Historical Review of Earthquake-Related Studies and Seismographic Recording in Utah

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3. Historical Review of Earthquake-Related Studies and Seismographic Recording in Utah

by Walter J. Arabasz

This discussion attempts to present an informative overview of the evolution of earthquake studies in Utah leading up to the present. The review is not exhaustive but contains references to most of the pertinent studies to which the reader may wish to refer.

Early Historical Period, 1850 to 1937

For the period prior to settlement of Utah's Wasatch Front area in 1847 by Mormon pioneers, no reliable accounts have been recorded (to our knowledge) of earthquakes felt by earlier Indians or trappers. Williams and Tapper (1953) provided the first thorough documentation of earthquakes in the Utah region dating to 1850, the year of publication of the first newspaper in Utah (The Deseret Weekly). Williams and Tapper's (1953) catalog of felt earthquakes in Utah for the period 1850-1949, based on their comprehensive study of non-instrumental earthquake records--including earlier catalogs such as that of Townley and Allen (1939)--remains a valuable summary. (The most complete historical catalog available is that prepared for section 8 of this volume.) Significant earthquakes identified elsewhere in the Intermountain area during the same period are summarized in Coffman and von Hake's (1973) "Earthquake History of the United States."

Early Instrumental Recording. Seismographic recording in the State of Utah began in 1907 with the installation of seismographs on the University of Utah campus in Salt Lake City. The instruments operated at a very low magnification, and most of the early records have been lost or destroyed, so that the value of the existing records chiefly relates to major earthquakes outside the Intermountain area. Thus the non-instrumental catalog of Williams and Tapper (1953) must still be relied on for the systematic identification of local earthquakes in Utah after 1907, and indeed through 1949.

Dr. James E. Talmage (Figure 3-1), President of the University of Utah from 1894 to 1897 and the first Deseret Professor of Geology (from 1894 to 1907), motivated the introduction of seismology to the University of Utah. After assuming leadership of the Department of Geology in 1897, he persistently recommended the installation of seismographic equipment (as indicated by an entry in his personal journal on June 29, 1907 [Brigham Young University Archives and Manuscripts]). Justification for such equipment was noted in the "Biennial Report of the President of the University of Utah to the Board of Regents" dated December 23, 1902. Two biennial reports later on December 12, 1906, it was again argued that:

Utah State Historical Society

Fig. 3-1. Dr. James E. Talmage in office on University of Utah campus, about 1904.

Salt Lake Tribune: June 30, 1907

Fig. 3-2. Dr. James E. Talmage with Bosch-Omori seismographs on University of Utah campus, 1907.

"It is important that facilities be provided the University for making correct observations on earthquakes and for recording the seismic disturbances which take place occasionally in this inter-mountain region. The professor of geology [James E. Talmage] is called upon from time to time for his opinion regarding these very important disturbances, as well as respecting other geological questions, and therefore he should be provided with the necessary quarters and instruments for the making of the proper observations."

In July 1907 Talmage resigned his position of professor at the University to devote more time to geological consulting and to duties for the Church of Jesus Christ of Latter-day Saints. Before his leaving the University, however, years of persistence were rewarded (Talmage, 1972):

"One of Dr. Talmage's last official acts as professor of geology was to fulfill a long-held ambition and direct the installation of a seismograph on the University of Utah campus. The installation was completed June 29, 1907, and extensively discussed in all of the Salt Lake City newspapers. The earthquake-detecting instrument was the first to be set up in the Mountain West and was one of a comparatively few in the nation and the world at that time."[1]

The "instrument" installed in 1907 (Figure 3-2) technically involved two Bosch-Omori horizontal-pendulum seismographs recording on smoked paper. A pendulum clock provided fairly accurate timing. According to Chamberlin (1960, p. 424), the instruments originally occupied a small room in the basement of the Museum (now the James E. Talmage Building). The low-magnification seismographs operated for nearly three decades until September 1939. Of some 155 preserved records, the earliest is dated March 26, 1908.

Dr. Frederick James Pack (Figure 3-3) succeeded Talmage in 1907 as the Deseret Professor of Geology and as head of the Department of Geology, positions which he held until his death in 1938. During his tenure, a "Seismograph Laboratory Building" was completed in 1935 to house "the University seismograph" (Chamberlin, 1960, p. 424). The small concrete building was constructed with a contribution from the Federal Emergency Relief Administration and still stands on campus south of the John R. Park Building.

Earthquake-related Studies. In terms of early scientific studies relating to Utah earthquakes, the classical geological studies of G. K. Gilbert (1890) and W. M. Davis (1901, 1903) focused attention on major

[1]The earliest seismographs in the United States were installed in 1887 in California by the University of California at Berkeley (Bolt, 1977). Those at Salt Lake City in 1907 were indeed among the earliest in the nation--and part of a generation of instruments installed in the United States in the aftermath of the great San Francisco earthquake of 1906.

Marriott Library, Univ. of Utah

Fig. 3-3. Dr. Frederick J. Pack inspecting recording drum of Bosch-Omori seismograph (ca. 1930?).

Fig. 3-4. Dr. Hyrum Schneider holding photographic recording from McComb-Romberg seismographs.

Salt Lake Telegram: June 10, 1942

faulting in the Wasatch Front area and on youthful fault scarps that clearly manifested the active nature of the Wasatch fault and its potential for generating severe earthquakes. (See Hintze, 1913, for references to early geological studies in Utah.) In a letter to the Salt Lake Tribune on September 16, 1883 (see Gilbert, 1884)[2], Gilbert described for local residents the location of conspicuous fault scarps within the Salt Lake Valley and warned of an eventual catastrophe similar to that of the great 1872 earthquake in Owens Valley on the eastern flank of the Sierra Nevada:

> "It is useless to ask when this disaster will occur. Our occupation of the country has been too brief for us to learn how fast the Wasatch grows; and, indeed, it is only by such disasters that we can learn. By the time experience has taught us this, Salt Lake City will have been shaken down, and its surviving citizens will have sorrowfully rebuilt it of wood; to use a homely figure, the horse will have escaped, and the barn door, all too late, will have been closed behind him."

Damaging earthquakes in Utah in the late 1800's and the early 1900's (such as in the Bear Lake Valley in 1884, near Richfield in 1901, and in Pine Valley north of St. George in 1902) must surely have attracted the attention of local geologists; however, no geological reports seem to have been written. One of the earliest scientific reports on local earthquakes was an oral presentation by Pack (1912)--perhaps also that by Jones (1911) --to the Utah Academy of Sciences. The first notable study to be published on the effects of a Utah earthquake was Pack's (1921) study of the Elsinore earthquake of 1921.

Some publications from the 1920's and early 1930's worth noting include: (1) reports by Schneider (1925), Pack (1926), Bailey (1926), Gilbert (1928), Eardley (1934), and Peterson (1936) relevant to late Quaternary faulting along the Wasatch fault and along the east side of Cache Valley; (2) Gilluly's (1928, 1932) studies of faulting along the west front of the Oquirrh Range; (3) a brief summary of historical earthquakes in Utah by Carlston and Woolley (1934); and (4) a discussion of earthquake-resistant design in structural engineering by Adams (1934).

In May 1933, F. F. Hintze, Associate Professor of Geology at the University of Utah, urged (apparently without success) that a local seismological society be formed "to study Utah earthquakes to determine what may be expected in earth tremors and whether the building code should be changed" (The Salt Lake Telegram, March 12, 1934, p. 1).

The March 1934 Hansel Valley (Kosmo) earthquake, one of the two largest historical earthquakes in Utah (the other: the 1901 Richfield earthquake) catalyzed considerable scientific interest. It also reinforced a

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[2]Gilbert (1884) incorrectly cites the Salt Lake Tribune of Sept. 20, 1883.

general warning made only nine months earlier in Salt Lake City by the eminent geologist Bailey Willis regarding earthquake potential in the Wasatch Front area (The Salt Lake Telegram, March 12, 1934, p. 1). The earthquake produced surface faulting along a zone 8 km long (with up to 0.5 m vertical displacement) and resulted in liquefaction and other ground-water effects (Shenon, 1936). To date, this remains the only documented instance of historic surface faulting in the Utah region. Richter (1935, p. 24) used the Hansel Valley earthquake as an example in defining his magnitude scale, assigning a magnitude of 7.0; the value of 6.6 generally reported (e.g., Coffman and von Hake, 1973; Jones, 1975) is apparently a body-wave or surface-wave magnitude (Gutenberg and Richter, 1954, p. 223). The most complete documentation of the earthquake's effects was made by Shenon (1934, 1935, 1936) of the U.S. Geological Survey. Accounts by other geologists, such as F. J. Pack and H. Schneider of the University of Utah appeared in local newspapers at that time.

More complete documentation of the earthquake's geological and geophysical aspects, including faulting, liquefaction, and seismological characteristics, is now in preparation by R. C. Bucknam and R. B. Smith. Other reports relating to the 1934 earthquake include those by Walter (1934), Taylor (1936), and Adams (1938). Neumann (1936) published an isoseismal map for the mainshock. "The Thomas C. Adams Collection," a collection of photographs and newspaper clippings documenting the 1934 earthquake, is filed in the Special Collections of the Marriott Library, University of Utah (Collection No. P0043, Manuscript No. 43).

The 1934 Hansel Valley earthquake resulted in two deaths--one direct and one indirect (see Cook, 1972, p. H15). To date only three other fatalities in Utah have been attributed to earthquake activity. Three coal miners were killed on July 18, 1957 near Castle Gate, Utah by methane gas released during "a slight earthquake" (Bull. Seism. Soc. Am. 47, p. 400). It is not clear whether this was a rockburst (or "bounce") or a sub-mine earthquake. According to The Sun-Advocate of Price, Utah (July 25, 1957, p. 1): "The men succumbed to gases which escaped from old workings following a heavy bounce which loosened the seals closing off the old entries."

In some respects the 1934 Hansel Valley earthquake was a milestone in Utah seismology because it influenced further development of seismographic instrumentation within Utah and stimulated local attention to earthquake-related problems evident in the following decade.

The Transition Years, 1938 to 1961

Growth of Instrumental Seismology. The period 1938 to 1961 marked a transition in Utah from historical (i.e., based on felt reports) to instrumental seismicity. Cooperative arrangements with the U.S. Coast and Geodetic Survey (USCGS) beginning in 1938 provided for the routine transmission of seismographic data from Salt Lake City to the USCGS for compilation and publication. At the time, there were five other reporting stations in the western United States. In 1939 Professor Hyrum Schneider (Figure 3-4), who succeeded F. J. Pack as Deseret Professor of Geology and Mineralogy, was listed by the USCGS as "in charge" of the Salt Lake seismographic station. Also during 1939, Mr. Andrew M. Anderson (Figure 3-5) acquired the position of "Seismograph Tender" at the Salt Lake station and continued as the station attendant until 1974. Dr. Kenneth L. Cook (Figure 3-6), Professor of Geophysics, assumed administrative responsibility for the station in 1952.

After completion of the "Seismograph Laboratory Building" in 1935, the Bosch-Omori horizontal seismographs were apparently housed there until their operation was discontinued in 1939 (the latest preserved records are dated September 22, 1939). They were replaced by photographically recording McComb-Romberg horizontal seismographs, which began operation May 17, 1939. In June 1954 a vertical-component Wilson-Lamison seismograph was added. Photographic records from the McComb-Romberg and Wilson-Lamison seismographs were routinely forwarded to the USCGS until July 1975.

Another milestone in the history of seismographic recording in Utah was the establishment by Professor J. Stewart Williams of the Oldham Seismograph Station in 1939 at the (then) Utah State Agricultural College in Logan (Williams, 1942). An accelerograph was installed in July 1939, and a two-component Wood-Anderson seismograph began operation January 26, 1940. A Sprengnether vertical-component seismograph was added in 1947. As in the case of the Salt Lake station at this time, the USCGS played an important cooperative role in the operation of the Oldham Seismograph Station, and seismograms were routinely transmitted to the USCGS through 1955. Some recording was temporarily continued on an irregular basis for several years, but few records were preserved.

J. Stewart Williams assisted the USCGS (later NOAA) as the designated "Collaborator in Seismology" for Utah from April 1942 through 1973. This role was earlier filled by Hyrum Schneider, from 1940 to 1942, and later by Kenneth L. Cook, after 1973.

For any period prior to 1962, the only seismograms now available in Utah are some seismograms from the Salt Lake City station on file at the University of Utah.[3] These include (1) the 155 preserved Bosch-Omori seismograms--representing 95 record-days during which some significant world-wide earthquakes between 1908 and 1939 were recorded, and (2) duplicate recordings from the USCGS horizontal-component seismographs after October 16, 1956. The most important instrumental Utah records existing for the pre-1962 period are those sent to the USCGS and now filed in government archives (Federal Record Center) in Washington, D.C. These include seismograms for the Salt Lake City station dating from 1939, seismograms

[3]A small collection of selected seismograms from the Logan station for 1956-1963 may still exist at Utah State University (J.S. Williams, personal communication, 1979.)

Salt Lake Telegram: June 10, 1942

Fig. 3-5. Mr. Andrew M. Anderson changing photographic seismogram at Salt Lake City station on U. of U. campus.

Salt Lake Tribune: March 27, 1976

Fig. 3-6. Dr. Kenneth L. Cook examining map of seismograph stations.

from the Logan station for 1940-1955, and possibly some of the pre-1939 Bosch-Omori records from Salt Lake City. (Instrumental data for some Utah earthquakes between 1916 and 1951 are included in Jones' [1975] compilation of data from Wiechert seismographs at Reno, Nevada.)

In 1950 the USCGS initiated routine epicentral determinations for moderate-size earthquakes (generally larger than about Richter magnitude 3) in the Intermountain area using data from widely spaced regional seismographs. Although there are pre-1950 instrumental epicenters for the Utah region (see section 8), chiefly located by the Caltech Seismological Laboratory in Pasadena, most early data reported to the USCGS were generally inadequate for earthquake locations in this area. The earliest reported instrumental epicenters are for the March 1934 Hansel Valley (Kosmo) earthquake and its aftershocks (Neumann, 1936; Gutenberg and Richter, 1954; Dewey et al., 1973; Jones, 1975). Between 1950 and 1962, instrumental locations were not systematically complete for the Utah region and the documentation of felt earthquakes continued to be important in compiling a Utah earthquake catalog (e.g., Cook and Smith, 1967; see also section 8).

Earthquake-related Studies. For the period 1938 to 1961, earthquake-related studies in Utah involved contributions in the following general categories: (1) seismicity summaries and early tectonic overviews, (2) studies of the macroseismic effects of felt and damaging earthquakes, (3) earthquake hazards of the Wasatch fault zone, and (4) seismic investigations of crustal structure.

Both Heck (1938) and Williams (1942) presented overviews of Utah's seismicity and its relation to regional geologic structure and active faulting. On a regional scale, the Intermountain area is encompassed in Woolard's (1958) study of seismicity and tectonics of the U.S. The most important summary of Utah seismicity during this period is that completed by Williams and Tapper (1953) for 1850 to 1949.

Studies of felt or damaging earthquakes during the period 1938 to 1961 were reported by: Williams (1943), for a 1943 earthquake within the Salt Lake Valley; Berg and Resler (1958), for a 1958 earthquake near Wallsburg; Hardy and Gaeth (1959), for a 1953 earthquake near Lehi; Hardy (1959), for a 1955 earthquake beneath Salt Lake City; Berg (1960), for earthquakes near Nephi in late 1958; and Algermissen and Cook (1962), for the Ephraim earthquake of 1961.

For nearly four decades until his death in 1971, R. E. Marsell of the University of Utah was notably influential in stimulating attention to earthquake hazards along the Wasatch Front. For the pre-1962 period, his systematic studies of the Wasatch fault zone near Salt Lake City (Marsell, 1946, 1953) are worth noting. Studies of the Wasatch Front area by one of Utah's eminent geologists, A. J. Eardley (e.g., Eardley, 1933, 1934, 1939, 1944), contributed significantly to an understanding of the Wasatch fault's geologic history, but Eardley did not explicitly focus on the fault's most recent history (and earthquake potential) as did Marsell. Eardley's meticulous mapping, however, indicates his careful attention to active faulting--as, for example, his map of the southern Wasatch fault (Eardley, 1934). Christiansen's (1952) description and discussion of young fault scarplets within Scipio Valley is also worth noting in this regard.

During the late 1950's seismological studies by researchers at the University of Utah chiefly involved seismic studies of crustal structure and wave propagation from explosions. Extensive efforts were being made at the time to map both regional and local crustal structure within the Utah region using various geophysical techniques. Also, the initiation of underground nuclear testing in 1957 in southern Nevada fostered studies involving the propagation of seismic waves from these blasts. Some representative studies for this period through 1961 at the University of Utah are cited by Berg et al. (1960) and by Cook and Smith (1967).

Modern Seismology and Network Recording, 1962 to 1978

Network Recording and Other Instrumentation. The year 1962 marked the beginning of a new era of seismographic recording and monitoring of local earthquakes in Utah. Under the direction of Dr. Kenneth L. Cook, Professor of Geophysics and (then) Head of the Department of Geophysics[4] at the University of Utah, the first three of the "University of Utah Seismograph Stations" began continuous operation. Three-component, short-period Benioff seismographs were installed: (1) at the Salt Lake station (SLC) in April 1962, (2) at Dugway, Utah (DUG), in May 1962, and (3) at Price, Utah (PCU), on the campus of Carbon College (now the College of Eastern Utah), also in May 1962. The University of Utah Board of Regents formally recognized the University of Utah Seismograph Stations as an entity in April 1966 in confirming the appointment of K. L. Cook as its first Director,[5] a position he held until June 1976.

The expansion of seismograph stations in Utah in the 1960's reflected on a local scale one of the major developments in the history of United States seismology that occurred following 1959--project Vela-Uniform (aimed at the detection and identification of underground nuclear explosions) and the establishment of the World-Wide Standardized Seismograph Network (WWSSN). The Dugway station was installed in cooperation with the USCGS as part of this world-wide network.

Between 1962 and 1973, K. L. Cook motivated the addition of other stations to the Utah network (see section 5 for more complete documentation of dates, instrumentation, and locations; see Cook [1974] for identification of sources of funding for the various stations). In December

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[4]Formed in 1952 and combined in 1968 with the Department of Geology into the current Department of Geology and Geophysics.
[5]Minutes of the Board of Regents, April 11, 1966. (See also Utah Geological and Mineralogical Survey Quarterly Review 1(8), 1966, p. 12.)

1963 cooperative arrangements were made with Dr. J. Stewart Williams, and later Dr. Clyde T. Hardy, of Utah State University for operation of the Logan (LOG) seismograph station. Next, a station was installed in Cedar City, Utah (CCU), on the campus of the College of Southern Utah in late 1968 with the cooperation of Dr. Harl E. Judd.

In 1970 three stations were added. In April 1970 the University of Utah assumed operation of the Uinta Basin Seismological Observatory (UBO) in northeastern Utah that continued until 1973. Management of the Flaming Gorge, Utah (FGU), station was assumed from the Bureau of Reclamation in July 1970. In August 1970, a station began operation within the Granite Mountain Records Vault (GMU) southeast of Salt Lake City in Little Cottonwood Canyon. Telephone telemetry of seismic signals from GMU to the University of Utah campus marked the first recording of telemetry signals from an unattended seismic station in the state. Another unattended station was installed at West Mountain, Utah (WMU), at the southern end of Utah Lake, in December 1973; signals were relayed to the University of Utah campus via radio telemetry. Thus the University of Utah Seismograph Stations formed a skeletal state-wide network of several independently recording stations during the 1960's, and in the early 1970's the important innovation of centrally recording signals from remote telemetered stations had been made.

Some other developments in instrumentation during the 1960's are worth noting. Wood-Anderson-type torsion seismographs (standard reference instruments for the Richter magnitude scale) were installed at PCU in May 1962 and at DUG in September 1963. Also, operation of the original Wood-Anderson seismographs at LOG was resumed in February 1964. Records from these instruments allow the important calibration of magnitudes for Utah local earthquakes since 1962 (see Griscom and Arabasz, this volume). Quartz-tube strainmeters were installed in the Granite Mountain Records Vault in October 1967 as the first step in developing a facility to continuously monitor local earth deformation (Cook, 1972). By late 1970 the facility included a three-component strainmeter, a tripartite mercury tiltmeter, and a three-component, short-period seismograph station.

The development and use of portable, high-magnification seismographs for recording microearthquakes (i.e., small earthquakes less than magnitude 3) also became important in the 1960's. Scientists from Stanford Research Institute were among the first to use such portable seismographs in Utah (Westphal, 1963; Westphal and Lange, 1966a,b). Vigorous involvement by the University of Utah in portable microearthquake instrumentation began in 1969 (see Smith, 1972) and greatly expanded in the following years, as discussed below.

The most significant modernization to date of earthquake recording in the Utah region began in 1974 through research grants to R. B. Smith, K. L. Cook, and S. H. Ward. Beginning in that year regional arrays of high-magnification, short-period telemetry stations were initiated for continuous microearthquake monitoring (discussed at length in sections 4 and 5). Professor S. H. Ward, Chairman of the Department of Geology and

Geophysics encouraged the development of the seismological research efforts and helped pave the way for future growth. By late 1978, signals from nearly 60 stations--widespread between Yellowstone National Park on the north and the Utah-Arizona border on the south--were being telemetered continuously to the University of Utah campus for central recording.

Funding for these facilities has come primarily from federal grants and contracts awarded to individual research scientists at the University of Utah: R. B. Smith, W. J. Arabasz, S. H. Ward, and K. L. Cook (Figures 3-7 to 3-9). In addition to continuing support from the State of Utah, funds have been provided by the U.S. Geological Survey (for studies of earthquake hazards and earthquake prediction along the Wasatch Front), the National Science Foundation (for studies of the regional seismicity and tectonics of the Intermountain seismic belt), and the Department of Energy (for studies of geothermal areas).

The modern University of Utah telemetered seismic network is thus a combination of discrete, diversely-funded sub-arrays. Cooperative arrangements allow the routine integration of all seismic data recorded by the University of Utah--including data from some of the original non-telemetry stations--for locating earthquakes throughout Utah and in neighboring states. Operational information for various stations of the University of Utah network during the 1970's is summarized in section 5.

Modern Seismology and Earthquake-related Studies Since 1962. The task of reviewing earthquake-related studies in Utah becomes a major one for the post-1962 period because of the extensive work done by a host of workers. Appendices A, B, and C provide useful summaries of work carried out at the University of Utah; Appendix D lists some pertinent studies of the Utah Geological and Mineral Survey. For convenience, we can consider post-1962 studies in several general categories--marking with an asterisk those references listed in Appendix B.

Just as the Vela-Uniform Program had spurred seismology a decade earlier, three developments had similar effects in the late 1960's and early 1970's: (1) active testing of the new concepts of plate tectonics, (2) intensified interest in earthquake prediction, and (3) federal commitment to reducing earthquake hazards. Much of the current earthquake-related research in Utah is an outgrowth of these developments.

General Seismicity of Utah. Since 1962, various summaries of Utah seismicity have been published by workers at the University of Utah[6] (see Appendix C), including a general review by Marsell (1966a) and Cook and Smith's (1967) major documentation of Utah earthquakes through mid-1965. Cook (1972) and Smith (1972) reviewed the seismicity of the Wasatch Front through 1970, and Smith (1974*) updated the review through 1974 (see also Arabasz et al., this volume, and Smith, 1978*). The earthquake history of Utah has also been summarized by the U.S. Geological Survey (1976, p. 8-22) and by von Hake (1977).

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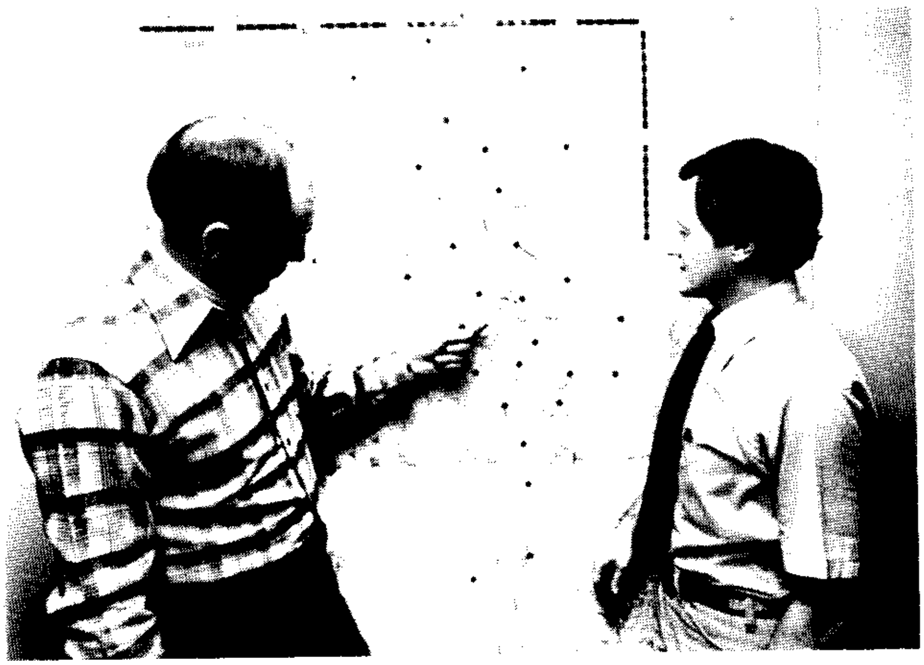
[6]The data of section 8 supersede all previously published catalogs.

Daily Utah Chronicle: Jan 21, 1974

Fig. 3-7. Drs. K. L. Cook (left) and R. B. Smith (right) examining calibration signals on helicorder.

Univ. of Utah Public Relations

Fig. 3-8. Dr. Stanley H. Ward operating interactive terminal in computer laboratory.



Univ. of Utah Review: Jan. 1978

Fig. 3-9. Drs. Robert B. Smith (left) and Walter J. Arabasz (right) with map of Univ. of Utah telemetered seismic network.

Regional Seismicity, Microseismicity, and Tectonics. Utah's geographic location--encompassing boundaries between three major physiographic provinces (Basin and Range, Middle Rocky Mountains, and Colorado Plateau)--and the central location of Salt Lake City within the Intermountain seismic belt have naturally fostered intense interest at the University of Utah in the regional seismicity and tectonics of the Intermountain west. For the best available introduction to the scientific problems involved, I refer the reader to Memoir 152 newly published by the Geological Society of America (Smith and Eaton, editors, 1978*).

The coherence of an extensive northward-trending earthquake belt through the Intermountain area had been noted by Heck (1938) and Woolard (1958) (see also Eardley, 1962, p. 505). Ryall et al.(1966) analyzed this belt as the "Rocky Mountain seismic zone." The earthquake belt is well defined in Barazangi and Dorman's (1969) global seismicity map of shallow earthquakes and was first called the "Intermountain Seismic Belt" in joint abstracts published by Sbar and Barazangi (1970) and Smith and Sbar (1970*). Subsequent papers by Sbar et al. (1972) and Smith and Sbar (1974*) extensively discussed the seismicity and tectonics of the Intermountain seismic belt forming the framework for a host of follow-up papers by R. B. Smith and students at the University of Utah, particularly involving results of regional microearthquake studies and studies of the Yellowstone region (see Smith, 1977*, 1978*; see also Appendix A). Smith (1978*) gives a new summary of the regional seismicity, tectonics, and earthquake hazards of the Intermountain region. The tectonics of the Basin and Range province was discussed by Cook (1966*, 1970a*).

Post-earthquake Studies of Aftershocks and Macroseismic Effects. Information from post-earthquake studies is available for several moderate-to-large earthquakes in the Utah region since 1962 in addition to that routinely published by the USCGS in their annual "United States Earthquakes." Focal mechanisms for the largest shocks between 1962 and 1970 were published by Smith and Sbar (1974*) and a new compilation for the western United States, including Utah, is given by Smith and Lindh (1978*).

Stanford Research Institute used portable seismographs to study aftershocks of the magnitude (M_L) 5.7 Cache Valley (Logan) earthquake of August 30, 1962 (Westphal and Lange, 1966a,b). Cook (1972) discussed effects of the earthquake, and Lander and Cloud (1964) published an isoseismal map of the mainshock. Six days after the 1962 Cache Valley earthquake a magnitude (M_L) 5.2 earthquake occurred near Magna, Utah, within the Salt Lake Valley, but went largely unstudied because of attention to the Cache Valley event. Lander and Cloud's (1964) summary of non-instrumental studies of the Magna earthquake is the best available.

Effects of the magnitude (M_L) 4.4 Juab Valley, Utah, earthquake of July 8, 1963, and its isoseismal map were discussed by Cook (1972) together with aftershock data from Westphal (1963) and Westphal and Lange (1966b). A magnitude (M_L) 5.6 earthquake occurred on August 16, 1966, in southeastern Nevada close to the Utah border. An isoseismal map was published by von Hake and Cloud (1968), and a University of Utah M.S. thesis was completed by

P. J. Beck (see Appendix A) on the mainshock and its associated earthquake sequence. An isoseismal map for the magnitude (M_L) 5.2 Marysvale, Utah, earthquake of October 4, 1967, was published by von Hake and Cloud (1969).

After 1969, portable seismographs became available at the University of Utah for studies of aftershocks and detailed seismicity. The first important study was a 1970 investigation of the seismicity and possible earthquake induction mechanism of coal mining in the Sunnyside area, Carbon County, Utah (Smith et al., 1974b*). Technical contributions in the third part of this volume related to field studies of (1) an earthquake swarm near Cedar City, Utah in November 1971; (2) aftershocks of the magnitude (m_b) 4.7 Heber City, Utah earthquake of October 1, 1972; (3) aftershocks of the magnitude (m_b) 6.1 Idaho-Utah border (Pocatello Valley) earthquake of March 28, 1975; and (4) aftershocks of a magnitude (M_L) 4.0 earthquake in Hansel Valley, Utah on November 5, 1976.

Available information on the March 1975 Idaho-Utah border earthquake is summarized by Arabasz et al. in section 12 of this volume. Descriptions of macroseismic effects of the mainshock were presented by Cook and Nye (1975*, also this volume), Kaliser (1975, 1976a) and Coffman and Stover (1977).

Another earthquake for which post-mainshock studies were carried out was a magnitude (M_L) 4.4 earthquake in Duchesne County, Utah, on September 30, 1977. Preliminary results of an aftershock study were reported by Carver et al. (1978); macroseismic effects of the shock are discussed by Cook in section 20 of this volume.

Studies of Earthquake Hazards and Active Faulting. Several papers relating to earthquake hazards of the Wasatch Front area were published by Marsell (1964a,b,c; 1966a,b; 1969) during the 1960's. Cook (1970b*) reviewed earthquake hazards in Utah for a 1967 "Governor's Conference on Geologic Hazards in Utah." Certainly one of the most significant steps toward a comprehensive analysis of geologic hazards in Utah was the publication of "Environmental Geology of the Wasatch Front, 1971" (Utah Geol. Assoc. Publ. 1, 1972). Contributions in this volume directly relevant to the Wasatch fault zone include those by Morisawa (1972), Van Horn (1972a), Hintze (1972), and Cluff and Slemmons (1972); the earthquake-related contributions by Cook (1972) and Smith (1972) have already been mentioned.

L. S. Cluff and his colleagues have been notably active in geological studies of the Wasatch fault zone for earthquake-hazard evaluation. Their work has involved: (1) systematic mapping of the fault zone (Cluff et al., 1970, 1973, 1974) using low-sun-angle photography (Cluff and Slemmons, 1972); (2) evaluation of the recent history of the fault (Cluff et al., 1975); and, most recently, (3) detailed work at specific sites to quantitatively determine recurrence intervals of surface faulting (Woodward-Clyde Consultants, 1975; Swan et al., 1978); further work is in progress.

Geologists of the U.S. Geological Survey have become extensively involved in studies of active faulting and earthquake hazards in Utah. R. C. Bucknam and R. E. Anderson have been involved in on-going studies of late Quaternary and Holocene faulting (Bucknam, 1977; Anderson, 1978;

Bucknam and Anderson, 1979a,b; Anderson and Bucknam, 1979). R. Van Horn has published studies near Salt Lake City of faulting (Van Horn, 1972a,b) and of inferred ground stability during earthquakes (Van Horn, 1975). Related work by W. E. Scott and R. D. Miller in the Wasatch Front area is summarized in Summaries of Technical Reports, Volume VII of the U.S. Geological Survey's National Earthquake Hazards Reduction Program. Other work by the U.S. Geological Survey is discussed below in the next category (see also U.S. Geological Survey, 1976).

Other pertinent studies of earthquake hazards in the Wasatch Front area include (1) that of Smith (1974*), which reviews a spectrum of local earthquake hazards; (2) Parry's (1974*) paper on liquefaction (see also thesis abstract by B. W. Buck in Appendix A, and Earthquake Information Bull. 8, 1976, p. 16-17); (3) Hamblin's (1976) study of patterns of displacement along the Wasatch fault, (4) Kaliser's (1976b) investigation of earthquake hazards posed by combustible gas along the Wasatch Front; and (5) the paper by Arabasz et al., in section 9 of this volume. (See also Appendix D for relevant publications of the Utah Geological and Mineral Survey.)

Earthquake Engineering and Strong-Motion Seismology. Until recently, few studies in earthquake engineering and strong-motion-seismology had been made in the Utah region--other than those completed by private engineering consultants. The only accelerogram available for a sizeable local earthquake remains the three-component record from the August 30, 1962 Cache Valley (Logan) earthquake (M_L = 5.7) recorded at Utah State University in Logan (Lander and Cloud, 1964). Probabilistic estimates of ground acceleration for the Utah region have been made by Algermissen and Perkins (1973, 1976). Estimates of stress conditions, ground acceleration, and relationships of mining patterns to induced earthquakes and rockbursts in the local mines of Carbon County were given by Smith et al. (1974*). Effects on local structures from postulated large earthquakes in the Wasatch Front area have been estimated by the U.S. Geological Survey (1976). King and Hays (1977) used aftershocks of the March 1975 Idaho-Utah border earthquake to investigate seismic attenuation in northern Utah. Studies of ground response in the Salt Lake City area have been completed by Hays et al. (1978); as part of the same general study, Wong (this volume) analyzed the site amplification of shear waves in the Salt Lake Valley.

Earthquake Prediction. Serious studies of the feasibility of earthquake prediction in the Utah region began about 1974 under the sponsorship of the U.S. Geological Survey's National Earthquake Hazards Reduction Program. Progess of work at the University of Utah has been reported in the semi-annual "Summaries of Technical Reports" published by the U.S. Geological Survey, Office of Earthquake Studies, Menlo Park, California. To date, no genuine prediction has been made for any earthquake in the Utah region, and local studies are still in the realm of "feasibility research." (Multidisciplinary instrumentation comparable to that now deployed, for example, in California, Japan, China, and the U.S.S.R. for earthquake prediction has not yet been available in Utah.)

General areas of earthquake-prediction research in Utah have included: (1) monitoring of local quarry blasts for temporal variations in seismic velocity before local earthquakes (Smith et al., this volume; Gaiser and Smith 1977*, see also thesis abstracts of R. E. Estill and J. E. Gaiser, Appendix A): (2) searches for premonitory variations in seismic characteristics (Arabasz and Richins, 1976*; Arabasz, 1977*), (3) analysis of space-time patterns of Utah seismicity for long-term forecasting (Arabasz and Griscom, 1978*); (3) active seismic experiments across earthquake-generating zones (Zandt et al., in prep.); and (4) analyses of temporal variations in earth-tide amplitudes, strain and tilt measurements, water flow, and radon emanation in the Granite Mountain Records Vault near Salt Lake City (e.g., Cook, 1972: Cook and Anderson, 1972*; Hamtak and Cook, 1975*; Sobczyk et al., 1978*; see also thesis abstracts by J. M. Anderson, F. J. Hamtak, R. K. Nye and S. M. Sobczyk, Appendix A).

Crustal Structure and Theoretical Seismology. Although not simply earthquake-related, extensive studies have been made since 1962 at the University of Utah in crustal seismology and signal processing. Results of these studies contribute importantly to the accurate location of local earthquakes and the interpretation of their seismic records. Numerous references are contained in Appendices A and B. In general, this includes the work of J. W. Berg, Jr., K. L. Cook, J. K. Costain, S. T. Algermissen, and others during the 1960's, and the studies of R. B. Smith (and his students), L. Braile, and G. R. Keller--involving modern techniques of seismic-refraction analysis--during the 1970's.

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[7] See also Van Horn (1977). Computer composite map showing inferred relative stability of the land surface during earthquakes, Sugar House Quadrangle, Salt Lake County, Utah, U.S. Geol. Surv. Map I-766-O.