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Contemporary seismicity, faulting, and the state of stress in the Colorado Plateau

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ABSTRACT

The contemporary seismicity of the Colorado Plateau based on seismic monitoring in the past 30 yr can be characterized as being of small to moderate magnitude, and contrary to earlier views, of a low to moderate rate of occurrence with earthquakes widely distributed. Concentrations of earthquakes have been observed in a few areas of the plateau. The most seismically active area of the Colorado Plateau is the eastern Wasatch Plateau–Book Cliffs, where abundant small-magnitude seismicity is induced by coal mining. The largest earthquakes observed to date, of estimated Richter magnitude (M_L) 5–6, have generally occurred in northern Arizona. Although very few earthquakes can be associated with known geologic structures or tectonic features in the Colorado Plateau, seismicity appears to be the result of the reactivation of pre-existing faults lacking surficial expression but favorably oriented to the tectonic stress field. The small to moderate size of the earthquakes and their widespread distribution are consistent with a highly faulted Precambrian basement and upper crust, and a moderate level of differential tectonic stress. Earthquakes in the plateau generally occur in the upper crust from the near-surface to a depth of 15–20 km, although events have been observed in both the lower crust and uppermost mantle in areas of low to normal heat flow. The latter suggests that temperatures are sufficiently low at these depths that brittle failure and hence earthquakes are still possible. The predominant mode of tectonic deformation within the plateau appears to be normal faulting on northwest- to north-northwest-striking faults with some localized occurrences of strike-slip faulting on northwest- or northeast-striking planes at shallow depths. The contemporary state of stress within the plateau is characterized by approximate northeast-trending extension in contrast to the previous belief that the plateau was being subjected to east-west tectonic compression. One area of the plateau, the eastern Wasatch Plateau and Book Cliffs, may still be characterized by compressive stresses; however, the nature of these stresses is not well understood.

INTRODUCTION

The Colorado Plateau in the western United States (Fig. 1) has attracted geologists since the 1800s because the geologic past has been readily revealed by the excellent bedrock exposures, the diversity of geologic structures, and the textbook stratigraphy. Few seismologic and seismotectonic investigations, however, have been conducted until recently, partly due to the belief that the plateau was nearly seismically quiescent and that no large earthquakes had occurred within the plateau in modern times. These observations, however, were based upon a historical earthquake record that was incomplete because of the sparse population, the relatively recent settlement of the region, and inadequate seismographic coverage prior to the 1960s.

In the early 1960s, seismographic coverage of the Colorado Plateau as well as much of the western United States improved greatly, due principally to the beginning of the Worldwide Standardized Seismograph Network. Several stations were installed within the intermountain United States, including the first seismographic station within the plateau established by the U.S. Bureau of Reclamation (USBR) at the proposed Glen Canyon dam (GCA) in 1958 (Fig. 2). These stations provided the capability to locate all moderate-size earthquakes (Richter magnitude $M_L \geq 4$) occurring within the Colorado Plateau. In the 1970s, seismographic coverage of the plateau's margins improved significantly with the installation of regional networks by the University of Utah Seismograph Stations (UUSS), the Los Alamos National Laboratory (LANL), and the USGS Albuquerque Seismological Laboratory (ASL) (Fig. 2). Despite the additional network coverage, however, detection of earthquakes smaller than M_L 2 within the plateau interior improved only slightly. This paper presents the results of the first major program of seismographic studies performed within the Colorado Plateau. This program, initiated by Woodward-Clyde Consultants (WCC) in 1979, included an extensive program of microearthquake monitoring. The results of these studies, combined with those of other recent studies to be discussed, allow a comprehensive characterization not heretofore possible of the contemporary seismicity, faulting, and state of stress of the Colorado Plateau.

GEOLOGIC AND TECTONIC SETTING

The Colorado Plateau has been characterized as a relatively coherent uplifted crustal block surrounded on three sides by the extensional block-faulted regime of the Basin and Range province and the Rio Grande rift (Thompson and Zoback, 1979) (Fig. 1). Geologic evidence attests to a lack of major crustal deformation in the plateau at least since the end of the Laramide orogeny 40 m.y. ago. Asymmetric basement uplifts with long sinuous northwest-to-northeast trends (Fig. 3) that are bounded on their eastern side by steeply dipping monoclines and associated structural basins are the major structural features of the Colorado Plateau. Three episodes in the structural evolution of the plateau have had significant impacts on the expression of recent tectonic activity: (1) Precambrian tectonics, (2) the Laramide orogeny, and (3) the Cenozoic structural differentiation of the Basin and Range–Colorado Plateau province.

Little is known of the Precambrian tectonics of this region. Prior to Cambrian time, however,

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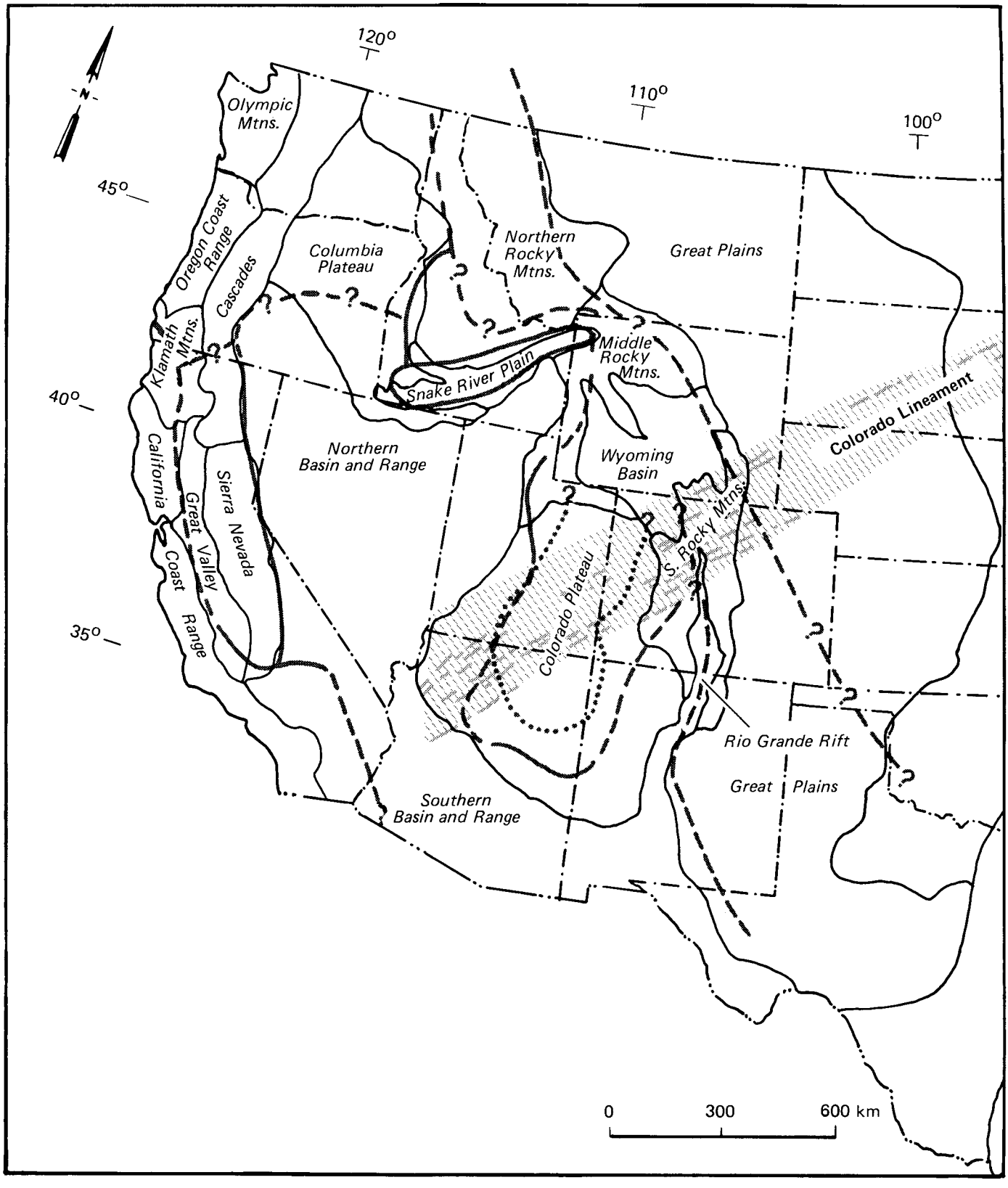

Figure 1. Physiographic provinces in the western United States. The stress province boundaries of Zoback and Zoback (1980) (heavy solid and dashed lines) and the Colorado lineament as defined by Warner (1978) (shaded area) are also shown. The dotted line within the Colorado Plateau represents the low heat-flow thermal interior of Bodell and Chapman (1982).

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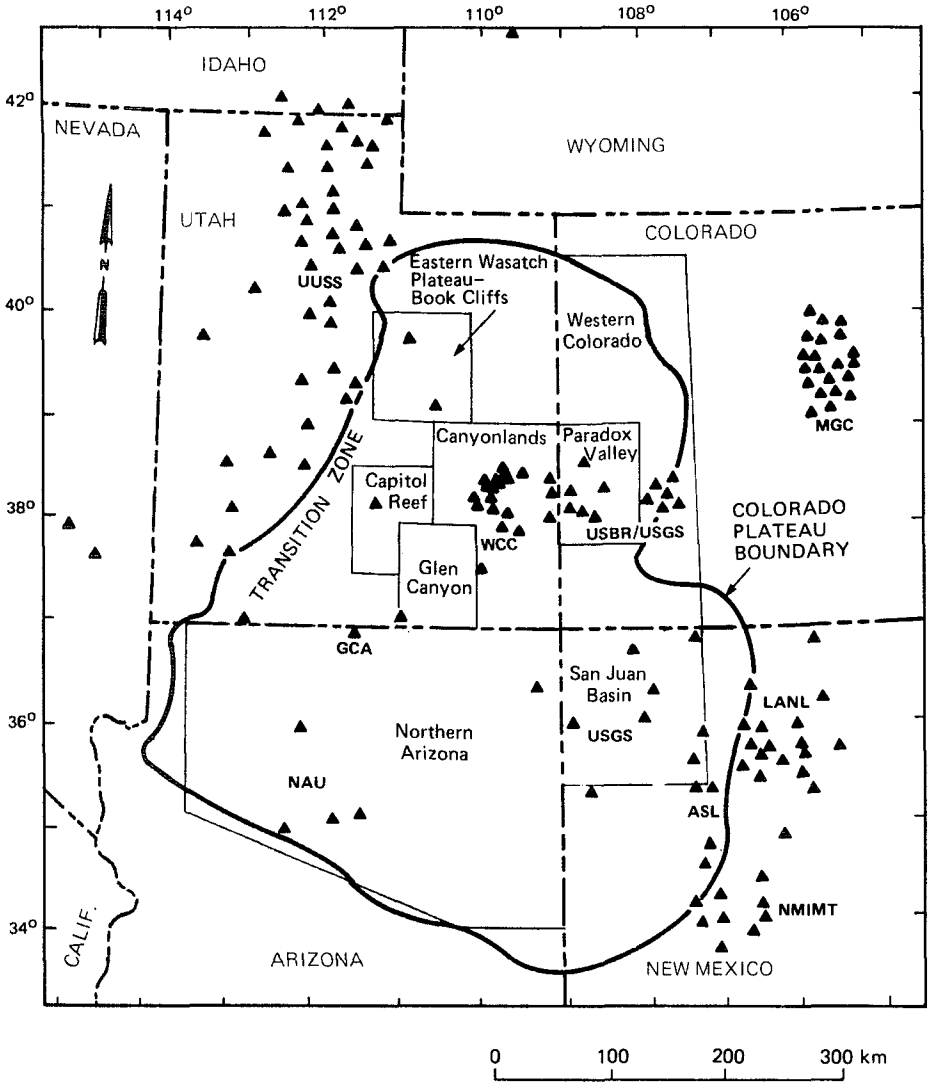

Figure 2. Seismographic stations in the Colorado Plateau (designated by triangles) in the early 1980s from which data were used in this study and index map of areas discussed in text. Appropriate network operators are also noted. Station GCA was the first permanent station installed in the Colorado Plateau.

the region must have undergone major deformation and metamorphism to produce the complex suite of metamorphic and igneous rocks exposed in the Grand Canyon and the Uncompahgre uplift (Fig. 3). Where the basement structure is exposed in the Grand Canyon, the east-dipping Grand Canyon monoclines pass downward into high-angle, west-dipping reverse faults in the lower Paleozoic or Precambrian rocks (Young, 1979). These basement faults have had a complex history of displacement, and, in many cases, the sense of displacement has been reversed several times (Shoemaker and others, 1978). There are two general trends of these faults recognized in the Grand Canyon area, northwest and northeast. Similar trends are inferred in the plateau interior from aeromagnetic and gravity data and from surficial geology (Hite, 1975).

The Laramide orogeny took place in the western United States from ~70 to 40 Ma. Most deformation within the Colorado Plateau took the form of reverse faulting on steeply dipping basement faults that die out into drape-folded monoclines in the sedimentary cover (Davis, 1978). Geologic evidence exists for resurgent development of the plateau monoclines throughout the Laramide orogeny (Young, 1979) and earlier (Baars, 1979; Peterson, 1980). Near the end of the Laramide, a few scattered igneous intrusions penetrated the western plateau region, including the Henry Mountains, which are composed of diorite and monzonite porphyry stocks and laccoliths that were intruded between 48 to 44 Ma (Armstrong, 1969) (Fig. 3).

Structural differentiation between the northern Basin and Range and the Colorado Plateau provinces started sometime after 29 Ma and appears to have been underway by 26 Ma (Rowley and others, 1979), coinciding with possibly the first episode of uplift (Morgan and Swanberg, 1985). By 24 Ma, the plateau was significantly lower than the adjacent Basin and Range. Crustal extension in the Basin and Range became widespread about 17 Ma (Stewart, 1978). This extension has been accommodated by both listric and planar normal faults which produce large rotations of fault blocks and also by large displacements on nonrotational low-angle faults (Wernicke and Burchfiel, 1982). Active extension in an east-west to northwest-southeast direction is now occurring in the northern Basin and Range province and the High Plateau subprovince of south-central Utah (Arabasz and Julander, 1986).

Crustal extension in central and southern Utah along the western margin of the plateau also extends eastward well beyond the physiographic boundary. A transition zone on the order of 50–100 km wide is characterized by related occurrences of late Cenozoic normal faulting, late Tertiary and Quaternary basaltic volcanism, high levels of seismicity (a part of the Intermountain seismic belt), high heat flow, and low P_n velocities relative to the plateau interior (Thompson and Zoback, 1979).

Thompson and Zoback (1979) proposed that Basin and Range extensional stresses in Arizona extend as much as 100–200 km into the Colorado Plateau. On the basis of the present-day crustal extension of the transition zone and the possible migration of volcanism toward the plateau interior, Best and Hamblin (1978) suggested that Basin and Range extensional stresses may be actively encroaching into the plateau. (See Arabasz and Julander [1986] for an excellent discussion of the transition zone.)

Smith and Sbar (1974) first stated that the northern Colorado Plateau is being subjected to tectonic compression between two zones of east-west– directed extension, the Intermountain seismic belt on the west and the Rio Grande rift on the east. This view of the plateau's state of stress was based principally on two composite focal mechanisms determined from mining-induced earthquakes at the Sunnyside coal mines in the Book Cliffs of east-central Utah (Smith and others, 1974) and induced earthquakes in the Rangely oil fields in the northwestern corner of Colorado (Raleigh and others, 1972). Thompson and Zoback (1979) further proposed that the stress field of the entire Colorado Plateau interior was compressional, dis-

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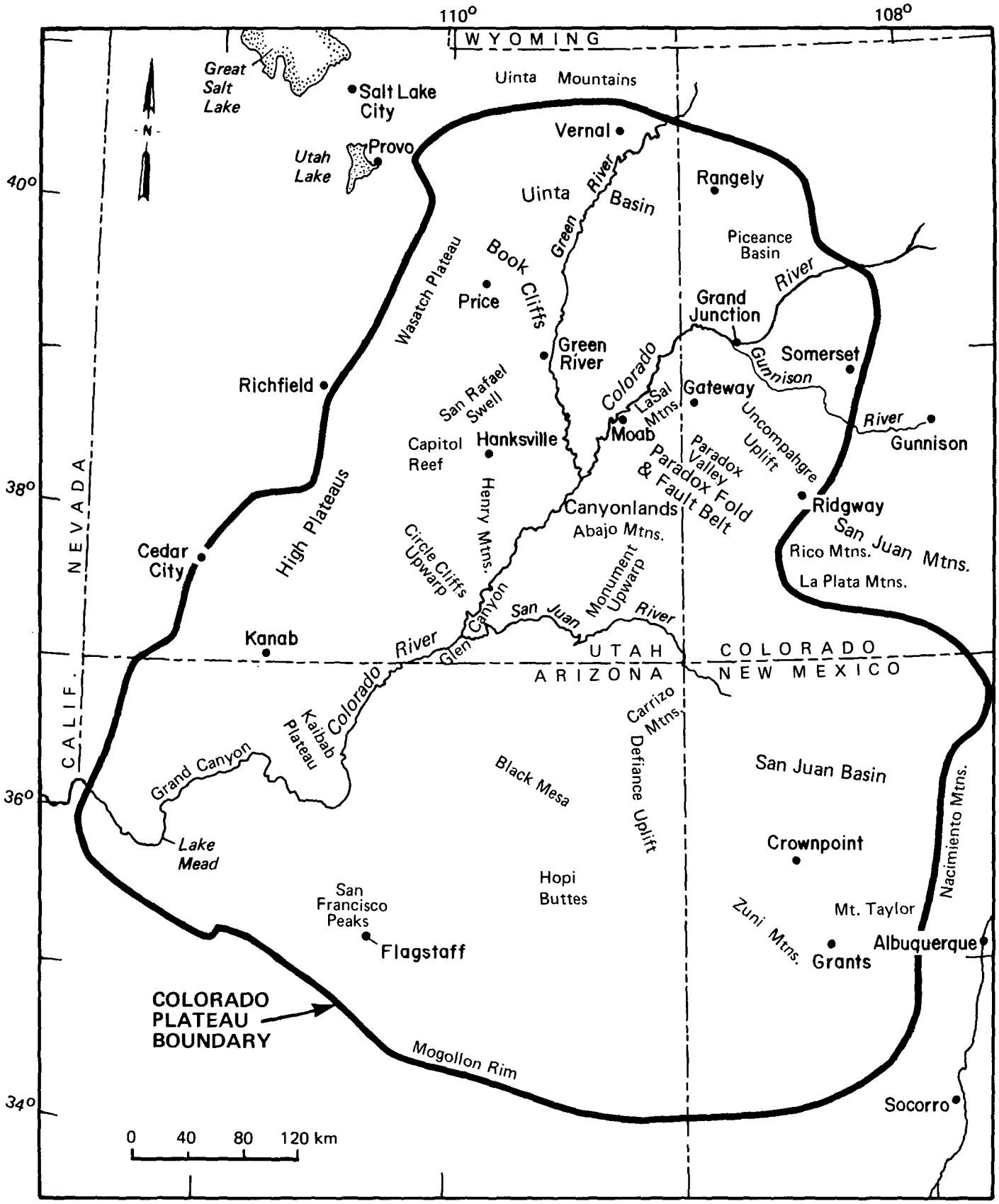

Figure 3. Major topographic and geologic features of the Colorado Plateau (modified from Hunt, 1956).

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tinctly different from the surrounding Basin and Range province and Rio Grande rift.

Zoback and Zoback (1980) defined a Colorado Plateau stress province, distinctly smaller than the physiographic province (Fig. 1), that could be characterized as a compressional stress regime with

$$S_1^{WNW} > S_2^{NNE} \simeq S_3^{V}$$

where S_1, S_2, and S_3 are the maximum, intermediate, and minimum principal stresses trending in west-northwest, north-northeast, and vertical directions, respectively. They also suggested that the occurrence of both strike-slip and thrust focal mechanisms demonstrates the existence of high horizontal stresses exceeding the lithostat.

Heat-flow measurements for the Colorado Plateau define a low heat-flow thermal interior (average of 60 mWm^{-2}) surrounded by a periphery some 100 km wide having substantially higher heat flow (average of 80–90 mWm^{-2}) (Bodell and Chapman, 1982). The location of the transition between the high heat-flow margins and the low heat-flow interior has probably resulted from lateral warming and weakening, in a rheological sense, of the sides of the plateau lithosphere (Bodell and Chapman, 1982). Such weakening eventually leads to crustal failure and is consistent with the normal faulting along the margins of the plateau. The source of the relative stability of the Colorado Plateau thus is probably related primarily to its thermal evolution in that the cooler interior has been stronger than the surrounding regions (Morgan and Swanberg, 1985). Because of the heating and uplift of the plateau's lithosphere during the Cenozoic, the stability of the plateau may be decreasing, and it may be breaking up, especially along its margins (Morgan and Swanberg, 1985).

HISTORICAL SEISMICITY

The historical earthquake record, as well as contemporary observations, show that significant sources of seismicity in the intermountain United States are present along the margins of the Colorado Plateau. These include part of the Intermountain seismic belt on the northwestern margin and the Rio Grande rift on the southeastern margin (Fig. 4). Both seismic zones exhibit a moderate to high level of seismicity and evidence for the occurrence of earthquakes as large as M_L 7.5 (Smith and Sbar, 1974; Sanford and others, 1979).

Based on the historical record prior to 1961, earthquakes within the plateau appear to have occurred infrequently (Fig. 4). This is due to inadequate seismographic detection of small to moderate-sized earthquakes prior to the 1970s (Wong and Simon, 1981). The first well-recorded observation of an earthquake in the Colorado Plateau was for an event of maximum Modified Mercalli (MM) intensity VI felt near Flagstaff, Arizona, on 2 February 1892. Most of the largest earthquakes observed within the plateau have also occurred in northern Arizona and were possibly of M_L 5–6 (Fig. 4). These include (Dubois and others, 1982) (1) an 18 August 1912 earthquake near the San Francisco Peaks of maximum intensity MM VII–VIII, (2) a 25 January 1906 earthquake near Flagstaff of maximum MM VII, (3) a maximum MM VII earthquake on 24 September 1910 near Cedar Wash, and (4) an event on 21 July 1959 near Fredonia with a maximum MM VI (estimated M_L 5½–5¾).

DATA ANALYSIS

The data analysis described herein was for earthquakes recorded by the WCC Canyonlands network and located within the Colorado Plateau, principally in southeastern Utah. Earthquake hypocenters were determined from P-wave and S-wave arrival times as input to the computer program HYPOELLIPSE (Lahr, 1980). Arrival times and first-motion data (for focal mechanisms) were read principally from the Canyonlands network and, to a lesser extent, the UUSS regional network in Utah (Fig. 2). For larger events greater than M_L ~2.5 within and adjacent to the Colorado Plateau, additional data were obtained from networks operated by the U.S. Geological Survey in the San Juan Basin and near Albuquerque; by LANL in northern New Mexico; by the New Mexico Institute of Mining and Technology (NMIMT) around Socorro, New Mexico; by the USBR and the USGS in the Paradox Valley and around Ridgway dam in southwestern Colorado; by Microgeophysics Corporation (MGC) in the Front Range near Denver; by Northern Arizona University (NAU) in northern Arizona; and by the USGS in southern Nevada. Data were also obtained from several stations throughout the Intermountain United States operated by the National Earthquake Information Service; and from the Kanab, Utah, station operated by Lawrence Livermore National Laboratory (Fig. 2).

The principal velocity model used for the earthquake locations was developed for the Colorado Plateau based on the crustal and upper-mantle velocity structure proposed by Roller (1965). The velocities of the top 1–2 km, which consists of the Phanerozoic sedimentary section, were modified based on borehole velocity measurements. The upper-mantle velocity used in the model (7.95 km/sec) was based on the analysis of P_n velocities from regional earthquakes and explosions (Humphrey and Wong, 1983b). Eleven other regional crustal velocity models were also used in the analysis for earthquakes located around the plateau's margin.

The estimated epicentral uncertainty for earthquakes instrumentally located in the Canyonlands region is ±1 to 2 km within the WCC network, decreasing to ±5 km outside the network. Computed focal depths have an estimated uncertainty of ±2–5 km. Regionally recorded earthquakes (beyond 50 km from the WCC network) have estimated uncertainties of ±5 and ±10 km in epicentral location and focal depth, respectively.

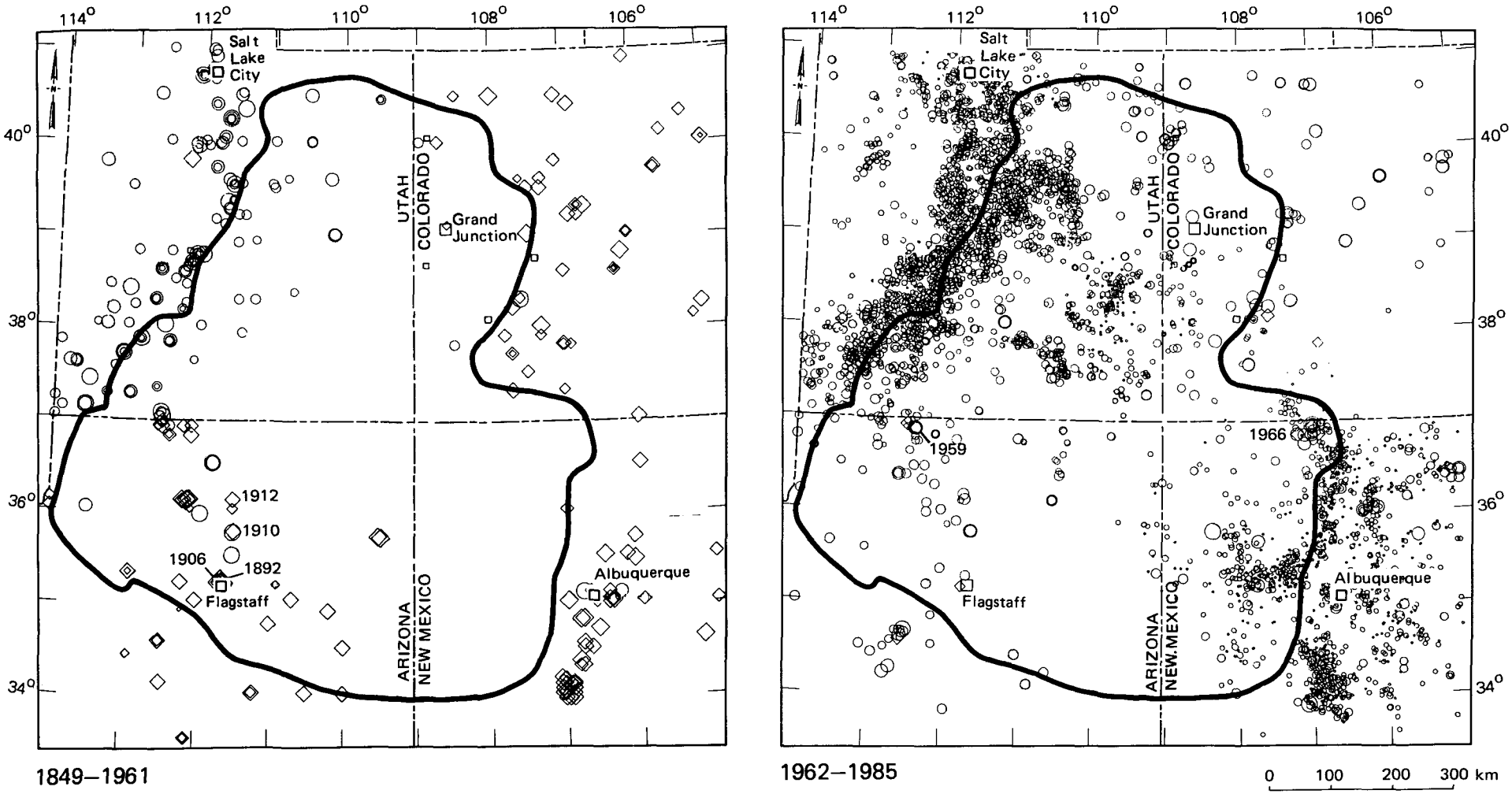
In a few cases, a master-event technique was used to locate suites of earthquakes. This technique is based on developing station delays incorporating the arrival-time residuals from a well-recorded event. Such delays compensate for heterogeneities in the crustal velocity structure and the near-surface geology beneath the seismographic stations that are not accounted for in the simplified plane-layered velocity models used in the locations. The hypocentral locations resulting from a master-event approach have improved relative locations and may have improved absolute locations, depending upon the accuracy of the master-event location.

Focal mechanisms were visually fit by trial-and-error to first-motion plots generated by the program HYPOELLIPSE. One of the major sources of uncertainty in the determination of focal mechanisms is the calculation of take-off angles which are critically dependent upon the crustal velocity structure and focal depth. Thus mechanisms, particularly for those earthquakes which were regionally recorded, were tested for sensitivity to focal depth and in some cases, velocity structure. Only those focal mechanisms which exhibited reasonably well-constrained nodal planes were considered. In general, the mechanisms in this study have estimated ±10° and ±20° uncertainties in the strikes and dips of the nodal planes, respectively.

For earthquakes located in the Canyonlands region, magnitudes based on coda durations measured from 24-hr paper records were estimated utilizing a formula developed by Griscom and Arabasz (1979) for the Utah region. For other events, magnitudes as assigned by other agencies were generally adopted.

CONTEMPORARY SEISMICITY AND SEISMOGENIC FAULTING

Based on seismological studies that have been performed principally since 1979, the contemporary seismicity, seismogenic faulting, and state of stress of the Colorado Plateau can now be



LEGEND

Earthquake epicenters

Magnitude M_L	Intensity MM
≥ 6	≥ VI
= 5	= V
= 4	= IV
= 3	= III
= 2	= II
= 1	= I

Symbol sizes are on a continuous nonlinear scale.

Figure 4. Historical and contemporary seismicity of the Colorado Plateau and adjacent regions, 1849 to 1961 and 1962 to 1985. Significant earthquakes and their years of occurrence are also shown. All known earthquakes of $M_L \geq 1.0$ are shown for the modern period, although a detection threshold of M_L 1.0 has been far from uniform throughout the Colorado Plateau region. Sources of data were numerous catalogs compiled by the University of Utah, U.S. Geological Survey, National Oceanic and Atmospheric Administration, DuBois and others (1982), Hadsell (1968), and Sanford and others (1981).

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characterized. The following is a region-by-region discussion (Fig. 2).

Canyonlands, Utah

The most intensely studied area of the plateau to date has been the Canyonlands region (Figs. 2 and 3). The first long-term seismographic network to be operated within the plateau was installed in July 1979 by WCC. The network consisted of 12 to 24 high-gain, short-period stations covering an approximate area of 30,000 km^2 with a detection threshold of at least M_L 1.0 (Wong and others, 1987).

From late July 1979 through June 1987, ~1,100 earthquakes up to M_L 3.3 were recorded and located in the Canyonlands region (Fig. 5). A low rate of occurrence (~10 events/month) punctuated by episodic bursts or swarms of as many as 35 events/day characterized the temporal behavior of seismicity in the region (Fig. 6). Such swarms generally lasted from a few days to several weeks and were usually preceded and followed locally by total quiescence. Spatially, seismicity was generally widespread with major concentrations in (1) the vicinity of the Cane Creek mine at Potash, (2) a 20-km stretch of the Colorado River northeast of its confluence with the Green River, (3) the vicinity of Happy Canyon and the Orange Cliffs, and (4) southwest of Mancos Mesa in the Glen Canyon area (see discussions on Glen Canyon) (Fig. 5).

Potash. The most seismically active area observed in the Canyonlands region (421 events) was in the vicinity of the Cane Creek mine (Wong and others, 1989b) (Fig. 7). The mine, previously a room-and-pillar mine at 1-km depth, contains potash which is extracted by the solution technique. The vast majority of these events were less than M_L 1.0; however, two events of M_L 3.3 and 3.0 occurred on 22 January and 10 February 1984, respectively. Events were scattered throughout the area without any obvious concentration in the mine vicinity. Focal depths ranged from the near-surface to 20 km (Fig. 8).

An examination of the temporal behavior of the microseismicity showed apparent increased levels of activity during periods of brine extraction (pumpdowns). Thus during 1984, high-resolution monitoring by a portable network (1-km station spacing) was conducted for 2 weeks before and 6 weeks during a major pumpdown (Wong and others, 1989b). A few hundred seismic events, similar in appearance to microearthquakes occurring throughout the region, appeared to be generally confined to the top 600 m of strata overlying the evaporite Paradox Formation, a few kilometers south of the mine; no events were located within the mine workings during the monitoring period. The activity observed was the highest level observed since microearthquake monitoring was initiated (Fig. 6). The temporal pattern exhibited a fairly strong correlation with the pumpdown cycle; thus some of the microearthquakes may be associated with subsidence that was observed occurring over the mine (Wong and others, 1989b). Those events deeper than 1 to 2 km and more than a few kilometers away from the mine are most likely tectonic in origin.

The first motions of the 64 largest microearthquakes fit either of 2 focal mechanisms; both of which exhibited strike-slip faulting on

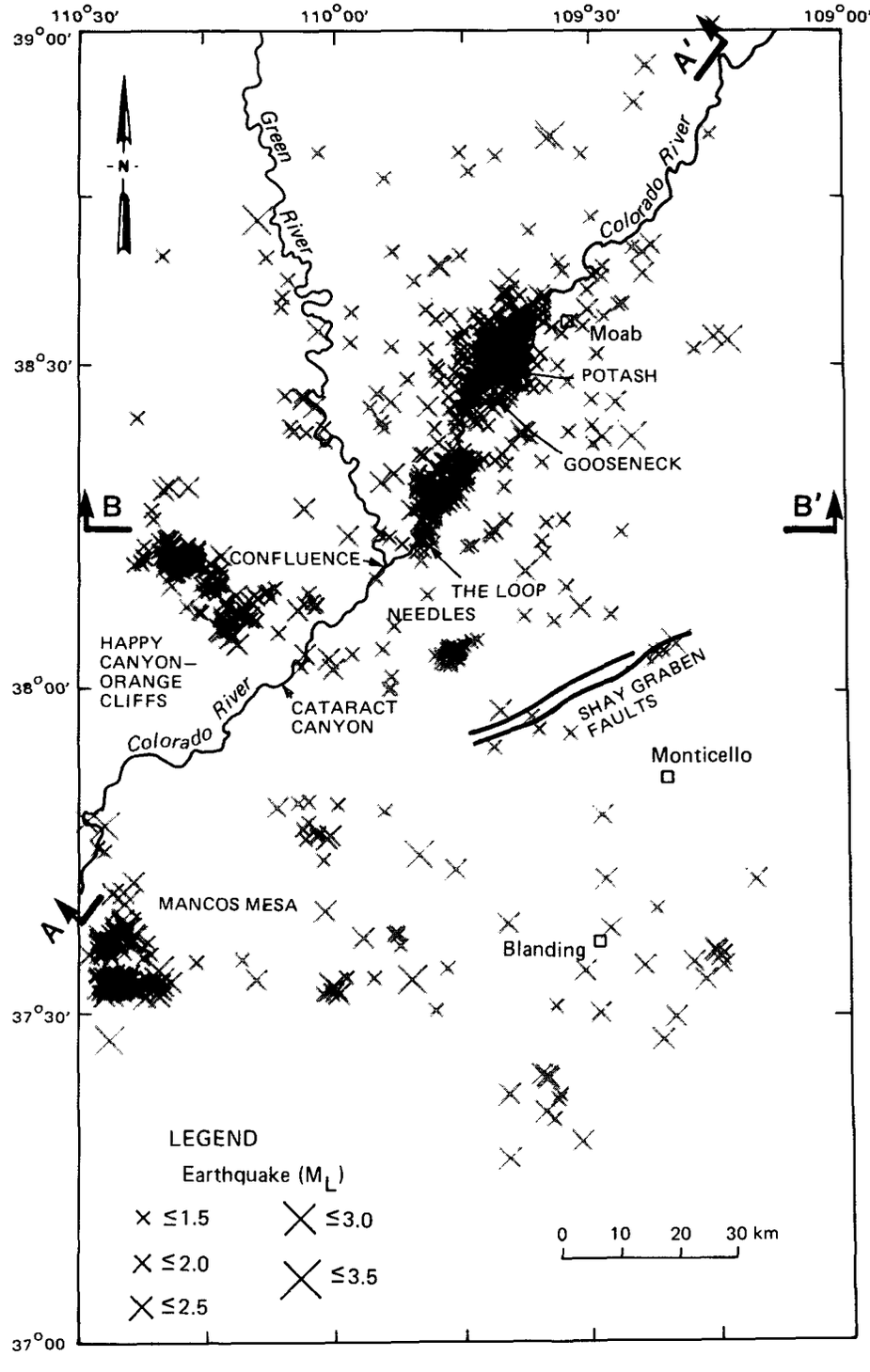

Figure 5. Seismicity of the Canyonlands region, July 1979 through July 1987. A–A′ and B–B′ indicate the locations of cross sections shown in Figure 8.

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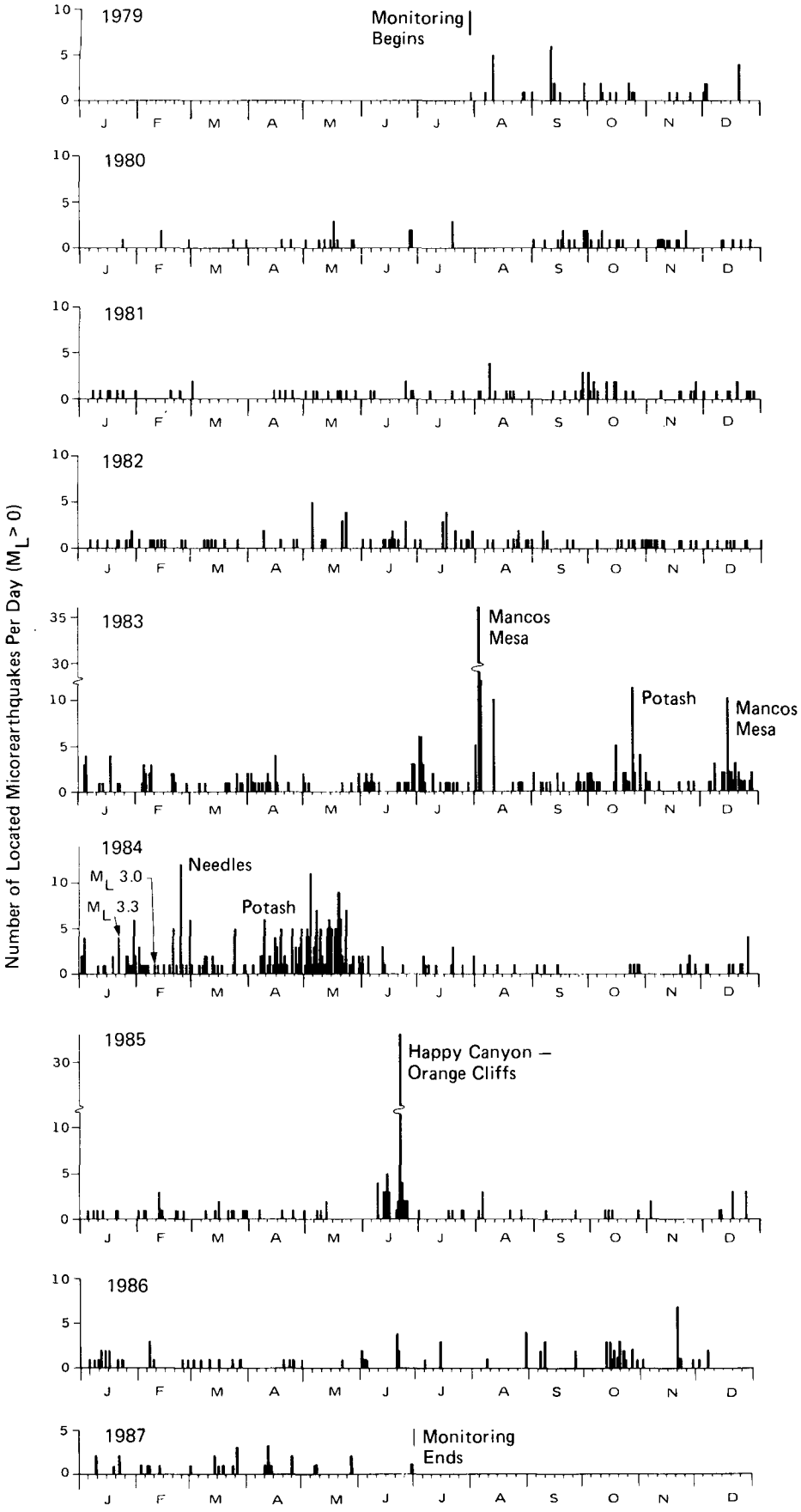

Figure 6. Temporal behavior of microearthquakes located throughout the Canyonlands region outlined in Figure 5.

northwest- or northeast-striking planes but contrasting principal stress directions (Wong and others, 1989b) (No. 1 and 2, Fig. 9a). These nonuniform stress conditions suggest that all three principal stresses may be nearly equivalent and that the deviatoric stresses were small. Small changes in the magnitudes of the principal stresses could result in a variety of stress fields and orientations of the deviatoric stresses. Such a "hydrostatic-like" stress state was observed in a hydraulic fracture experiment in the Piceance Basin, Colorado, also within the Colorado Plateau. Such a stress condition may be caused by the shallow depth (~500 m) and rather weak rock in the basin (conditions similar to the Potash area) (Zoback and Zoback, 1980).

Colorado River. In addition to the Potash area, earthquakes were also concentrated along the stretch of the Colorado River between Moab and the Confluence, especially near the Loop and, to a lesser extent, the Gooseneck (Fig. 7). The Loop area was the site of a sequence of ~150 events in late July (when monitoring began) through October 1979 (20 located), with the largest event of M_L 2.4 (Wong and Simon, 1981) (Fig. 6). Subsequent activity was generally low to moderate and episodic except for a small burst of activity in May 1980. Focal depths generally ranged from 2 km (the top of the Precambrian basement) to 15 km (Fig. 8). In contrast, the concentration of 67 microearthquakes in the vicinity of the Gooseneck (Fig. 7) was unusually shallow, generally less than 2 ± 1 km deep, placing the events within the sedimentary section above the Precambrian basement.

On the basis of aeromagnetic data, the Loop part of the river appears to be underlain by a fault or fault zone in the Precambrian basement that has experienced previous left-slip displacement (Case and Joesting, 1972) (Fig. 7). Hite (1975) proposed that several northeast-trending features in the region, including the Colorado River below Moab, may be structurally controlled by basement shear zones or strike-slip faults. Although seismographic coverage has been concentrated along the Confluence-Moab stretch, very few earthquakes ($M_L > 0.5$) have been observed elsewhere along the river. It is possible that only this linear stretch of the river has underlying basement faults that are favorably oriented to the contemporary tectonic stress field. Note that the river deviates in its trend outside this stretch. An issue that remains unre-

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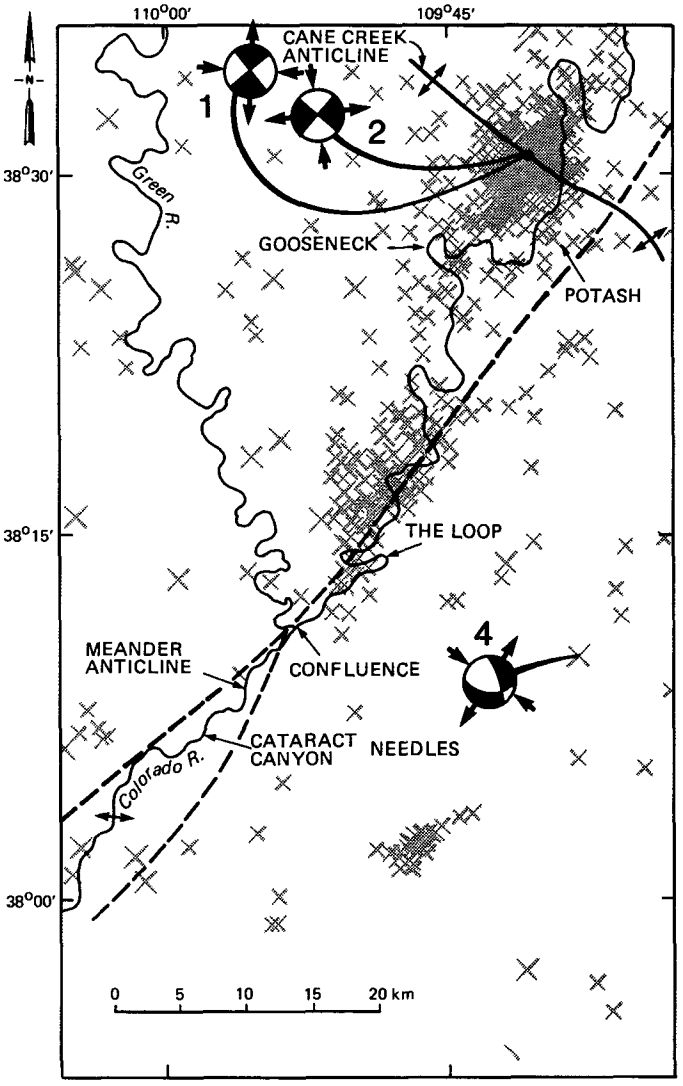

Figure 7. Seismicity from July 1979 through July 1987, schematic focal mechanisms, and major geologic structures along the Colorado River in the Canyonlands region. Shaded areas of focal mechanisms (lower hemispheric projections) represent compressional quadrants. Inward- and outward-directed arrows are the horizontal projections of the P and T axes, respectively. The P and T axes approximate the maximum and minimum principal stress directions. Detailed focal mechanisms are shown in Figure 9. Heavy dashed line is an inferred basement fault.

solved is whether there exists a cause-and-effect relationship between the seismicity and the river, as has been suggested by McGinnis (1963) for the Mississippi River.

Areas outside the Colorado River. One of the most active areas away from the Colorado River is represented by the concentration of ~150 events northeast of Happy Canyon and the Orange Cliffs (Fig. 5). These earthquakes occurred throughout the monitoring period; the most intense activity was a swarm of 54 events in June 1985, 32 of which occurred on 21 June (Fig. 6). The largest event in this area was one of M_L 1.8. These earthquakes appeared to be relatively deep, generally 15 to 25 km, although focal depths were not well constrained (Fig. 8).

Since July 1979, seven microearthquakes have been observed in the near-vicinity of the Shay Graben faults (Fig. 5), the only faults known to exhibit Quaternary displacement within the Canyonlands region, although it has not been resolved whether the displacement is of tectonic origin or due to salt flowage or dissolution. The relationship of these events with the Shay Graben faults is unclear due to location uncertainties and the lack of focal mechanisms.

Three focal mechanisms have been determined for earthquakes away from the Colorado River: (1) a predominantly normal faulting mechanism for a microearthquake at a depth of 11 km east-southeast of the Confluence (no. 4, Figs. 7 and 9a); (2) a reverse/thrust faulting mechanism for an event, 17 km deep and 30 km northwest of Monticello (no. 3, Fig. 9a); and (3) a normal faulting mechanism for a microearthquake, 7 km deep, beneath the LaSal Mountains (no. 5, Fig. 9a).

Deep Earthquakes. Most earthquakes in the intermountain region, as in most of the western United States, occur in the upper crust, no deeper than 15–20 km (Smith, 1978; Wong and Chapman, 1986). Although most of the seismicity in the Canyonlands region also occurred at such depths, many well-located microearthquakes appeared to originate below a depth of 20 km (Fig. 8). These events appeared to be distributed throughout the lower crust to a depth of ~40 km with two events in the upper mantle at depths of 53 and 58 km.

Several investigators have suggested that the maximum temperature allowable for earthquake occurrence in the crust is 350 ± 100 °C, which corresponds to an approximate depth of 15–20 km in most intraplate/intracontinental regions (Brace and Byerlee, 1970; Sibson, 1982; Chen and Molnar, 1983). Below 15–20 km, crustal temperatures are sufficiently high that the ductile strength of crustal rocks becomes less than their brittle strength, and the rocks will deform aseismically rather than by the brittle failure mode of stick-slip. In the mantle below certain intraplate or intracontinental regions, the ductile strength of the rocks is greater than their brittle strength, even at the higher temperatures, because of the different composition of the rocks. Thus intraplate earthquakes may occur in the upper mantle and have been observed in several areas worldwide (Chen and Molnar, 1983). Chen and Molnar (1983) have estimated the limiting temperature for earthquake occurrence in mantle materials to be close to 600 °C and possibly as high as 800 °C.

Based upon a measured average heat flow of 58 ± 6 mWm^{-2} and average continental geotherms parametric in surface heat flow, temperatures beneath the Canyonlands region appear to range from 300–600 °C in the lower crust and 600–800 °C in the uppermost mantle (Wong and Chapman, 1986). These uppermost mantle temperatures and the lower crustal temperatures less than ~450 °C are in good agreement with the temperatures suggested for earthquake occurrence. If temperatures in the lowermost crust exceed 500 °C, however, this could imply that the Moho beneath the Colorado Plateau is not a sharp boundary and that lower crustal rocks are transitional to upper-mantle rocks in terms of composition and strength (Wong and Chapman,

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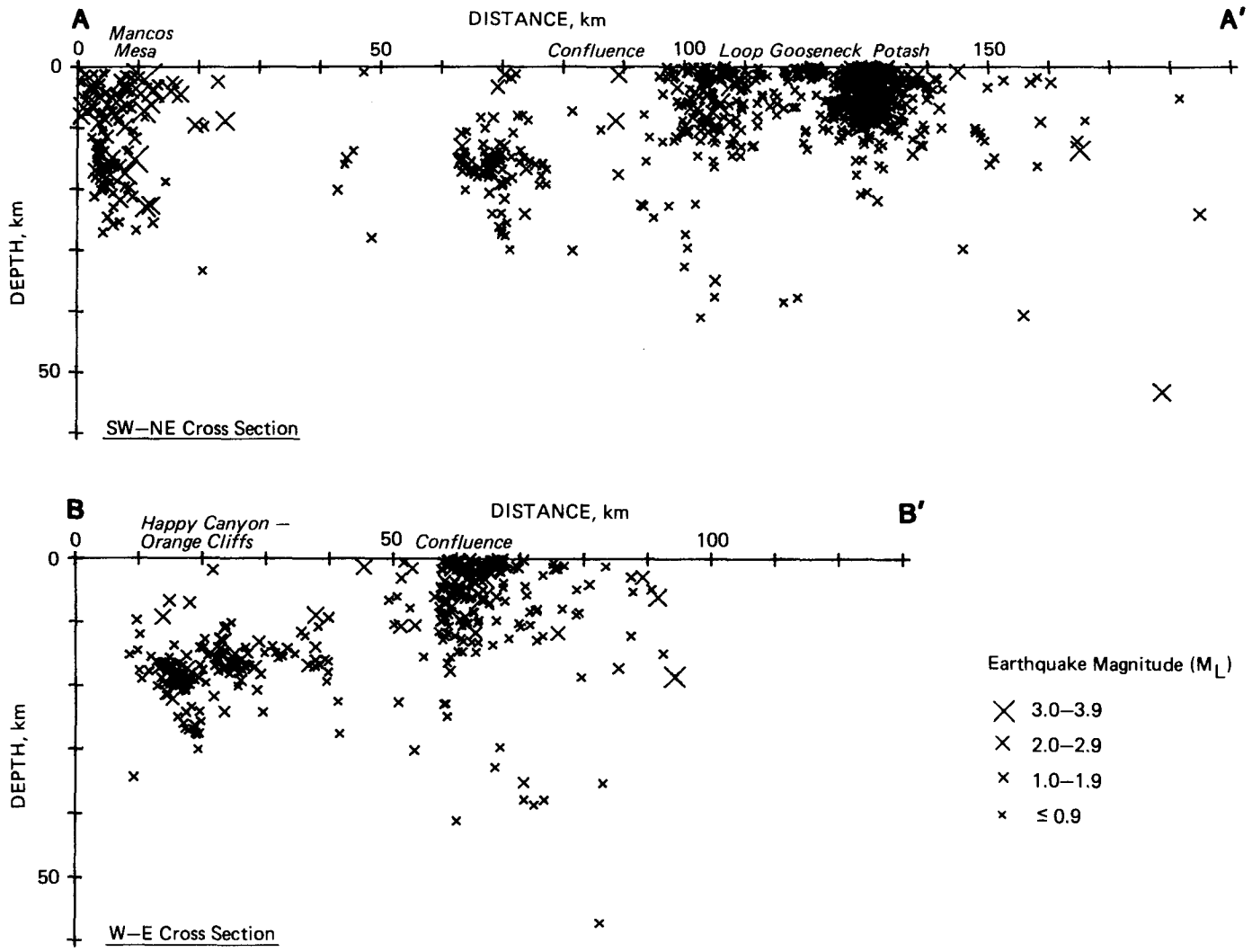

Figure 8. Seismicity cross sections through the Canyonlands region keyed to Figure 5.

1986). The relatively low upper-mantle temperatures must also be reconciled with the relatively high temperatures inferred from low P_n velocities and high electrical conductivities (Morgan and Swanberg, 1985).

Glen Canyon, Utah. The first microearthquake study performed in the Colorado Plateau for the purpose of assessing the local seismicity was the operation of a six-station temporary network during the filling of Lake Powell in 1969 (Sbar and others, 1972). On the basis of observations from the nearby Canyonlands network, the Glen Canyon region encompassing Lake Powell (Figs. 2 and 3) has been characterized by both isolated single events and swarms of earthquakes since 1979. Two swarms occurred in August and December 1983 with several events of M_L greater than 2.5 occurring in both sequences (Fig. 10). Focal mechanisms for the 4 August 1983 M_L 2.7 and the 12 December 1983 M_L 2.8 earthquakes are similar; both exhibit predominantly normal faulting on either a northwest-striking, southwest-dipping plane or a north-striking, east-dipping plane (Figs. 9a and 10). The T-axes trend northeast-southwest.

To examine the source of the well-recorded August 1983 swarm, events were relocated using a master-event technique. Although in map view the events appear to be diffusely distributed, cross sections reveal an east-dipping, approximately north-striking fault (Fig. 11), compatible with a nodal plane in the 4 August 1983 focal mechanism (Figs. 9a and 10).

The largest earthquake (M_L 4.0) known to have occurred in the southeastern Utah part of the Colorado Plateau was felt in the Glen Canyon region on 22 August 1986 (Fig. 10). The focal mechanism for the earthquake exhibits normal faulting on west-northwest– to northwest-striking fault planes (Fig. 9a). This event was followed by a M_L 2.9 earthquake on 7 November 1986, which also exhibited normal faulting (Figs. 9b and 10). The predominance of normal faulting in the Glen Canyon region in response to north-northeast– to northeast-directed tectonic extension contrasts sharply with the view that the interior of the Colorado Plateau is in a compressional state of stress (Fig. 10).

Capitol Reef, Utah

Another seismically active area observed within the Colorado Plateau in recent times is in the vicinity of Capitol Reef National Park, northwest of the Glen Canyon region (Figs. 2 and 3). From December 1978 through January 1980, a swarm of at least 38 earthquakes (M_L 1.0–3.6) was observed (Humphrey and Wong, 1983a). Five earthquakes in the sequence exceeded M_L 3; the largest event (M_L 3.6) oc-

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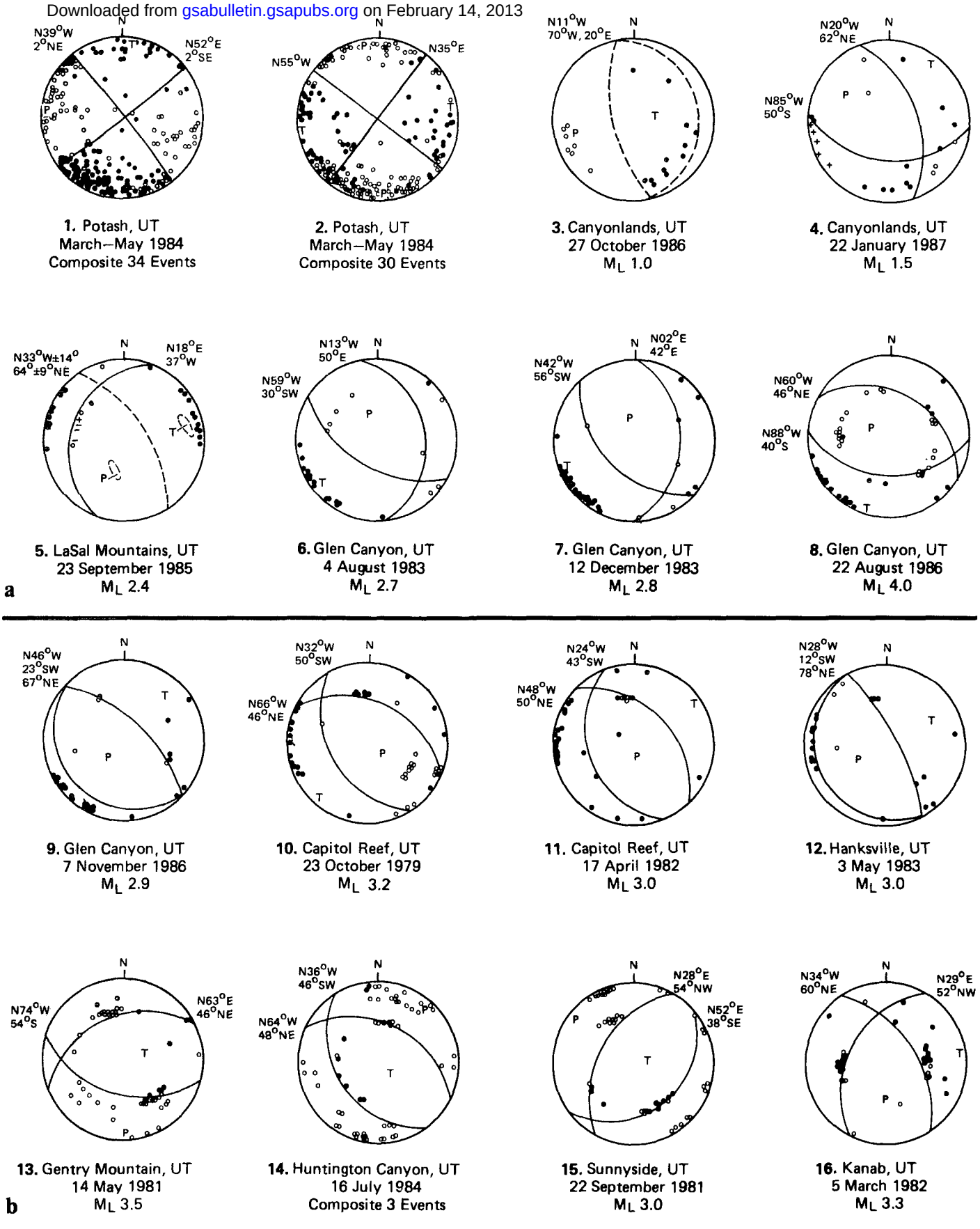

1. Potash, UT
March–May 1984
Composite 34 Events

2. Potash, UT
March–May 1984
Composite 30 Events

3. Canyonlands, UT
27 October 1986
M_L 1.0

4. Canyonlands, UT
22 January 1987
M_L 1.5

5. LaSal Mountains, UT
23 September 1985
M_L 2.4

6. Glen Canyon, UT
4 August 1983
M_L 2.7

7. Glen Canyon, UT
12 December 1983
M_L 2.8

8. Glen Canyon, UT
22 August 1986
M_L 4.0

a

9. Glen Canyon, UT
7 November 1986
M_L 2.9

10. Capitol Reef, UT
23 October 1979
M_L 3.2

11. Capitol Reef, UT
17 April 1982
M_L 3.0

12. Hanksville, UT
3 May 1983
M_L 3.0

13. Gentry Mountain, UT
14 May 1981
M_L 3.5

14. Huntington Canyon, UT
16 July 1984
Composite 3 Events

15. Sunnyside, UT
22 September 1981
M_L 3.0

16. Kanab, UT
5 March 1982
M_L 3.3

b

Figure 9. Focal mechanisms of earthquakes in the Colorado Plateau region determined in this study. Equal-area projections of the lower hemisphere are shown. Solid circles are compressional; open circles are dilatational first motions. Locations of the respective earthquakes are shown in Figure 14.

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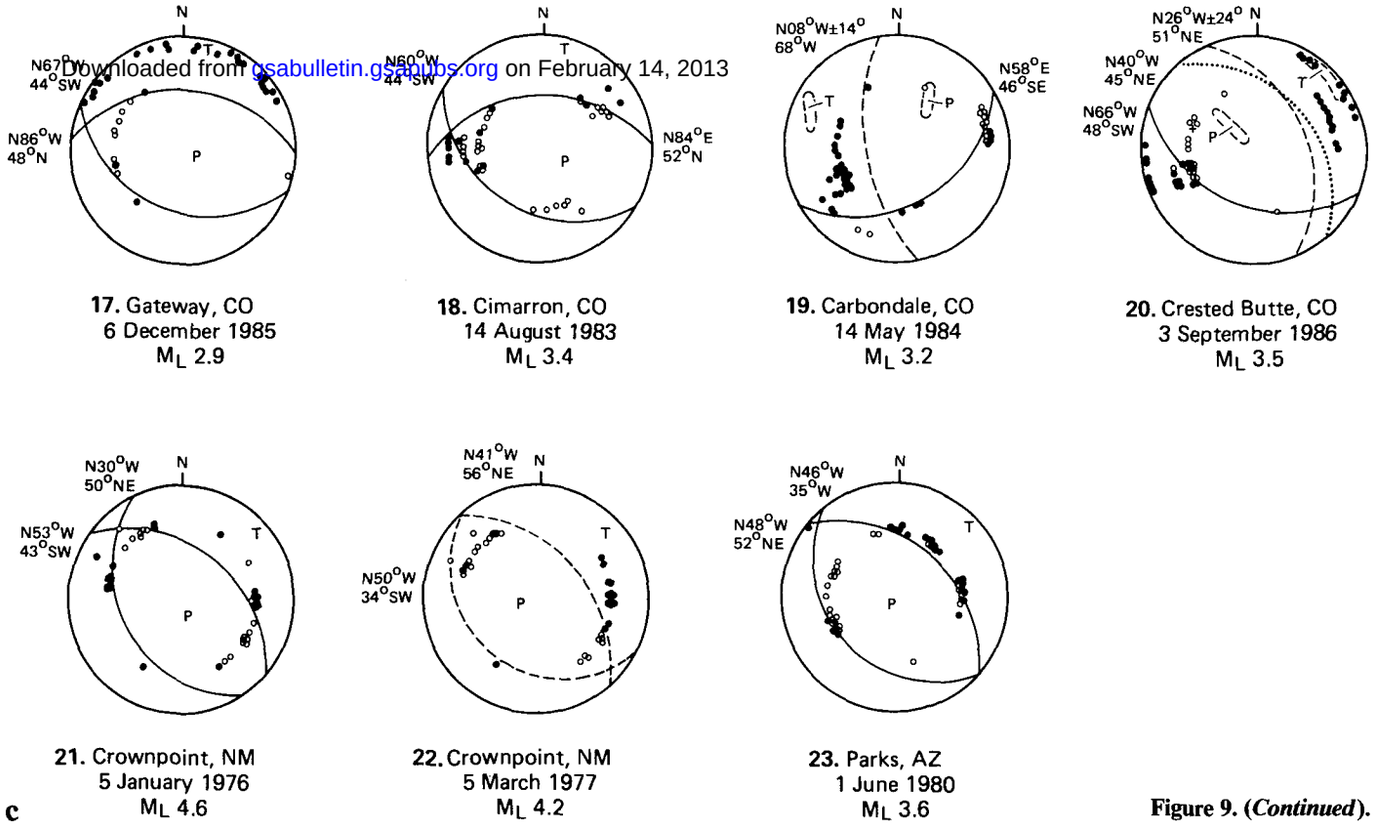

17. Gateway, CO
6 December 1985
M_L 2.9

18. Cimarron, CO
14 August 1983
M_L 3.4

19. Carbondale, CO
14 May 1984
M_L 3.2

20. Crested Butte, CO
3 September 1986
M_L 3.5

21. Crownpoint, NM
5 January 1976
M_L 4.6

22. Crownpoint, NM
5 March 1977
M_L 4.2

23. Parks, AZ
1 June 1980
M_L 3.6

c

Figure 9. (*Continued*).

curred on 29 April 1979 and was felt locally (MM III). Prior to this sequence, only two earthquakes had been known to occur in this area, a M_L 4.3 event on 30 September 1963 and, possibly, a poorly located M_L 2.6 event on 19 August 1969.

Employing a master-event technique, the 19 largest relocated events clustered in a structurally complex area where the Waterpocket fold and the Caineville monocline (two of the major monoclines of the Colorado Plateau) join, and just west of the northwest-trending Henry Mountains (Fig. 12). Most of the Capitol Reef events were shallower than 10 km in depth.

A focal mechanism was determined for one of the largest events (M_L 3.2) (no. 10, Fig. 9b). Focal mechanisms have also been determined for a M_L 3.0 earthquake on 17 April 1982 just to the northwest of the 1979–1980 swarm, and a rare felt earthquake near Hanksville on 3 May 1983 (M_L 3.0) (Fig. 9b). All three mechanisms exhibit predominantly normal faulting on northwest-striking planes in apparent response to a northeast minimum principal stress. These mechanisms and the epicentral locations suggest a recurrence of movement (in an opposite sense) along postulated Laramide basement reverse faults that controlled the development of the Waterpocket fold and the Caineville monocline (Humphrey and Wong, 1983a).

Eastern Wasatch Plateau–Book Cliffs, Utah

The most microseismically active area observed within the Colorado Plateau has been the eastern Wasatch Plateau–Book Cliffs (Figs. 2 and 3). Since the late 1800s, coal has been extracted by underground mining, and based upon several studies, the seismicity appears to be mining-induced (Dunrud and others, 1973; Smith and others, 1974; McKee and Arabasz, 1982; Wong, 1985) (Fig. 13). Studies of this mine seismicity began in the Sunnyside district in 1963 when the U.S. Geological Survey established the first microseismic network. An unusual aspect of this mining-induced seismicity is that most of the events occurred *beneath* the mines to depths of 2–3 km. High-resolution microearthquake monitoring in 1984 in the Gentry Mountain area also revealed that the vast majority of submine events displayed a non–double-couple, implosional focal mechanism which contrasts with the double-couple, quadrantal pattern for shear failure displayed by tectonic earthquakes (Wong and others, 1989a). Simultaneous monitoring in the East Mountain coal mining area to the south revealed typical shear failure events mixed in with possible non–double-couple events (Williams and Arabasz, 1989). The shear events appear to be indistinguishable from tectonic earthquakes and may be considered mining-"triggered" earthquakes (Wong and others, 1989a). The small mining-induced stress changes that occur more than a few hundred meters from the mine workings suggest that the seismic events are occurring on critically stressed, pre-existing zones of weakness (Wong, 1985).

The reverse faulting, double-couple focal mechanisms that were determined in the 1984 studies were similar to reverse-faulting mechanisms with north- to northeast-trending P-axes determined in previous studies (Wong, 1985) (Figs. 9b and 13). A composite mechanism of several microearthquakes observed beneath the Sunnyside Mine in the Book Cliffs determined by Smith and others (1974) and a mechanism determined in this study for Sunnyside (no. 15, Fig. 9b) also exhibited reverse faulting, but with northwest-trending P-axes (Fig. 13). This nonuniformity in the maximum principal stress directions between the eastern Wasatch Plateau and the Book Cliffs over a distance of 60 km implies a nonuniform stress field possibly not dominated by tectonic stresses (see further discussion).

Recently, on 14 August 1988, a M_L 5.3 earthquake preceded by at least six foreshocks and followed by numerous aftershocks occurred in the San Rafael swell (Fig. 3), 30 km southeast of East Mountain (Fig. 13). This is the largest

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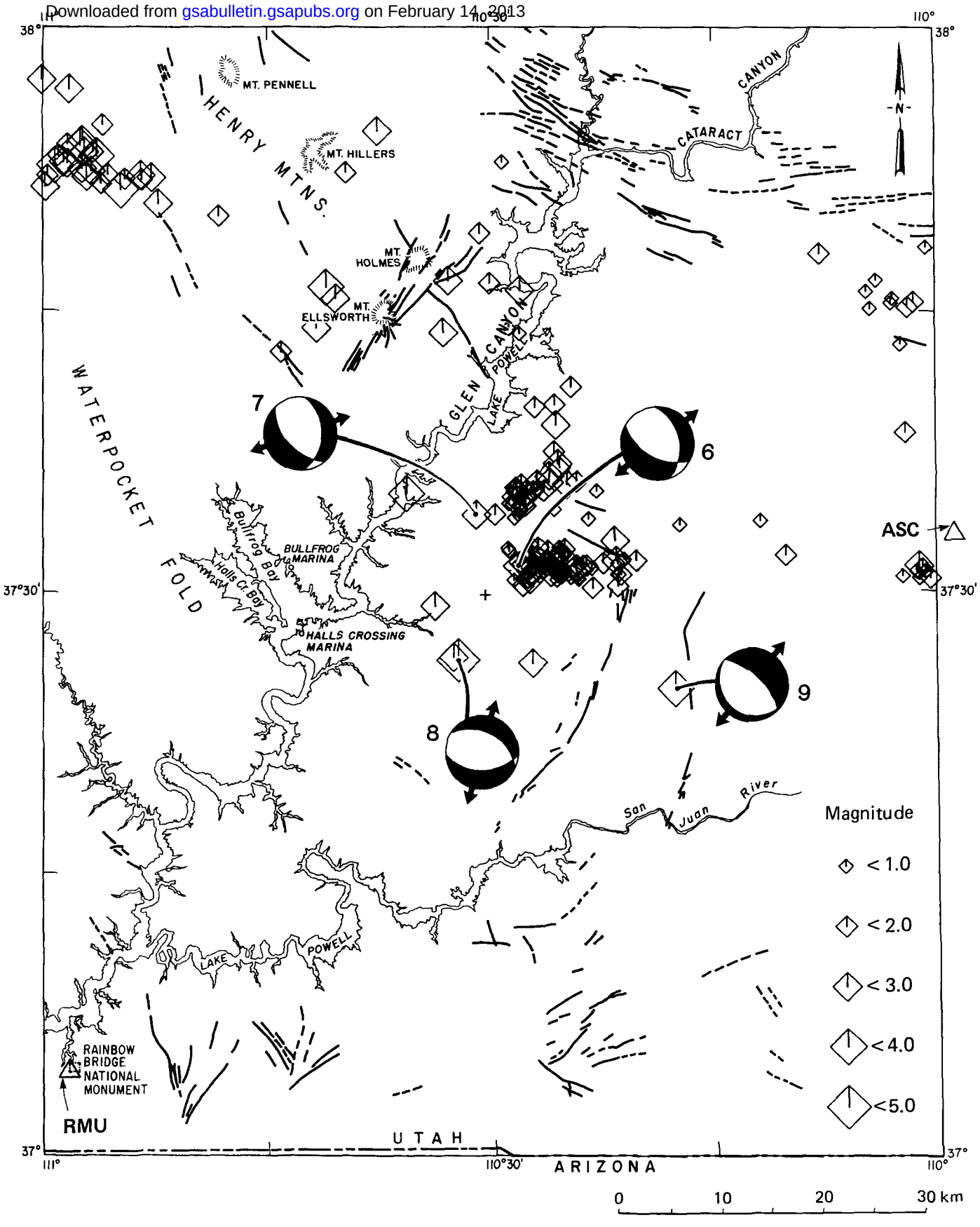

Figure 10. Seismicity and schematic focal mechanisms (symbols as in Fig. 7) of the Glen Canyon region, July 1979 through December 1986. Faults shown as heavy lines are taken from Hintze and Stokes (1964). Detailed focal mechanisms are shown in Figures 9a and 9b. Station ASC of the Canyonlands network and RMU of the UUSS network are the closest stations.

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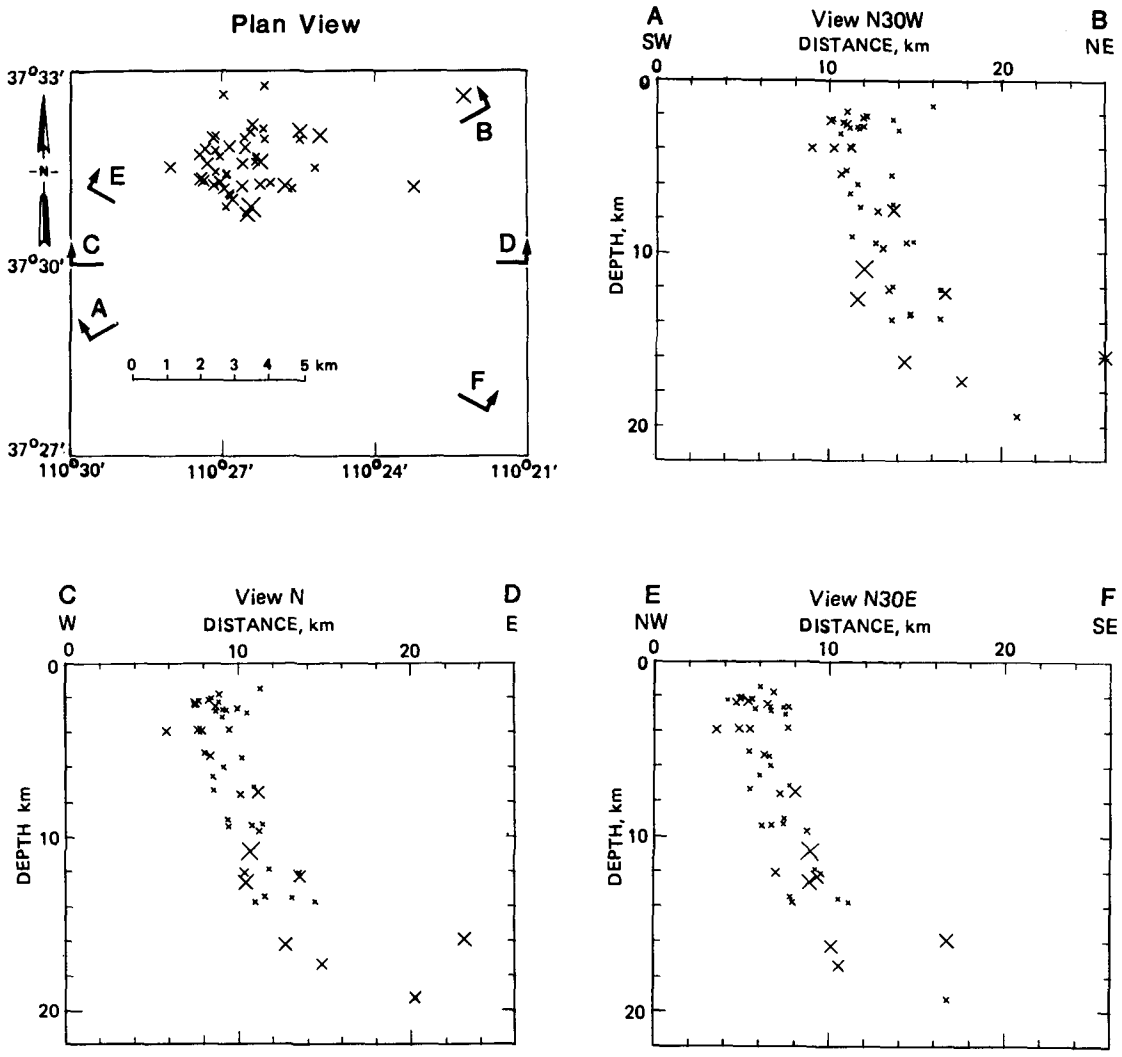

Figure 11. Epicentral and cross-sectional views of the master-event-relocated earthquakes in the August 1983 Glen Canyon swarm.

earthquake known to have occurred within the Colorado Plateau outside of northern Arizona. Aftershock monitoring was carried out by UUSS, and the data are currently being analyzed (Nava and others, 1989).

Paradox Valley, Colorado

A ten-station network was installed in June 1983 by the U.S. Geological Survey and the USBR covering an area of 5,000 km^2 centered on the Paradox Valley in southwestern Colorado (Martin and Spence, 1986) (Figs. 2 and 3). The seismicity in this area appears to be low-level, diffusely distributed, and of small magnitude, similar to that observed in the adjacent Canyonlands region. The largest earthquake observed to date has been one of M_L 3.1 (Martin and Spence, 1986). Several relatively deep microearthquakes exceeding 20 km in depth have also been located in the vicinity of this network.

Western Colorado

Seismicity studies in the Colorado part of the plateau outside the Paradox Valley (Fig. 2) have been few in number. What is known about the earthquake activity in this region is thus based on relatively inadequate regional seismographic coverage. The first earthquake investigation conducted within the plateau in western Colorado was the study of fluid-induced seismicity at the Rangely oil fields (Raleigh and others, 1972) (Fig. 3). An important result of that study, relevant to the seismotectonics of the plateau, was that the focal mechanisms exhibited right-slip on a northeast-striking plane (as suggested by the epicentral alignment) in response to an apparent east-west maximum principal stress and north-south minimum principal stress (no. 34, Fig. 14). Other microearthquake studies performed in the region have included microseismic monitoring of coal-mining–induced seismicity near the town of Somerset (Osterwald and others, 1972) and a 3-month survey in 1979 performed by the USBR in the vicinity of the proposed Ridgway Dam (Sullivan and others, 1980) (Fig. 3). In the latter, the Ridgway fault was thought to be seismically active based on 13 events located within 6 km to the south of the surface trace of the fault. Further studies may be aided by a five-station permanent network that has operated in the vicinity of the Ridgway fault since 1985 (Martin and Spence, 1986).

On 6 December 1985, a small earthquake of M_L 2.9 preceded by three microearthquakes and followed by at least three possible aftershocks was recorded by the Canyonlands and Paradox Valley networks. The sequence occurred ~16 km north of Gateway, Colorado, along the southwestern flank of the Uncompahgre uplift (Ely and others, 1986) (Fig. 15). The main shock appears to have occurred within the Ute Creek graben at a depth of ~8 km, suggesting

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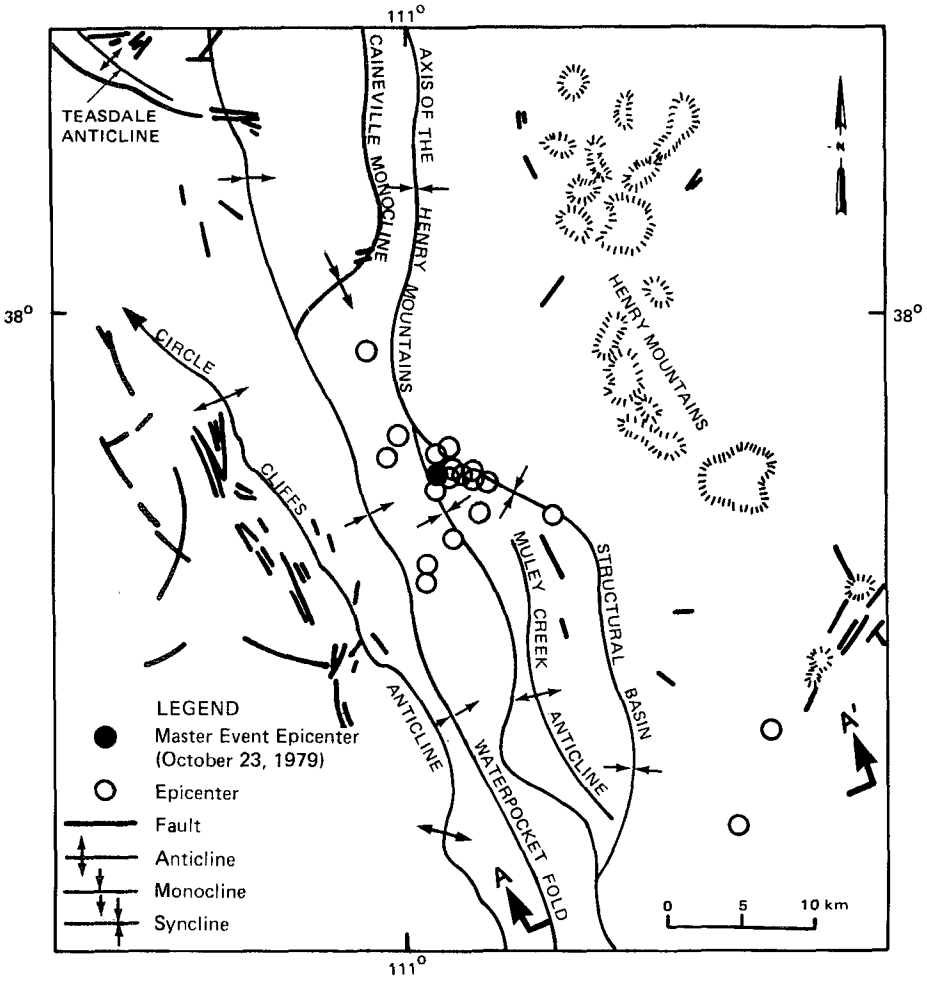

Figure 12. Seismicity near Capitol Reef National Park based upon master-event relocations, 1979–1980. Geologic features are taken from Hintze and Stokes (1964).

that the earthquakes may have been due to seismic slip on a reactivated part of the deep-seated, northeast-dipping fault zone beneath the flank of the Uncompahgre uplift or perhaps slip on one of the bounding faults of the Ute Creek graben (Fig. 15). The latter have been classified as potentially active by Kirkham and Rogers (1981). The main shock focal mechanism displays normal faulting on either an east-west-striking, north-dipping plane or a west-northwest-striking, southwest-dipping plane in response to a north-northeast minimum principal stress (Fig. 9c). This mechanism is similar to several focal mechanisms determined for western Colorado east of the Colorado Plateau (Wong, 1986) (Fig. 14).

San Juan Basin, New Mexico

Based on regional monitoring, principally by LANL and to a lesser extent by the ASL, seismicity in the San Juan basin (Figs. 2 and 3) appears to be similar to seismicity in the rest of the plateau: of low to moderate level, diffusely distributed, and of small to moderate magnitude (Sanford and others, 1981; Wong and others, 1984). From 1980–1981, the U.S. Geological Survey installed and operated a seven-station network in and around the San Juan basin (Jaksha, 1985). Supplementing arrival times with data from the LANL, 127 earthquakes ($M_L <$ 2.5) were located. Reliably determined focal depths ranged from 6 to 33 km for events recorded by the widely spaced stations (average, 70 km) (Jaksha, 1985).

The most significant earthquakes in the region were in an intense sequence of at least 200 events that began on 22 January 1966 near Dulce, New Mexico (Fig. 4). The sequence was located just within the plateau physiographic boundary and to the west of the Rio Grande rift near the Colorado–New Mexico border (Cash, 1971). The main shock was the largest earthquake in New Mexico since 1938 with a body-wave magnitude (m_b) of 5.5 and maximum intensities of MM VII or VII+. A focal mechanism for the main shock exhibits seismic slip on a north- or north-northwest-striking normal fault (Herrmann and others, 1980) (no. 37, Fig. 14).

In 1976 and 1977, two earthquakes of M_L 4.6 and 4.2, respectively, occurred near the town of Crownpoint (Wong and others, 1984). Both events were felt extensively in the Four Corners region with maximum reported MM intensities of VI, and both produced some minor damage. Relocation of the events placed them along the southern part of the San Juan basin. Although located within the Colorado Plateau stress province as proposed by Zoback and Zoback (1980), focal mechanisms exhibited normal faulting along northwest-striking planes and a northeast minimum principal stress direction (Wong and others, 1984) (nos. 21 and 22, Figs. 9c and 14).

An unusual aspect of the earthquakes near Crownpoint is that they originated at focal depths of 40–45 km (Wong and others, 1984). Based upon an average heat flow of 76 ± 14 mWm^{-2}, temperatures at the source depths of the earthquakes are estimated to be in the range of 600–1000 °C (Wong and Chapman, 1986). The large temperature range reflects the large uncertainty in the heat flow. The lower end of this range would be compatible with the occurrence of brittle failure in the upper mantle.

On the southern margin of the San Juan basin, earthquakes are concentrated along a northeast trend that coincides with the Jemez lineament extending from the Zuni uplift to the Nacimiento uplift (Sanford and others, 1979) (Fig. 4). The presence of several Pliocene and Pleistocene age volcanoes, including the Jemez and Mount Taylor volcanic centers, is consistent with this seismicity being associated with a transition zone between the Colorado Plateau and the southern Basin and Range.

Northern Arizona

Smith and Sbar (1974) proposed that the southern end of the Intermountain seismic belt coincides with the Paunsagaunt fault in northwestern Arizona as it dies out in an area of Quaternary volcanic flows at the north rim of the Grand Canyon (Fig. 4). The generally poor seismographic coverage of the state until recently has precluded the clear delineation of seismogenic sources within Arizona (Fig. 2). On the basis of a re-evaluation of the historical seismicity in northern Arizona, however, earthquakes appear to be concentrated along an arcuate belt called the "Northern Arizona seismic belt" in the southwestern part of the plateau (Brumbaugh, 1987). Somewhat consistent with

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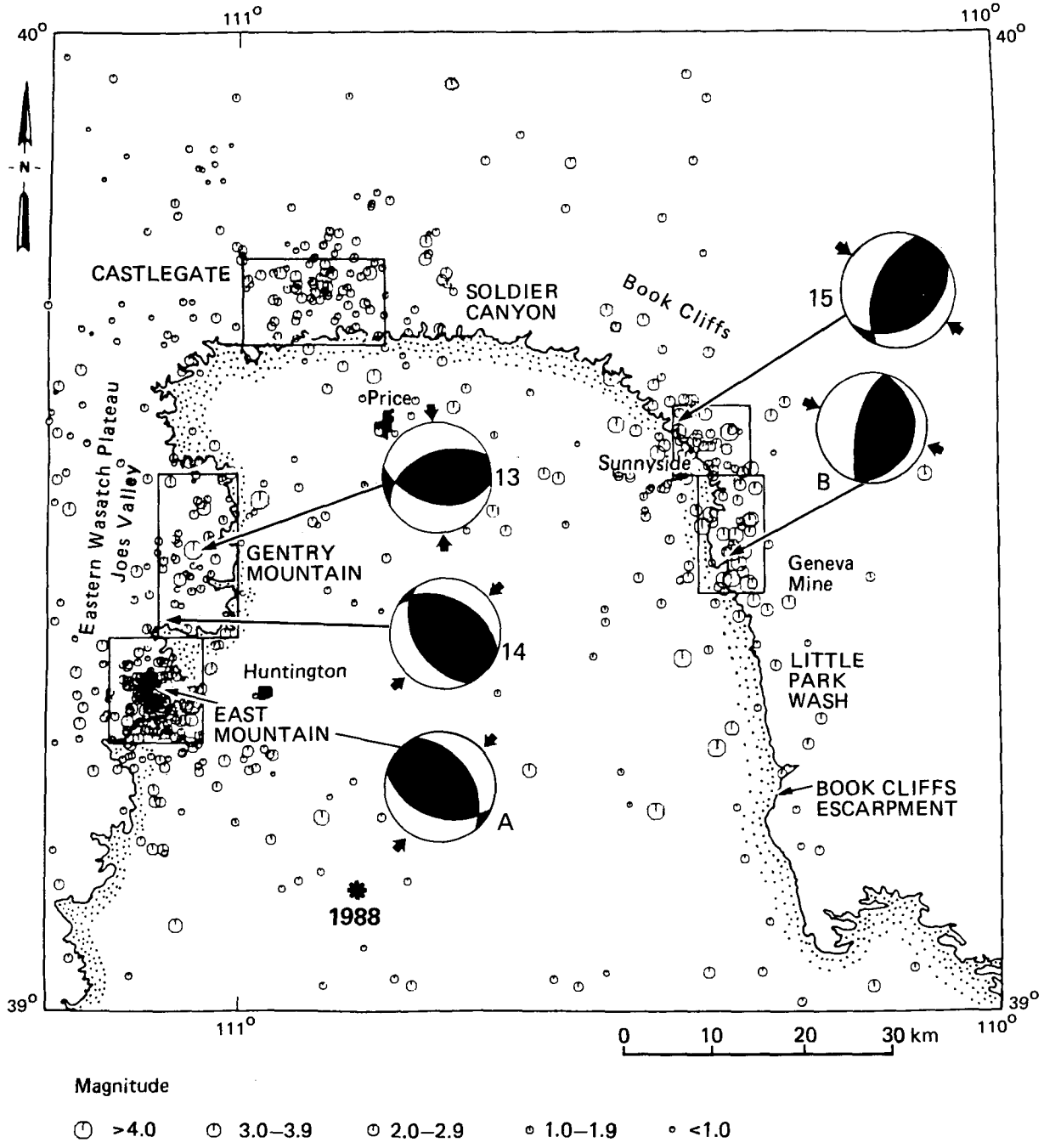

Figure 13. Seismicity, 1962–1981, schematic focal mechanisms (symbols as in Fig. 7), and mining districts in eastern Wasatch Plateau–Book Cliffs, Utah. Epicentral data are from UUSS. Focal mechanism A is a composite from McKee and Arabasz (1982); focal mechanism B is a composite from Smith and others (1974); 13, 14, and 15 are shown in detail in Figure 9b. The 14 August 1988 San Rafael earthquake of M_L 5.3 is also shown.

the known seismicity, systematic mapping of Quaternary faults in Arizona reveals that the greatest concentration of late Quaternary normal faults occurs near the Colorado Plateau margin in the northwestern and north-central part of the state with lesser concentrations in central and southeastern Arizona and the Lake Mead area (Pearthree and others, 1983). No Quaternary faults have been recognized in the interior of the plateau in northeastern Arizona. Within the plateau, detailed microearthquake investigations have been conducted in the Kaibab Plateau and the San Francisco volcanic field. During a six-week period in 1981, 296 events of $M_L \leqslant 2.5$ were recorded by a 12-station network in the Kaibab Plateau (Krueger-Kneupfer and others, 1985). Events ranged in depth from 5 to 20 km, with epicenters clustered near late Cenozoic faults. Single-event focal mechanisms exhibited normal faulting and an average T-axis orientation of east-northeast–west-northwest (no. 42, Fig. 14).

A focal mechanism of a M_L 3.6 earthquake in 1980 near Parks, based on regional record-

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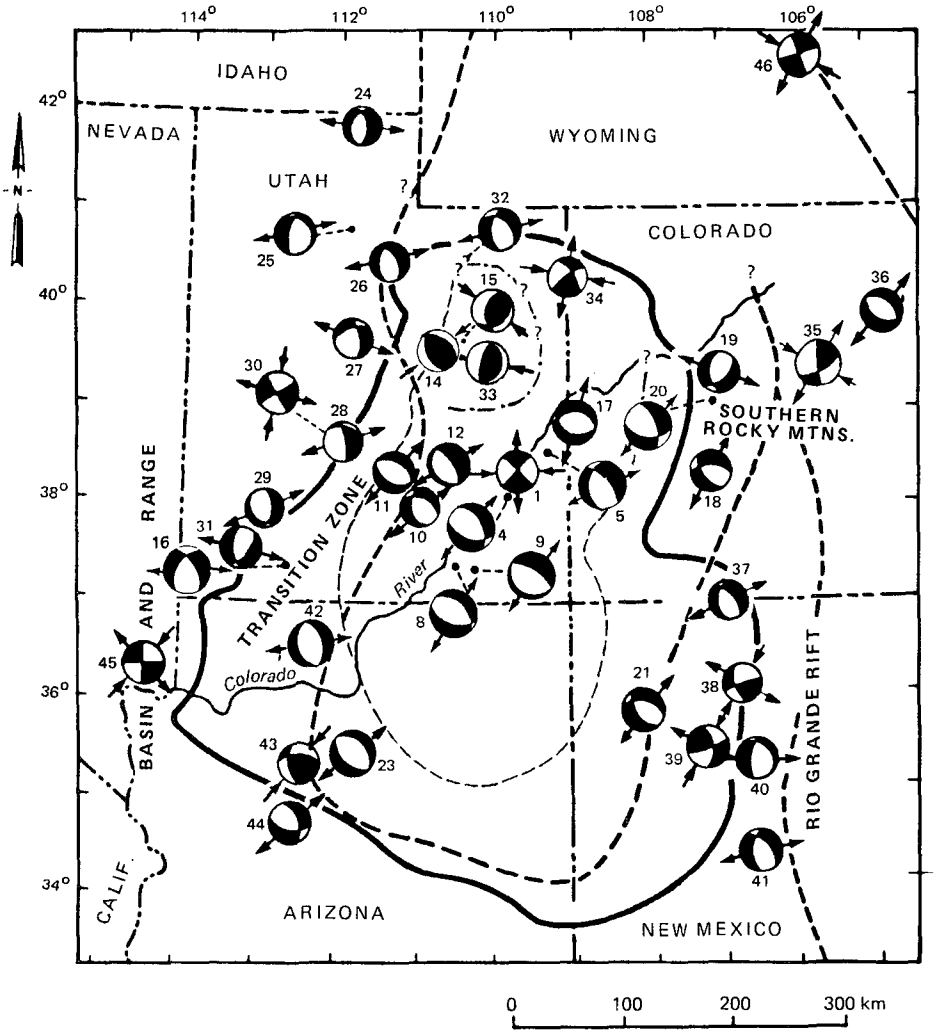

Figure 14. Schematic focal mechanisms (symbols as in Fig. 7) of the Colorado Plateau and adjacent regions. Data sources are listed in Table 1. Solid line represents the physiographic boundary of the Colorado Plateau. Heavy dashed lines are the stress provinces as defined by Zoback and Zoback (1980). Light dashed line represents the boundary of the low heat-flow thermal interior of the Colorado Plateau as defined by Bodell and Chapman (1982). Dashed and dotted line surrounds the eastern Wasatch Plateau–Book Cliffs area which appears to be characterized by a compressive state of stress.

TABLE 1. FOCAL MECHANISMS OF THE COLORADO PLATEAU AND ADJACENT REGIONS

Number	Source
1–23	This study; see Figure 9
24–29	Arabasz and others, 1980
30	Arabasz and Julander, 1986
31	Richins and others, 1981
32	Carver and others, 1983
33	Smith and others, 1974
34	Raleigh and others, 1972
35	Butler and Nicholl, 1986
36	Herrmann and others, 1981
37	Herrmann and others, 1980
38, 39	Sanford and others, 1979
40	Jaksha and others, 1981
41	Weider, 1981
42	Krueger-Kneupfer and others, 1985
43	Brumbaugh, 1981
44	Eberhart-Phillips and others, 1981
45	Rogers and Lee, 1976
46	Langer and others, 1985

ings, also exhibits normal faulting on northwest-striking planes and a northeast-directed T-axis similar to the Kaibab Plateau mechanisms (no. 23, Figs. 9c and 14). In contrast to this relatively high level of activity, M. Schnapp and others (unpub. data) recorded only nine local earthquakes during a seven-week period in the San Francisco volcanic field in 1976. Other monitoring efforts by NAU in the volcanic field have also revealed a low level of microearthquake activity (D. Brumbaugh, NAU, 1987, personal commun.). Recently, a five-station regional network has been installed by NAU in northern Arizona with the goal of improving the characterization of the contemporary seismicity.

Colorado Lineament

Hite (1975) suggested that the northeast-trending basement structures in the Canyonlands region may represent a segment of a much more extensive fault system. Warner (1978) assigned the name Colorado lineament to a 2,100-km-long system of northeast-trending Precambrian faults that extend from northern Arizona northeastward to Minnesota through the Colorado Plateau and are followed along much of their trend by the Colorado River (Fig. 1). Brill and Nuttli (1983) proposed that the Colorado lineament is a source zone for the larger earthquakes (m_b 4 to 6) in the west-central United States, including the Intermountain region, based on the spatial coincidence of several earthquakes within the lineament. A statistical analysis by Wheeler (1985) also supported this hypothesis. Wong (1981), however, argued that the Colorado lineament was not recognizable as a seismic source zone within the Intermountain United States because observed seismicity was not sufficient to establish continuity of activity along the lineament. Furthermore, only specific parts of the lineament should be considered as seismic source zones because it traverses several tectonic stress provinces (Wong, 1983).

On the basis of the observations of seismicity in the Canyonlands region, some earthquakes may be associated with possible northeast-striking Precambrian faults that underlie a part of the Colorado River (Fig. 7). The existence of a lineament in the Canyonlands region is still speculative, however. Elsewhere in the plateau, the orientation of fault planes as exhibited by focal mechanisms of earthquakes occurring within the Colorado lineament are oblique or perpendicular to the northeast trend of the lineament (Fig. 14). Additional information will be required (including investigations to verify the existence of the lineament and to define its geometry) before the hypothesized role of the Colorado lineament as a seismogenic source in the west-central United States can be understood.

CONTEMPORARY STATE OF STRESS

The focal mechanisms determined in this study contributed significant stress information to characterize the contemporary state of stress of the Colorado Plateau (Figs. 9 and 14). In contrast to a plateau interior being subjected to generally east-west tectonic compression, the combined data presented in this study imply a state of stress within the Colorado Plateau characterized by a rather uniform northeast-trending extension (Fig. 16). The predominance of the

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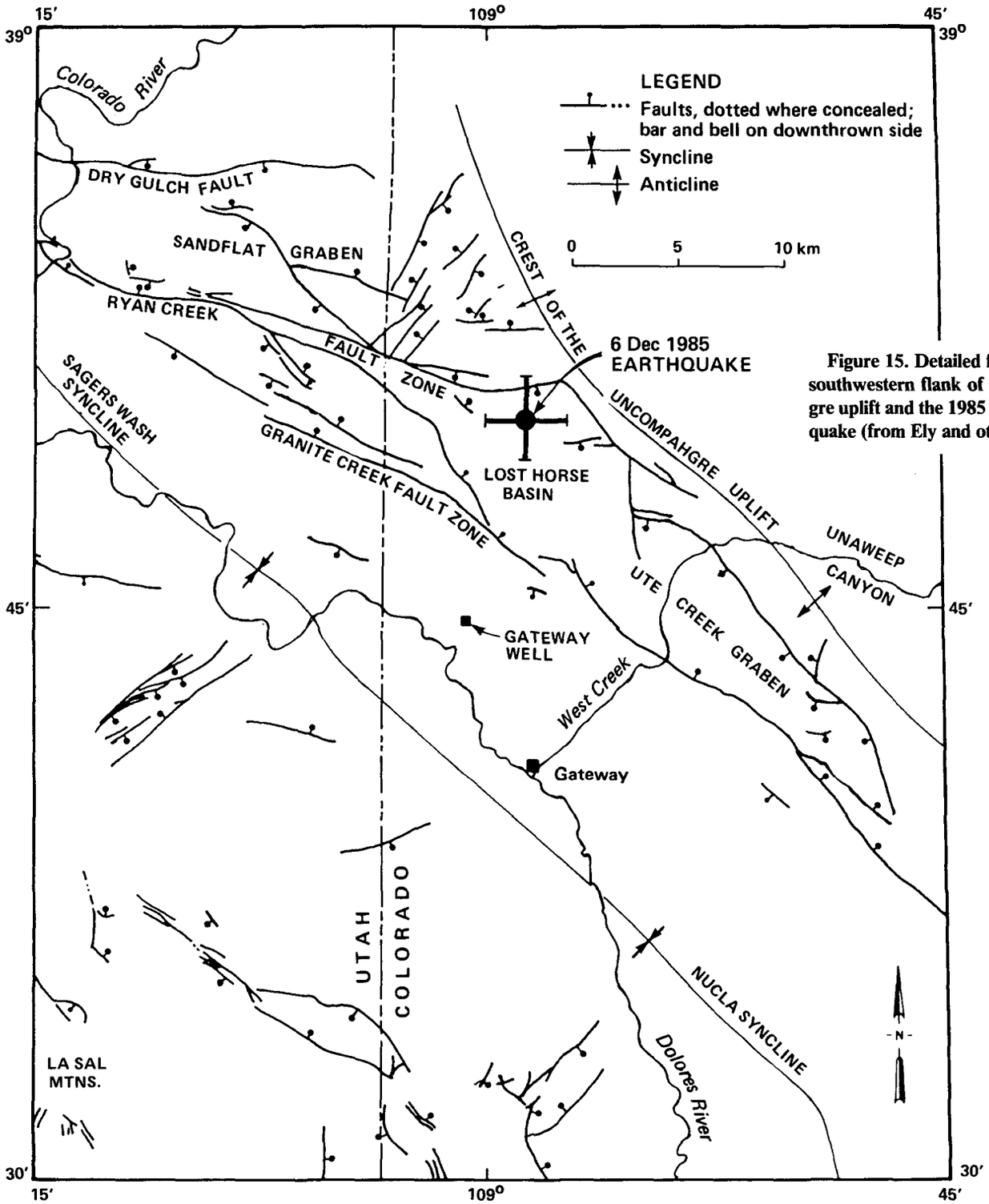

Figure 15. Detailed fault map of the southwestern flank of the Uncompahgre uplift and the 1985 Gateway earthquake (from Ely and others, 1986).

nearly vertical P-axes also attests to normal faulting as being the dominant style of contemporary seismic slip within the plateau. The direction of the minimum principal stress is rotated ~70° counterclockwise from the approximate west-northwest direction that characterizes the surrounding Basin and Range–Rio Grande rift province. (Within the Basin and Range–Colorado Plateau transition zone, the minimum principal stress direction varies from east-west to east-northeast–west-southwest along the Wasatch Front [Zoback, 1983] to west-northwest in central and southwestern Utah [Arabasz and Julander, 1986; Bjarnason and Pechmann, 1989].) On the basis of this difference in principal stress direction, the plateau appears to be a distinctive stress province as originally proposed by Zoback and Zoback (1980), although its boundaries are

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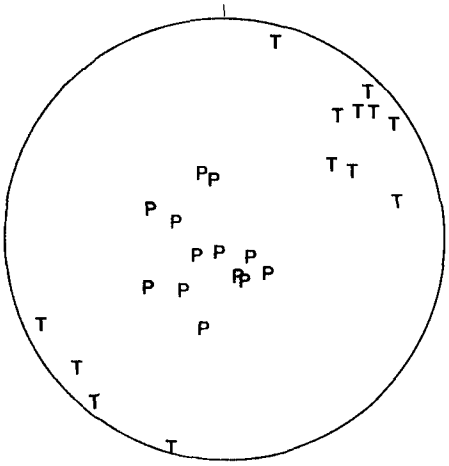

Figure 16. Summary of P and T axes from focal mechanisms of earthquakes within the Colorado Plateau as shown in Figure 14. Focal mechanisms of strike-slip earthquakes at shallow depths, of earthquakes along the plateau's margins, and within the eastern Wasatch Plateau–Book Cliffs are not included because they are not considered to be indicative of the state of stress of the Colorado Plateau.

not so clearly defined as along the transition zone in Utah. For instance, in Colorado, the limited data suggest that the minimum principal stress direction also trends in an approximate northeast direction throughout much of the state. Thus the distinction between a Colorado Plateau stress province and a Southern Great Plains province as defined by Zoback and Zoback (1980) is not clear and will require additional data (Wong, 1986) (Fig. 14). A tectonic boundary for the southern plateau in Arizona has been suggested by Brumbaugh (1987) on the basis of concentrations of seismicity and volcanism, crustal thickening, and a change in structural style.

Morgan and Swanberg (1985) have suggested that prior to 10 Ma, the plateau was topographically low with respect to the adjacent Basin and Range province, and they argue that this topography would have generated a compressional stress field at least in the uppermost crust. At ~10 Ma when the plateau first rose above the Basin and Range during the second major episode of uplift, this stress field would have been reversed (that is, extension) especially on the plateau's margins. On the basis of the new stress observations contained in this study, reversal of the plateau's stress field may have proceeded further along than was previously thought and may be nearly complete, with the possible exception of the eastern Wasatch Plateau–Book Cliffs.

The reverse faulting focal mechanisms in the eastern Wasatch Plateau–Book Cliffs still attest to a compressive state of stress (Figs. 13 and 14). Yet the lack of uniformity in the maximum principal stress direction, north to northeast in the eastern Wasatch Plateau and northeast to east-northeast in the Book Cliffs, questions the nature of these stresses. Mechanisms A, B, 13, and 15 probably represent earthquakes induced by underground coal mining activities (Fig. 13). Mechanism 14 represents a composite of several shallow events (depths less than 1.5 km) that were located away from any active mines in Huntington Canyon and thus outside the influence of any mining-induced stress changes. Although the similarity between mechanisms A and 14, and to some extent, between 13 and 14, implies that the state of stress, at least in the eastern Wasatch Plateau, is not associated with coal mining, the shallow depths of the events (less than 2–3 km) could allow local effects to mask the regional extensional stresses that prevail throughout much of the plateau's crust.

SUMMARY

Although major deformation within the Colorado Plateau ended at the close of the Laramide orogeny, the plateau is still seismically active. The contemporary seismicity can be characterized as being of small to moderate magnitude, and contrary to earlier views, of a low to moderate rate of occurrence with earthquakes widely distributed. Concentrations of earthquakes have been observed in Capitol Reef, Glen Canyon, and along the Colorado River in the Canyonlands region. By far the most seismically active region of the plateau, however, is the eastern Wasatch Plateau–Book Cliffs, where abundant small-magnitude seismicity has been and is presently induced by coal mining. The largest earthquakes observed to date, of possible M_L 5–6, have generally occurred in northern Arizona. Seismicity in the plateau appears to be the result of the reactivation of pre-existing faults not expressed at the surface but favorably oriented to the tectonic stress field; very few earthquakes can be associated with known geologic structures or tectonic features in the plateau. The generally small size of the earthquakes and their widespread distribution is consistent with a highly faulted Precambrian basement and upper crust, and a moderate level of differential tectonic stresses. Earthquakes in the plateau generally occur in the upper crust from the near-surface to a depth of 15–20 km, although events have been observed in both the lower crust and uppermost mantle in areas of observed low to normal heat flow. The latter suggests that temperatures are sufficiently low that brittle failure and hence earthquakes are still possible. The predominant mode of tectonic deformation within the plateau appears to be normal faulting on northwest- to north-northwest–striking faults, with some localized occurrences of strike-slip displacement on northwest- or northeast-striking planes at shallow depths.

The contemporary state of stress within the plateau is characterized by approximately northeast-trending extension in contrast to the previous belief that the plateau was being subjected to tectonic compression. This further suggests that reversal of the plateau's stress field due to uplift has proceeded further along than was previously thought. The eastern Wasatch Plateau–Book Cliffs, however, may still be characterized by compressive stresses; the nature of these stresses is not well understood. The concept of an extensional Colorado Plateau supports the idea of the plateau as a coherent, relatively stable crustal block (although such stability may be decreasing as stated by Morgan and Swanberg, 1985) that is responding to the same tectonic forces influencing much of the western Cordillera. The ~70° counterclockwise rotation in the minimum principal stress direction from the northern Basin and Range province suggests that the plateau's response to these extensional stresses may be somewhat different from the surrounding regions and that the plateau should be considered a distinctive stress province. This is not surprising given the differences between the Colorado Plateau and the adjacent provinces in both crustal and lithospheric properties (thickness, seismic velocities, heat flow) and its uplift history.

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