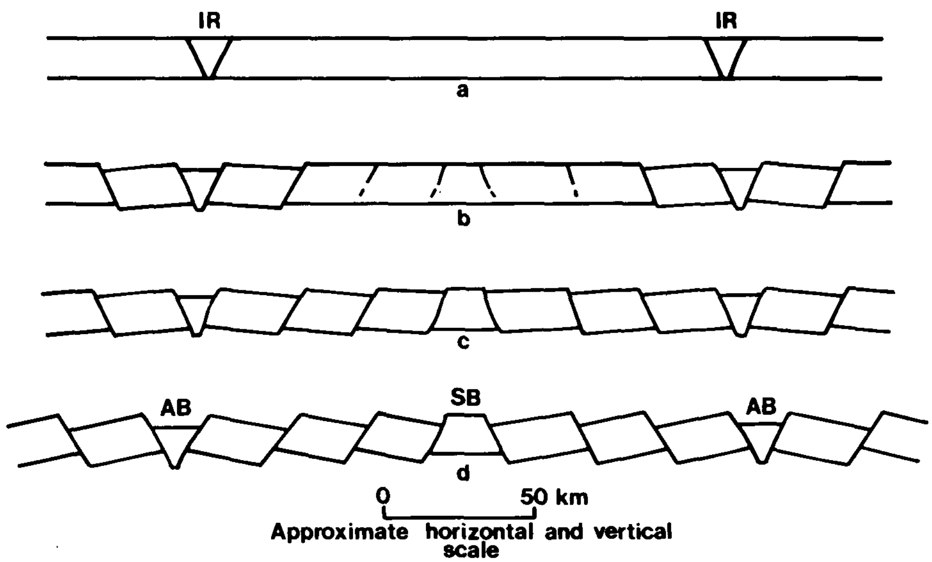

Figure 5. Sequence of development (a, b, c, d) of tilted basin-range fault blocks. Shown in terms of tilted block model; a similar diagram can be constructed using the listric fault model. IR, initial rupture; AB, antiformal boundary; SB, synformal boundary.

In this scheme, the Brothers fault zone in Oregon, which marks the northern limit of well-defined basin-range structure (Lawrence, 1976), is the present-day analog of the transverse boundaries.

The initial sites of rupture that produced basin-range block faulting, if such sites are indeed located at antiformal boundaries, were in some places medial to the region undergoing extension, but in other places, near the margins. This relation is evident in Nevada and Utah where a major antiformal boundary occurs medially in the province between the southern two major transverse boundaries, but farther north occurs near the margins of the province. The position near the margins seems particularly significant, because in these regions much of the entire Basin and Range Province is included between the suggested initial sites of rupture. Thus, the development of basin-range structure, if the interpretations described above are correct, is not related simply to an outward migration or restriction of tectonic activity toward the margins of the province, as proposed by Scholz and others (1971) and Christiansen and McKee (1978).

ACKNOWLEDGMENTS

Dann C. Johannesen helped prepare the map showing regional tilt patterns, and many of my colleagues helped by indicating sources of data. My ideas were stimulated considerably by conversations with C. E. Chapin, G. P. Eaton, J. G. Moore, W. A. Rehrig, A. H. Lachenbruch, and M. L. Zoback. The manuscript was reviewed by C. E. Chapin, G. P. Eaton, J. C. Moore, W. A. Rehrig, G. A. Thompson, and M. L. Zoback.

REFERENCES CITED

Anderson, R. E., 1971, Thin skin distension in Tertiary rocks of southeastern Nevada: Geological Society of America Bulletin, v. 82, p. 43–58.

Anderson, R. E., and Ekren, E. B., 1977, Late Cenozoic fault pattern and stress field in the Great Basin and westward displacement of the Sierra Nevada block — Comment: Geology, v. 5, p. 388–389.

Atwater, Tanya, 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, no. 12, p. 3513–3535.

Chapin, E. C., and others, 1978, Exploration framework of the Socorro geothermal area, New Mexico: New Mexico Geological Society, Special Publication 7, p. 115–129.

Christiansen, R. L., and McKee, E. H., 1978, Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia Intermontane regions, *in* Smith, R. B., and Eaton, G. P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 283–311.

Davis, G. H., and Coney, P. J., 1979, Geologic development of the Cordilleran metamorphic core complexes: Geology, v. 7, p. 120–124.

Eaton, G. P., 1980, Geophysical and geological characteristics of the crust of the Basin and Range Province, *in* Burchfiel, B. C., Silver, L. T., and Oliver, J. E., eds., Continental structure and evolution: National Academy of Science, National Research Council Studies in Geophysics (in press).

Ekren, E. B., and others, 1976, East-trending structural lineaments in central Nevada: U.S. Geological Survey Professional Paper 986, 16 p.

Gilbert, C. M., and Reynolds, M. W., 1973, Character and chronology of basin development, western margin of the Basin and Range Province: Geological Society of America Bulletin, v. 84, p. 2489–2510.

Heiskanen, W. A., and Vening Meinesz, F. A., 1958, The Earth and its gravity field: New York, McGraw-Hill Book Company, Inc., 470 p.

Howard, E. L., 1976, A paleostructural interpretation of the eastern Great Basin portion of the Basin and Range Province, *in* Hill, J. G., ed., Geology of the Cordilleran hingeline: Rocky Mountain Association of Geologists, p. 47–58.

Hunt, C. B., and Mabey, D. R., 1966, General geology of Death Valley, California — Stratigraphy and structure: U.S. Geological Survey Professional Paper 494-A, p. A1–A165.

Lawrence, R. D., 1976, Strike-slip faulting terminates the Basin and Range Province in Oregon: Geological Society of America Bulletin, v. 87, p. 846–850.

Morton, W. H., and Black, R., 1975, Crustal attentuation in Afar, *in* Pilger, A., and Rösler, A., eds., Afar depression of Ethiopia, Inter-Union Commission on Geodynamics: International Symposium on the Afar Region and Related Rift Problems, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany, Proceedings, Scientific Report No. 14, p. 55–65.

Proffett, J. M., Jr., 1977, Cenozoic geology of the Yerington district, Nevada, and implications for the nature and origin of Basin and Range faulting: Geological Society of America Bulletin, v. 88, p. 247–266.

Rehrig, W. A., and Heidrick, T. L., 1976, Regional tectonic stress during the Laramide and late Tertiary intrusive periods, Basin and Range Province, Arizona, *in* Wilt, J. C., and Jenney, J. P., eds., Tectonic digest: Arizona Geological Society Digest, Tucson, Arizona, v. 10, p. 205–228.

Rowley, P. D., and others, 1978, Blue Ribbon lineament, an east-trending structural zone within the Pioche mineral belt of southwestern Utah and eastern Nevada: U.S. Geological Survey Journal of Research, v. 6, no. 2, p. 175–192.

Sales, J. K., 1976, Model studies of continental rifting: Geological Society of America Abstracts with Programs, v. 8, no. 6, p. 1083.

Scholz, C. H., Barazangi, M., and Sbar, M. L., 1971, Late Cenozoic evolution of the Great Basin, western United States, as an ensialic interarc basin: Geological Society of America Bulletin, v. 82, p. 2979–2990.

Slemmons, D. B., 1967, Pliocene and Quaternary crustal movements of the Basin and Range Province, USA, *in* Sea level changes and crustal movements of the Pacific: Pacific Science Congress, 11th, Tokyo, 1966, Symposium 19: Osaka City University, Journal of Geosciences, v. 10, article 1, p. 91–103.

Stewart, J. H., 1978, Basin and range structure in western North America — A review, *in* Smith, R. B., and Eaton, G. P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 1–31.

Stewart, J. H., and Johannesen, D. C., 1979, Map showing regional tilt patterns of late Cenozoic basin-range fault blocks in western United States: U.S. Geological Survey Open-File Report 79-1134, scale 1:2,500,000.

Thompson, G. A., 1960, Problems of late Cenozoic structure of the basin ranges: International Geological Congress, 21st, Copenhagen, part 18, p. 62–68.

Wright, L. A., and Troxel, B. W., 1973, Shallow-fault interpretation of basin and range structure, southwestern Great Basin, *in* de Jong, K. A., and Scholten, Robert, eds., Gravity and tectonics: New York, John Wiley & Sons, p. 397–407.

Zoback, M. L., and Thompson, G. A., 1978, Basin and range rifting in northern Nevada: Clues from a mid-Miocene rift and its subsequent offsets: Geology, v. 6, no. 2, p. 111–116.

MANUSCRIPT RECEIVED BY THE SOCIETY JULY 2, 1979
REVISED MANUSCRIPT RECEIVED OCTOBER 10, 1979
MANUSCRIPT ACCEPTED DECEMBER 13, 1979