Waste Isolation Pilot Plant

Compliance Certification Application

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A STUDY OF EARTHQUAKES IN THE PERMIAN BASIN OF TEXAS-NEW MEXICO

BY A. M. ROGERS AND A. MALKIEL

ABSTRACT

A microearthquake seismograph network has been employed to study earthquakes occurring in the Permian Basin of Texas and New Mexico. The earthquakes are predominantly located on the Central Basin platform, although a few occur in the Delaware Basin. The majority of the earthquakes occur at the depths of sedimentary rocks, and the focal depths are also coincident with the depths at which hydrocarbon production and water-flood (secondary recovery) operations are conducted. Comparison of the historic earthquake activity with water-flood data shows that there was a possible increase in the number of large earthquakes ($M > 3.0$) in the mid-1960's when the number of water-flood projects and their injection pressures increased. The first felt event occurred in 1966. This tentative correlation suggests that the earthquakes are related to hydrocarbon production in this area.

INTRODUCTION

Recent seismic activity has been observed in a region of the Permian Basin of West Texas called the Central Basin platform (CBP). This study was initiated to obtain an improved understanding of the seismotectonics of the area because this information was of importance in assessing the seismic risk to a proposed radioactive waste disposal site in southeastern New Mexico, and CBP seismicity is the only significant activity within 100 km of the proposed storage site (Sanford and Toppozada, 1974; Sanford, 1976; personal communication). These earthquakes are of additional interest because they occur in the vicinity of major oil fields, and many of these fields have been or are currently undergoing secondary recovery operations. Shurbet (1969) and Sanford and Toppozada (1974) have suggested that the CBP earthquakes are related to the water injection-secondary recovery operations in the CBP oil fields. Other areas in Texas and Oklahoma may have experienced earthquakes related to hydrocarbon production. Docekal (1970) points out that the 1957 Gladewater, Texas, earthquakes occurred in the East Texas oil field on the western flank of the Sabin Uplift, and that an earthquake in 1956 near Catoosa, Oklahoma, occurred in an area of considerable oil accumulation. More recently, on June 16, 1978, a magnitude 5.3 (M_L) earthquake occurred near Snyder, Texas, in the Cogdell oil field (S. Harding, personal communication). On the other hand, Sanford *et al.* (1976) note that earthquakes occur in the Texas Panhandle and the eastern plains of New Mexico in geological settings similar to the CBP, but in areas where hydrocarbons are not produced.

The historical earthquakes that occurred in this area through 1974 are listed in Table 1, and their epicenters are shown in Figure 1 (Sanford *et al.*, 1978). The first earthquakes that are known in the CBP region occurred in June 1964 and were detected during the 10-month operation of a seismograph station temporarily installed 120 km south-southwest of the CBP (Sanford and Toppozada, 1974). Sanford and Toppozada associated these events with the CBP on the basis of *S*-*P*-wave arrival times. Because earthquakes were noted from the start of operation of this station, it seems likely that the CBP region was seismically active before 1964.

However, Sanford and Toppozada (1974) queried local historical societies and newspapers for earthquake reports and found that the first felt event occurred in 1966. In this respect it is noteworthy that the population in Ward and Winkler counties peaked around 1960 (U.S. Dept. Commerce, 1920–1970). The earthquakes on November 8, and November 21, 1964, and February 3, 1965, were strongly recorded at Socorro, New Mexico (SNM), and the temporary station. The SNM station began operation in 1961 and should have detected events of this size (Table 1) prior to 1964 had they occurred; however, no CBP events have been noted on these records before 1964 (A. Sanford, personal communication). The station at

TABLE 1

ALL KNOWN HISTORICAL EARTHQUAKES IN THE CBP REGION PRIOR TO DECEMBER 1976*

Date Mo/Day/Yr	Time (GMT)	Latitude	Longitude	M_{b-Lg}			M_{LD}	M_L†	M_{CORR}	Intensity
				ALQ	LUB	JCT				
11/08/64	09:25:59	31.900	103.000	2.5	3.5			2.7	3.0	
11/21/64	11:21:24	31.900	103.000	2.6	3.6			2.5	3.1	
02/03/65	19:59:32	31.900	103.000	2.9	3.8			3.0	3.3	
08/30/65	05:17:30	31.900	103.000	2.4	3.5	2.8		2.6	2.9	
08/14/66	15:25:47	31.900	103.000	3.0	3.6			2.8	3.3	VI‡
07/30/71	01:45:50	31.700	103.100	3.5	3.8			3.1	3.6	
07/31/71	14:53:48	31.600	103.100	3.3	4.4	3.8		3.2	3.8	
09/24/71	01:01:54	31.600	103.200	2.9	3.6			3.0	3.2	
11/21/74	18:59:06	32.100	102.700	2.3				2.4	2.7	
01/19/76	04:03:30	31.905	103.074	2.8			3.5	2.4	3.2	IV§
01/22/76	07:21:57	31.902	103.075	2.2		3.2	2.8	2.0	2.5	
01/25/76	04:48:28	31.903	103.082	3.2			3.9	3.1	3.6	V§
05/01/76	11:13:41	32.271	103.136	2.3	3.2		3.0		2.7	
08/05/76	18:53:09	31.566	103.020	—			3.0	3.0	2.7	
08/26/76	15:22:18	31.795	102.588	—			3.0	1.7	2.7	
09/17/76	02:47:45	32.212	103.102	2.5			3.0	2.1	2.7	
09/17/76	03:56:29	31.416	102.544	2.4			3.4		3.1	
12/12/76	23:00:14	31.525	102.528	2.1			3.2		2.9	
04/26/77	09:03:07	31.902	103.083				3.1	2.6	2.8	V§
07/22/77	04:01:10	31.796	102.733	2.8			3.3		3.0	

* Includes a selected group of earthquakes occurring after this date ($M_{LD} \geqq 3.0$) for the purpose of comparing magnitudes determined in this study with magnitudes at standard stations. ALQ, LUB, and JCT columns are M_{b-Lg} magnitudes determined at Albuquerque, New Mexico, and Lubbock and Junction City, Texas, respectively. M_{LD} is local magnitude using coda duration, and M_L is an equivalent Richter magnitude (Sanford *et al.*, 1978). M_{CORR} is the "true" magnitude estimate (see text). Locations of earthquakes prior to 1976 are from Sanford *et al.* (1978).

† Data from Sanford *et al.* (1978).

‡ Data from von Hake and Cloud (1968).

§ Data from U.S. Geological Survey (1976, 1977).

Lubbock, Texas, which has been in operation since 1956 and is closer to the CBP than SNM recorded the first recognized CBP event on August 14, 1966 (Shurbet, 1969). Shurbet (1969) also noted an aftershock series in conjunction with this earthquake. Based on the increase in felt earthquakes and the increase in instrumental detection of events on the CBP, Table 1 offers some evidence that there was an increase in the occurrence of felt earthquakes and events above about magnitude 3 in the mid-1960's.

Based on this information, a seismic array was installed that encompassed the locations of the largest historical events (Sanford and Toppozada, 1974). Since the

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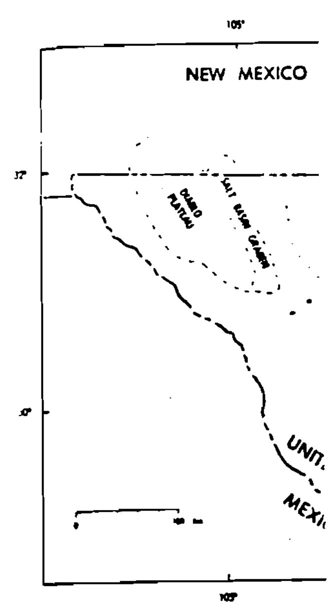

FIG. 1. Selected tectonic feat
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N PRIOR TO DECEMBER 1976*

—	M_{LD}	M_L†	M_{CODA}	Intensity
		2.7	3.0	
		2.5	3.1	
		3.0	3.3	
		2.6	2.9	
		2.8	3.3	VI‡
		3.1	3.6	
		3.2	3.8	
		3.0	3.2	
		2.4	2.7	
	3.5	2.4	3.2	IV§
	2.8	2.0	2.5	
	3.9	3.1	3.6	V§
	3.0		2.7	
	3.0	3.0	2.7	
	3.0	1.7	2.7	
		2.1	2.7	
			3.1	
			2.9	
	3.1	2.6	2.8	V§
	3.3		3.0	

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installation of the array, the locations of historic earthquakes (Figure 1) have been revised (Sanford *et al.*, 1978), and the revised locations suggest that some of the events may have occurred outside the study area.

Geological Setting

The Central Basin platform, which is the principal structure within the Permian Basin, separates the Delaware Basin on the west from the Midland Basin to the east (Figures 1 and 2). The west edge of the CBP is delineated by the inferred West Platform fault, a complex N.10°W.-trending fault zone with as much as 1.5 km of vertical displacement on individual faults. In the vicinity of the seismic array, the eastern edge of the CBP is defined by a fault zone of east dipping wedges and

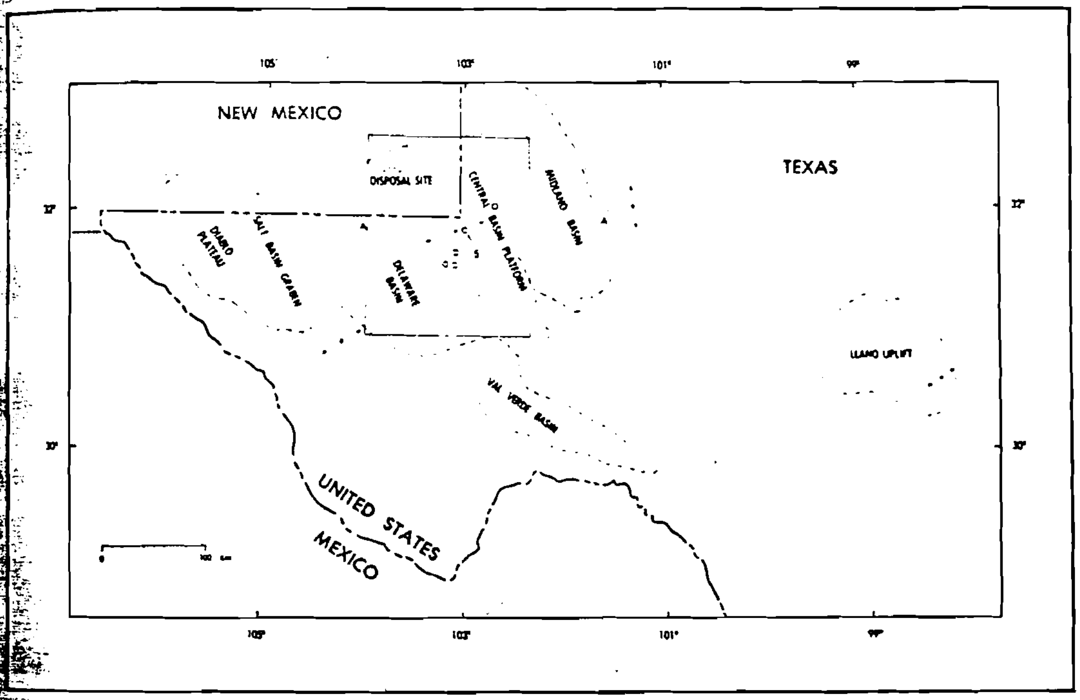

Fig. 1. Selected tectonic features in central and west Texas, historical earthquakes in the Central Basin platform region (open circles), and the direction of least horizontal compressive stress at several locations (arrows). Dashed arrows indicate stress determined from focal mechanisms, and solid arrows are *in situ* stress measurements. The number 5 points to the location of 5 historical earthquakes. AA′ is the trend of the geological cross section in Figure 2. Rectangle encloses the area shown in Figures 4 and 5.

vertical faults with approximately half the vertical displacement of the West Platform fault. The flat, featureless surface in the CBP area does not demonstrate any evidence of recent movement, and does not reflect any of the subsurface structures, which have primarily been inferred from well logs (Hills, 1970).

Basin development began in early Paleozoic, as indicated by the thickening of the pre-Permian sediments in this area. Hills (1970) postulates that in Late Mississippian time broad swells with axes trending north-northwest developed in response to an east-northeast compression. Northwest-trending transcurrent faults were formed, possibly along a zone of weakness in the Precambrian, during the same time period.

As this stress relaxed, the region submerged and deposition began, most intensely in the surrounding basins and at a slower rate on the higher folded platform region.

The accompanying rapid sinking of the basins led to the more pronounced development of the platform. In Late Pennsylvanian time, north-south compressional forces related to strong deformation occurring south of the CBP caused renewed lateral movement along the faults bounding the CBP. This movement shifted the Delaware Basin several kilometers northward relative to the CBP, and the CBP moved northward a lesser distance relative to the Midland Basin. Hills (1970) estimates the movement on the western edge of the CBP to be less than 16 km.

Sedimentation was renewed in Early Permian as tectonic stresses relaxed, and massive reef development on the western edge of the CBP and elsewhere restricted the influx of sediments to the Delaware Basin. This reef is now the primary aquifer supplying water for secondary recovery injection projects. Hydrocarbon traps occur in Permian and older rocks at depths varying from about 800 to 3700 m and are formed predominantly by anticlinal folds and buried hills (Herald, 1957).

Mesozoic deposits are mostly absent, although nonmarine Triassic deposits as

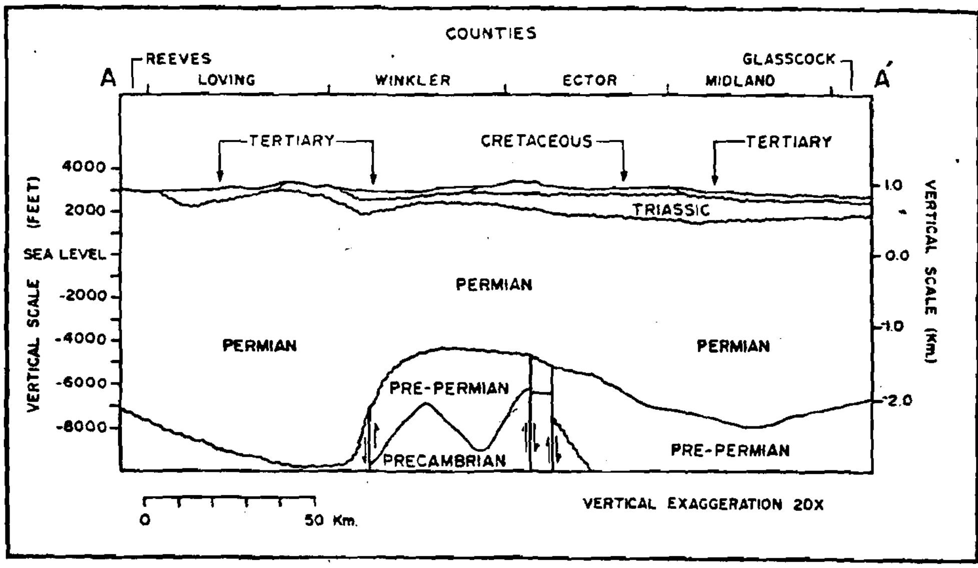

Fig. 2. Geological cross section of the Central Basin platform. Adapted from American Association of Petroleum Geologists (1973).

thick as $\frac{1}{2}$ km are found. The final depositional episode is marked by approximately 30 m of Upper Cretaceous fossiliferous limestone.

No Mesozoic or Cenozoic tectonic activity is known in the CBP region. However, some eastward tilting of the Delaware Basin and upward movement of its western edge in early Tertiary time has resulted in normal faulting along the west edge of the Delaware Basin (Hills, 1970).

The surface geology of the area makes effective operation of a seismic array difficult. Much of the surface includes the drainage system of Monument Draw and is covered with a veneer of partially stabilized sand dunes. Where the sand is more than a meter thick, good geophone coupling is difficult to obtain. Stations KT1, KM2, KM5, KT8, KM9, KME, and KTT (Figure 3) are affected by this problem. The stations KT7, KT4, and KTX, along the west edge of the array, are on caliche, which has been exposed because the ground is higher in that area. Station KM6 is situated on an outcrop of Cretaceous limestone and provides good sensitivity for

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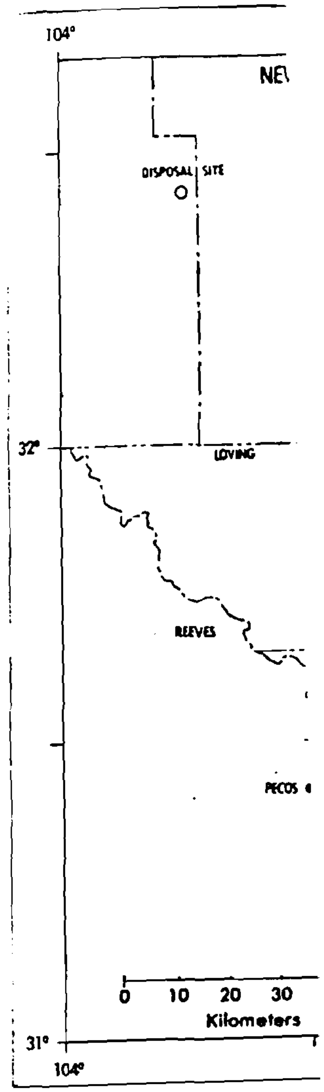

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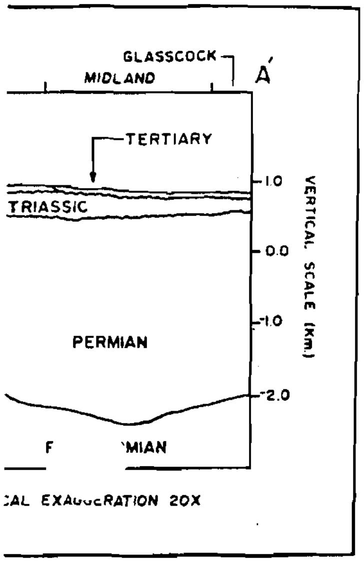

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events located to the east. Well logs in the area indicate that all station sites except KM6 are underlain by an average of 200 m of alluvium. The effect of unfavorable surface geology and high cultural noise results in less than optimum station gains for a microearthquake study.

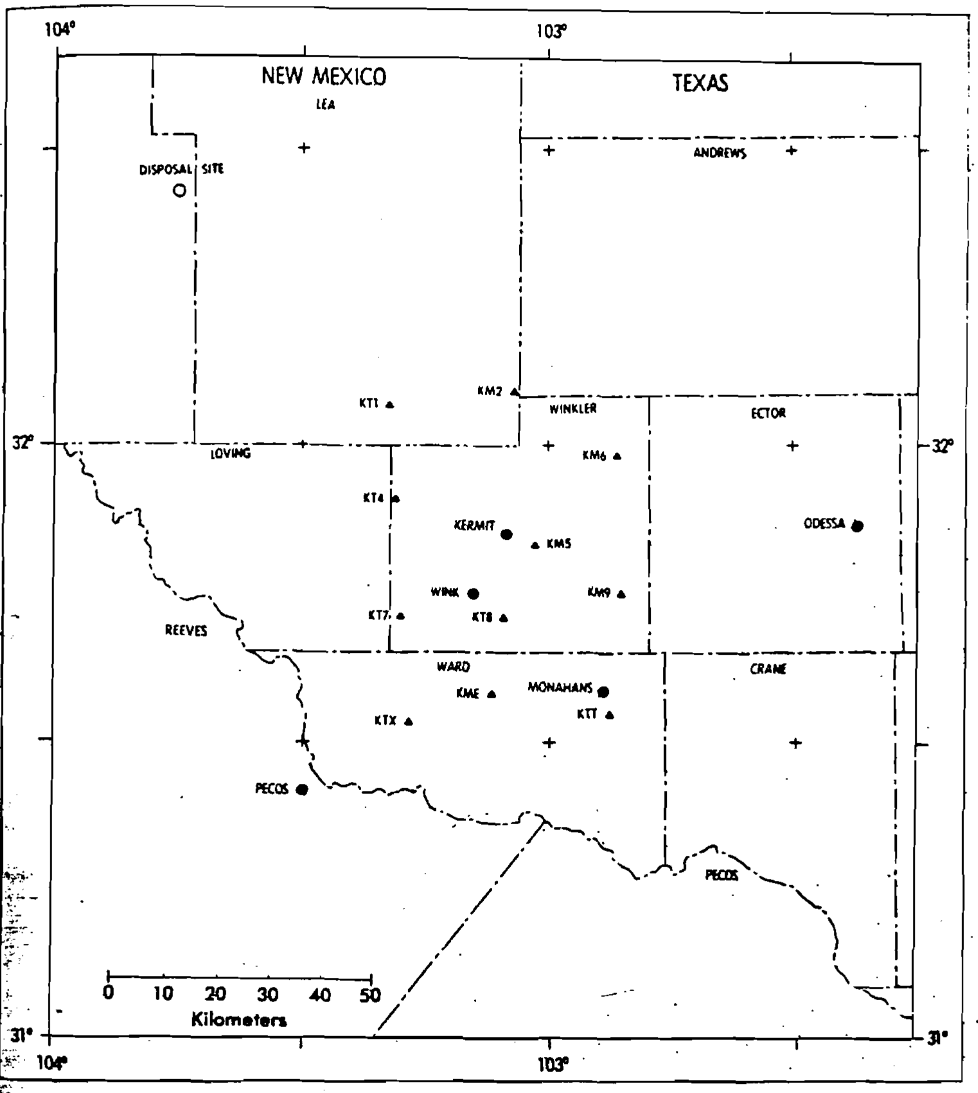

FIG. 3. Current location of the seismograph stations (solid triangles) in relation to surrounding cultural features. Dashed lines indicate county and state boundaries.

INSTRUMENTATION

The Kermit seismic network consists of 11 self-contained radio telemetry systems covering an area of 2200 km^2. Each field station is equipped with a vertical component seismometer, an amplifier-voltage controlled oscillator, and a VHF transmitter. Seismometers employed are Mark Products L-4C models with a natural period of 1 sec and a computed damping factor of 0.67 (use of trade names in this report is for descriptive purposes only and does not constitute endorsement by the

U.S. Geological Survey). A calibration coil in each seismometer is used to check output and polarity of the system. Low-level seismic signals are fed into an Interproducts amplifier-VCO unit, which modulates the frequency of an audio range carrier. Separate carrier frequencies are assigned to each station within each group of six stations. Typical amplifier gains are 66 or 72 dB, as determined by ambient background noise. These settings correspond to a magnification of 25,000 to 50,000 near 1 Hz (when Develocorder records are read in a 20× viewer). The magnification increases approximately 6 dB/octave to 10 Hz. The system peaks at 15 Hz and falls off at 36 dB/octave above 30 Hz. Repco VHF-FM transmitters, operating from batteries at approximately 1.5 watts, are used to transmit the signals to receivers that are centrally located at the Winkler County Airport, at distances ranging from 12 to 40 km. Some signal deterioration was tolerated for the longer radio links to gain the greatest possible coverage. At the receiver site the mixed output from each group of six receivers are telemetered via two phone lines to Golden, Colorado, where they are recorded along with a time code.

The facilities at Golden consist of discriminators, variable attenuators, a crystal clock, a 20-channel Develocorder microfilm recorder, and one Helicorder visible recorder. The data from the highest quality station (KT7) are recorded on the Helicorder as they came in, to allow rapid identification of earthquakes. In addition to Kermit data, the Albuquerque Seismic Observatory short-period seismic station (ALQ) is recorded on the film to document distant arrivals from the larger Kermit events ($M_L > 3.5$). Film recording speed is 3 cm/min, and optical enlargement of 20× permits resolution of ±0.01 sec for impulsive arrivals. Direct recording of WWV time signals also ensures absolute timing to ±0.01 sec.

The average level of detection within the array is magnitude $M_L = 2.0$, which is relatively high, owing to the less-than-optimum surface geology and unfavorable operating environment. The detection threshold of individual stations varies from a high of $M_L = 2.5$ in oil fields with sandy surface conditions to a low of $M_L = 0.5$ along the west edge of the array, where low levels of pumping and caliche "bedrock" allow higher gain to be used.

Factors that cause detection thresholds to vary with time include increased oil exploration and drilling, road construction, unpredictable grazing of cattle, and random electronic failures (such as may result from lightning strikes). When landowner permission could be secured, station locations were changed to take advantage of sites with lower background levels.

Magnitude Estimates

Duration magnitudes (M_{LD}) were calculated for earthquakes occurring during the monitoring period (Lee and Lahr, 1972) (Table 1). Because the duration magnitude scale was derived using California earthquakes, we have compared these magnitudes with amplitude magnitudes determined using nearby WWSSN station records. Body wave magnitudes using the *Lg* phase (M_{b-Lg}) (Nuttli, 1973) were computed for data from standard stations in Albuquerque, New Mexico (ALQ), Lubbock, Texas (LUB), and Junction City, Texas (JCT), and are shown in Table 1. The equivalent local magnitude M_L of Sanford *et al.* (1978) is also shown for comparison. We find that M_{LD} averages about 0.7 units higher than the ALQ M_{b-Lg}; however, ALQ may be anomalously low, as it averages about 0.8 units lower than LUB. Jordan *et al.* (1965) noted in amplitude studies of *Pn* and *P* phases that lower than normal amplitudes were observed in the Rio Grande trough region of New Mexico and higher than normal amplitudes were observed in the sedimentary areas of southwest Texas.

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Romney *et al.* (1962) also noted in amplitude studies of the Gnome explosion in southeastern New Mexico that attenuation of Lg, $\bar{P}$, and Pn was higher for waves propagating westward across New Mexico than for waves propagating eastward across Texas. This information suggests that while ALQ is too low LUB is too high relative to the "average station." The mean magnitude from these two stations may represent a value closer to the true value. Then, depending on which data were available, the "true" magnitude would be approximated by adding 0.4 to ALQ, subtracting this amount from LUB, averaging ALQ and LUB, or subtracting 0.3 units from M_{LD}. M_{CORR} in Table 1 are the corrected magnitudes for this group of events.

Earthquake Locations

The earthquake locations shown in Figures 4, 5, and 6 and listed in the Appendix were determined using the hypocenter location program HYPO71 (Lee and Lahr, 1972) and the crustal model given in Table 2. Earthquakes that were detected but proved unlocatable are also included in the Appendix. Some 3-station locations were computed by fixing the focal depth at 5.0 km. Quantities related to the reliability of the epicenter are listed with the locations, the most important being the root-mean-square error (rms), standard error in the epicenter (erh) and hypocenter (erz), the epicentral distance in km to the nearest station (dmin), and the largest azimuthal separation between stations in degrees (gap). The solution quality (q) defined by Lee *et al.* (1971) is a grade based on these quantities, where A is the best location and D is the poorest. It should be noted that the evaluation of the standard errors involves assumptions which may not be met. Consequently, the standard errors given may not represent actual error limits. Both the computed locations and standard errors depend on the crustal model used and the array geometry. That is, the locations and error estimates will be improved by crustal models that closely approximate the structure underlying the array. In order to obtain the most reliable epicenter the array geometry should be such that the gap is less than 180 degrees. The most reliable focal depth is obtained when dmin is less than the focal depth (Lee *et al.*, 1971). A more complete discussion of location errors is given by Lee *et al.* (1971).

TABLE 2
Crustal Model Used for Earthquake Locations
(Stewart and Pakiser, 1962)

Layer	Depth to Top of Layer (km)	P-Velocity (km/sec)
1	0.0	4.93
2	4.2	6.14
3	19.2	6.72
4	31.1	7.10
5	50.8	8.23

In this study two crustal models were tried. A more complex model (8 layers) than that given in Table 2 was constructed by incorporating data from a 3.7-km deep well log located near Kermit, Texas, with the refraction data of Stewart and Pakiser (1962). This model did not result in substantially different locations or standard errors. For 17 of the best-located events the model produced changes in the epicenter less than ±0.3 km, focal depth less than ±0.1 km, the standard error in the epicenter less than ±0.1 km, and the standard error in the focal depths less than ±1.0 km. In a few cases, however, the standard error in the focal depth becomes unstable and large variations are observed. The fact that both models produced similar results does not imply that the locations or their standard errors are accurate, but only that given the current level of information on crustal structure, velocities and location procedures, these locations are the best possible.

In order to mitigate the crustal model inadequacies, station corrections were determined for the final locations using 17 of the best-located events. A station correction was determined by iteratively summing the mean station residual for these earthquakes and using the sum as that station's correction in successive runs. Three runs were required to obtain the final residuals which were then used to locate all the events.

S-wave arrival times were incorporated into the location procedure for 25 per cent of the events. S data were used wherever possible, and were particularly useful for locating earthquakes outside the array boundaries. A P/S velocity ratio of 1.78 was assumed to convert theoretical P-wave arrival times into equivalent S arrivals (Lee and Lahr, 1972). While the majority of the earthquakes in this study are not well located due to the low station density of the array and the operating conditions described above, the data are accurate enough to delineate several areas of activity. Active areas within the array are constrained by some good quality locations, while active regions outside the array are constrained by a few relatively good epicentral locations derived using S-wave arrivals.

A comparison of the seismicity and oil fields (Midland Map Co., 1977) is shown in Figure 4. Although, in some cases, injection wells may occur outside the oil field boundaries shown, these wells are typically located within several hundred meters of the boundary. Several of the largest events that have occurred during this study were felt with intensity IV and V at Kermit and occurred in the vicinity of the Keystone unitized oil field. These events were well recorded at all the stations operating at the time and are among the best-located earthquakes in this study. To the northwest of Kermit one B-quality location and several of lesser quality may occur within one or more of the four small fields in that area. Two earthquakes (B and C quality) occur within the boundaries of the Ward-Estes unitized oil field. It is noteworthy that none of the best-located earthquakes occur outside of oil field boundaries. The poor location quality of other groups of events makes their association with oil fields tenuous, but the occurrence of many of the remaining earthquakes within oil field boundaries or in proximity to them suggests a correlation. On the other hand, there are large areas of hydrocarbon production that do not appear to be seismic, such as the region north-northwest of Odessa.

Some discussion of the relative quality of the locations of active areas outside the array is warranted. For instance, the group of earthquakes in the vicinity of the Dollarhide field include 9 events using S-wave phases and an average of 6 readings (P and S wave) per location with two events using 10 readings. Of the group of 10 earthquakes 34 km west-southwest of Odessa, 9 incorporate S phases averaging 8 readings per location. The more dispersed group of 12 events about 20 km west-southwest of Odessa include 2 events using S phases and a mean of 7 readings per location. The dispersed group of 9 events east-southeast of Monahans include 3 earthquakes using S readings and a mean of 8 readings per event. The large group of earthquakes in the vicinity of the War-Wink gas field are small magnitude earthquakes (typically $M_D < 2.0$) having typically poor locations. Three events use S phases, and the mean number of readings per location is 4. On the other hand, the occurrence of several C quality locations in this group suggests that earthquakes in

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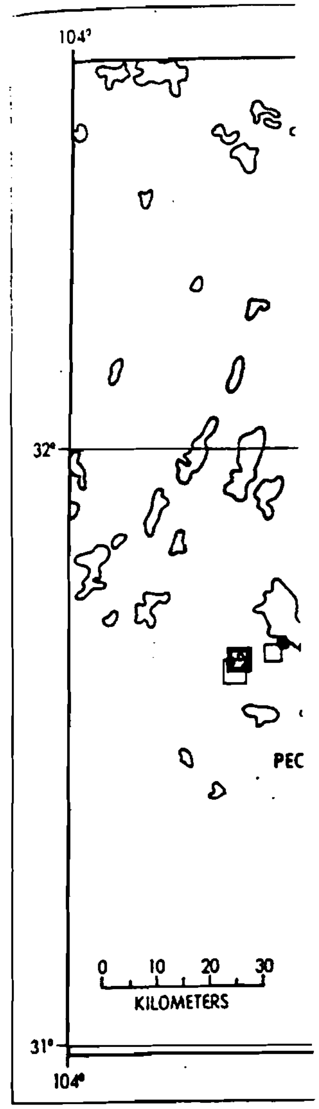

FIG. 4. Earthquakes located
earthquakes in the range: 3.0 <
+'s: $M_{LD} \leq 1.0$. The square fig
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s, station corrections were t-located events. A station : mean station residual for orrection in successive runs. s which were then used to

on procedure for 25 per cent were particularly useful for /S velocity ratio of 1.78 was o equivalent S arrivals (Lee s in this study are not well nd the operating conditions ate several areas of activity. good quality locations, while w relatively good epicentral

d Map Co., 1977) is shown in y occur outside the oil field thin several hundred meters e occurred during this study curred in the vicinity of the recorded at all the stations earth s in this study. To seve. lesser quality may at area. Two earthquakes (B rd-Estes unitized oil field. It kes occur outside of oil field of events makes their associ- any of the remaining earth- em suggests a correlation. On production that do not appear dessa.

ns of active areas outside the quakes in the vicinity of the and an average of 6 readings) readings. Of the group of 10 rporate S phases averaging 8 12 events about 20 km west- and a mean of 7 readings per heast of Monahans include 3 gs per event. The large group as field are small magnitude or locations. Three events use on is 4. On the other hand, the suggests that earthquakes in

this area are occurring in the vicinity of the War-Wink field. Other active areas include earthquakes which are typically more poorly located than those discussed above because no S phases could be incorporated into their locations.

Pre-Permian faults that have been inferred from drilling and all located earth-

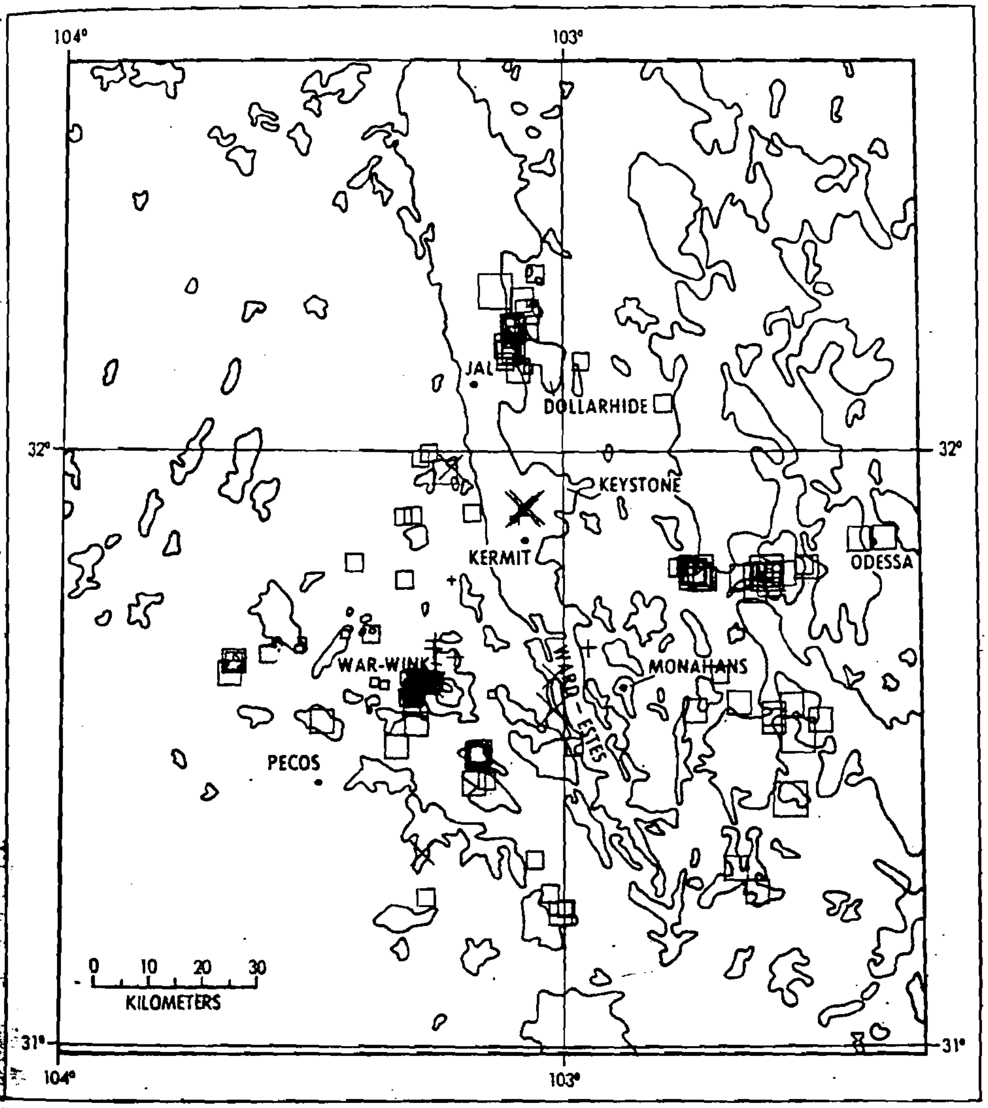

FIG. 4. Earthquakes located after January 1976 using the current operating network. Large X's are earthquakes in the range: $3.0 < M_{LD} \leq 4.0$; small x's: $2.0 < M_{LD} \leq 3.0$; large +'s: $1.0 < M_{LD} \leq 2.0$; small +'s: $M_{LD} \leq 1.0$. The square figures in 4 sizes indicate earthquakes in the same magnitude ranges given above with the largest square indicating the largest range. Earthquakes indicated by a square are less reliable with a quality of C or D and gap >180°. All oil fields are indicated by solid lines, and the location of several major fields is shown.

quakes are shown in Figure 5. The faults, which are buried approximately 1.2 km below the surface, are taken from 1:9600 scale maps provided by Geomap Corp. (R. O. Wilde, written communication). In general, it is not possible to associate the earthquakes with specific faults, although an earthquake lineation in the southwest corner of the array appears to occur on a short fault segment. Generally, seismicity occurs on both the eastern and western boundaries of the CBP. The occurrence of events southwest of Wink, Texas, indicate the Delaware Basin may be seismically active in areas where the basin is 5 to 6 km deep.

The rectangular area in Figure 5 encloses the events that have been plotted in

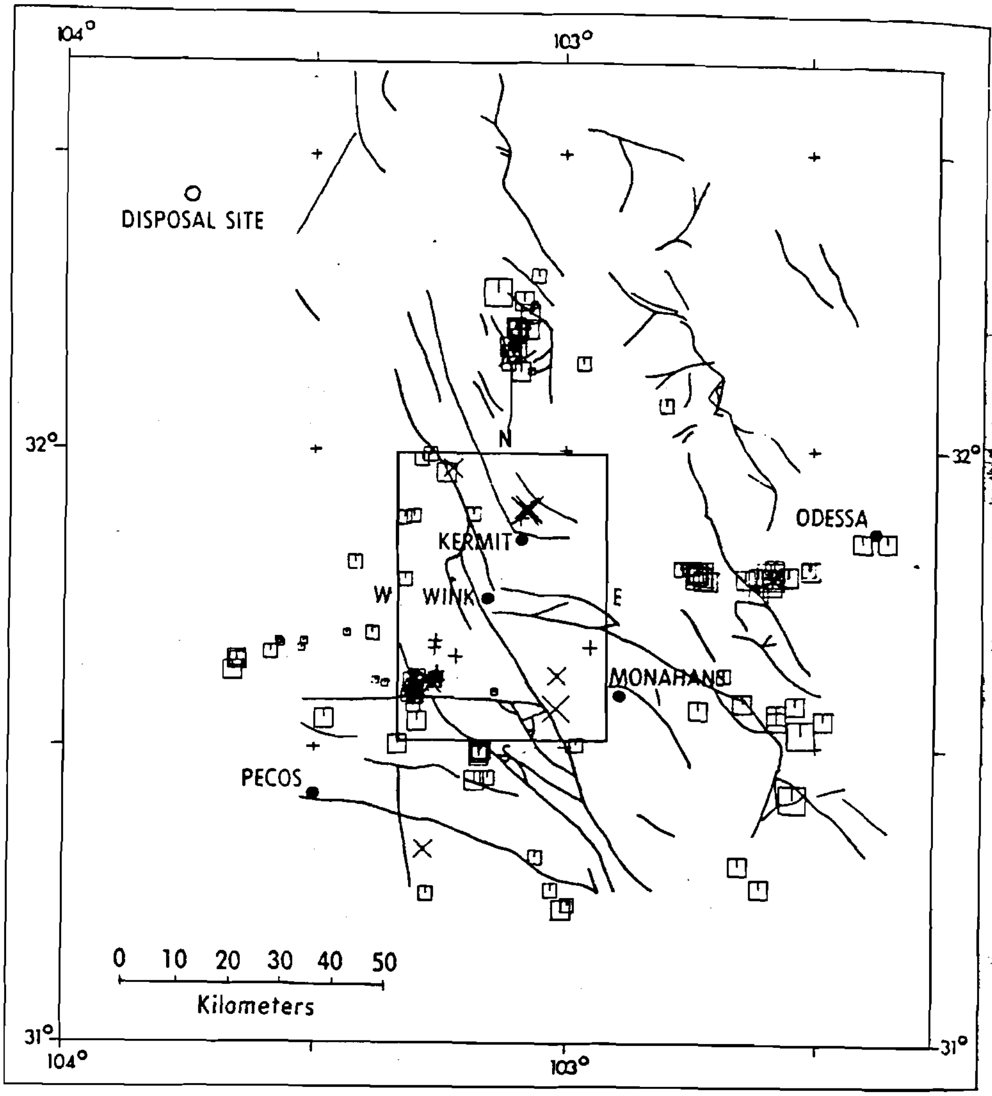

FIG. 5. All located earthquakes and inferred pre-Permian faults taken from a 1:9600 scale map provided by Geomap Corp. (R. D. Wilde, written communication). The rectangular figure encloses the events that are shown in cross section in Figure 7. Large X's are earthquakes in the range: $3.0 < M_{LD} \leq 4.0$; small x's: $2.0 < M_{LD} \leq 3.0$; large +'s: $1.0 < M_{LD} \leq 2.0$; small +'s: $M_{LD} \leq 1.0$. The square figures in 4 sizes indicate earthquakes in the same magnitude ranges given above with the largest square indicating the largest range. Earthquakes indicated by a square are less reliable with a quality of C or D and gap >180°.

vertical sections in Figure 6; however, only earthquakes satisfying the conditions erh ≦ 5.0 km and erz ≦ 3.0 km are included. In the Appendix, 29 events satisfy these criteria. Of these earthquakes, 4 occur at depths (d) below the surface of the basement rock ($d \geqq 3.7$ km), ($\bar{d} = 6.6$ km, $\overline{erz} = 1.8$ km); 9 occur at depths of the faulted pre-Permian rocks ($1.2 \leqq d \leqq 3.7$), ($\bar{d} = 2.3$ km; $\overline{erz} = 1.4$ km), and 16 occur

EARTHQUAKES IN T

at shallower depths ($d \leqq 1.2$
unknown. Six earthquakes
occur at depths less than
assessing the accuracy of th
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the focal depth, the mean dis
a range of 1.6 to 37.9 km.
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focal depth standard errors
error places the events in the
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FIG. 6. Vertical N-S and E-W c
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at shallower depths ($d \leqq 1.2$ km), ($\bar{d} = 0.42$ km; $\overline{erz} = 1.4$ km), where major faulting is unknown. Six earthquakes have $\overline{erz} \leqq 3.0$ km and gap < 180, and of these events 4 occur at depths less than 1 km and 2 occur at depths between 1 and 3.4 km. In assessing the accuracy of these depths for the select group of 29 earthquakes, it should be noted that no earthquakes were located with a station that was within one focal depth, the mean distance to the nearest station being $\overline{dmin} = 13.8$ km with a range of 1.6 to 37.9 km. Although the true accuracy of the depths and their standard error estimates are unknown, the data suggest that the majority of the earthquakes occur in sedimentary rock. Eleven of the earthquakes are occurring at depths shallower than the hydrocarbon producing zones ($d < 0.8$ km), but their focal depth standard errors are large enough so that in all but 2 cases, 1 standard error places the events in the producing zones.

Comparison of the historic activity (Figure 1) with the events located in this study (Figures 4 and 5) shows that the group of five historic events south of the New Mexico-Texas border occurs at about the same coordinates as the felt events in this study. The earthquake that occurs on the western edge of the CBP falls on the West Platform fault, but in an area where no other activity has been detected. The

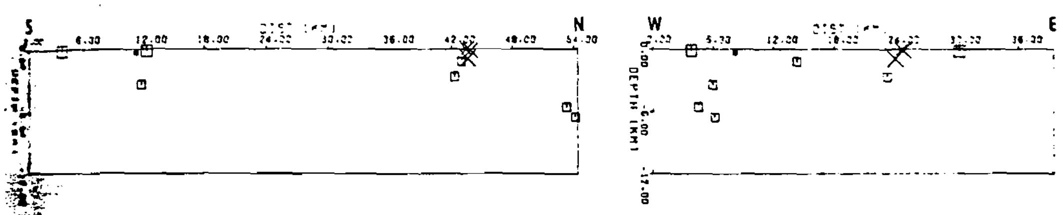

FIG. 6. Vertical N-S and E-W cross sections of the events shown within the rectangular area in Figure 5. The magnitude ranges indicated by the symbol sizes are the same as in Figures 4 and 5. However, a square symbol in this figure is assigned if the standard error in depth exceeds 3.0 km (no restriction on "gap") or if the location quality is D. No events shown were located with fewer than 5 phase readings.

earthquake epicenter located just west of the CBP in the Delaware Basin coincides closely with a pocket of activity noted in this study.

Focal Mechanisms and Tectonics

Only four events produced a sufficient number of clear first-motion polarities to permit an attempt at a fault-plane solution. All of these events occurred at about the same location a few kilometers southwest of the Keystone unitized oil field. Three of the events occurred within a 7-day period in January 1976 ($M_{LD} = 3.5$, 2.8, 2.9); the fourth event occurred in April 1977 ($M_{LD} = 3.1$). The first three earthquakes are shown as composite focal mechanisms in Figure 7, A and B, and indicate two equally likely solutions—(A) normal faulting and (B) strike-slip with a component of normal faulting. Although solution B has only one inconsistent polarity and A has two, it is difficult to choose a preferred solution on this basis, because the additional inconsistency is near a nodal plane in both cases.

Inferred faulting parameters offer no additional constraint on the focal mechanism solutions. The inferred fault (depth ≧1.2 km) on the southwest side of the Keystone field and northeast of the epicenters strikes northwest and dips 74° NE (Herald, 1957). The earthquakes, however, are shallow (0.12, 0.01, 0.89 km) and are displaced 3 to 4 km to the southwest of the fault trace. The standard error in the epicenters ranges between 0.2 and 1.1 km, and the standard error in the focal depth ranges between 0.3 and 1.2 km for these earthquakes. It is unlikely, therefore, that the earthquakes are related to this fault. The dip and slip direction on the two faults to the west and south of the epicenters is unknown, but if we assume that they slip 74° NE, the depths of the events would have to be approximately 9 km to be associated with these faults. The strike of the majority of faults is predominantly north-northwest, indicating that the westward dipping planes in solutions A and B striking

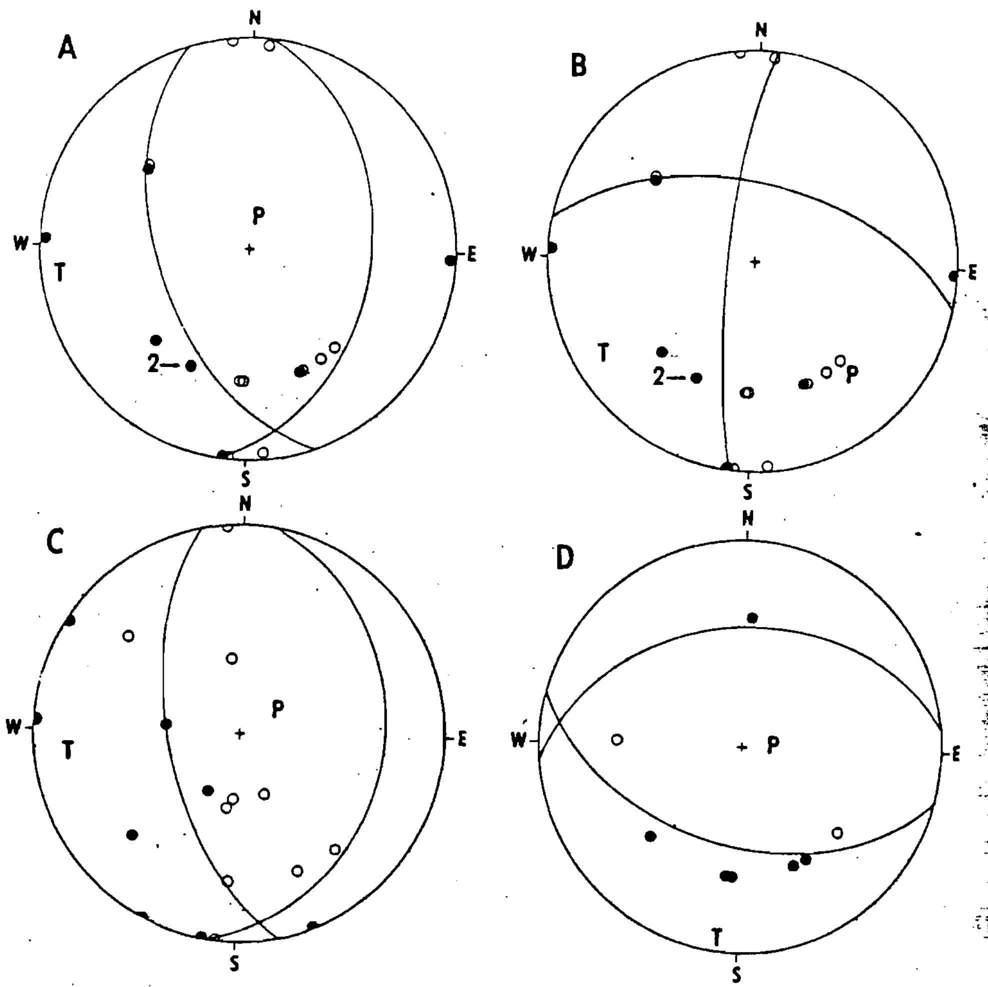

FIG. 7. (A) Composite plot (lower hemisphere) of first motions for earthquakes occurring near the Keystone oil field on January 19, January 22, and January 25, 1976. There are 16 consistent and 2 inconsistent first motions. Solid circles are compressions and open circles are dilatations. P is the compression axis, and T is the tension axis. (B) Composite plot of first motions for the same three events used in (A). This alternate solution has 17 consistent and 1 inconsistent first motions. (C) Composite plot of first motions for the same three events used in (A), but reduced to the focal sphere using a more detailed crustal model derived from a well log. (D) A non-unique focal mechanism for the earthquake of April 26, 1977.

approximately north might be preferred. However, the fault to the south of the epicenters strikes west-northwest, adding some weight to the possibility the north-dipping plane in solution B is the preferred fault plane.

Solution C is a composite mechanism for the same three earthquakes with first motions reduced to the focal sphere using a more detailed crustal model. This model, discussed above, may simulate actual travel paths more closely than the simple

location model. The fact tha
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The data for the fourth ev
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TABLE OF

Field/County	σ_1*(kg/cm²)	σ_3
1. Glasscock/ Howard	150	
2. Glasscock/ Burnet	154	1
3. Glasscock/ Winkler	115–126	

* Greatest horizontal compressive
† Least horizontal compressive st
‡ HF, hydraulic fracture method.
§ OC, overcoring method.
‖ Estimated from the stress gradi

of broad subsidence persiste
occurrence of normal faultin
In Figure 1, the regional te
in this study and others (Sa
Hooker and Johnson, 1969) a
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the 1931 Valentine earthqua
with a strike N 40° W dipp
similar to the CBP composit
cation) has shown that this s
likely. The strike-slip solutio
NW, that strike N 59° W an
southwest, similar to that sh
trends south-southeast. This
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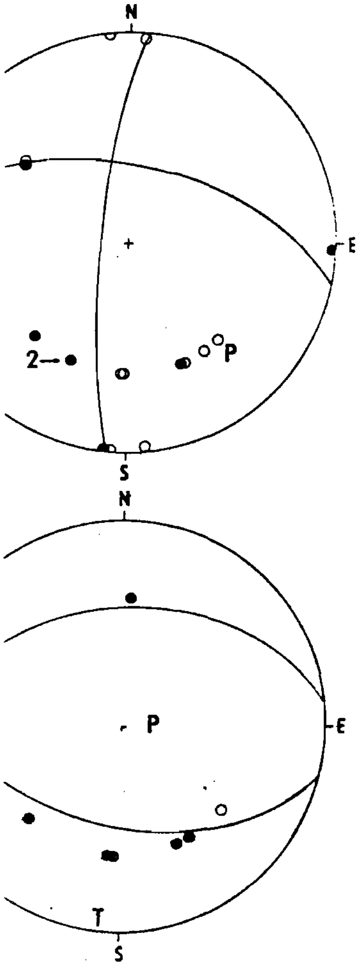

...ns for earthquakes occurring near the ... 1976. There are 16 consistent and 2 ... open circles are dilatations. P is the ... first motions for the same three events ... stent first motions. (C) Composite plot ... iced to the focal sphere using a more ... focal mechanism for the earthquake of

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location model. The fact that C, a normal solution, is the only fit to these data using the well-log model supports an A or C solution rather than the strike-slip B solution.

The data for the fourth event, shown in Figure 7D, do not fit the normal solution and do not permit a unique mechanism to be obtained. Normal, thrust, and strike-slip solutions are possible for this earthquake, which has a focal depth of 4.0 km and standard errors for the epicenter and focal depth of 0.5 and 99 km, respectively. No change in the focal mechanism solution was observed by either holding the focus fixed at shallower depths or by use of the well-log crustal model. The normal solution shown is the only one relatively consistent with the composite mechanism for solution A and C. A pure strike-slip solution (not shown) is relatively consistent with composite solution B.

Rosepiler and Reilinger (1977) have examined leveling data along a line from El Paso to the vicinity of Dallas, which crosses the Permian Basin and the CBP. A broad zone of subsidence that developed in the interval 1934 to 1956 and extended 600 km east-northeastward from the Diablo Plateau was noted and attributed a tectonic origin by Rosepiler and Reilinger. While it is not clear that such movements can be related to the occurrence of earthquakes (Castle *et al.*, 1976) or if this pattern

TABLE 3

TABLE OF *in situ* STRESS MEASUREMENTS IN TEXAS

Field/County	σ_1* (kg/cm²)	σ_3† (kg/cm²)	Depth (m)	Method	Trend of σ	Reference
1. Glasscock/ Howard	150	85	485	HF‡	N 73 E	Kehle (1964)
2. Glasscock/ Burnet	154	103	<50	OC§	N 33 W	Hooker & Johnson (1969)
3. Glasscock/ Winkler	115–126	89–115	500	HF ‖	—	H. A. Von Schonfeldt (Univ. of Texas, written commun., 1973)

* Greatest horizontal compressive stress.
† Least horizontal compressive stress.
‡ HF, hydraulic fracture method.
§ OC, overcoring method.
‖ Estimated from the stress gradients.

of broad subsidence persisted after 1956, this type of movement would favor the occurrence of normal faulting.

In Figure 1, the regional tectonic zones and least compressive stresses determined in this study and others (Sanford and Toppozada, 1974; Fraser and Pettitt, 1962; Hooker and Johnson, 1969) are shown for comparison. The dashed arrows are stress directions determined from *in situ* stress measurements (listed in Table 3). In this study we chose the A and C (Figure 7) tension axis as marginally preferable. The minimum compressive stress axis plotted southwest of the Delaware Basin is from the 1931 Valentine earthquake (30.9° N, 104.2° W), and indicates normal faulting with a strike N 40° W dipping 74° SW (Sanford and Toppozada, 1974), which is similar to the CBP composite solutions A and C. D. B. Dumas (written communication) has shown that this solution is not unique and a strike-slip solution is equally likely. The strike-slip solution indicates motion on planes dipping 70° NE and 70° NW, that strike N 59° W and N 40° E, respectively. The tension axis trends west-southwest, similar to that shown in Figure 1, but the pressure axis is horizontal and trends south-southeast. This solution then supports the Kermit solution B (Figure 7B). The hydrofrac measurement east of the Midland Basin (eastern shelf) and the overcoring measurement in the Llano Uplift are inconsistent, although R. O. Kehle (personal communication, 1977) has found that the majority of unpublished *in situ* stress measurements in Texas, including some obtained on the CBP, are similar to that on the eastern shelf (maximum compressive stresses trend N 65° E and minimum compressive stresses trend N 25° W). Thus, the *in situ* stress directions do not support the occurrence of focal mechanisms A or C, for which the greatest compressive stress is vertical. While solution B has more nearly horizontal minimum and maximum principal stresses, the orientation of these stresses does not agree with that of stresses on the eastern shelf but does agree with the stress orientation of the Llano Uplift measurement. In conclusion, there do not appear to be enough data at present to convincingly determine the direction of tectonic forces and the type of faulting on the CBP.

Kehle (1964) suggested that hydrofrac data in Texas indicate a relatively relaxed tectonic condition, because the magnitude of the horizontal stress is not much greater than that of the horizontal stresses that would be produced by the overburden [approximately one-third the overburden pressure of 0.23 kg/cm^2/m (1 psi/

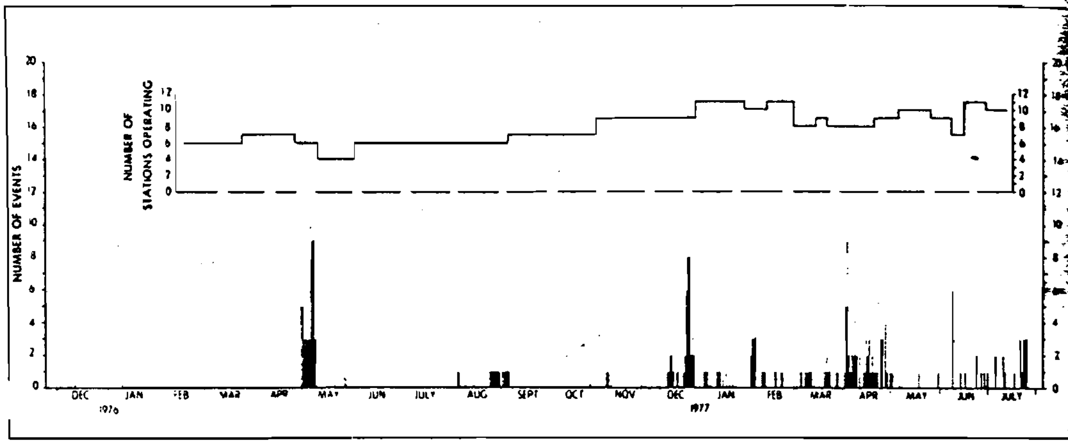

FIG. 8. Number of local events per day detected by the array and the number of stations operating versus time.

ft)]. The Texas *in situ* stress measurements in sedimentary rock (1 and 3, Table 3) indicate horizontal compressive stresses comparable to the overburden pressure and 2 to 4 times greater than the horizontal stresses due to the overburden. In the Eastern United States, which has been characterized as a region of high horizontal compressive stress (Sbar and Sykes, 1973), horizontal stresses range from 4 to 60 times the expected overburden-induced horizontal stress. However, stress measurement 2 (Table 3) made in a granitic, domed, Paleozoic structure, is at least 13 times higher than the overburden-induced horizontal stress and is in the range of the high horizontal stresses of the Eastern United States. These observations suggest that the basin sedimentary rocks may not be stressed as highly as the underlying crystalline basement rocks. The ratios of the greatest compressive stress to the least compressive stress in Texas range between 1.10 and 1.76, whereas, in the Eastern United States, this ratio ranges between 1.20 to 13.0 (Sbar and Sykes, 1973). The fact that this ratio is not as large in Texas as in the East also supports the argument that tectonic forces are lower than in the East. If the tectonic stresses acting in this area are not large, it may be reasonable to speculate that the stress directions are controlled more by local geological conditions than by a uniformly acting regional force.

Fraser and Pettitt (1962) have suggested that the direction of least compressive stress at the eastern shelf site is controlled by the local dip in the sediments rather than by active tectonic forces. This line of reasoning could also be applied to the CBP earthquakes. That is, tensional stress might be induced along the boundaries of the platform by the regional subsidence that has occurred to the southwest in the Delaware Basin and northeast in the Midland Basin.

Temporal Variation in Seismicity

Figure 8 shows the number of events detected by the array and the number of stations operating versus time. Although some earthquakes with magnitudes near 0 are recorded, fewer than ten events are detected during many months. This rate is relatively low in comparison with the rates in many active areas in the East [for instance, Blue Mountain Lake, New York (Sbar *et al.*, 1975) or SE Missouri (Stauder *et al.*, 1976)].

A few periods of swarm-type earthquake occurrences were observed. The April-May 1976 swarm in the Dollarhide region contained several magnitude 2 events; and a magnitude 3 earthquake occurred on May 1, early in the swarm. A second swarm began on December 12, 1976, with a magnitude 3.2 event followed by a series of earthquakes in the magnitude range 1 to 2. A magnitude 2.8 earthquake on December 19 was followed by a large number of events in the magnitude range 0 to 1.5. A third swarm in March-April 1977, which occurred in the same area, was composed of events ranging in magnitude from near 0 to 3.1.

There is an apparent increase in the number of felt events since this monitoring period began. These earthquakes and their maximum reported intensities are given in Table 1. This reporting increase may be attributed to an increasing awareness among the local populace of the earthquake monitoring program, but may also be due to an actual increase in the number of large events ($M > 3$) that coincided with the start of the monitoring program. Examination of the M_{CORR} column in Table 1 suggests that the number of events per year of magnitude 3 or greater during the monitoring period has been at least three times greater than during the historic period.

Figure 9 shows the interval frequency of occurrence of earthquakes for the CBP region for the 19-month period January 1976 to August 1977. The record of seismic activity appears to be incomplete below $M_{LD} < 3.0$, and, therefore, a least squares line, fit to the data for $M_{LD} \geqq 3.0$, is given by

$$\text{Log}_{10} N_I = 5.10 - 1.28\, M_{MID}.$$

While this equation fits the data well, a maximum likelihood fit was tried because it weights the points with the greatest number of events more heavily. This equation, fit over the same magnitude interval is given by

$$\text{Log}_{10} N_I = 4.36 - 1.04\, M_{MID}.$$

If we assume that the second equation can be extrapolated beyond the range of given magnitudes (a tenuous assumption at best), then there is a 63 per cent probability (Algermissen and Perkins, 1976) of observing a magnitude (M_{LD}) 4.5 to 5.5 in any 11-year period. No event of this magnitude has occurred in the Kermit area in the past 13 years. This equation also indicates that there is a 63 per cent probability of observing a magnitude 5.5 to 6.5 in any 120-year period. Several years of additional data will be required, however, to accurately establish the recurrence of earthquakes in the region.

Figure 10 shows the number of active secondary recovery projects versus time in Winkler and Ward counties that affect more than 1,000 acres. These data were obtained from the biennial publication of the Texas Railroad Commission, *A Survey of Secondary Recovery Operations in Texas.* These counts have been made as carefully as possible, but they may reflect errors or omissions in oil field operator reports. The figure shows that the number of projects rapidly increased in the early 1960's, reached a peak in 1968, and has decreased slightly since that time. A rapid increase in the number of projects employing average injection pressures greater than 70 kg/cm^2 (1000 psi) also occurred coincidently with the increase in total projects. Four fields in the Ward-Winkler county area employed injection pressures exceeding 140 kg/cm^2 (2000 psi). The Keystone field, which was the earliest of these, began high-pressure injection in 1962–1963. These data indicate that the increase in number of injection projects and the increase in number of high-pressure fields occurred prior to and in rough conjunction with the occurrence of the first known earthquakes in the area (1964). If this correlation is correct, one possible cause of these earthquakes is the reduction of frictional stress on existing faults by increasing fluid pressures. That is, if the frictional stress is reduced below the shearing stress, an earthquake can occur. This phenomenon was observed at the Rocky Mountain

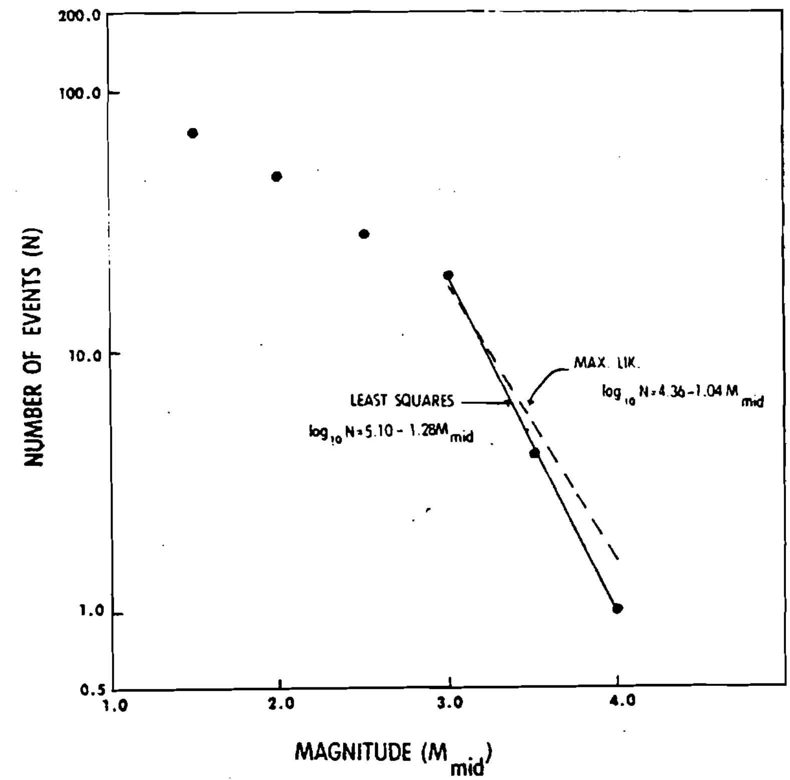

FIG. 9. Interval frequency of occurrence of Central Basin platform earthquakes and two regression lines for the period January 1976 to August 1977.

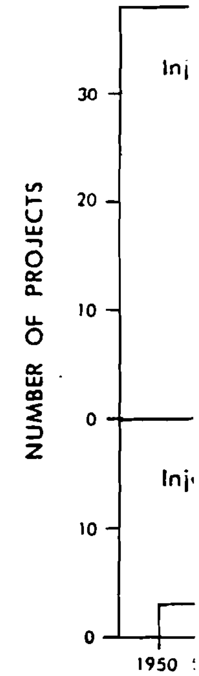

FIG. 10. Number of active se
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We wish to thank A. R. Sanford
and R. J. Archuleta who contribu

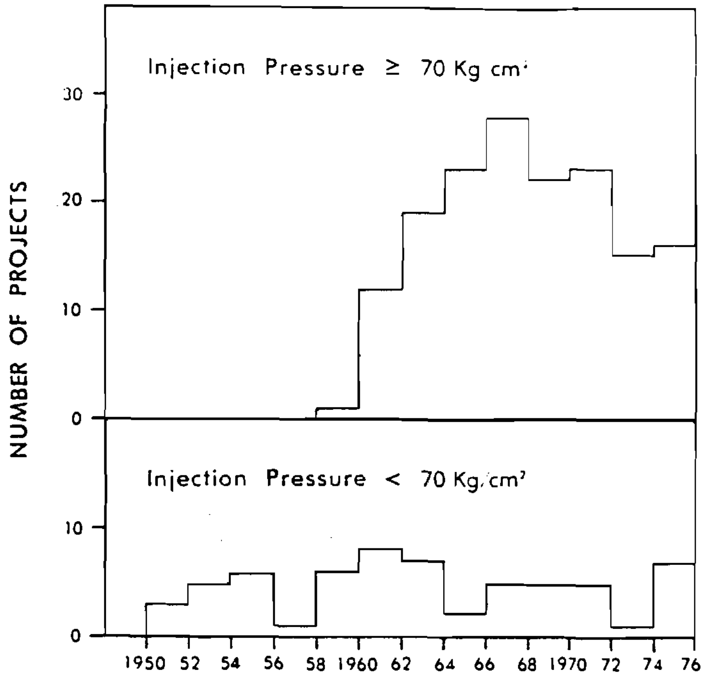

FIG. 10. Number of active secondary recovery (water flood) projects that affected more than 1000 acres in Ward and Winkler counties for two ranges of injection pressure, versus time. The data were obtained from records of the Texas Railroad Commission.

Arsenal near Denver (Healy *et al.*, 1968) and at Rangely, Colorado (Raleigh *et al.*, 1972).

CONCLUSIONS

The data of this study indicate that the CBP is seismically active over at least a 130-km distance extending to the southwest from near the southeastern corner of New Mexico. Some earthquakes may also have epicenters in the Delaware Basin. The locations of the earthquakes on the CBP suggest an ill-defined relationship to the complex northwest-trending pre-Permian fault system that bounds the CBP on the west and east. Examination of the depths of the best-located events indicates that the majority of the earthquakes occur at the depths of sedimentary rocks within the hydrocarbon producing zones.

Although the time of the first earthquakes in the region is not known, the first felt event was in 1966, and there is no reason to suspect that earthquakes would not have been felt before that time. This time coincides with a rapid increase in the number of injection projects and the coincidental increase in the injection pressures that began in the early 1960's and peaked around 1968. These weak correlations suggest a causal relation between the earthquakes and hydrocarbon production that could be related to increased fluid pressures along faults. Verification of this model for CBP earthquakes, however, will require improved earthquake locations that can be used to identify injection wells associated with the earthquakes, clearly defined focal mechanisms, and a record of the increase in reservoir pressures with time.

ACKNOWLEDGMENTS

We wish to thank A. R. Sanford, D. H. Shurbet, W. H. K. Lee, R. O. Kehle, D. B. Dumas, J. C. Lahr, and R. J. Archuleta who contributed helpful comments and criticism on the material in this paper. T.

Bice and D. B. Dobbs installed the seismograph array and frequently aided the authors in the field maintenance work.

Appendix

A list of all known earthquakes on the CBP from December 12, 1975 through June 26, 1977.

Selected Headings	*Explanation*
mag	Duration magnitude.
no	Number of station readings used to locate earthquake.
gap	Largest azimuthal separation between stations in degrees.
dmin	Epicentral distance in km to the nearest station.
rms	Root mean square error of time residuals, in seconds.
erh	Standard error of the epicentral, in km.
erz	Standard error of the focal depth, in km.
q	Solution quality of hypocenter (Lee and Lahr, 1972).

1975	hr	mn	sec	lat n	long w	depth	mag	no	gap	dmin	rms	erh	erz	q
DEC 12	14	24					3.39							
1976	**hr**	**mn**	**sec**	**lat n**	**long w**	**depth**	**mag**	**no**	**gap**	**dmin**	**rms**	**erh**	**erz**	**q**
JAN 10	1	50					3.11							
13	23	23					2.50							
19	4	3	30.37	31-54.32	103- 4.44	0.12	3.47	6	124	22.1	0.07	1.1	1.2	C
22	7	21	56.98	31-54.09	103- 4.52	0.01	2.83	9	144	21.3	0.06	0.4	0.5	B
25	4	43	27.71	31-54.17	103- 4.93	0.69	3.92	9	142	21.1	0.04	0.2	0.3	B
FEB 4	15	14	21.16	31-40.01	103-31.71	5.00*	0.86	3	273	21.6	0.00			C
4	15	19	35.61	31-39.49	103-35.39	5.00*	1.30	3	287	27.5	0.00			C
4	15	32	17.27	31-40.71	103-34.40	5.00*	0.26	3	282	25.6	0.00			C
4	15	41	3.56	31-40.71	103-31.42	5.00*	0.51	3	271	20.9	0.00			C
4	15	57	51.37	31-41.55	103-26.26	5.46	0.93	4	232	12.6	0.10			C
4	16	9	7.56	31-40.43	103-34.14	5.00*	0.66	3	282	25.2	0.00			C
4	16	15	30.77	31-41.56	103-23.20	19.93	1.24	4	215	7.9	0.16			C
19	8	23	55.43	31-36.77	103-39.46	5.00*	2.05	3	298	34.1	0.01			C
19	8	45	31.52	31-37.64	103-39.97	5.00*	2.05	3	300	35.3	0.01			C
19	9	23	36.63	31-36.77	103-39.46	5.00*	1.85	3	298	34.1	0.01			C
29	22	22	59.36	31-47.04	103-13.58	0.03	****	4	156	11.2	0.14			C
MAR 15	2	30	47.26	32- 9.14	102-57.52	0.12	1.56	5	279	14.5	1.04	31.5	14.1	D
15	23	7	7.20	32- 9.06	103- 6.91	5.00*	1.17	3	276	6.7	0.32			D
20	16	15	55.53	32-17.95	103- 3.29	0.35	1.70	5	304	23.3	0.26	20.2	8.5	D
27	22	25	21.00	32-12.65	103- 6.25	0.06	1.49	9	285	13.1	0.14	5.5	2.5	D
APR 12	8	2	34.66	32-10.01	103- 6.62	0.45	2.38	5	291	8.3	0.13	38.8	2.9	D
21	8	40	7.43	32-12.45	103- 6.03	0.25	2.53	6	250	12.8	0.04	0.4	0.3	C
29	17	46					0.44							
30	15	11					0.62							
30	7	29					0.53							
30	7	33					0.53							
30	8	44					0.53							
30	9	34					0.53							
30	9	53					1.61							
30	10	23					0.69							
30	10	34					0.42							
30	10	35					0.44							
30	10	37					0.69							
30	11	17					0.53							
30	11	43					-.27							
30	12	29					1.29							
30	12	40					0.42							
30	13	14					0.75							
30	13	19					0.44							
30	14	13					0.99							
30	14	37					0.53							
30	15	54					0.53							
30	15	55					0.53							
30	16	57					0.33							
30	16	57					1.63							
30	17	14					0.09							
30	18	7					0.99							
30	19	14					0.53							
30	19	23					0.53							
1976	**hr**	**mn**	**sec**	**lat n**	**long w**	**depth**	**mag**	**no**	**gap**	**dmin**	**rms**	**erh**	**erz**	**q**
APR 30	19	38					0.08							
30	19	50					0.69							
30	19	51					2.08							
30	19	57					0.53							
30	19	58					0.08							
30	20	15					0.53							

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te earthquake.
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. station.
s, in seconds.

l.
(Lahr, 1972).

	dmin	rms	erh	erz	q
	dmin	rms	erh	erz	q
	22.1	0.07	1.1	1.2	C
	21.3	0.06	0.4	0.5	A
	21.1	0.04	0.2	0.3	B
3	21.6	0.00			C
7	27.5	0.00			C
2	25.6	0.00			C
1	20.9	0.00			C
2	12.6	0.10			C
2	25.2	0.00			C
5	7	0.16			C
8		0.01			C
0		.01			C
8		0.01			C
6		0.14			C
9	14.5	1.04	31.5	14.1	D
6	6.7	0.32			D
4	23.3	0.26	20.2	8.5	D
.5	13.1	0.14	5.5	2.5	D
1	8.3	0.13	38.8	2.9	D
0	12.8	0.04	0.4	0.3	C

gap dmin rms erh erz q

1976		hr mn	sec	lat n	long w	depth	mag	no	gap	dmin	rms	erh	erz	q
	30	20 46					0.33							
	30	21 15					1.59							
[illegible]	1	0 12					0.33							
	1	1 29					0.53							
	1	11 13	41.84	32-16.23	103- 8.16	9.92	3.04	8	316	20.0	0.15	2.9	4.1	C
	1	12 49					0.22							
	1	20 50					1.69							
	2	1 4					0.76							
	2	6 17					0.69							
	2	16 57					0.94							
	3	3 45					0.53							
	3	5 57					1.13							
	3	6 55					0.06							
	3	7 27					0.53							
	3	7 45					0.53							
	3	7 50					0.62							
	3	8 0	40.12	31-59.34	103-17.25	5.56	1.96	5	221	9.1	0.07	3.9	2.3	D
	3	8 4					0.53							
	3	9 24					1.69							
	3	9 29					-.27							
	3	9 40					0.08							
	3	10 5					1.77							
	3	10 8					1.04							
	3	11 27	41.76	31-55.02	103-16.20	6.54	2.00	5	239	9.7	0.03	1.4	0.8	C
	3	17 46					1.29							
	3	17 51					0.69							
	4	7 3					1.04							
	4	14 6					1.59							
	4	15 5	39.10	31-57.94	103-14.30	0.16	2.32	5	267	9.5	1.64	10.6	4.6	D
	5	11 34					0.53							
	5	11 57					0.94							
	5	12 41					1.54							
	6	4 6					0.53							
	6	5 7					0.44							
	6	6 3					0.82							
	6	6 40					0.69							
	6	10 2					1.04							
	6	11 47					0.44							
	6	11 48					0.76							
	6	11 50					0.76							
	6	14 7					0.69							
	6	15 45					0.69							
	6	16 43					1.13							
	6	17 18	23.61	31-55.45	103-13.53	6.68	2.59	6	87	11.1	0.21	1.9	4.5	B
MAY	6	17 28					1.93							
	6	17 29					1.36							
	7	0 32					0.69							
	7	1 16					1.81							
	7	2 45					0.53							
	7	2 49					0.88							
	7	4 16					0.88							
	7	9 11					1.17							
	7	14 1					0.69							
	7	18 16					1.13							
	7	22 42					1.48							
	8	1 55					0.88							
	8	2 6					0.88							
	8	2 53					1.21							
	8	6 9					1.04							
	8	9 29					0.53							
	8	11 2					0.76							
	8	11 45					0.76							
	8	11 46	41.79	31-53.80	103-11.08	1.17	1.90	6	253	12.4	0.75	3.2	2.4	D
	8	17 46					0.69							
	8	22 24					0.69							
	8	22 25					0.82							
	9	4 26					0.88							
	9	4 57					1.13							
	9	7 14					0.99							
	21	13 15					2.88							
	27	21 16	6.85	31-53.56	103-18.21	5.00*	1.60	3	188	2.2	0.37			D
	28	16 15	23.57	31-53.41	103-19.34	5.00*	1.49	3	183	2.3	0.66			D
	1	19 5					****							
	10	16 36					1.04							
	15	2 20	0.53	31-34.68	102-38.70	0.76	2.39	7	281	22.8	0.21	11.0	5.6	D
	15	8 50	20.93	31-32.92	102-28.97	6.65	2.67	13	281	37.9	0.21	2.0	2.5	C
	16	16 31	14.43	31-47.10	103-19.21	5.00*	1.68	3	188	8.5	0.28			C
	5	18 53	9.17	31-33.96	103- 1.18	9.29	3.01	4	161	13.3	0.02			C
	6	21 12	35.59	31-46.65	102-35.10	0.06	2.59	4	305	38.2	0.18			C
	10	9 3	12.21	31-51.31	102-21.06	0.14	2.39	7	295	52.4	0.31	18.7	66.4	D
	10	9 12	29.55	31-45.93	102-36.75	0.14	2.09	4	303	25.9	0.12			C
	13	10 15	16.21	31-47.73	102-33.13	0.55	2.87	9	286	32.2	0.18	6.5	27.2	D
	15	5 8					****							
	15	13 52					1.04							
	15	15 3					1.21							
	15	16 42					1.29							
	25	1 27	49.24	31-33.56	102-34.59	3.89	2.79	9	284	29.0	0.14	10.5	40.0	D
	26	15 22	17.67	31-47.69	102-35.30	0.75	3.03	11	281	28.9	0.16	4.1	19.6	D
	27	19 44					1.29							
	28	17 21					2.08							
	29	15 10					1.93							
	30	15 44					1.89							
	31	12 46	21.14	31-33.57	102-44.05	7.84	2.78	9	262	14.2	0.28	7.9	4.2	D
SEP	2	20 6					1.99							
	3	21 0	24.71	31-32.81	103-28.95	4.00	2.47	4	286	18.4	0.72			D
	4	21 14					2.11							

1976	hr mn sec	lat n	long w	depth	mag	no	gap	dmin	rms	erh	erz	q
SEP 5	10 39 49.44	32- 9.71	103- 6.34	0.18	1.68	5	242	7.7	0.11	2.3	1.6	C
5	16 10 27.71	31-36.61	103-18.33	5.00*	2.24	3	188	9.0	0.02			C
5	20 53				2.11							
6	17 52				1.89							
10	19 18 43.40	31-54.35	103- 5.11	5.00*	2.25	3	138	3.0	0.00			C
10	19 25				2.22							
17	2 47 45.38	32-12.73	103- 6.10	0.20	2.98	10	235	13.3	0.13	1.2	1.2	C
17	3 56 28.90	31-24.97	102-32.64	1.66	3.44	7	293	35.1	0.09	3.9	3.6	D
19	10 23 24.36	32- 8.23	103- 5.43	7.29	2.41	6	299	5.0	0.34	10.2	5.2	D
22	20 13				1.42							
22	21 0				1.36							
OCT 5	22 12				1.04							
14	11 3 0.08	32-12.50	103- 4.43	2.74	2.32	6	262	13.1	0.30	6.0	4.3	D
22	5 6 15.86	31-34.48	102-32.34	3.03	2.94	7	292	32.7	0.17	8.0	29.2	D
25	0 27 4.16	31-46.43	102-34.82	6.59	2.95	7	282	26.9	0.13	5.2	4.9	D
25	10 52 27.31	31-51.19	102-24.13	0.17	2.15	5	322	44.6	0.07	20.6	104.5	D
26	10 44 44.08	31-19.56	103-16.95	0.46	2.81	7	166	22.7	0.31	3.4	3.9	C
NOV 4	23 27 53.95	31-40.11	103-15.68	0.12	1.74	4	127	6.2	0.01			C
5	22 55 30.40	31-39.26	103-13.14	5.00*	1.63	3	143	12.9	0.00			C
6	22 30 23.58	31-40.83	103-15.58	0.16	1.64	4	116	5.4	0.08			C
26	3 9				1.66							
DEC 12	23 0 14.00	31-31.47	102-31.68	7.59	3.21	11	268	33.7	0.09	1.5	1.8	C
12	23 25 55.99	31-32.83	102-34.59	0.13	2.33	7	264	29.0	0.16	8.1	62.7	D
13	23 5 38.67	31-46.77	103-25.27	1.54	1.51	4	219	14.7	0.13			C
14	19 54				1.42							
14	23 28				1.42							
15	8 51 43.94	31-37.49	102-41.00	5.00*	1.88	3	254	43.2	0.03			C
15	17 28				1.73							
15	18 1				1.59							
15	17 28				1.73							
15	18 1				1.62							
15	18 20				1.73							
15	19 4				1.73							
15	19 20				1.73							
15	23 9				1.73							
15	23 11				1.96							
16	18 37				1.21							
18	18 27 45.65	31-37.32	103- 1.07	0.17	2.26	6	120	10.8	0.15	0.6	1.4	B
19	1 35				0.33							
19	21 26 15.96	31-47.36	102-39.34	0.25	2.61	5	265	21.1	0.17	0.3	0.2	C
19	23 53				0.88							
19	23 54 22.66	32-10.72	103- 6.88	1.45	2.26	6	254	10.4	0.12	3.7	1.9	D
19	23 55				0.94							
19	23 55				0.88							
19	23 56 46.54	32-15.35	103- 4.96	1.04	2.85	6	277	18.1	0.23	7.3	3.9	D
22	7 17				0.53							
23	18 59				0.53							
23	22 44				0.33							
DEC 24	1 38				0.33							
24	5 26				0.53							
24	7 34 53.25	31-36.64	103-17.84	5.00*	1.45	3	180	8.9	0.47			D
24	10 31				0.33							
24	19 24				0.08							
24	19 40				0.33							
25	1 23				0.94							
25	1 33				0.88							
25	1 41				0.88							
25	1 41				0.88							
25	1 49				0.94							
25	2 13				0.94							
25	2 16				1.09							
25	2 30				1.17							
25	2 38				1.29							
25	3 0				1.21							
25	3 7				1.13							
25	3 36				1.36							
25	3 36				1.29							
25	3 50				1.54							
25	4 17				1.36							
25	4 25				1.48							
25	4 34				1.21							
25	4 54				0.94							
25	4 59				0.44							
25	5 0				0.82							
25	5 6				0.82							
25	5 16				0.76							
25	5 53				0.39							
25	7 58				0.22							
25	12 35				0.33							
25	12 56 34.93	31-37.69	103-15.33	0.41	1.18	4	135	10.2	0.23			C
25	13 33				0.44							
25	17 0				****							
25	17 48				0.53							
25	20 2				0.33							
25	22 26				0.22							
26	3 55				0.33							
26	3 59				0.44							
26	7 26				0.33							
26	9 41				0.33							
26	9 58				0.08							
26	12 15 4.58	31-37.60	103-15.56	0.00	1.17	4	139	10.2	0.24			C
26	17 9				0.53							
26	22 16				0.69							
27	1 30				0.33							
27	4 23				0.33							
28	5 13				0.53							
28	7 14				0.33							
28	11 12				0.08							

1976	hr mn sec	lat n
DEC 28	18 38	
29	10 1	
29	13 18	
1977	hr mn sec	lat n
JAN 4	22 58	
5	22 33	
5	23 27	
[illegible]	20 20 27.21	31-30.25
12	15 6	
13	17 53	
14	10 34	
14	11 15	
14	11 18	
14	13 33 33.40	31-35.92
15	22 31	
17	4 39 59.47	31-36.56
20	23 1 1.19	31-36.63
22	9 7	
FEB 2	3 26	
2	5 32	
3	1 27	
3	22 25	
3	23 38	
4	3 58	
4	7 21	
4	7 40	
5	7 19	
5	7 34	
5	16 17	
5	21 4	
9	3 12	
10	1 22 50.52	32-10.28
11	11 49	
17	10 25	
17	14 10 36.76	32-11.85
21	2 1	
22	13 3	
MAR 1	11 50 45.87	31-15.05
3	15 6	
5	22 56 9.97	31-16.09
6	23 10	
8	9 18	
9	3 53	
10	7 22	
11	23 56	
12	0 5 23.83	31-37.17
12	0 15	
14	11 20	
14	15 39	
17	15 14 13.27	32- 6.31
20	3 1	
1977	hr mn sec	lat n
MAR 20	3 26	
20	5 29	
20	7 54 7.96	32-12.40
21	6 17	
22	1 59	
22	14 5	
23	11 2 51.83	31-48.50
24	10 31 36.26	31-36.89
24	21 13 10.42	31-40.19
28	5 10	
29	0 35 34.92	31-36.99
APR 2	19 28	
3	12 36 59.05	31-14.00
3	12 39 57.38	31-15.49
3	13 48 9.15	31-29.62
3	14 24 7.11	31-29.38
3	15 5	
4	0 44 5.30	31-29.08
4	0 57	
4	1 33 3.87	31-18.85
4	1 47 50.36	31-26.59
4	4 35 56.80	31-29.75
4	4 47 29.90	31-29.51
4	5 1 29.84	31-13.52
4	21 40 16.25	31-35.28
4	22 55 53.95	31-35.13
5	19 23 3.16	31-35.05
5	23 38	
6	23 22 30.85	31-35.28
7	5 45 39.43	32-14.10
7	18 56 55.56	31-35.53
7	22 32 29.28	31-36.06
8	17 6	
8	23 45	
9	9 44 39.54	31-36.91
9	11 4 14.24	31-37.10
9	22 17	
9	22 26	
9	22 33	
10	10 40	
10	11 18	

	dmin	rms	erh	erz	
	7.7	0.11	2.3	1.6	
	9.0	0.02			
		).00			
	)	0.13	1.2	1.2	
	35.1	0.09	3.9	3.6	
	5.0	0.34	10.2	5.2	
2	13.1	0.30	6.0	4.3	
2	32.7	0.17	8.0	29.2	
2	26.9	0.13	5.2	4.9	
2	44.6	0.07	20.6	104.5	
5	22.7	0.31	3.4	3.9	C
7	6.2	0.01			C
3	12.9	0.00			C
6	5.4	0.08			C
8	33.7	0.09	1.5	1.8	C
4	29.0	0.16	8.1	62.7	D
9	14.7	0.13			C
.4	43.2	0.03			C
20	10.8	0.15	0.6	1.4	B
65	21.1	0.17	0.3	0.2	C
54	10.4	0.12	3.7	1.9	
77	18.1	0.23	7.3	3.9	D
180	**	0.47			D
135	10.2	0.23			C
139	10.2	0.24			C

1976	hr	mn	sec	lat n	long w	depth	mag	no	gap	dmin	rms	erh	erz	q
DEC 28	16	38					0.44							
29	10	1					0.33							
29	13	18					0.33							
1977	hr	mn	sec	lat n	long w	depth	mag	no	gap	dmin	rms	erh	erz	q
JAN 4	22	58					1.73							
5	22	33					1.04							
6	23	27					1.42							
9	20	20	27.21	31-30.25	102-58.80	5.00*	1.95	3	237	10.3	0.55			D
12	15	6					0.33							
13	17	53					0.76							
14	10	34					0.33							
14	11	15					****							
14	11	18					1.13							
14	13	33	33.40	31-35.92	103-18.35	5.00*	1.12	3	190	7.7	0.32			D
16	22	31					0.76							
18	4	39	59.47	31-36.56	103-15.95	0.52	0.25	4	147	9.1	0.33			D
20	23	1	1.19	31-36.63	103-15.93	5.00*	1.75	3	146	9.2	0.00			C
22	9	7					0.06							
FEB 2	3	26					0.69							
2	5	32					0.08							
3	1	27					0.69							
3	22	25					1.13							
3	23	38					0.76							
4	3	58					0.44							
4	7	21					0.69							
4	7	40					0.53							
5	7	19					0.53							
5	7	34					0.53							
5	18	17					0.53							
5	21	4					0.53							
9	3	12					0.53							
10	1	22	50.52	32-10.26	103- 6.00	2.04	2.03	6	200	9.1	0.22	3.2	2.9	D
11	11	49					0.33							
17	10	25					0.44							
18	14	10	36.76	32-11.85	103- 5.83	3.89	1.17	5	206	11.9	0.20	4.3	445.8	D
21	2	1					0.44							
22	13	3					0.33							
MAR 1	11	50	45.87	31-15.05	103-16.61	4.01	2.00	4	308	31.0	0.80			D
3	15	6					0.36							
5	22	56	9.97	31-16.09	102-39.22	2.14	2.35	9	314	34.6	0.27	23.1	358.4	D
6	23	10					0.44							
8	9	18					0.44							
9	3	53					0.44							
10	7	22					0.44							
11	23	56					1.39							
12	0	5	23.83	31-37.17	103-17.64	5.00*	1.90	3	181	9.9	0.46			D
12	0	15					1.36							
14	11	20					0.44							
14	15	39					0.33							
17	15	14	13.27	32- 6.31	103- 4.16	2.21	0.95	6	320	5.1	0.16	5.5	2.3	D
20	3	1					0.22							
1977	hr	mn	sec	lat n	long w	depth	mag	no	gap	dmin	rms	erh	erz	q
MAR 20	3	26					0.53							
20	5	29					0.33							
20	7	54	7.96	32-12.40	103- 5.80	0.99	2.22	8	229	12.9	0.22	3.3	2.5	D
21	6	17					1.29							
22	1	59					0.69							
22	14	5					0.53							
23	11	2	51.83	31-48.50	102-30.68	4.69	1.93	6	312	33.3	0.15	17.9	262.9	D
24	10	31	36.26	31-36.89	103-16.26	3.93	0.81	4	152	9.5	0.01			C
24	21	13	10.42	31-40.19	102-57.03	2.65	1.77	4	131	12.5	0.01			C
28	5	10					0.22							
29	0	35	34.92	31-36.99	103-16.41	3.43	1.67	5	154	9.7	0.01	0.2	0.2	C
APR 2	19	28					0.08							
3	12	36	59.05	31-14.00	102-59.75	5.00*	1.70	3	337	40.0	0.26			C
3	12	39	57.38	31-15.49	103- 1.74	5.00*	1.91	3	334	36.5	0.20			C
3	13	48	9.15	31-29.62	103-10.45	0.12	2.36	5	212	10.7	0.30	5.4	5.2	D
3	14	24	7.11	31-29.38	103-10.42	0.04	2.43	6	215	11.1	0.25	2.6	2.3	D
3	15	5					0.33							
4	0	44	5.30	31-29.08	103-10.38	0.29	2.37	5	218	11.5	0.47	6.1	5.1	D
4	0	57					1.46							
4	1	33	3.87	31-18.85	103- 3.54	5.00*	1.70	3	329	29.8	0.15			C
4	1	47	50.36	31-26.59	103-10.86	3.96	2.11	5	245	14.1	0.44	13.9	984.8	D
4	4	35	56.80	31-29.75	103-10.13	0.41	2.11	6	210	10.2	0.27	1.6	1.4	C
4	4	47	29.90	31-29.51	103-10.34	0.17	1.77	5	213	10.8	0.21	2.6	2.5	D
4	5	1	29.84	31-13.52	103- 0.47	5.00*	2.09	3	337	40.5	0.24			C
4	21	40	16.25	31-35.28	103-18.82	5.00*	1.68	3	199	6.8	0.22			C
4	22	55	53.95	31-35.13	103-17.85	5.00*	1.77	3	184	6.1	0.25			C
5	19	23	3.16	31-35.05	103-18.18	5.00*	1.60	3	190	6.1	0.23			C
5	23	38					1.04							
6	23	22	30.85	31-35.28	103-18.82	5.00*	1.66	3	199	6.8	0.22			C
7	5	45	39.43	32-14.10	103- 4.29	1.53	2.91	7	314	15.8	0.18	16.8	5.2	D
7	18	56	55.56	31-35.53	103-17.87	5.00*	1.67	3	183	6.9	0.28			C
7	22	32	29.28	31-36.06	103-17.98	5.00*	1.78	3	184	7.9	0.21			C
8	17	6					0.82							
8	23	45					0.61							
9	9	44	39.54	31-36.91	103-16.50	4.12	0.64	4	156	9.5	0.02			C
9	11	4	14.24	31-37.10	103-16.01	1.80	0.56	4	147	10.0	0.00			C
9	22	17					0.77							
9	22	26					0.69							
9	22	33					0.76							
10	10	46					1.54							
10	11	18					1.64							

1977		hr	mn	sec	lat n	long w	depth	mag	no	gap	dmin	rms	erh	erz	q
	12	23	15	26.44	31-15.75	102-36.70	0.21	2.24	9	318	40.4	0.22	23.4	294.4	D
	12	22	39					0.33							
	14	6	4	36.34	32-10.95	103- 6.45	2.97	0.92	4	282	10.5	0.12			C
	15	16	19					0.33							
	16	1	21	11.35	31-36.69	103-18.27	5.00*	0.51	3	187	9.1	0.23			C
	16	6	44	21.98	31-37.05	103-15.89	3.91	1.25	4	145	9.9	0.03			C
	16	14	38	39.61	31-36.72	103-15.02	0.34	0.52	7	131	9.8	0.42	1.0	1.3	C
	17	20	52	35.26	31-37.60	103-18.46	5.00*	0.63	3	188	9.2	0.06			C
	17	21	47					1.29							
APR	18	15	23					0.53							
	18	18	8	24.08	31-36.39	103-15.96	6.63	2.14	7	147	8.7	0.14	1.8	6.4	C
	18	21	51					0.33							
	19	22	55					1.64							
	20	12	59	58.72	31-36.54	103-18.75	5.00*	0.74	3	194	9.0	0.18			C
	20	16	54	19.49	31-36.47	103-21.63	5.00*	0.19	3	243	10.9	0.05			C
	21	16	29					0.08							
	22	22	56	35.08	32-15.00	103- 3.76	5.00*	0.88	3	330	17.5	0.00			C
	23	18	58	46.69	31-35.61	103- 8.55	0.01	0.69	4	207	20.1	0.91			D
	25	10	12	51.11	32- 4.91	102-47.60	5.94	1.35	6	275	26.0	0.07	1.4	17.6	D
	25	18	54					0.33							
	25	20	23					0.82							
	26	9	3	7.34	31-54.13	103- 4.95	4.02	3.10	8	126	9.2	0.07	0.5	98.5	C
	26	9	5	50.39	31-53.44	103- 5.41	2.67	1.06	5	135	8.6	0.02	0.4	0.5	C
	26	18	30					1.04							
	28	12	54	36.93	31-46.34	102-30.43	0.46	2.16	7	290	33.7	0.27	14.1	418.5	D
	28	12	55	40.47	31-47.52	102-35.13	4.21	2.17	7	280	26.1	0.14	5.2	220.9	D
	28	12	57	20.33	31-47.79	102-35.57	4.77	1.73	7	278	39.2	0.17	2.1	252.5	D
	28	15	22	37.68	31-47.59	102-36.76	3.14	2.46	8	275	23.6	0.19	6.4	8.6	D
	29	3	9	40.38	31-47.70	102-34.55	1.25	1.73	6	306	27.1	0.12	11.7	214.0	D
MAY	1	21	33	58.72	31-26.66	103- 9.30	5.00*	1.89	3	321	14.9	0.02			C
	2	17	8					2.02							
	7	17	32	58.67	31-36.74	103-22.79	0.73	0.73	4	234	12.5	0.00			C
	19	4	25	30.60	31-37.05	103-15.65	0.20	1.00	4	141	10.0	0.15			C
	31	3	13					1.04							
JUN	9	5	25					0.53							
	9	4	10					0.06							
	9	9	42					0.33							
	9	11	37	35.36	31-36.76	103-15.63	5.00*	1.33	3	232	11.5	0.01			C
	9	12	18					0.53							
	9	12	44					0.44							
	14	18	5					1.45							
	17	21	53					2.29							
	24	3	19					-.27							
	24	21	11					1.36							
	27	15	54					0.44							
	29	23	55	46.57	31-32.62	103-17.60	0.14	2.76	5	202	1.6	0.45	0.6	0.8	D
JUL	1	1	6	15.20	31-33.26	103-20.14	5.00*	2.45	3	299	5.3	0.73			D
	6	5	27					0.44							
	6	20	57					0.22							
	11	12	31	55.67	31-47.13	102-43.53	2.53	2.74	10	269	13.1	0.13	1.3	1.0	C
	11	13	29	49.80	31-47.57	102-43.57	2.49	2.19	9	273	13.3	0.12	1.4	1.1	C
	12	17	6	6.30	31-47.14	102-42.89	4.86	2.44	9	275	14.0	0.12	1.3	13.4	D
	14	12	37	30.57	31-47.76	102-44.27	0.97	2.90	8	266	12.4	0.14	1.7	1.4	C
	22	4	1	13.09	31-47.76	102-43.95	3.42	3.35	8	266	12.9	0.10	2.7	135.8	D
	22	4	10	10.47	31-47.60	102-44.02	2.30	2.50	7	271	12.6	0.13	2.0	1.4	C
	22	4	36	50.95	31-45.47	102-45.16	0.39	1.67	6	264	11.6	0.09	2.2	1.4	C
	23	22	46					0.53							
	24	9	23	5.45	31-44.05	102-44.07	2.24	2.49	10	267	12.9	0.14	1.5	1.2	C
	24	16	49					0.88							
JUL	24	21	3					1.13							
	25	14	52					0.76							
	25	17	45	48.07	31-34.21	103-18.22	5.00*	1.27	3	196	4.6	0.00			C
	25	19	44					0.53							
	26	2	1	9.26	31-48.32	102-46.16	0.27	1.45	9	257	10.4	0.17	2.4	1.8	C
	26	3	38					0.44							
	26	13	22	2.72	31-48.47	102-45.02	0.09	1.17	4	266	12.0	0.01			C

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