THE DULCE, NEW MEXICO EARTHQUAKE
JANUARY 23, 1966

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ABSTRACT: On January 22, 1966 at 18:56:38.0, Mountain Standard Time (January 23, 1966, 01:56:38.0 GMT), an earthquake of magnitude 5.5 occurred in north-central New Mexico near the town of Dulce. There was damage to homes and school buildings, but there were no injuries. Intensity at Dulce was VII on the Modified Mercalli Intensity scale. Many aftershocks followed the main event, and on January 29, three temporary seismograph stations were installed in the area.

FOREWARD

A preliminary report on this earthquake written during 1966 was never published. Renewed interest in the seismicity of New Mexico has been the motivating factor in revising and publishing this article. Several references are made to the U.S. Coast and Geodetic Survey (USCGS) which in 1966 was responsible for earthquake epicenter location. The Coast and Geodetic Survey is now the National Ocean Survey, and the Seismology Division of the USCGS is now part of the Geological Survey.

Additional information on the main event and its aftershocks has been published by the USCGS in MSA-129 by von Hake and Cloud (1968), by Sanford and Cash (1969), and Cash (1971).

INTRODUCTION

On January 22, 1966 at 18:56:38.0, Mountain Standard Time (January 23, 1966, 01:56:38.0 GMT), an earthquake of magnitude 5.5 (m b) was felt
over a wide area of northern New Mexico and southern Colorado. Many aftershocks of lesser intensity continued to occur for several months after the main earthquake. The main earthquake caused damage at Dulce, New Mexico, a small town of about 2,000 people where the Department of Interior, Bureau of Indian Affairs, maintains the headquarters for the Jicarilla Apache Indian Reservation. There were no reported injuries from this earthquake.

The Dulce area had experienced an earthquake about 66 years earlier on May 4, 1900. Our only record of this event is a press item entitled "50 Years Ago" that appeared in the Albuquerque Journal, May 4, 1950:

“A terrific earthquake shock occurred in Northern New Mexico Monday. It was especially severe at Nonoro, Lumberton, and Edith. No buildings were destroyed, and no one was injured.”

Microfilm of the Albuquerque papers for the period May 4-12, 1900, was searched, but no additional information on this event was found.

Stuart A. Northrop, New Mexico collaborator in seismology for the Coast and Geodetic Survey, made an earthquake questionnaire coverage of northern New Mexico and southern Colorado. Data from these questionnaires were used to construct the isoseismal map in Figure 1. A maximum intensity rating of VII was originally given the Dulce area based on the Modified Mercalli Intensity scale of 1931. However, both Hoffman (1975, p. 11) and Northrop (1976, p. 79) have assigned an intensity rating of VII-VIII. Perhaps it should be VII+.

By Monday morning, January 24, 1966, the worldwide seismograph station at the Albuquerque Seismological Laboratory (ASL) had recorded approximately 90 aftershocks. John P. Hoffman and Frank Werner of the ASL proceeded to the epicentral area to make a field investigation and a preliminary survey of the structural damage at Dulce and adjacent towns. The greater part of the area where the earthquake was felt is an elevation of 6,000 feet (2000 m) or higher, mountainous, and sparsely populated. Several feet of snow covered the ground which limited field investigation.

Due to the continued aftershock activity, three temporary seismograph stations were installed near the epicentral area. Deep snow and extremely cold weather conditions imposed limitations on the location of these seismograph stations; however, good seismic data were recorded and a number of the aftershocks were located.

PHYSIOGRAPHY

The Dulce-Lumberton area is located in the Navajo section of the Colorado Plateau province of the Intermontane Plateau major division, about 32 km west of the boundary of this section, province, and major division with the Southern Rocky Mountains province of the Rocky Mountain system major division. This province and major division boundary, as drawn by Fenneman and Johnson (1930), passes northward through Chama and thence northwestward through Pagosa Springs, Colorado.

The San Juan Basin, a great saucer-shaped depression that extends over more than 25,000 square km, mostly in northwestern New Mexico but partly in southwestern Colorado, may be considered a subsection of the Navajo section. In the tectonic map (Figure 2), note that Dulce is on the northeast rim of the San Juan Basin and on the boundary between this and the Archean Arch. It is suggested that the boundary between the Colorado Plateau and the Southern Rocky Mountains provinces might be drawn through Dulce rather than farther east through Chama.
The area is one of young plateaus carved in Upper Cretaceous sandstone and shale. Dulce and Lumberton are on Amargo Arroyo, which drains westward into Navajo River, a tributary of the San Juan River.

Both Dulce and Lumberton are in the broad outcrop belt of the Upper Cretaceous Lewis Shale (Figure 3, diagonally cross-hatched from upper right to lower left). The Lewis Shale is about 600 meters thick.
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STRUCTURE

The Archuleta Arch or anticlinorium "lies along the northeastern side of the San Juan Basin and forms a low structural divide between the basin and the narrow downwarp of the Chama Basin...As part of the San Juan Basin rim the arch connects the San Juan Dome (beyond the north edge of the tectonic map, Figure 2) to the northwest with the Gallina-French Mesa-Nacimiento uplift to the south. It is about 75 miles (120 km) long from northwest to southeast and 6 to 16 miles (10 to 25 km) wide....The general arch is modified by numerous short folds and faults and is transected in its middle part by the northerly trending Archuleta Dike swarm" (Kelley and Clinton, 1960, p. 49).

The discordance between the northwesterly trending faults and the northerly trending dikes shows up clearly in Figure 2. Inclination of faults is steep to vertical. Displacement on most faults does not exceed 100 meters and on many it is less than 30 meters.

According to Kelley (1955, p. 48), the Archuleta Arch or anticlinorium "consists of a series of irregular curving, short folds, which are considerably disrupted by faults. The faults are steep.... Perhaps the most significant feature of this group of faults is the transverse west-northwesterly swerve or cross trend that is developed southwest of Chama....In a belt about 8 miles (13 km) in width; the folds, as well as the faults, swerve from a northerly trend in the south into the transverse trend and finally back again to a north-northwesterly trend parallel to the anticlinorium."

Dane (1948) dates the principal folding in this area as latest Eocene. He believes that some faulting was associated with the folding, but that the major faulting occurred in latest Miocene time. In Figure 3, note Monero Dome southeast of Lumberton, and Dulce Dome South of Lumberton; note also the several northwesterly trending faults associated with these domes. Dane (1948) observes that "although most of the folding is due to horizontal compression, some of the sharp domical folds and the complementary local closed structural depressions suggest the effects of vertically applied uplifting forces. The source of such forces is not known."

VISIBLE EFFECTS AND DAMAGE

The main earthquake was felt over approximately 15,000 square miles (39,000 square km) in north-central New Mexico and south-central Colorado. This is a sparsely settled area, and it was difficult to obtain sufficient data for a satisfactory isoseismal map. To the south and west of Dulce,
New Mexico, there are large areas of little or no habitation and the iso-
sesmal lines in Figure 1 should be considered as tentative.

The original isothermal map (USC&GS MSA-129, p. 35) published by von-
Hake and Cloud (1968, p. 15) was modified by Northrop (1976, Figure 3,
who added a southeastward projecting lobe to include both Los Alamos and
Jemez Springs in the felt area.

The greatest amount of structural damage occurred at Dulce, New
Mexico, to the Bureau of Indian Affairs school and dormitory complex and
also to the Dulce independent schools. The independent school building
is a multi-winged single-story structure, constructed of concrete columns
with masonry filler walls, and wood frame and plaster interior partitions.

The BIA dormitories, maintained for the Indian school students, had
extensive damage to both interior and exterior of the buildings. These
dormitories are two-story structures. There was considerable plaster fall
from ceilings, and several outside brick walls had vertical fractures from
ground to roof. These fractures occurred where the two wings of the build-
ing met the center structure at angles of about 140°. Both of the dormi-
tories were evacuated and were not being used by the students at the time
of the field investigation on January 25. The steam-heating plant for the
BIA school complex, constructed in 1909, was damaged to the extent that it
will probably be condemned.

The Dulce school suffered considerable minor damage including 162
windows either cracked or broken. There were many cracks in the plaster
walls and separation of mortar from concrete support columns. However,
an inspection by an architect revealed no structural damage to the building
itself, and he felt that the school could be adequately repaired.

Approximately 1 mile (1.6 km) to the north and northwest of Dulce,
plateaus rise abruptly from the valley floor to heights of 500 feet (152 m)
or more. These are locally referred to as rimrock and are badly eroded
by wind, frost action, and rain. Dulce residents stated that a great
deal of the rimrock fell down the slopes. A prominent point on the hori-
zon, generally known as Dulce Point, had a complete change of configura-
tion due to collapse of the rock.

Throughout the Dulce area a number of chimneys were damaged. At the
BIA dormitory buildings there were several instances where tall chimneys,
5 to 6 feet (2 m) above the roofline were not damaged, while nearby
smaller chimneys of 1 to 2 feet (0.3 to 0.6 m) above the roofline had a
number of bricks dislodged. There were also a number of cases of spal-
ling of stucco from the walls of homes that were of wood-frame construction.

Considerable loss did occur from bottle and package goods which fell
from shelves throughout the area (Figure 5). Items on shelves facing north
were thrown to the floor, while items on the opposite side did not seem to
be greatly disturbed. Several people living in trailers reported that the
motion of the trailers was fairly violent. Earth sounds accompanying the
earthquake were reported by many persons and were described as a roaring
noise of considerable intensity.

Figure 5. Fallen groceries from north side of aisle, Dulce, NM

The total damage in the Dulce area was estimated at about $200,000
making this by far New Mexico's costliest earthquake in recent times.

The State Highway Patrol reported considerable fallen rock on New
Mexico Highway 17, 10 to 15 miles (16 to 24 km) west of Dulce. Some
minor cracking of the highway appeared where large fills were made.
A rancher located 13 miles (21 km) to the south reported that his adobe ranch house was considerably shaken, but no damage occurred. At the Cahucha Ranch, about 7 miles (11 km) southeast of Dulce, where one of the temporary seismograph stations was established, the owner stated that the ground motion was heavy and abrupt, but no structural damage occurred. The rancher stated that the ground motion was distinctly from north to south and was accompanied by a roaring ground noise. Objects were observed being displaced and toppled, first on the north wall of the room and then on the south wall, as the ground wave passed through the house.

At Lumberton, New Mexico, a small town 4 miles (6.4 km) east of Dulce (Figure 6), the main earthquake was generally felt by all persons. Some minor damage occurred, mainly cracked walls and a few fallen chimneys. A noise like an explosion or sonic boom accompanied the earthquake. Twenty-three aftershocks, of varying degrees of lesser intensity, were felt in Lumberton through January 29. The ground motion and noise were reported as coming from the north.

At Edith, Colorado, approximately 5 miles (8 km) northeast of Dulce, the main earthquake was felt by all persons. The houses were shaken heavily, but were not damaged. The ground motion and accompanying noise seemed to come from the west. One rancher, living south of Edith, reported that he had felt light tremors accompanied by rumbling noises occasionally during the past few years.

At Chromo, Colorado, 11 miles (18 km) northeast of Dulce, the main earthquake was generally felt, but no structural damage occurred. Some loss occurred in the grocery store where a few bottled items, with a high center of gravity, fell to the floor and were broken.

FORESHOCKS AND AFTERSHOCKS

The Dulce earthquake was followed by a large number of aftershocks with a majority of them concentrated in a relatively small area near the town of Dulce. A total of 163 aftershocks were recorded at Albuquerque, a distance of 227 km southeast of the epicentral area, through February 21, 1966. One hundred and three of these occurred in the first three days. The seismograph at ASL is a short-period WWSSN system with a magnification of 200,000 at a period of one second. No foreshocks were located on the ASL seismograms for three weeks previous to the earthquake. The temporary station at Chama recorded 413 aftershocks between January 29 and February 21. Chama records were used in preference to the other temporary stations as the quality of the records was better and the noise level lower. January 29 was the first complete day of recording at Chama, and magnification for the system was approximately 28,000 at a period of one second. Many of the aftershocks recorded had amplitudes of only 1 to 2 mm and could be considered as microearthquakes.
was assumed to be 5 km/sec (Stewart and Pakiser, 1962). Large temperature diurnal caused galvanometer drift and considerable time errors in the crystal clocks. Time corrections were based on keyed time pulses which are good to ±0.1 second. Overall accuracy of the readings is good to ±0.2 second.

Locations of 13 of the aftershocks from the records of the temporary stations were determined using the HYPO 71 epicenter program (Lee and Lahr, 1975). Depth of focus was adjusted to 5, 10, or 15 km, and the epicenter with the smallest residuals was used. These events were selected primarily because they were well recorded at all three stations. Instrumentation problems, muddy roads, and inclement weather resulted in the loss of considerable data particularly at the Cachucha Ranch station. Figure 6 shows the location of these aftershocks with relation to Dulce and Lumberton, New Mexico. The epicenter of the main event is also included using coordinates as listed in the Bulletin of the International Seismological Centre (1970).

During the rest of January, the USGS at Washington, D.C. located 28 aftershocks. An additional ten events were located during the month of February 1966. These events were located to the nearest tenth degree of longitude and latitude and are plotted in Figure 7. Depth of focus for all of these events was restrained to either 5 or 10 km.

![Focal mechanism for Dulce earthquake](image)

**Figure 8.** Focal mechanism for Dulce earthquake.

The focal mechanism for the main event is shown in Figure 8. This solution was obtained on a CDC 6600 using the procedures described by Dillinger et al. (1971). First motion data from 22 stations were obtained from the Bulletin of the International Seismological Centre, 1970, and also through direct examination of WWSSN records. An additional twelve readings were obtained from Cash's dissertation (1971). The nodal plane striking North 41°W agrees very well with the northwest trending structure of the Archuleta Arch shown in Figure 2. This plane is a reverse fault dipping 52° towards the NE. The second plane strikes almost due east-west, dips south at an angle of 45°, and is also a reverse fault.

**MAGNITUDE AND ENERGY**

Between January 23 and January 31, 112 aftershocks from the Dulce earthquake were recorded at ASL. Most of these were small events, and when $P_n$ was not readable, $P_g$ amplitudes were noted. Magnitudes were determined using equations developed by Evernden (1967) for both $P_g$ and $P_n$ data.

$$m_g = -8.00 + 1.14 \log A/T + 3.42 \log \Delta,$$

$$m_n = -7.55 + 1.21 (\log A/T + 3.04 \log \Delta),$$

where: $m_g$ = Magnitude determined from $P_g$ amplitudes,

$m_n$ = Magnitude determined from $P_n$ amplitudes,

$A$ = Ground amplitude in millimicrons

$T$ = Wave period in seconds,

$\Delta$ = Distance from epicenter in km

Magnitudes for $P_n$ were also determined using the equation developed by Gutenberg and Richter (1956).

$$m_n = Q + q + s,$$

where: $m_n$ = Magnitude determined for $P_n$ amplitudes,

$Q$ = The depth distance factor equal to 5.3 for a distance of 2',

$q = \log_{10} A/T,$

$\Delta$ = Trough-to-peak amplitude reduced to ground motion in microns,

$T$ = Wave period in seconds,

$s$ = Station correction factor (assumed to be zero).

Energy released was determined from

$$\log E = 5.8 + 2.4 m_n.$$
Table 1 lists the magnitudes and the total energy released during the nine-day period. A comparison of the magnitude values indicates good agreement between $m_{6.0}$ and $m_{7.8}$, but $m_{6.0}$ averages 0.8 greater. In his paper, Evernden states that for near regional events $m_{6.0}$ will usually give significantly higher readings when compared with results for the same event at teleseismic distances. Magnitudes for five of the larger aftershocks in this time period were determined by the USC&GS Epicenter Section in Washington, D.C. A comparison of the magnitudes for these five events is shown below:

<table>
<thead>
<tr>
<th>Washington</th>
<th>$m_{6.0}$</th>
<th>4.2</th>
<th>4.3</th>
<th>4.5</th>
<th>4.6</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque</td>
<td>$m_{6.0}$</td>
<td>3.9</td>
<td>4.4</td>
<td>4.2</td>
<td>4.9</td>
<td>4.3</td>
</tr>
<tr>
<td>$m_{6.0}$</td>
<td>3.2</td>
<td>3.7</td>
<td>3.3</td>
<td>4.25</td>
<td>3.5</td>
<td></td>
</tr>
</tbody>
</table>

The magnitudes for $m_{6.0}$ are consistently lower than the Washington values with the difference ranging from 1.2 to 0.35 orders of magnitudes. The $m_{6.0}$ values for Albuquerque, which were determined using the same method as Washington, never varied from the assigned magnitudes by more than ±0.3.

Total energy for the 132 aftershocks using $P_n$ magnitudes was $1.12 \times 10^{15}$ ergs. One aftershock accounts for $10 \times 10^{15}$ ergs or almost 90% of the total. The main shock was assigned a magnitude of 5.5. This is equivalent to $10,000 \times 10^{15}$, almost 100 times greater than the total aftershock energy released during the nine days immediately following the earthquake. From February 1 through May 7, 44 aftershocks were recorded at ASL with a total energy release of $0.265 \times 10^{15}$ ergs. On May 8 and 9 there was a sudden burst of activity near Dulce consisting of eight aftershocks. The largest had a magnitude of 3.8 ($m_{6.0}$). The total energy release for the eight events was $1.33 \times 10^{15}$ ergs. From May 10 through August 25, 30 aftershocks were recorded at the Albuquerque Observatory. Total energy released was $1.6 \times 10^{15}$ ergs most of which was due to one event of magnitude 3.9. After August 25 very few aftershocks were recorded, and they were quite small.

CRUSTAL STRUCTURE

The location of Dulce, near the boundary of the Colorado Plateaus province and the Southern Rocky Mountains province, makes the depth to Moho difficult to determine. Jackson and Pakiser (1966) estimate depth to Moho near Durango, Colorado, to be 41 km, and near Raton, New Mexico, to be 54 km. These points are located 80 km northwest and 217 km due east of Dulce, respectively. After reviewing the available literature (Jackson and Pakiser, 1966; Stewart and Pakiser, 1962; Roller, 1964; Herrin and Taggart, 1962; Ryall and Stuart, 1963), the crustal structure assumed for the Dulce area is shown in Figure 9.

The total number of aftershocks recorded at ASL through August 25, 1966, was 214 with a total energy release of $1.43 \times 10^{15}$ ergs. This is only 0.15% of the energy released by the main shock.
Assuming a focal depth of 10 km, reflections off the Moho would take about 13.1 seconds to arrive at Chama. Unfortunately, on most of the aftershocks for which origin times were available, the events were sufficiently strong that it was not possible to read the records. Of the 13 aftershocks on Figure 6 only four were readable in the section where reflections from the Moho would occur. On three of these events a strong arrival was present with + 0.1 second of the calculated reflection times, and on the fourth record the closest arrival was 0.3 second. Reflection time from the Moho for the S wave was computed to be 22.8 seconds. On the four readable records, an arrival was present at 22.3 seconds + 0.1 second.

The crustal structure depicted in Figure 9 was assumed to be uniform between Dulce and ASL, a distance of 227 km. Travel time for Pn over this distance was computed to be 36.3 seconds. ASL is located in the Basin and Range province close to the southeastern edge of the Colorado Plateaus province. No data are available for depth to Moho near ASL other than the aforementioned articles, which cover much of the surrounding area in eastern New Mexico and northern Arizona. Pn is the refracted wave along the 6.8 km/sec - 7.8 km/sec interface. Actual travel time for the Pn wave from the epicenter to ASL was 36.4 seconds. P*, the direct wave, followed Pn at ASL by 1.9 second. This gives an actual travel time for Pn of 38.3 seconds, versus a computed travel time of 37.8 seconds. P*, the refracted wave along the 6.0 km/sec - 6.8 km/sec interface, has a computed arrival time of 36.5 seconds, very close to the P arrival. This phase was not apparent on the records. A distinct phase appeared on the records 4.3 seconds after Pn. This does not coincide with arrival times for any refracted and/or converted phases for the crustal structure as shown in Figure 9. There is evidence for a 7.8 km/sec - 8.3 km/sec discontinuity in the Basin and Range and Colorado Plateaus provinces at depths ranging from 80 to more than 100 km (Jackson and Pakiser, 1966). Assuming a depth of 95 km to this layer in north-central New Mexico, a reflection would arrive in 40.7 seconds, or approximately 4.3 seconds after Pn. The reflection angle from this discontinuity over a distance of 225 km would be between 45 and 50 degrees giving a maximum of reflected energy. While these data are consistent, multiple reflections cannot be ruled out considering the uncertain depth of focus.

ACKNOWLEDGMENTS

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REFERENCES

A COMPUTER METHOD FOR DETERMINATION OF VALID FOCAL MECHANISMS
USING P-WAVE FIRST MOTIONS

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ABSTRACT: Most techniques for determining focal mechanisms attempt to find a unique focal mechanism. However, for the usual case in which only a limited number of P-wave first motions are available, the focal mechanism can only be limited to a domain in which any solution will be equally valid. If the data contain incorrect readings then only domains with a limited number of errors can be found. A computer program to facilitate the defining of domains in which the P, T or B axis define valid focal mechanisms is presented and evaluated. The shape of the domain gives insight into the influence of recording station locations on the focal mechanisms. P-wave amplitudes or S-wave polarization, if available, could be used to indicate a preferred focal mechanism within the domain of valid solutions.

INTRODUCTION

Computerized techniques for determining focal mechanisms using P-waves have been developed by Knopoff (1961), Kasahara (1963), Wickens and Hodgson (1967), and Keilis-Borok et al. (1972). Programs using S-wave polarization have been constructed by Udias (1964), Hirasawa (1966), Stevens (1967), and Keilis-Borok et al. (1972). Programs using P and S-wave data have been developed by Udias and Baumann (1969), Chandra (1971) and Dillinger, et al. (1972). With the possible exception of the method presented by Dillinger et al. (1972), these programs attempt to find a unique focal mechanism. However, in the case where P-wave first motions from small events are recorded by only a few stations, the focal mechanism can only be limited to domains in which any solution will be equally valid. For well constrained data the domain size will be small and conversely for poorly distributed data with possible errors the domains will be large and distorted. The objective of this report is to present a simple technique and computer program to determine the domain of valid focal mechanisms and to demonstrate the use of these domains in the interpretation of first motion data.