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THE CROWNPOINT, NEW MEXICO, EARTHQUAKES OF 1976 AND 1977

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Abstract

In 1976 and 1977, two unusually deep earthquakes of M_L 4.6 and 4.2, respectively, occurred near the town of Crownpoint in northwestern New Mexico. Both events were felt extensively in the Four Corners region with maximum reported Modified Mercalli intensities of VI. These earthquakes are two of the larger earthquakes observed within the Colorado Plateau and are among the strongest earthquakes reported in New Mexico outside the Rio Grande rift. Relocations of the events placed them within the Chaco slope along the southern portion of the San Juan basin—an area that appears to have exhibited a low level of historical seismicity and tectonism possibly since Laramide times. The most significant aspect of the 1976 and 1977 Crownpoint earthquakes is their focal depths of 41 and 44 km, respectively. Such depths would locate the events in the lowermost crust in the vicinity of the Moho in sharp contrast to the upper crustal origin of most intraplate earthquakes. Although located within the Colorado Plateau, revised fault plane solutions exhibit normal faulting along northwest-trending planes and northeast-southwest-trending minimum compression, which are characteristic of Basin and Range–Rio Grande rift extension. This observation suggests that this portion of the Colorado Plateau is located within a tectonic transition zone between the Basin and Range–Rio Grande rift and Colorado Plateau stress provinces.

Introduction

Two earthquakes of magnitude (M_L) 4.6 and 4.2 occurred on 5 January 1976 at 11:23 p.m. local time (0623 UTC) and 5 March 1977 at 8:00 p.m. local time (0300 UTC), respectively, near the town of Crownpoint in northwestern New Mexico. Both events were felt in New Mexico, Arizona, Utah, and Colorado with maximum reported Modified Mercalli (MM) intensities of VI. These earthquakes are two of the strongest events observed in New Mexico outside the Rio Grande rift and within the Colorado Plateau. The two events are significant because: (1) they occurred in the southern portion of the San Juan basin known as the Chaco slope, a region that has historically exhibited a low level of seismicity, and also near the boundary between the Colorado Plateau and Basin and Range–Rio Grande rift stress provinces as defined by Zoback and Zoback (1980); and (2) the source of the earthquakes appears to be located in the vicinity of the lower crust-upper mantle boundary.

The following is a discussion of new location determinations of the main shocks, revised fault plane solutions, intensity data, and the results of a brief aftershock survey. The implications of these data are discussed in the context of the regional seismotectonic setting and our present-day knowledge of deep focus intraplate earthquakes.

Geologic Setting

The Colorado Plateau is a moderately deformed platform surrounded by more highly deformed orogenic systems of the Cordilleran fold belt. Monoclines appear to be the most distinctive structural features of the plateau, and much of the plateau's deformation has occurred along them (Kelley, 1955). However, geograph-

ically widespread uplifts and structural basins are the features that most clearly define the major tectonic divisions of the plateau (Woodward and Callender, 1977). The San Juan basin, one of the three largest basins, is a large, roughly circular sediment-filled depression in the southeastern corner of the Colorado Plateau (Kelley, 1955). Structures of the San Juan basin and adjacent uplifts developed principally during the Laramide orogeny in late Cretaceous and early Tertiary time, whereas epeirogenic uplift of the Colorado Plateau occurred later in the Tertiary (Woodward and Callender, 1977). The basin is encircled on three sides by the Hogback monocline, which separates the basin from the Nacimiento uplift and Gallina-Archuleta arch to the east; the San Juan dome to the north; and the Four Corners platform to the west. The basin is bounded on the south by the Chaco slope. In a broader sense, the basin may be considered to extend southward to the Zuni uplift, in which case the Chaco slope is only a subdivision of the San Juan basin (Kelley and Clinton, 1960).

The Chaco slope is a homocline characterized as a strip of low northerly regional dip, approximately 180 km in length and 50 to 65 km wide. The overall regional dip is approximately 1° and the structural relief is nearly 800 m. The northern margin of the slope is marked by a reduction in the northward regional dip from 30 to 40 m/km to approximately 15 m/km (Hackman and Olson, 1977). Along the southern margin, the slope merges into the Zuni uplift without an obvious boundary (Kelley and Clinton, 1960).

Structurally, the Chaco slope is characterized by broad gentle flexes that parallel the strike of the beds, small plunging anticlines, and small elliptical dome-like anticlines. Numerous small high-angle faults that trend from north to east are associated with these folds (Kelley and Clinton, 1960). An en-echelon belt of right-stepping northeast striking normal faults 5 to 10 km south of the northern margin of the slope approximately parallels its dip inflection (Hackman and Olson, 1977). This zone may represent a deep-seated, left-lateral Laramide wrench fault that strikes west-northwest. The Crownpoint earthquakes are located epicentrally within this zone but, as will be discussed later, at considerable depth.

Historical Seismicity

The historical seismicity record for New Mexico extends back to the mid-1800s, when the state was first occupied by the United States. However, because the vast majority of the state's population settled within the Rio Grande Valley, the detection of earthquakes in other portions of the state, including the San Juan basin, was poor until 1962, when several WWSSN stations were installed in New Mexico and neighboring states (Sanford *et al.*, 1979). In 1973 and 1976, the number of seismographic stations increased dramatically as the Los Alamos National Laboratory and the Albuquerque Seismological Laboratory of the U.S. Geological Survey began operation of two permanent seismographic networks located primarily within the Rio Grande rift. Thus, the most complete and accurate instrumental record for the San Juan basin essentially begins in 1973. The seismicity of the region for the period 1973 through 1982 is shown in Figure 1 (Cash *et al.*, 1983). The accuracy of the epicenters outside the Rio Grande rift is at best ±5 km because most of the events were located outside the existing networks.

The majority of seismicity in northwestern New Mexico appears to define the eastern and southern margins of the San Juan basin and possibly the Colorado Plateau (Figure 1). On the eastern margin of the basin, the seismicity appears to be

associated with the major north-south system of faults related to the Nacimiento uplift and Gallina-Archuleta arch (Sanford *et al.*, 1979). Cretaceous and early Cenozoic sediments along the basin margin dip steeply westward from these faults. Several earthquakes have been located in such regions of high bedrock gradients, including the strongest earthquake in New Mexico since 1938, the 23 January 1966 Dulce earthquake (m_b 5.5, M_S 4.9) (Sanford *et al.*, 1981).

On the basin's southern margin, a trend of epicenters that extend from the Zuni uplift northeast to the southern end of the Nacimiento uplift-Gallina-Archuleta

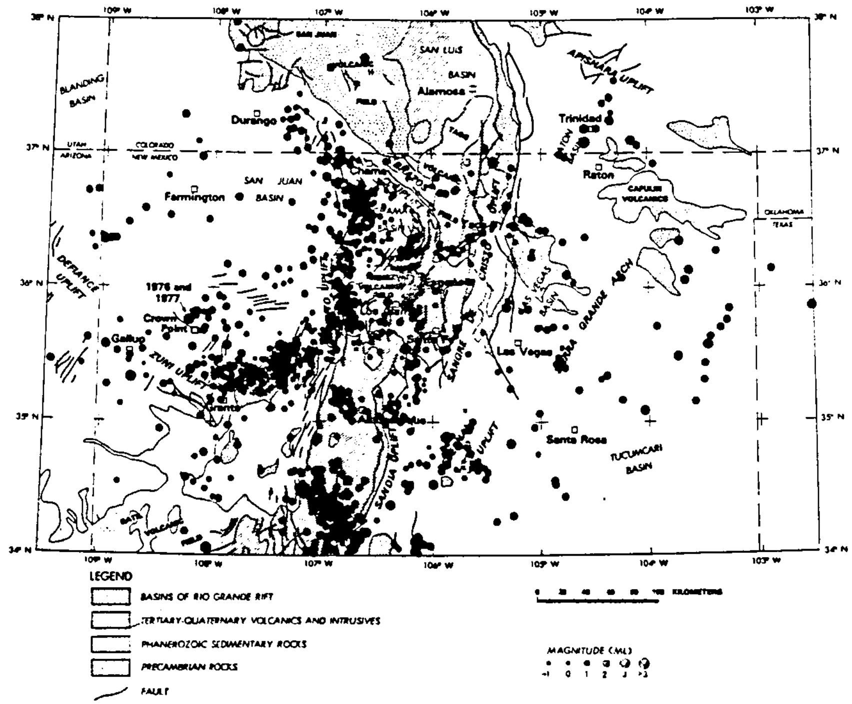

FIG. 1. Seismicity for the period September 1973 to December 1982 and generalized geology of northern New Mexico (Cash *et al.*, 1983).

arch epicentral alignment (and possibly farther) (Figure 1) coincides with the Jemez lineament (Sanford *et al.*, 1981). The lineament is defined by several Pliocene and Pleistocene age volcanoes, including the Jemez and Mt. Taylor volcanic centers. Within the basin, the seismicity can be characterized as low level, diffusely distributed, and of small magnitude, which is consistent with other observations of seismicity within the Colorado Plateau interior (Wong *et al.*, 1983). The 1976 and 1977 Crownpoint earthquakes are among the largest events observed in the plateau.

Observations and Data Analysis

Epicentral locations. Locations of the Crownpoint earthquakes were determined by the National Earthquake Information Service (NEIS), which employed a standard least-squares algorithm utilizing Jeffrey-Bullen travel time tables, and by the Los Alamos National Laboratory, which employed a computer adaptation of the graphical arc technique. For this study, the events were relocated utilizing the hypocentral location program HYPOELLIPSE (Lahr, 1979) and multiple velocity models. Crustal and upper mantle velocity models for the San Juan basin (Jaksha and Evans, 1984), the Colorado Plateau (Wong *et al.*, 1983), or southern Arizona (Warren, 1969) were assigned to each seismographic station used in the location, based upon the model in which the travel time of the respective seismic wave was longest. Arrival time and first motion data were collected from all known seismographic stations operating in the intermountain United States at the times of the earthquakes. The HYPOELLIPSE relocations are improved over the earlier locations because only high quality *P*-wave arrivals (*S* waves were generally unreadable), and more appropriate velocity models were used, and because azimuthal coverage was improved. The locations determined in this study and the NEIS locations are listed in Table 1. Within the accuracy of the two solutions (as illustrated by the diameters of the epicenters which are equal to the standard errors in location), the Crownpoint earthquakes may have occurred in the same location and thus may have a common source (Figure 2).

TABLE 1

Hypocentral Locations and Origin Times

	5 January 1976		5 March 1977	
	NEIS	This Study	NEIS	This Study
Origin time	0623 32.9	0623 33.9	0300 54.7	0300 55.8
Latitude	35°N 50.6′	35°N 49.0′	35°N 54.9′	35°N 44.9′
Longitude	108°W 20.5′	108°W 12.7′	108°W 17.2′	108°W 13.3′
Focal depth	25.0 km (Fixed)	40.5 km	21.8 km	43.6 km
rms	1.2 sec	0.37 sec	1.1 sec	0.29 sec
Standard errors				
Epicenter	3.1 km	3.4 km*	3.1 km	2.4 km*
Depth	—	6.5 km†	12.5 km	3.6 km†

* Larger horizontal axes of one standard deviation error ellipsoid.

† Greatest vertical deviation of one standard deviation error ellipsoid.

Focal depths. The most unusual characteristic of the 1976 and 1977 Crownpoint earthquakes is their focal depths, determined in this study to be 40.5 ± 6.5 and 43.6 ± 3.6 km, respectively. Although the focal depths calculations are not well constrained because of the lack of a close seismographic station (the closest was approximately 80 km away), they are considered reliable because of the good fit to the *P*-wave data. As a test of the calculated focal depths, the root mean square (rms) of the travel-time errors of both earthquake locations was determined as a function of depth employing the previously mentioned velocity models (Figure 3) and variations of single and multiple models. In all cases, both events exhibit strong rms minima at the 40 to 45 km depths, and large rms values at shallower depths.

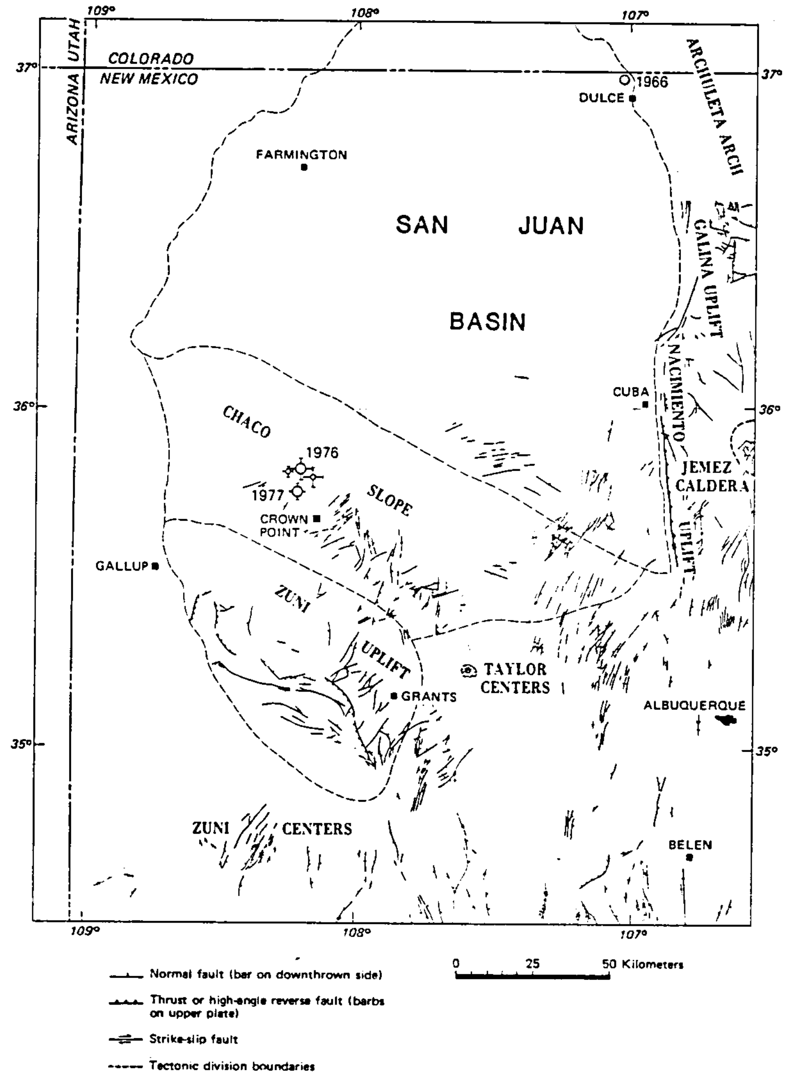

FIG. 2. Epicentral locations of the 1976 and 1977 earthquakes and two aftershocks of the 1976 main shock. The epicentral bars are equivalent to the standards errors in the location. Also shown is the epicenter of the 1966 Dulce earthquake. Tectonic divisions are taken from Kelley and Clinton (1960) and faults are from Hackman and Olson (1977).

This observation suggests that the P-wave data constrain the earthquakes at the 40 to 45 km depths fairly well.

Dewey (1982) determined values of 44 and 41 km, respectively, for the 1976 and 1977 events, using the method of joint hypocenter determination. The nuclear explosion "Gasbuggy," which occurred in the San Juan basin 35 km southwest of Dulce, was employed as the calibration event. The uncertainty of these depths is

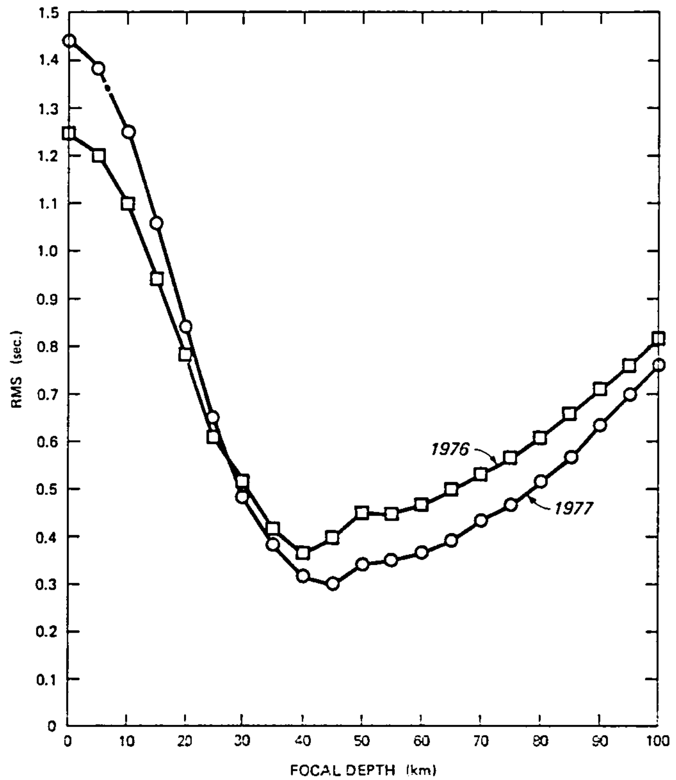

FIG. 3. rms of the location determinations versus focal depth for the 1976 and 1977 earthquakes.

estimated to be 5 to 10 km (J. Dewey, U.S. Geological Survey, personal communication, January, 1984).

These depths are also consistent with a strong near-surface reflected phase that is exhibited on several seismograms. Figure 4 shows the first 25 sec of the short-period Benioff seismograms recorded at the WWSSN stations Tucson, Arizona, Golden, Colorado, and Dugway, Utah, for the 1977 event. All three records exhibit an impulsive phase at 8.0 sec after the initial P_n arrival despite the range in distances. Records of the 1976 event also display a distance-independent phase at

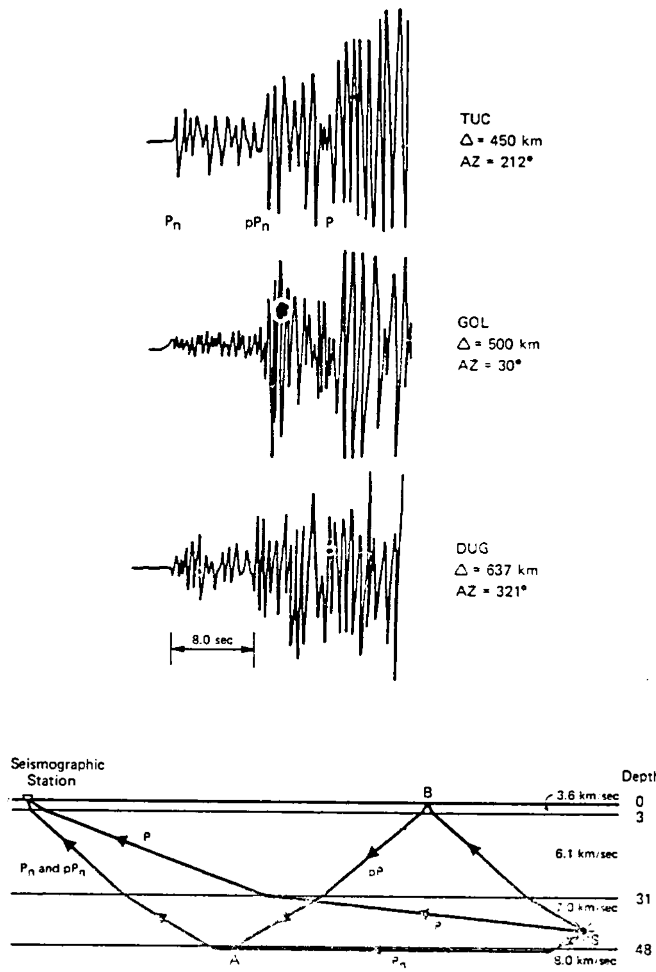

FIG. 4. The first 25 sec of the 1977 Crownpoint earthquake as recorded on the short-period Benioff seismographs at the WWSSN stations at Tucson, Arizona, Golden, Colorado, and Dugway, Utah. Also, a simplified diagram of the ray paths for P_n and pP_n in the plane-layer velocity model for the San Juan Basin (Jaksha and Evans, 1984). The time interval between P_n and pP_n is simply the time difference between waves traveling along the path SA as P_n and SBA as pP.

approximately 8.0 sec which is believed to be pP_n. Based on a velocity model of the crust and upper mantle for the San Juan basin (Jaksha and Evans, 1984), the interval between P_n and pP_n for an earthquake at a depth of 43 km recorded at regional distances greater than approximately 200 km should be 8.0 sec (Figure 4).

The direct P wave of the 1976 earthquake (M_L 4.6, m_b 5.0) was recorded at 26

seismographic stations beyond a distance of 70° with 23 stations recording an impulsive arrival based on the ISC Bulletin. By comparison, the 4 February 1976 Chino Valley, Arizona, earthquake (M_L 5.1, m_b 4.9) had a focal depth of 12 km, and its direct P wave was recorded at only four stations beyond 40° (none impulsive). This difference in transmitted energy for earthquakes of similar size occurring in similar geologic settings suggests that the 1976 Crownpoint earthquake was significantly deeper, possibly in the higher Q lower crust/upper mantle. The total crustal thickness in the vicinity of Crownpoint is estimated to be 48 km (Jaksha and Evans, 1984), and given the uncertainty of this value and that of the focal depths, the two earthquakes probably occurred in the lowermost crust in the vicinity of the Moho.

Magnitudes and intensity data. Several agencies employing different techniques have estimated the magnitudes of the 1976 and 1977 earthquakes. NEIS determined m_b 5.0 and 4.6 values based on short-period Benioff seismograms recorded at WWSSN stations, and M_L 4.6 and 4.2 from the Wood-Anderson seismograph at Albuquerque. Wechsler *et al.* (1980) determined M_L 4.6 and 4.3 based on coda durations recorded by the Los Alamos network.

Isoseismal maps for the 1976 and 1977 earthquakes were produced by NEIS (Simon *et al.*, 1978, 1979) (Figure 5). In the 1976 earthquake, the maximum MM intensity VI was observed at several locations in Arizona, Colorado, and New Mexico. Although the towns of Crownpoint and Standing Rock were located within 20 km of the epicenter, only minor damage, generally in the form of cracked plaster, was sustained (Simon *et al.*, 1978). Some groceries shaken off store shelves were reported in Farmington and Fence Lake, New Mexico. No noticeable changes were noted at the Indian Ruins in Chaco Canyon National Monument, located approximately 35 km northeast of the epicenter. The ruins contain some free-standing uncemented, rock walls over 4 m high. The maximum intensity observed in the 1977 event was also MM VI; however, only two instances occurred, and they were within 70 km of the epicenter. Slightly displaced fences were noted at Crownpoint, and existing cracks were widened considerably in the town of Prewitt (Simon *et al.*, 1979) (Figure 5).

For comparison, the M_S 4.9 shallow focus 1966 Dulce earthquake (3 km; Herrmann *et al.*, 1980) had a maximum reported MM intensity of VII+ with considerably more structural damage than was incurred in either of the Crownpoint earthquakes. Damage occurred principally in the town of Dulce, approximately 5 km south of the epicenter. This damage took the form of plaster fallen from ceilings, cracks in brick walls, broken windows, cracked plaster walls, fallen or damaged chimneys, and fallen groceries in stores (Hoffman and Northrop, 1977). The relative lack of damage in the 1976 Crownpoint earthquake may be caused in part by its 41-km depth.

Total felt areas for the 1976 and 1977 events were 115,000 and 51,400 km², respectively. The total felt area for the Dulce earthquake, although not well constrained, was estimated to be 39,000 km² (Hoffman and Northrop, 1977). The 1976 Chino Valley earthquake (M_L 5.1, m_b 4.9), which was located in a similar geological setting, had a total felt area of 25,000 km². The much greater felt area for the comparable or slightly smaller 1976 earthquake (M_L 4.6, m_b 5.0) would also support a greater than normal depth for this event.

Fault plane solutions. Fault plane solutions were produced employing the program HYPOELLIPSE (Lahr, 1979) using revised hypocentral locations, a greater number of first motions, and the recently determined velocity model for the San Juan basin (Jaksha and Evans, 1984). A known depth to the Moho below the San Juan basin

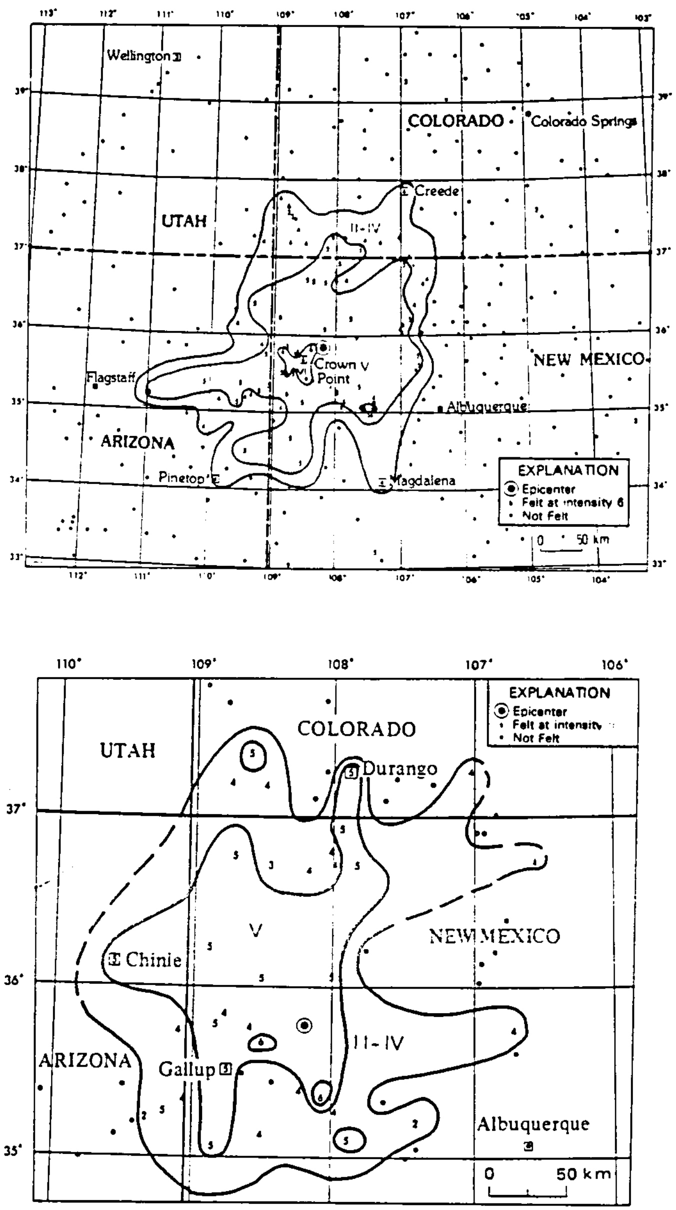

FIG. 5. Isoseismal maps of the 1976 and 1977 earthquakes, *top* and *bottom*, respectively (Simon *et al.*, 1978, 1979). Epicenters shown were revised in this study.

was particularly crucial in determining the take-off angles from the focus, because the Crownpoint hypocenters were located in the vicinity of the Moho.

The Crownpoint earthquake fault plane solutions in Sanford *et al.* (1979), which were not well constrained, exhibited strike-slip faulting on northwest- or northeast-trending planes for the 1976 event and oblique-strike-slip faulting on north-north-east- or west-northwest-trending planes for the 1977 event. The revised fault plane solutions are similar: both exhibit normal faulting on northwest-trending planes and a tectonic stress field characterized by northeast-southwest-trending minimum compression (Figure 6). The similarity of the fault plane solutions is further evidence that the 1976 and 1977 earthquakes had the same source.

Aftershocks. On 6 January 1976, portable microearthquake recorders were deployed at 11 sites by the Los Alamos National Laboratory, the U.S. Geological Survey Albuquerque Seismological Laboratory and the U. S. Geological Survey,

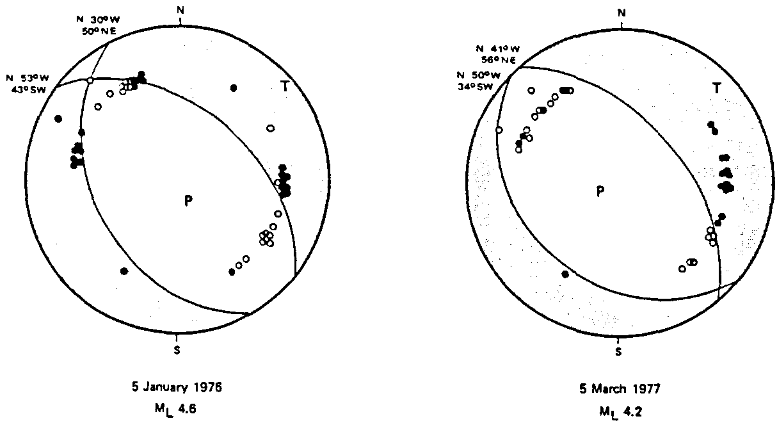

FIG. 6. Fault plane solutions of the 1976 and 1977 earthquakes. Shown are equal-area projections of the lower hemisphere. Solid circles are compressions and open circles are dilatations. *P* and *T* represent compression and tension axes respectively.

Denver. Five aftershocks are known to have occurred following the main shock (Table 2). The aftershocks on 7, 8, and 12 January were recorded on portable recorders; of these three events, sufficient data were acquired to locate the 8 and 12 January aftershocks (Figure 2). The events located at depths of 22.8 ± 3.2 km and 32.0 ± 2.2 km, respectively. Because of the closeness of the portable stations (stations were within one focal depth of the events), these locations are considered more accurate than the main shock location. Epicentrally, the aftershocks locate within 3 km of the main shock, and within one standard error of the main shock location (Figure 2). Although the aftershocks are not as deep as the main shock, they are still deep for intraplate earthquakes in the Western United States. The difference in focal depth between the shallowest aftershock and the main shock would make it unlikely that the aftershock occurred in the rupture zone of the main shock. It is possible, however, that the aftershock was triggered by the main shock either on a continuation of the same fault or an associated fault.

Two aftershocks of the 1977 earthquake were regionally recorded by the Los Alamos National Laboratory network (Wechsler *et al.*, 1980): a M_L 0.8 event on 5 March at 0528 UTC and a M_L 2.2 event on 9 March at 1835 UTC. No aftershock monitoring was attempted after the 1977 main shock.

The small number of aftershocks for the 1976 and 1977 events is in contrast to the 1966 Dulce earthquake, which was followed by 132 aftershocks in the 9 days subsequent to the main shock and several hundred in the following few years. However, it is not unusual for moderate-sized earthquakes in New Mexico to have very few aftershocks (A. Sanford, NMIMT, personal communication, 1984).

DISCUSSION

Tectonic implications. The Basin and Range-Rio Grande rift stress province is characterized as a region of active crustal spreading where normal faulting is the primary mode of deformation. The tectonic stress field consists of a vertical maximum compressive stress and north-northeast-trending intermediate compressive stress, both of which are greater than the west-northwest-trending minimum compressive stress (Zoback and Zoback, 1980). This stress field is in contrast to the Colorado Plateau interior stress field, which is characterized by a generally east-

TABLE 2
1976 AFTERSHOCKS

Date	Origin Time (UTC)	Latitude	Longitude	Depth (km)	M_L	rms (sec)	ERH (km)	ERZ (km)	DMIN (km)
5 Jan. 1976	0844	—	—	—	1.6	—	—	—	—
7 Jan. 1976	0550	—	—	—	0.0	—	—	—	—
8 Jan. 1976	0019 48.7	35°48.7′	108°15.3	22.8	0.0	0.13	1.6	3.2	15.2
12 Jan. 1976	1042 20.3	35°47.2′	108°14.1′	3.20	1.1	0.23	3.3	2.2	31.6
16 Jan. 1976	2207	—	—	—	2.3	—	—	—	—

west maximum compressive stress and a minimum compressive stress that is oriented either vertical or north-south (Zoback and Zoback, 1980; Wong *et al.*, 1983). Zoback and Zoback (1980) defined an approximate boundary between the Basin and Range–Rio Grande rift and Colorado Plateau (interior) stress provinces in northwestern New Mexico based principally on the earlier versions of the fault plane solutions of the Crownpoint earthquakes (Figure 7).

The 1976 fault plane solution in Sanford *et al.* (1979) was similar to solutions for seismicity in the Colorado Plateau interior, showing predominantly strike-slip faulting with an east-west-trending maximum compression indicative of the plateau stress field (Wong *et al.*, 1983). The earlier solution of the 1977 earthquake (also a strike-slip mechanism) (Sanford *et al.*, 1979), however, showed a northeast-southwest-trending minimum compression more reflective of the Basin and Range–Rio Grande rift stress province. The revised, almost identical, Crownpoint earthquake fault plane solutions now suggest that at least in the lower crust/upper mantle beneath this portion of New Mexico, Basin and Range–Rio Grande rift-like tectonic stresses and deformation predominate (Figure 6).

Assuming that the tectonic stress field at depths of 40 to 45 km is representative of the stress field at upper crustal depths, the most significant implication of the Crownpoint earthquake fault plane solutions is that the boundary between the

Colorado Plateau and Basin and Range–Rio Grande rift stress provinces in New Mexico is west of the approximate boundary defined by Zoback and Zoback (1980). However, the presence of normal faulting (or a vertical maximum compressive stress) is in itself insufficient proof for Basin and Range–Rio Grande rift extensional stresses. At depths of 40 to 45 km, normal faulting may simply be the predominant mode of faulting caused by the vertical stresses (lithostatic pressure) being greater than the horizontal stresses. For instance, a change in focal mechanisms from primarily strike-slip faulting for earthquakes shallower than 6 km to normal faulting

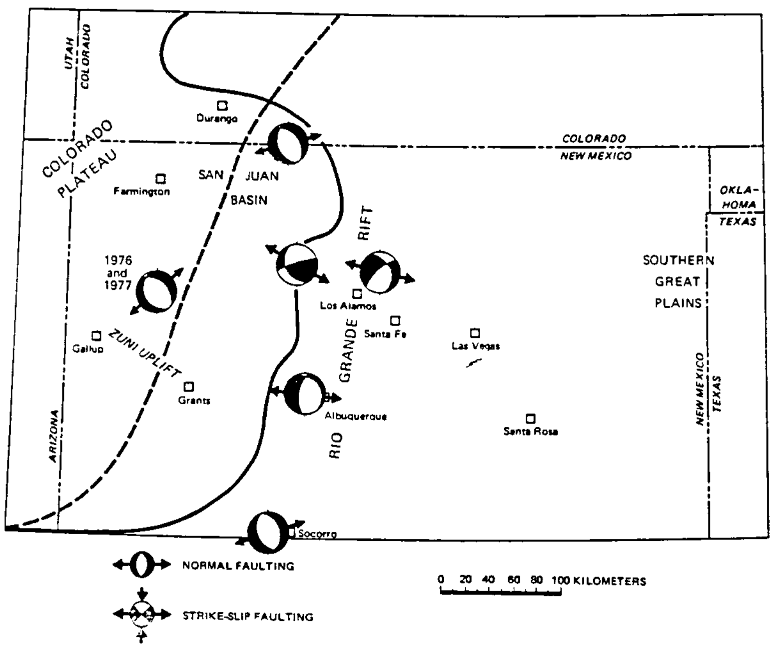

FIG. 7. Fault plane solutions for northern New Mexico. Dashed line represents approximate boundary of Colorado Plateau stress province as defined by Zoback and Zoback (1980). Solid line represents the Colorado Plateau physiographic province boundary. Outward directed arrows on the fault plane solutions are the horizontal projections of the T axes. The two solutions near Los Alamos from Sanford *et al.* (1979) are provisional. Other solutions are from Herrmann *et al.* (1980), Jaksha *et al.* (1981), and Wieger (1981).

for events deeper than 10 km has been observed in the western Great Basin. Vetter and Ryall (1983) attributed this change to increasing overburden pressure resulting in a rotation of the maximum compressive stress from horizontal at depths less than approximately 6 km to vertical below a depth of 9 km.

The Crownpoint fault plane solutions exhibit normal faulting similar to the normal faulting solutions along the Rio Grande rift (Figure 7). However, the direction of extension (northeast-southwest) is rotated from 30° to 60° counterclockwise from the extensional direction observed along the rift (approximately east-west). This rotation could be insignificant considering the variability of fault plane

solutions as observed even in localized areas. It could also reflect the control of preexisting zones of weakness or the location of the Crownpoint earthquakes in the transition zone between the Colorado Plateau and Basin and Range–Rio Grande rift stress provinces. The direction of extension exhibited in fault plane solutions for several earthquakes in the transition zone in south-central Utah also shows the direction of extension trending northeast-southwest, rotated slightly counterclockwise from the extensional direction farther west in the Basin and Range (Wong *et al.*, 1983). In this case and for the Crownpoint area, the direction of extension strikes nearly parallel to the approximate boundary of the Colorado Plateau interior as defined by Zoback and Zoback (1980) (Figure 7). More stress data will be necessary to determine whether the Colorado Plateau-Rio Grande rift transition zone in New Mexico is characterized by an extension direction rotated counterclockwise from the direction of extension within the rift.

Focal depths and thermal implications. Because the source of the Crownpoint earthquakes is probably near the Moho, these events are probably not associated with any geologic structure expressed at the surface. Their occurrence is possibly more a manifestation of material composition, conditions of temperature, pressure (including pore pressure), and zones of weakness in the lower crust and/or upper mantle. Most earthquakes in the intermountain United States occur in the upper crust, above a depth of 15 to 20 km. Earthquakes along the Rio Grande rift generally occur at depths no greater than 20 km (Sanford *et al.*, 1981), and probably the vast majority are no deeper than 15 km. Smith (1978) noted that 96 percent of the earthquakes observed in detailed microearthquake surveys of the Intermountain seismic belt are shallower than 15 km, which may represent the maximum depth of brittle deformation in the areas along the belt.

Chen and Molnar (1983) observed that, on a world-wide basis, in intraplate regions of extensional tectonics where high geothermal gradients are expected, most seismicity occurs above 15 km and the lower crust is generally aseismic, except possibly in the lowermost crust. In the Basin and Range province, the depth of 15 km corresponds to an approximate temperature of 350° ± 100°C. Below such depths, crustal temperatures are sufficiently high that the ductile strength of crustal rocks becomes less than their brittle strength and the rocks will deform ductilely (aseismically) rather than by the brittle failure mode of stick-slip (Chen and Molnar, 1983). Apparent exceptions include the Sierran foothills of central California, where seismicity has been observed at depths of 12 to 38 km in the lower crust (Wong and Savage, 1983). However, the entire crust beneath the foothills may be cooler than 350°C.

In the upper mantle below certain intraplate or intracontinental regions, the ductile strength of the rocks can be greater than their brittle strength even at the higher temperatures because of the different composition of the rocks. Thus, intraplate earthquakes can also occur in the upper mantle and have been observed in several areas world-wide. Chen and Molnar (1983) suggested that many of these areas are ones of recent continental convergence and thick crust, although they have also noted several exceptions, such as a M_L 3.6 earthquake located at a depth of 90 km in northeastern Utah (Zandt and Richins, 1980).

Wong *et al.* (1983) observed several microearthquakes in southeastern Utah occurring at depths of 38 to 40 km; one event was as deep as 58 km. The Moho is estimated to be at a depth of 40 km in this portion of the Colorado Plateau interior. Although the uplift of the Colorado Plateau is believed to be caused by the warming of a cool remnant subducted slab beginning approximately 20 m.y. ago (Thompson

and Zoback, 1979), upper mantle temperatures in the Colorado Plateau at present have been suggested to be relatively high. Temperatures of 1000° to 1200°C at a depth of 50 km have been reported based upon magnetotelluric measurements made near Farmington, New Mexico, in the northern portion of the San Juan basin (Pedersen and Hermance, 1981). Reiter *et al.* (1979) predicted temperatures of 350°C at a depth of 20 km and 900°C at 60 km. This latter upper mantle temperature is more compatible with the limiting temperatures of 600° to 800°C for earthquake occurrence in mantle materials, as suggested by Chen and Molnar (1983).

The Crownpoint earthquakes are located in a region that may be transitional not only between the Colorado Plateau and Basin and Range–Rio Grande rift stress provinces but also in terms of heat flow. The earthquakes are located between the interior of the San Juan basin, which is characterized by low values of 1.5 heat flow units or less, and the Zuni uplift, whose heat flow ranges from 2.0 to 2.5 heat flow units (Reiter *et al.*, 1975). The occurrence of the Crownpoint earthquakes at depths of 22 to 44 km suggests that temperatures in the lower crust beneath the southern San Juan basin are low enough to allow the occurrences of brittle failure. Further studies of the relationship between earthquake occurrence, crustal and upper mantle temperatures and material composition, and data on the crust and upper mantle temperatures beneath this portion of the transition zone will be required to improve our understanding of these deep intraplate earthquakes.

Summary

In 1976 and 1977, two moderate-sized earthquakes occurred near Crownpoint, New Mexico, in a region that has historically exhibited a low level of seismicity. They are among the largest of the few earthquakes reported felt in northwestern New Mexico. Fault plane solutions of the Crownpoint earthquakes suggest that a northwest-trending normal fault is the source of the events and that the Colorado Plateau-Basin and Range–Rio Grande rift stress provinces boundary is located further west than was previously thought. The unusual aspect of these two earthquakes is that they appear to originate in the lowermost crust in the vicinity of the Moho. Such deep intraplate earthquakes may reflect specific material composition and thermal conditions in the lower crust/upper mantle that are conducive to brittle deformation; however, they are probably not associated with any geologic feature expressed at the surface.

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