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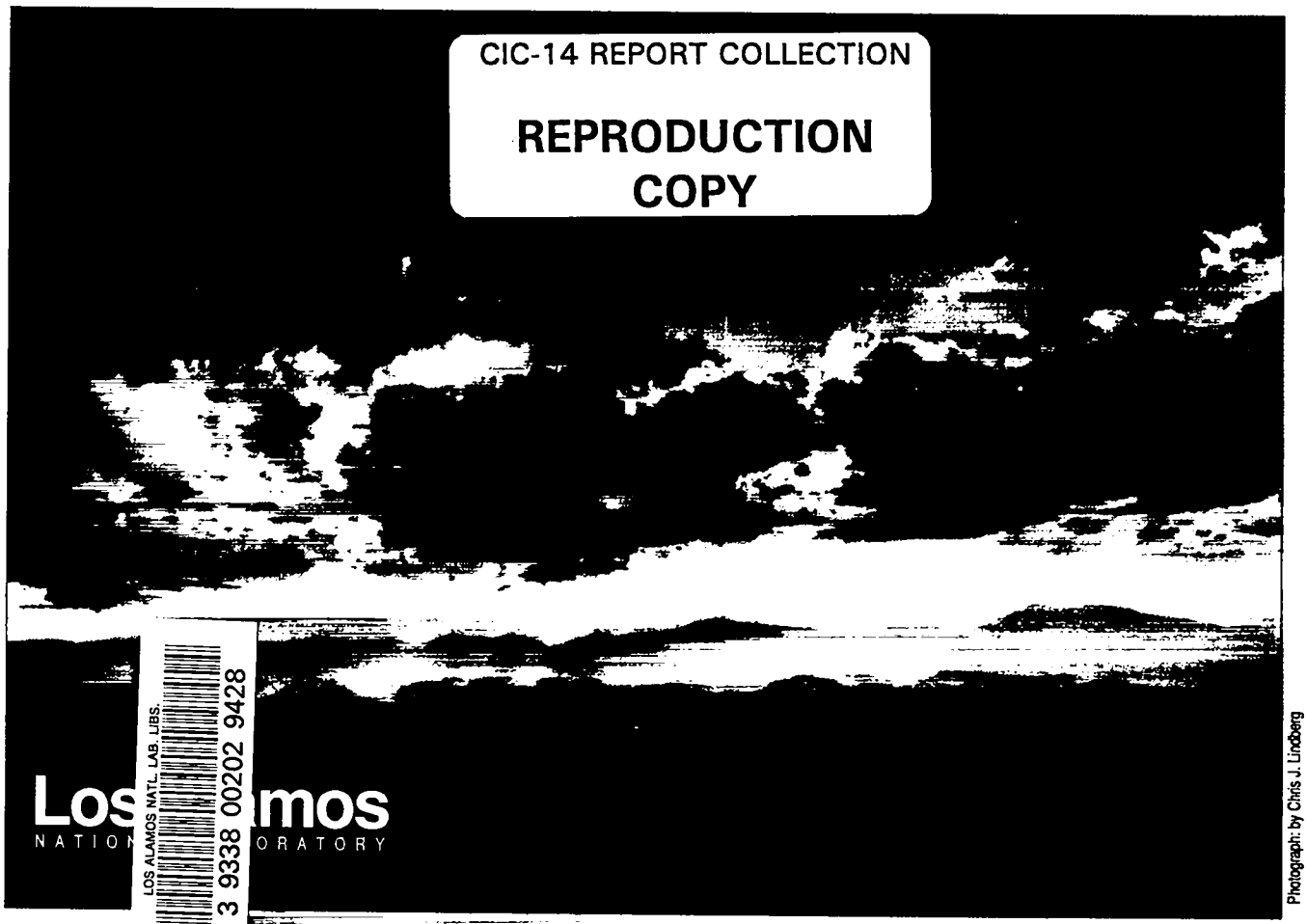

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Allen H. Cogbill
Steven R. Taylor

Geophysics Group
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

A high-frequency seismic reflection survey was conducted 7 weeks prior to and 17 weeks after the nuclear event DIVIDER in an effort to try to image a possible spallation surface resulting from the event. No nuclear events have been conducted at the Nevada Test Site since the DIVIDER event, implying that any spall surface that might have developed as a result of the DIVIDER event was unaffected by subsequent nuclear events. A industry-standard seismic vibrator was used as the seismic source for both surveys. Both surveys used the same recording hardware, a 24-channel EG&G Geometrics 2420 seismic recorder with in-field correlation capability recording the output of 40-Hz vertical geophones. Despite considerable effort to insure that the pre- and post-event surveys were recorded using the same procedures, the post-event survey, while of reasonable (40-180 Hz) bandwidth, showed nearly a factor of 10 less signal amplitude, and was generally of poor quality. The poor quality of the post-event survey made identification of any coherent reflecting horizons very difficult except over limited lateral extent. As result, no spall or other detachment surface could be identified in the post-event survey. Thus the DIVIDER pre- and post-event seismic reflection surveys, similar to surveys performed prior to and after the BEXAR event, were inconclusive with respect to the identification of possible spall surfaces that might have developed as a result of the nuclear event.

INTRODUCTION

A number of studies have addressed the possible effects of spall on regional and teleseismic waveforms. The complexities introduced by spall on radiated signals can have an impact on monitoring capabilities. For example, Taylor and Randall (1989) showed examples of how spall may affect the performance of spectral discriminants. Burdick *et al.* (1984) attributed anomalously large *pP* delays commonly observed for explosions to effects of spall for both teleseismic *P* waves and *Pn*. In a complete moment tensor inversion of the explosion HARZER, Patton (1988) discussed the effects of spall on the *Lg* phase. Simulation studies of spall by McLauglin *et al.* (1988) indicate that spall may have a greater impact on regional signals (particularly *Lg*) in high-velocity environments such as those found at test sites of the former Soviet Union. Given the remarkable stability of *Lg* as a yield estimator in the Soviet Union [Hansen *et al.* (1990)], it is important to understand the effects of spall on regional signals. The important parameters necessary to model the spall process on seismic signals are reviewed in Taylor *et al.* (1992).

Much can be learned about spallation from observation of close-in acceleration waveforms. These can provide information on characteristic times, escape velocities, lateral extent, and depth of spall (giving the spalled mass) if adequately instrumented (*e.g.*, Stump, 1985). However, for nuclear explosions it is prohibitively expensive to adequately sample the spall region. Typically, acceleration records are acquired at just the free surface and possibly in the emplacement hole and it is not possible to obtain a three-dimensional view of the spall process.

As an attempt to obtain an improved image of the lateral and depth extent of spall, we conducted a pilot study assessing the utility of collecting pre- and post-shot reflection data from the spall zone of the NTS nuclear event DIVIDER. We hoped that by comparing records from pre- and post-shot reflection surveys, some change might be observed due to the effects of spall on the local geology. A similar study was performed on the BEXAR event (Miller and Steeples, 1991), but was unsuccessful for a number of reasons explained later. We hoped to benefit from the experience of the BEXAR survey.

THE BEXAR SEISMIC REFLECTION SURVEY

Rick Miller and Don Steeples of the Kansas Geological Survey (KGS) conducted pre- and post-event seismic reflection surveys in the vicinity of the BEXAR nuclear event, an underground test conducted on Pahute Mesa in early 1991. Although the KGS survey was originally designed as a "high-frequency" survey in order to exploit the potentially higher spatial resolution available at higher frequencies, the actual dominant frequencies recorded were ~50 Hz, well below the desired frequencies of 200 Hz or greater. Miller and Steeples did not provide an explanation of why the recorded seismic data were of so much lower frequency than desired, but longtime experience in attemping to obtain good downhole seismic data on Pahute Mesa indicates that severe attenuation as well as poor geophone and source energy coupling are the rule in its dry, volcanic terrane. Miller and Steeples recommended the following for any future seismic studies of spall:

1. That future studies be conducted as far away from previous undergound nuclear events as practical, in order to permit any observed reflections to be associated uniquely with a test.

2. That high explosives be used as an energy source, rather than the 0.50-caliber rifle source used in their study.

3. That a 48-channel seismic system be used, rather than the 24-channel system used by them.

4. That the chance of success was probably greater in Yucca Flat than on Pahute Mesa.

5. That future experiments utilize *P*-wave sources only, rather than shear wave sources. Miller and Steeples used both types of sources, but had no success at all with shear wave sources.

Subsequent to the BEXAR experiment, we considered a pre- and post-event seismic survey for the GREENWATER, a test planned in Area 20. GREENWATER was attractive not only because of its relatively large planned yield, but also because it was located several km from previous test sites. However, inspection of the site conditions near GREENWATER revealed many operational difficulties that would make successful execution of a seismic survey unlikely. Thence, we turned our attention to DIVIDER, an

event located on the eastern margin of Yucca Flat. Ultimately, the GREENWATER event was canceled.

We chose to conduct the pre- and post-event seismic survey near DIVIDER using the following data acquisition equipment:

1. A 24-channel seismic recording system.

2. A seismic vibrator as an energy source.

3. High-frequency (40-Hz) receivers (geophones).

The scheduling of the DIVIDER event near the close of the fiscal year made the contracting of the pre- and post-event survey difficult; thus we chose to provide the data acquisition from resources in EES-3, rather than using a contractor. This limited the recording system to a 24-channel system, rather than the 48-channel system recommended by KGS. A seismic vibrator was used because we felt that it would provide at least as good bandwidth and signal-to-noise ratio as small explosive charges (a seismic vibrator was not considered as a possible source by Miller and Steeples, probably because their recording system is incapable of recording the required signals from the vibrator). Another reason for performing the survey with available equipment was that a series of short seismic reflection surveys were already planned at NTS for the summer of 1992; thus, the DIVIDER survey could be conducted in conjunction with other seismic surveys, providing a significant cost savings.

SITE DESCRIPTION

The DIVIDER site was well-characterized prior to detonation to insure that no geologic features existed that would adversely affect containment of the event. The site description that follows is excerpted principally from the site characterization developed by the nuclear test containment program at Los Alamos.

DIVIDER was located near the eastern edge of Yucca Flat, where the dominant surface features are alluvial fans from the hills forming the eastern side of the valley (Figure 1). The closest shot-induced fea-

tures are from the TOMATO event in U3ek, approximately 400 m to the southwest. A surface crater with mostly radial and concentric cracking exists due to that event. The only recent event in the area was LAREDO in U3mh, located nearly 1300 m north of DIVIDER.

The stratigraphic sequence in U3ml consists of a relatively thin layer of alluvium underlain by volcanic tuffs that lie unconformably upon rocks of Paleozoic age, probably carbonates. The predicted Paleozoic rock depth is about 600 m. Overlying the Paleozoic rocks are 231 m of Tunnel Beds and older tuffs, which are in turn overlain by 134 m of Crater Flat, Wahmonie and Pre-Timber Mountain tuffs. The predicted cavity region for DIVIDER, from 301 to 379 m, is entirely within this sequence of primarily bedded, zeolitized tuffs. The overlying non-welded to moderately-welded Rainier Mesa and Ammonia Tanks tuffs are themselves overlain by 107 m of tuffaceous alluvium.

DIVIDER is located in a generally north-south trending structural block between two west-dipping, inferred faults. There is a third inferred fault on the east side of the west-east cross section (Figure 2). Surface gravity data from the Yucca Flat gravity data set (station spacing roughly 200 m) were augmented by a more detailed (38-m station spacing) gravity profile across the DIVIDER site. Additionally, a ground magnetic survey having 3-m station spacing was performed along the same line as the gravity profile. Together, these geophysical data permitted construction of the west-east cross-section. Borehole gravimeter data from U3ml constrained the location of structure with 100 m of U3ml. The dip of the beds on the cross section reflect those dips observed in the downhole photography. Several locations in the tuffs showed a westward dip ranging from 11° to 17°. The north-south cross section (Figure 3) is parallel to structure and therefore rather featureless.

A complete suite of geophysical logs was run in U3ml; Figure 4 shows a subset of these logs. Because of concern for the tendency of the alluvium in this part of the valley to slough, the hole was drilled through the alluvium, then some geophysical logs were taken prior to the installation of an intermediate casing. Because the borehole wall through the alluvium was invaded with drilling fluid, much of the geophysical data in the alluvial portion of the borehole is suspect and unlikely to be representative of the

formation.

Two types of velocity data are available from U3ml. First, a downhole geophone survey, sometimes caslled a checkshot survey, was performed. Such a survey provides the one-way travel time from the surface to a geophone clamped at various depths in the borehole, and is very useful for converting seismic reflection data from time to depth. However, such measurements provide poor spatial resolution of velocity changes. Additionally, though, a dry-hole acoustic tool was run in U3ml. This tool measures seismic velocity in the borehole by measuring the transit time from a source placed against the borehole wall to one or more receivers clamped to the borehole wall. At U3ml, 3 receivers were used, at distances from the source of 3, 6, and 12 feet from the source. The tool's depth was changed in 5-foot increments, thus providing a reasonably well-resolved plot of seismic *P*-wave velocity *versus* depth. Figure 5 shows the travel-time curve resulting from the checkshot survey in U3ml, and Figure 6 shows the velocities measured using the dry-hole acoustic tool. Note that no alluvial velocities were measured by the acoustic tool, for the alluvial interval had been cased at the time the log was run.

An abrupt increase velocity occurs at a depth of ~160 m, corresponding to the top of the welded zone in the Rainier Mesa Tuff. At this horizon, seismic velocity increases from 1250 m/s to 2750 m/s within 10 m. Such an increase in velocity should provide a coherent reflector to map, provided that the stratigraphic unit does not change its properties rapidly laterally. The sparse velocity data above 160 m depth suggest that no good reflecting horizons are present above the top of the welded Rainier Mesa.

SEISMIC DATA ACQUISITION

The DIVIDER seismic surveys used a seismic vibrator provided and operated by Halliburton Geophysical Services as the seismic source. The surveys were designed to obtain relatively high frequency seismic data; a linear sweep from 40 to 180 Hz was used, with the data being sensed by 40-Hz, vertical-component, single geophones (Mark Products L-40A). Because of the relatively high frequencies used (the

predominant width of seismic pulses recorded was 10 ms, corresponding to a frequency of 100 Hz) and the low seismic velocities of the medium, the wavelengths of the seismic waves recorded were as small as 8 m. Thus, a small geophone group interval of 2 m was used. While such a group interval is small enough to prevent spatial aliasing of the recorded wavefield, the fact that a 24-channel system was used meant that the spread length was only 46 m (the survey was an "end-on" survey). Such a small spread length is adequate for shallow investigations, but at deeper depths, the moveout is very small. The result is that the total amount of moveout at greater 2-way times is insufficient to permit substantial attenuation of multiple reflections.

Each sweep of the vibrator was 7 s in length; the data were recorded using a sample rate of 500 ms, and correlated with the calculated base-plate force signal that was provided by the vibrator controller. The latter signal was "hard-wired" from the vibrator controller to the seismic recorder. Every effort was made to insure that the recording procedures post-shot were identical to those pre-shot. However, the pre-shot data quality was visibly superior to the post-shot data quality. It is not quite clear why this was the case. The vibrator controller was the identical unit that was used for the pre-shot survey, but the vibrator itself was a different unit, although it had the same nominal specifications. The pre-shot and post-shot surveys used the same wiring from the vibrator controller to the seismic recorder, and the same nominal downforce was used for each sweep. However, the ground force signal recorded was several times lower in amplitude in the post-shot survey compared to the pre-shot survey. Because the data are correlated with this ground-force signal, the overall signal levels of the correlated seismic data are significantly lower for the post-shot seismic survey compared to the pre-shot survey. Figure 7 illustrates the relative signal levels for a selected trace (channel 24 of VP 87) from the respective surveys.

Prior to execution of DIVIDER, the maximum radius of spall was estimated to be 500-600 m from SGZ. Because the objectives of the seismic surveys were to map a possible detachment surface created by spall, the seismic line was established along a line trending east of DIVIDER, beginning 150 m from SGZ and ending 700 m from SGZ, thus spanning the expected spall radii. The line was not established any closer

than 150 m from SGZ because we knew that post-event access would be restricted to distances greater than 150 m. Vibrating points (VP's) were denoted 101 to 375, with VP 101 located furthest east and VP 375 closest to SGZ (Figure 8). As previously noted, the survey was an "end-on", 24-channel survey, with a near-offset of 12 m and a geophone interval of 2 m, resulting in a spread length of 46 m and a far-offset of 58 m. The seismic line was coincident with a portion of the line along which the previously-mentioned gravity and magnetic surveys had been conducted, and crossed a fault mapped by these pre-shot surveys. The location of this fault was quite obvious during data acquisition; the location mapped by the seismic survey was coincident with the previously-inferred location, which was derived largely from the ground magnetic survey.

The pre-event survey was conducted 31 July - 01 August, 1992, and the post-event survey was conducted 26-29 January, 1993. The DIVIDER event was executed on September 23, 1992. There have been no nuclear tests conducted at the Nevada Test Site since the DIVIDER event; thus, there is no chance that an event conducted after DIVIDER would have had any influence on the geology in the vicinity of the DIVIDER event.

RESULTS

Figure 9 shows selected shot gathers from the pre-event survey. Overall signal-to-noise levels were acceptable, but, as can be seen from the shot gathers, few obvious, coherent reflectors appear. This lack of reflecting horizons was typical of the shot gathers of the pre- and the post-event survey, and of course degraded the utility of the surveys immensely. Without at least one reflecting horizon to follow, the determination of stacking velocities and static corrections was difficult. Figure 10 is a spectral plot of a randomly selected, correlated trace from VP 87.

Figure 11a and 11b show the stacked pre-event seismic section. Processing on the section was minimal: after demultiplexing, the data were band-pass filtered, early arrivals were muted, and then stacked. Much effort was spent attempting to determine proper stacking velocities. The best-fit stacking velocities were relatively low (no higher than 900 m/s), but such velocities are not abnormally low for shallow reflection data from Yucca Flat.

Close to the shot (CDP's 515 - 450 on Figure 11a) we obtained the best reflectors. Despite the overall poor quality of the seismic line, we hoped that these near-in reflecting horizons would be useful for the spall study. Unfortunately, the data quality in the post-event survey was so poor that virtually no reflectors could be identified at the equivalent location on the post-event section. While it is possible that the poor data quality results from an effect induced by the nuclear event, I consider such an explanation highly implausible, simply becuase seismic surveys in other portions of Yucca Flat have been conducted near expended events. Such surveys often show coherent reflectors, indicating that the effects of a nearby shot on the data quality are minimal. However, this statement must be qualified, as earlier seismic surveys are crtainly not "high-frequency" surveys. Earlier surveys used seismic data in the bandwidth 10-80 Hz, whereas the bandwidth for this survey was 40-180 Hz. It is possible, but unlikely, that the DIVIDER event and its associated spall resulted in greater near-surface variations in velocity. Such variations (resulting in greater "static" errors in seismic processing jargon) have a larger effect on high-frequency data than on conventional data. Considerable effort was made to account for such possible static errors, but such efforts were hampered by the lack of a single, coherent reflector on the seismic section.

On the post-event, stacked seismic section, a reflector appears at ~225 ms at CDP 340. The reflector continues eastward for at least 40 m before becoming undiscernible. This reflector is not observed in the pre-event data at all, despite considerable efforts to extract tit from the pre-event data. The reflector occurs ~360 m from SGZ at a depth of roughly 140 m. We do not have a good explanation for this reflectors lack of appearance on the pre-event section. However, the horizontal location is approximately coincident with significant surface cracking observed as a result of the DIVIDER event (Figure 1), and thus the reflector is possibly related to whatever mechanism caused the surface cracking, which is presumably movement along a fault. It is unclear what physical mechanism would account for inducement of a reflector; as a result, I favor the view that the data quality on this portion of the pre-event line was simply too poor to bring out this reflector.

CONCLUSIONS

Pre- and post-event seismic reflection surveys searching for possible spall surfaces have now been carried out for two NTS events, BEXAR and DIVIDER. BEXAR was an event conducted on Pahute Mesa, whereas DIVIDER was fired in Yucca Flat; thus, such seismic surveys have been conducted in both of the

two major geologic subregions of NTS. Neither set of surveys was able to identify a spall surface. While it is entirely possible that the lack of such identification is due to the fact that both surveys used only 24-channel recorders rather that 48- or 96-channel recorders, the fact that data quality was mediocre-to-poor for each survey is certainly the major reason for failure to identify a spall surface, assuming that such a surface existed. Poor data quality is a common result for NTS seismic surveys, and thus we would predict likely failure for any future effort to identify a spall surface at NTS using seismic reflection methods. At other nuclear test sites such surfaces, if created by a test, might well be discernible using seismic reflection methods, depending, of course, very strongly upon local geologic conditions.

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FIGURE CAPTIONS

Figure 1. Plan map showing the location of DIVIDER site, U3ml. The line trending S17°E from U3ml is located along the seismic reflection line, which started 800 m from U3Ml and terminated 150 m from U3ml. NNE-trending lineations located ~350 m east of U3ml have been interpreted as associated with a fault that was identified pre-event using ground magnetic surveys.

Figure 2. West-east geologic cross-section through the DIVIDER emplacement hole, U3ml.

Figure 3. North-south geologic cross-section through the DIVIDER emplacement hole, U3ml.

Figure 4. Selected logs from U3ml. Stratigraphic unit abbreviations are as explained in Figures 2 and 3. Note that U3ml#1 was a so-called satellite hole drilled only 11 m from U3ml.

Figure 5. Geophone (checkshot) log from U3ml.

Figure 6. *P*-wave velocities in U3ml measured using a dry-hole acoustic log.

Figure 7. Comparison of pre-shot and post-shot correlated trace amplitudes. Each trace corresponds to channel 24 at VP 87. Note that the pre-shot amplitudes are roughly 10 times as great as the post-shot amplitudes.

Figure 8. Map showing the relationship of the seismic line to the location of U3ml. Note that VP 101, the first VP on the line, is furthest from U3ml.

Figure 9. Examples of pre- and post-event shot gathers from the DIVIDER surveys. Note the lack of obvious reflecting horizons on either of these shot gathers, which were not atypical. The amplitudes of the pre- and post-event surveys appear comparable in this display due to the application of AGC prior to plotting [compare Figure 7].

Figure 10. Amplitude spectrum of the pre-shot trace that appears in Figure 7.

Figure 11a. Stacked seismic section from the pre-event survey, CDP's 10-300. The locations of ground-motion stations fielded during the DIVIDER event are shown above the section. The nomenclature of such stations provides the distance from the staton to SGZ; *e.g.*, GM1660 is the ground motion station located 1660 ft from SGZ.

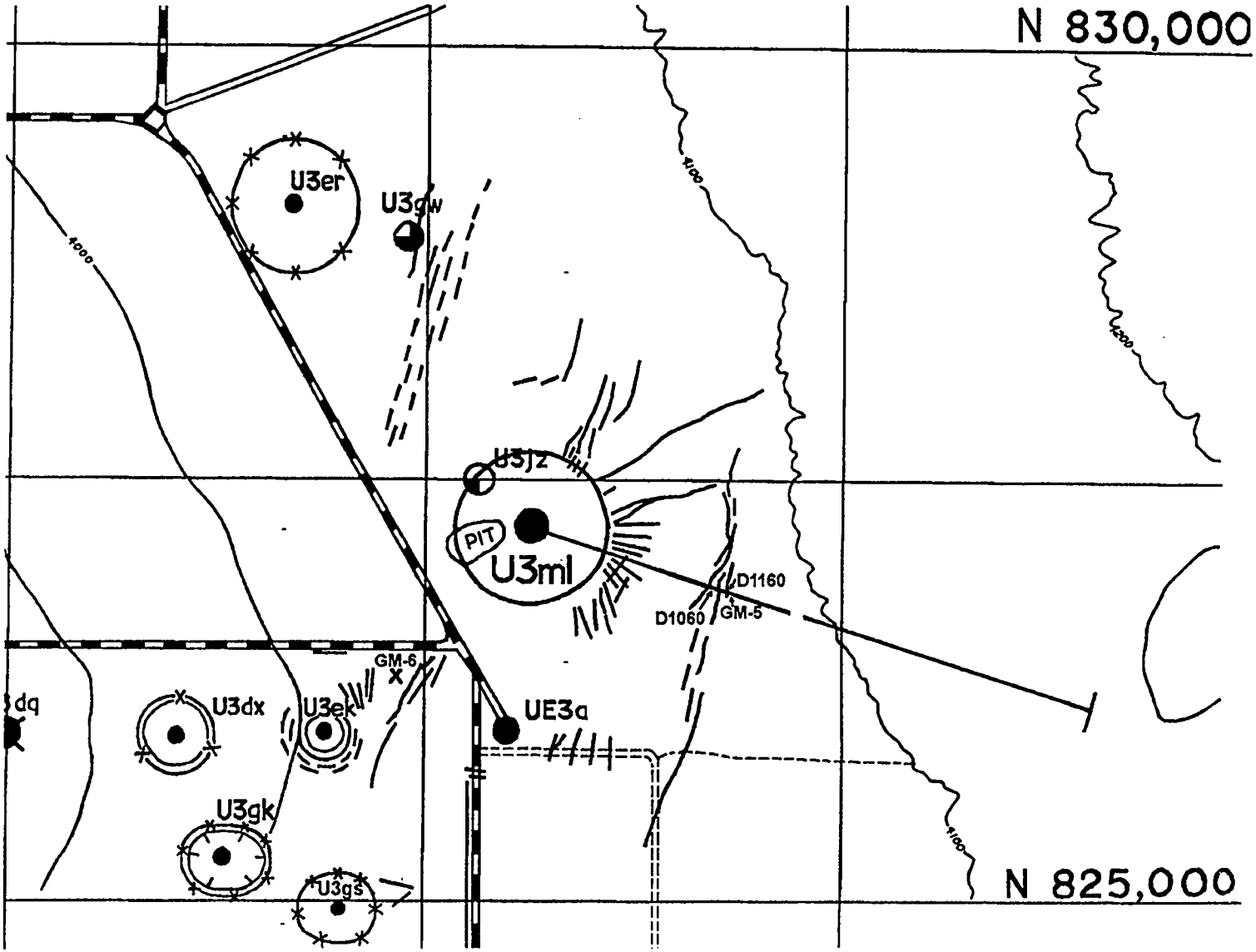
Figure 11b. Stacked seismic section from the pre-event survey, CDP's 250-515. The locations of

ground-motion stations fielded during the DIVIDER event are shown above the section. The nomenclature of such stations provides the distance from the staton to SGZ; *e.g.*, GM0660 is the ground motion station located 660 ft from SGZ.

Figure 12. Amplitude spectrum of the post-shot trace that appears in Figure 7.

Figure 13a. Stacked seismic section from the post-event survey, CDP's 10-300. The locations of ground-motion stations fielded during the DIVIDER event are shown above the section. The nomenclature of such stations provides the distance from the staton to SGZ; *e.g.*, GM1660 is the ground motion station located 1660 ft from SGZ.

Figure 13b. Stacked seismic section from the post-event survey, CDP's 250-515. The locations of ground-motion stations fielded during the DIVIDER event are shown above the section. The nomenclature of such stations provides the distance from the staton to SGZ; *e.g.*, GM0660 is the ground motion station located 660 ft from SGZ.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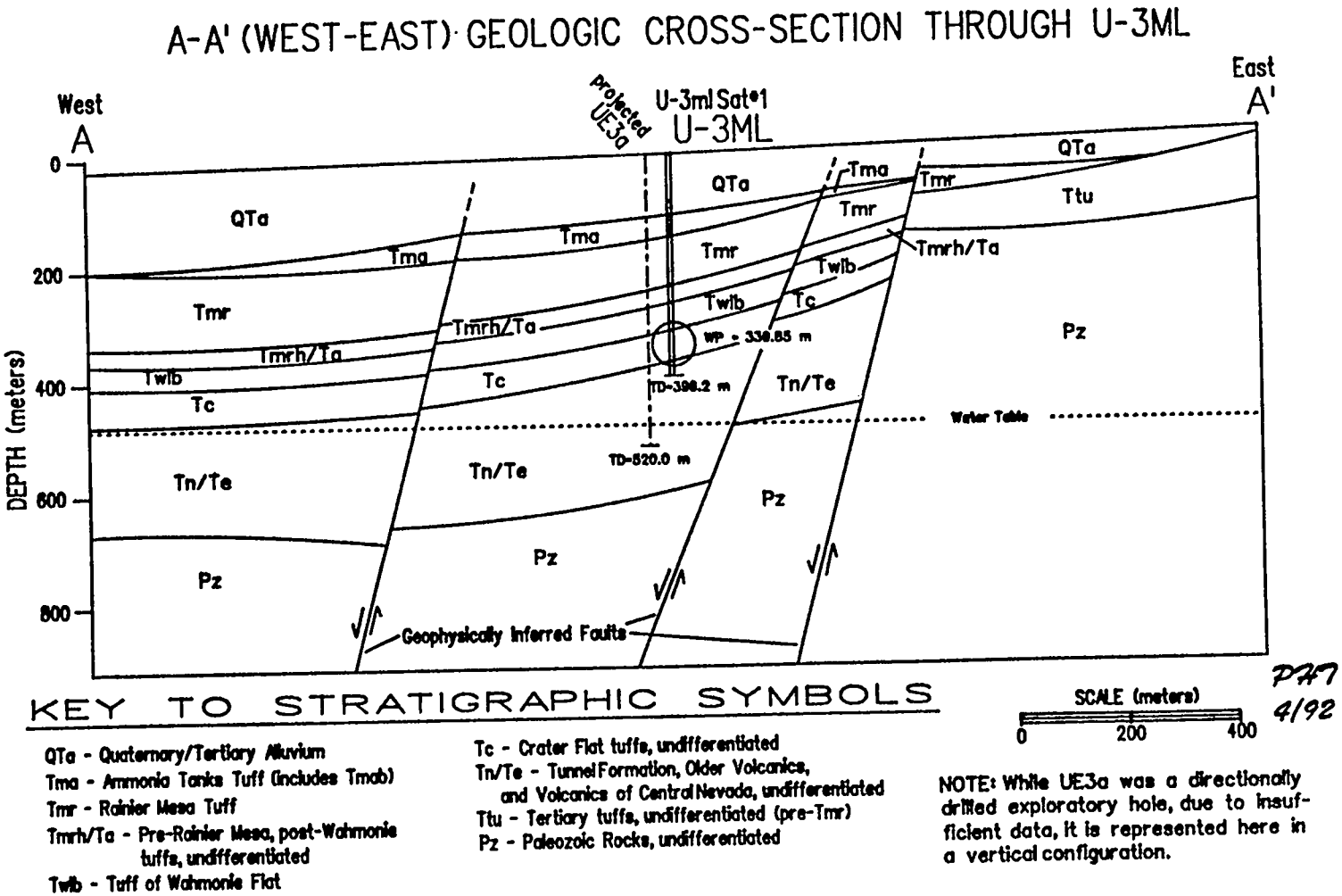
4100
4200

Figure 1.

Figure 2.



KEY TO STRATIGRAPHIC SYMBOLS

QTa - Quaternary/Tertiary Alluvium
Tma - Ammonia Tanks Tuff (includes Tmab)
Tmr - Rainier Mesa Tuff
Tmrh/Ta - Pre-Rainier Mesa, post-Wahmonie tuffs, undifferentiated
Twlb - Tuff of Wahmonie Flat
Tc - Crater Flat tuffs, undifferentiated
Tn/Te - Tunnel Formation, Older Volcanics, and Volcanics of Central Nevada, undifferentiated
Ttu - Tertiary tuffs, undifferentiated (pre-Tmr)
Pz - Paleozoic Rocks, undifferentiated

NOTE: While UE3a was a directionally drilled exploratory hole, due to insufficient data, it is represented here in a vertical configuration.

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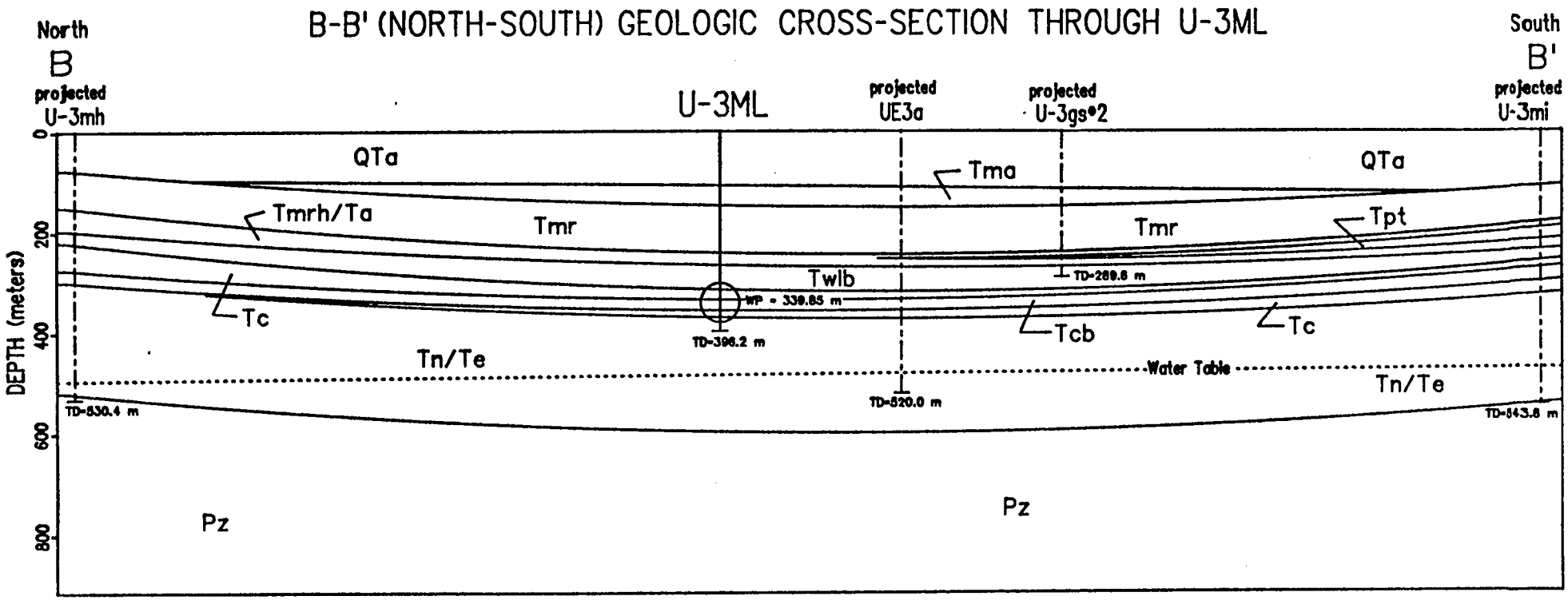
Figure 3.



SCALE (meters)

0 200 400

NOTE: While UE3a was a directionally drilled exploratory hole, due to insufficient data, it is represented here in a vertical configuration.

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QTa - Quaternary/Tertiary Alluvium
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Tpt - Topopah Spring Tuff
Twlb - Tuff of Wahmonie Flat
Tc - Crater Flat bedded tuffs, undifferentiated
Tcb - Bullfrog Tuff
Tn/Te - Tunnel Formation, Older Volcanics, and Volcanics of Central Nevada, undifferentiated
Pz - Paleozoic Rocks, undifferentiated

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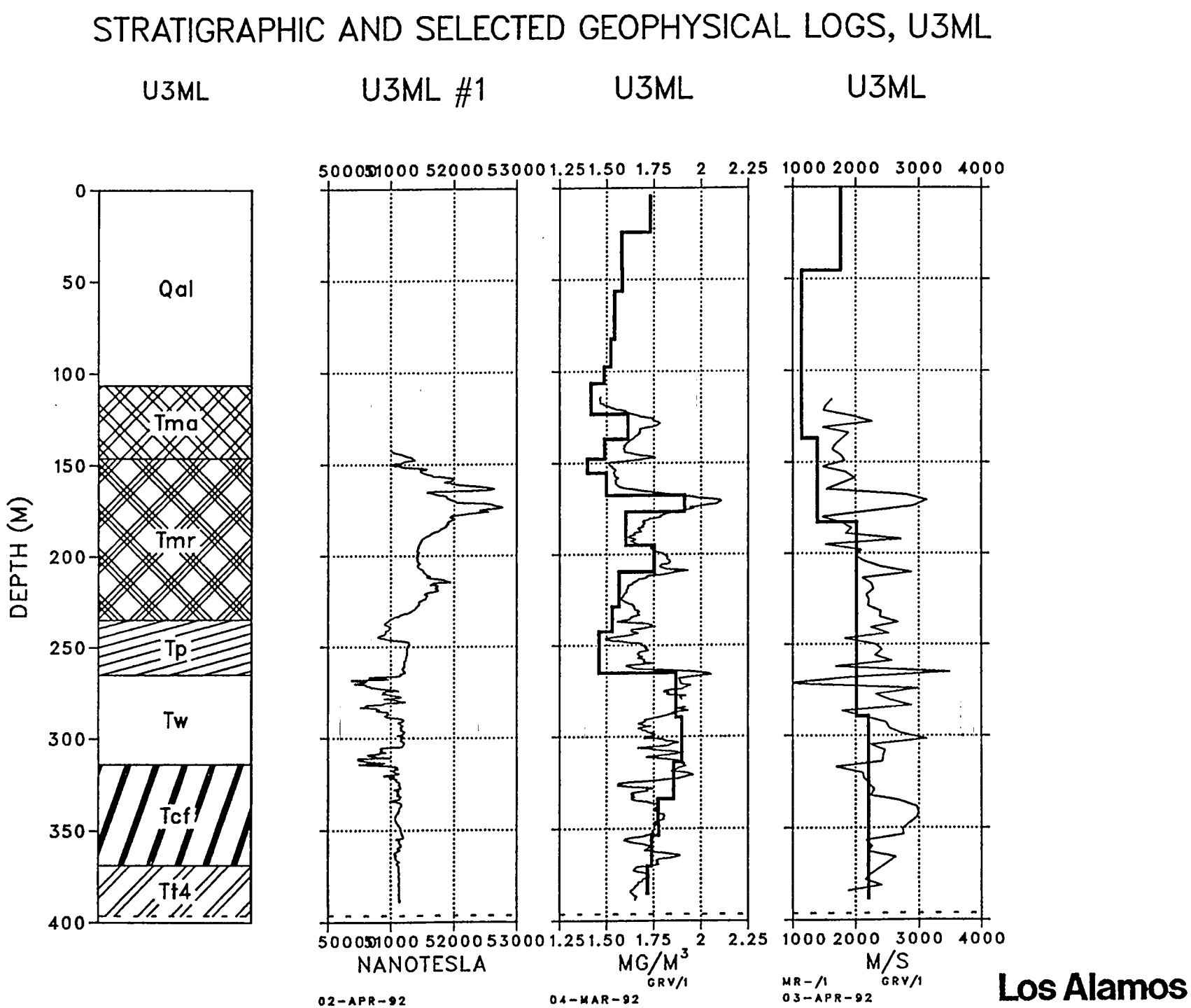
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300
350
400
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Tma
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Tp
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Tcf
Tt4
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GRV/1
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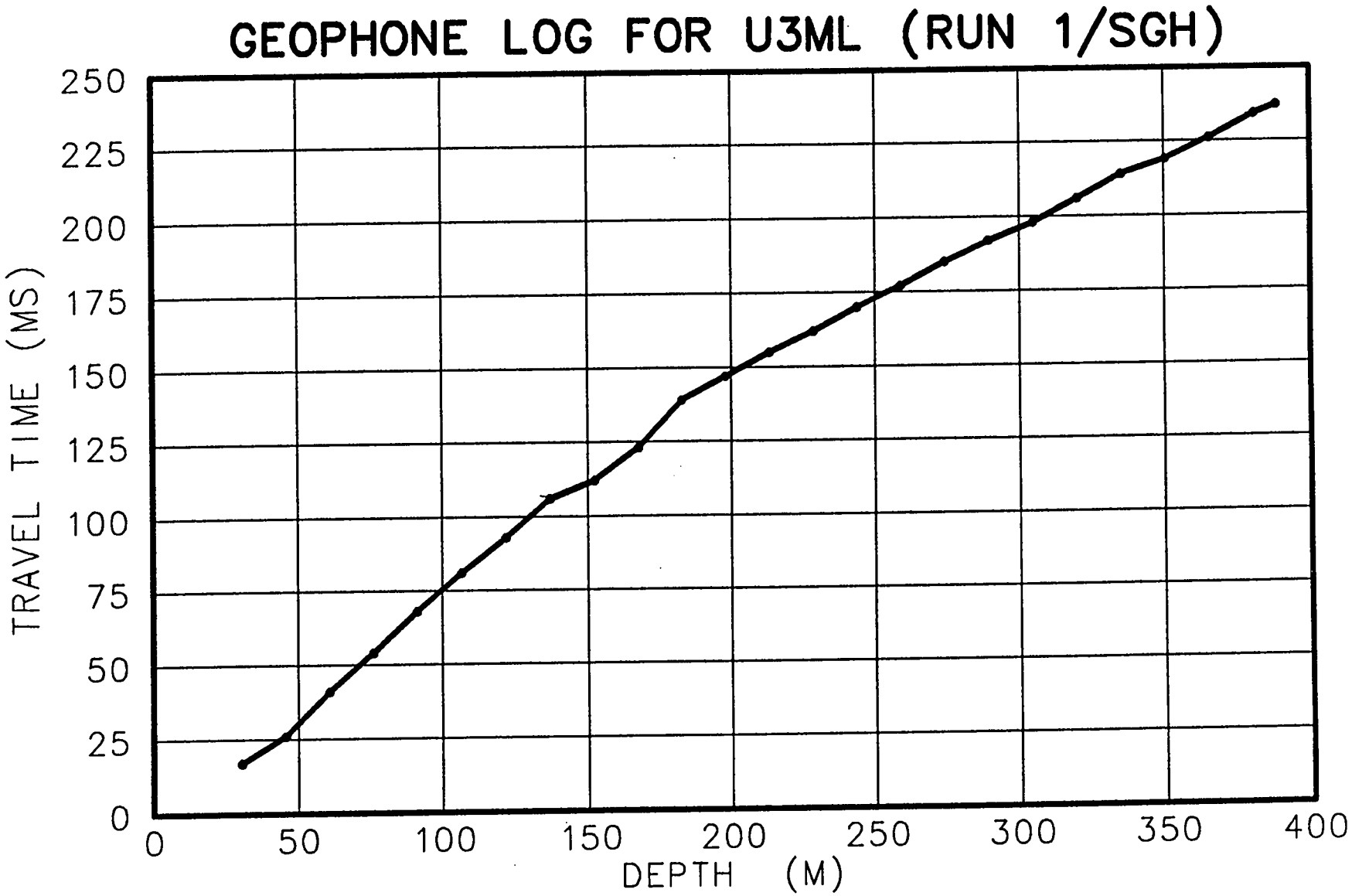
Figure 4.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150
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100
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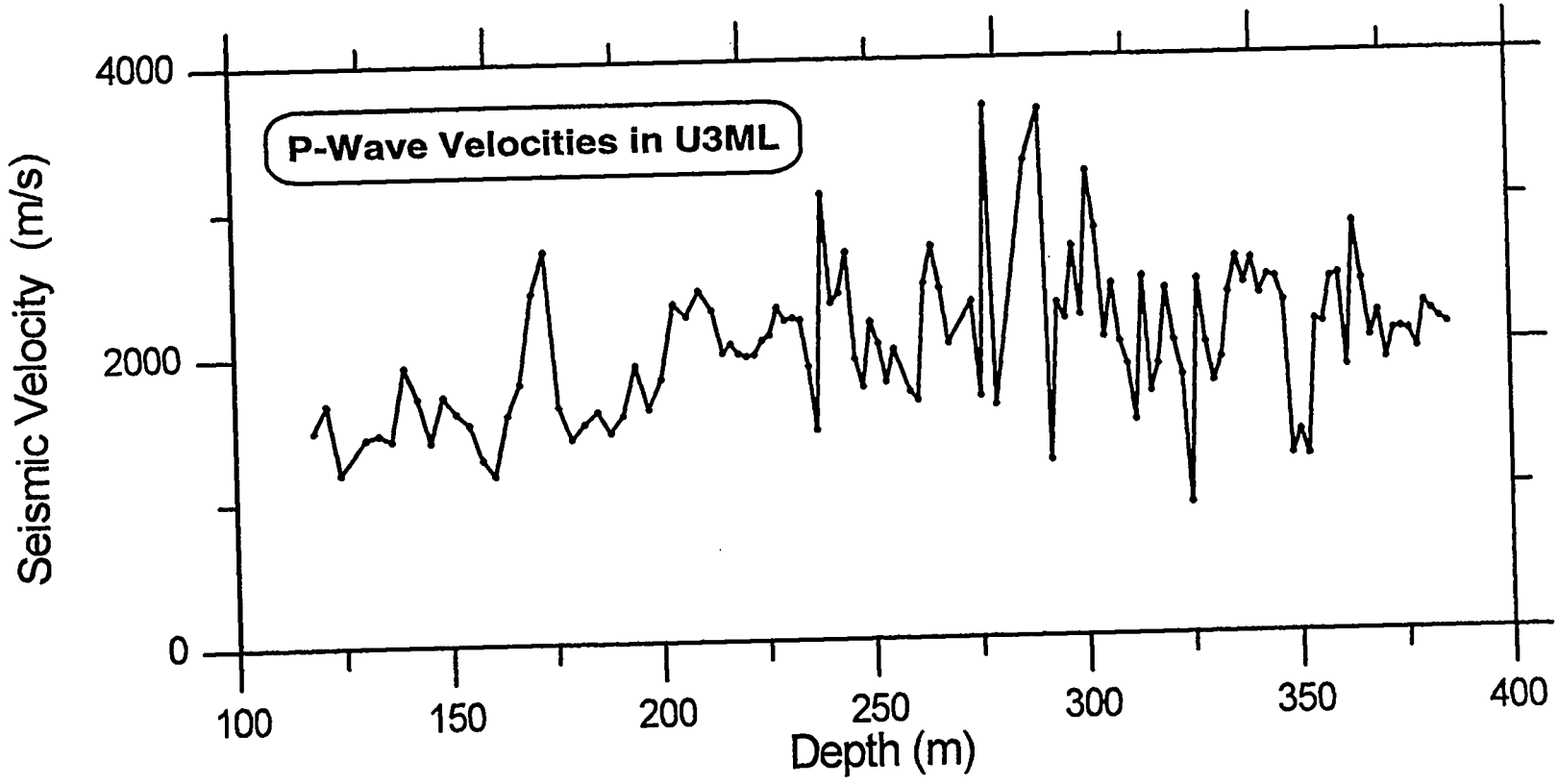
150
200
250
300
350
400
DEPTH (M)

Figure 5.


P-Wave Velocities in U3ML
Seismic Velocity (m/s)
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100
150
200
250
300
350
400
Depth (m)

Figure 6.

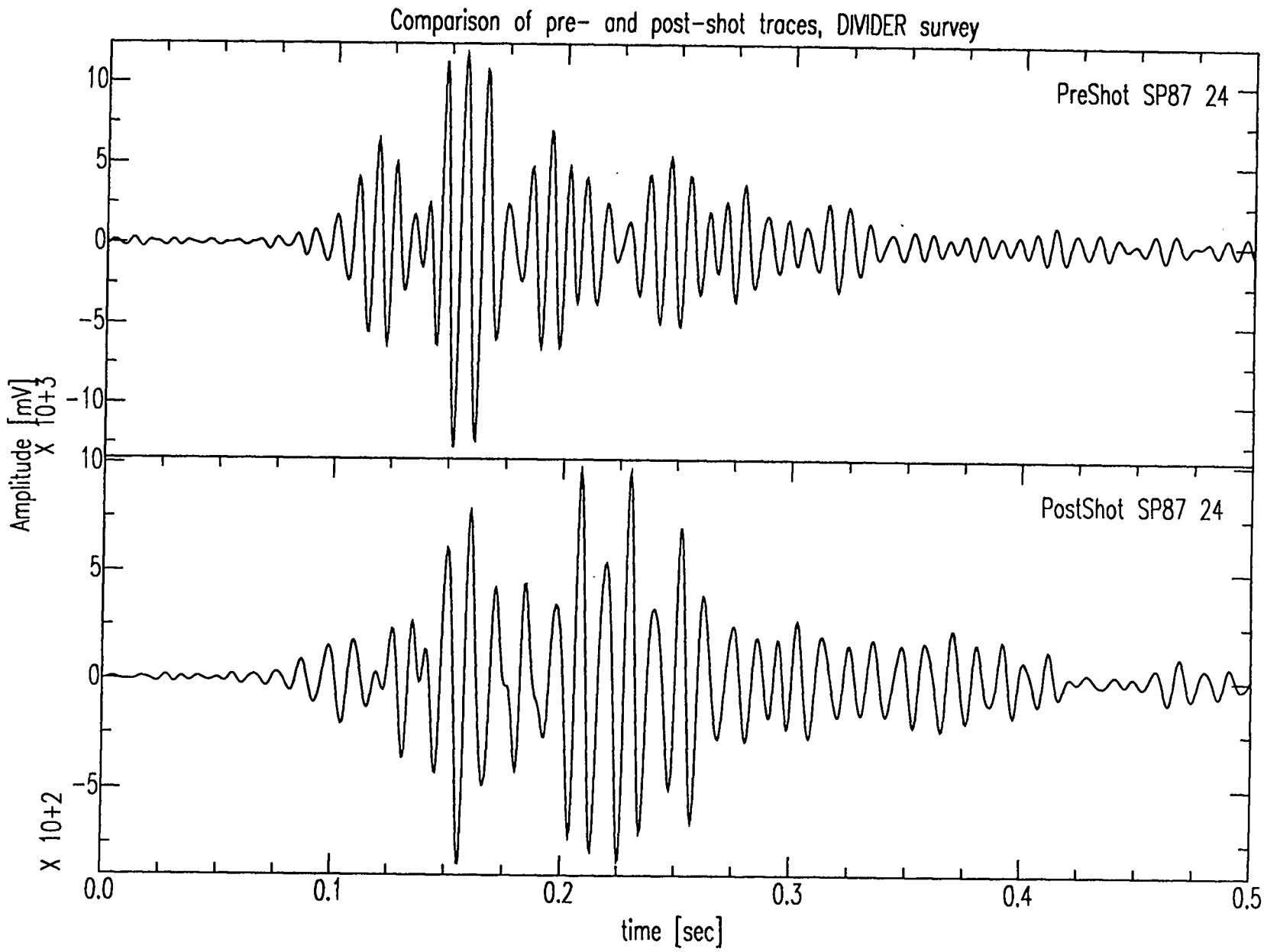

Comparison of pre- and post-shot traces, DIVIDER survey
PreShot SP87 24
PostShot SP87 24
Amplitude [mV]
X 10+3
X 10+2
10
5
0
-5
-10
0.0
0.1
0.2
0.3
0.4
0.5
time [sec]

Figure 7.

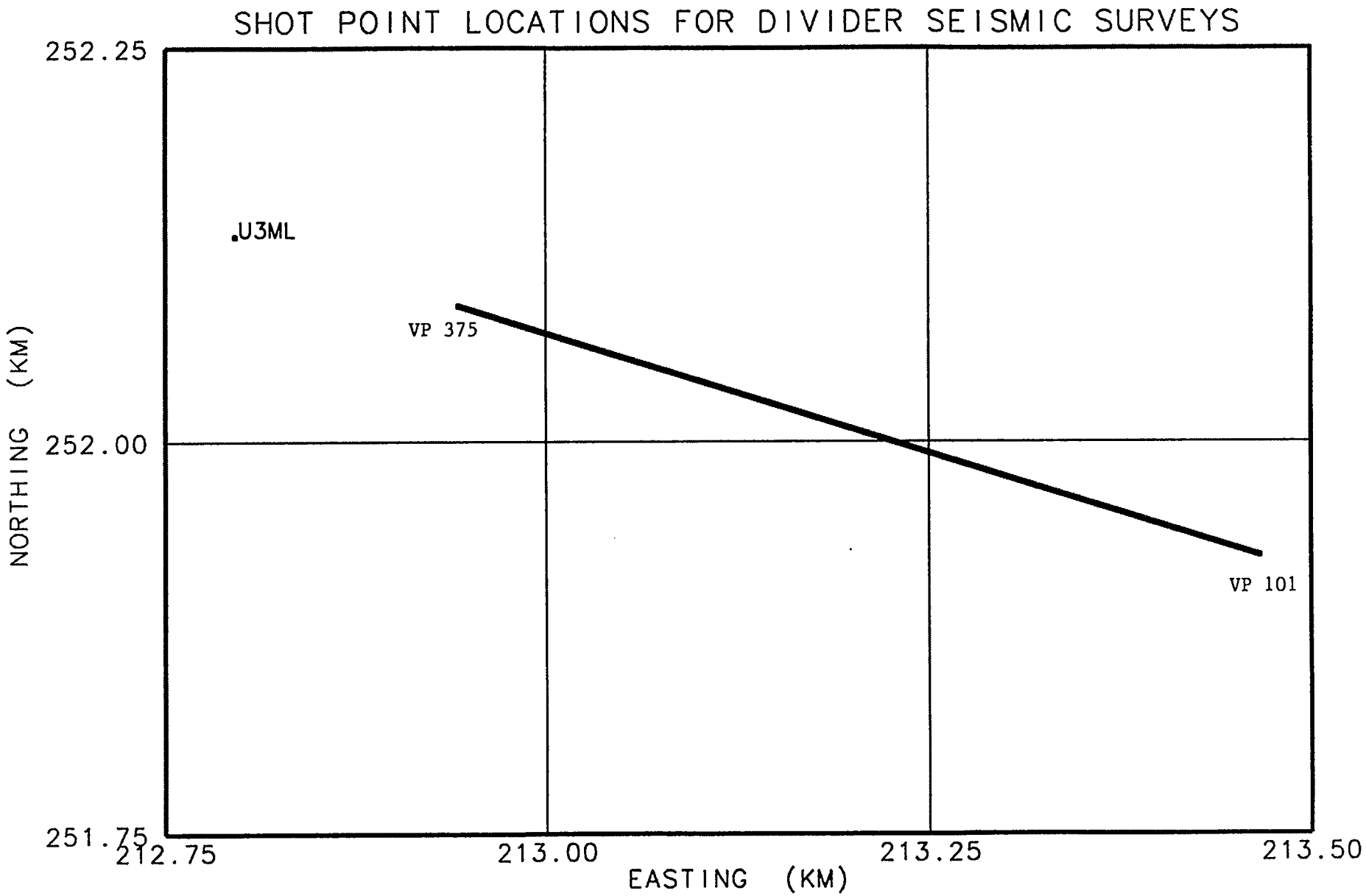

SHOT POINT LOCATIONS FOR DIVIDER SEISMIC SURVEYS
252.25
252.00
251.75
NORTHING (KM)
.U3ML
VP 375
VP 101
212.75
213.00
213.25
213.50
EASTING (KM)

Figure 8.

Figure 9.

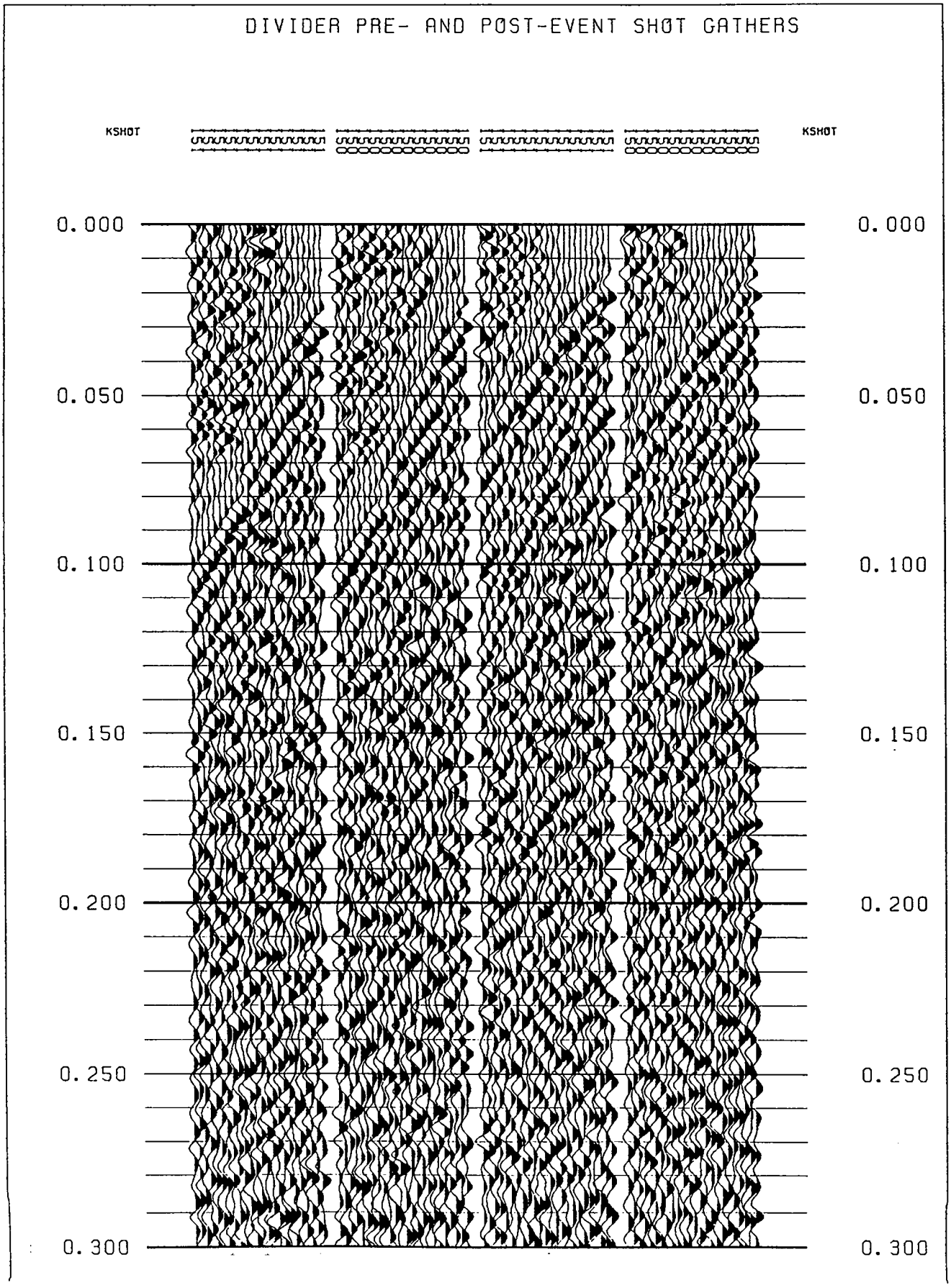

DIVIDER PRE- AND POST-EVENT SHOT GATHERS
KSHOT
KSHOT
0.000
0.050
0.100
0.150
0.200
0.250
0.300
0.000
0.050
0.100
0.150
0.200
0.250
0.300

Figure 10.

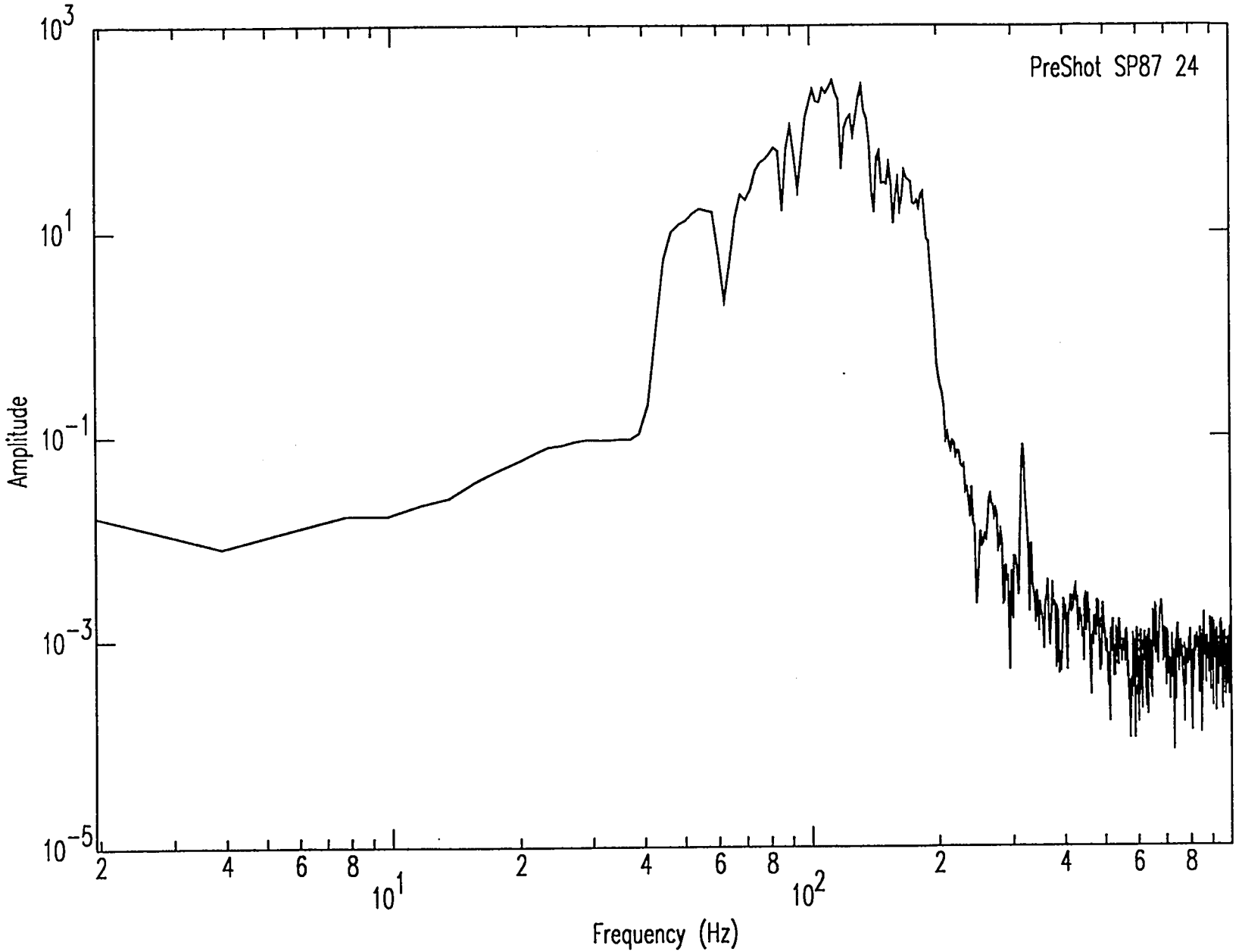

PreShot SP87 24
Amplitude
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
2
4
6
8
10^1
2
4
6
8
10^2
2
4
6
8
Frequency (Hz)

Figure 11a.

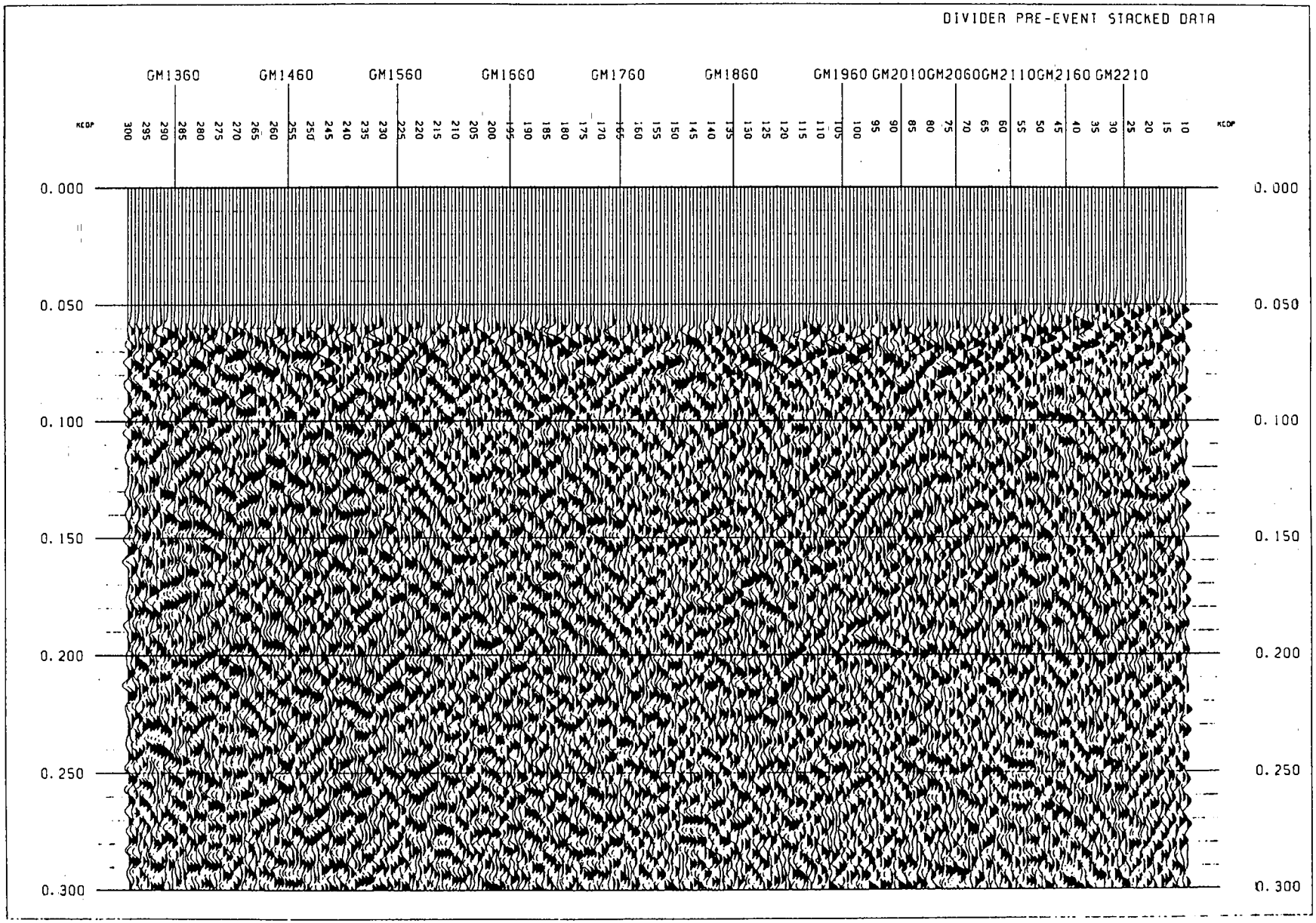

DIVIDER PRE-EVENT STACKED DATA
GM1360
GM1460
GM1560
GM1660
GM1760
GM1860
GM1960
GM2010
GM2060
GM2110
GM2160
GM2210
KCDP
0.000
0.050
0.100
0.150
0.200
0.250
0.300

Figure 11b.

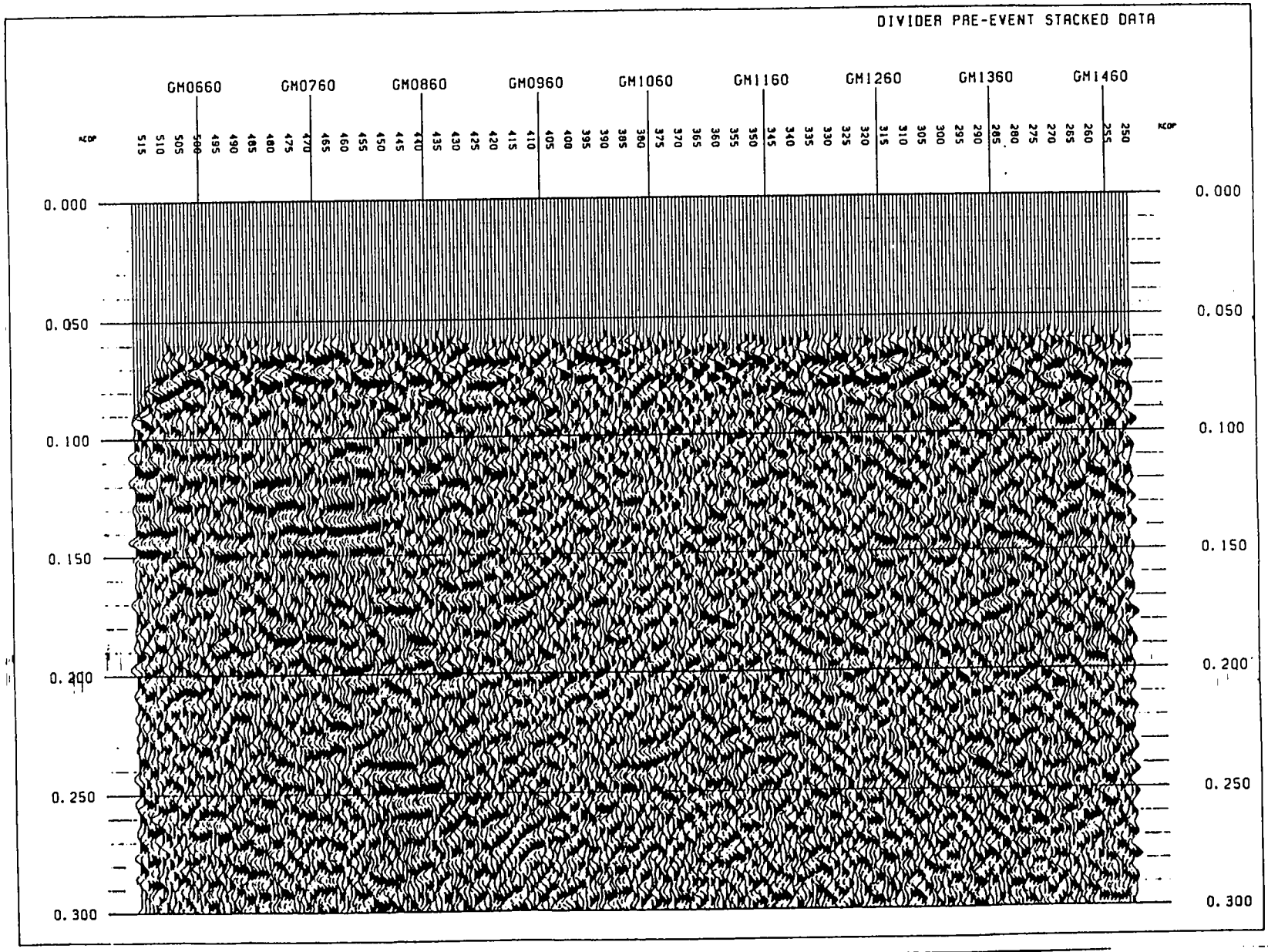

DIVIDER PRE-EVENT STACKED DATA
GM0660
GM0760
GM0860
GM0960
GM1060
GM1160
GM1260
GM1360
GM1460
0.000
0.050
0.100
0.150
0.200
0.250
0.300

Figure 12.

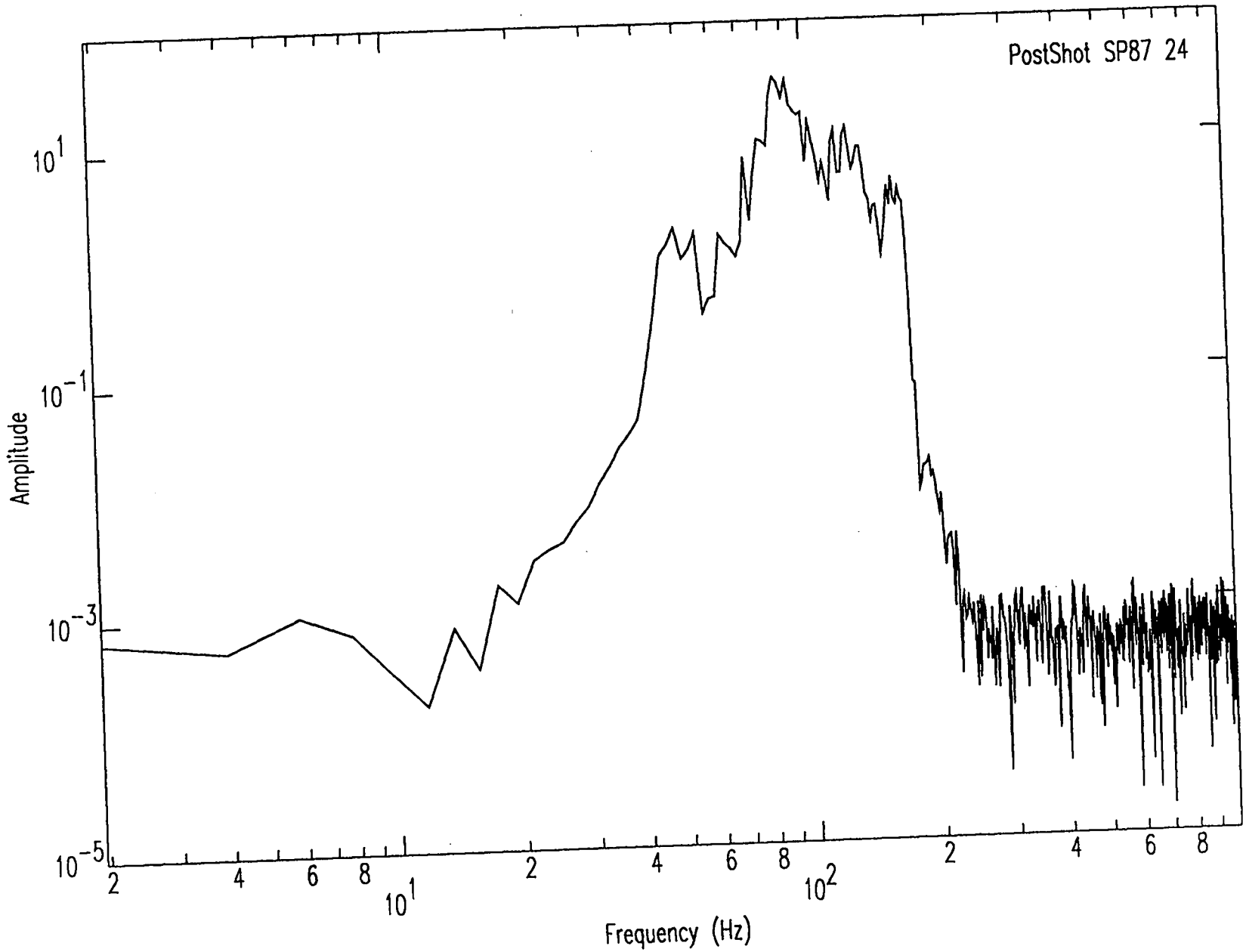

PostShot SP87 24
Amplitude
10^{1}
10^{-1}
10^{-3}
10^{-5}
2
4
6
8
10^{1}
2
4
6
8
10^{2}
2
4
6
8
Frequency (Hz)

Figure 13a.

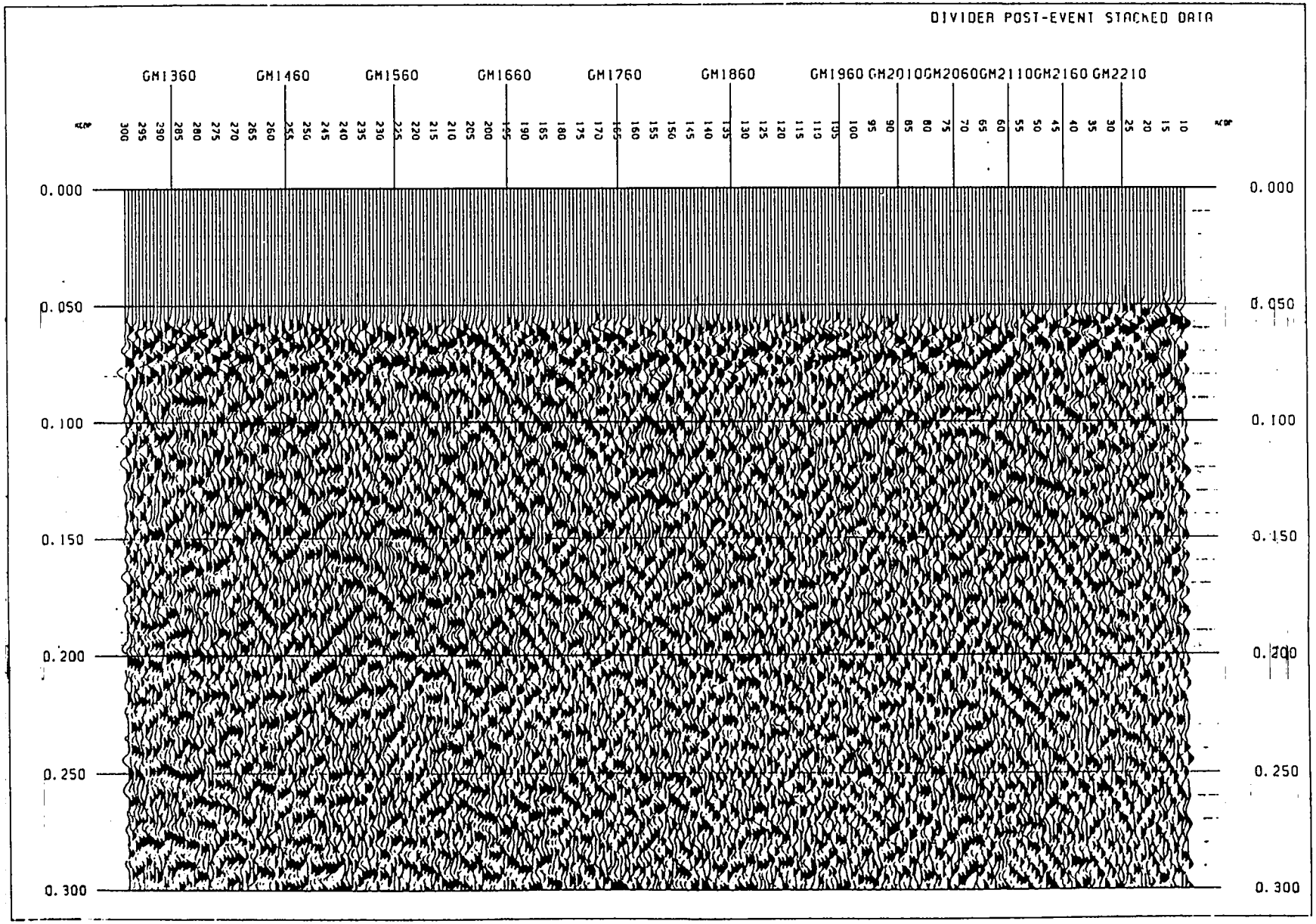
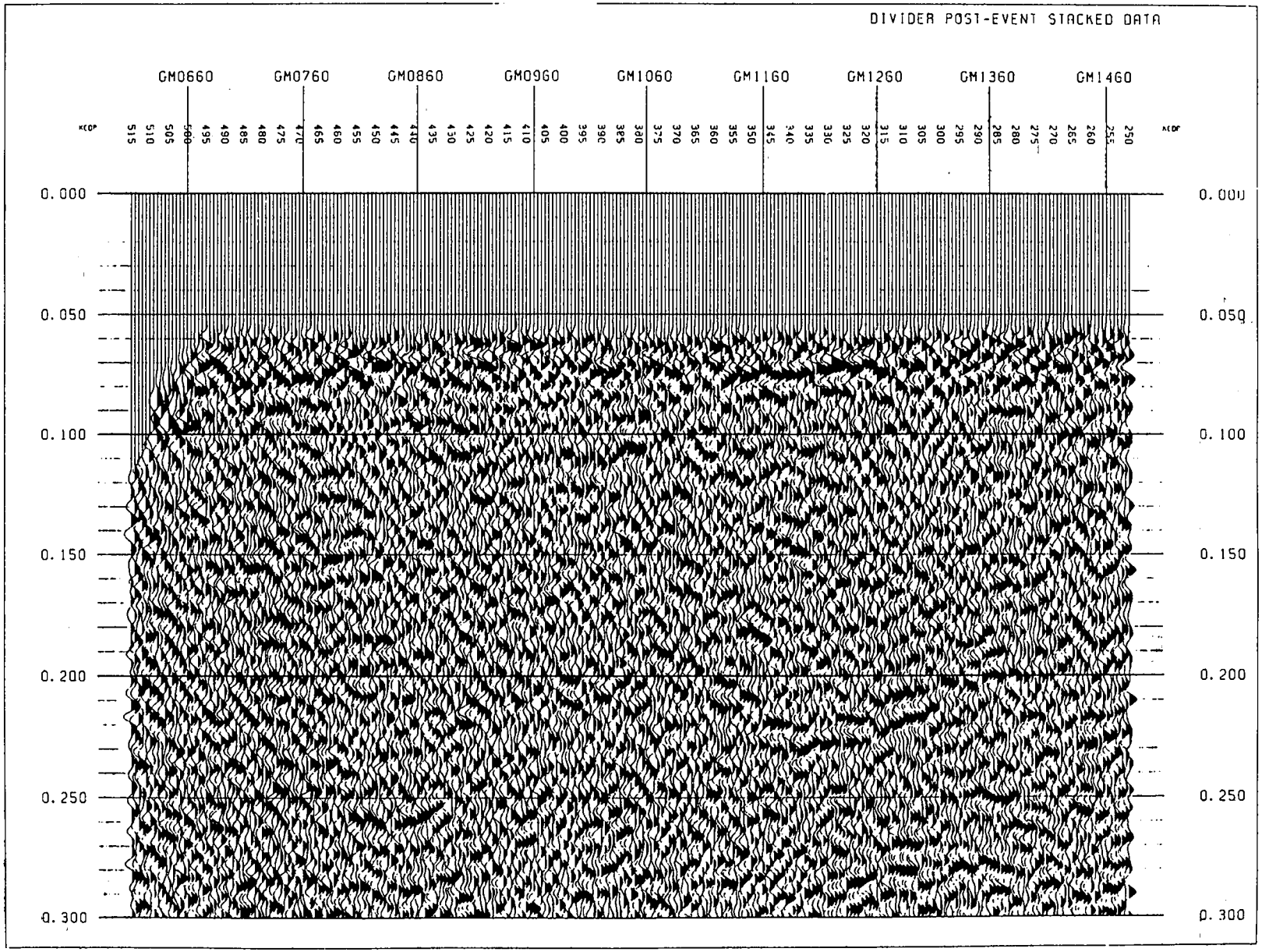

DIVIDER POST-EVENT STACKED DATA
GM1360
GM1460
GM1560
GM1660
GM1760
GM1860
GM1960
GM2010
GM2060
GM2110
GM2160
GM2210
0.000
0.050
0.100
0.150
0.200
0.250
0.300

Figure 13b.


DIVIDER POST-EVENT STACKED DATA
GM0660
GM0760
GM0860
GM0960
GM1060
GM1160
GM1260
GM1360
GM1460
KCDP
0.000
0.050
0.100
0.150
0.200
0.250
0.300

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