ABSTRACT

Continuous microseismic monitoring networks have been established around three U.S. Department of Energy geopressured-geothermal design wells in southwestern Louisiana since summer 1980 to assess the effects well development may have on subsidence and growth fault activation. The results obtained from this monitoring have shown several unusual characteristics associated with Gulf Coast seismic activity. The observed activity is classified into two dominant types, one with identifiable body phases and the other with only surface wave signatures. The latter type comprises over 99% of the reported 1000+ microseismic event locations. The problem with the slow-moving surface-wave signature events is that rainfall and weather-associated frontal passages seem closely related to these periods of seismic activity at all three wells.

After relatively short periods and low levels of flow testing at the Parcperdue and Sweet Lake prospects, seismic monitoring has shown little credible correlation to inferred growth fault locations during periods of flow testing. Longer periods and higher volumes of flow testing at the Rockefeller Refuge prospect should provide a truer indication of induced seismicity attributable to geopressured-geothermal development.

INTRODUCTION

In recent years much interest has been focused on projects which study the feasibility of alternative sources of energy. One such project is the development of geopressed-geothermal methane. Three geopressured-geothermal design wells sponsored by the U.S. Department of Energy (DOE) have been tested in southwestern Louisiana. These sites are the Sweet Lake, Parcperdue, and Rockefeller Refuge prospects (Fig. 1).

The production of geopressed methane involves extracting brines from deep underground formations, stripping off the methane, and reinjecting the methane-depleted fluid into disposal wells at a shallower depth. Economic development of this resource depends on the feasibility of extracting large quantities of brine at production rates near 20,000 barrels per day. Such high volumetric transfer rates may substantially change local stress regimes in the subsurface. Subsidence and growth fault activation are two important environmental concerns invoked by these changes in underground stress.

The numerous growth faults of the Gulf Coast display extensive movement, yet there are no historical records of large-magnitude earthquakes, and very few felt reports...
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Fig. 1. Locations of the DOE Sweet Lake, Parcperdue, and Rockefeller Refuge geopressed-geothermal prospects.

of earthquakes appear throughout the region's recorded history. Considering the aseismic nature of the region, these displacements must necessarily be explained by a series of small microevents or possibly a form of creep. The aim of the current monitoring program is to study the possibility of small-magnitude displacements, characterized by microseismic activity along existing growth faults, which may bound the geopressed-geothermal reservoirs.

Under DOE sponsorship, seismic monitoring networks have been established around the three geopressed-geothermal Louisiana design wells to assess the possible effects of well development on subsidence and growth fault activation.

LOUISIANA MICROSEISMIC MONITORING NETWORKS

The seismic networks that have been deployed around the Parcperdue, Sweet Lake, and Rockefeller Refuge prospects are shown in Figs. 2-4. Continuous microseismic monitoring at Parcperdue began in August 1980 and continued through November 1983. The Sweet Lake and Rockefeller Refuge networks have been on-line since late summer 1981 and continue to operate at present.

Each network has consisted of from five to eight short-period vertical seismometers installed in boreholes up to 30 m (100 ft) deep to reduce the adverse effect of surface cultural noise on the data. The seismic signals detected at each site within a network are sent to the central recording facility, where the individual station signals are demultiplexed from their respective carriers and
Fig. 2. Locations of microearthquakes recorded at the Parcperdue test site, 1981-83 (Van Sickle and Groat, 1981).
continuously recorded. Records are scanned daily to detect possible natural seismic activity. All events that are thought to be local microearthquakes are processed to obtain hypocenter locations and relative magnitudes. The hypocenter is determined by using computer algorithms similar to HYPO71 (Lee and Lahr, 1975). Magnitudes are calculated on the basis of event duration. Since a magnitude scale has not been developed for the Gulf Coast, the absolute values of computed magnitudes may not be valid. However, they do serve as good indicators of the relative size of events.

Magnitudes calculated for microearthquakes recorded at the three Louisiana networks indicate that all events have been small, with magnitudes less than 1.5. The exception to this is the magnitude 3.8 earthquake that occurred on October 16, 1983, northwest of the Sweet Lake prospect.

DATA ANALYSIS

Microseismic monitoring has never before been attempted in the Louisiana Gulf Coast area. The present microseismic networks associated with geopressured-geothermal development are the first. The lack of instrumentally recorded seismic activity in the Gulf Coast has made interpretation of the recorded seismic signals difficult to identify.
Fig. 4. Seismic station locations of the Rockefeller Refuge microseismic monitoring network.

**Types of Signals**

Various signal sources have been tentatively identified through the course of this study. Geophysical exploration blasting accounts for much of the observed activity as does cultural noise, such as cars and trucks. Occasionally, at Rockefeller Refuge, periods of extremely regular seismic energy appear every 10 seconds in the form of short bursts of 3 to 4 seconds' duration. The origin of these signals remains a mystery, although they do seem to roll across the network from a seaward direction, possibly indicating the source to be offshore.

Apart from these signals, two other types of signals have been recorded by the three networks: type I, or body wave, events and type II, or surface wave, events. Type I events are classified as microearthquakes and typically are characterized by a P-wave arrival (primary compressional/dilatational), S-wave arrival (secondary, shear waves) and, in some instances, a surface wave arrival. Type I events display P-wave velocities of from 1.5 to 6.0 km/s (5000 to 20,000 ft/sec) and contain seismic signatures typical of microearthquakes reported throughout the world.

Type II, or impulsive Rayleigh wave, events are signals consisting entirely of surface (Rayleigh) waves. They are characterized by an impulsive first arrival and usually occur as bursts of activity from 0.5 to 12 hours long. The apparent
velocity with which these events traverse the networks is essentially sonic (0.35 km/s, or 1,150 ft/s). This velocity, in addition to its sonic characteristics, is similar to velocities of fundamental mode Rayleigh waves derived for a portion of the Gulf Coast in Texas. Because the sediment velocities in southern Louisiana are similar to those in coastal Texas, the initial conclusion was that these recorded arrivals may be fundamental mode Rayleigh waves originating from local microseismic activity (Mauk, 1983). Mauk (1984) has also suggested that the type II events may be attributed to leaking energy from microearthquakes within a near-surface low-velocity layer, which would tend to trap the seismic energy within it. However, the frequency and velocity range of the type II events is also occupied by acoustical transmissions through the air (thunder or sonic booms), and significant coupling of atmospheric acoustic and earth Rayleigh waves is very common.

Currently, over 1000 microearthquakes have been reported at all three networks. Only 13 of these are classified as type I events; the rest are type II events. Many of the type II events have been attributed to well production and postproduction periods at Parcperdue and Sweet Lake prospects. Fig. 5 shows the temporal distribution of suspected seismic events with well production at the Parcperdue facility (Mauk, 1984). Based on this figure, type II events seem to show a correlation to production and postproduction periods at Parcperdue. Because of the implications associated with coproduction and postproduction seismicity, it is of the utmost importance to determine if the observed impulsive Rayleigh wave events are of atmospheric or earth origin.

![temporal_distribution](image)

Fig. 5. Temporal distribution of important seismic activity at Parcperdue, 1981-83, with well production periods (data from Mauk, 1984).
Type II Microearthquakes

To determine the origins for the type II events, recorded Rayleigh wave events were compared with weather-related phenomena originating around each seismic network. The most accurate, reliable, and localized weather-related data was found to be hourly radar summary charts from the National Weather Service office at Lake Charles, Louisiana (Fig. 1). The radar summary charts do not necessarily record thunder and lightning strikes, but they do indicate areas and intensity of rainfall and thunderstorms within a 400-km (250-mi) radius of Lake Charles.

Comparison of events recorded throughout the Parcperdue monitoring program with available radar summary charts indicates an extremely strong correlation to thunderstorm activity near the Parcperdue recording network. Between January 1981 and August 1983, only 2 of 98 reported type II events did not correlate with thunderstorm activity. In each instance when type II earthquake activity began, thunderstorms were moving close to or over the network. The type II events would then abate as the thunderstorms moved away or dissipated. On March 30, 1983 (Fig. 5, day 89), more than 35 type II events were reported between 0600 and 1900 UTC (universal time, coordinated). This represents the largest and most intense period of activity reported throughout the Parcperdue monitoring program. Review of the hourly summary charts showed a large mass of thunderstorms engulfing the Parcperdue seismic monitoring network during the entire time of reported type II seismic activity.

A strong correlation was also found in the records of seismicity at Sweet Lake when compared to the meteorological records of Lake Charles. For the period of seismic data collection beginning in January 1981, a complete history of weather activity shows that days in which large numbers of small Rayleigh wave events were detected correspond very closely in time to thunderstorm activity in the area. This phenomena was demonstrated on April 17, 1982. The largest single period of seismic activity reported throughout the Sweet Lake monitoring program, with over 63 type II events, occurred between 1200 and 1400 UTC on April 17, 1982. The radar summary chart for this day and time shows a mass of severe thunderstorms approaching the network from the northwest at 1130 UTC, passing directly over it between 1230 and 1330 UTC, and by 1430 UTC well off to the southeast moving offshore.

At Sweet Lake and Parcperdue on days with good weather, the type II events that have been observed are very few and appear to be traversing the network from origins far outside it. In the last two months of monitoring at Parcperdue, October and November 1983, several type II events were reported (Fig. 5). Unlike previous type II events, these have no thunderstorms associated with them. They appear as single events occurring intermittently with time. It is unclear, at this time, what the origin of these signals may be, but they are not thought to be caused by local earthquake activity. Possible explanations include sonic booms from military aircraft or surface waves from distant teleseisms.

Type I Microearthquakes

Of the 13 type I microearthquakes recorded throughout the study period, eight occurred within the Parcperdue network and five were within or near the Sweet Lake network.

The Parcperdue type I event locations are shown in Fig. 2, together with inferred locations of growth faults at a depth of 4900 m (16,000 ft) (Van Sickle and Groat, 1981). From the computed depths of 1800-6000 m (6000-20,000 ft) and locations, there seems to be a relatively close spatial relationship between type I events.
and inferred growth fault locations. The degree of correlation is sufficiently high to assume that these events were the result of small movements along these growth faults.

The five type I events which occurred near the Sweet Lake network include the October 16, 1983, Lake Charles event, its associated foreshock of September 11, 1983, and the aftershocks of December 4 and 5, 1983, and January 14, 1984. On October 16, 1983, at 1941 UTC an earthquake centered in the northwest corner of the Sweet Lake seismic monitoring network occurred (Fig. 3). The earthquake was recorded on seismograph instruments as far away as Ontario, Canada. The National Earthquake Information Service assigned it a magnitude of 3.8. Although no damage resulted, it was widely felt by many residents of Lake Charles, 12.8 km (8 mi) north of the epicenter. A total of eleven stations were used from both the Rockefeller Refuge and Sweet Lake microseismic monitoring networks in determining the earthquake's epicenter and depth of about 12 km (40,000 ft). A small shock in the same general area preceding the main event occurred on September 11, 1983 (Fig. 3) and is interpreted as a foreshock. The three events of December 5 and 6, 1983, and January 14, 1984 (Fig. 3) are most likely related aftershocks of the main event. The magnitudes of these additional events fall well below 1.0, with depths between 8 and 10 km (26,000 and 33,000 ft). The associated depths of this foreshock, main shock, and aftershock series would indicate activity far below any geopressured-geothermal producing horizon and may reflect movement in or near the crystalline basement.

SEISMICITY AND WELL PRODUCTION

Production testing at Parcperdue began on April 22, 1982, and continued intermittently through November 16, 1982 (Fig. 5). The well was permanently shut in February 5, 1983. When all type II events are removed from consideration during this relatively short testing period, only one microearthquake was observed. It occurred on October 26, the 183rd day of production after more than one million barrels of brine had been withdrawn. Event no. 8 on Fig. 2 shows the location of this event, which was 2.5 km (8000 ft) deep. Since this is the only recorded coproduction event, there does not seem to be any significant seismic activity related to short-term testing at Parcperdue.

Sweet Lake had two major periods of production testing, the first from June 1981 through February 1982 and the second from November 1983 through March 1984. As in the Parcperdue case, when all suspected type II events are eliminated, no apparent seismic activity is associated with either period of Sweet Lake well production. The series of events associated with and including the October 16, 1983, Lake Charles event most probably cannot be attributed to any geopressured-geothermal producing horizon, owing to their relative depth of occurrence.

The Rockefeller Refuge test program has evolved into the most productive of the three prospects. Testing has been ongoing since November 1983 at average production rates of approximately 16,000 barrels of brine per day. Although many curious signals have been observed from the Rockefeller Refuge microseismic recording network, no credible microearthquakes have been correlated with production so far. Indeed, no local events have yet been recorded by the Rockefeller Refuge network.

SUMMARY

Three years of microseismic monitoring data at the Parcperdue, Sweet Lake, and Rockefeller Refuge geopressured-geothermal prospects have displayed many different and curious signal characteristics. Two main signal types have been reported from
all three networks. These include the type I, or body wave, events which more closely resemble microearthquakes reported from other areas of the world and type II, or Rayleigh wave, events that display characteristics more closely related to sonic waves. Type I events have been recorded at two of the three prospects, Sweet Lake and Parcperdue. Seismic activity occurring around Sweet Lake does not appear to be associated with geopressed-geothermal development; instead, this activity displays origins far below current or prospective geopressed-geothermal producing horizons. The type I events associated with Parcperdue display a probable correlation with suspected growth faults at depth; however, no credible evidence of coproduction seismicity exists. Type I activity is intermittent with most of the Parcperdue events occurring prior to production. Only one type I event took place during flow testing; one other event occurred a year after shut-in. With the use of highly localized weather data, there is strong evidence that almost all type II events are attributable to thunderstorm activity in the vicinity of each network.

When suspected atmospheric events are removed from consideration, there is no apparent correlation of seismic activity with geopressed-geothermal test well production so far. This does not seem so surprising when the short production histories and relatively small volumes of fluid produced at Parcperdue and Sweet Lake are considered. Long-term, high-volume testing, such as that being done at Gladys McCall, will be the real test of whether microseismicity and growth fault activation can be induced by geopressed-geothermal development.

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REFERENCES


