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Final Report

Noninstrusive Characterization at Rocky Flats Using 3-D Seismic Reflection Techniques

September 1994

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LIST OF ACRONYMS AND ABBREVIATIONS

A/D	Analog/Digital
ACU	Acquisition Control Unit
AGC	Automatic Gain Control
ALARA	As low as reasonably achievable
bpi	Bits per inch
CDP	Common depth point
cm	Centimeter
CMP	Common midpoint
CPU	Central Processing Unit
CRT	Cathode Ray Tube
DAM	Data Acquisition Memory
Db	Decibels
DC	Direct Current
DOE	U.S. Department of Energy
DT&E	Demonstration, Testing, and Evaluation
EG&G	EG&G Rocky Flats, Inc.
Enserch	Enserch Environmental Corporation
EPMS	Enserch Performance Measurement System
ERD	Environmental Restoration Division
F_c	Cutoff Frequency
F_o	Frequency of Origin
FK	Frequency-Distance
FPA	Floating point average
fps	Feet per second
ft	Feet
GB	Gigabyte
HASP	Health and safety plan
HR	High-resolution
Hz	Hertz
I/O	Input/Output Incorporation
IHSS	Individual Hazardous Substance Site
Kg	Kilograms
lb	Pound
LSB	Least significant bit
Mini-Vib	Industrial Vehicles, Inc. Mini-Vib T-2500
MB	Megabyte
ms	Milliseconds
mw	Milliwatts
NMO	Normal Move Out
OU2	Operable Unit 2
oz	Ounce

P-wave	Compressional wave
PC-PMS	Performance Measurement System
PF	Preamplifier Filter
PRDA	Program Research and Development Announcement
QA	Quality assurance
QC	Quality control
RAM	Random Access Memory
R_c	Circuit Resistivity
RFP	Rocky Flats Plant
RMS	Root Mean Square
R_s	Source Resistivity
S/N	Signal-to-Noise
S-wave	Shear wave
SEG	Society of Exploration Geophysicists
SH	Directional component of S-wave motion in horizontal plane
SV	Directional component of S-wave motion in vertical plane
v	Volts
V_p	P-wave velocity
Vrms	Voltage root mean square
Vs	S-wave velocity
XT	Distance-Time
°C	Degrees Centigrade
µfd	Microfarad
2-D	Two-dimensional
3-D	Three-dimensional

1.0 INTRODUCTION

1.1 SCOPE OF WORK

A three-dimensional (3-D), high-resolution (HR) seismic reflection evaluation was conducted at the Rocky Flats Plant (RFP), near Golden, Colorado, to demonstrate the applicability of nonintrusive characterization techniques to detect buried objects, contamination, and geological/hydrological features at RFP. The evaluation was conducted as part of the U.S. Department of Energy's (DOE) request for demonstration, testing, and evaluation (DT&E) of nonintrusive techniques, under DOE Program Research and Development Announcement (PRDA) No. DE-RA05-91OR22000.

The overall goal of the PRDA program is to reduce the spread of contamination, time spent investigating contaminated media or contamination sources, and costs associated with the foregoing by using noninvasive technologies. The original proposal for PRDA included a 3-D HR seismic reflection demonstration, a two-dimensional (2-D) shear wave reflection demonstration, and a seismic inversion demonstration. The rationale for selecting these technologies to meet the aforementioned goals was as follows:

Reduction	Rationale
Contamination	Eliminate secondary drilling wastes Minimize intrusive activity Eliminate chances for downward migration and cross contamination by contaminants due to drilling
Time	Seismic surveys are rapid compared to drilling for similar characterization
Costs	Seismic surveys are less expensive than drilling for similar characterization and data density Seismic surveys help to optimize future borehole locations saving time and money

The PRDA procurement was delayed for a prolonged period, resulting in a reduction in scope to keep the project costs within the original budget. The seismic inversion demonstration was deleted and was not included in the final contract signed on September 30, 1993.

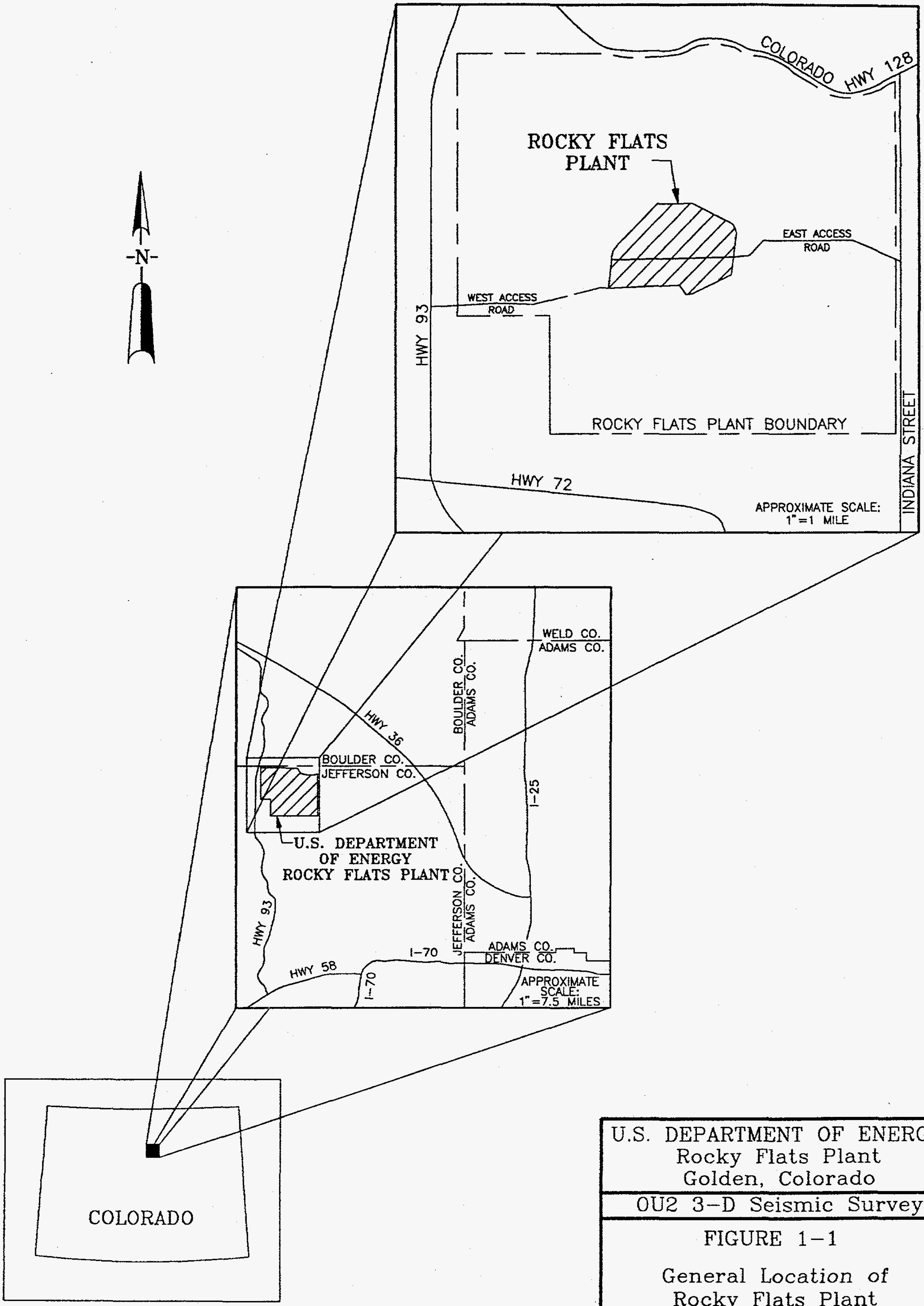
Initially, it was proposed that the Arapahoe Formation sandstones that occur in Operable Unit 2 (OU2) be characterized to determine their potential as contaminant pathways. After the contract was finalized, the DOE Project Manager decided that although the Arapahoe Formation sandstones were sufficiently characterized by former investigations (including 2-D HR seismic reflection data), a feature identified by these former investigations, located in OU2 and known as the Bedrock Step, was of further interest as a potential contaminant pathway. The DOE Project Manager requested that the 3-D HR seismic reflection demonstration be used to image and to determine the origin of the Bedrock Step. Although the ideal location to image the Bedrock Step was located within the boundary of an individual hazardous substance site (IHSS), the 3-D seismic reflection demonstration was re-located to an area immediately adjacent to the IHSS for health and safety reasons.

Once field work had begun, EG&G requested that various changes be made to the field procedures for health and safety reasons, the result of which was a reduction in the final scope of work. Accordingly, the 2-D shear wave demonstration was deleted and the 3-D HR seismic reflection technology retained to attempt to image the Bedrock Step and to determine the origin and cause of the feature.

1.2 SITE DESCRIPTION

RFP is a DOE nuclear weapons facility managed by EG&G. RFP is located approximately 16 miles northwest of Denver, Colorado in northern Jefferson County (Figure 1-1).

OU2 is located just to the east of the plant complex. Previous remedial investigations conducted at RFP have identified potential soil, surface water, and groundwater contamination in the vicinity of OU2. OU2 consists of the following three sites: the 903 Pad, Mound, and East Trenches (Figure 1-2). The trenches, IHSSs 111.2 through 111.6, are in such close proximity to the Bedrock Step, that the importance of determining the cause of the Bedrock Step, and the potential for a contaminant migration pathway associated with the Bedrock Step, is appropriate.



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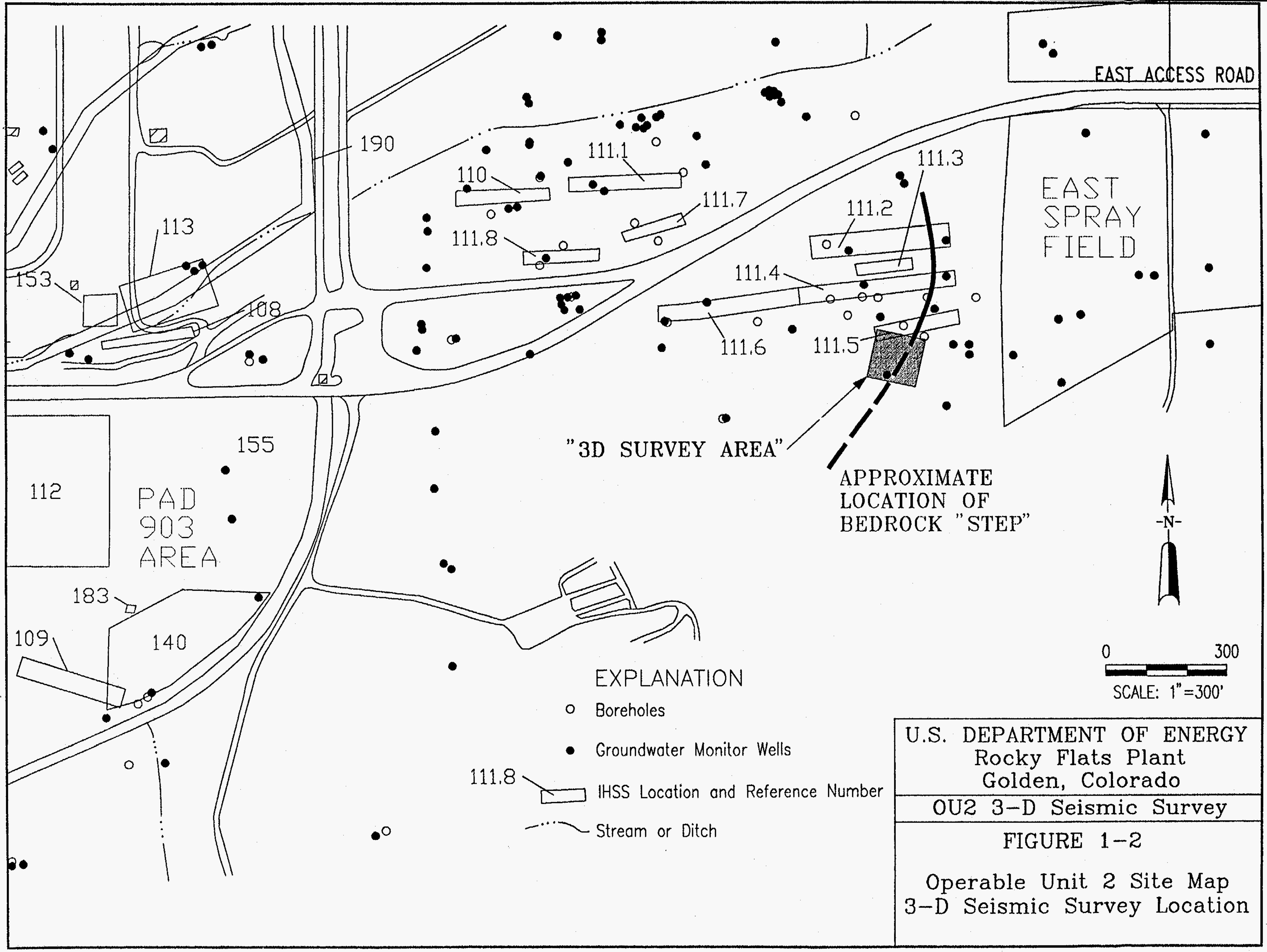
OU2 3-D Seismic Survey

FIGURE 1-1

General Location of Rocky Flats Plant



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OU2 3-D Seismic Survey

FIGURE 1-2

Operable Unit 2 Site Map
3-D Seismic Survey Location

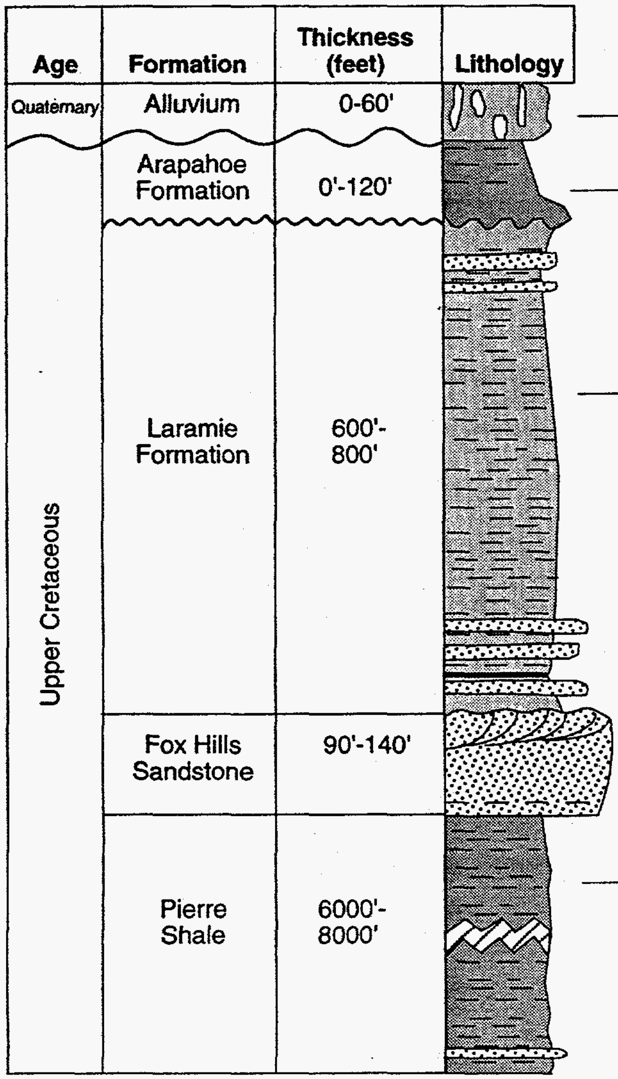
1.3 GEOLOGIC SETTING

RFP is located along the western edge of the Denver Basin. It is bounded on the west by the Colorado Front Range and is underlain by more than 10,000 feet (ft) of Pennsylvanian to Upper Cretaceous sedimentary rocks of the Denver Basin that have been locally folded and faulted. The sedimentary bedrock is unconformably overlain by unconsolidated Quaternary alluvial sands and gravels.

The geologic section beneath OU2 consists of the Rocky Flats Alluvium and the Upper Cretaceous Arapahoe and Laramie Formations (Figure 1-3).

The Quaternary-age Rocky Flats Alluvium, deposited unconformably over the erosional surface of the Upper Cretaceous Arapahoe and Laramie Formations, occurs at the surface of OU2. This alluvium averages 20 ft in thickness in OU2 and consists of unconsolidated, poorly sorted gravel, sand, and clay deposited at the base of the Colorado Front Range (Hurr 1976). Calcium carbonate, in the form of caliche, is locally present in the unit (Rockwell International 1987).

The Arapahoe Formation consists of claystones and sandstones deposited in a fluvial-deltaic environment (Weimer 1973). The sandstones are lenticular and occasionally exceed 20 ft in thickness. The sandstones are quartzose, locally conglomeratic, and commonly silty and clayey. A medium frosted-grained sandstone is present at the surface in certain areas (EG&G 1992).
The Laramie Formation comprises sandstones, siltstones, claystones, and coals deposited in fluvial-deltaic and lacustrine environments (Weimer 1973). The Laramie Formation around RFP is approximately 600 to 800 ft thick and is informally subdivided into a lower, predominantly sandstone unit and an upper, predominantly claystone unit. Both the Arapahoe and upper Laramie Formations were deposited in low-energy fluvial/deltaic systems. Sedimentation in these systems results in widespread, thick deposits of claystones and siltstones of low permeability, along with narrow, thin, and localized deposits of more permeable channel sandstones. The lower Laramie sandstones and underlying Fox Hills Sandstone collectively comprise the Laramie/Fox Hills Aquifer and are a major source of water in some parts of the Denver Basin.



Age	Formation	Thickness (feet)
Quaternary	Alluvium	0-60'
Upper Cretaceous	Arapahoe Formation	0'-120'
	Laramie Formation	600'-800'
	Fox Hills Sandstone	90'-140'
	Pierre Shale	6000'-8000'

Conglomerate, unconsolidated, poorly sorted gravel, sand and clay

Claystone, sandy claystone, and clayey sandstone, medium to coarse sandstone and chert pebble conglomerate locally at base - gray to yellowish orange

Sandstone and claystones - gray, fine- to medium-grained; thin coal beds in lower part; ironstone nodules

Sandstone - Light olive gray to yellowish brown fine- to medium-grained, cross-bedded and laminated silty sandstone and shale at base

Shale - dark gray, silty, bentonitic; few thin, silty sandstones

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Figure 1-3

Generalized Stratigraphic Section for the Rocky Flats Plant Vicinity

After LeRoy and Weimer 1971

The Cretaceous-age Pierre Shale consists of 6,000 to 8,000 ft of clayey marine shale. The lower portion of the formation is composed of massive to thin-bedded silty bentonitic claystone with a few very thin, noncalcareous siltstone beds. The upper portion of the formation is composed of thin-bedded to massive, silty, bentonitic shale with a few limestone concretions and thin, poorly cemented sandstone beds (Wells 1967).

1.4 PREVIOUS STUDIES

Task 3 of the Phase I Geological Characterization at RFP, which involved a shallow HR seismic reflection program, identified several sandstone bedrock channels in the Arapahoe or Laramie bedrock beneath the Rocky Flats Alluvium at OU2 (EG&G 1991). Where present, the uppermost bedrock channel is often in direct hydraulic contact with the alluvium. For the most part, a confirmation borehole drilling program has verified the previous seismic program results (Woodward-Clyde 1993).

The Task 3 Shallow HR seismic reflection program also identified a thickening in the Rocky Flats Alluvium due to a drop in bedrock elevation east of the trenches (EG&G 1991). In the Phase II Geologic Characterization Data Acquisition (EG&G 1992), a drop of 30 ft in bedrock elevation at OU2 is interpreted from seismic and borehole data (Figure 1-2). The Woodward-Clyde drilling program confirmed the presence of the Bedrock Step. Further, it is reported that the Laramie-Arapahoe contact drops more than 100 ft over a horizontal distance of less than 1,000 ft in the OU2 area. To explain the abrupt elevation change in the Laramie-Arapahoe contact three geologic models were proposed: folding, stratigraphic or erosional discontinuity, or faulting. This 3-D seismic reflection demonstration was conducted in a site appropriate to evaluate the hypothesized models against imaged subsurface geometry.

2.0 FIELD PROCEDURES AND DATA ACQUISITION

2.1 3-D HR SEISMIC REFLECTION

The location of the 3-D seismic survey is shown in Figure 1-2. For 2-D HR seismic reflection profiling, the geophones (receivers) were arranged linearly. For the 3-D seismic reflection surveys, the geophones were arranged in an areal grid pattern. The geophones detect seismic energy caused by a single point source that is first directed at the ground surface and that is then reflected back from subsurface horizons. The seismic data were collected and recorded on a 9-track computer tape in Society of Exploration Geophysicists (SEG) D format and sent to a data processing center.

Subsurface data were sorted by common depth point (CDP) or common midpoint (CMP) into groups called cells or bins. Each CDP has one or more source and receiver pairs (see Figure I-1 in Appendix 1). Each source and receiver pair is called a fold; 12 source and receiver pairs are referred to as a 12 CDP fold. An increase in fold generally causes an increase in data quality because there is a reduction in random noise that results from stacking the multiple source and receiver pairs. The data acquisition parameters used for this 3-D seismic survey yielded a variable fold that ranged from 1 fold to 100 fold and averaging over 40 fold across the survey area. A discussion of the CDP technique can be found in Appendix I.

The 3-D data set represents a volume of subsurface data. The length and width of the data volume are expressed in feet. The depth dimension is expressed in units of two-way travel time, i.e., the time required for a seismic wave to travel down from the surface and reflect upward from a subsurface horizon. The length and width of the survey was 100 ft by 100 ft, yielding a total coverage of 10,000 square ft. The source-point interval was 5 ft and the receiver interval was 10 ft. Figure 2-1 shows the source and receiver layout for the 3-D survey. Seismic data was acquired using this layout, yielding a CDP cell interval of 2.5 ft by 5 ft. The entire layout was then shifted 2.5 ft laterally (east) and repeated, yielding a final CDP cell interval of 2.5 ft by 2.5 ft. The seismograph was configured for a recording length of 0.5 seconds, allowing for

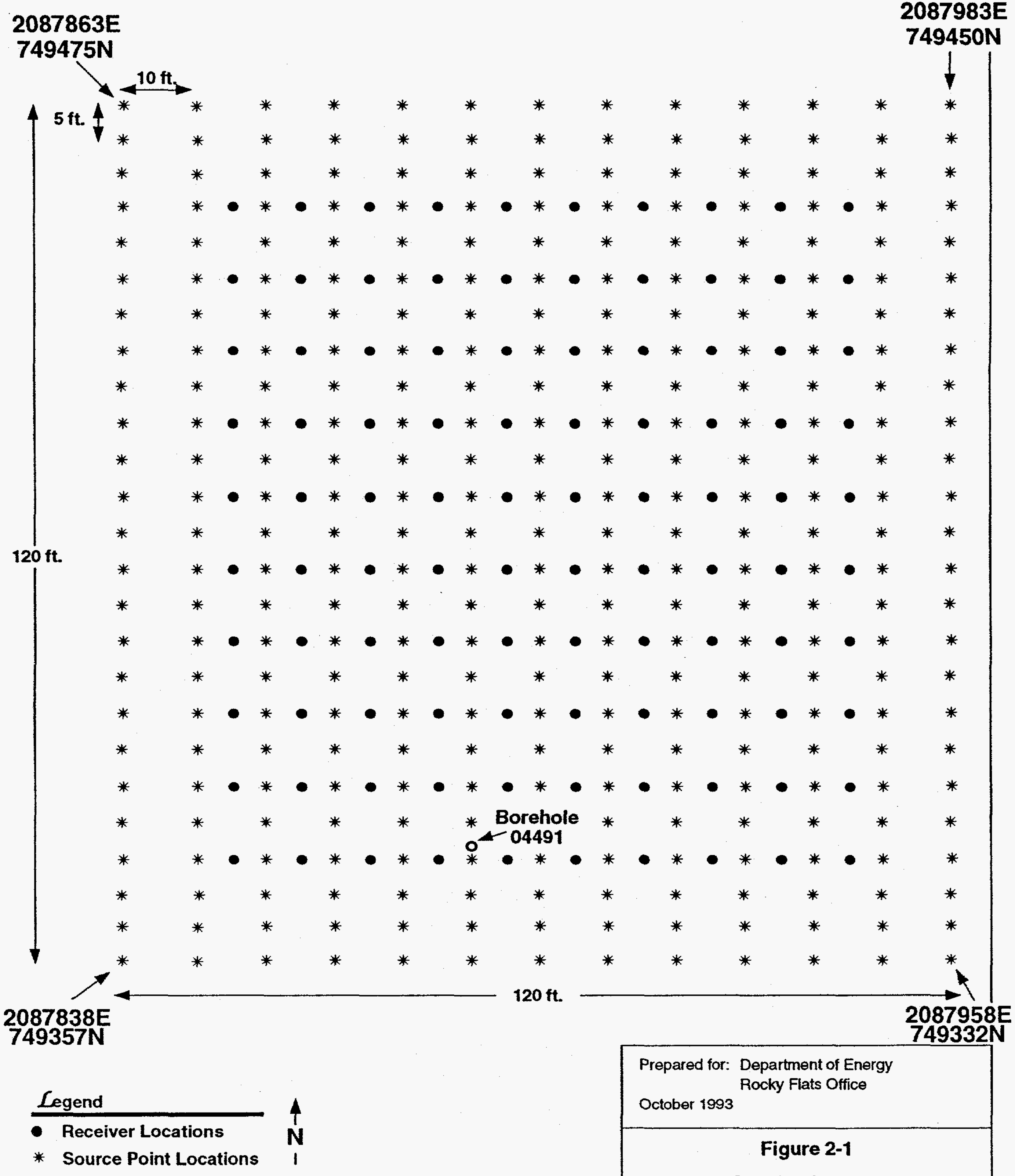

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Figure 2-1

3-D Seismic Survey
Source - Receiver Locations

the recording of seismic reflections from subsurface horizons as deep as approximately 1,500 ft below ground surface.

2.2 FIELD TESTS

Prior to data acquisition, field tests were conducted to determine the optimum seismic source parameters. An Industrial Vehicles, Inc. Mini-Vib T-2500 (Mini-Vib) vibratory source was tested to determine the parameters sweep frequency, sweep length, and the number of sweeps per source point. A discussion on vibratory source theory can be found in Appendix I. A total of 96 geophones were laid out linearly (2 ft spacing), with the Mini-Vib set up at the end of the geophone spread. Each parameter was tested separately while holding each of the other parameters constant (i.e., the sweep frequency and sweep length were held constant while the number of sweeps was varied). For each parameter tested, the field records were compared to determine which sweep setting provided the best signal frequency and signal amplitude content. The optimum parameters selected for data acquisition were a 3-second sweep from 40 Hertz (Hz) to 250 Hz, with 10 sweeps per source point.

The data from the Mini-Vib sweep tests were compared to an 8-gauge cartridge shot record generated from the previous 2-D seismic survey performed in OU2. In general, the 8-gauge cartridge produced more source-generated noise than the Mini-Vib. Although a spectral analysis indicated that the 8-gauge cartridge provided higher frequencies than the Mini-Vib, it is likely those frequencies were due to the source-generated noise. The amplitude of the data generated by the Mini-Vib was higher (40 to 250 Hz range) than the data generated by the 8-gauge cartridge. Based on the higher amplitude data, the repeatability, and the power of correlation, the Mini-Vib was chosen for the 3-D seismic survey source. The 3-D seismic survey data acquisition parameters used are shown in Table 2-1.

2.3 EQUIPMENT

DOE's EG&G Geometrics ES-2420 digital reflection seismograph was configured to record 96 channels of data concurrently at a sampling interval of 0.50 milliseconds (ms). High-frequency

Table 2-1 3-D Shallow HR Seismic Reflection Data Acquisition Parameters Page 1 of 1

Equipment	Parameters
Geophone Station Spacing	10 feet x 10 feet
Seismic Source Spacing	5 feet x 10 feet
Geophones Per Station	1
Geophone Frequency	100 Hertz
Number of Recording Channels	96
Recording Sample Rate	0.5 milliseconds
Record Length	0.5 seconds
Low-Cut Filter	40 Hertz
Alias Filter	360 Hertz
Common Depth Point Fold	Variable (1–100)
Sweep Frequencies	40–250 Hertz
Sweep Length	3 seconds
Number of Sweeps per Source Point	10

100 Hz geophones were used to record the high-frequency energy necessary for the desired resolution (Knapp 1988). Custom geophone cables with 10-ft takeouts (geophone connectors) were used for the survey. As discussed above, the Mini-Vib was the vibratory seismic source used for the seismic survey. All equipment used for the 3-D seismic data acquisition was rigorously tested using the manufacturer's suggested procedures prior to the commencement of field activities to ensure each piece of equipment was operating properly. In addition, each piece of equipment was tested daily prior to data acquisition to ensure continued high performance. Seismic reflection equipment specifications can be found in Appendix II.

3.0 SEISMIC DATA PROCESSING

Once the seismic data were acquired, they were sent to the seismic data processing center for processing, enhancement, and display. The 3-D shallow HR seismic reflection data require the use of sophisticated algorithms to reconstruct the complex cellular 3-D geometries between source and receivers. The end product is a 3-D volume of seismic data representing an acoustic image of the subsurface.

The processing sequence (Figure 3-1) included a variety of computer programs that are normally applied to CDP seismic data. Computer programs have many functions, including editing and removing unwanted noise, enhancing frequency content, sorting data traces into CDP format, applying static and velocity functions, scaling the data for presentation, migrating the data to remove raypath imaging effects, and plotting the data as well as a variety of other data analysis techniques. The proper design and use of these programs effectively enhances data presentation. The seismic data processing center's report can be found in Appendix V.

Output from seismic data processing steps was reviewed by the Processing Task Manager, Technical Manager, and Project Technical Advisor, all of whom are experienced seismic geophysicists, to ensure valid software application and quality data processing results.

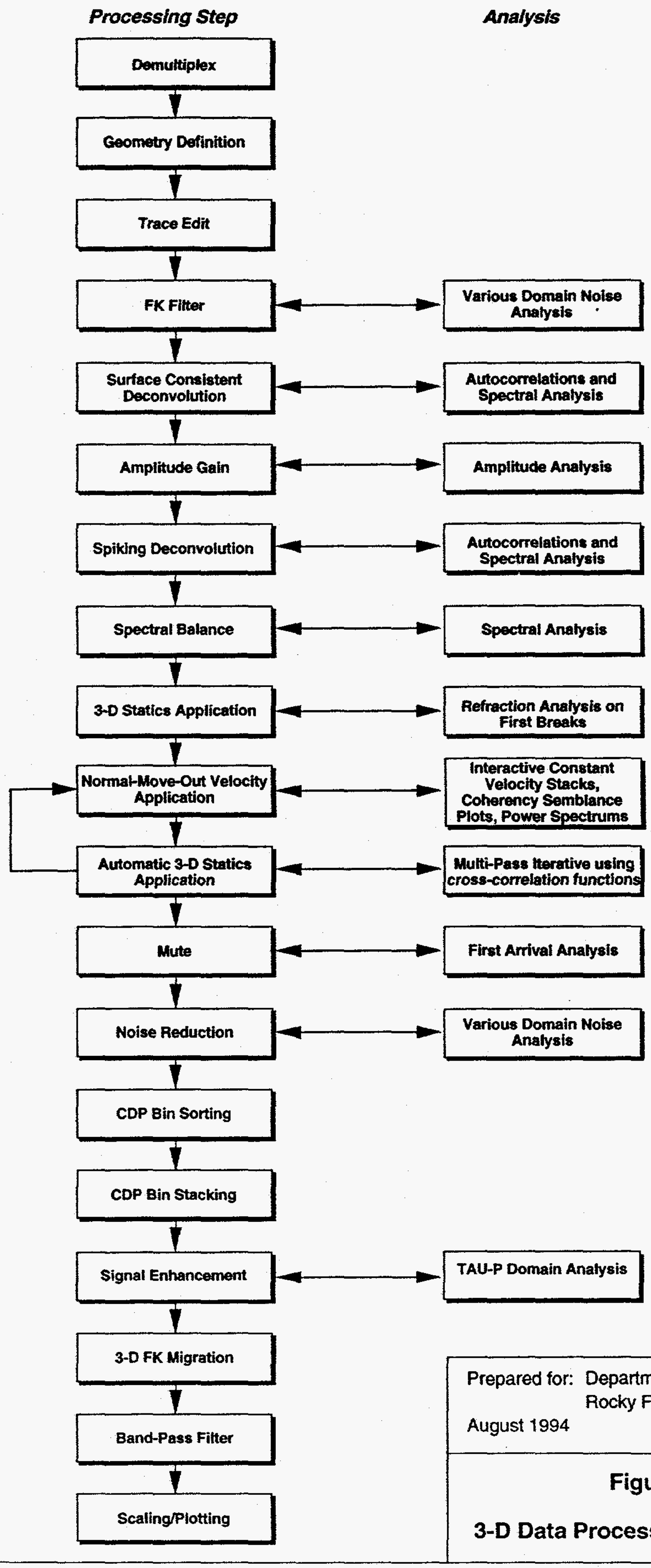

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Figure 3-1

3-D Data Processing Flow Diagram

4.0 DATA INTERPRETATION

Seismic data interpretation involves the identification of seismic events that relate to geological features. Often, particular reflections have distinctive characteristics that can be identified and correlated throughout a site. For example, well-cemented sandstone units exhibit high acoustic impedances and positive reflection events, and coals exhibit low acoustic impedances and strong negative reflection events.

The interpretation of the 3-D seismic data volume from OU2 involved the analysis of the final processed data. The analysis was enhanced by using a 3-D work station to interactively slice the data volume into vertical and horizontal profiles. The seismic data are displayed in conventional variable area wiggle trace, color amplitude, and time-slices and in true 3-D perspective with full rotation, tilt, and highlighting. The use of the 3-D work station also allows the interpreter to pick several seismic events throughout the data volume and contour them interactively. The contour maps are displayed as conventional 2-D contour, 3-D net, and color shaded.

The specific objective of the data interpretation was to identify and map the alluvial-bedrock contact. Previous investigative data in the area, including 2-D seismic reflection profiles and borehole data, were integrated to enhance the interpretation. In the case of weathering, no discontinuities should be expressed in the data volume, other than those caused by normal sedimentary deposition. The identification of a slump or a fault depends on the ability to identify discontinuities in beds and possible localized folding. Regional dip at OU2 is to the east (EG&G 1993). In the case of slumping, the bedrock will most likely slide downdip on a slump plane dipping down to the east. Previous seismic reflection investigations at RFP have demonstrated the existence of west-to-east thrust faults related to the Laramide Orogeny (EG&G 1993a). Therefore, if the Bedrock Step is caused by thrust faulting, the fault plane would dip towards the west.

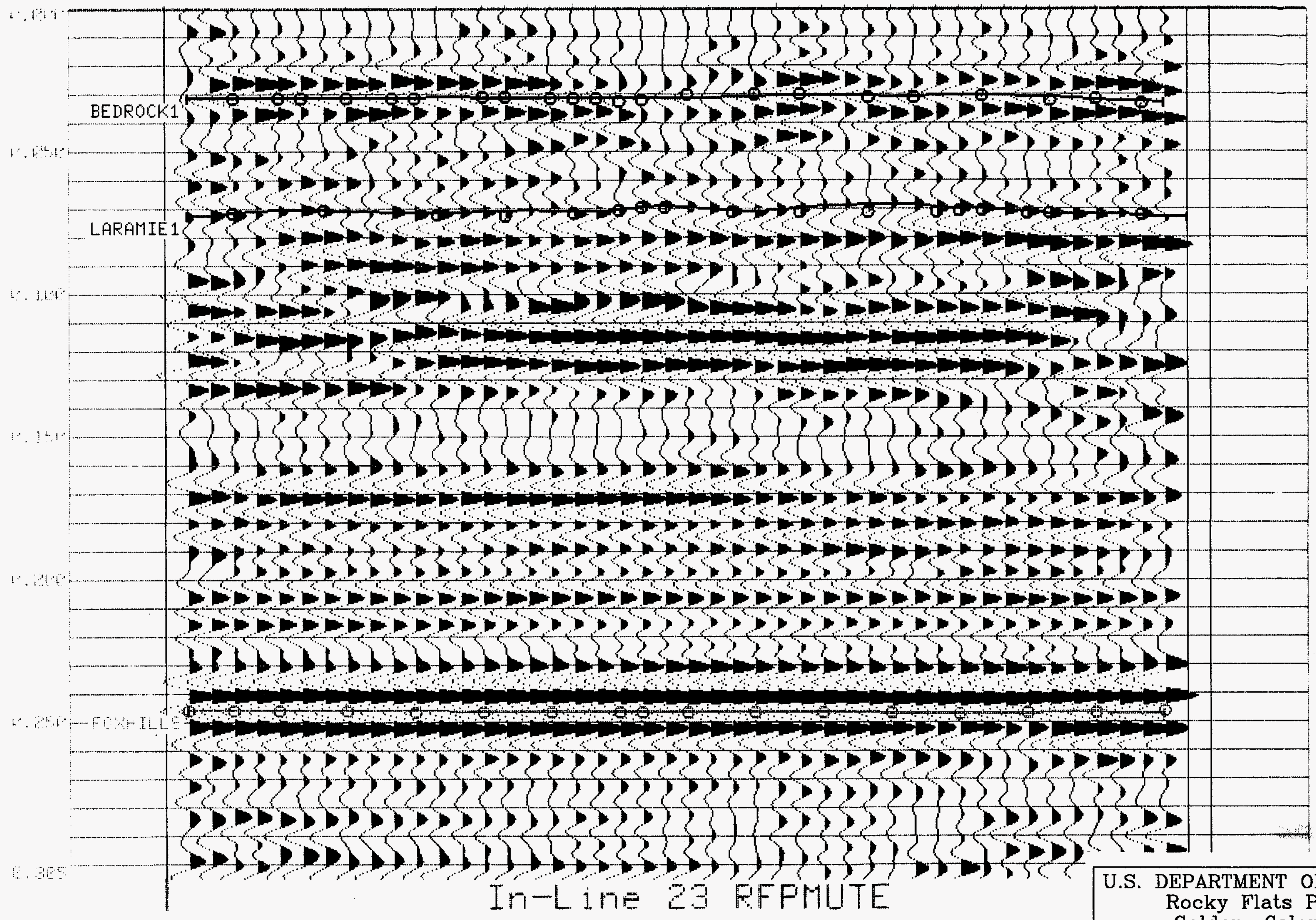
Previous seismic and borehole investigations in the 3-D survey area have not identified any significant Arapahoe or upper Laramie sandstones. Sandstones were not identified during the interpretation of the 3-D data volume.

Three seismic events were interpreted and mapped across the 3-D survey area. Figure 4-1 shows an interpreted seismic profile through the center of the survey area. The interpreted seismic events are the following:

- a very shallow reflector (colored red) at approximately 25 ms that has been interpreted as the alluvial-bedrock contact
- an upper Laramie Formation reflector (colored green) at approximately 70 ms
- a deep reflector (colored orange) at approximately 245 ms that has been interpreted as the top of the Fox Hills sandstone

The alluvial-bedrock contact was mapped because one of the objectives of the seismic survey was to identify the Bedrock Step. The upper Laramie reflector was mapped to identify any possible lateral stratigraphic discontinuities, shallow faults, or folds in the upper bedrock that may have caused the Bedrock Step. The Fox Hills reflector was mapped to identify any deep faulting or folding that may have caused the Bedrock Step.

Figure 4-2 shows the relative locations of each of the in-line and cross-line seismic profiles generated through the survey area. The seismic profiles are provided as Appendix IV. On the In-line #23 seismic profile (Figure 4-1), the positive amplitude reflection immediately above (approximately 5 ms) the red line was identified as the alluvial-bedrock reflector. The red interpretation line was picked along the negative amplitude reflection underlying the alluvial-bedrock reflection since this negative reflection was more consistent throughout the survey area and easier to interpret. The small red circles along this event are the tie points corresponding to the cross-line interpretations. These circles are displayed and utilized to ensure that the interpretation is consistent throughout the survey area.



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OU2 3-D Seismic Survey

FIGURE 4-1
Seismic Profile for
In-Line 23

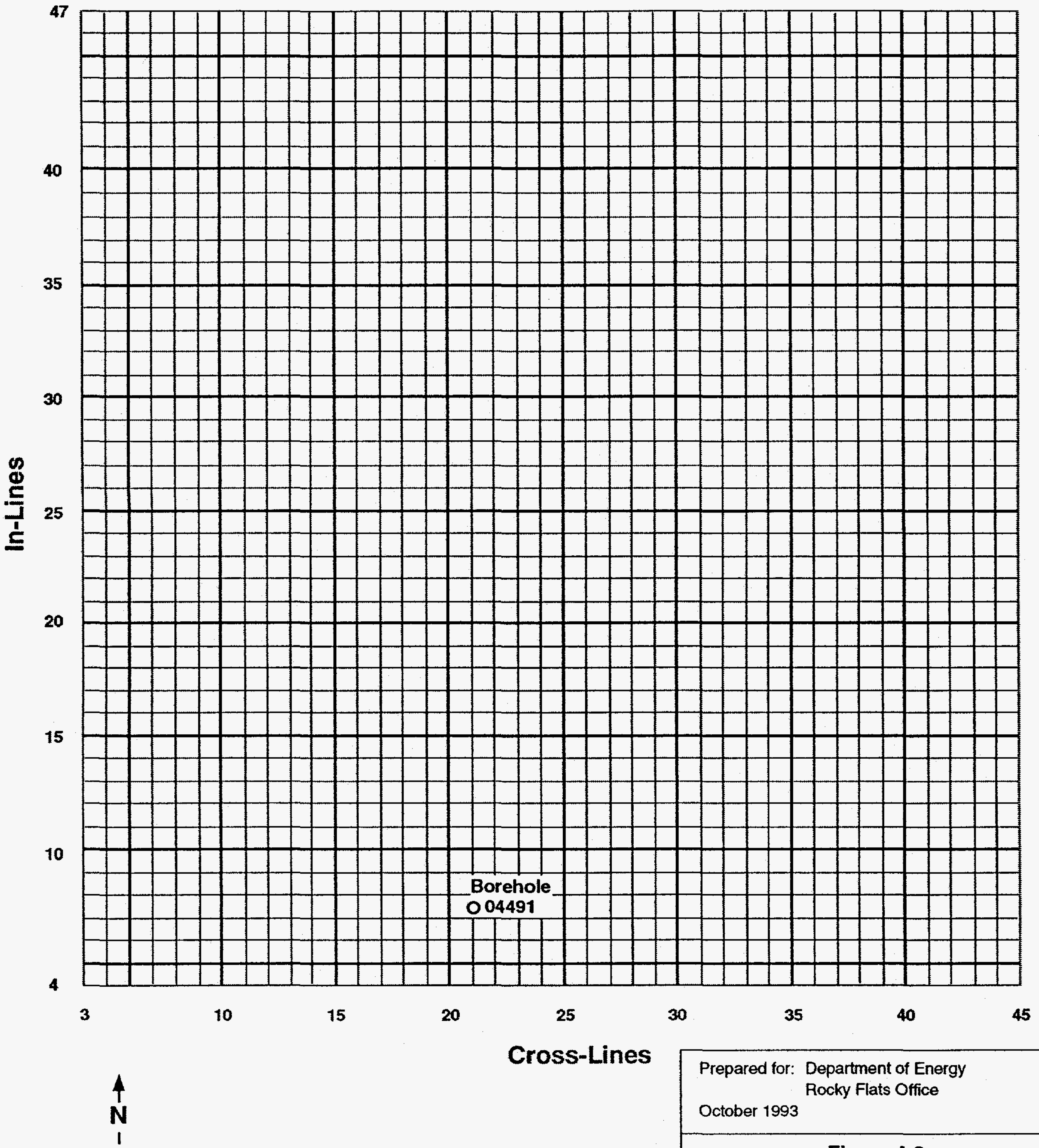

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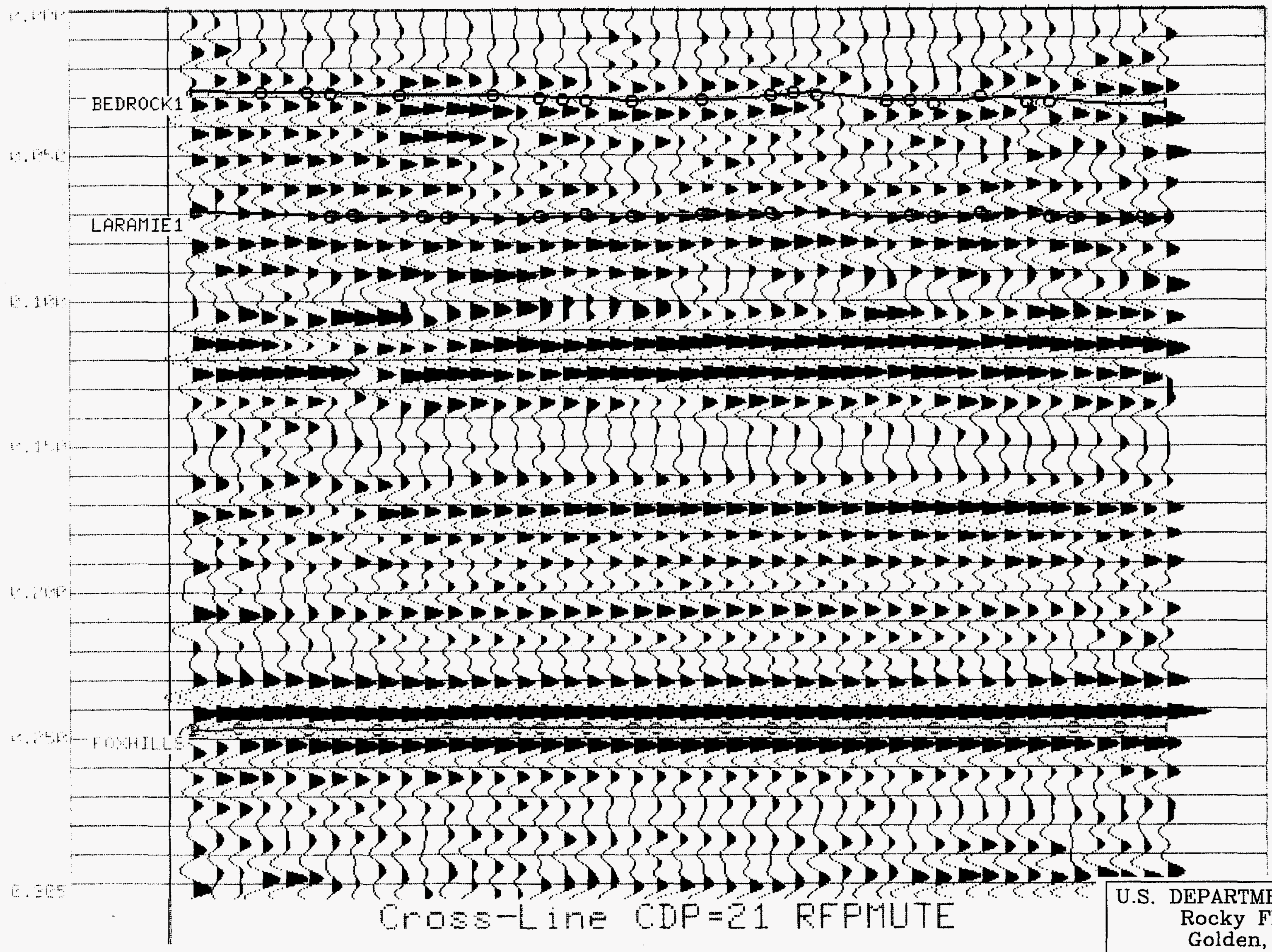
Figure 4-2

3-D Seismic Survey Line Location Map

Borehole 04491, located within the survey area on the south side (Figure 4-2), encountered bedrock at 27 ft. At the borehole location, the positive amplitude reflection corresponding to the top of the bedrock occurs at 23 ms, yielding a seismic velocity of 2,350 feet per second (ft/sec) for the alluvium. Based on previous vertical seismic profiles performed in boreholes at RFP (EG&G 1993b, EG&G 1990), this seismic velocity is reasonable for the alluvium.

The positive amplitude reflection corresponding to the alluvial-bedrock contact occurs between 22 and 36 ms. Because the CDP fold and signal strength are low along the edges and corners of the survey area, the interpretation is not reliable and emphasis should not be placed on it. The interpretation shows that the bedrock reflector is generally flat, with no significant dip or discontinuities. This interpretation holds true throughout the survey area. Figure 4-3 is a cross-line seismic profile through the middle of the survey area. Similar to In-line #23, Cross-line #21 shows a flat-lying bedrock reflector with no folding or faulting present. Figure 4-4 is the horizontally compressed seismic profile for Cross-line #23 and shows subtle structure at the alluvial-bedrock contact. The alluvial-bedrock contact is at 23 ms on the south (left) side of the profile and at 29 ms on the north (right) side of the profile. This difference translates to approximately 6 ft of relief (using a seismic velocity of 2350 ft/sec for the alluvium), which corresponds to an approximate 3.5 degree dip to the north across the grid. This subtle structure is reflected in the time-structure map of the alluvial-bedrock contact shown in Figure 4-5. This map shows the top of the bedrock dipping down to the north. Shown in Figure 4-6 is a 3-D perspective of the alluvial-bedrock contact structure map.

The upper bedrock reflector (colored green) is the upper-most reflector of a package of high-amplitude reflections that range between 70 and 135 ms. This reflector is a generally flat-lying horizon throughout the survey area, as indicated by the time-structure map shown in Figure 4-7. There is approximately 5 ms of structure across the survey area, which corresponds to 6 to 7 ft (3.5 degrees northeast dip). This 3-D perspective of the upper Laramie time-structure is shown in Figure 4-8. Similar to the alluvial-bedrock time-structure map, there does not appear to be any faulting or significant folding at this horizon.



Cross-Line CDP=21 RFPMUTE

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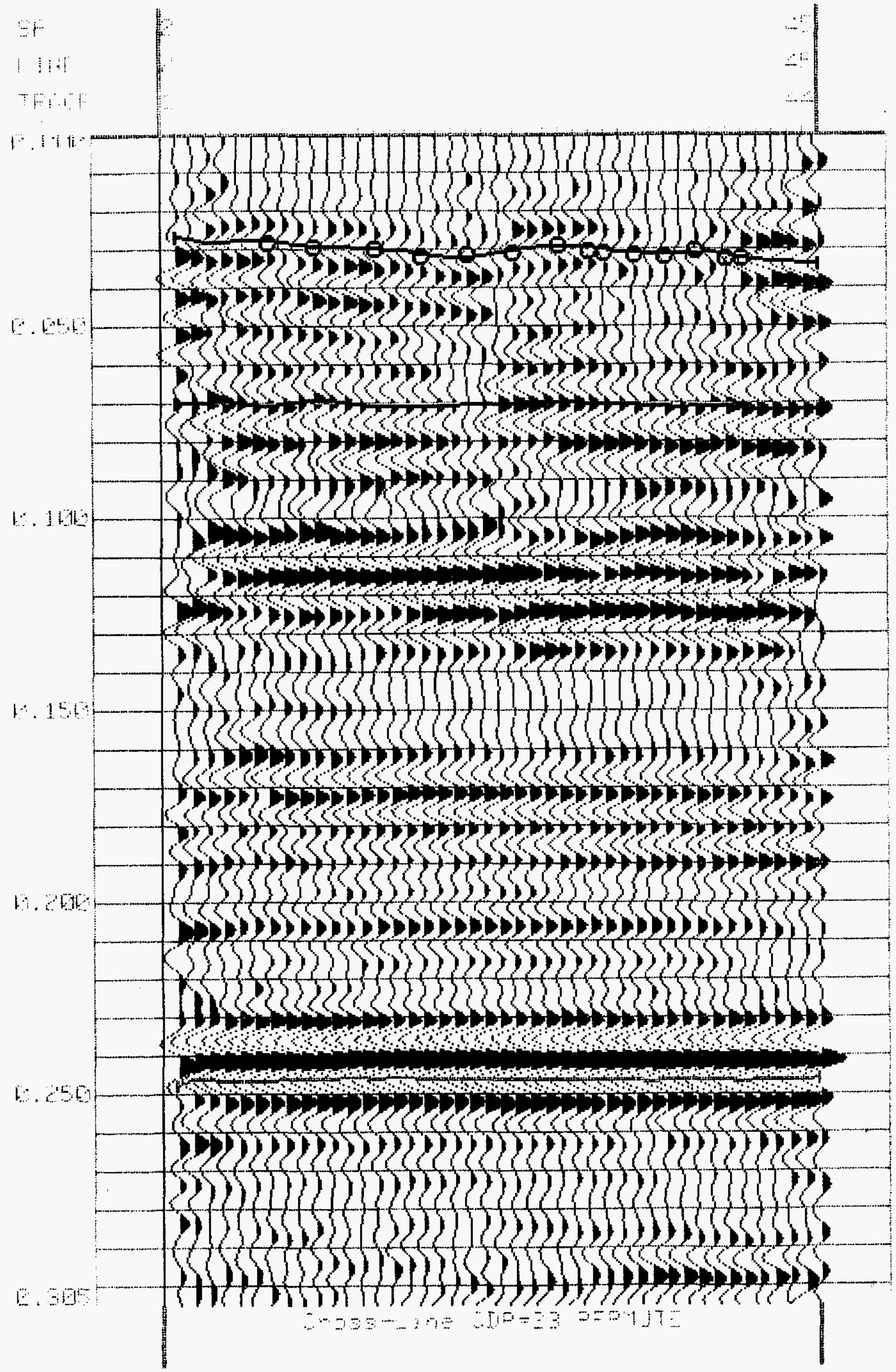
OU2 3-D Seismic Survey

FIGURE 4-3

Seismic Profile for
Cross-Line 21



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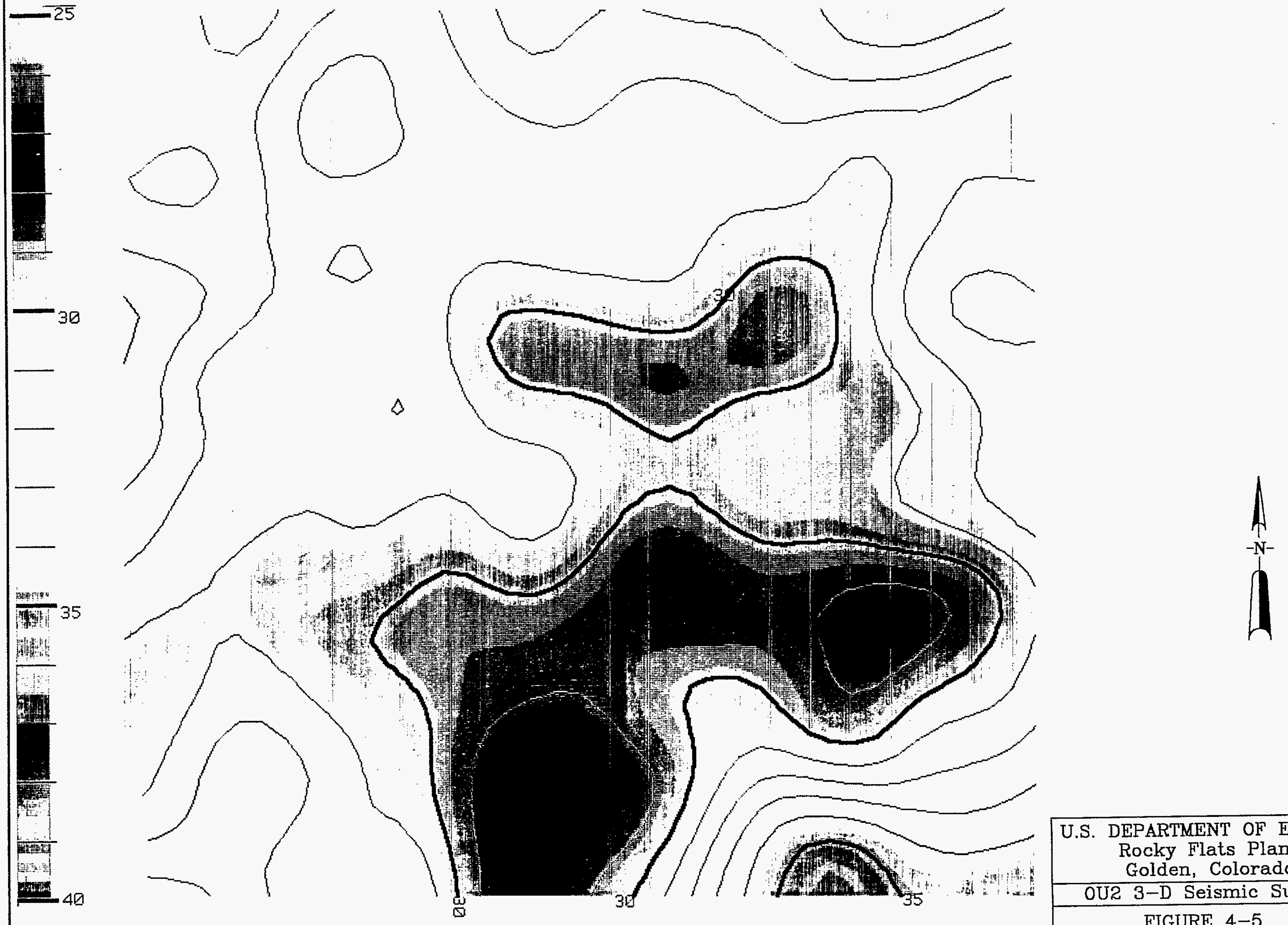
OU2 3-D Seismic Survey

FIGURE 4-4

Seismic Profile for
Cross-Line 23



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0U2 3-D Seismic Survey

FIGURE 4-5
Time-Structure Contour Map
of the Top of
Bedrock Reflector

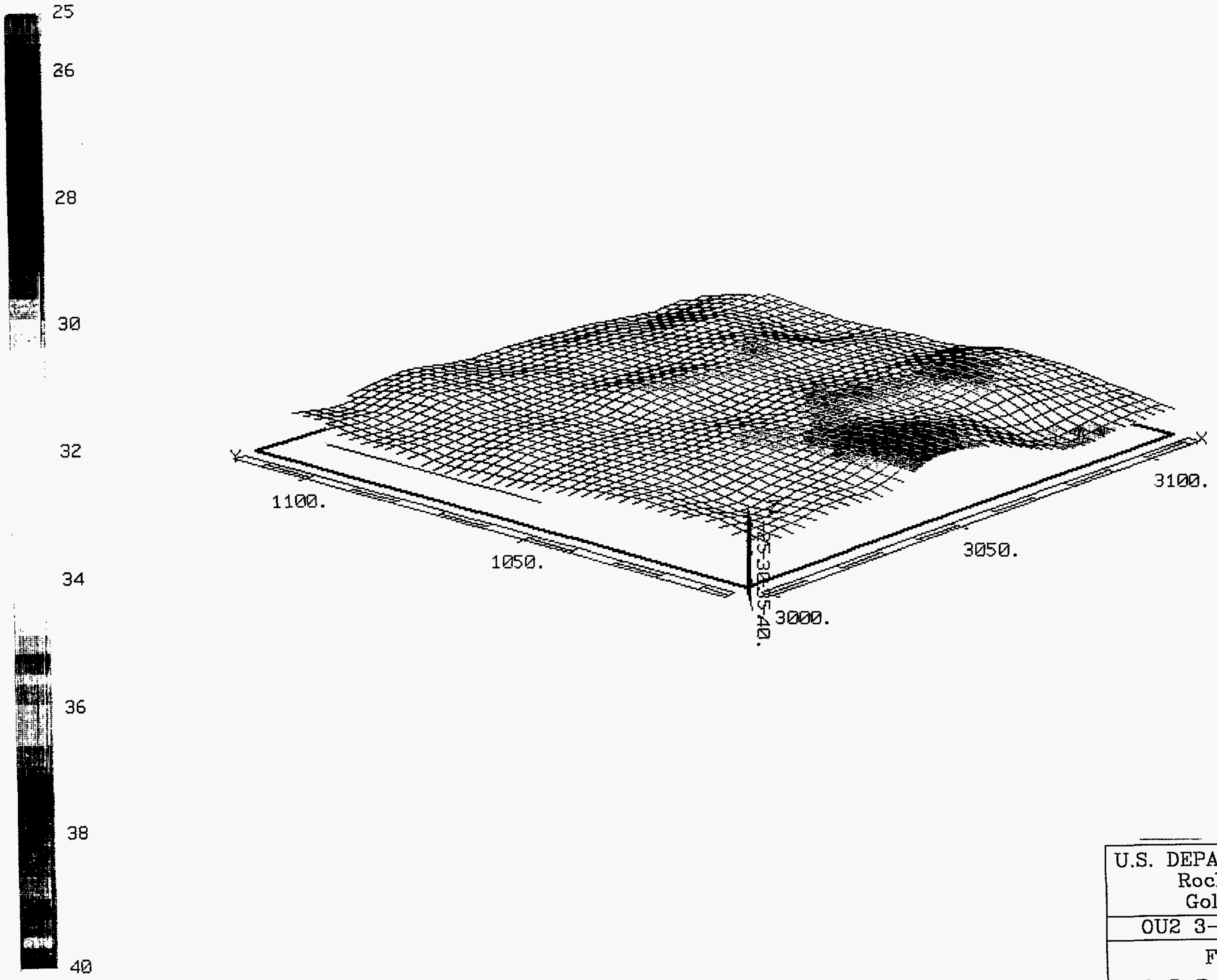

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FIGURE 4-6

3-D Perspective View of
the Top of Bedrock
Reflector

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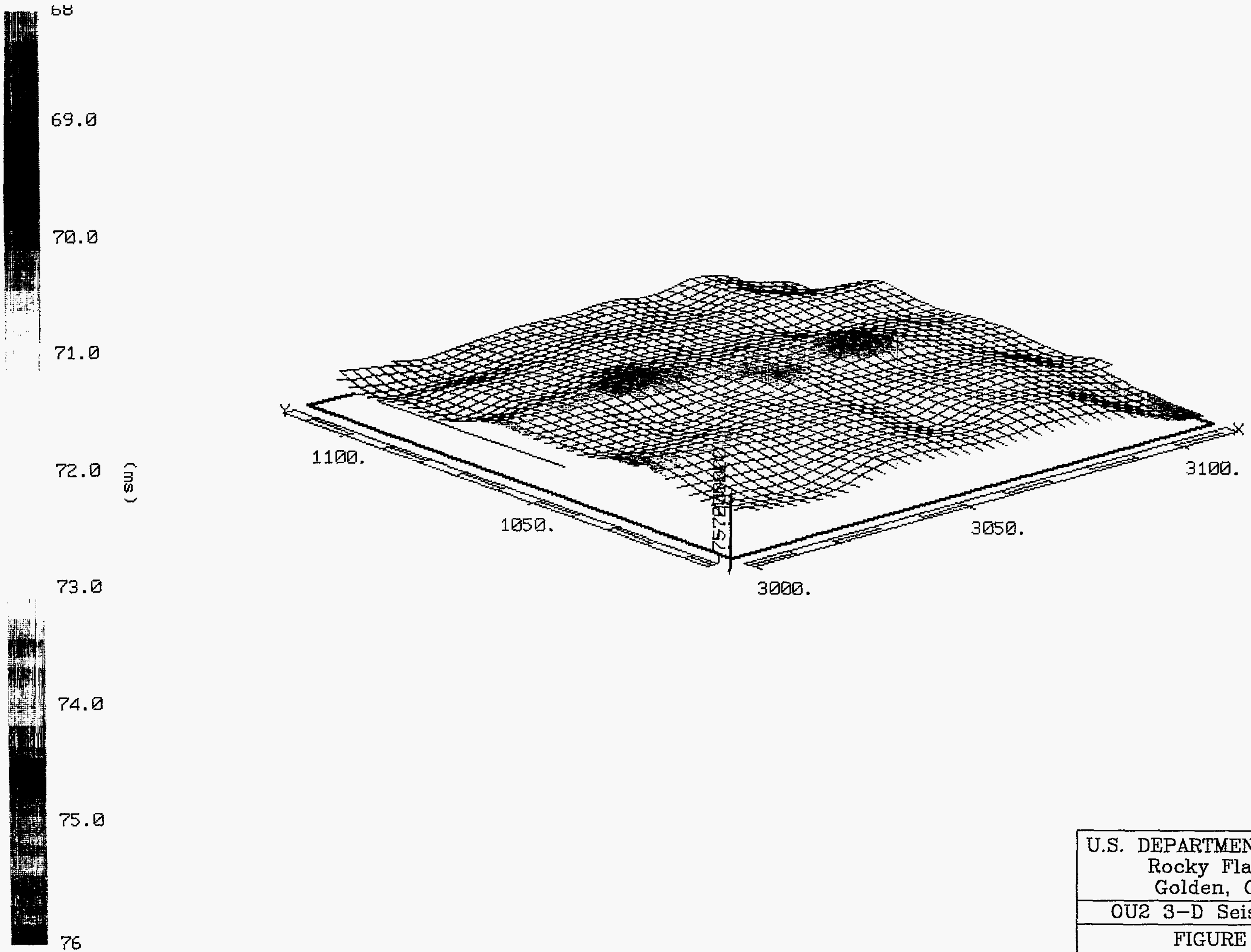
FIGURE 4-7
Time-Structure Contour Map
of the Upper Laramie
Reflector



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OU2 3-D Seismic Survey

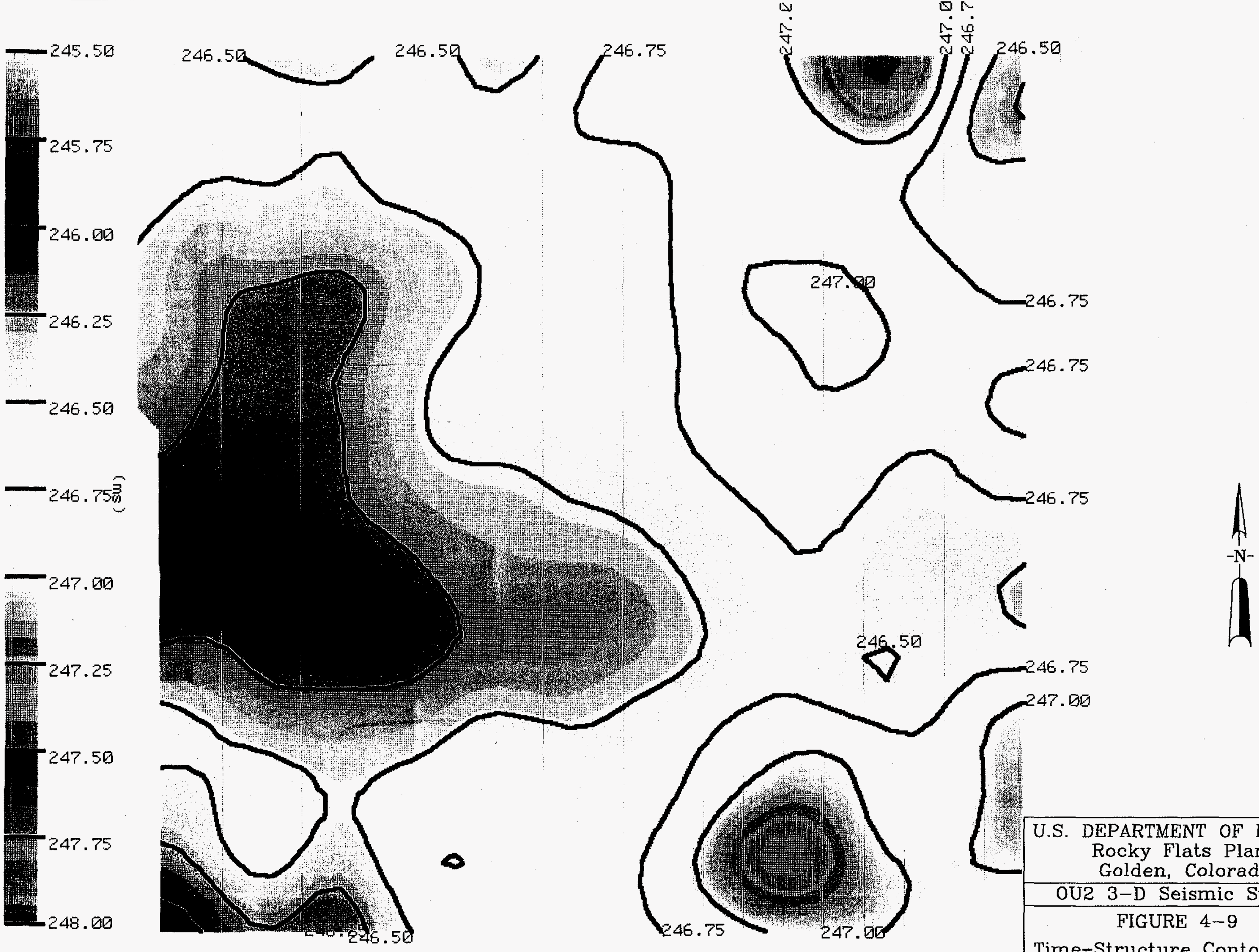
FIGURE 4-8

3-D Perspective View of the Upper Laramie Reflector

The Fox Hills Sandstone reflector (colored orange) is also generally flat across the survey area. The time-structure map and 3-D perspective map are shown in Figures 4-9 and 4-10, respectively. These maps show an approximate 3 degree dip to the east. This is consistent with previous seismic investigations in the area.

Displays that were useful as part of the interpretation process are seismic profiles with colored amplitudes displayed (Figure 4-11). These displays aided in identifying the three seismic reflectors mapped based on their characteristic amplitudes.

Time-slices were also used to identify structural features. A time-slice is an areal amplitude map of the seismic data over the entire survey area at a specific seismic time (or depth). A time-slice is similar to a level map used in the mining industry. Figures 4-12 through 4-15 are time-slices of the 3-D data at 114 ms through 117 ms, respectively. The red and yellow colors indicate positive, high-amplitude reflections, while the grays represent negative amplitude reflections. These reflections are part of the package of reflections between 70 and 135 ms discussed above. These reflections migrate to the east as time increases, which means that dip on these events is down to the east. There do not appear to be any discontinuities cutting across the time-slices, indicating gently dipping, planer reflectors across the 3-D survey area (i.e. no faults or folds). Time-slices were generated at 1 ms intervals for the entire data set, from 0 ms to 300 ms, and no significant structural features were observed.



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OU2 3-D Seismic Survey

FIGURE 4-9

Time-Structure Contour Map of the Fox Hills Sandstone Reflector

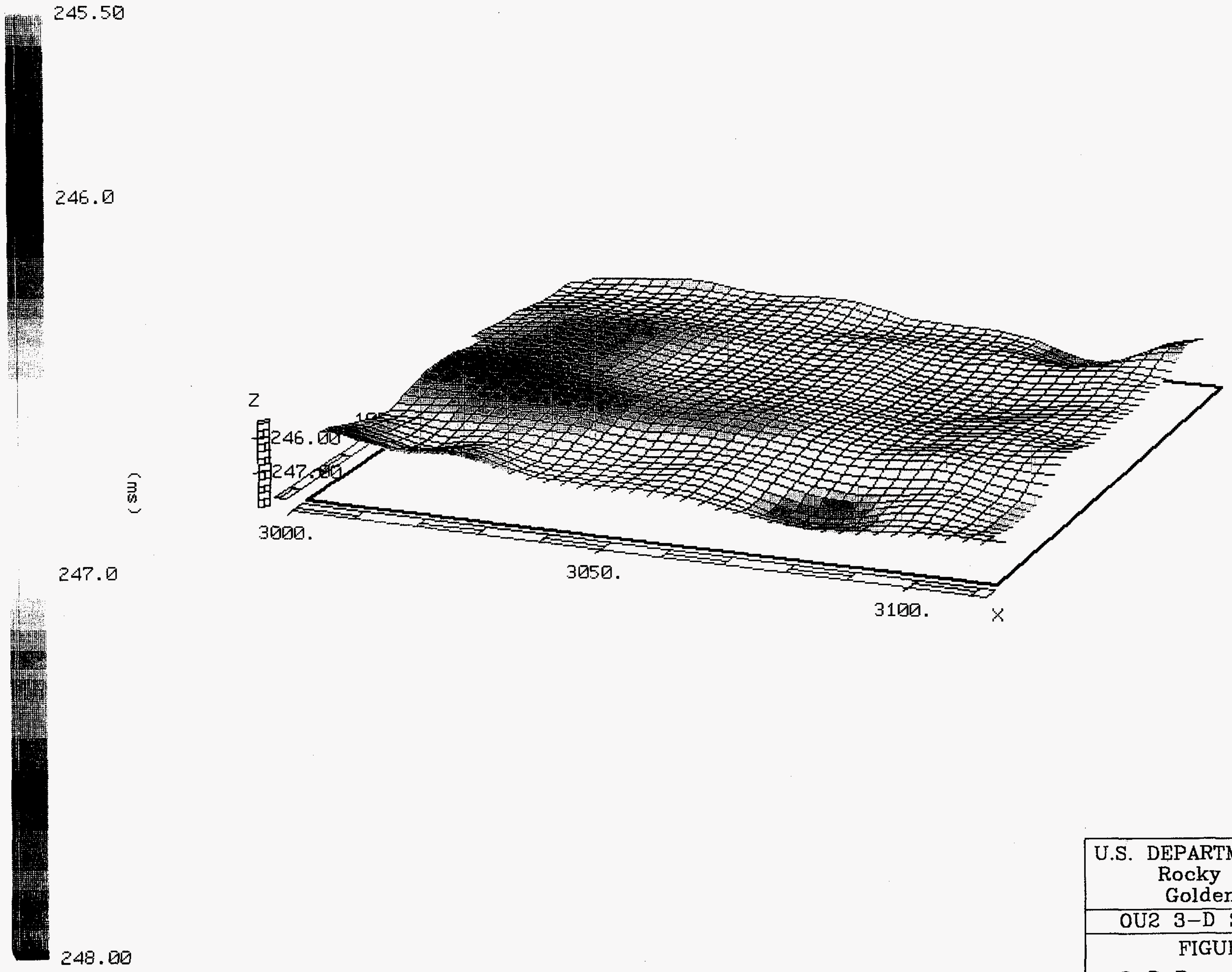

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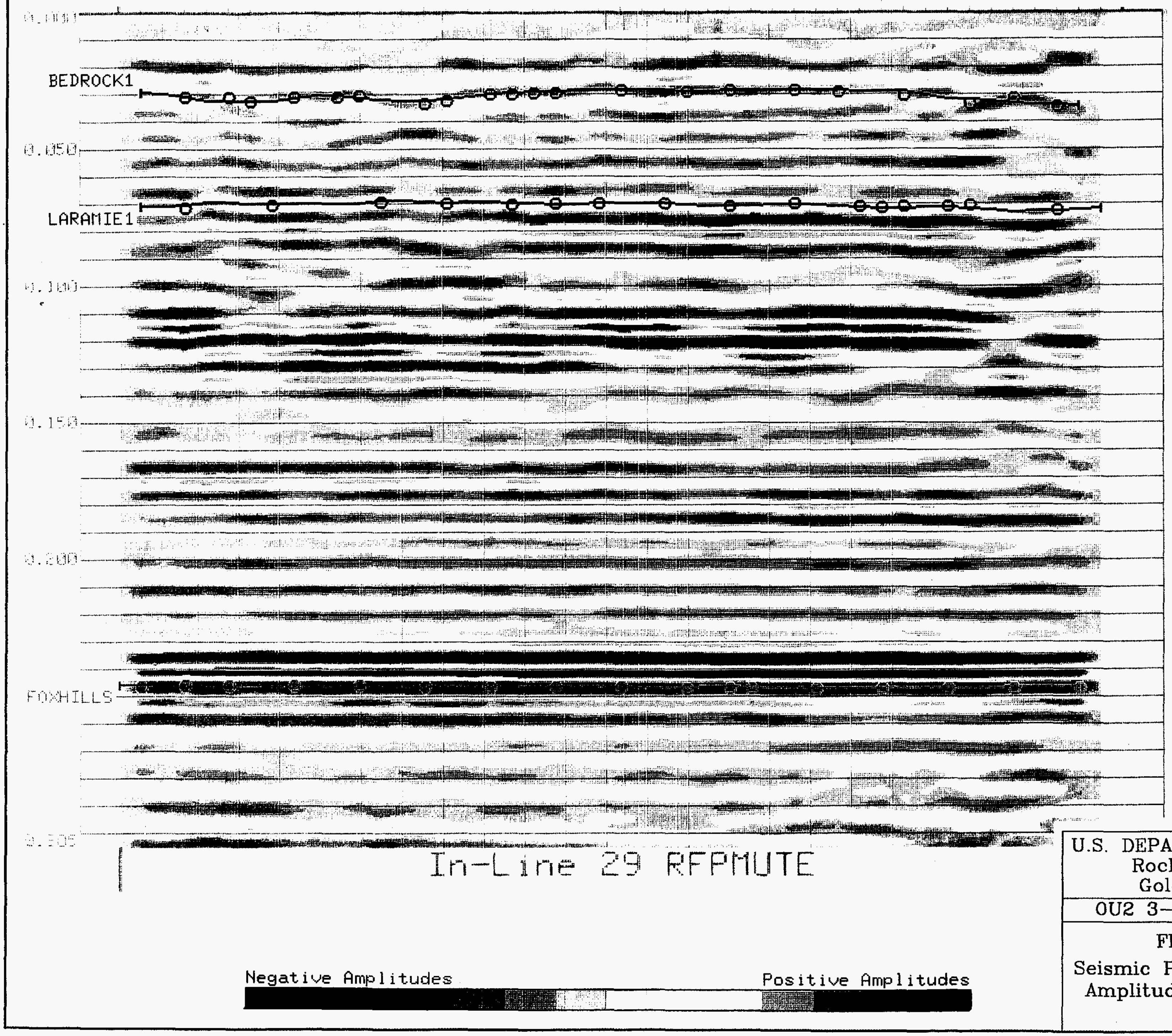
FIGURE 4-10

3-D Perspective View of the Fox Hills Sandstone Reflector



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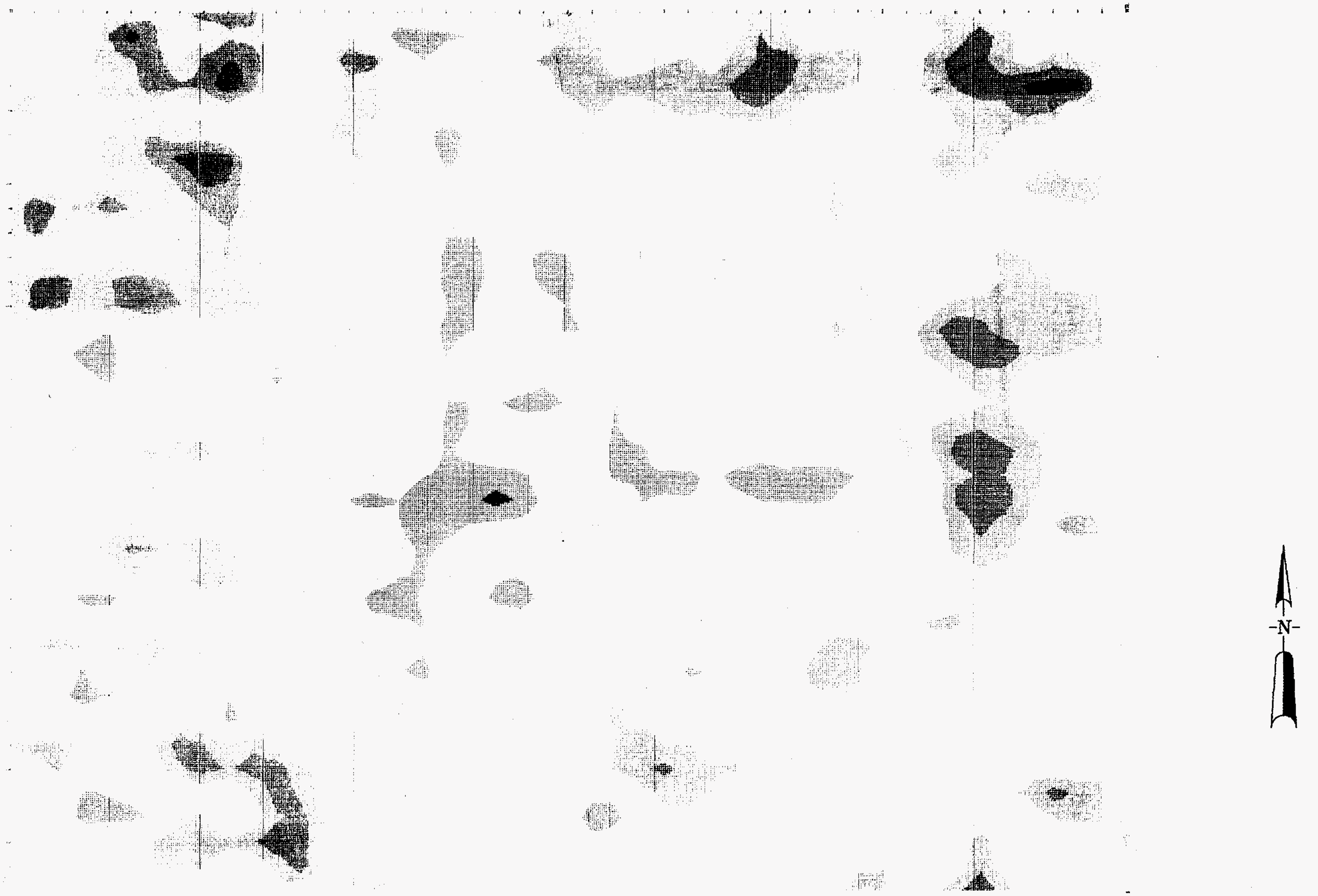
OU2 3-D Seismic Survey

FIGURE 4-11

Seismic Profile with Colored Amplitudes for In-Line 29



Negative Amplitudes Positive Amplitudes

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FIGURE 4-12

Time Slice Amplitude
Display: 114 ms

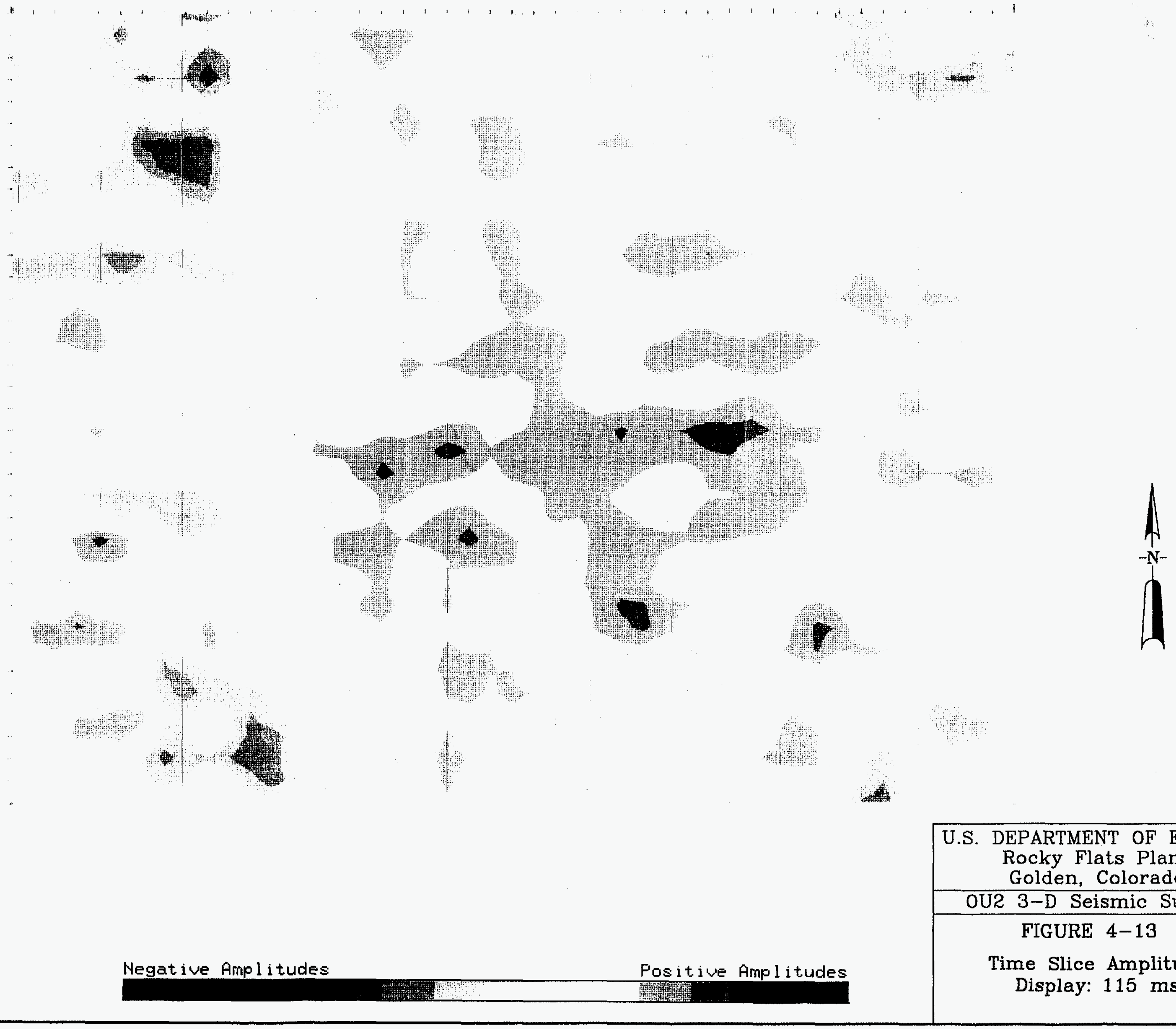

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FIGURE 4-13

Time Slice Amplitude
Display: 115 ms

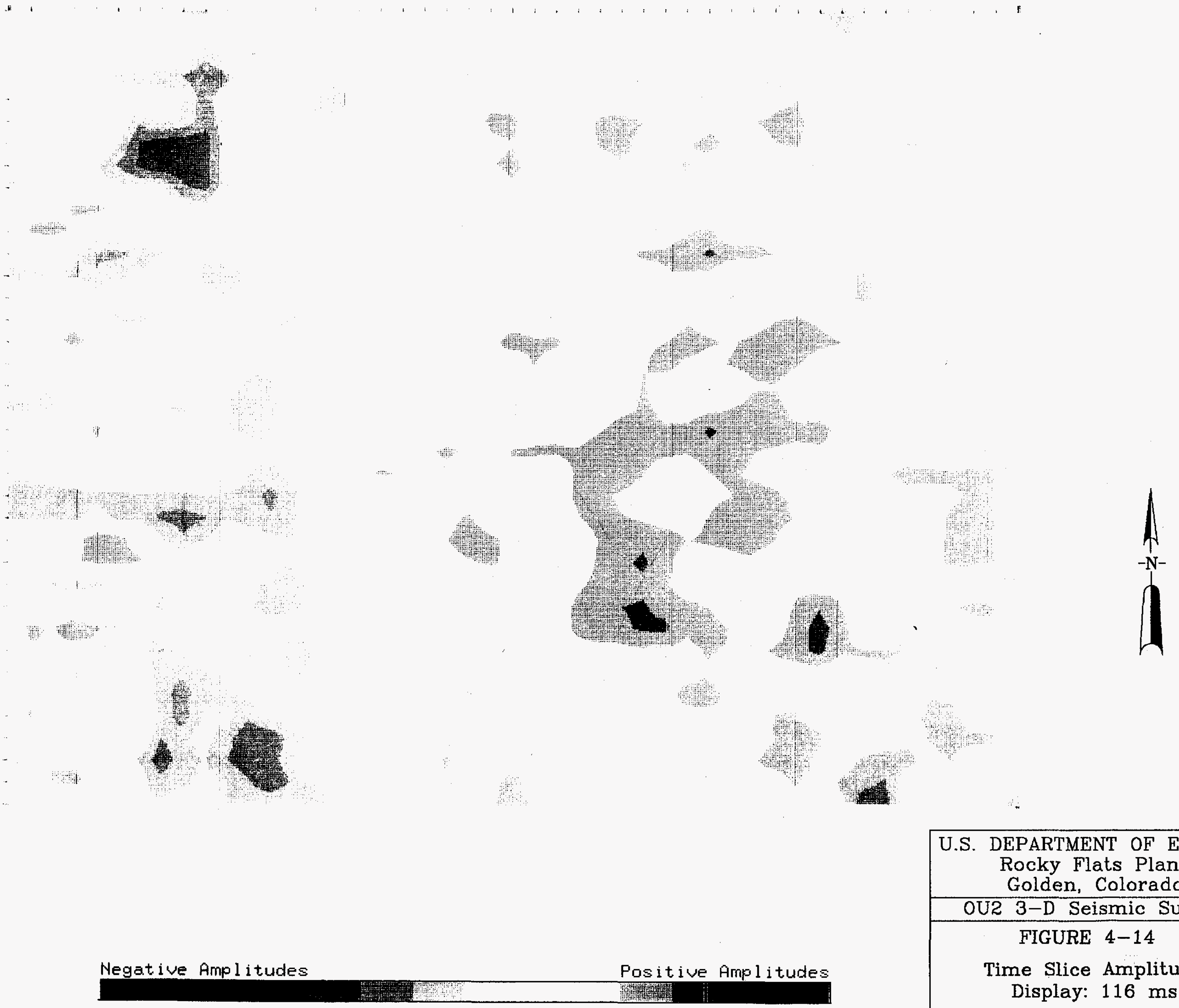

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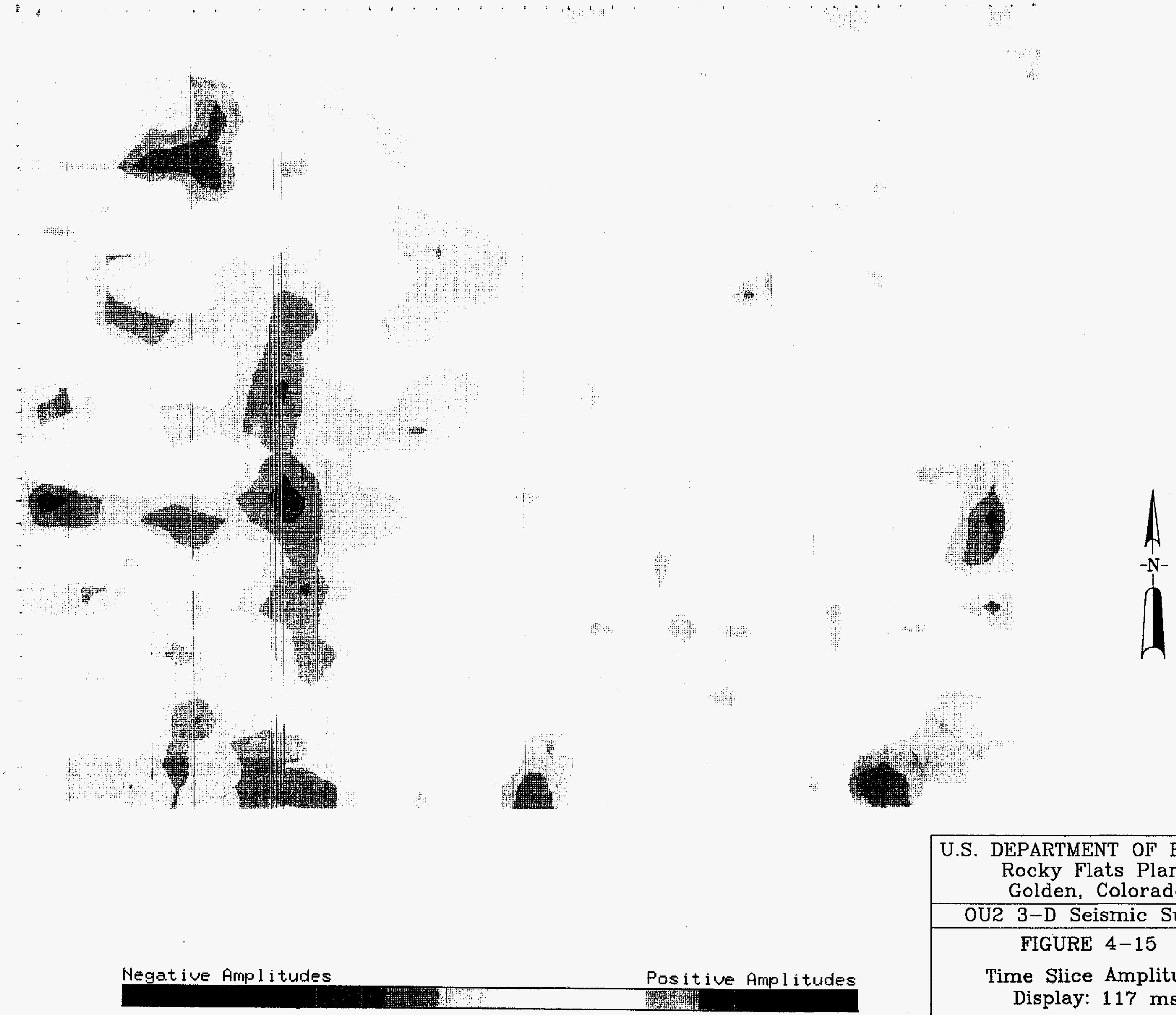
FIGURE 4–14

Time Slice Amplitude
Display: 116 ms



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OU2 3-D Seismic Survey

FIGURE 4-15

Time Slice Amplitude Display: 117 ms

5.0 CONCLUSIONS

5.1 GEOLOGIC

Based on the interpretation of the 3-D seismic reflection data collected, there does not appear to be a step in the bedrock at the survey location. Also, there does not appear to be any faulting or significant folding in the bedrock sediments down to the Fox Hills Sandstone. The seismic reflections are generally very continuous throughout the survey area. Dip on the shallow bedrock reflectors is approximately 3.5 degrees to the north, but changing to 3 degrees to the east at the Fox Hills Sandstone reflector. The discontinuities that do exist are where the CDP fold and signal strength are low (i.e., those at the edges and corners of the survey). There are some localized converging and diverging reflections in the mid-level Laramie sediments that appear to be stratigraphic rather than structural in nature.

Because no structural features can be observed on the seismic data in the survey area, the cause of the Bedrock Step observed north of the survey area cannot be determined. Based on the borehole data to the north of the survey area, and on the depth to bedrock logged in BH 04491 (27 ft), located within the survey area, the survey area is located on trend with the Bedrock Step. The lack of evidence of any structural features at the 3-D survey area indicates that the Bedrock Step terminates abruptly to the north of the 3-D survey area. If this is the case, the Bedrock Step is a local feature and therefore likely an erosional feature or a result of localized slumping.

5.2 3-D SEISMIC METHOD

The data are generally very high quality and superior to the 2-D seismic data collected previously in OU2. This higher quality is likely due to the following:

- The Mini-Vib source was able to generate a larger amount of energy in the useable frequency range than the 8-gauge cartridge.

- The Mini-Vib source generates seismic energy over a period of time (3 seconds), that renders unwanted, random noise (wind, traffic, etc.) less significant. Previous 2-D seismic data at OU2 using the 8-gauge seismic source contained a large amount of noise from traffic and drill rigs.

- The Mini-Vib source was able to stack 10 sweeps at each source point, increasing the signal strength by approximately 3 times over just 1 sweep.

- The 3-D nature of data acquisition allows for better cancellation of source generated noise.

- The CDP fold was generally much higher for this 3-D seismic survey than the previous 2-D seismic data. In the middle of the 3-D survey area CDP fold reached 100, and averaged over 40 for the entire area, while the CDP fold for the previous 2-D seismic data was 24. The 3-D seismic data have an increase in signal strength of approximately 1.3 to 2 times over the 2-D seismic data.

- The weather and ground surface conditions were much better during the 3-D seismic data acquisition than during the previous 2-D seismic data acquisition, allowing for better geophone to ground coupling.

Based on the knowledge gained from the demonstration and testing, 3-D seismic reflection can be an excellent, cost-effective tool to characterize the subsurface geology at RFP. Depending on the objectives of any future geologic characterization or studies, a 3-D seismic survey can be designed to significantly reduce costs relative to this demonstration. Based on the quality of the seismic data collected during this testing, a 3-D CDP fold of 20 to 30 is sufficient to image the subsurface geology. For larger surveys, there are a variety of techniques to collect 3-D data such that the CDP fold is distributed evenly across an area. Also, by increasing the number of recording channels (by adding additional channels to the DOE's seismograph or using one of several seismographs available that have more channels), the number of source points can be reduced without reducing the CDP fold or data quality. By reducing the number of source points, data acquisition time and associated costs can be reduced, and data processing costs can be reduced.

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Appendix I

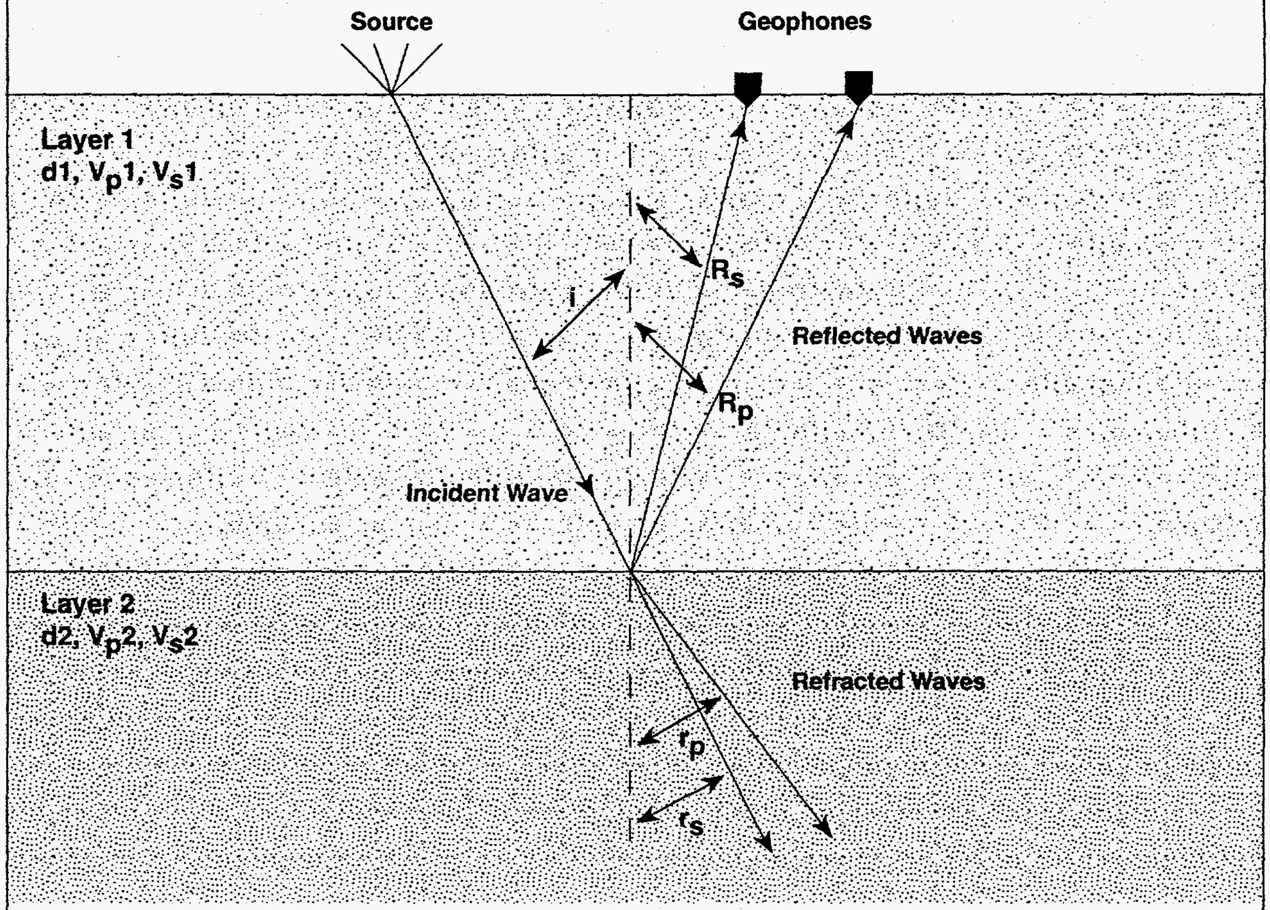
Theory of Seismic Reflection Techniques

SEISMIC REFLECTION TECHNIQUE

A seismic source generates energy that manifests itself as seismic waves. Seismic waves propagate within solids as disturbances traveling through the materials with velocities dependant upon the elastic properties and densities of the materials. Typical commercial seismic sources include simple mechanical devices, explosives, and vibrating machinery. These sources generate two types of seismic waves; body and surface waves. Body waves consist of compressional waves (P-waves) and shear waves (S-waves). The selection of an appropriate source and its directionality, and the subsequent source-detector geometry are the dominant factors in determining the type of waves generated by the source and received by the sensors. In general, most sources that are excellent generators of P-waves can be modified in concert with the sensor geometry to provide measurable S-wave motion.

Seismic wave energy attenuates with distance partly due to frictional heat loss through absorption of energy by the host material. Absorption is dependent on several characteristics of the seismic medium; based on experimental data, sedimentary materials tend to have higher absorption rates than igneous rocks. Although attenuation mechanisms are not fully understood in all earth materials, the fact remains that higher frequency energy is absorbed at a greater rate than lower frequency energy. Since seismic waves propagate as spherical wave fronts, the wave spreads out over a spherical area. Thus, the energy per unit area varies inversely as the square of the distance from the source.

A seismic wave will travel through a medium along a ray path until a discontinuity is encountered. For P-waves, the particle motion lies in a plane parallel to the direction of the wave. S-waves are characterized by particle motion perpendicular to the direction of wave travel. A discontinuity can be caused by a change in lithology or fluid content of a porous medium. At a discontinuity, part of the wave will be reflected and another part refracted in accordance with Snell's Law as illustrated in Figure I-1.



Legend

V_s	Shear (S-wave) Velocity
V_p	Compressional (P-wave) Velocity
d	Density
i	Angle of Incidence
r_p	Angle of Refraction, P-wave
r_s	Angle of Refraction, S-wave
R_p	Angle of Reflection, P-wave
R_s	Angle of Reflection, S-wave

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Figure I-1

Illustration of Snell's Law

The relative amplitude of a reflected P-wave resulting from the boundary of two layers, Layer 1 and Layer 2, can be expressed in the form

$$R = \frac{d_2 V_2 - d_1 V_1}{d_2 V_2 + d_1 V_1}$$

where:

R = reflection coefficient
d = density in grams per cubic centimeter of medium
V = velocity of P-wave through medium

The product of the density and velocity is known as the acoustic impedance. If the acoustic impedance increases across an interface, then the reflected wave has a positive amplitude. Conversely, if the acoustic impedance decreases across an interface, the reflected wave has a negative amplitude.

The refracted P-wave makes an angle, r, expressed by the relation

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$

where:

i = angle of incidence
r = angle of refraction
V_1 = velocity of P-wave through Layer 1
V_2 = velocity of P-wave through Layer 2

When sin i = V_1/V_2, sin r becomes unity and r becomes 90 degrees. The refracted wave does not penetrate the medium, but travels along the interface between the two materials. Angles i and r are measured relative to the normal at the intersection of the interface and the incident wave.

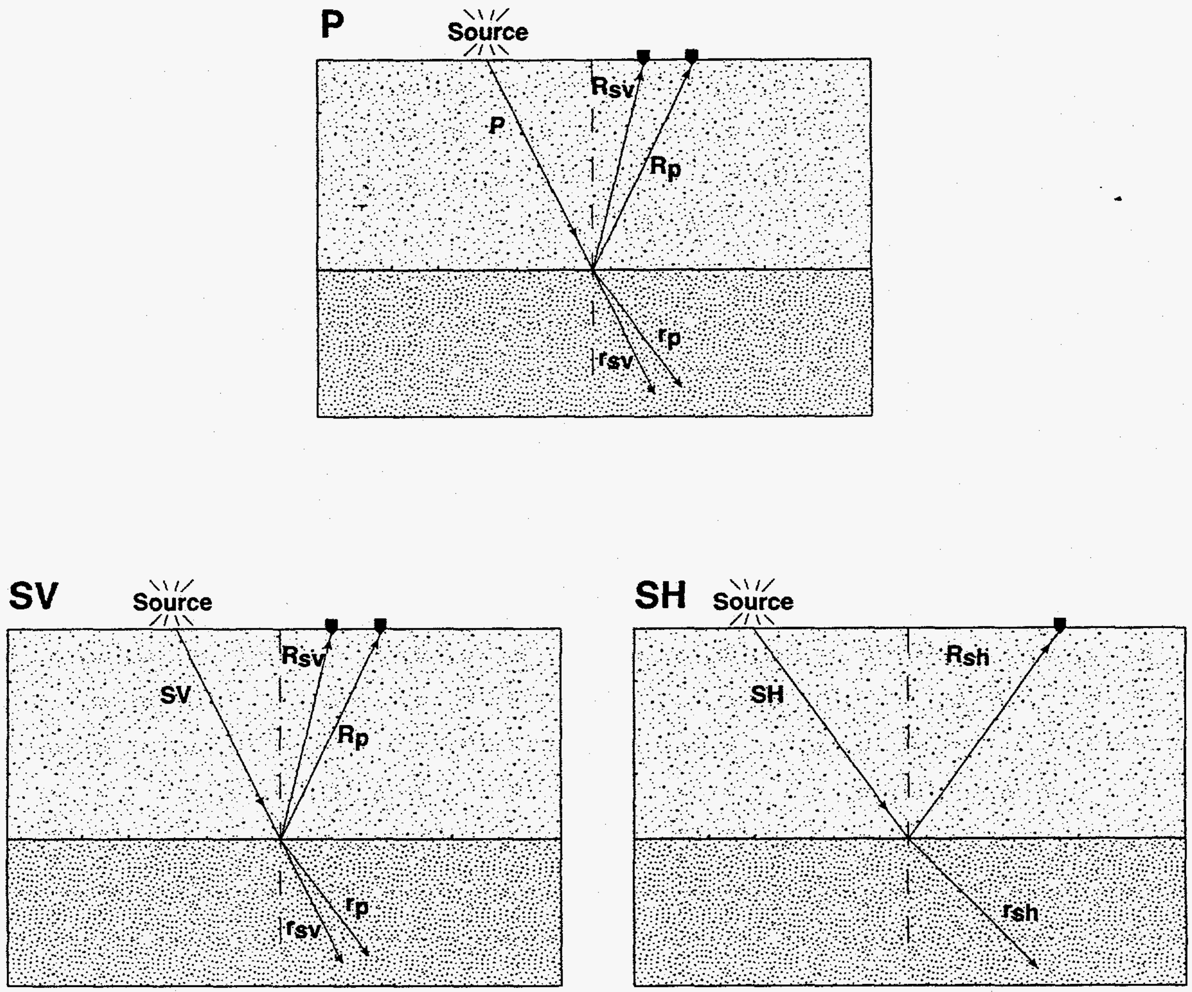
The equations for the transmission and reflection of S-waves impinging upon a boundary are similar to those for P-waves. However, S-waves are characterized by two directional components; one component of motion is parallel to the ground surface (SH), and one component lies in the vertical plane (SV). Figure I-2 exhibits the resultant waves generated by surface sources oriented to produce primarily P, SV, and SH type waves.

Where seismic waves strike any irregularity along a surface, such as a corner or a point where there is a sudden change of curvature, the irregular feature acts as a point source radiating waves in all directions. Such radiation is known as diffraction. The amplitude of a diffracted wave falls off rapidly with distance away from a source.

Another seismic phenomenon, the interbed multiple reflection, is illustrated in Figure I-3. A wave reflects upward from the interface between Layer 2 and Layer 3. Returning to the surface, the wave reflects downward from the Layer 1 - Layer 2 interface, because any change in acoustic impedance at an interface boundary can cause a reflection. The wave again reflects from the top of Layer 3 and successfully returns to the surface.

Figure I-3 also shows the types of seismic waves generated by a surface source that will be detected by a geophone. The air wave travels at the speed of sound in air (approximately 1,100 feet per second. The direct wave travels from the source to the geophone within the uppermost medium. This wave is normally faster than the air wave but slower than the other illustrated waves. The refracted wave has the earliest arrival time. The reflected wave is slower than the refracted wave. A multiple reflected wave has a longer arrival time than the reflected wave because of the greater distance traveled. Because of the varying velocities of the different waves it is possible to design seismic field parameters to record the waves of primary interest.

According to signal theory, the amount of information present in a seismic reflection signal is proportional to the bandwidth. The bandwidth of a seismic signal is the range of frequencies contained within. The maximum frequency that can be recorded reliably is equal to one-half of



Legend

V_s	Shear (s-Wave) Velocity
V_p	Compressional (p-Wave) Velocity
d	Density
i	Angle of Incidence
r_p	Refracted p-wave
r_s	Refracted s-wave
R_p	Reflected p-wave
R_s	Refelcted s-wave

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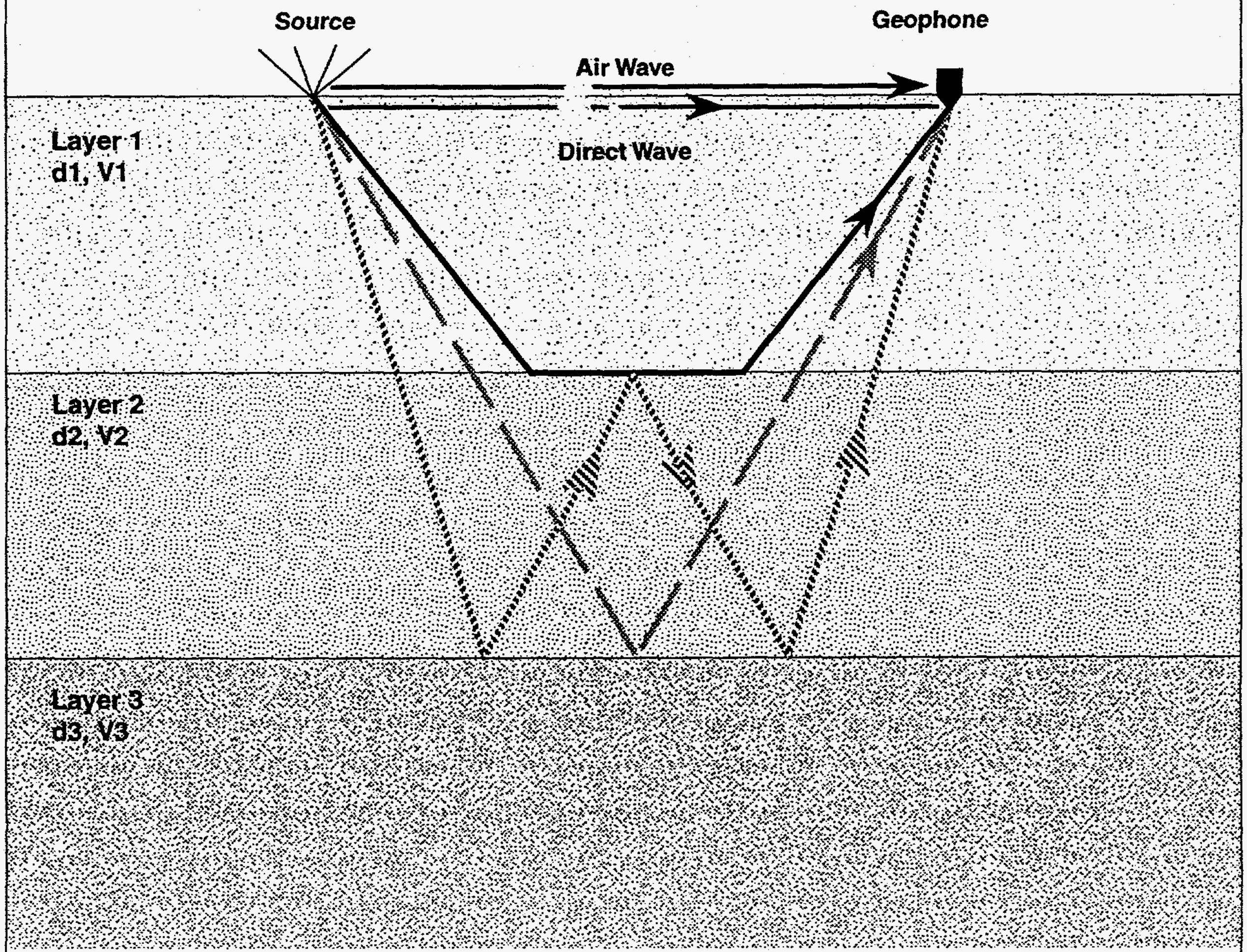
Figure I-2

P, SV, and SH Waves



Legend

━	Refracted Wave
┅	Reflected Wave
⋯	Multiple Reflection
V	P - Wave Velocity
d	Density

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Figure I-3

Types of Seismic Waves

the sampling frequency or rate. This is known as the Nyquist frequency. At a 0.25-millisecond sampling rate, the Nyquist frequency is 2,000 hertz.

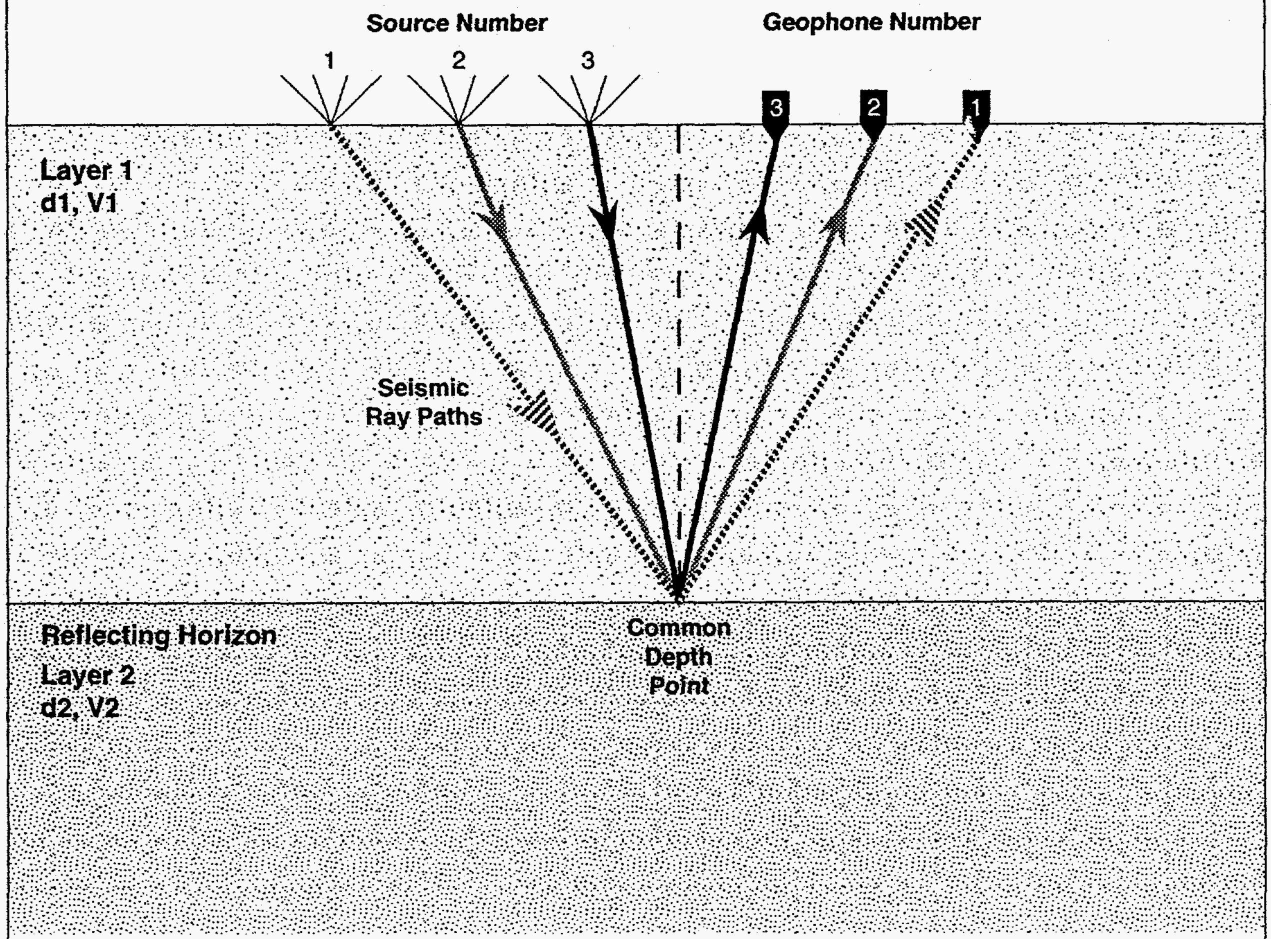
COMMON DEPTH POINT METHOD

Seismic reflection techniques build on basic seismic principles. Development of digital recording techniques in the 1960s catalyzed great advances in seismic reflection acquisition, processing, and interpretation. Seismic noise is any unwanted signal; sometimes it is random and other times it is coherent (e.g., an operating water pump or a nearby electric powerline). To reliably interpret a seismic event, the signal-to-noise (S/N) ratio must be at least 1:1.

The common depth point (CDP) technique has enabled the recording and display of reflection events that have S/N ratios less than unity. The CDP technique records reflections from multiple offsets at different source and receiver pairs as illustrated in Figure I-4. For each CDP the number of source and receiver pairs recorded is called the fold. Six fold data, also called 600 percent stack, has six source and receiver pairs. The S/N ratio doubles for each quadruple increase in the CDP fold. The CDP fold can be calculated by the following equation:

$$CDP\ fold = \frac{receiver\ spacing}{2\ x\ source\ spacing}\ x\ number\ of\ recording\ channels$$

The processing of seismic reflection data can be an intensive procedure and requires human guidance at each step. After acquisition, the seismic reflection data are processed from source record format into CDP record format. Each CDP record will have the same number of traces equal to its fold. Because the distance between source and receiver is greater for the longer offsets of a reflection event (source-receiver 1 as opposed to source-receiver 3, Figure I-4), the recorded reflection event itself will record at a later time. The difference in time for a particular event on adjacent traces is termed normal moveout. Data are corrected for normal moveout during processing, and all traces in the CDP record are merged or summed together (stacked). This enhances the real events and cancels undesirable random noise, thus increasing the S/N ratio.



Legend

- **d** **Seismic Velocity**
- **V** **Density**

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Figure I-4

Common Depth Point Technique

Before stacking, data are corrected for elevation variations, resulting in a static correction. After stacking, automatic statics are performed to correct for velocity variations in the near-surface weathered layer. Digital filters are applied at various steps in the processing to eliminate undesirable noise and enhance the reflection events. Post-stack filtering may include enhancing individual reflection events to improve the interpretation by statistically comparing adjacent seismic traces for continuous events versus random noise.

Seismic events recorded from a geophone appear to arrive from directly beneath the geophone. Where the reflecting horizon is dipping, the position of the event is incorrect. Dipping events migrate downdip. If necessary, these events can be migrated back to their true location. Depending on the data and objectives of the interpreter, this process can be done either before or after stacking (i.e., pre-stack or post-stack migration).

Recording shallow reflection events requires modification of standard seismic reflection techniques. In standard seismic reflection techniques 12 or more geophones are grouped together as an array. Typical distances between groups are tens to hundreds of feet. In shallow high-resolution seismic reflection work geophone arrays are eliminated and individual geophones are used. Geophone spacings are reduced to a few feet, depending on the depth to the shallowest target. Shallower targets require closer geophone spacings. The number of recording channels needed is dependent on the depth to the deepest target of interest and the geophone and source spacing. Vertical resolution is limited by the bandwidth of the recorded signal and the sampling frequency. Horizontal resolution is limited by the bandwidth of the recorded signal and the geophone spacings.

SEISMIC DATUM

The seismic datum is an arbitrary reference surface that corrects seismic data for local topographic variations. The start time of each record is corrected to the seismic datum. In general, if this reference datum is below the ground surface then some shallow data will be lost. If the datum is above the ground surface then the earliest seismic events are recorded and preserved on the seismic profile. Conventional seismic reflection utilizes a seismic datum below the ground surface because there is little interest in shallow events, however, the high-resolution seismic programs at the Rocky Flats Plant are targeting the early or shallow events. Therefore, a seismic datum above the ground surface is used. For example, if a borehole has an elevation of 5,900 feet (ft), the seismic line intersecting the borehole might have a seismic datum elevation of 5,975 ft. If a sandstone was encountered in the borehole at a depth of 120 ft, the seismic depth of the sandstone would be 195 ft on the seismic profile because the seismic datum is 75 ft higher than the borehole ground surface elevation.

THE VIBROSEIS SOURCE

The energy source used in Vibroseis is a vibrator which transfers seismic energy into the ground by shaking it for several seconds. As opposed to the impulse sources which typically transfer their energy in an impulse lasting only milliseconds, the Vibroseis source transfers energy continuously for periods which typically may range from 1 second to 16 or even 32 seconds. The total energy transferred from the vibrator could be made comparable to the energy from the impulse source merely by adjusting the duration of energy release. However, the power, or rate at which the vibrator transferred energy would always be much smaller than the power of the impulse source. This means that the vibrator can provided adequate energy while exerting relatively small force on the ground surface. This small force makes the Vibroseis system eminently suitable for use where surface damage is particularly undesirable.

The vibrator actually vibrates through a predetermined frequency range in a predetermined period of time. This is called the *Vibroseis sweep*. The *duration* of the sweep (in seconds) is often referred as the *sweep length*. Change of frequency with time is linear throughout the sweep. Sweep spectra are usually described by the starting and finishing frequencies of the sweep ($f_1 \sim f_2$). A 12-56 sweep then starts at 12 Hz and ends at 56 Hz and a 40-10 sweep starts at 40 Hz and ends at 10 Hz. Vibroseis sweeps typically have a bandwidth of 2 octaves.

When using an impulse source, if we want to record seismic events up to say 6 seconds of 2-way travel time, we arrange for our recorder to "listen for" and record signals for 6 seconds after the start of the seismic impulse (T/O).

When using Vibroseis however, if we want to record seismic events up to 6 seconds of 2-way travel time, we must arrange for our recorder to record during the whole length of the sweep and then continue "listening" and recording for 6 seconds after the end of the sweep.

Record Length = Sweep Length + Max 2-way travel time required.

A single reflection incident to the surface of the earth lasts as long as the sweep. If we use an 8-second sweep, each reflection is 8 seconds long. The result of this is that seismic events overlap each other to the extent that the raw field trace is a composite of so many overlapping events as to be completely meaningless without undergoing special processing.

In order to become meaningful, each trace must be subjected to a method of *signal compression* which will compress each long seismic event into a wavelet comparable to the Ricker wavelet of the impulse energy source.

Each trace of a raw Vibroseis record is subjected to a process called *correlation* which serves to compress each seismic event into a single wavelet. After correlation the record looks very similar to a record obtained with an impulse energy source. The length of the correlated record is equal to the length of the original recording minus the sweep length.

Correlated record length = Raw record length - Sweep length

A 14-second raw record obtained using an 8-second sweep would therefore yield a 6-second correlated record.

The frequency content of a seismic record made with an impulse source can be controlled only by filtering in the recorder or in processing. However, a correlated Vibroseis record contains only these frequencies which were contained in the sweep. It follows that choice of "correct" sweep frequencies should eliminate the need for filtering either at the recorder (other than anti-alias filter) or in processing.

Each reflection on a raw Vibroseis trace lasts as long as the sweep and has the same frequency constant as th sweep. Each reflection (and indeed, each seismic event caused by the sweep) has exactly the same from as th sweep itself.

Correlation in Vibroseis is merely as means of measuring the degree of correlation (or similarity) between the sweep that was put into the ground and the seismic trace that was recorded. If we slide the sweep past the trace, maximum correlation will occur whenever the sweep is opposite a reflection or other event. It is therefore possible to extract events from the raw trace.

Vibroseis crews in the United States often work along busy highways or even along downtown streets. The noise generated by passing traffic would be an insurmountable problem for any system other than Vibroseis. With Vibroseis however, the correlation process extracts only those traffic noise frequencies which are contained in the sweep and rejects all others. As the traffic noise frequencies do not follow the sweep sequence of frequencies, they appear on the correlated record as relatively low-level background noise.

This "noise rejection by correlation" also applies to wind noise. However, as with any other surface energy source, we also use *multiplicity* to control wind noise.

Wind noise is essentially random in nature, so the detected wind noise will differ from geophone to geophone and tend to be reduced by mixing within the geophone array. Also, with Vibroseis, as with other surface sources, we sum records in the field. The component records of the sum have differing wind noise content, so the noise tends to be "summed down".

Appendix II
Seismic Reflection Equipment

INSTRUMENT SPECIFICATIONS

- EG&G Geometrics ES-2420 Digital Reflection Seismograph
- Mark Products L-40 A2 100-Hertz (Hz) Geophones
- Input/Output RLS-240M Rota-Long Switch

In the event of unforeseen circumstances, equivalent instruments will be substituted for equipment listed below.

EG&G GEOMETRICS ES-2420 DIGITAL REFLECTION SEISMOGRAPH

The following specifications apply to an operating environment of 0 to 40 Degrees Centigrade (°C), after a 5-minute warmup period (EG&G Geometrics 1984).

Analog Performance Specifications

Preamplifier Gain:	32 (30.1 decibels [dB]) 64 (36.1 dB) 128 (42.1 dB)

Selected by switches on printed circuit board.

Input Impedance:	Differential, 20K ohms, .01 microfarads (µfd) Common Mode, 5K ohms, .02 µfd
Maximum Differential Input Voltage:	@ 30 dB, 0.640 volts (v) peak to peak @ 36 dB, 0.320 v @ 42 dB, 0.160 v

Maximum DC Common Mode
Voltage: 10.0 v

Transient Protection: Transients with energy less than 0.75 Joule and voltage less than 200 v will not damage instrument

Alias Filters:

6 dB Slope Cutoff Frequency (F_c in Hz)	Stop Band Frequency (Hz)	Stop Band Attenuation (dB)
45	125	80
180	500	80
360	1,000	78
720	2,000	78
1,440	4,000	78

6 dB corner frequency tolerance:	3% max
Time delay, constant from 5 Hz to F_c within	± 2%
Time delay similarity between channels	± 2%

Low Cut Filter: Frequency: 5 to 320 Hz in 5 Hz increments
3 dB corner frequency tolerance: 3% max
Type: Butterworth
Attenuation slope: 18 dB/octave

Notch Filter: 50 or 60 Hz or out, selected from front panel
6 dB bandwidth 9 Hz typical Frequency of Origin (F_o)
±3.65 minute ±6.80 max
50 dB bandwidth 0.5 Hz typical F_o ±0.1 minute

Floating Point Digitizer

Instantaneous-floating-point amplifier with 16 gain ranges (6 dB per step) followed by a 15-bit Analog/Digital (A/D) converter. Amplifier gain range is automatically selected for each sample to maximize the precision of the mantissa value.

Exponent:	4-bit unsigned binary number representing the gain range, where zero represents maximum gain (minimum signal)
Mantissa:	15-bit, twos-complement binary
Full scale input voltage:	± 10.24 v
Gain step relative accuracy:	0.1%
A/D converter accuracy:	0.2%
A/D converter linearity:	0.01%

System Response

Signal to Noise Ratio:	100 dB (3 to 180 Hz, 42 dB preamp gain, 600 ohm input, notch & low-cut filters out, alias filter set to 180 Hz)
Frequency Response:	Lower 3 dB frequency, 1.6 Hz ±10% Upper 3 dB frequency, determined by alias filter
Gain accuracy:	1%
Gain similarity between channels:	2%
Total Harmonic Distortion:	0.05% floating point average (FPA) in minimum gain, Preamp gain minimum. Input: 0.226 voltage root mean square (Vrms) 3 to 1,000 Hz
Crossfeed:	<80 dB, 3 to 2,000 Hz
Timing:	Time base accuracy 0.002%

Sample skew: Within 8 channel group, 1/40 milliseconds (ms)/channel.

Operating Characteristics

Sample Interval, write-to-memory: 1/4, 1/2, 1, 2, or 4 ms
Front panel selectable

Real time clock: Built in digital clock with time of day and day of year. Battery backup provides continuous timekeeping.

Basic accuracy 3 seconds per month at 25 °C. Time recorded on tape.

Maximum Record Length: Set from front panel to maximum of 99 seconds in direct-to-tape. In stack-to-memory maximum length determined by sample interval:

1/4 ms	4.096 seconds
1/2 ms	8.192 seconds
1 ms	16.384 seconds
2 ms	32.768 seconds
4 ms	65.536 seconds

Delay Start: Postpones sampling of data by front-panel selected delay up to 9.999 seconds in 0.001 second increments.

ES-2420 Acquisition Control Unit (ACU) Power Supply: Operates from 10 to 18 v DC

DP2420 Printer Power Supply: Operates from 10 to 14 v DC

DMT2420 Tape Drive Power Supply: Operates from 10 to 16 v DC

Dimensions

ACU: 28 x 16 x 23.5 inches (22.5 with 71 x 41 x 60 cm cover removed)

Expansion Module: same as ACU

Portable Tape Deck:	same as ACU
Plotter:	15 x 15 x 18 *inches* 38 x 38 x 46 centimeters

Weights

Acquisition Control Unit:	110 pounds (50 kilograms [Kg]) with 4 channels 7 pounds (lbs) (3 Kg) for each additional 8-channel board set
Printer:	40 lbs (18 Kg)
Portable Tape Deck:	100 lbs (45 Kg)
Environmental:	Operating temperature, 0 to 45°C continuous operation with built-in forced air cooling. Can be operated in cyclic conditions to temperature of 50°C. Storage temperature - 40 to 70°C Humidity 10 to 95% noncondensing May be operated in vertical position in light rain (cover closed on tape recorder, protection for plotter) Weatherproof with transit lid closed

Cathode Ray Tube (CRT) Display

512 by 512 dot matrix graphic display of seismic data and acquisition parameters. Can display at maximum expansion of one dot per sample, or compressed in 3 dB steps up to maximum of 16,196 samples on screen. Also displays a time cursor and scale lines and selected parameters (e.g, battery voltage constant, file number, and status messages).

TAPE DATA FORMAT

Tape format:	Nine-track, Society of Exploration Geophysicists (SEG) D, 2 1/2 byte, multiplexed

Data density: 1,600 bits per inch

6Block size: Fixed blocking, equal to an integral number of scans, as close as possible to a user selected maximum or ungapped

Channel set descriptor: One for all channels

Sample skew: Not written to tape. For each set of Channels (usually 8) supported by a Data Acquisition Memory (DAM) board - Preamplifier Filter (PF) board pair, sample skew starts at zero and increased by 1/40 ms per channel. The maximum sample skew for any channel in the system is thus 7/40 ms.

Data word: Ones complement, twenty bits with a one-bit sign, four-bit binary exponent, and 14-bit mantissa. The least significant bit (LSB) is zero.

Geophone Specifications - Mark Products L-40 A2

Standard Frequency Range	100 Hz
Frequency Tolerance	+7%
Standard Coil Resistance+10% (Ohms)	325, 510, 780
Distortion @ Resonance @ 0.7 inches/second	0.2% MAX
Transduction Constant, v/inches/second (Rc= circuit resistivity)	0.031 Rc
Open Circuit Damping (f=frequency)	$\frac{47.9}{f}$
Coil Current Damping (Rs=source resistivity)	$\frac{20.8\ Rc}{f\ (Rc + Rs)}$
Suspended Mass, Grams	5.7
Case-to-Coil Motion, peak to peak inches	0.080
Intrinsic Power Sensitivity milliwatts (mw)/inches/second	0.96
Basic Unit Diameter, inches	1.25
Basic Unit Height, inches	1.37
Basic Unit Weight, ounces	5.0

ROTA-LONG SWITCH SPECIFICATIONS - INPUT/OUTPUT RLS-240M

The following specifications are presented in summary form from the operations manual (Input/Output Inc. 1981a).

- 240 input stations
- Unlimited types of recording configurations
- Size: 20 inches wide x 20 inches tall x 6.50 inches deep
- 120 recording channels
- Auxiliary connector permits diagnostic cable tests with an ohmmeter or I/O Break Check
- Weight: 40 lb

REFERENCES

EG&G Geometrics
1984 ES-2420 Digital Reflection Seismograph Operation Manual.

Input/Output, Incorporated
1981a RLS-240M Manual Rota-Long Switch Operations Manual, 12 pp.

Appendix III
Glossary of Geophysical Terms

GLOSSARY

A selection of relevant geophysical terms extracted from
Encyclopedic Dictionary of Exploration Geophysics (Sheriff, 1984),
Applied Geophysics (Telford et al., 1976),
Geophysical Prospecting (Dobrin, 1976; Dobrin and Savit, 1988).

ACCELEROMETER -	A geophone whose output is proportional to the acceleration of earth particles. For example, a moving coil geophone, with velocity response proportional to frequency (as may be the case below the natural frequency) operates as an accelerometer.
ACOUSTIC - IMPEDANCE	Seismic velocity multiplied by density. Reflection coefficient at normal incidence depends on changes in acoustic impedance.
ACOUSTIC LOGGING -	A borehole logging survey which will display any of several aspects of seismic-wave propagation, i.e., a sonic, amplitude, character or 3D-log.
AIR WAVE -	Energy from the shot which travels in the air at the velocity of sound: $V = 1051 + 1.1F$ ft/s, where F = Fahrenheit temperature, or $V = 331.5 + 0.607C$ m/s, where C = Celsius temperature.
ALIAS -	Data in sampled form have an ambiguity where there are fewer than two samples per cycle. This creates a situation where an input signal at one frequency appears to have another frequency at the output of the system. Half of the frequency of sampling is called the folding or Nyquist frequency, f_N, and a frequency larger than this, $f_N + Y$, appears to have the smaller frequency f_N-Y. To avoid this ambiguity, frequencies above the Nyquist frequency must be removed by an anti-alias filter before the sampling. Otherwise the system will react as if the spectral characteristics were folded back at the Nyquist frequency. Thus, for a system sampled over 4 ms, or 250 times per second, the Nyquist frequency is 125 cps; if, for example, 50 cps is within the pass band, then 200 cps will also be passed if an anti-alias filter is not used, appearing upon output to have a 50 cps frequency. The pass bands obtained by folding about the Nyquist frequency are also called "alias bands," "side lobes," and "secondary lobes." Aliasing is an inherent property of all sampling systems and applies to digital seismic recording

	and also to the sampling which is done by the separate elements of geophone and shotpoint arrays.
ANALOG -	(1) A continuous physical variable (such as voltage or rotation) which bears a direct relationship (usually linear) to another variable (such as earth motion) so that one is proportional to the other. (2) Continuous, as opposed to discrete or digital.
ANOMALY -	A deviation from uniformity in physical properties, often of exploration interest. For example, a travel time anomaly, Bouguer anomaly, free-air anomaly.
APPARENT VELOCITY -	(1) The phase velocity which a wavefront appears to have along a line of geophones. (2) The inverse of the slope of a time-distance curve.
ATTENUATION -	A reduction in amplitude or energy caused by the physical characteristics of the transmitting media or system. Usually includes geometric effects such as the decrease in amplitude of a wave with increasing distance from a source. Also used for instrumental reduction effects such as might be produced by passage through a filter.
AUTOMATIC GAIN CONTROL (AGC) -	A system in which the output amplitude is used for automatic control of the gain of a seismic amplifier, usually individual for each channel, although multi-channel devices are sometimes used.
BEDROCK -	Any solid rock, such as may be exposed at the surface of the earth or overlain by unconsolidated material.
BODY WAVES -	P-waves and S-waves, which travel through the body of a medium, as opposed to surface waves.
CABLE -	The assembly of electrical conductors used to connect the geophone groups to the recording instrument.
CAPACITANCE -	The ratio of charge (Q in coulombs) on a capacitor to the potential across it (V in volts) is the capacitance (C in farads): $C = Q/V$
CHANNEL -	(1) A single series of interconnected devices through which geophysical data can flow from sources to recorder. Most seismic systems are 24

	channel, allowing the simultaneous recording of energy from 24 groups of geophones. (2) A localized elongated geological feature resulting from present or past drainage or water action; often presents a weathering problems. (3) An allocated portion of the radio-frequency spectrum.
CHANNEL WAVE -	An elastic wave propagated in a layer of lower velocity than those on either side of it. Energy is largely prevented from escaping from the channel because of repeated total reflection at the channel boundaries or because rays which tend to escape are bent back toward the channel by the increasing velocity away from it in either direction.
CHARACTER -	(1) The recognizable aspect of a seismic event, usually in the waveform, which distinguishes it from other events. Usually a frequency or phasing effect, often not defined precisely and hence dependent upon subjective judgment. (2) A single letter, numeral, or special symbol in a processing system.
COMMON DEPTH POINT (CDP) -	The situation where the same portion of subsurface produces reflections at different offset distances on several profiles.
COMPRESSIONAL WAVE -	An elastic body wave in which particle motion is in the direction of propagation. (Same as P-waves, longitudinal wave, dilation wave).
CONVERTED WAVE -	A wave which is converted from longitudinal to transverse, or vice versa, upon reflection or refraction at oblique incidence from an interface.
CRITICAL ANGLE -	Angle of incidence, q_c, for which the refracted ray grazes the surface of contact between two media (of velocities V_1 and V_2): $\sin q_c = V_1/V_2$
CRITICAL DISTANCE -	(1) The offset at which the reflection time equals the refraction time; that is, the offset for which the reflection occurs at the critical angle (see Sheriff, 1984 p. 45). (2) Sometimes incorrectly used for crossover distance, the offset at which a refracted event becomes the first break.

CROSSFEED -	Interference resulting from the unintentional pickup of information or noise on one channel from another channel. Also crosstalk.
CROSS-HOLE METHOD -	Technique for measuring in situ compressional (p) and/or shear (s) wave velocities by recording transit times from a source within one borehole to receivers at the same elevation in one or more other boreholes. Sources may be explosive or directional to enhance either P- or S-wave generation.
CROSS SECTION -	A plot of seismic events.
DATUM -	(1) The arbitrary reference level to which measurements are corrected. (2) The surface from which seismic reflection times or depths are counted, corrections having been made for local topographic and/or weathering variations. (3) The reference level for elevation measurements, often sea level.
DELAY TIME -	(1) In refraction work, the additional time required for a wave to follow a trajectory to and along a buried marker over that which would have been required to follow the same marker considered hypothetically to be at the ground surface or at a reference level. Normally, delay time exists separately under a source and under a detector; and is dependent upon the depth of the marker at wave incidence and emergence points. Shot delay time plus geophone delay time equals intercept time (See Dobrin, 1988 p. 472). (2) Delay produced by a filter.
DIELECTRIC CONSTANT -	A measure of the capacity of a material to store charge when an electric field is applied. It is the dimensionless ratio of the capacitivity (or permittivity, the ratio of the electrical displacement to the electric field strength) of the material to that of free space.
DIFFRACTION -	(1) Scattered energy which emanates from an abrupt irregularity of rock type, particularly common where faults cut reflecting interfaces. The diffracted energy shows greater curvature than a reflection (except in certain cases where there are buried foci), although not necessarily as much as the curve of maximum convexity. It frequently blends with a reflection and obscures the fault location or becomes confused with dip. (2) Interference produced by scattering at edges. (3) The phenomenon by which energy is transmitted laterally along a wave crest. When a portion of a wave train is interrupted by a barrier, diffraction allows waves to propagate into the region of the barrier's geometric shadow.

DIGITAL -	Representation of quantities in discrete units. A digital system is one in which the information is contained and manipulated as a series of discrete numbers as opposed to an analog system, in which the information is represented by a continuous flow of the quantity constituting the signal.
DOWN-HOLE METHOD -	Technique for measurement of in situ compressional and shear wave velocities utilizing a seismic source at ground surface and a clamped triaxial geophone at depth in a borehole. Shear wave energy is often enhanced by use of directional sources such as striking the ends of a weighted plank.
END LINE -	Shotpoints that are shot near the end of the spread.
FIRST BREAK -	The first recorded signal attributable to seismic wave travel from a known source. First breaks on reflection records are used for information about the weathering. Refraction work is based principally on the first breaks, although secondary (later) refraction arrivals are also used. Also first arrival.
FOLD -	The multiplicity of common-midpoint data. Where the midpoint is the same for 12 offset distances, e.g., the stack is referred to as "12-fold".
FREQUENCY DOMAIN -	A representation in which frequency is the independent variable; the Fourier transform variable when transforming from time.
GAIN -	An increase (or change) in signal amplitude (or power) from one point in a circuit or system to another, often from system input to output.
GALVANOMETER -	A part of a seismic camera consisting of a coil suspended in a constant magnetic field. The coil rotates through an angle proportional to the electrical current flowing through the coil. A small mirror on the coil reflects a light beam, which exhibits a visual record of the galvanometer rotation.
GEOPHONE -	The instrument used to convert seismic energy into electrical voltage. Same as seismometer.
GEOPHONE STATION -	Point of location of a geophone on a spread, expressed in engineering notation as 1+75 taken from 0+00 at the beginning of the line.

GROUP VELOCITY -	The velocity with which most of the energy in a wave train travels. In dispersive media where velocity varies with frequency, the wave train changes shape as it progresses so that individual wave crests appear to travel at a different velocity (the phase velocity) than the overall energy as approximately enclosed by the envelope of the wave train. The velocity of the envelope is the group velocity. Same as dispersion.
HYDROPHONE -	(Pressure detector) A detector which is sensitive to variations in pressure, as opposed to a geophone which is sensitive to particle motion. Used when the detector can be placed below a few feet of water, as in marine or marsh or as a well seismometer. The frequency response of the hydrophone depends on its depth beneath the surface.
IMBRICATE FAULTING -	A series of nearly parallel and overlapping minor thrust faults, high angle reverse faults, or slides, and characterized by rock slices, sheets, plates, blocks, or wedges that are approximately equidistant and have the same displacement and that are all steeply inclined in the same direction (toward the source of stress).
IMPEDANCE -	The apparent resistance to the flow of alternating current, analogous to resistance in a dc circuit. Impedance is (in general) complex, of magnitude Z with a phase angle g. These can be expressed in terms of resistance R (in ohms), inductive reactance $X_L = 2pL$, and capacitive reactance $X_c = 1/2pnC$: $Z = [R^2 + (X_L - X_C)^2]^{1/2,}$ $g = \tan^{-1}[(X_L - X_C)/R].$ Z is in ohms when frequency n is in hertz, L is inductance in henrys, and C is capacitance in farads.
IN-LINE OFFSET -	A spread which is shot from a shotpoint which is separated (offset) from the nearest active point on the spread by an appreciable distance (more than a few hundred feet) along the line of spread.
INPHASE -	Electrical signal with the same phase angle as that of the exciting signal or comparison signal.
LEAD -	An electrical conductor for connecting electrical devices. Geophones are connected to cables at the takeouts via leads on the geophones.

LINE -	A series of profiles shot in line.
LOVE WAVE -	A surface seismic channel wave associated with a surface layer which has rigidity, characterized by horizontal motion perpendicular to the direction of propagation with no vertical motion.
LOW-VELOCITY LAYER -	A near-surface belt of very low-velocity material often abbreviated LVL; also called weathering.
MAGNETIC PERMEABILITY -	The ratio of the magnetic induction B to the inducing field strength H: denoted by the symbol m: $m = B/moH$ mo is the permeability of free space = $4p10^{-7}$ weber/ampere meter or (henrys/meter) in SI system, and 1 gauss/oersted in the cgs system, so that the permeability m is dimensionless. The quantity mmo is sometimes considered the permeability (especially in the cgs system).
MIS-TIE -	(1) The time difference obtained on carrying a reflection, phantom, or some other measured quantity around a loop; or the difference of the values at identical points on intersecting lines or loops. (2) In refraction shooting, the time difference from reversed profiles which gives erroneous depth and dip calculations.
MULTIPLE -	Seismic energy which has been reflected more than once. Same as long-path multiple, short path multiple, peg-leg multiple, and ghost.
MULTIPLEX -	A process which permits transmitting several channels of information over a single channel without crossfeed. Usually different input channels are sampled in sequence at regular intervals and the samples are fed into a single output channel; digital seismic tapes are multiplexed in this way. Multiplexing can also be done by using different carrier frequencies for different information channels and in other ways.
NOISE -	(1) Any undesired signal; a disturbance which does not represent any part of a message from a specified source. (2) Sometimes restricted to energy which is random. (3) Seismic energy which is not resolvable as reflections. In this sense noise includes microseisms, shot-generated noise, tape-modulation noise, harmonic distortions, etc. Sometimes

	divided into coherent noise (including non-reflection coherent events) and random noise (including wind noise, instrument noise, and all other energy which is non-coherent). To the extent that noise is random, it can be attenuated by a factor of n by compositing n signals from independent measurements. (4) Sometimes restricted to seismic energy not derived from the shot explosion. (5) Disturbances in observed data due to more or less random inhomogeneities in surface and near surface material.
NOISE SURVEY -	A mapping of ambient, continuous seismic noise levels within a given frequency band. As some geothermal reservoirs are a source of short-period seismic energy, this technique is a useful tool for detecting such reservoirs. Also called ground noise survey.
OBSERVER -	The geophysicist in charge of recording and overall field operations on a seismic crew.
ON-LINE -	Shotpoints that are shot at any point on a spread other than at the ends of the spread.
OSCILLOGRAPH -	An instrument that renders visible a curve representing the time variations of electric phenomena.
OSCILLOSCOPE -	A type of oscillograph that visually displays an electrical wave on the screen of a cathode ray tube type.
PERMITTIVITY -	Capacitivity (q.v.) of a three-dimensional material, such as a dielectric. Relative permittivity is the dimensionless ratio of the permittivity of a material to that of free space; it is also called the dielectric constant.
PHASE VELOCITY -	The velocity with which any given phase (such as a trough or a wave of single frequency) travels; may differ from group velocity because of dispersion.
PLANT -	The manner in which a geophone is placed on or in the earth; the coupling to the ground.
PROFILE -	The series of measurements made from several shotpoints into a recording spread from which a seismic data cross section or profile can be constructed.
PROFILING -	A geophysical survey in which the measuring system is moved about an area (often along a line) with the objective of determining how

	measurements vary with location. Specifically, a resistivity, IP, or electromagnetic field method wherein a fixed electrode or antenna array is moved progressively along a traverse to create a horizontal profile of the apparent resistivity.
RADAR -	A system in which short electromagnetic waves are transmitted and the energy scattered back by reflecting objects is detected. Acronym for "radio detection and ranging." Ships use radar to help "see" other ships, buoys, shorelines, etc. Beacons sometimes provide distinctive targets. Radar is used in aircraft navigation (see Doppler-radar), in positioning, and in remote sensing.
RADIO FREQUENCY -	A frequency above 3kHz. Radio frequencies are subdivided into bands.
RAYLEIGH WAVE -	A seismic wave propagated along the free surface of a semi-infinite medium. The particle motion near the surface is elliptical and retrograde, in the vertical plane containing the direction of propagation.
RAYPATH -	A line everywhere perpendicular to wavefronts (in isotropic media). The path which a seismic wave takes.
REFLECTION SURVEY -	A survey of geologic structure using measurements made of arrival time of events attributed to seismic waves which have been reflected from interfaces where the acoustic impedance changes.
RESOLUTION -	The ability to separate two features which are very close together.
SEISMIC AMPLIFIER -	An electronic device used to increase the electrical amplitude of a seismic signal. (See geophone)
SEISMIC CAMERA -	A recording oscillograph used to produce a visible pattern of electrical signals to make a seismic record.
SEISMIC VELOCITY -	The rate of propagation of a seismic wave through a medium.
SEISMOGRAM -	A seismic record.

SHEAR WAVE -	A body wave in which the particle motion is perpendicular to the direction of propagation. (Same as S-wave, equivoluminal, transverse wave).
SHOOTER -	The qualified, licensed individual (powderman) in charge of all shotpoint operations and explosives handling on a seismic crew.
SHOT DEPTH -	The distance down the hole from the surface to the explosive charge, often measured with loading poles. With small charges the shot depth is measured to the center or bottom of the charge, but with large charges the distances to both the top and bottom of the column of explosives are usually given.
SHOT INSTANT -	(Time Break [TB], Zero Time) - The time at which a shot is detonated.
SHOTPOINT -	Point of location of the energy source used in generating a particular seismogram. Expressed either sequentially for a line (i.e. SP 3) or in engineering notation (i.e. SP 3+00).
SIGNAL ENHANCEMENT -	A hardware development utilized in seismographs and resistivity systems to improve signal-to-noise ratio by real-time adding (stacking) successive waveforms from the same source point and thereby discriminating against random noise.
SIGNAL-TO-NOISE RATIO SOUNDING-	The energy (or sometimes amplitude) divided by all remaining energy (noise) at the time; abbreviated S/N.
SOLE FAULT -	A low-angle thrust fault forming the base of a thrust sheet; also, the basal main fault of an imbrication.
SOUNDING -	Measuring a property as a function of depth; a depth probe or expander. Especially a series of electrical resistivity readings made with successively greater electrode spacing while maintaining one point in the array fixed, thus giving resistivity-versus-depth information (assuming horizontal layering); electric drilling, probing, VES (vertical electric sounding).
SPREAD -	The layout of geophone groups from which data from a single shot are recorded simultaneously.
STONELEY	

WAVE -	A type of seismic wave propagated along an interface.
SURFACE WAVE -	Energy which travels along or near the surface (ground roll).
SYNTHETIC SEISMOGRAM -	An Artificial seismic record manufactured from velocity log data used to compare with and actual seismogram to aid in identify events or in predicting how stratigraphic variations might affect seismic record. Often constructed from sonic log data alone although density data may also be incorporated.
TAKEOUT -	A connection point to a multiconductor cable where geophones can be connected.
THRUST FAULT -	A fault with a dip of 45 degrees or less over much of its extent, on which the hanging wall appears to have moved upward relative to the footwall. Horizontal compression rather than vertical displacement is its characteristic feature.
TIME BREAK (TB)-	The mark on a seismic record which indicates the shot instant or the time at which the seismic wave was generated.
TIME DOMAIN -	1. Expression of a variable as a function of time, as opposed to its expression as a function of frequency (frequency domain). Processing can be done using time as the variable, i.e., "in the time domain". For example, convolving involves taking values at successive time intervals, multiplying by appropriate constants, and recombining; this is equivalent to filtering through frequency-selective circuitry. It is also equivalent to Fourier transforming, multiplying the amplitude spectra, and adding the phase spectra ("in the frequency domain"), and then inverse-Fourier transforming. 2. Time-domain induced polarization is called the pulse method (q.v.)
TOMOGRAPHY -	The reconstruction of an object from a set of its projections. Tomographic techniques are utilized in medical physics as well as in cross-borehole electromagnetic and seismic transmission surveys.
TRACE -	A record of one seismic channel. This channel may contain one or more geophones. A trace is made by a galvanometer.

UPHOLE METHOD-	Also called the Meissner technique, a method of reconstructing wave front diagrams by shooting at several depths and recording on a full surface spread of geophones. Derived wavefront diagrams yield a true picture of wavepaths and, therefore, layering in the subsurface.
WAVE TRAIN -	(1) The sum of a series of propagating wave fronts emanating from a single source. (2) The complex wave form observed in a seismogram obtained from an explosive source.

REFFERENCE

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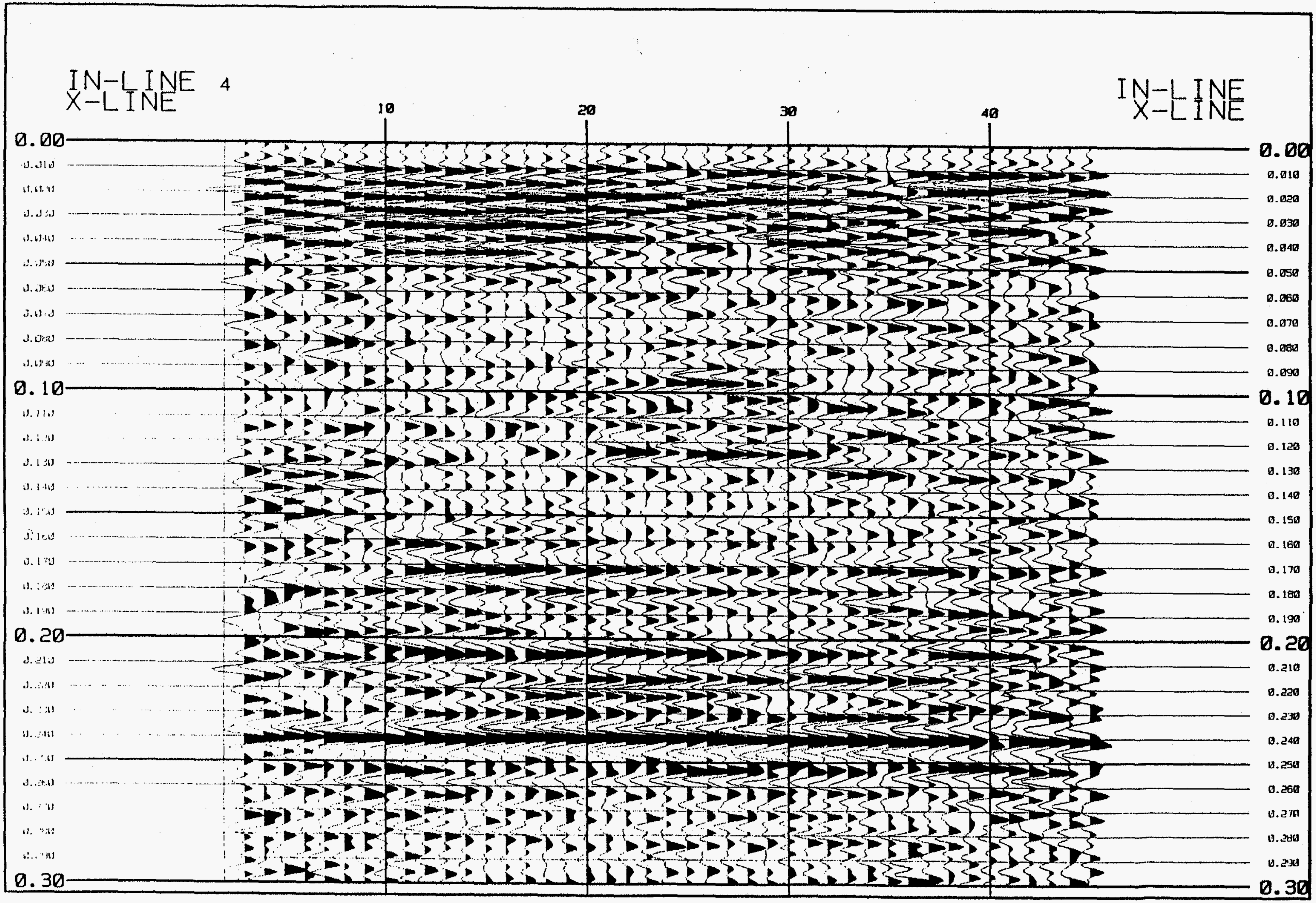
Sheriff, Robert E. (Compiler). 1984. Encyclopedic Dictionary of Exploration Geophysics. Society of Exploration Geophysicists, Tulsa, OK, 323 pp.

Telford, W.M., L.P. Geldart, R.E. Sheriff, and D.A. Keys. 1976. Applied Geophysics, Cambridge University Press.

Appendix IV
In-line and Cross-line Seismic Profiles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10
20
30
40
IN-LINE
X-LINE
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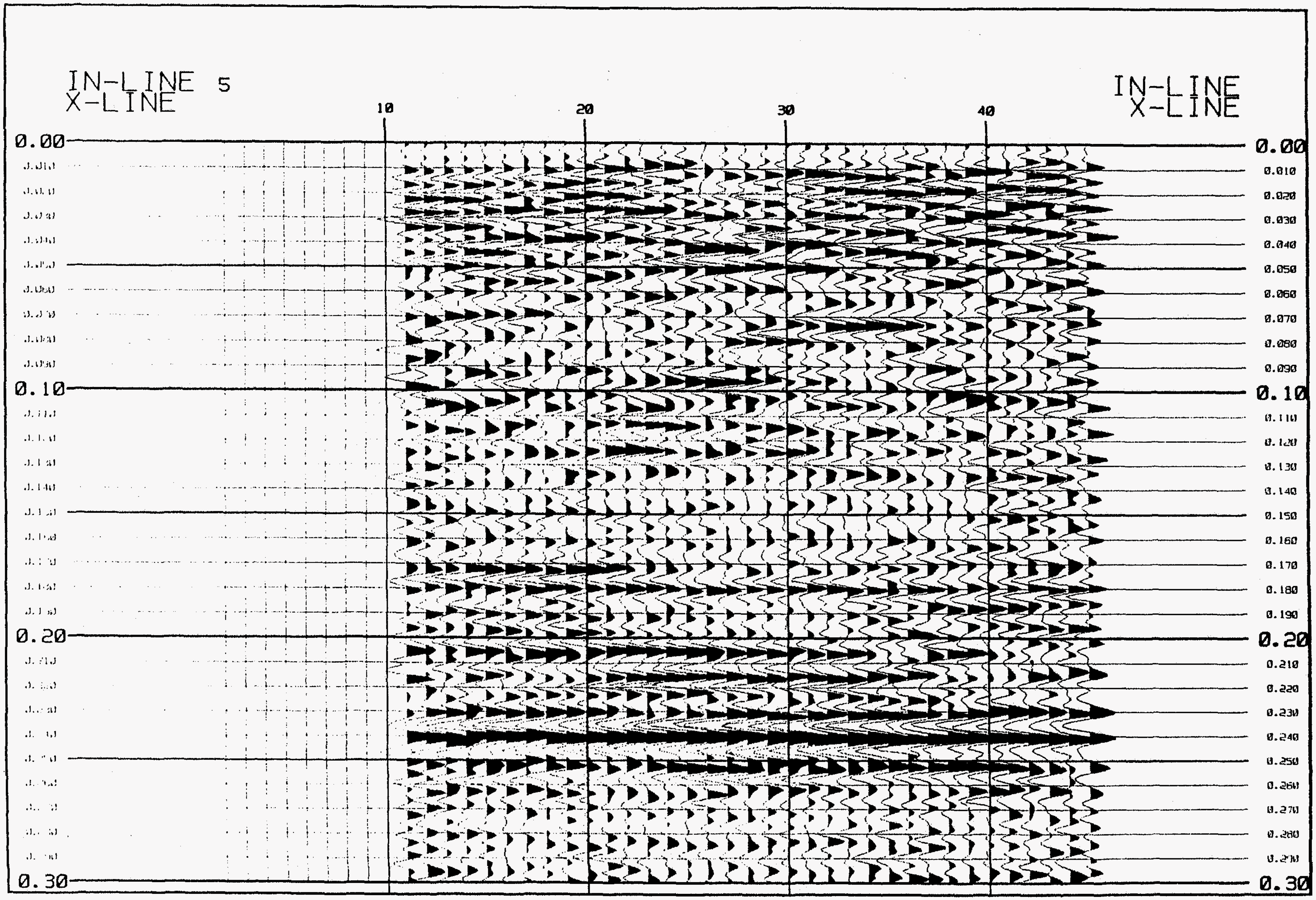
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080
0.090
0.10
0.110
0.120
0.130
0.140
0.150
0.160
0.170
0.180
0.190
0.20
0.210
0.220
0.230
0.240
0.250
0.260
0.270
0.280
0.290
0.30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IN-LINE
X-LINE
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40
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0.010
0.020
0.030
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0.050
0.060
0.070
0.080
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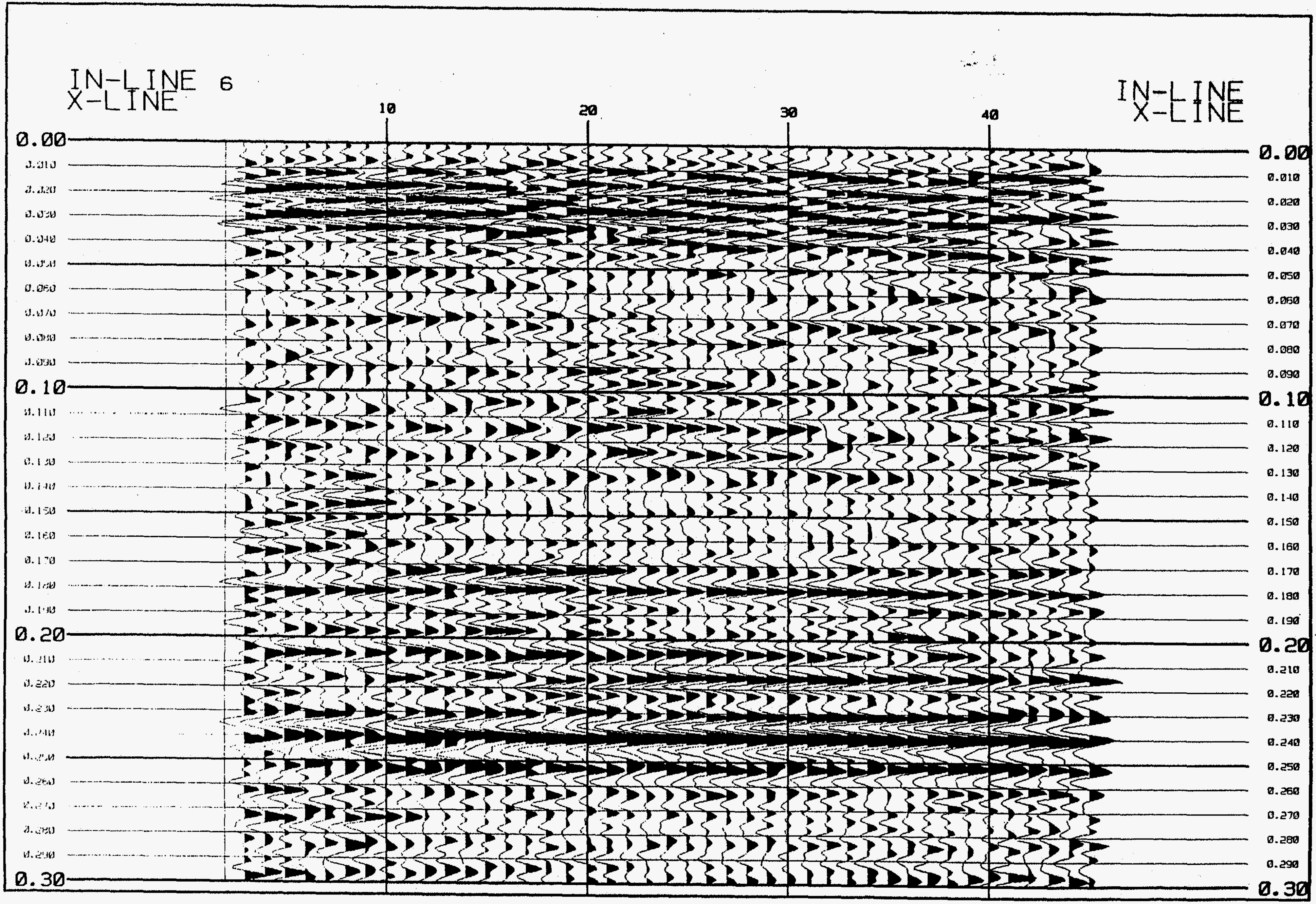
0.10
0.110
0.120
0.130
0.140
0.150
0.160
0.170
0.180
0.190
0.20
0.210
0.220
0.230
0.240
0.250
0.260
0.270
0.280
0.290
0.30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X-LINE
IN-LINE
X-LINE
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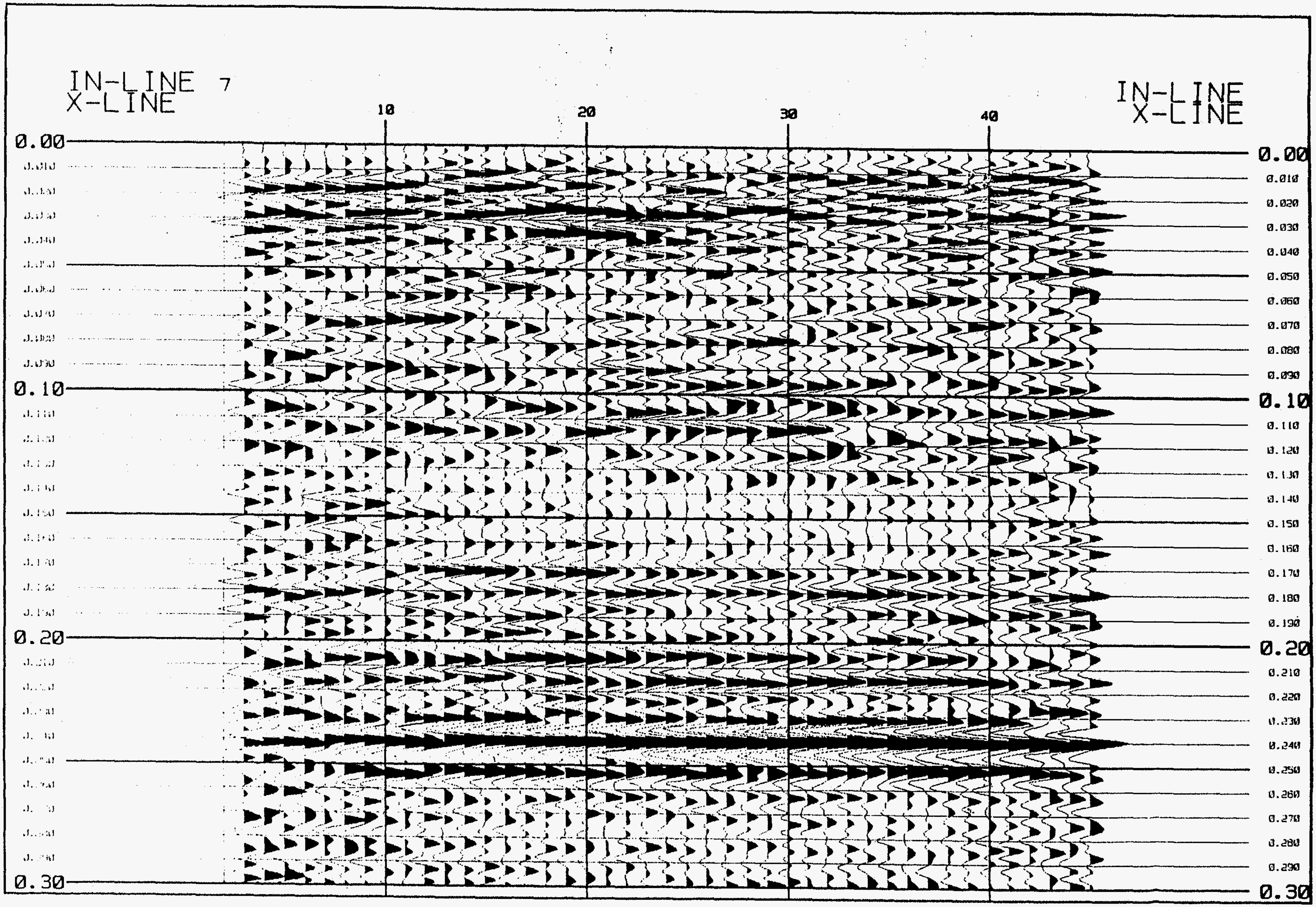
20
30
40
0.00
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080
0.090
0.10
0.110
0.120
0.130
0.140
0.150
0.160
0.170
0.180
0.190
0.20
0.210
0.220
0.230
0.240
0.250
0.260
0.270
0.280
0.290
0.30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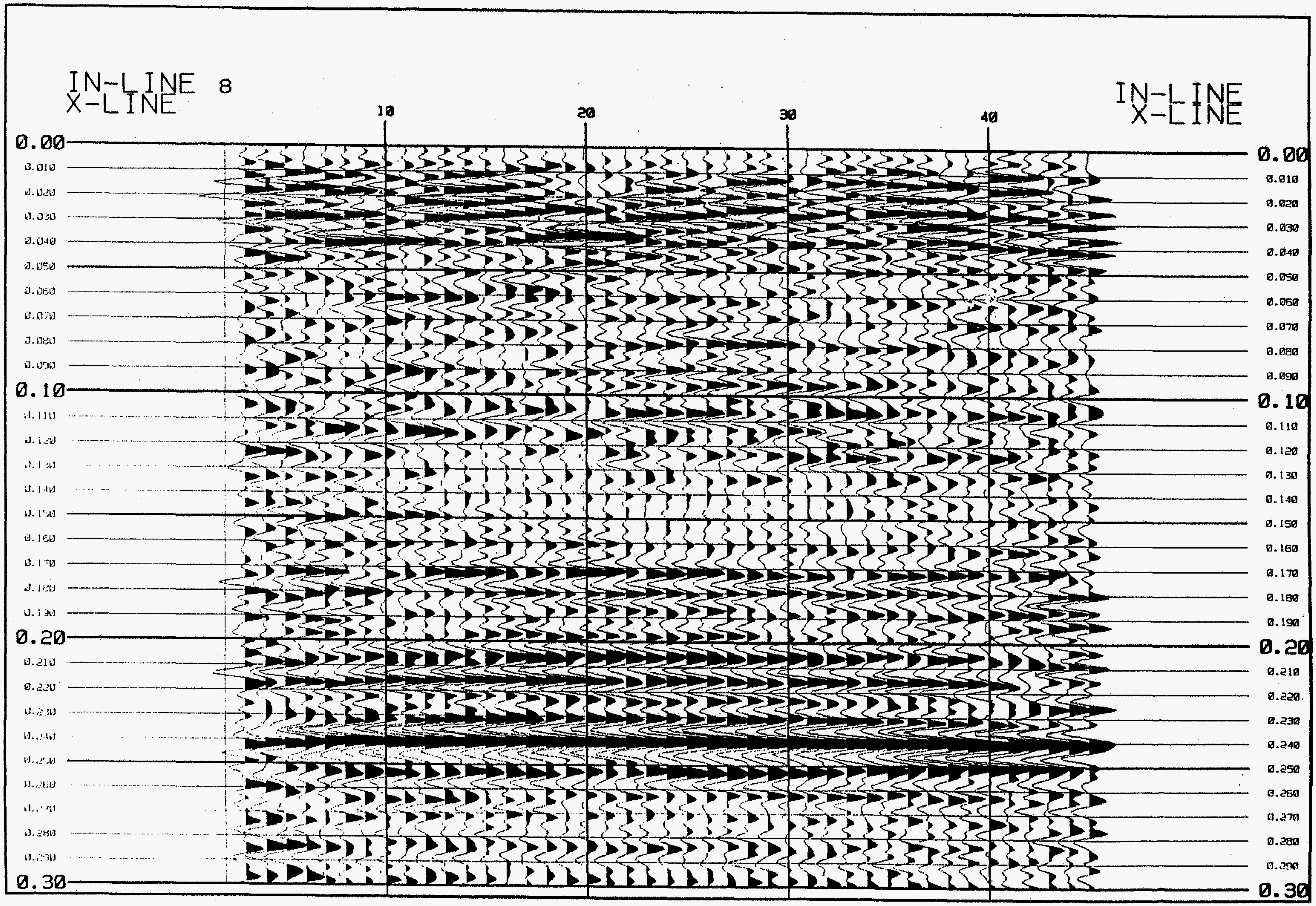
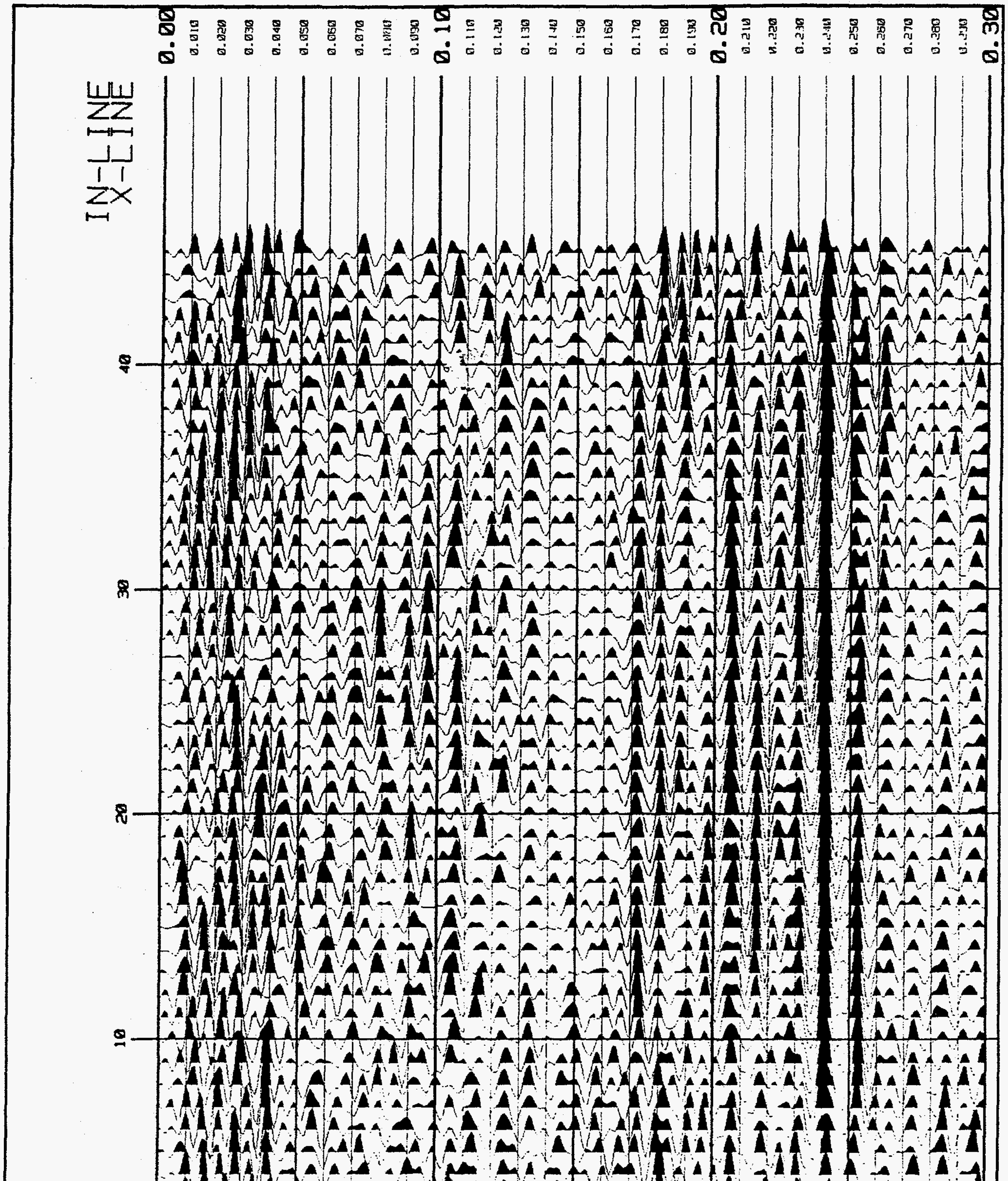
X-LINE
IN-LINE
X-LINE
10
20
30
40
0.00
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080
0.090
0.10
0.110
0.120
0.130
0.140
0.150
0.160
0.170
0.180
0.190
0.20
0.210
0.220
0.230
0.240
0.250
0.260
0.270
0.280
0.290
0.30


IN-LINE 8
X-LINE
IN-LINE
X-LINE
10
20
30
40
0.00
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080
0.090
0.10
0.110
0.120
0.130
0.140
0.150
0.160
0.170
0.180
0.190
0.20
0.210
0.220
0.230
0.240
0.250
0.260
0.270
0.280
0.290
0.30



IN-LINE 9
X-LINE
IN-LINE
X-LINE
0.00
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080
0.090
0.10
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0.270
0.280
0.290
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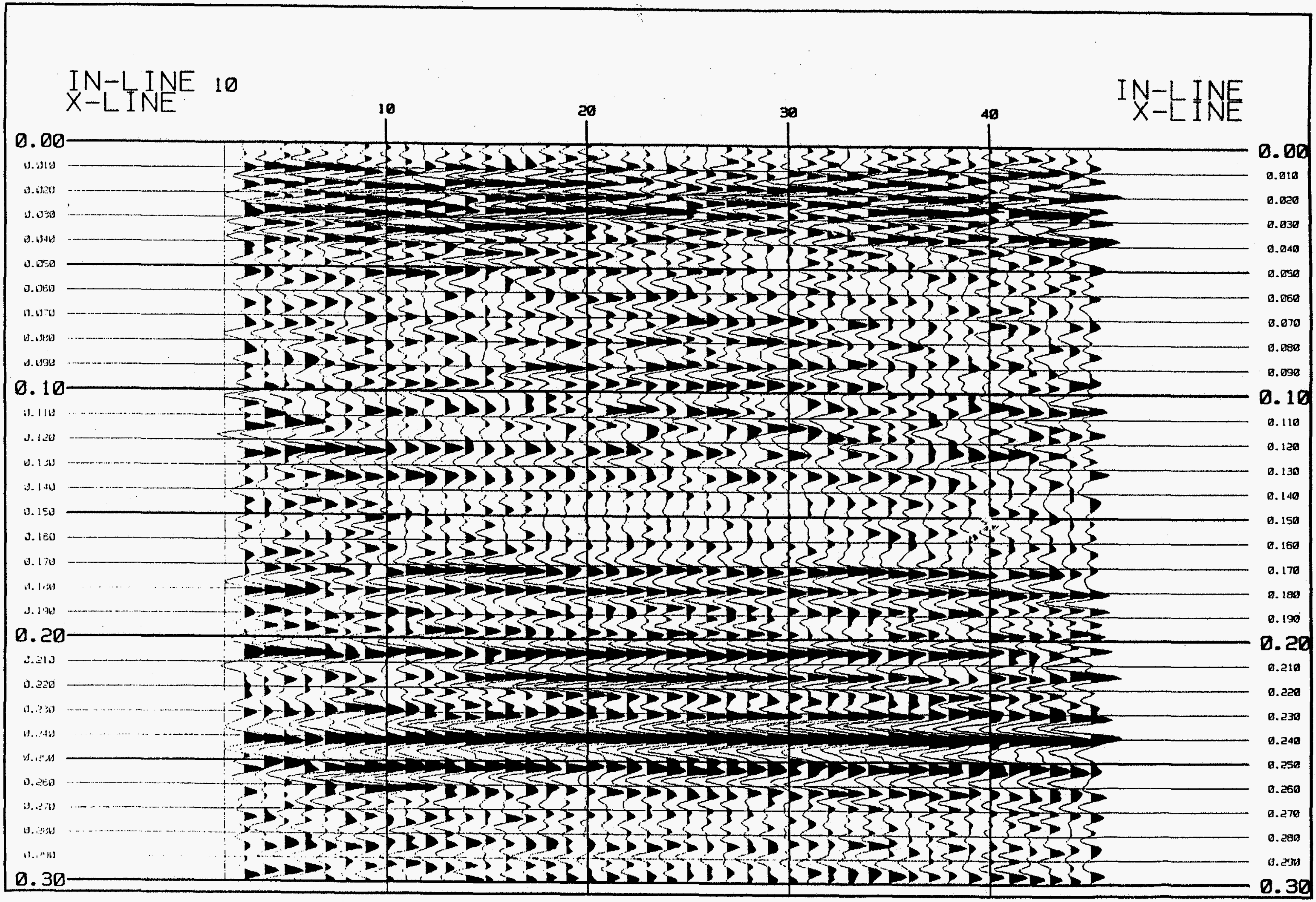
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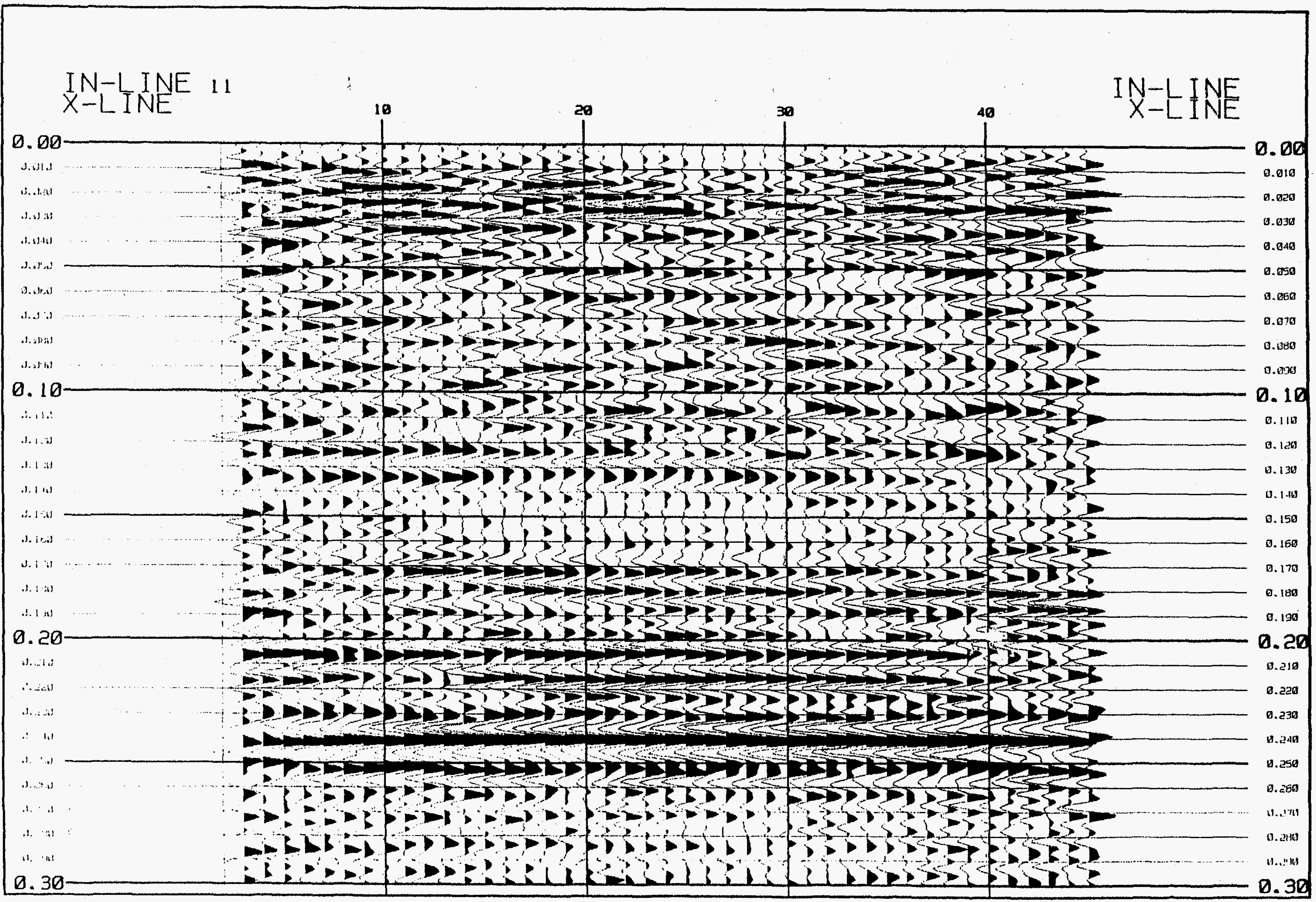
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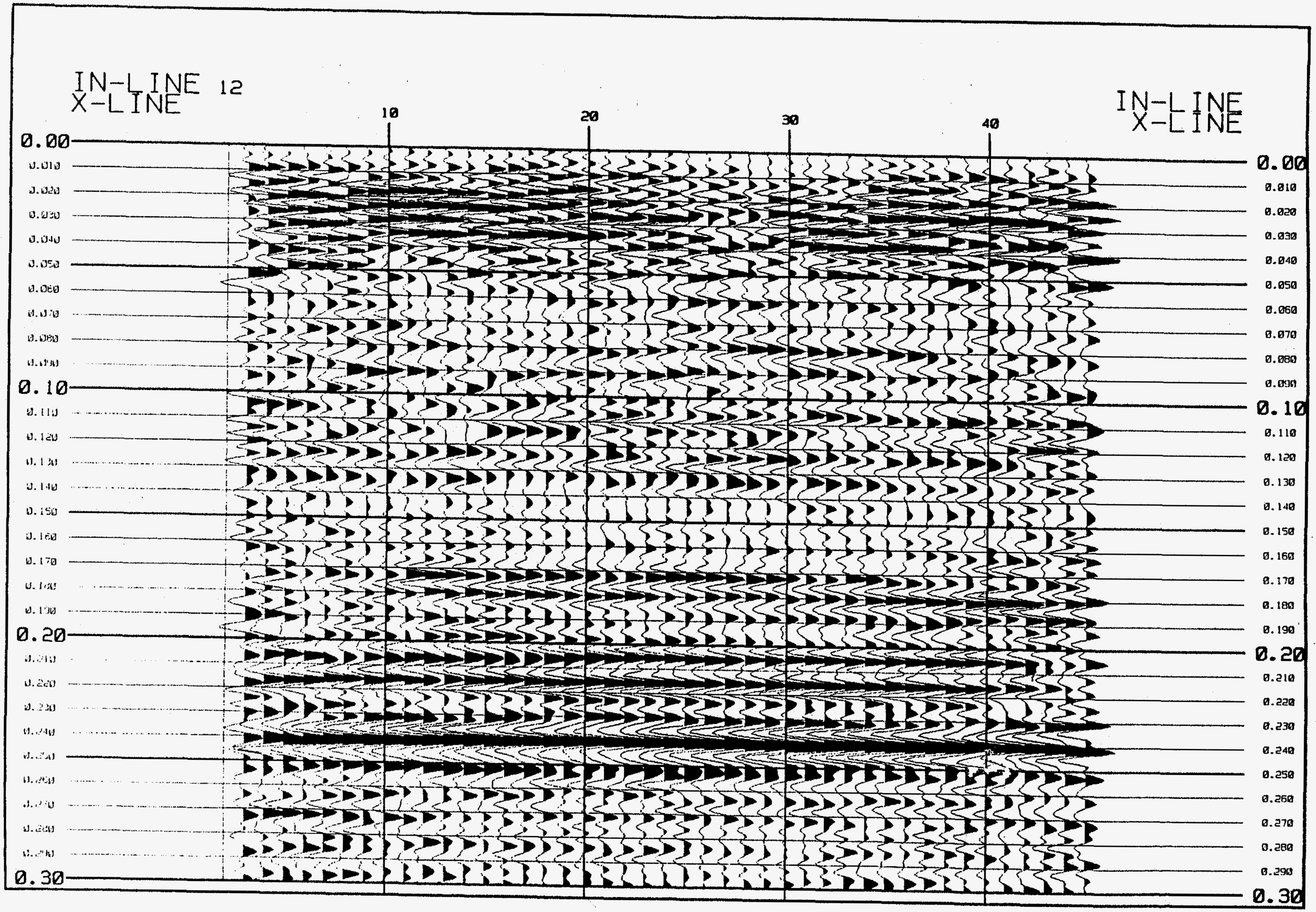
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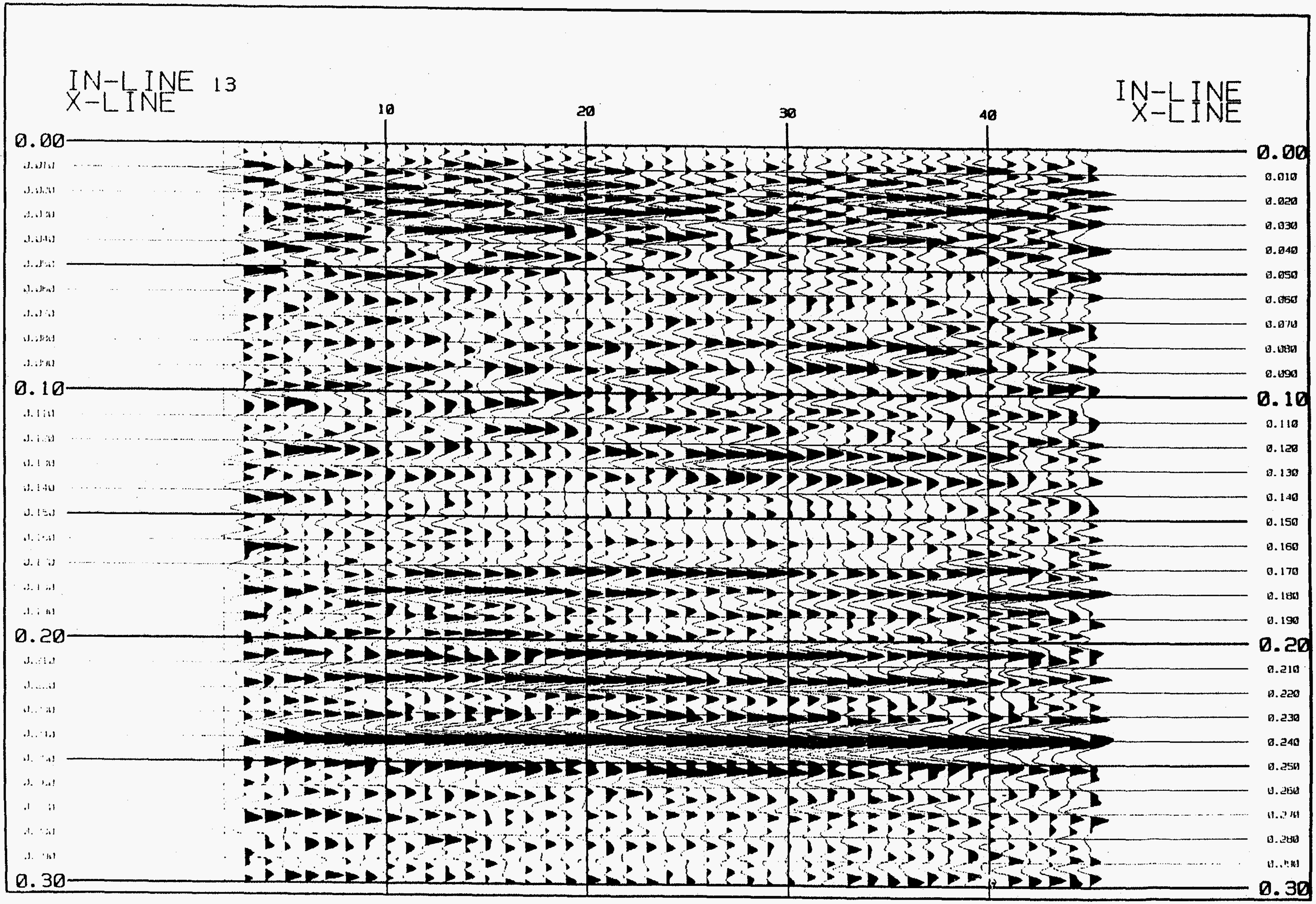
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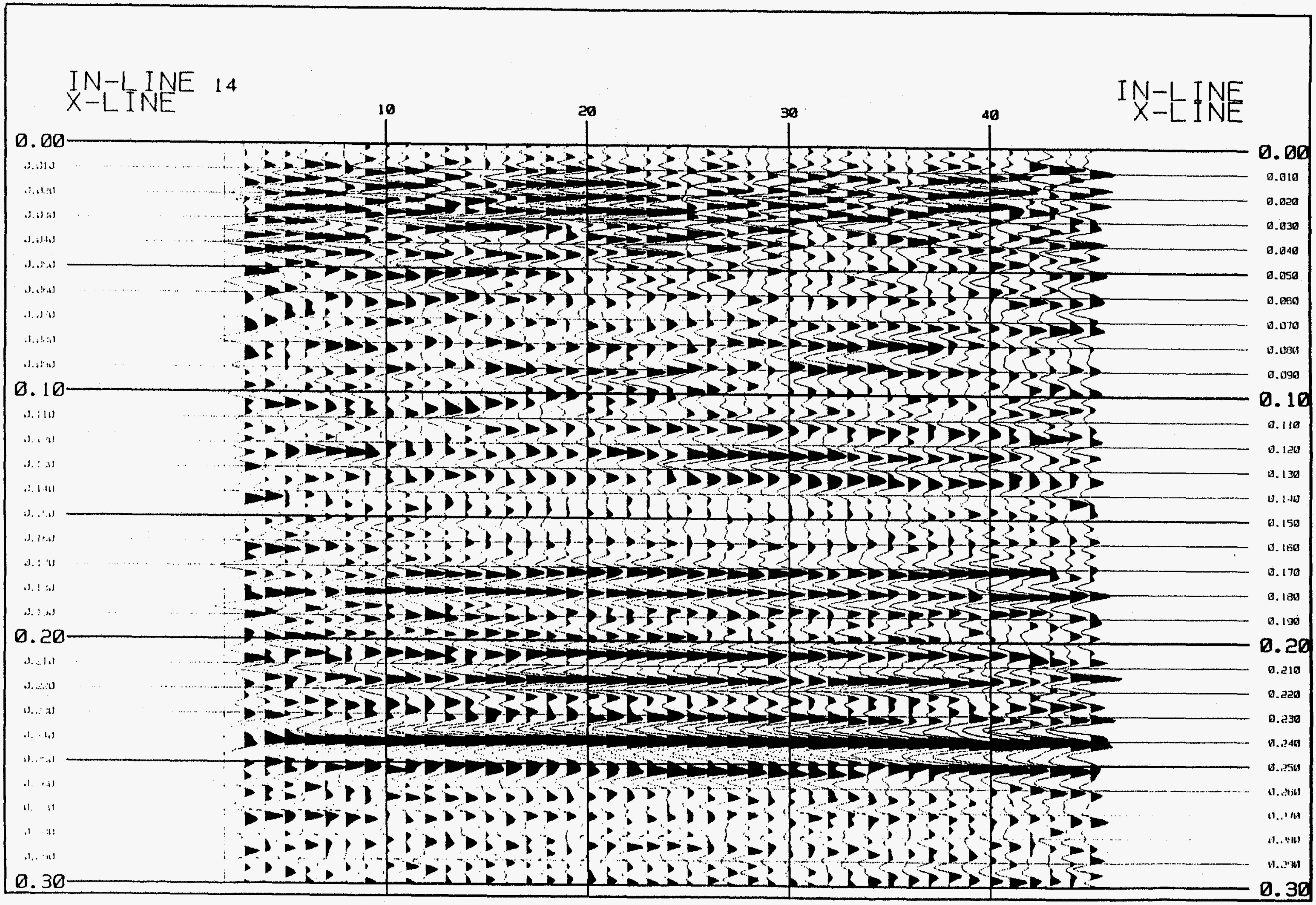
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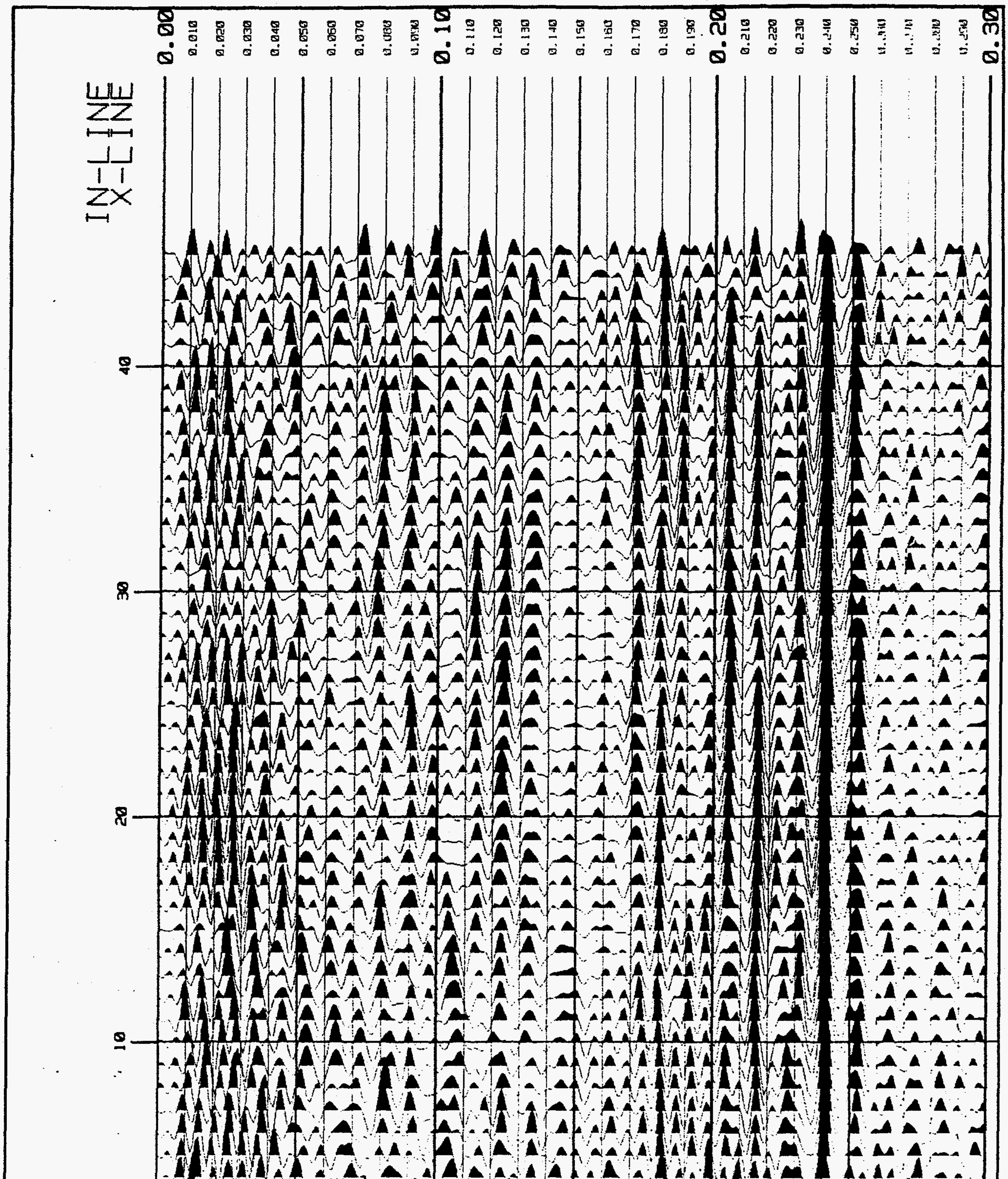
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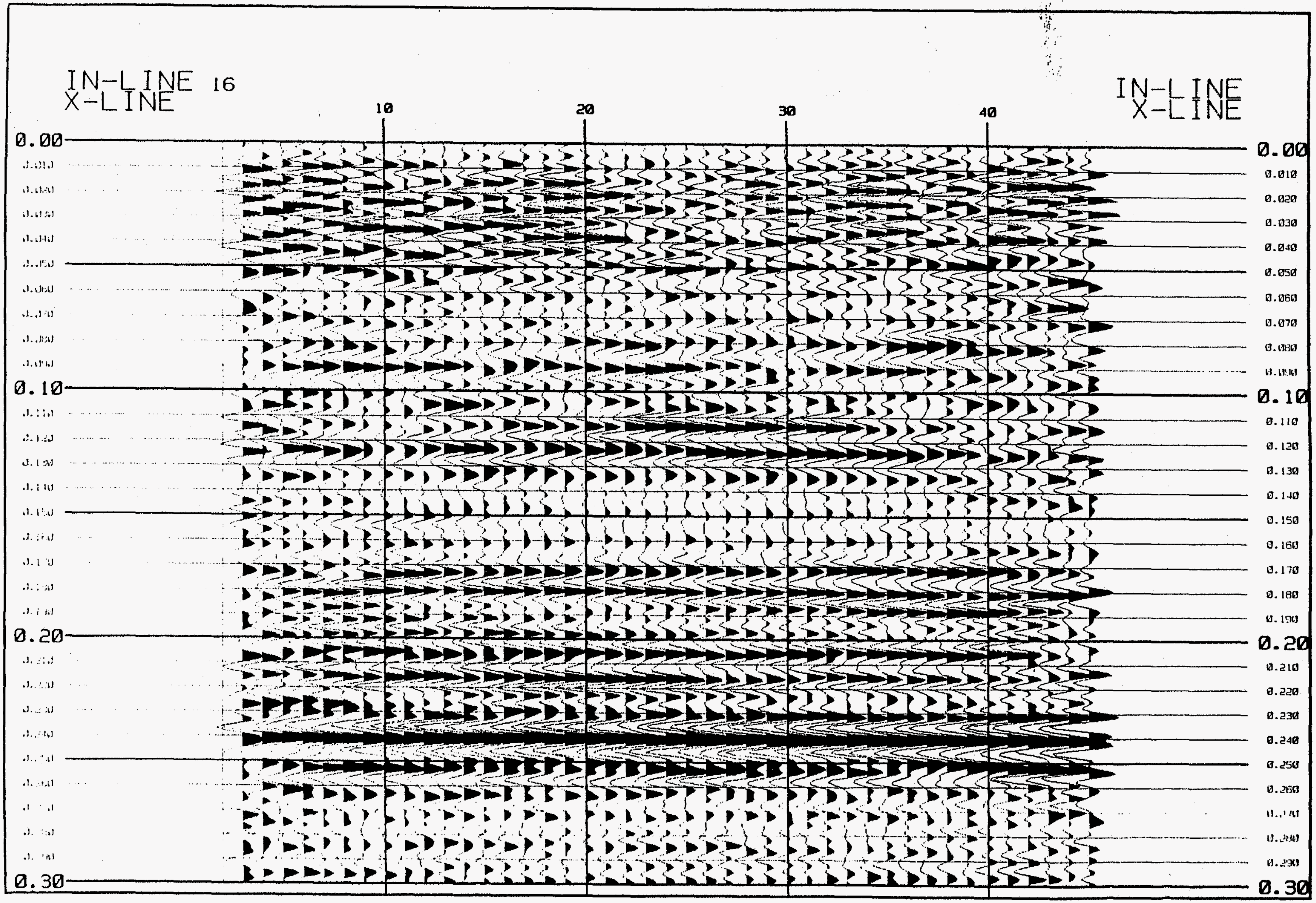
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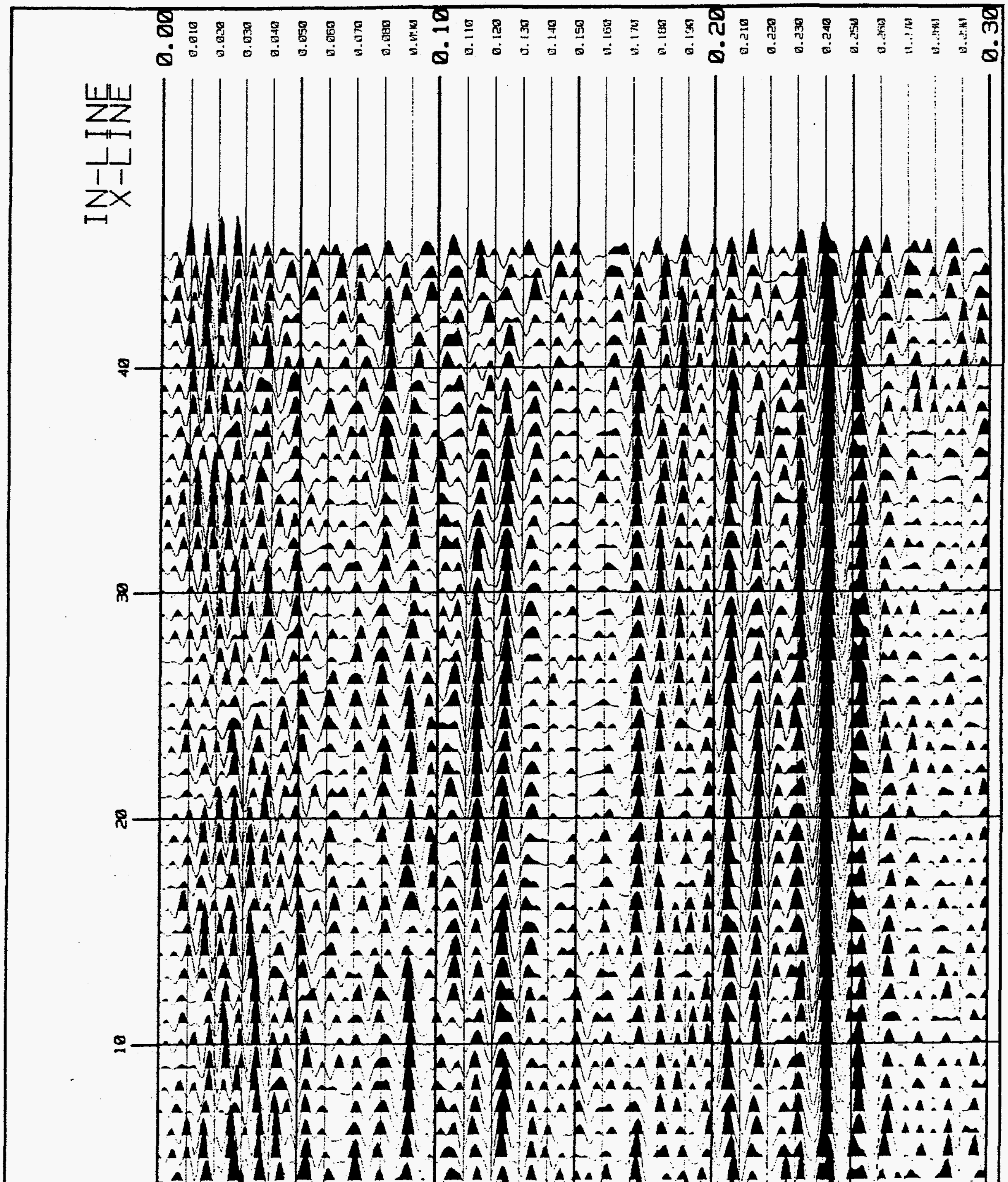
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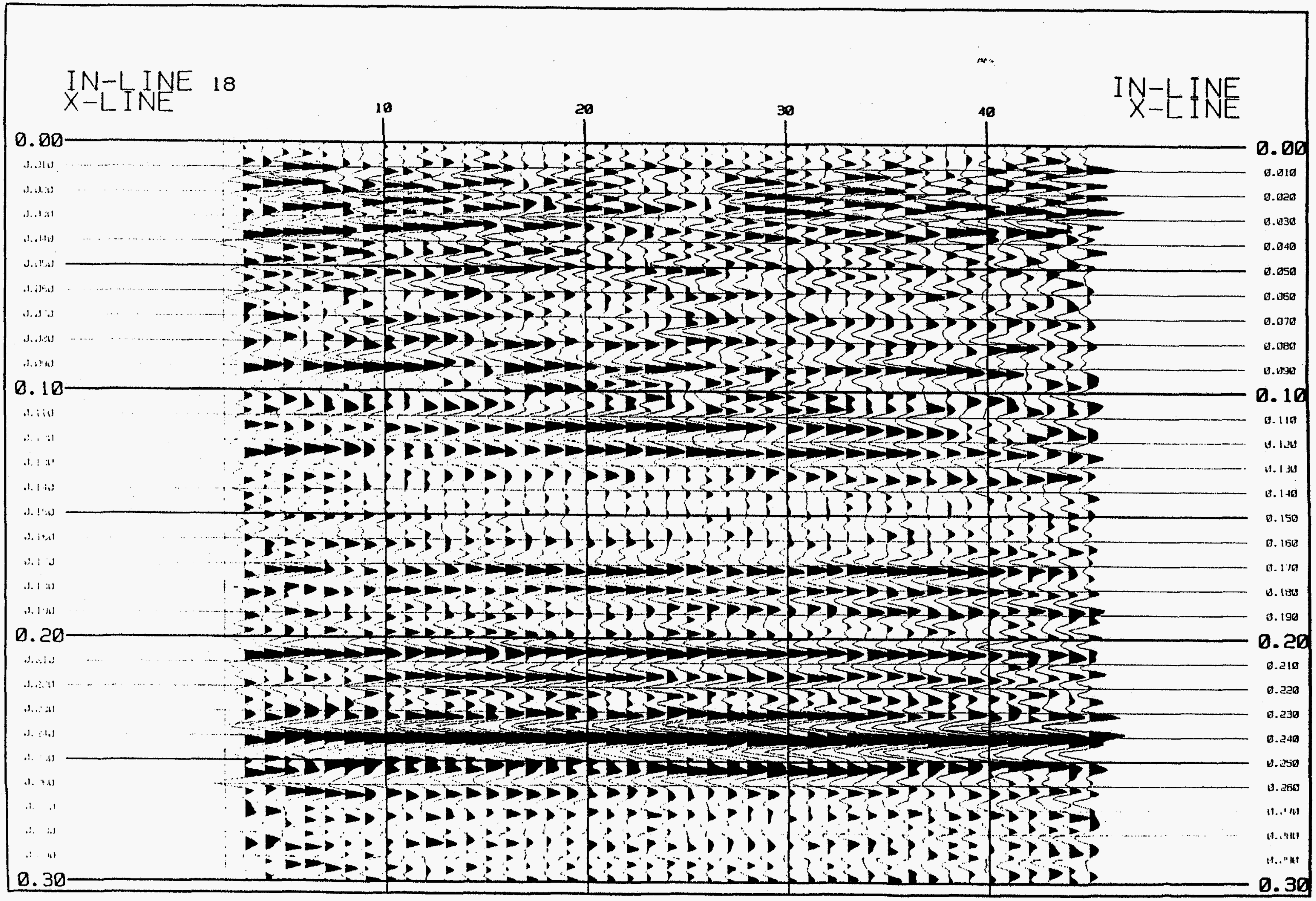
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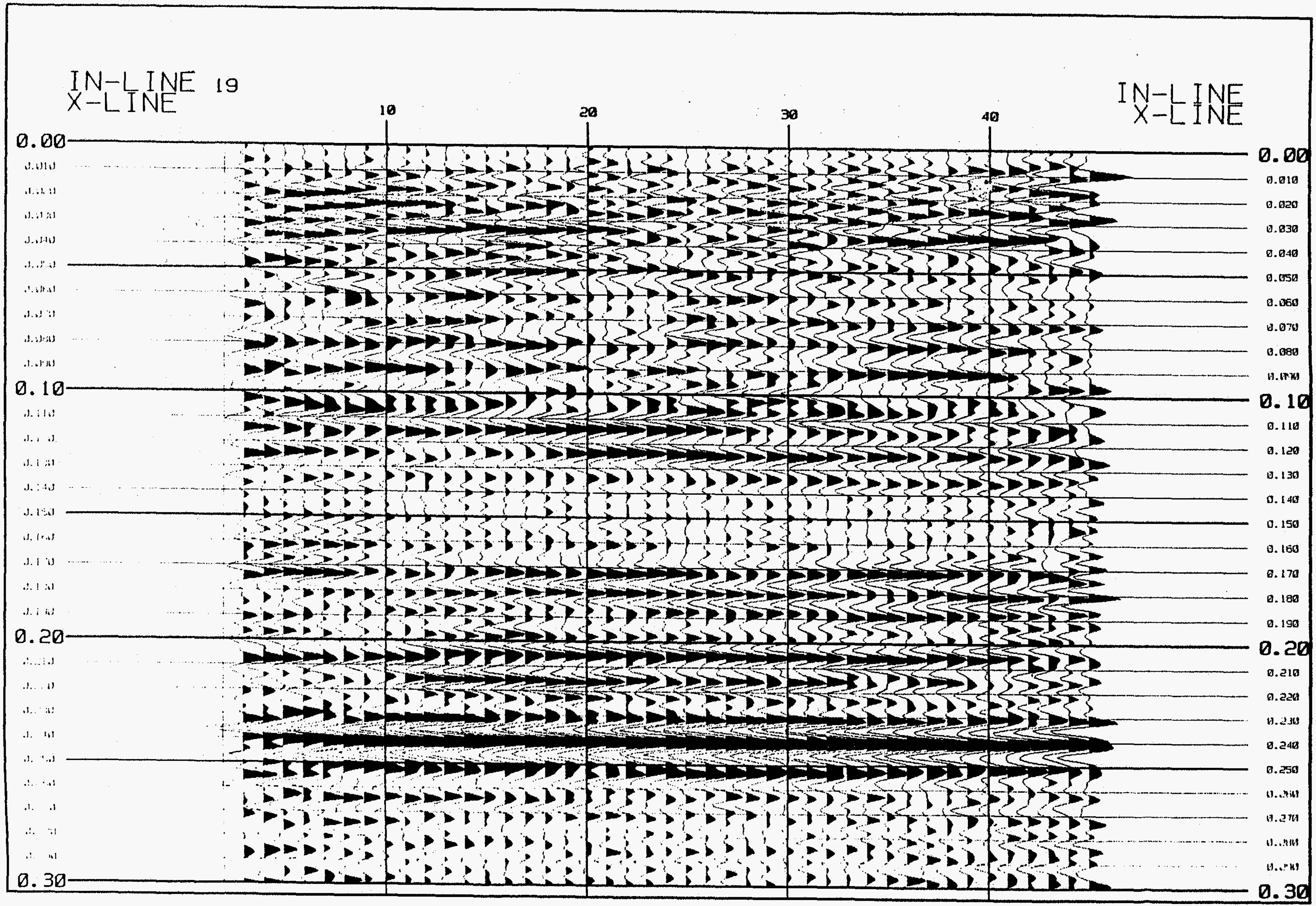

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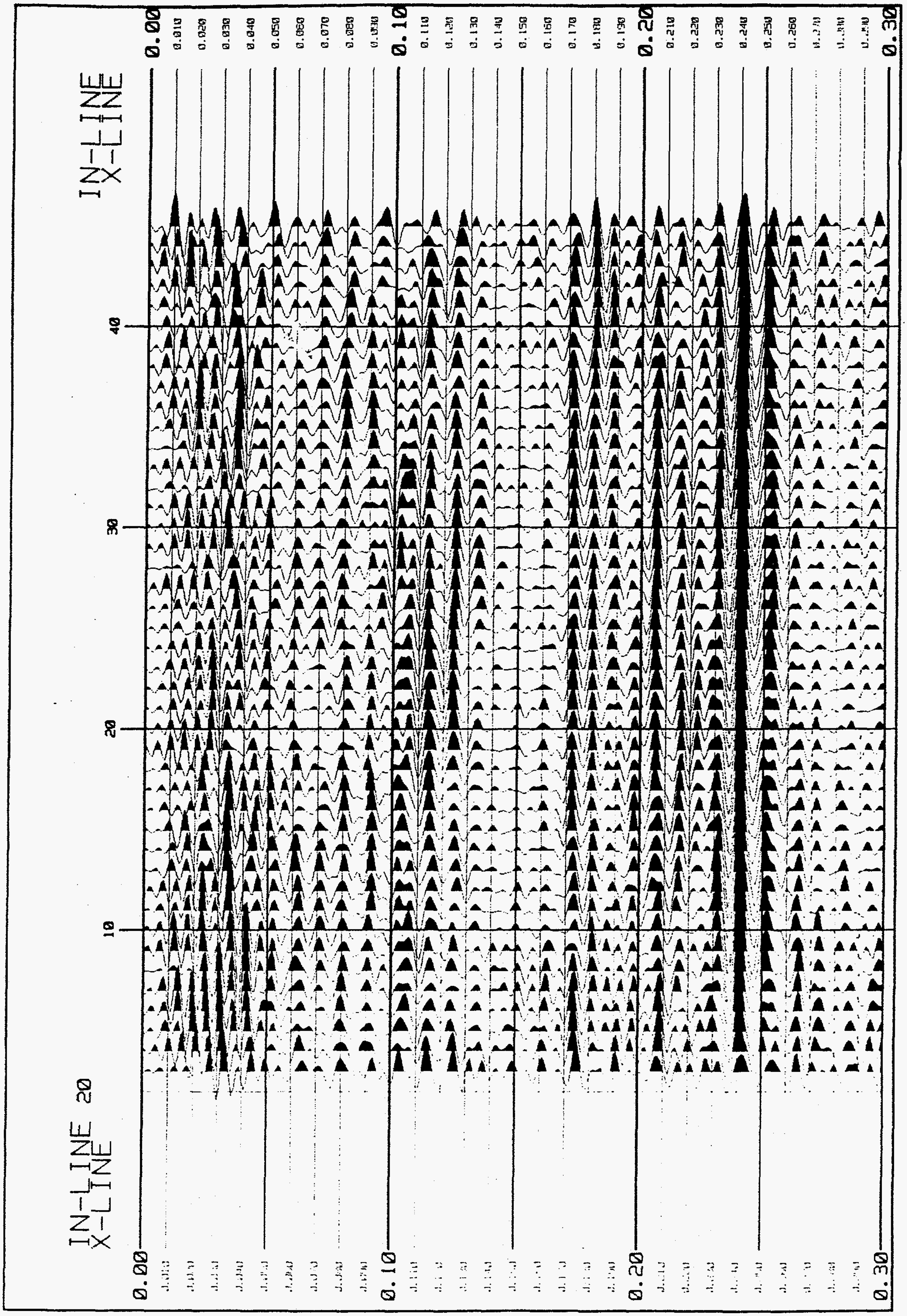

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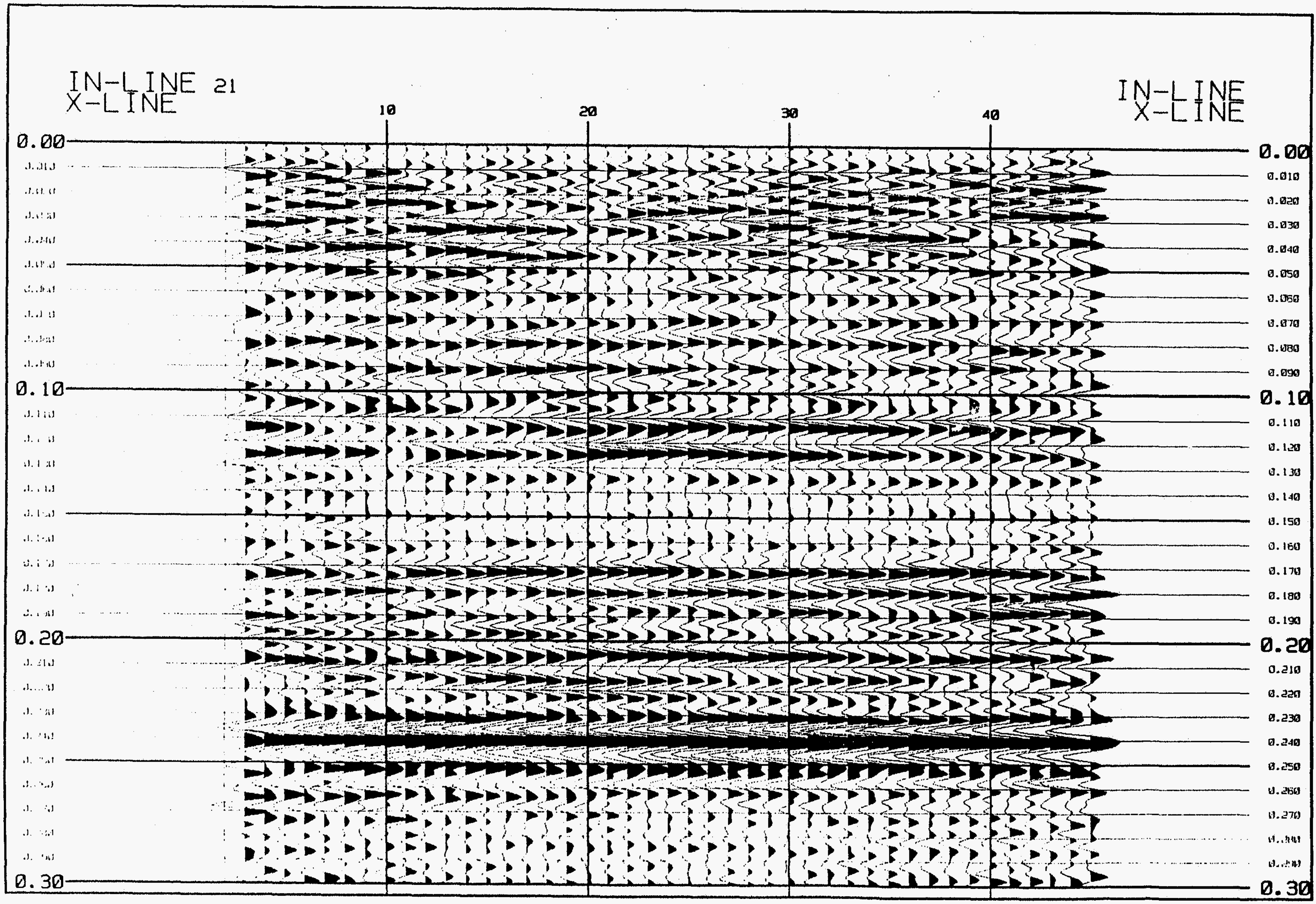
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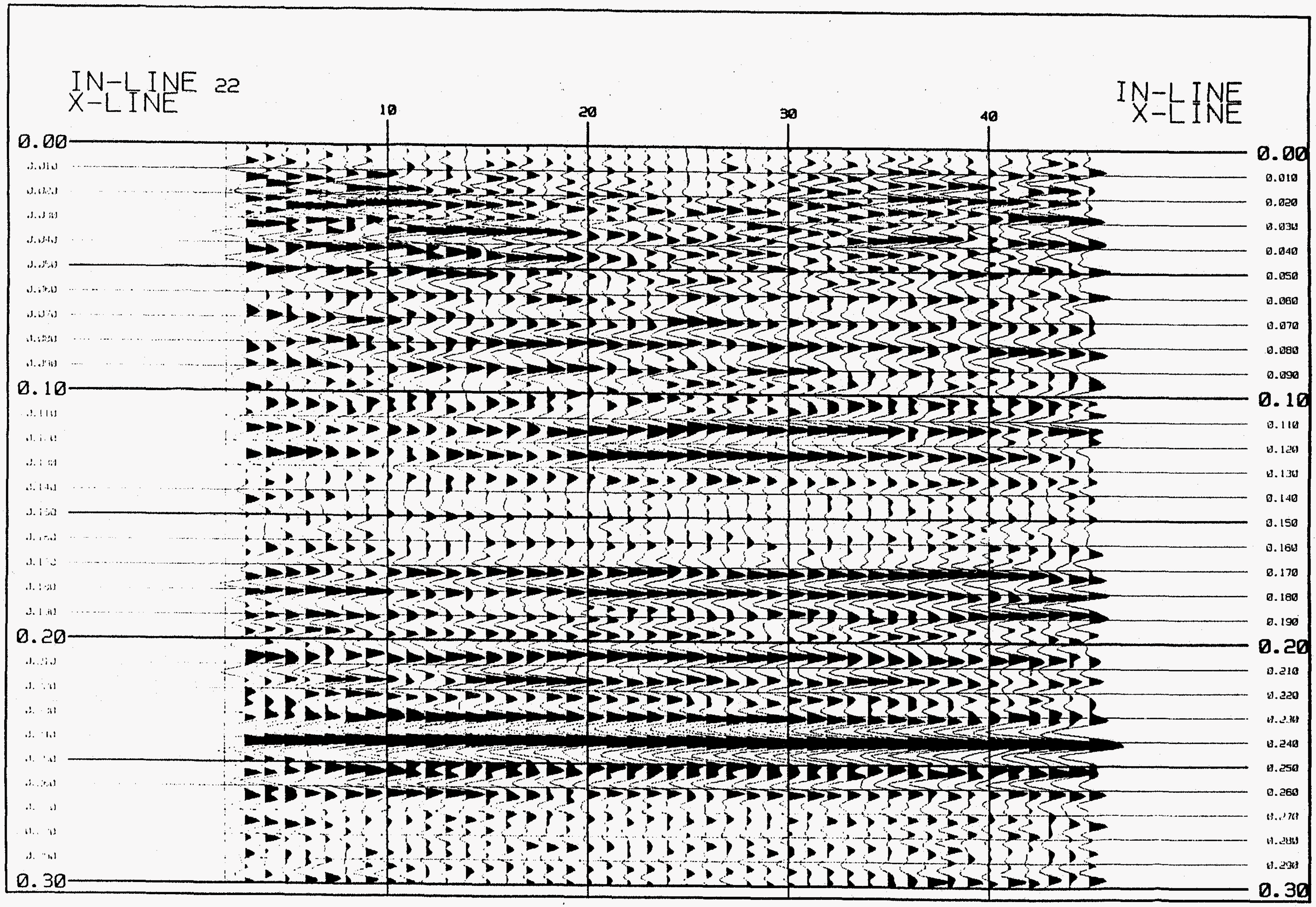
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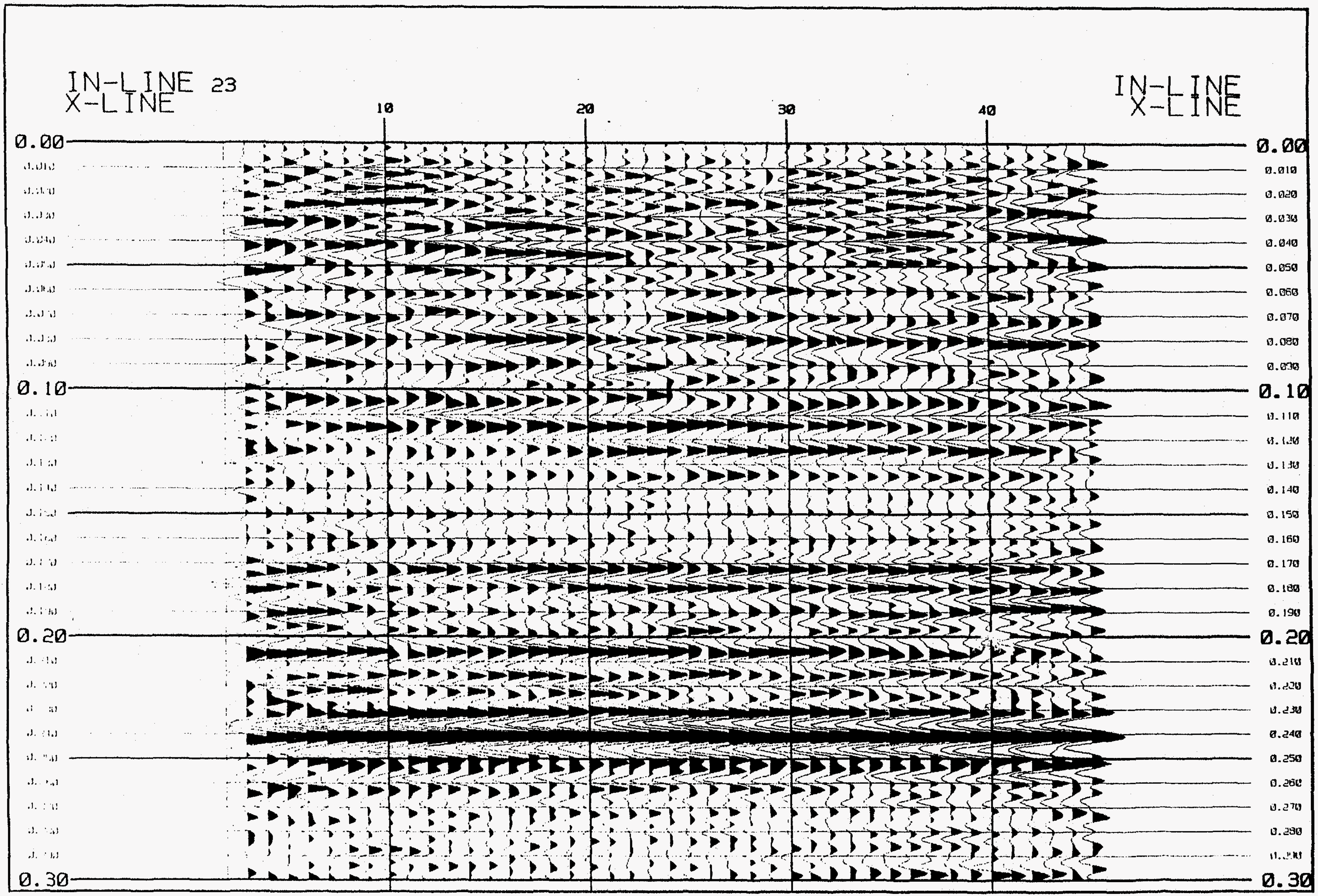

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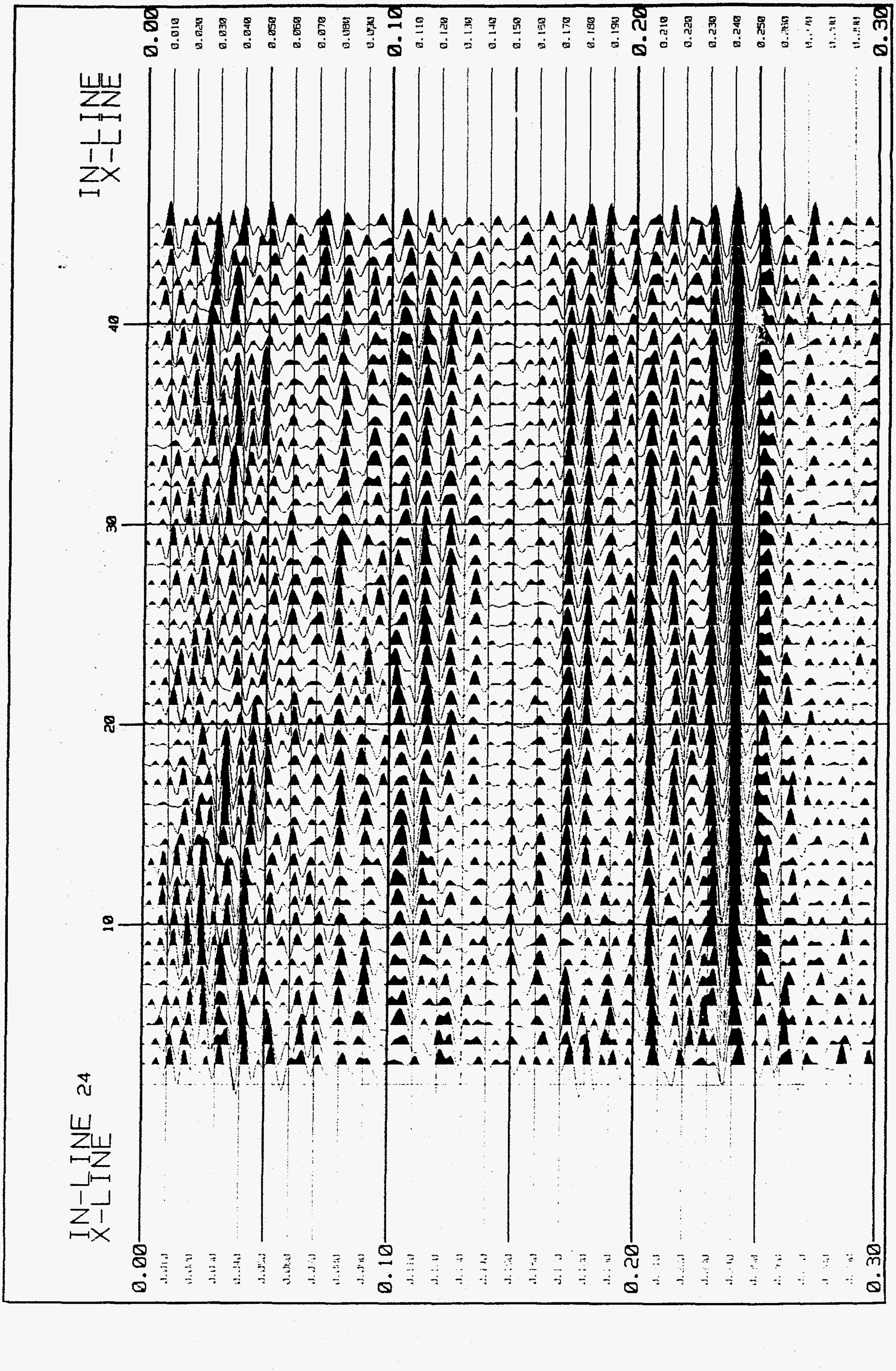
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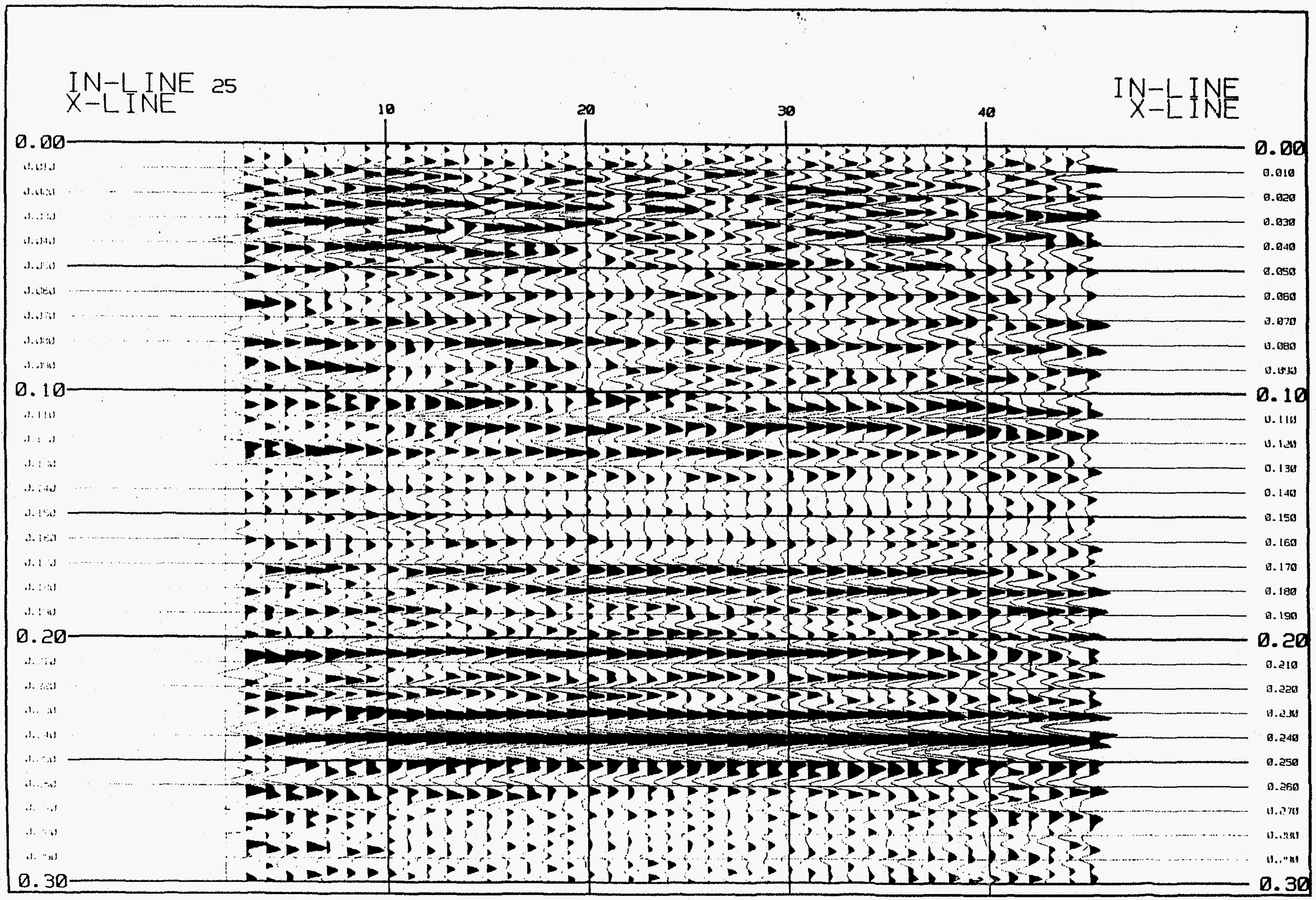
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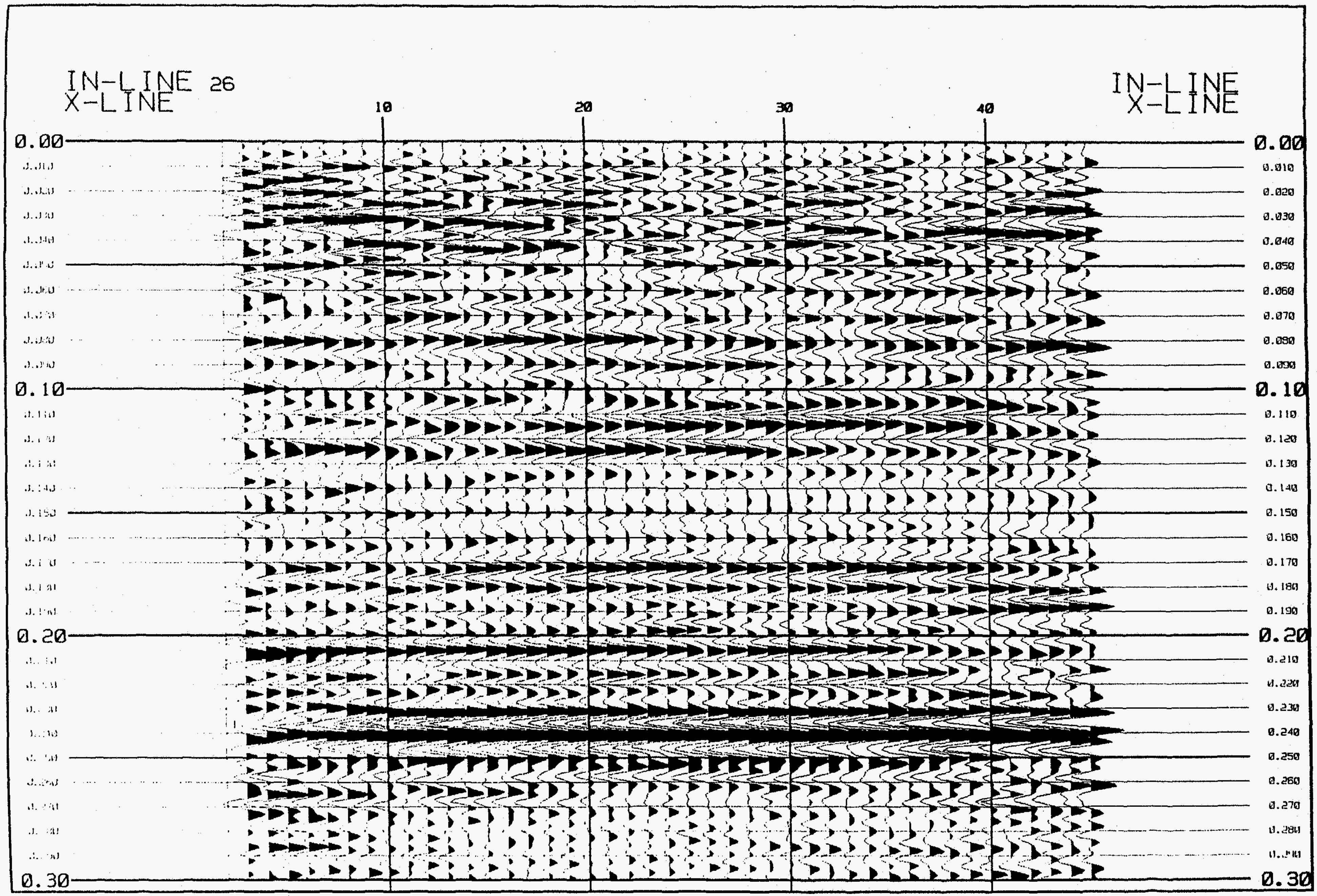
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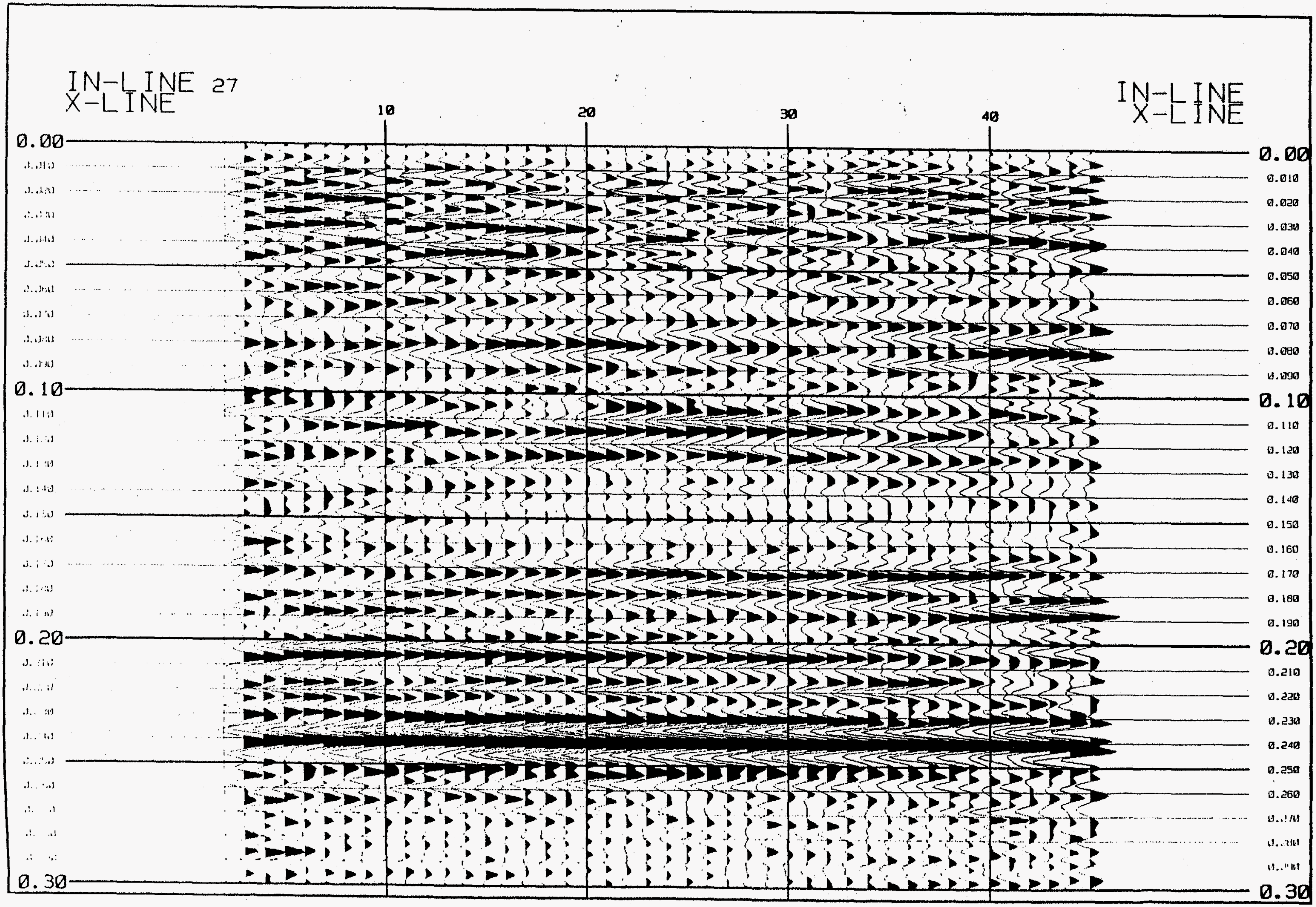
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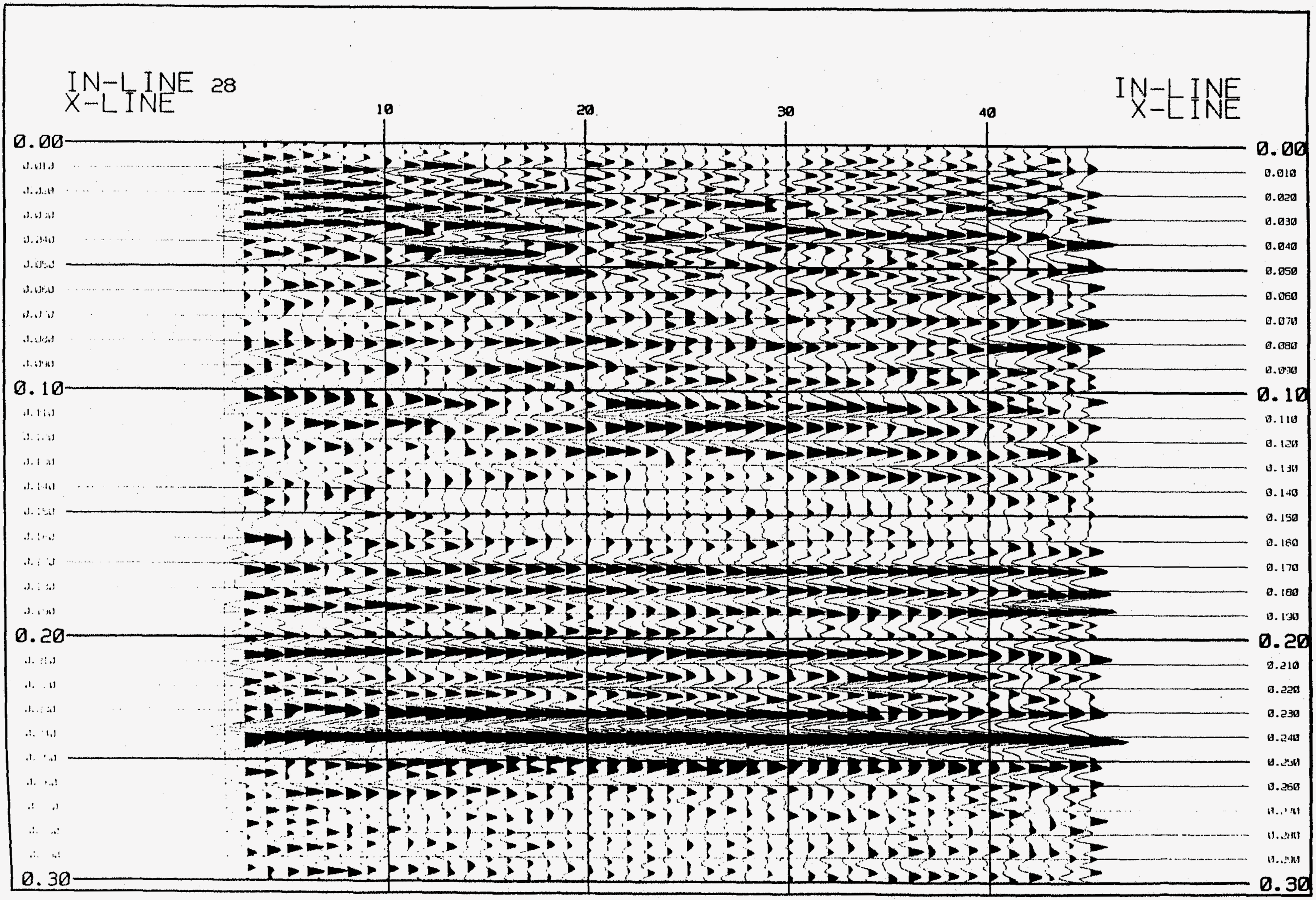
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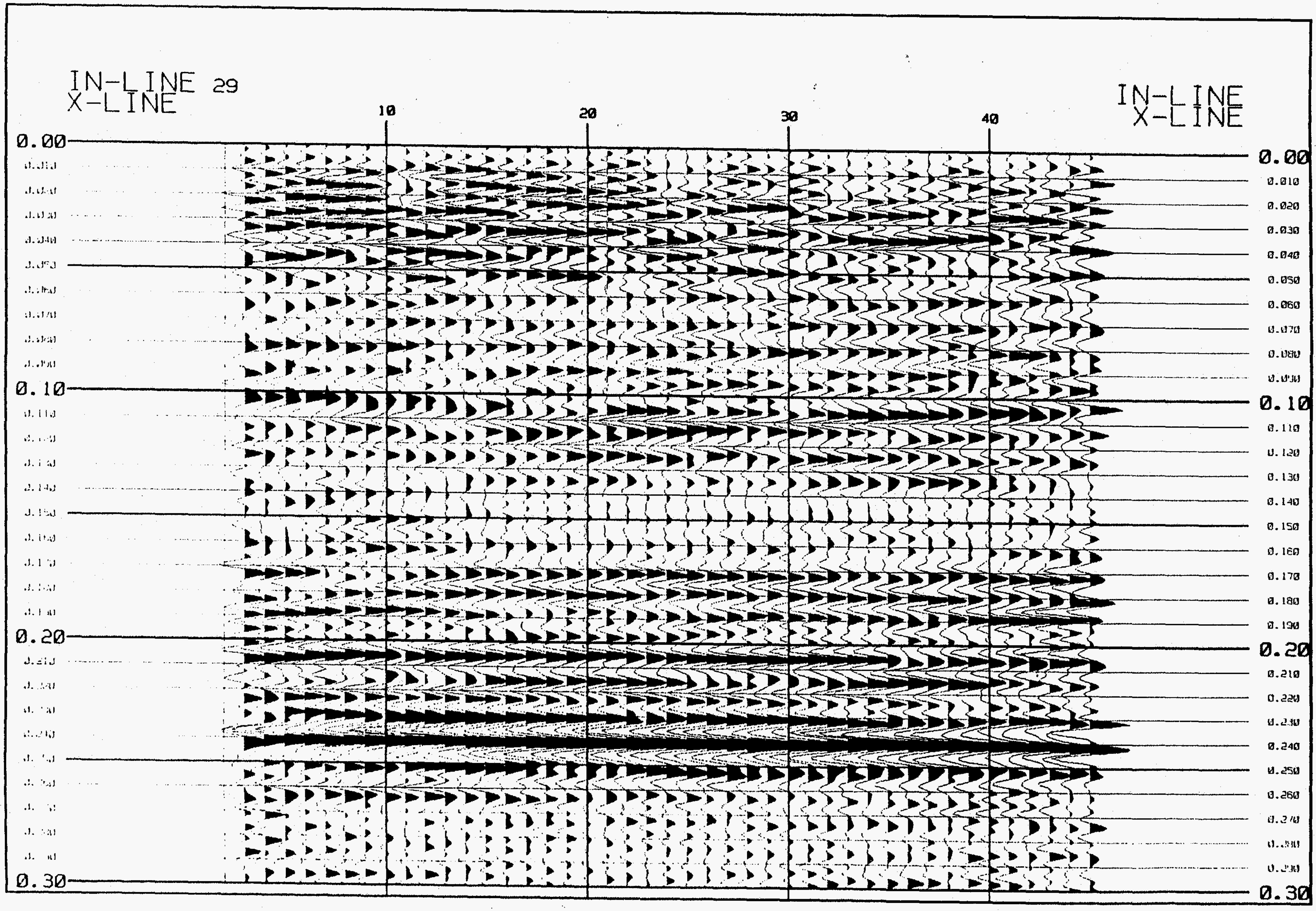
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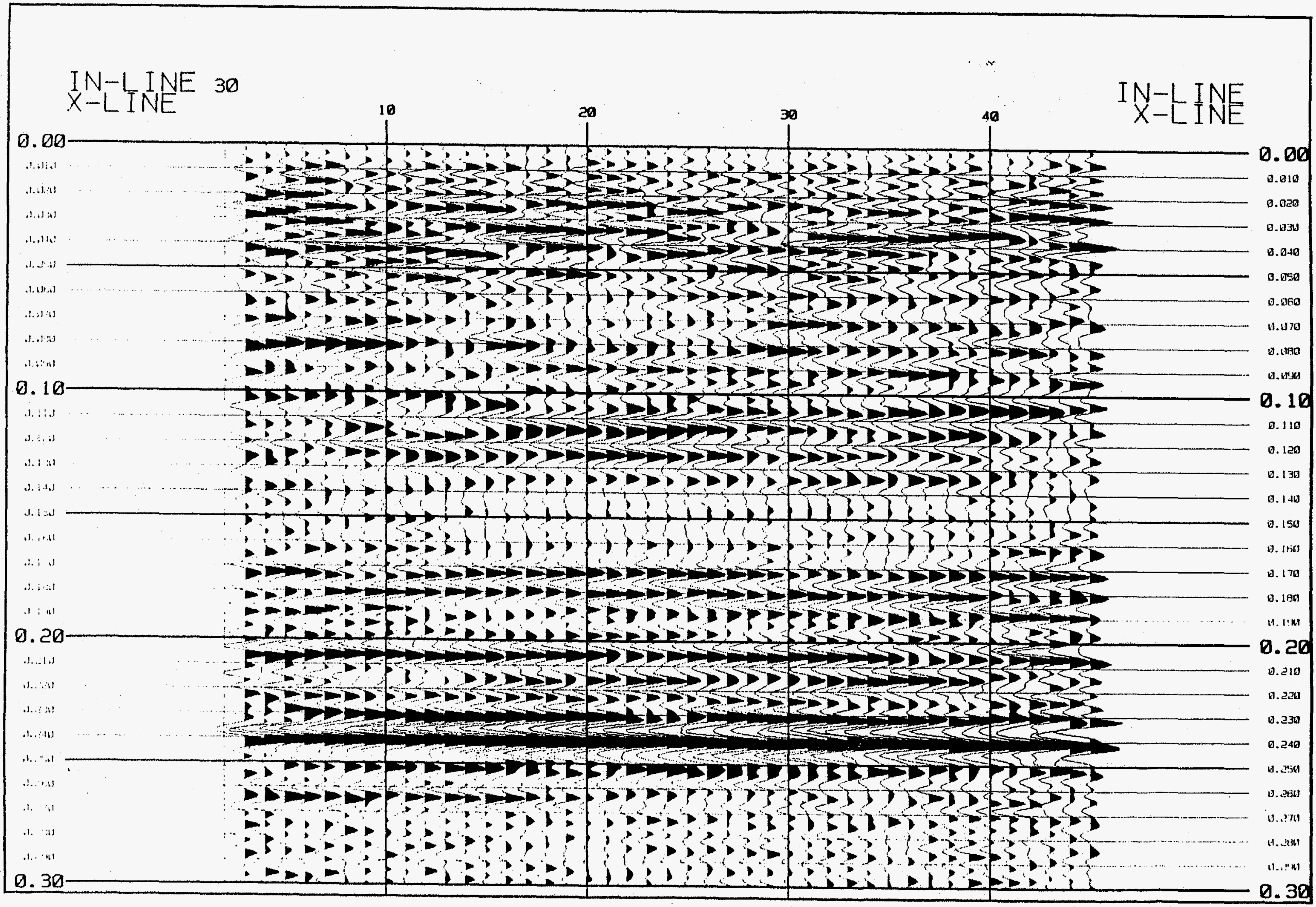
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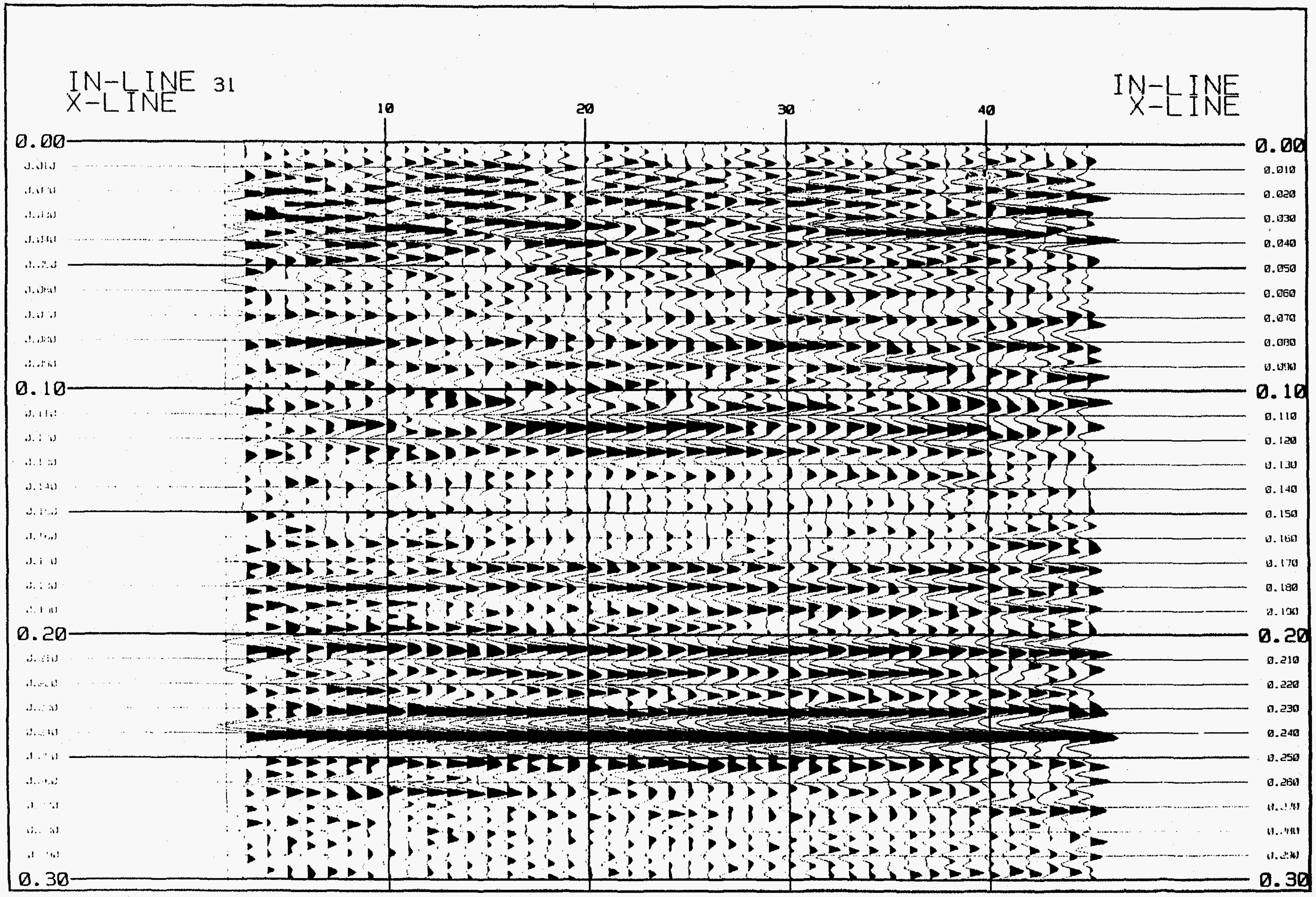
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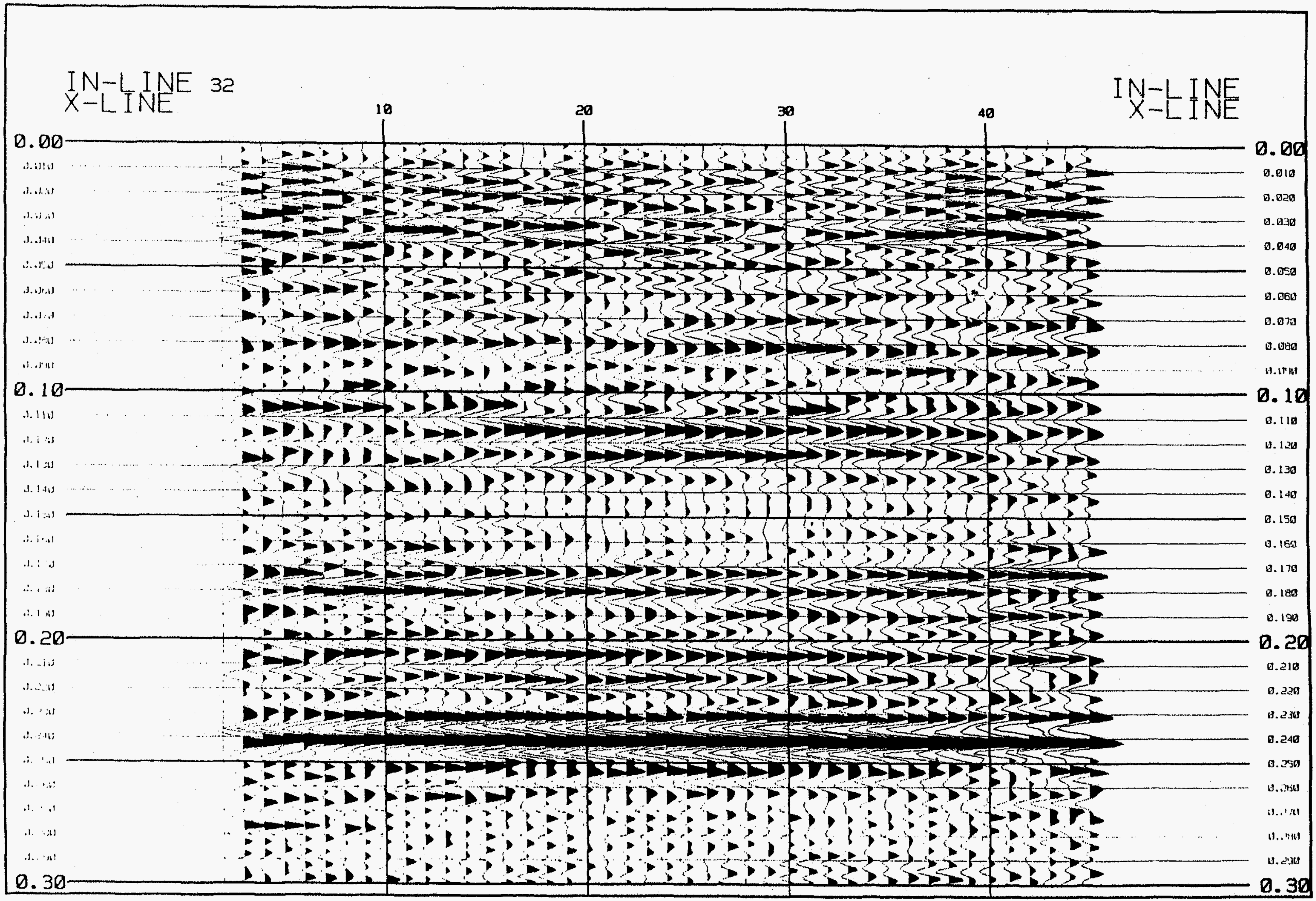
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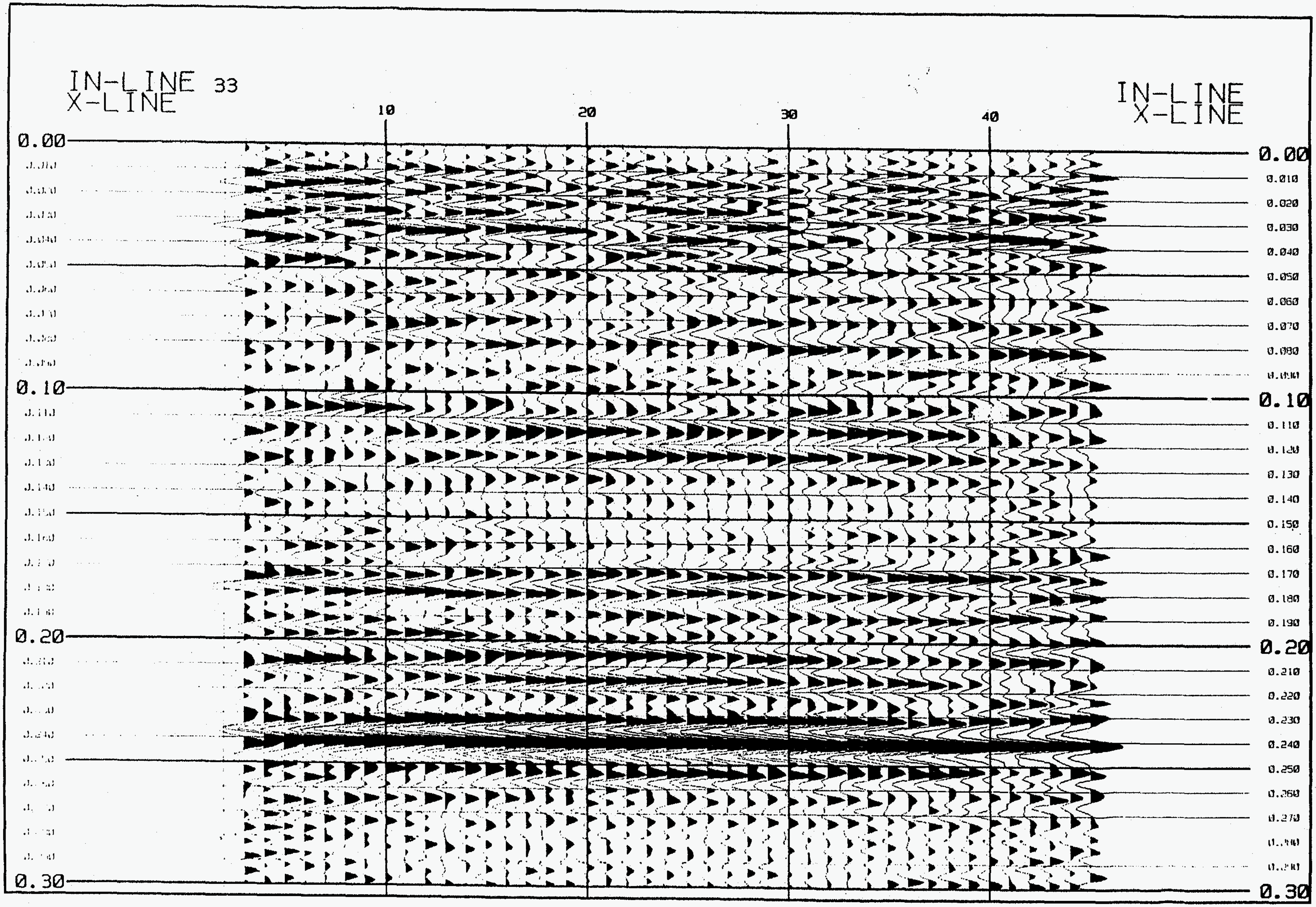
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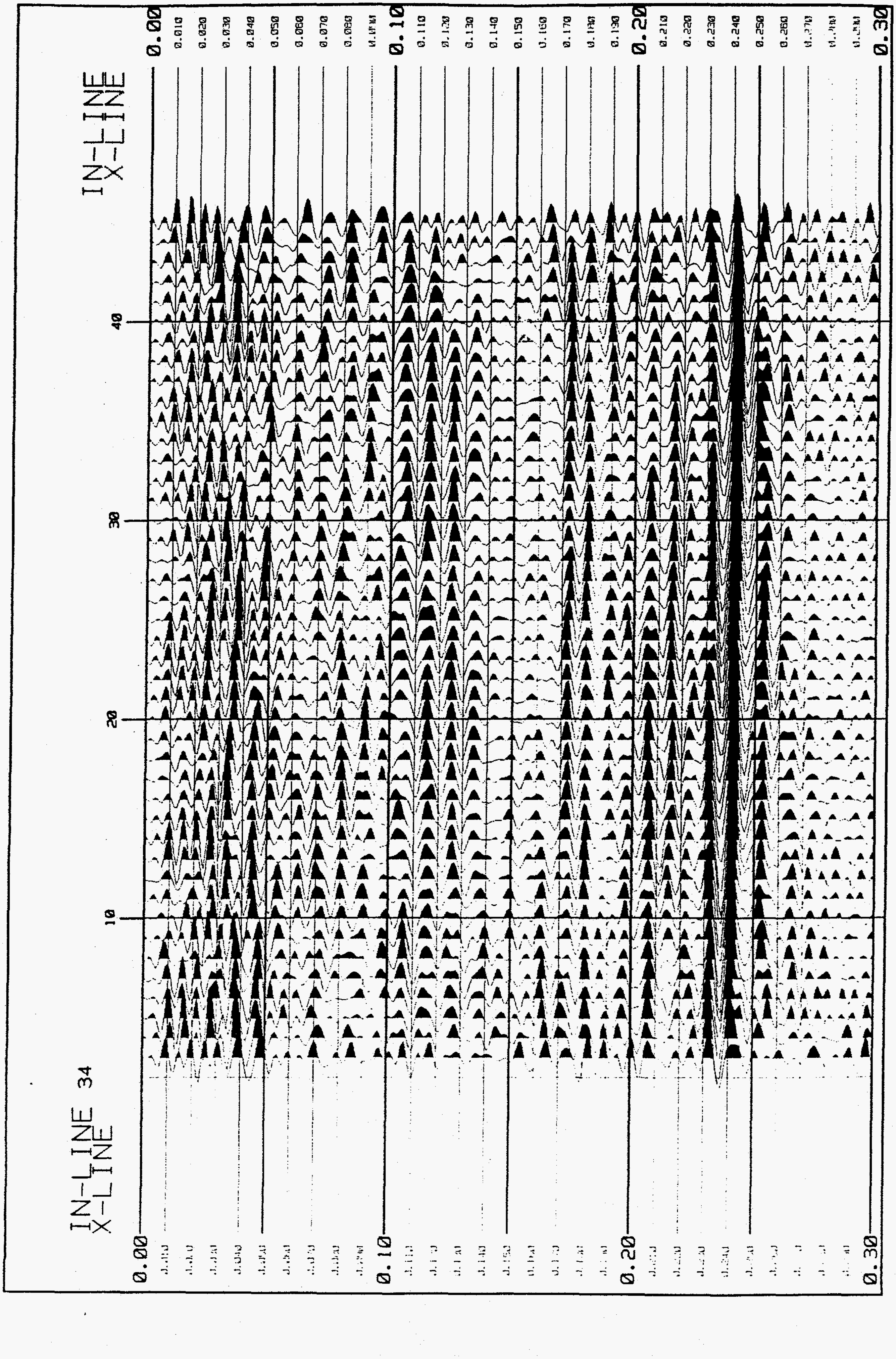
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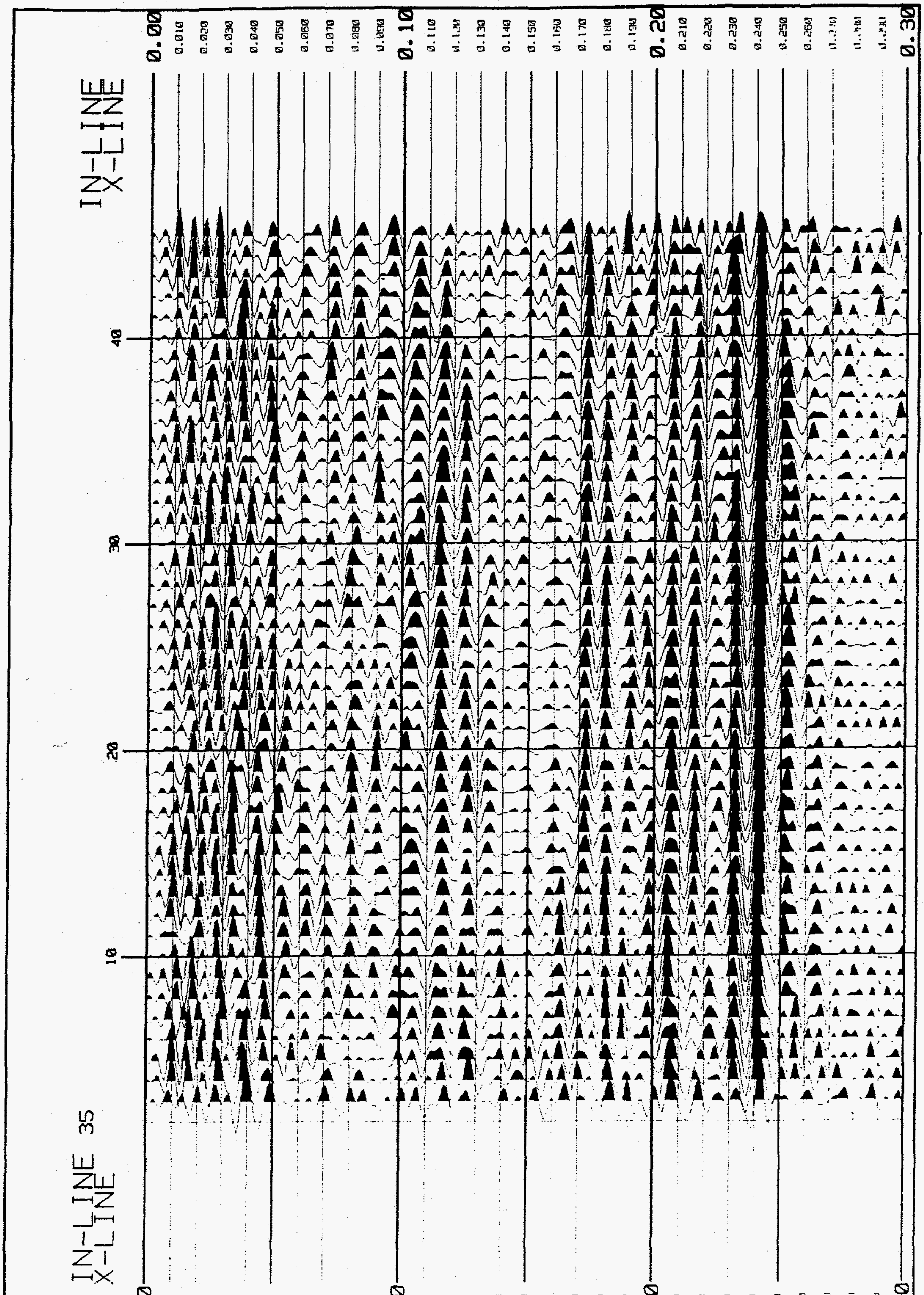

IN-LINE 35
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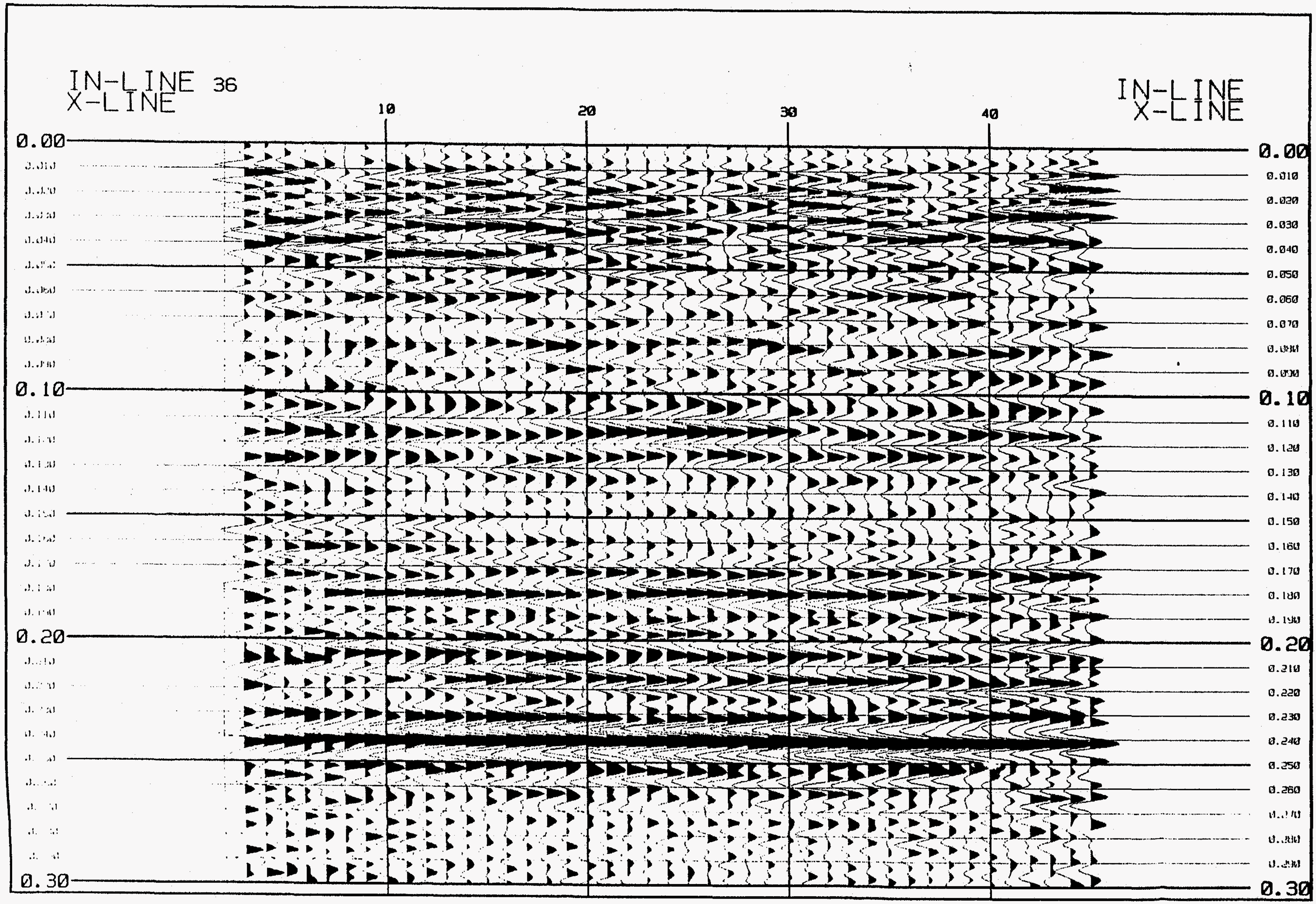
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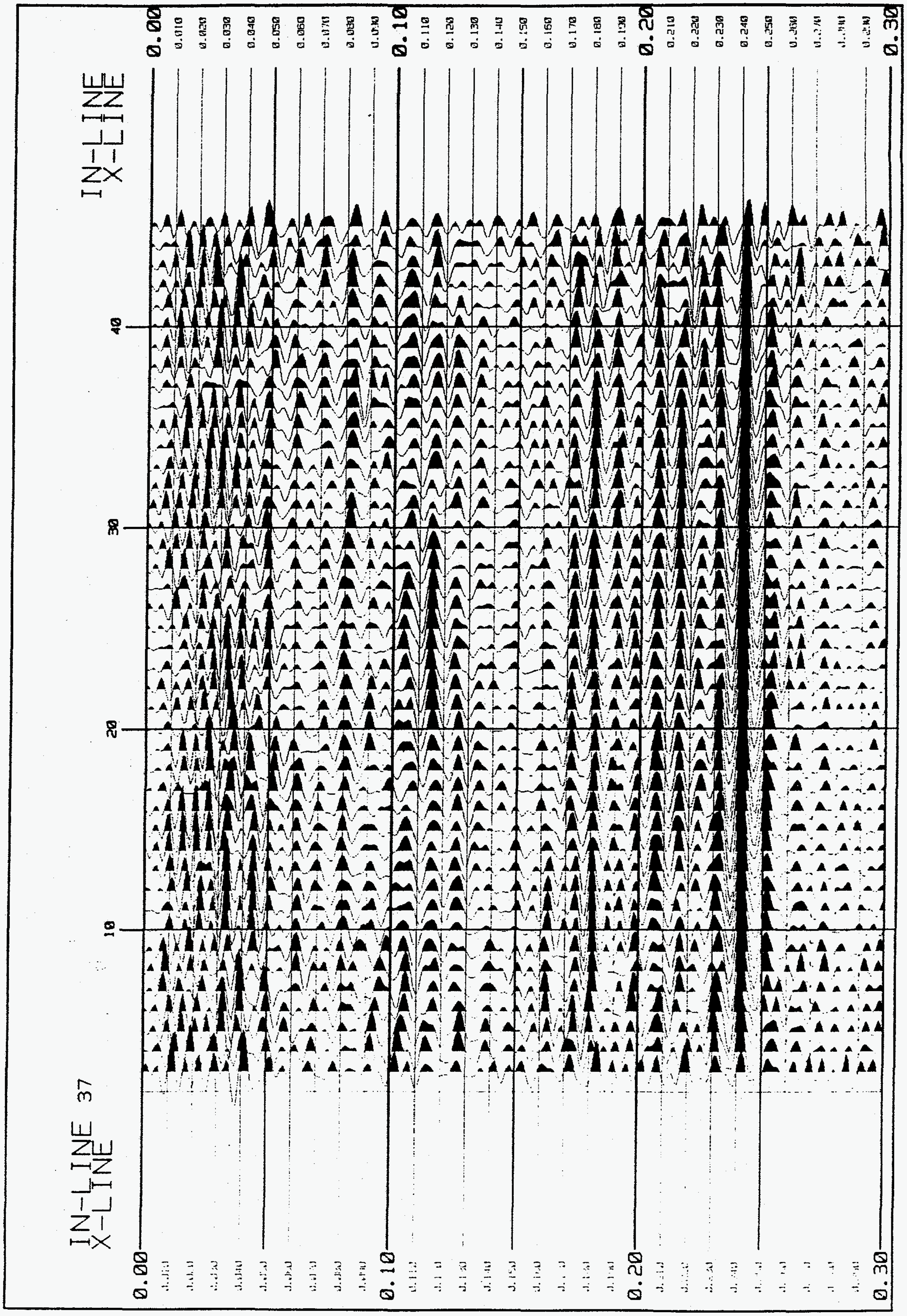
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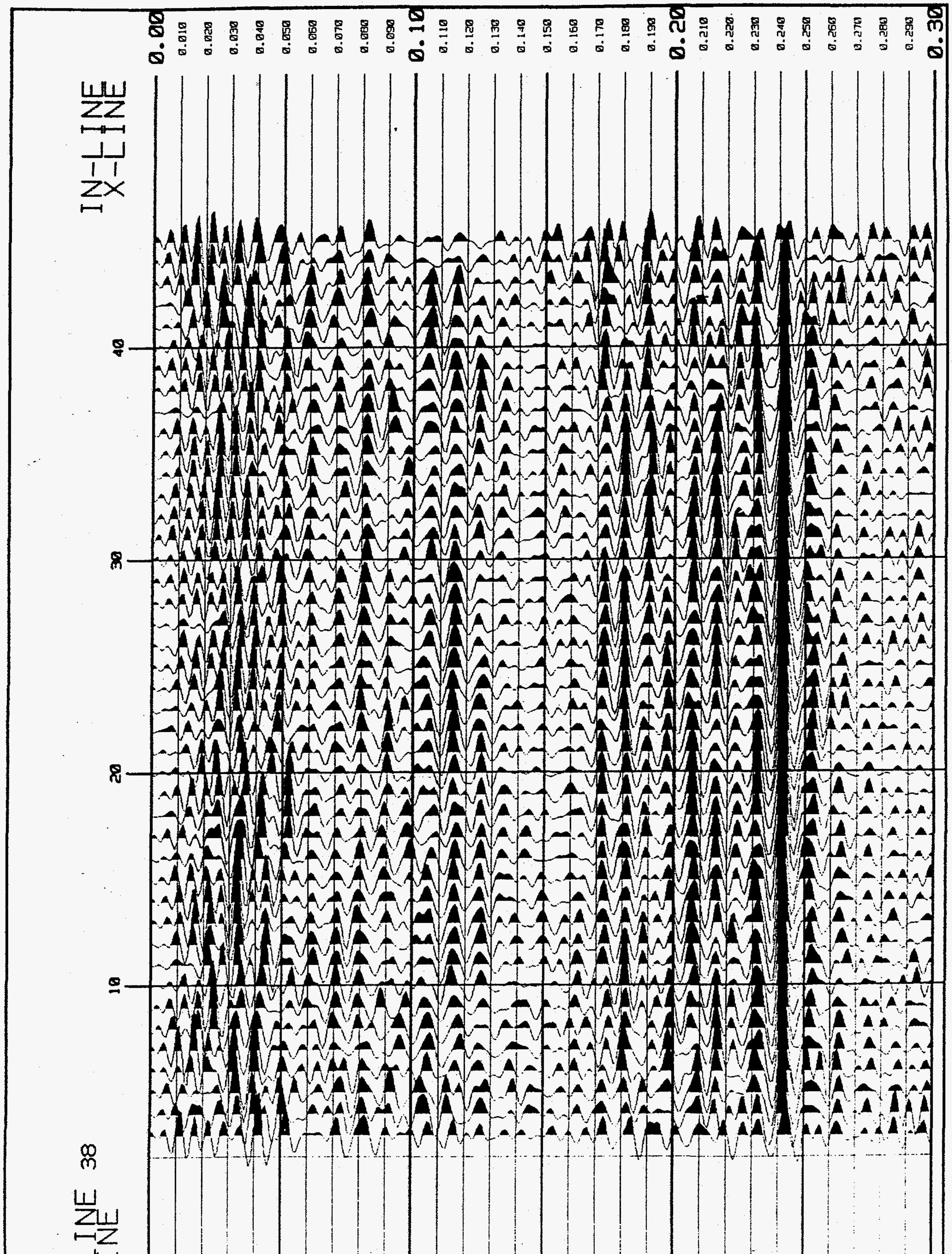
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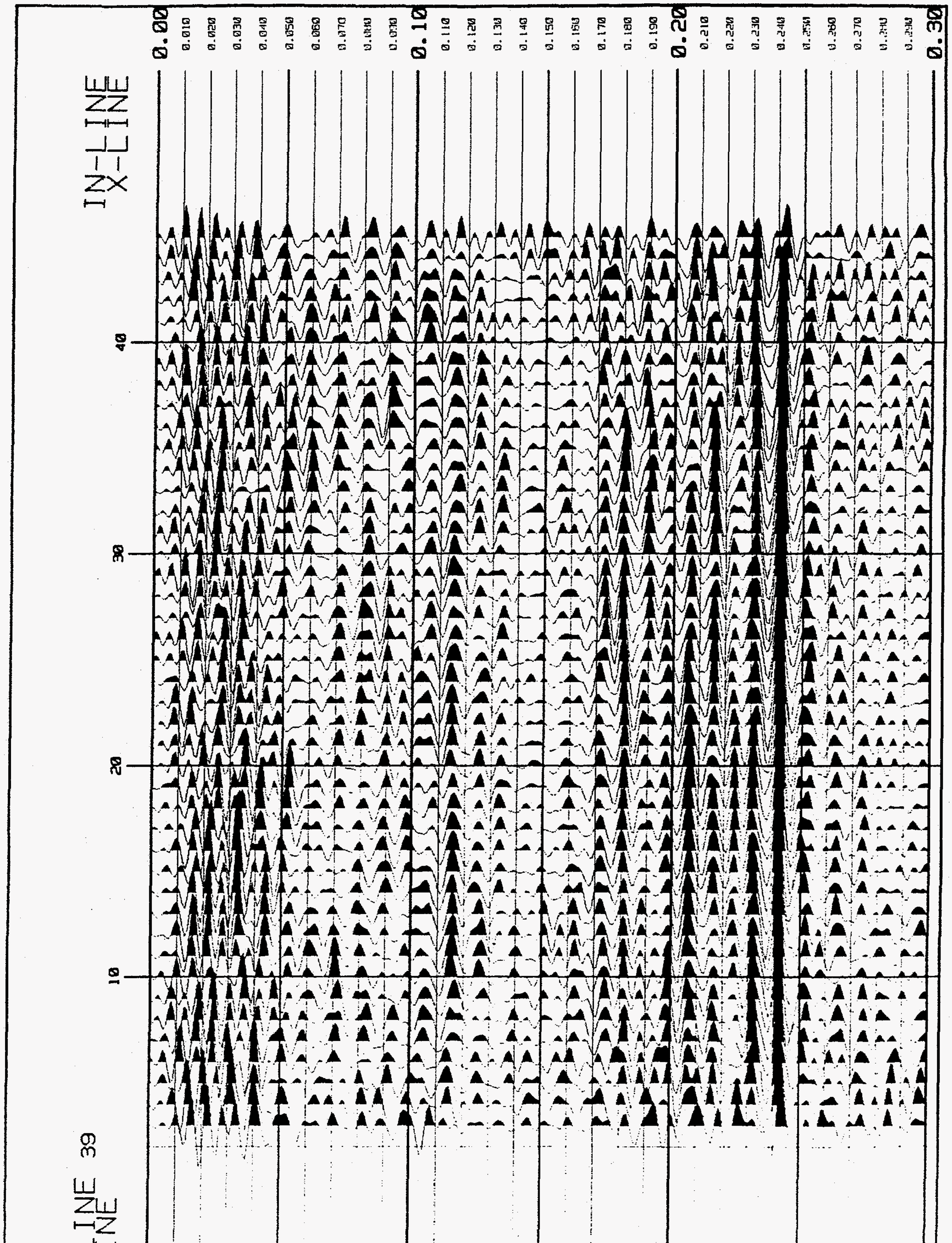

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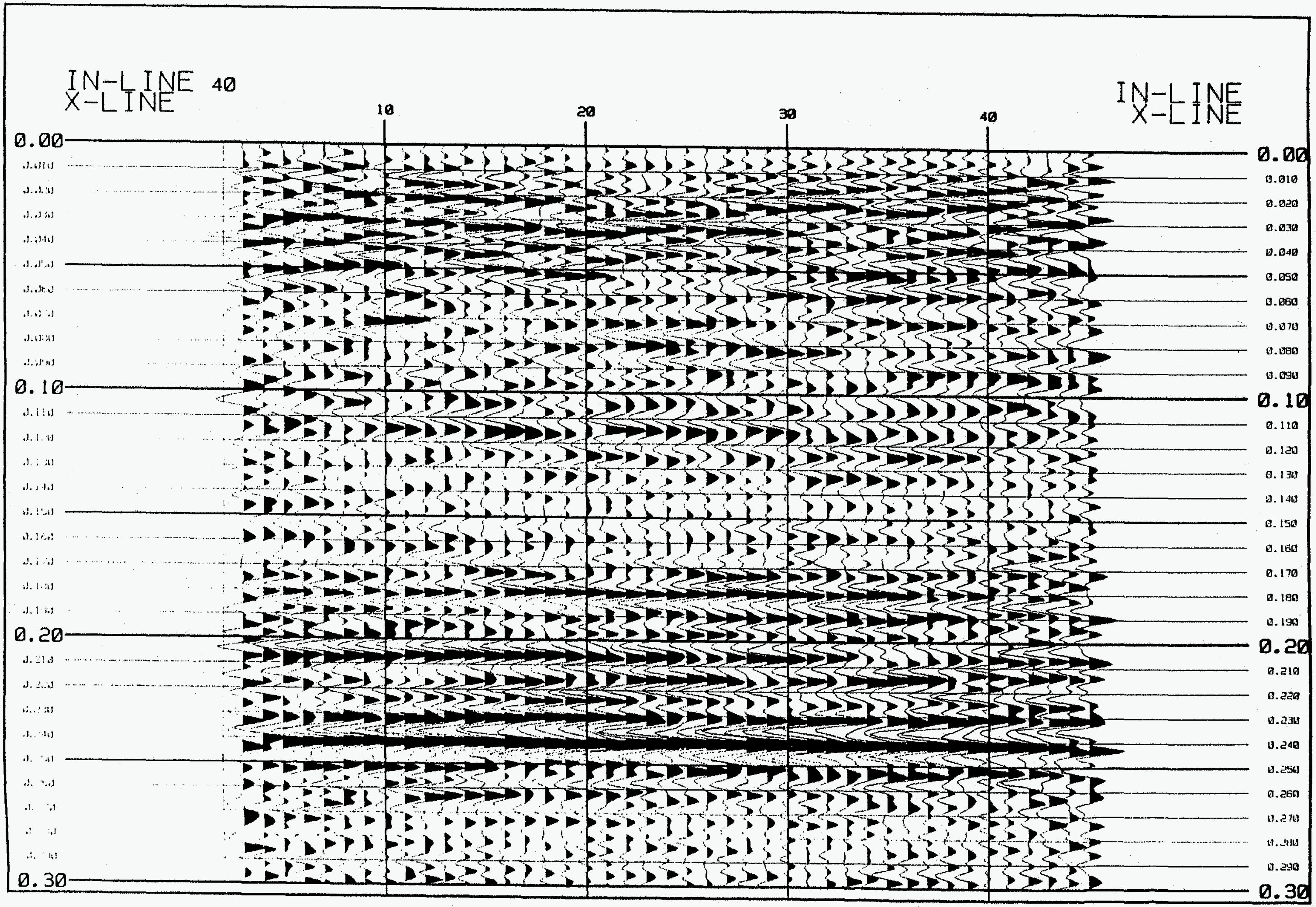
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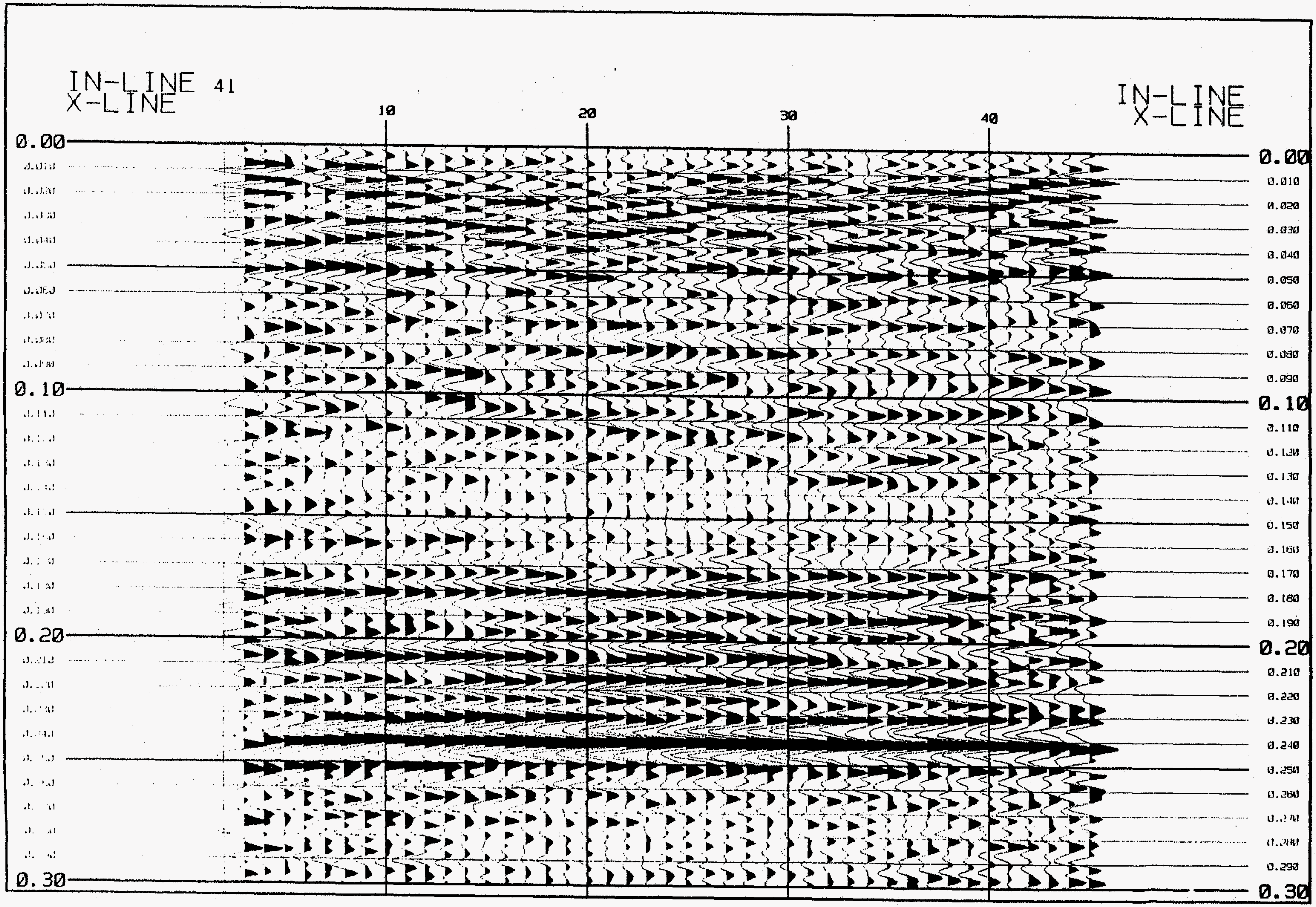
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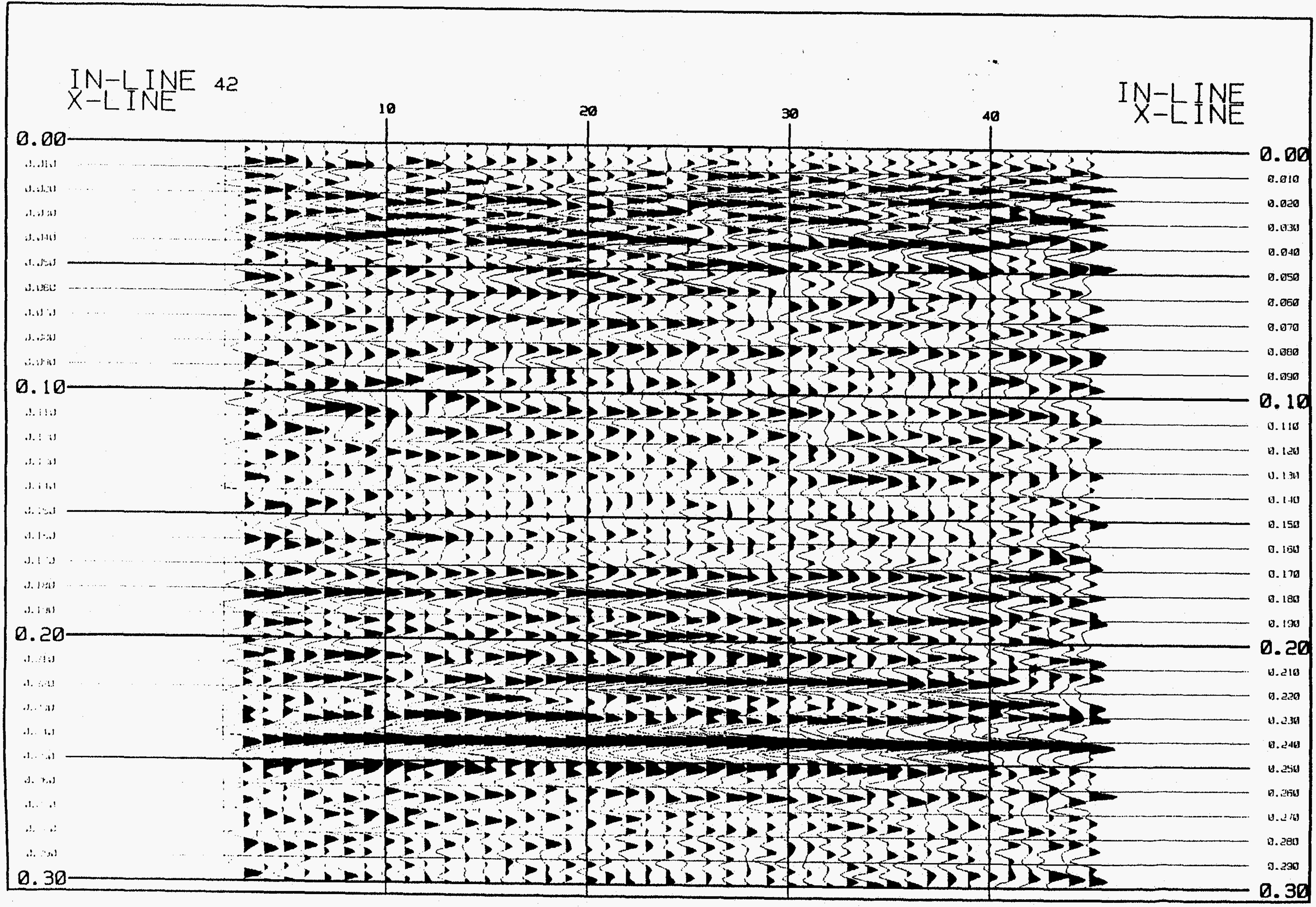
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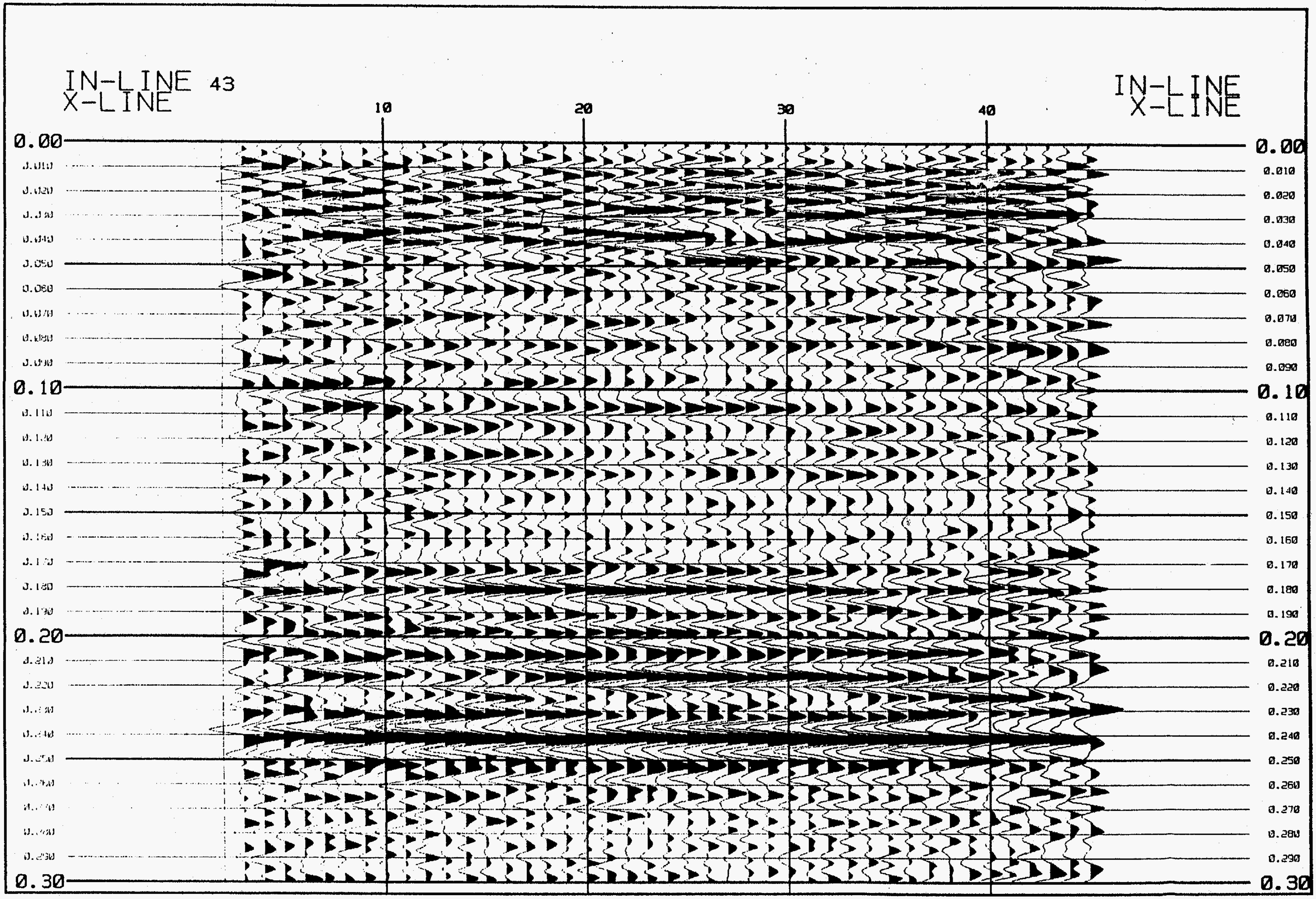
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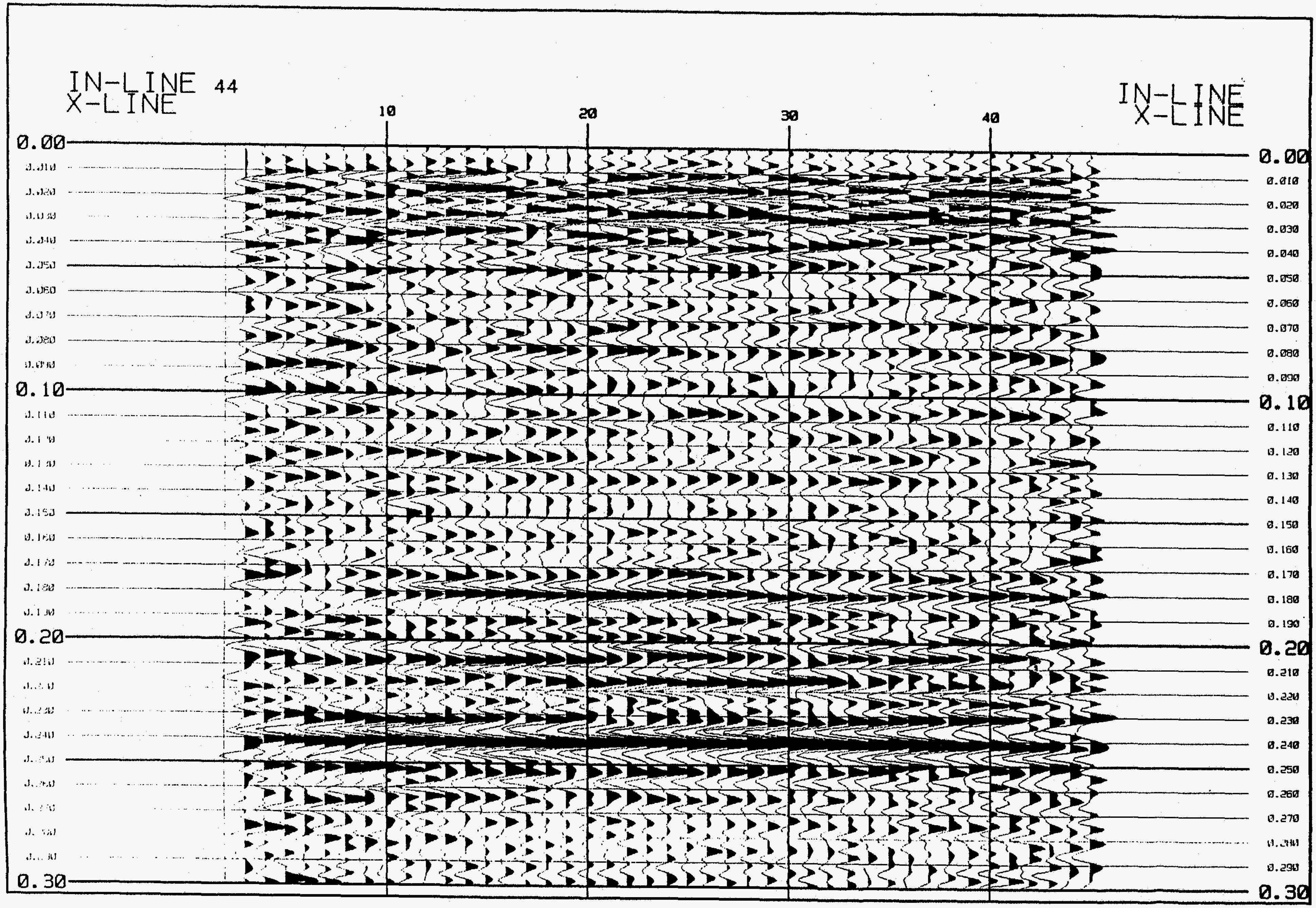
IN-LINE 44
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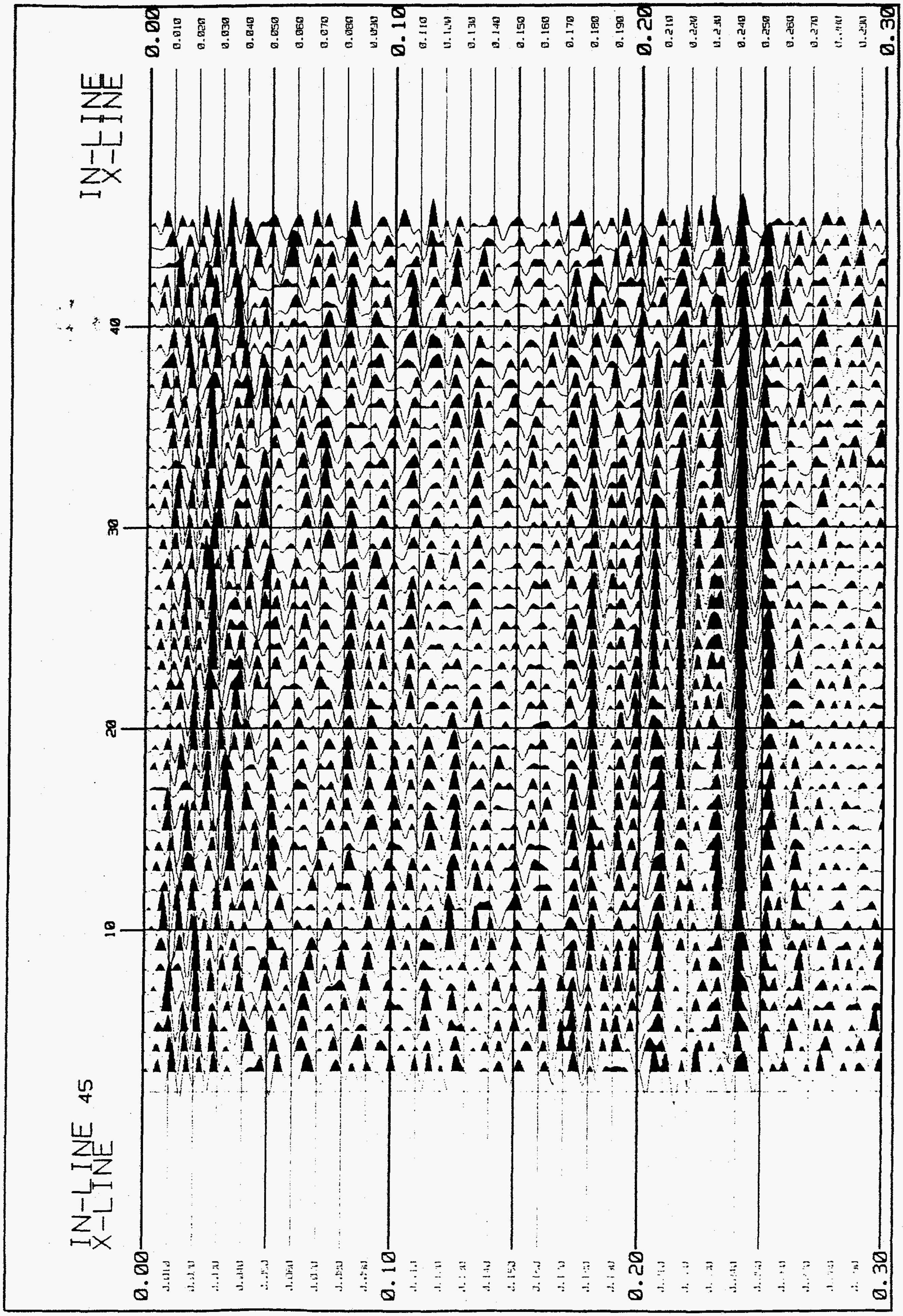

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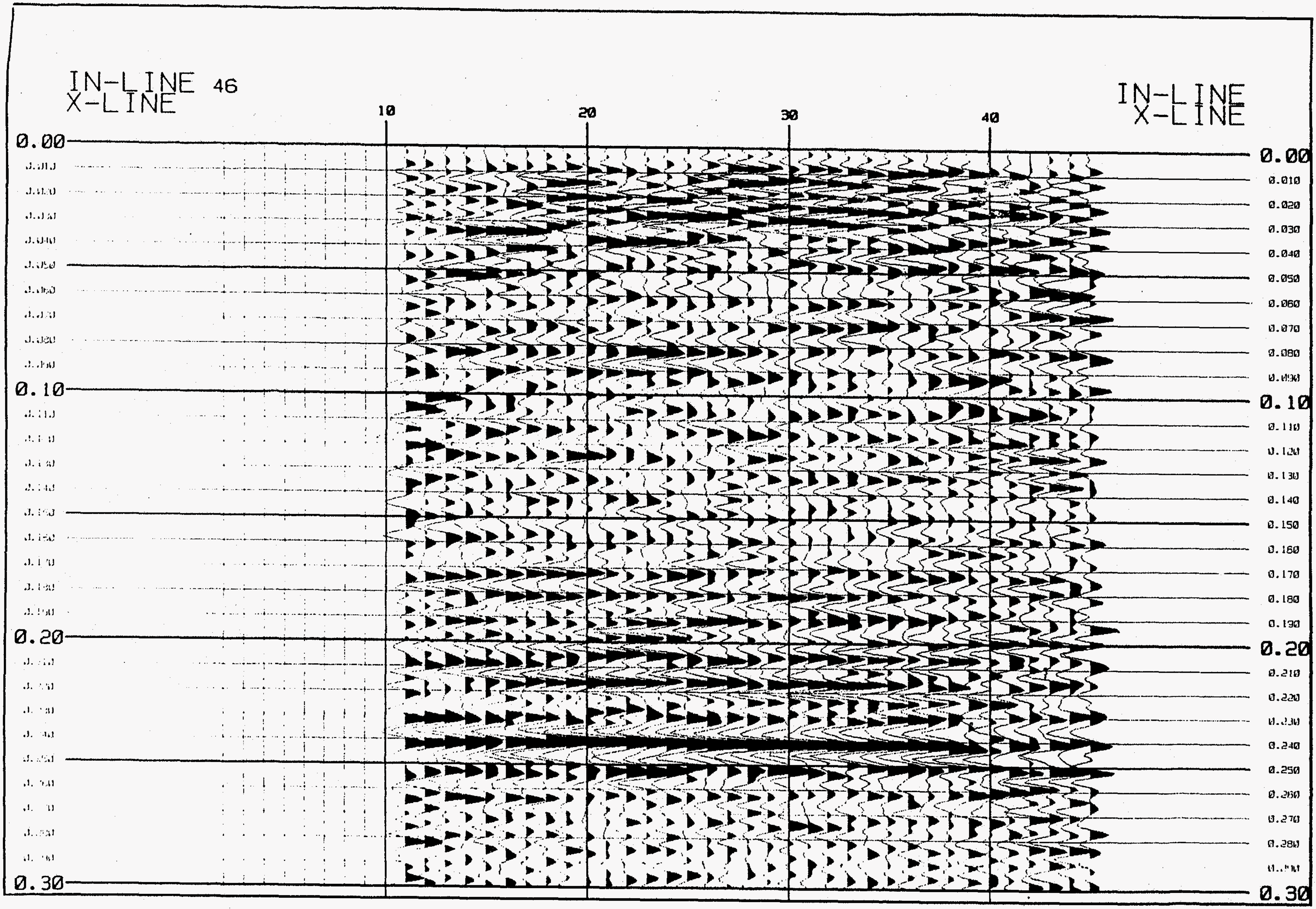
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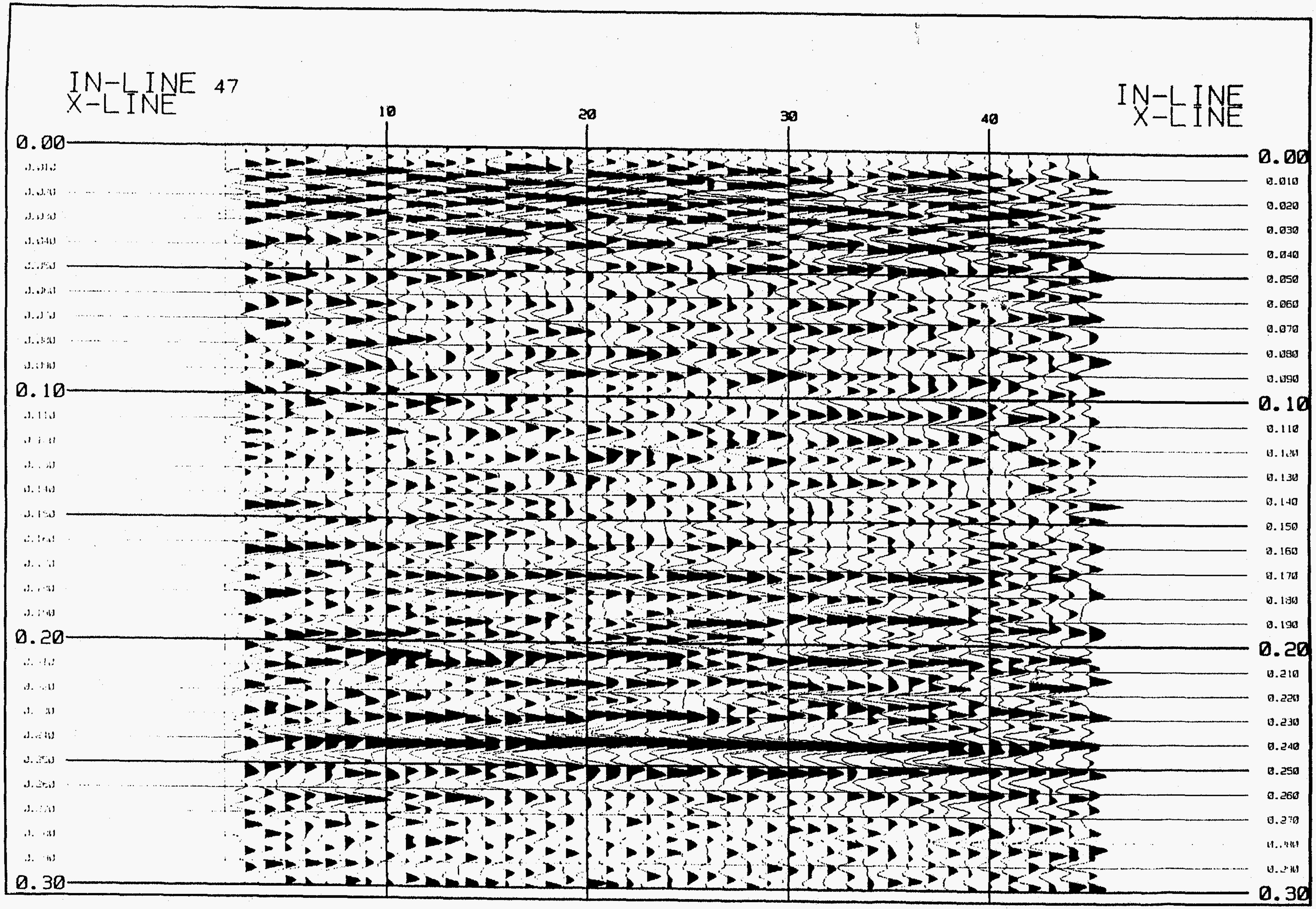IN-LINE 47
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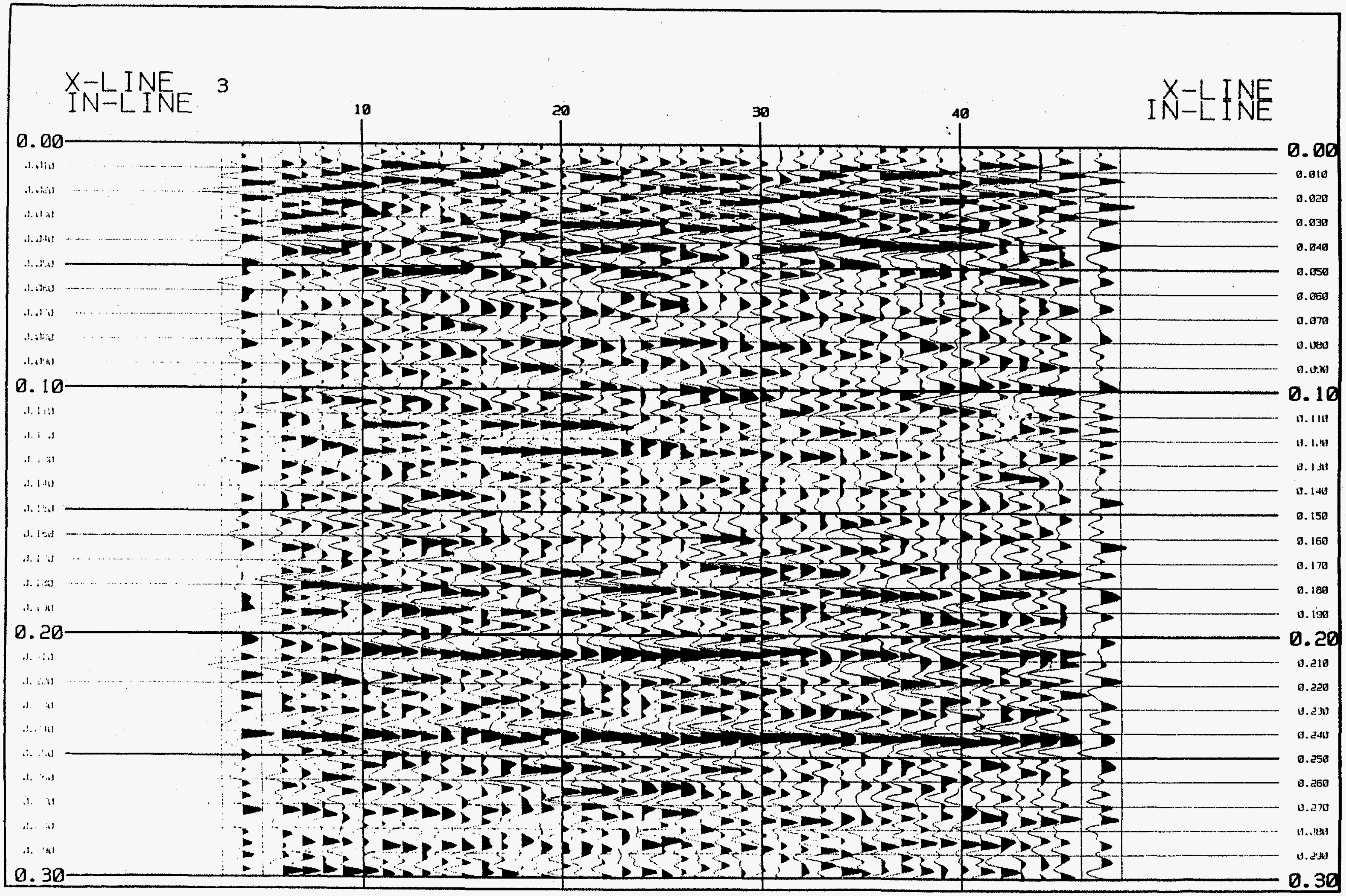
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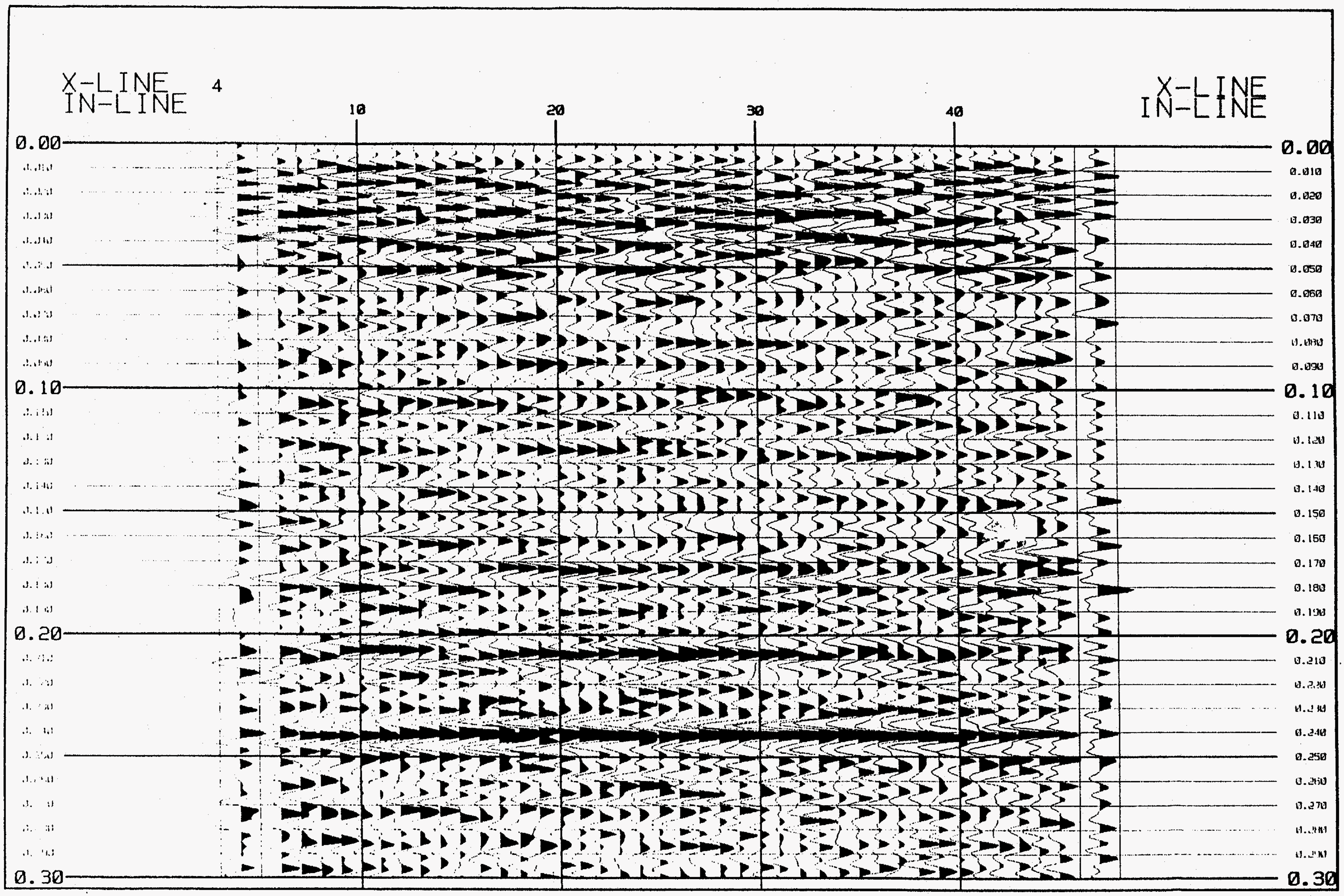
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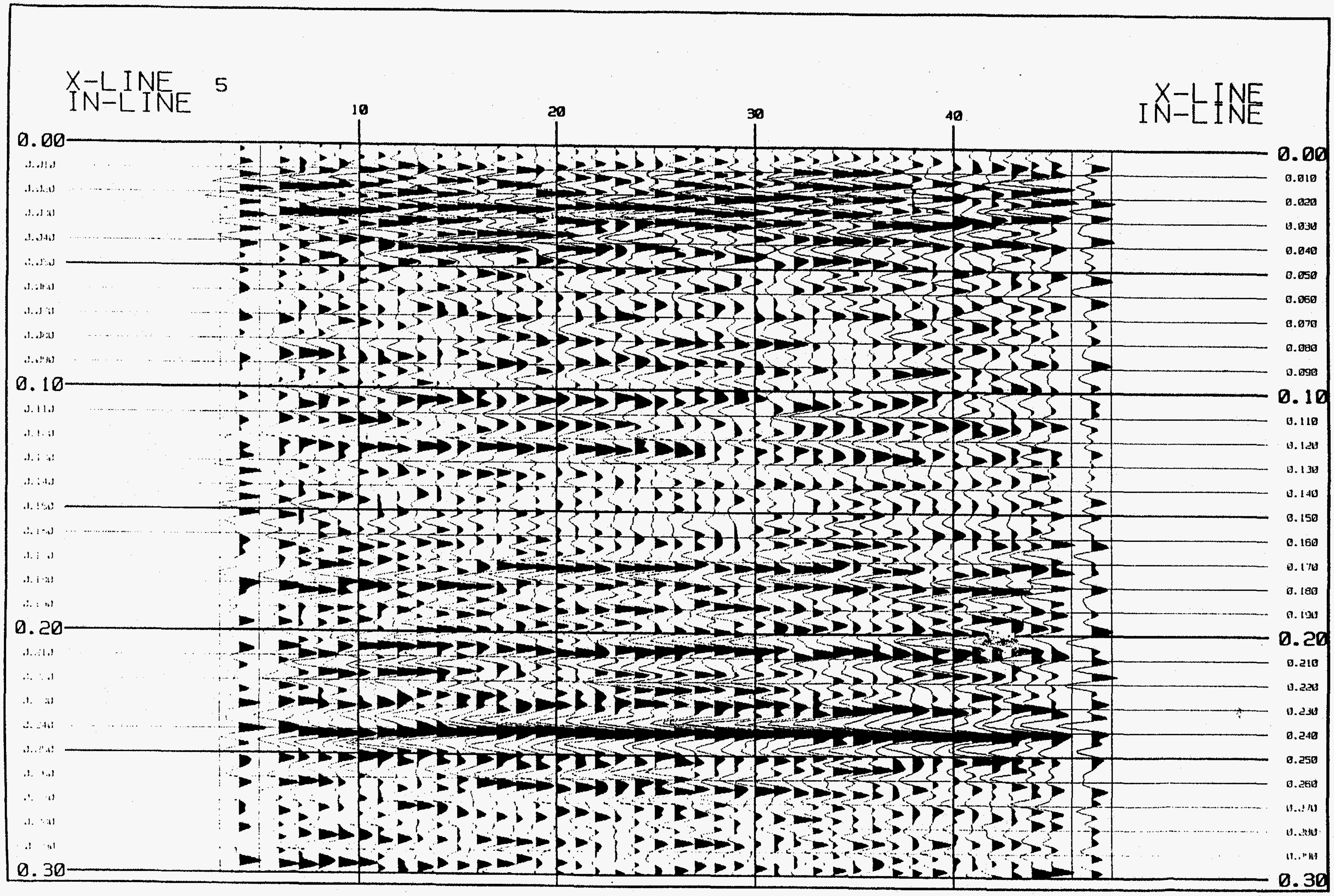
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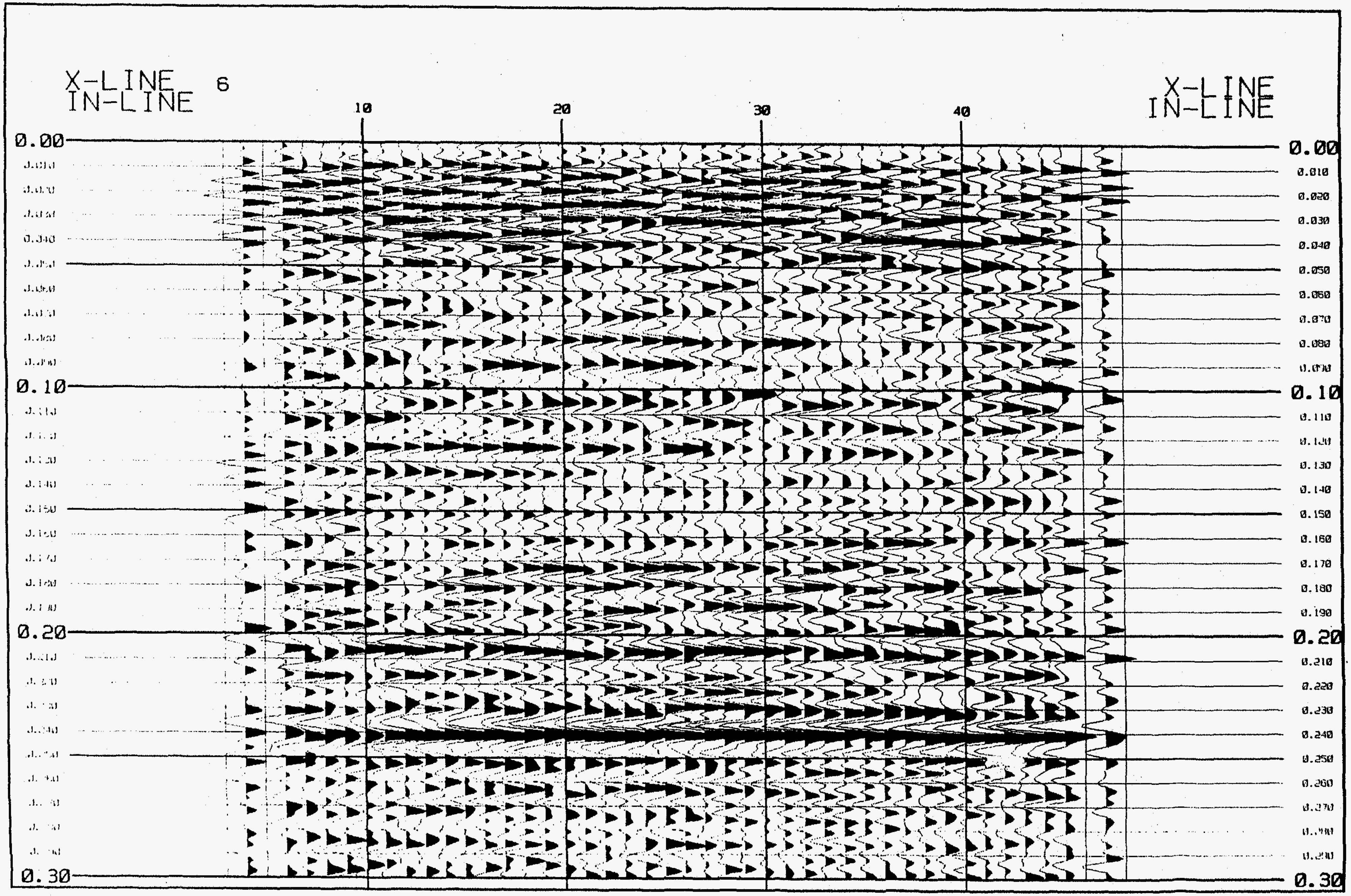
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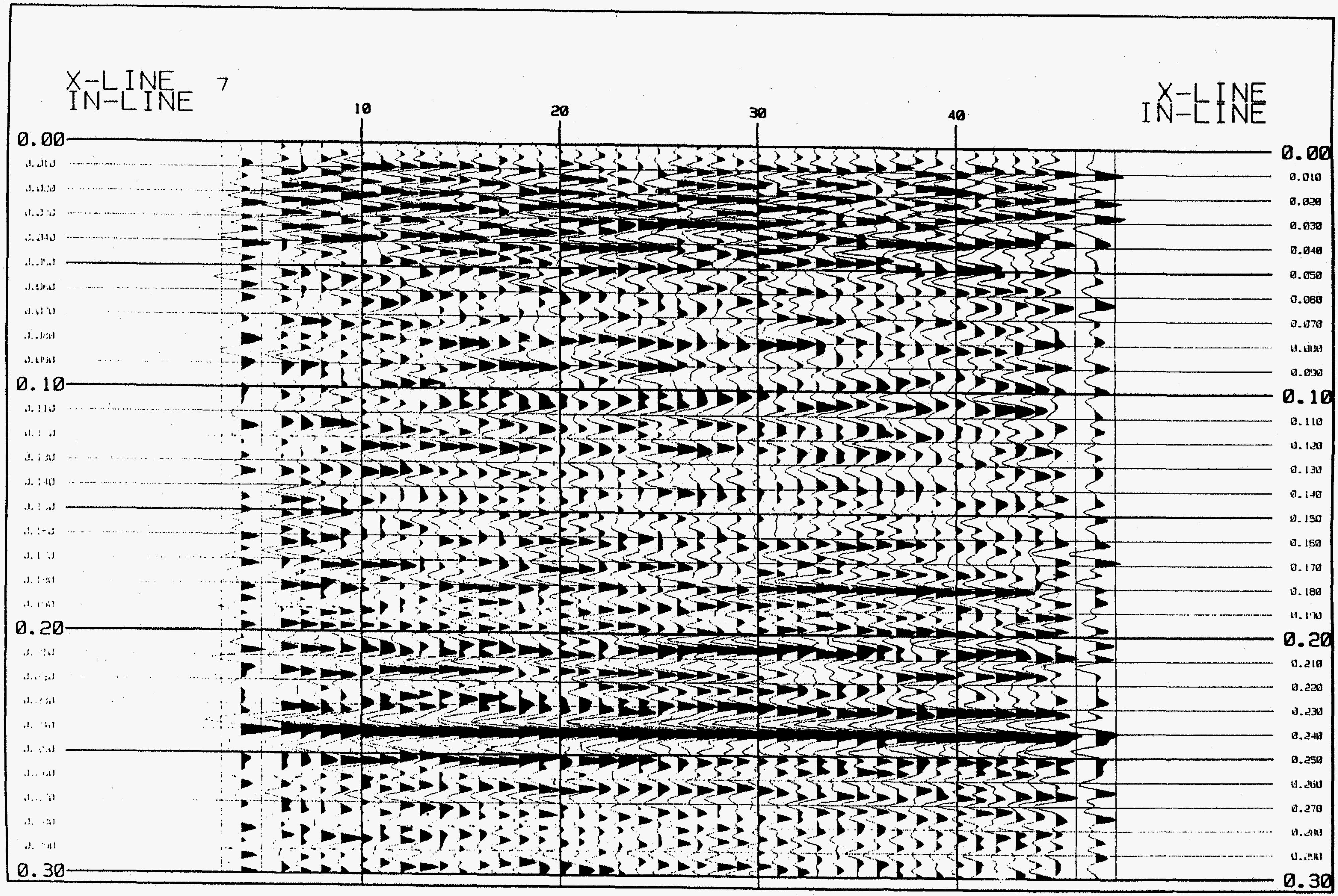

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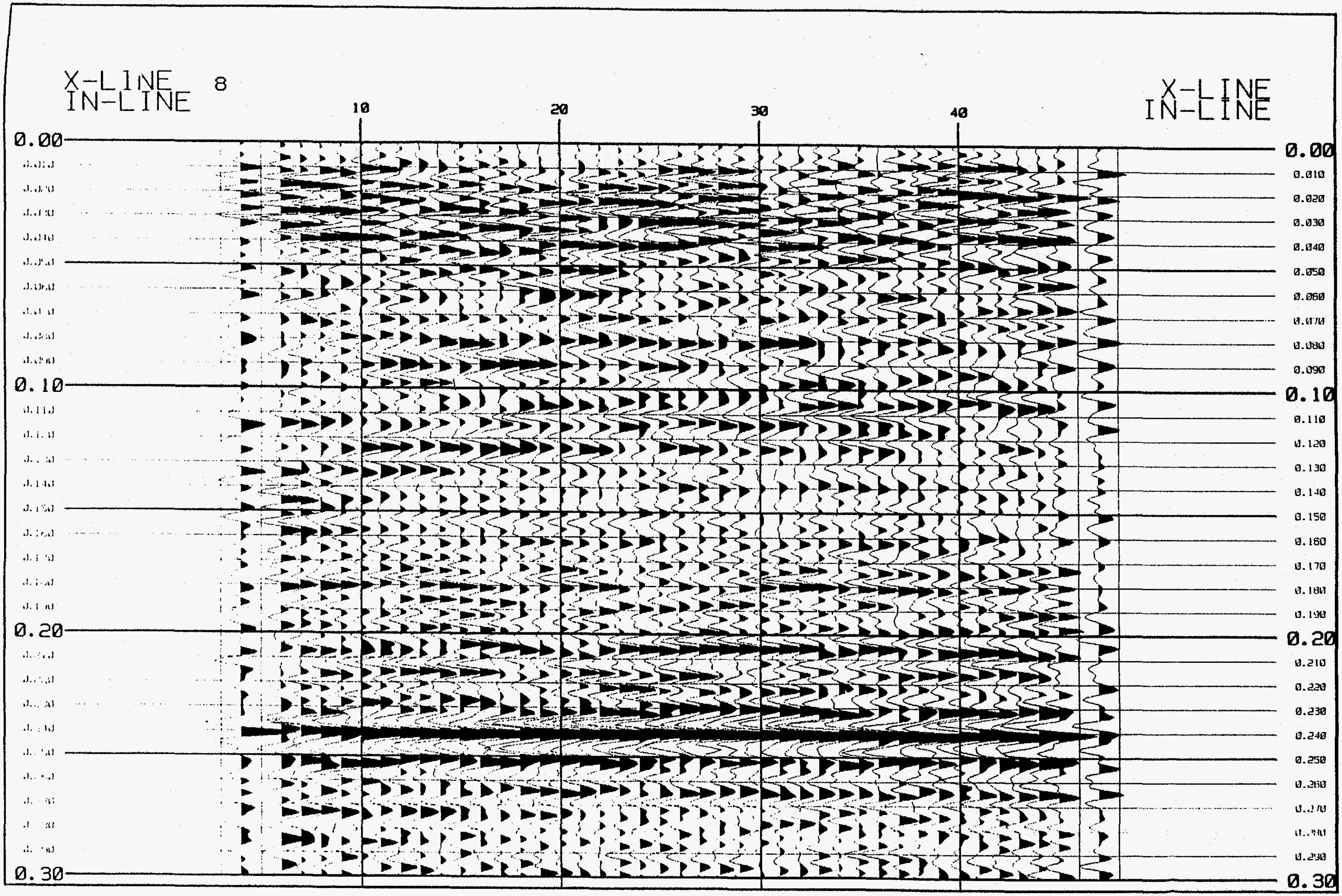
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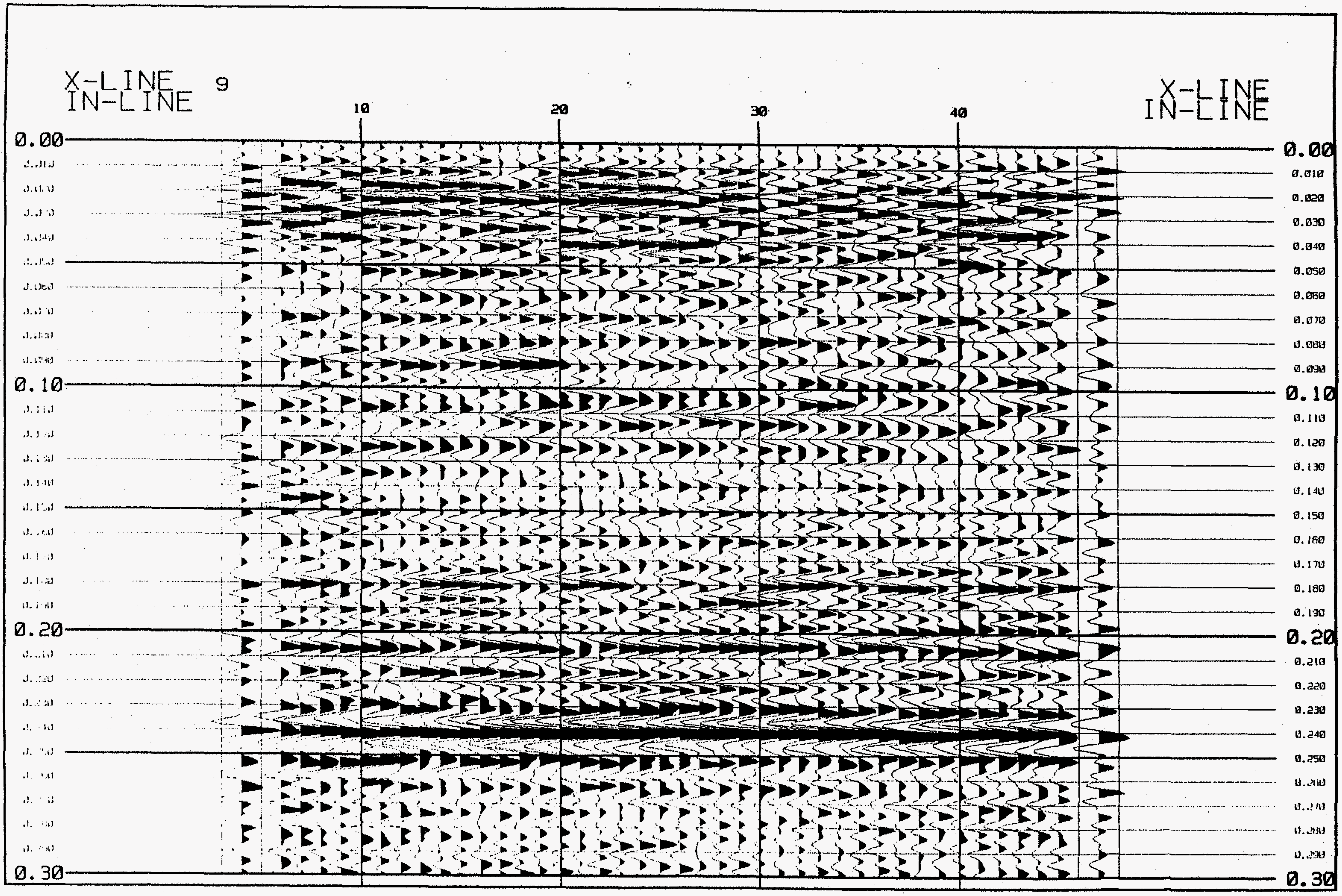
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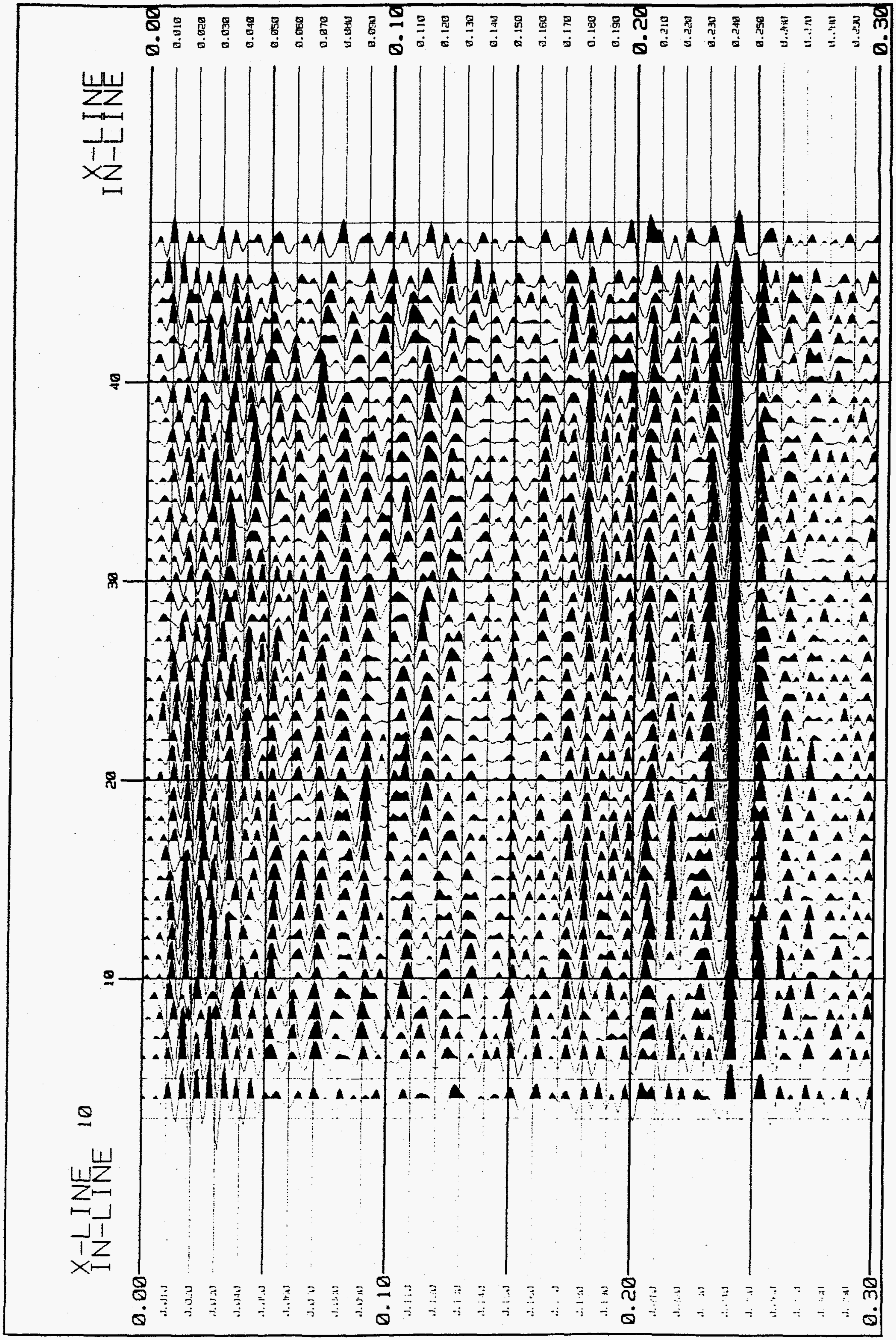
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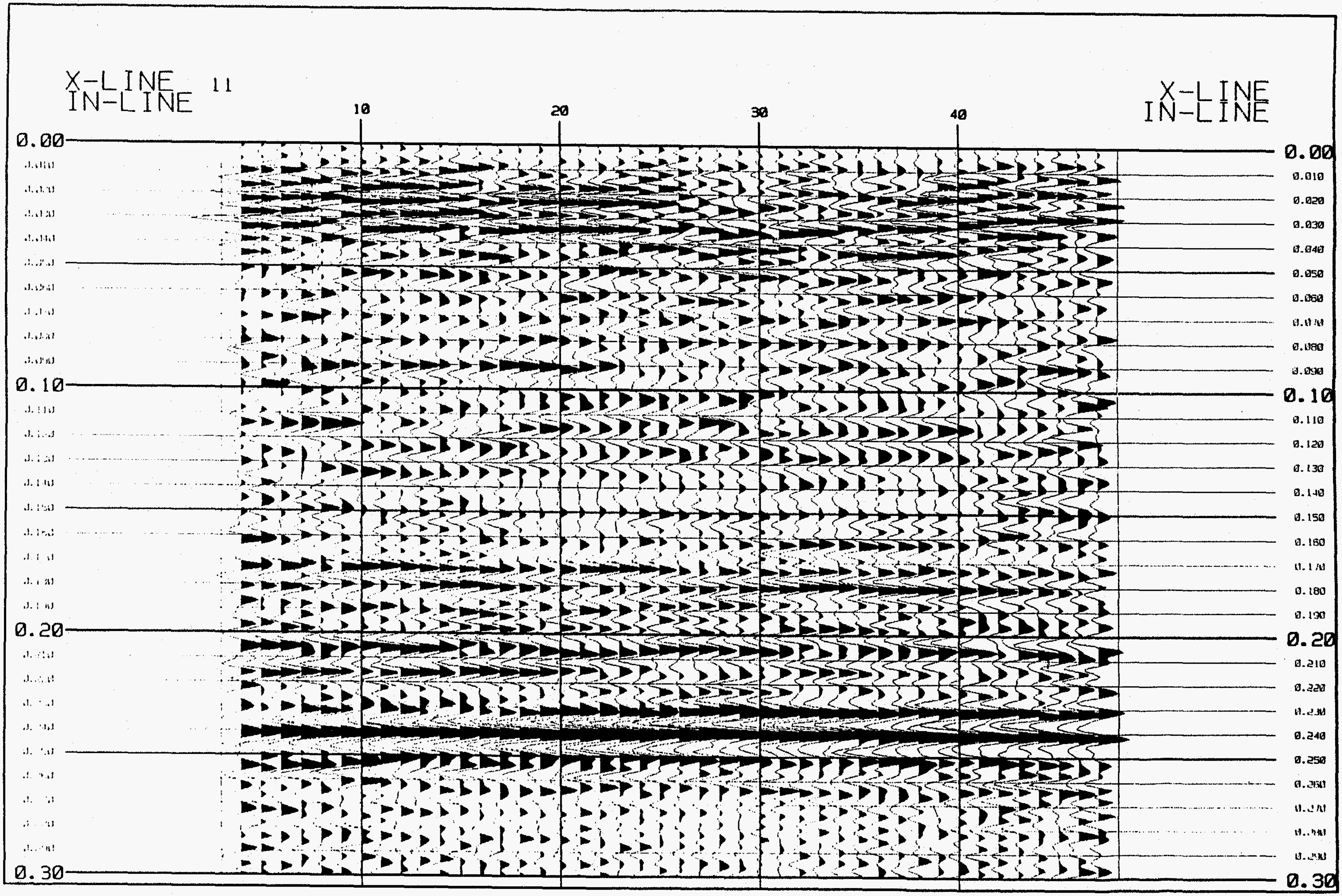
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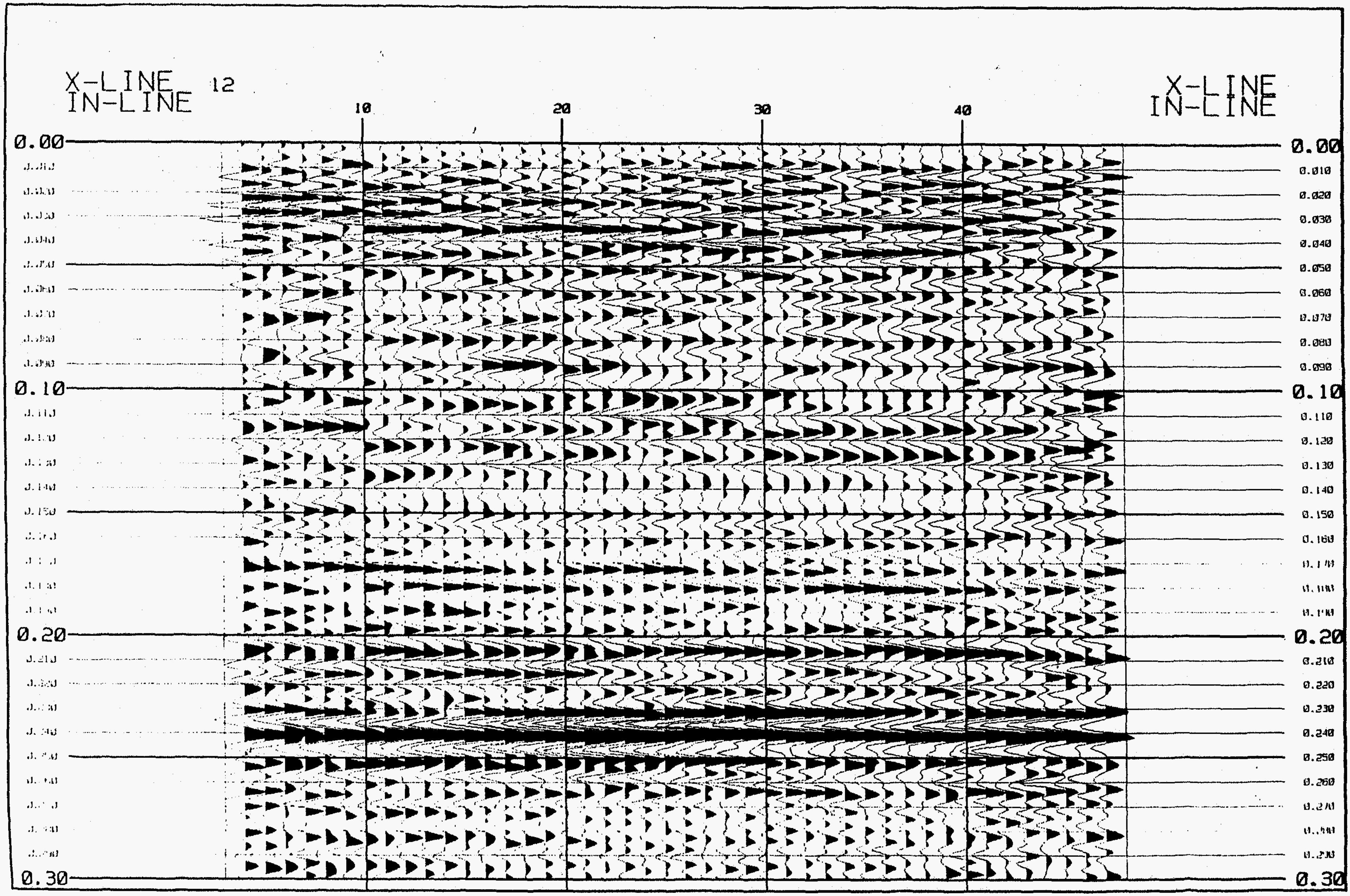
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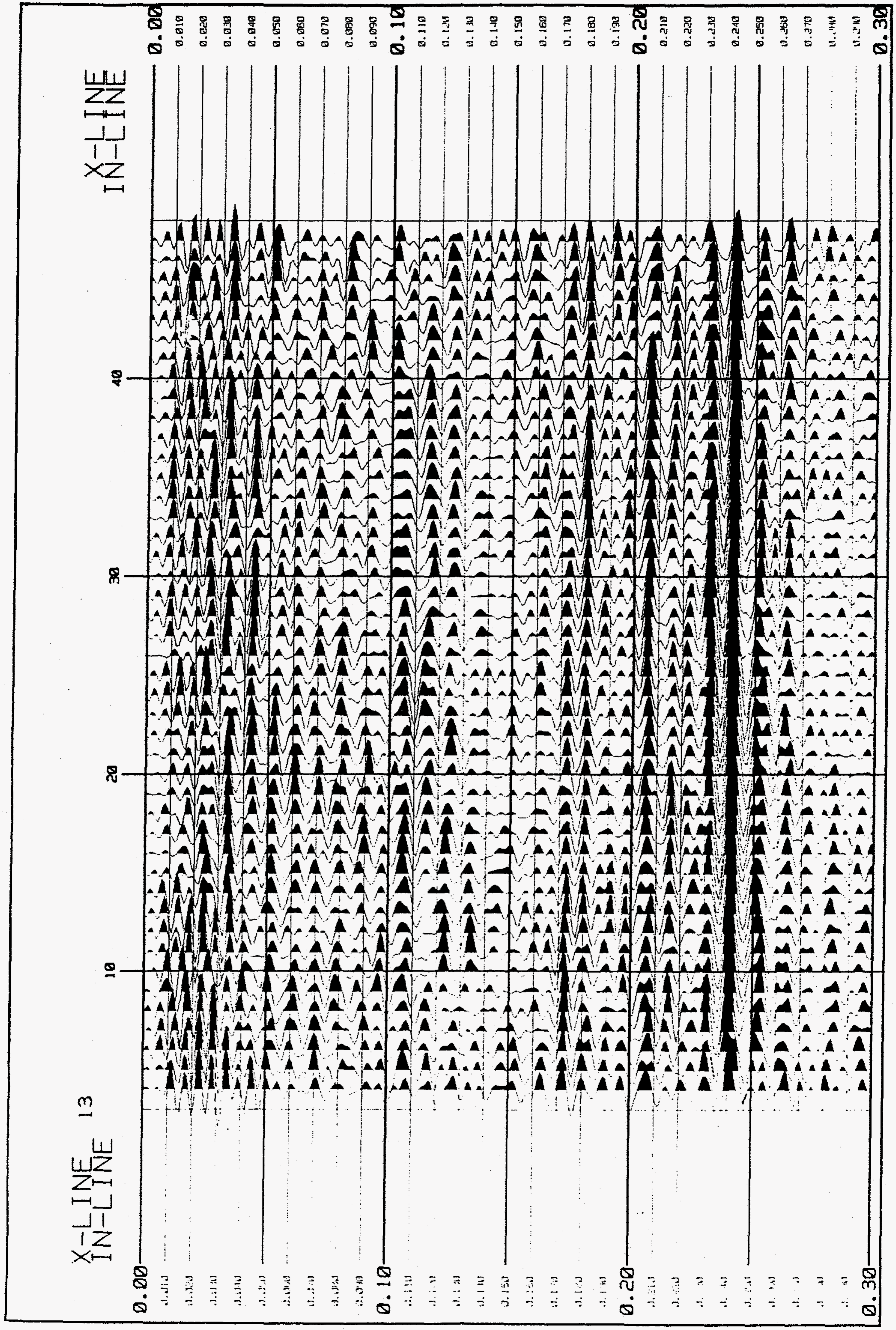
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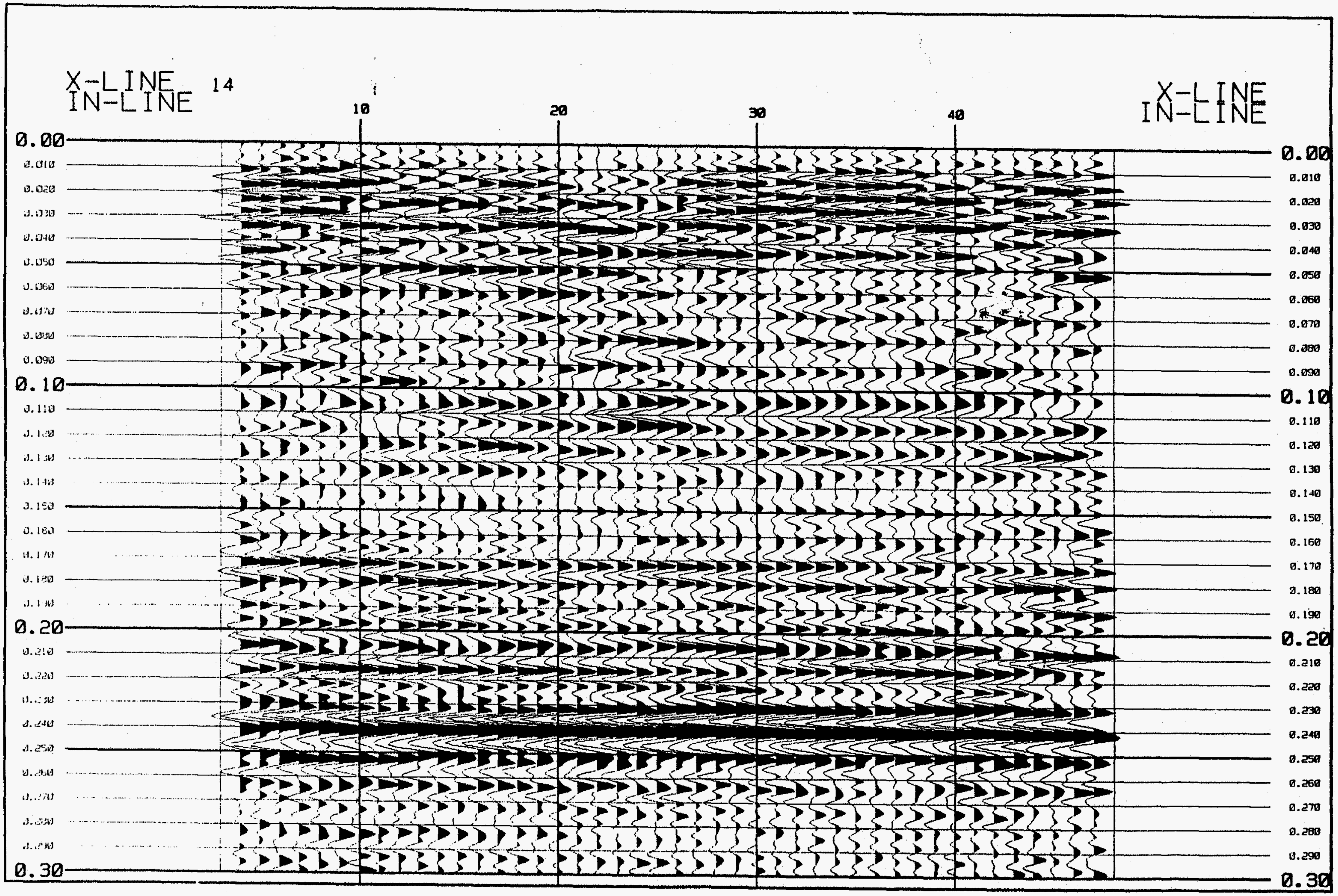
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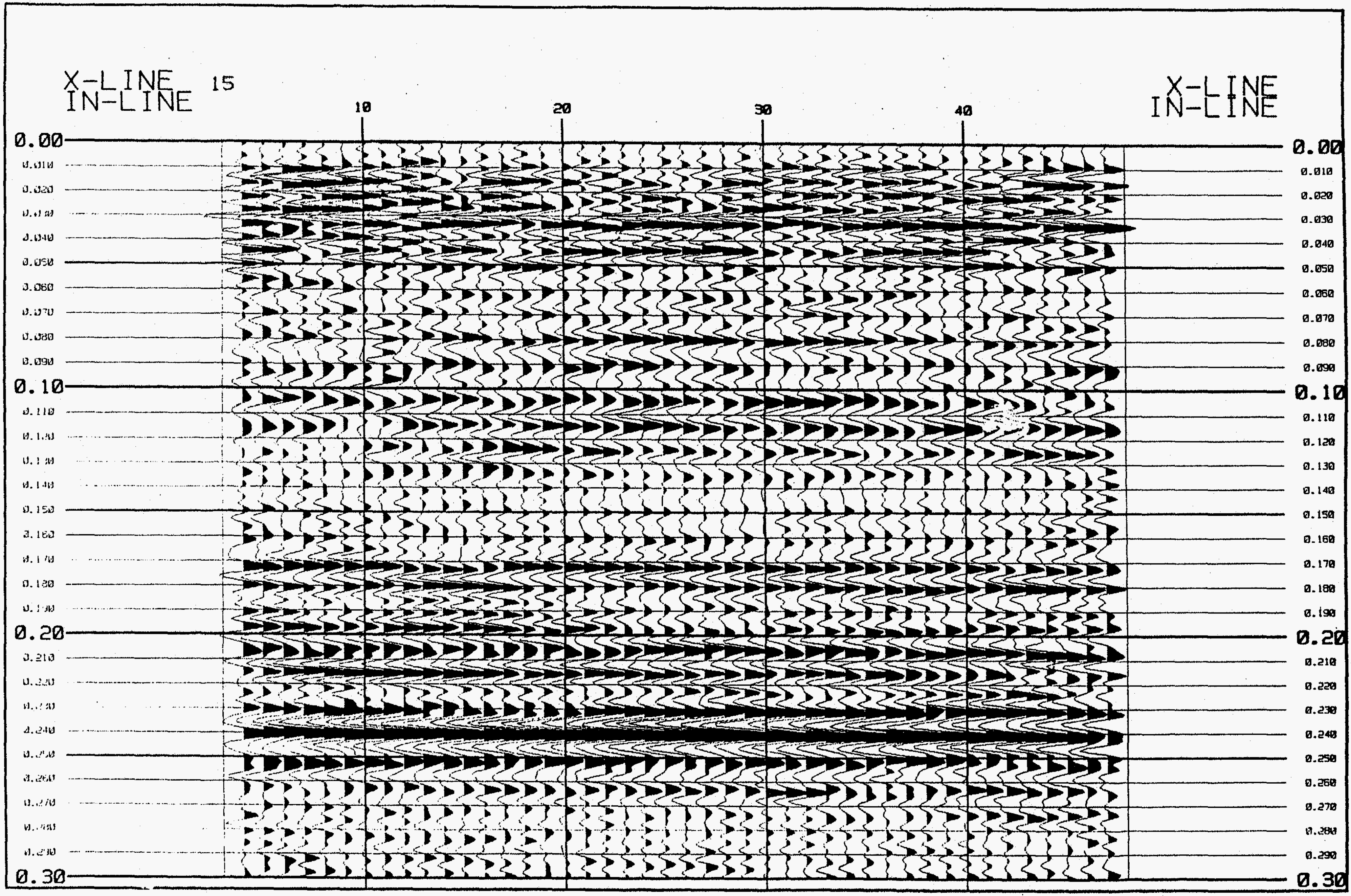
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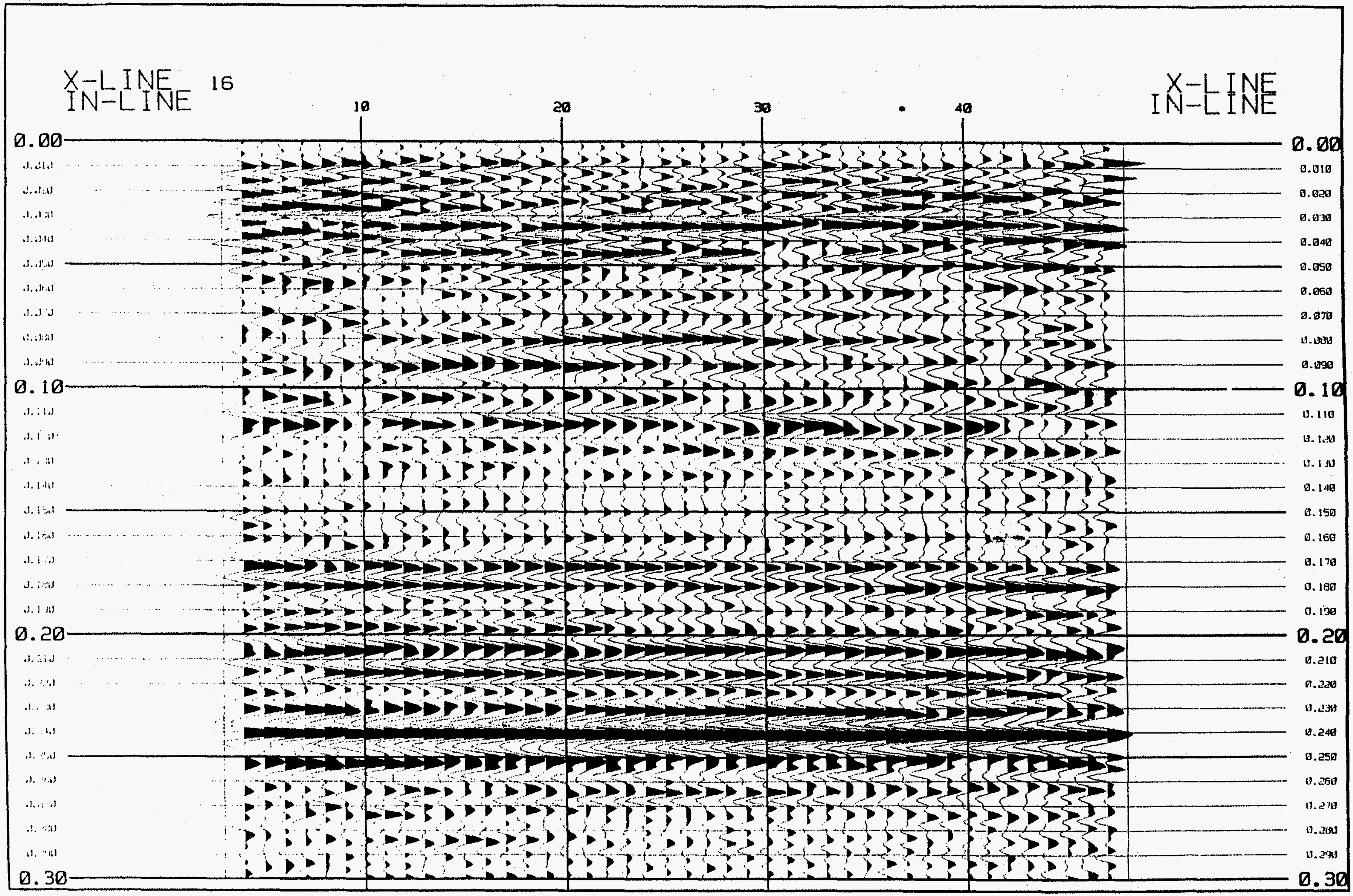
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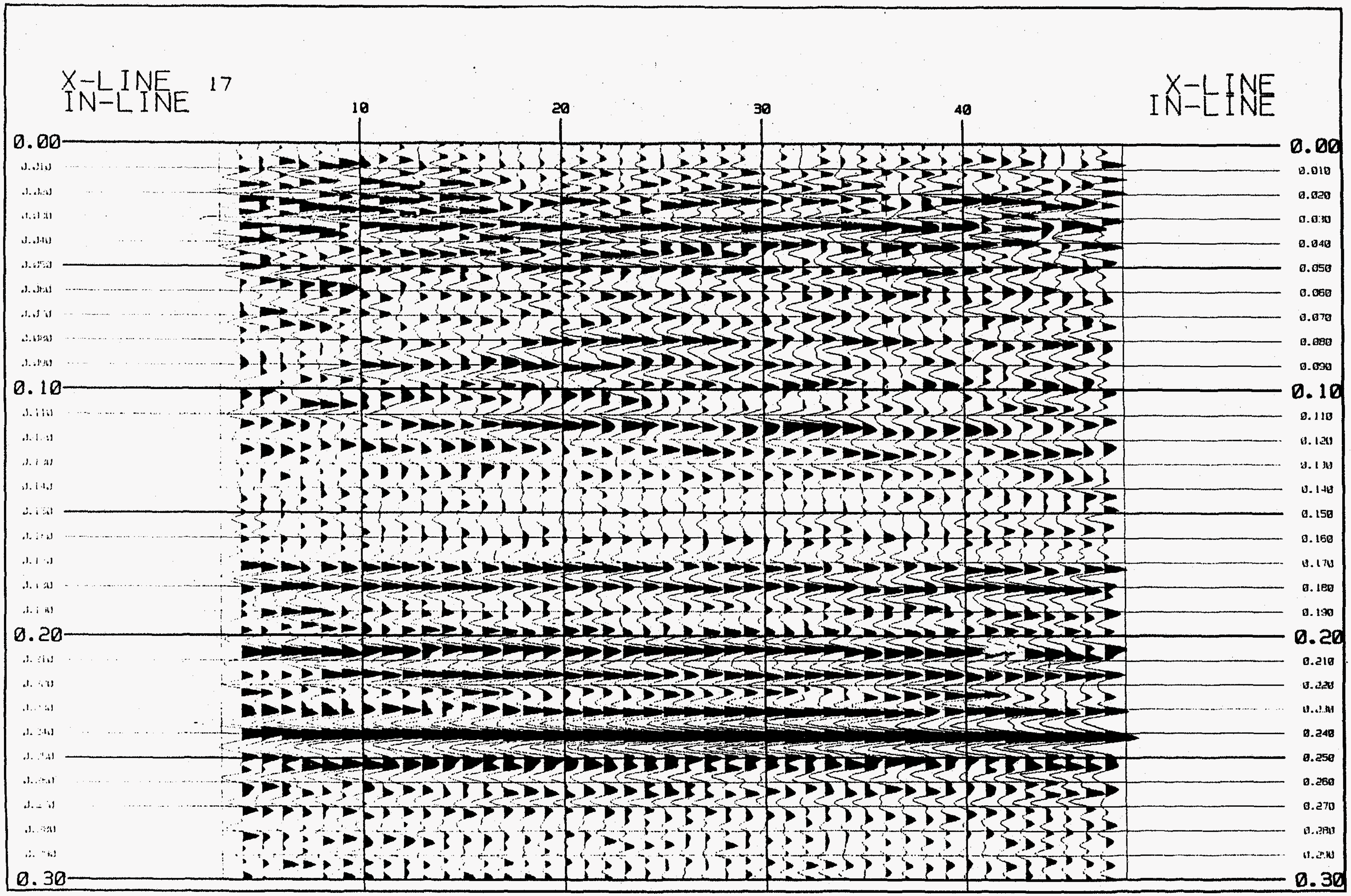
X-LINE 17
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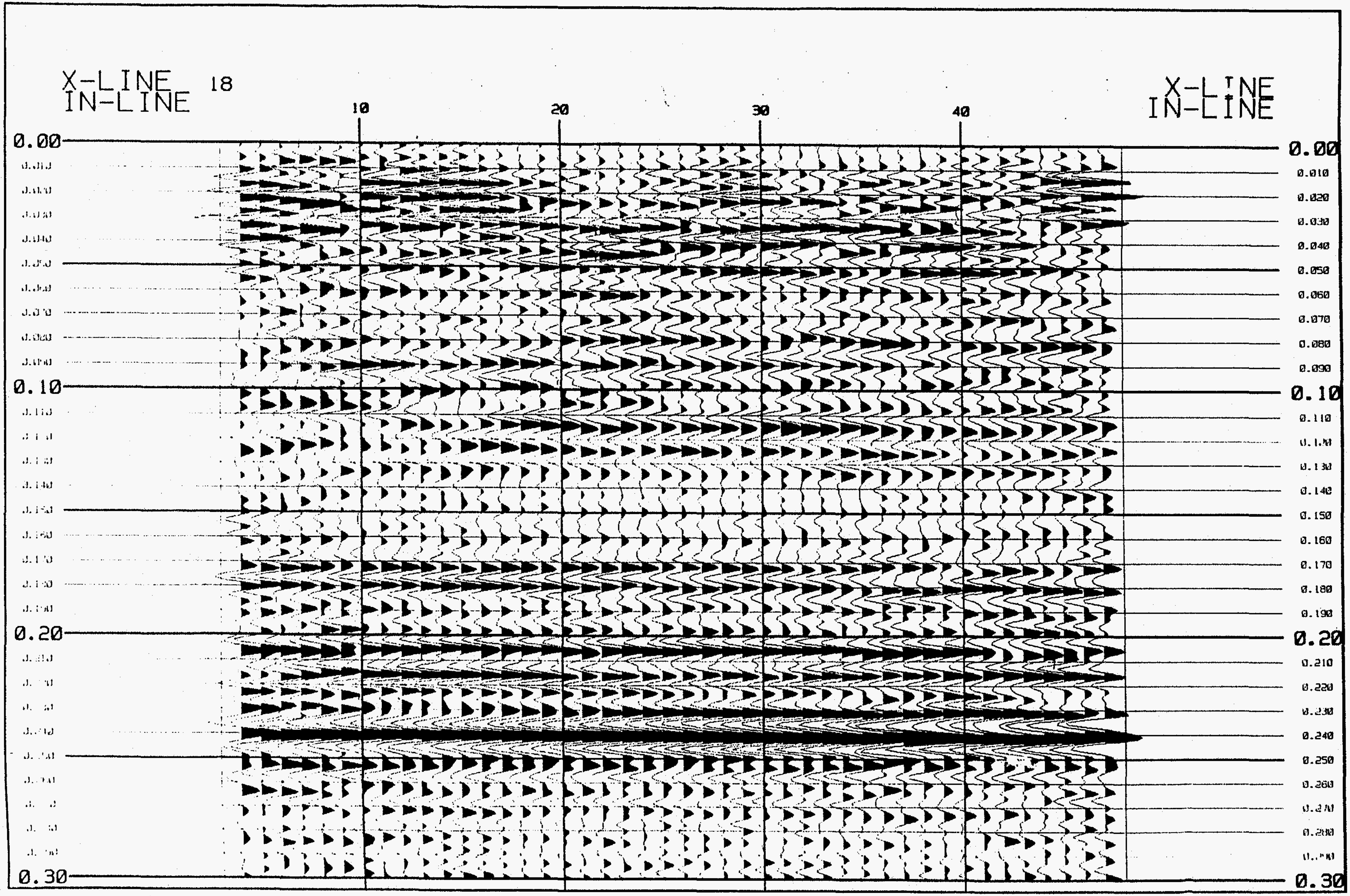

X-LINE 18
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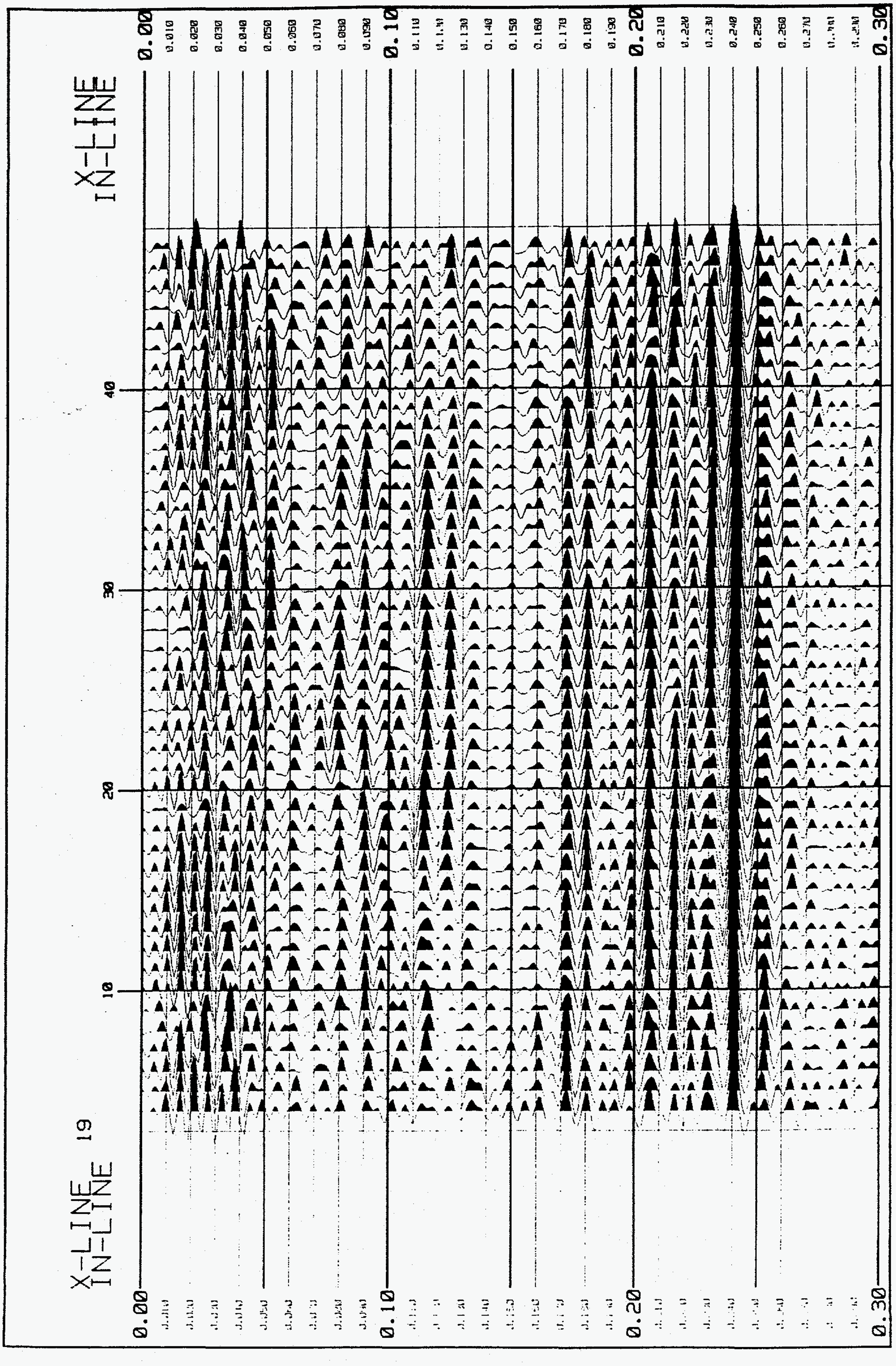
X-LINE 19
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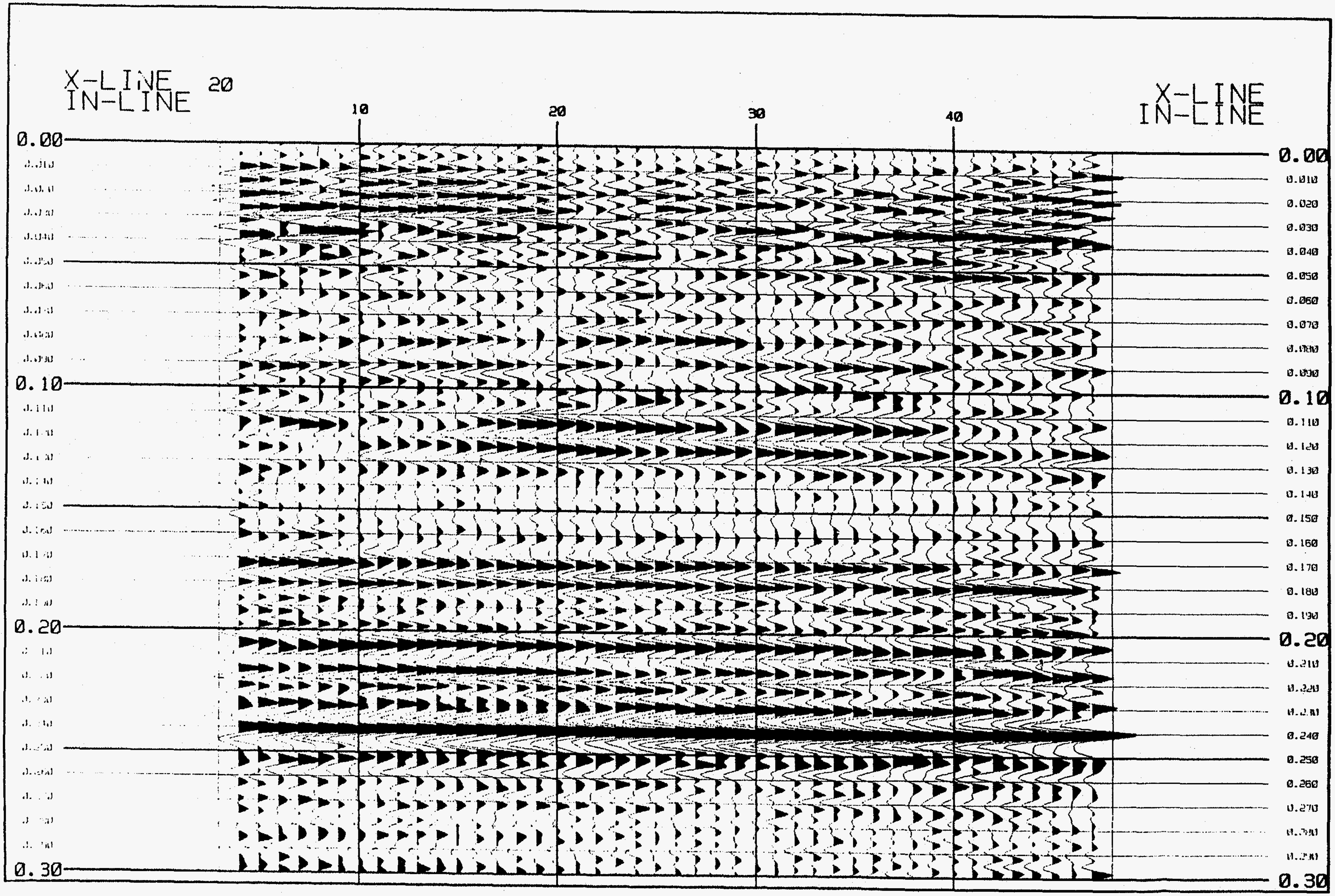
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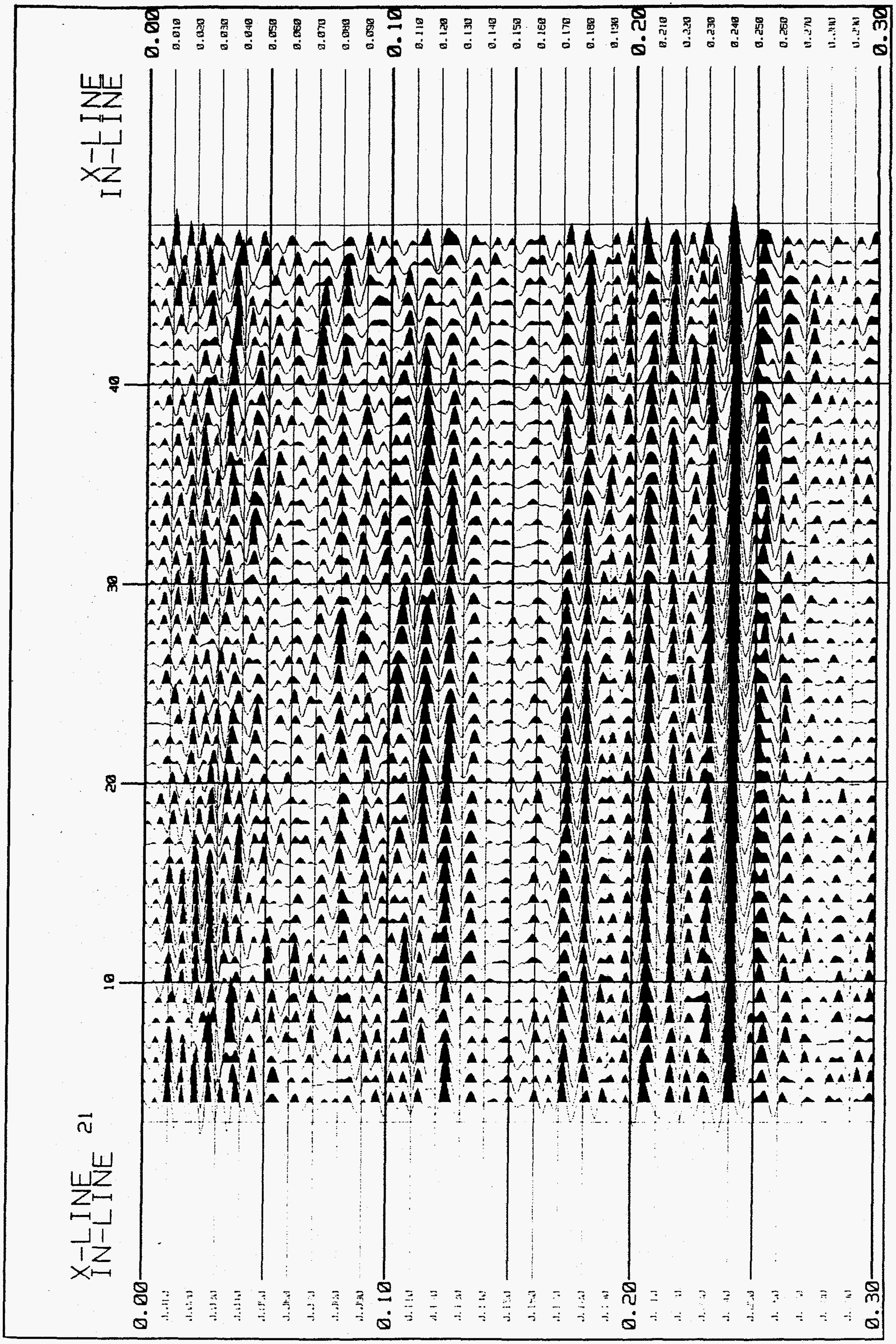
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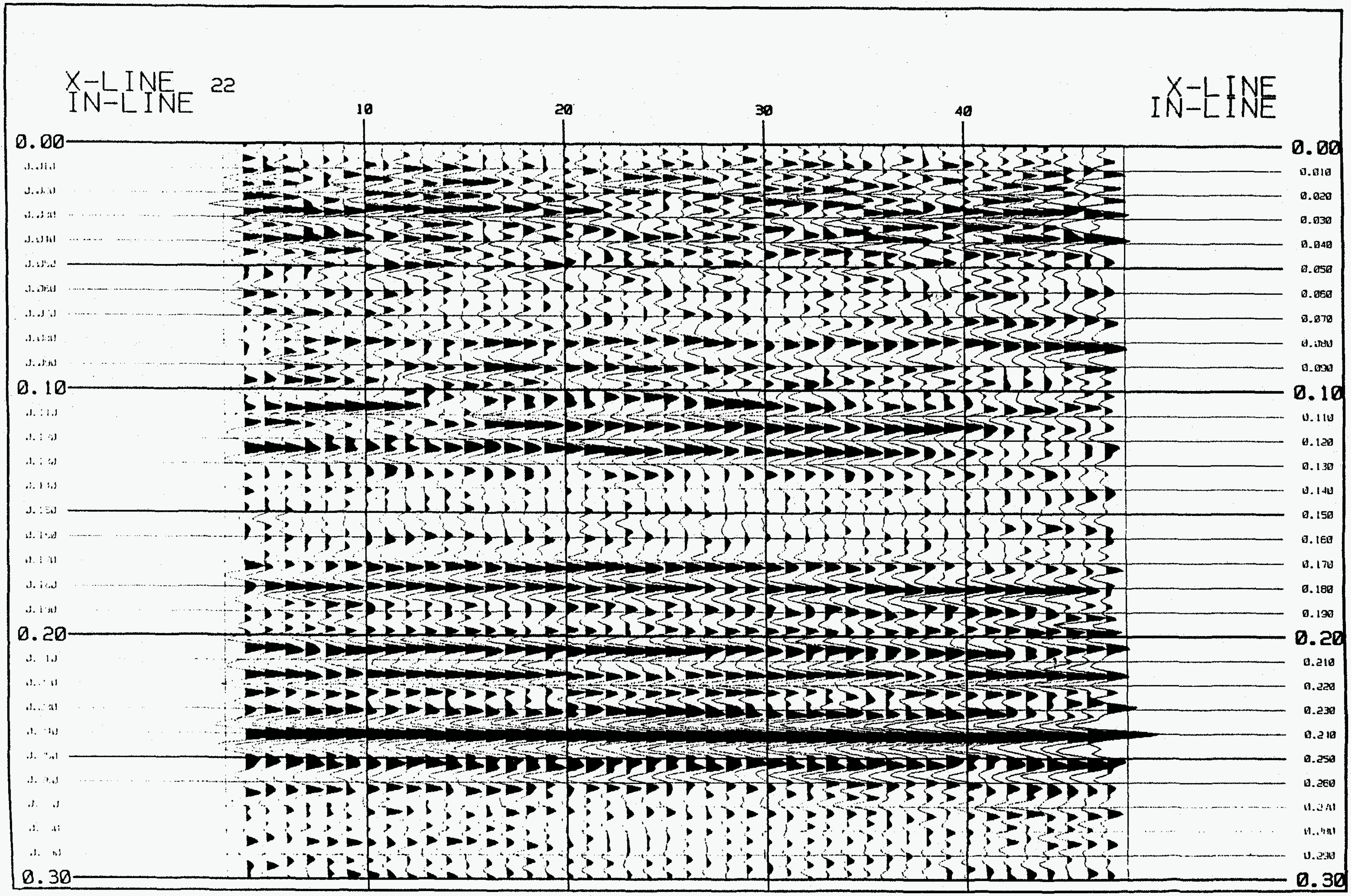

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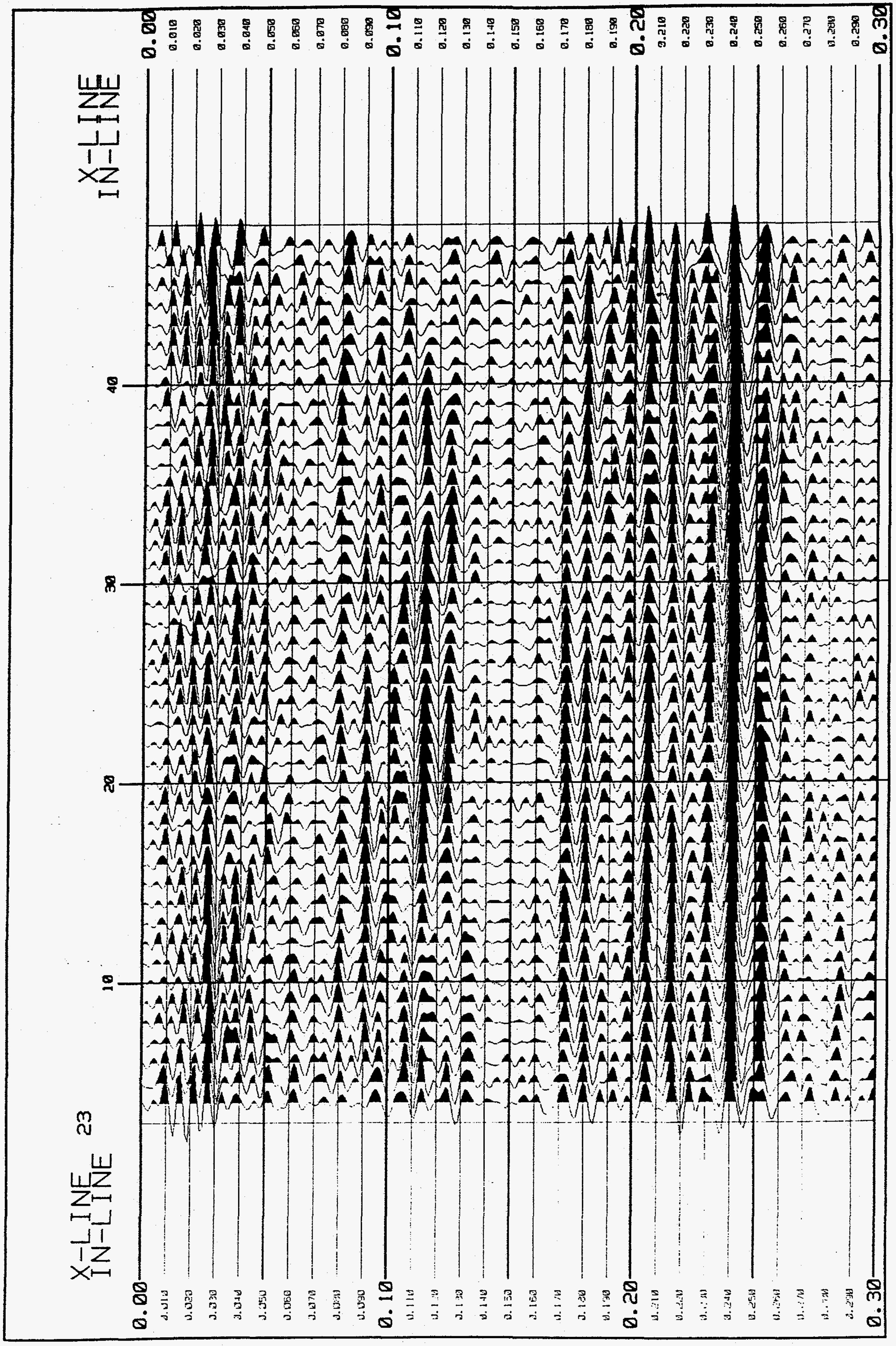
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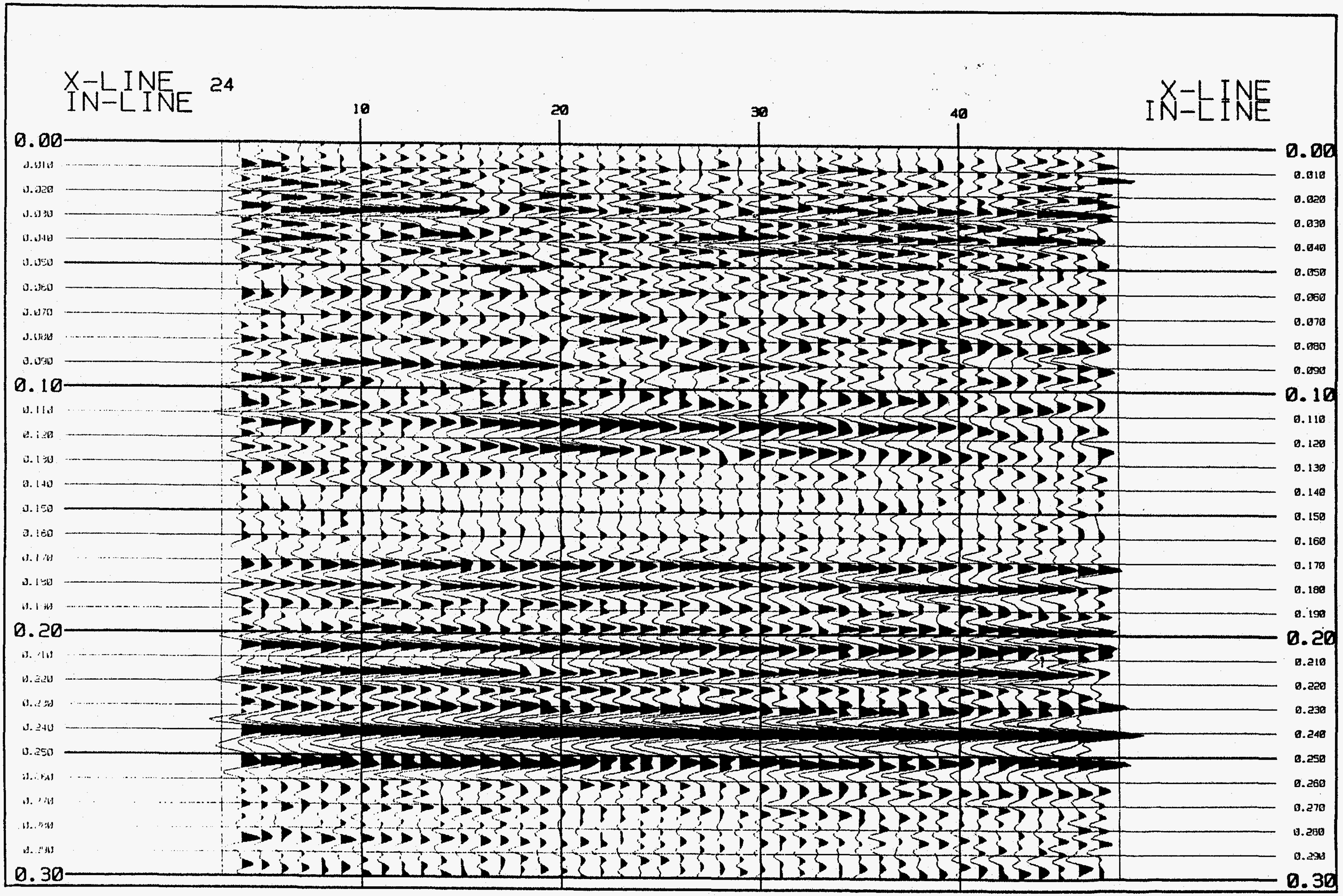
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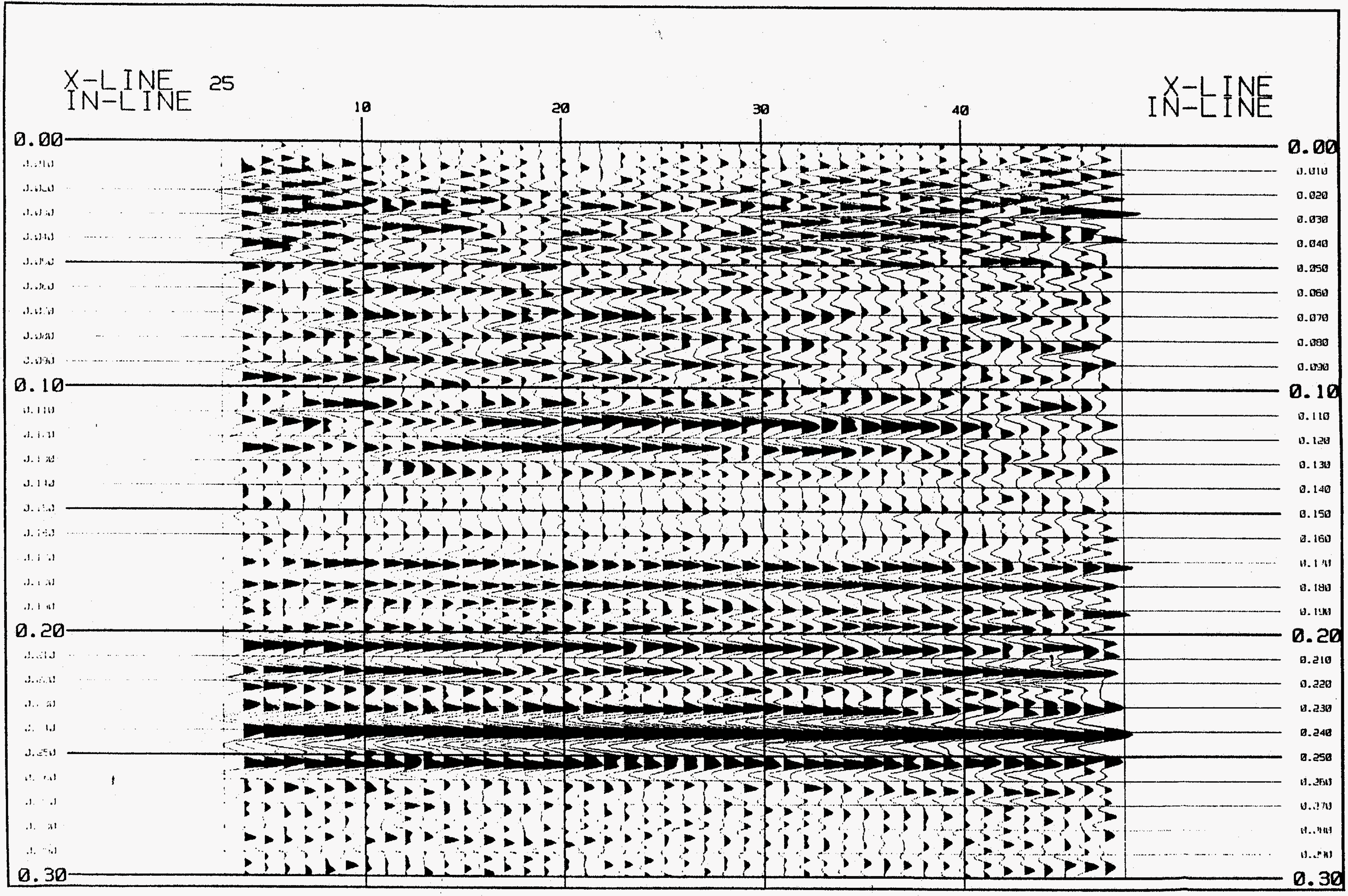
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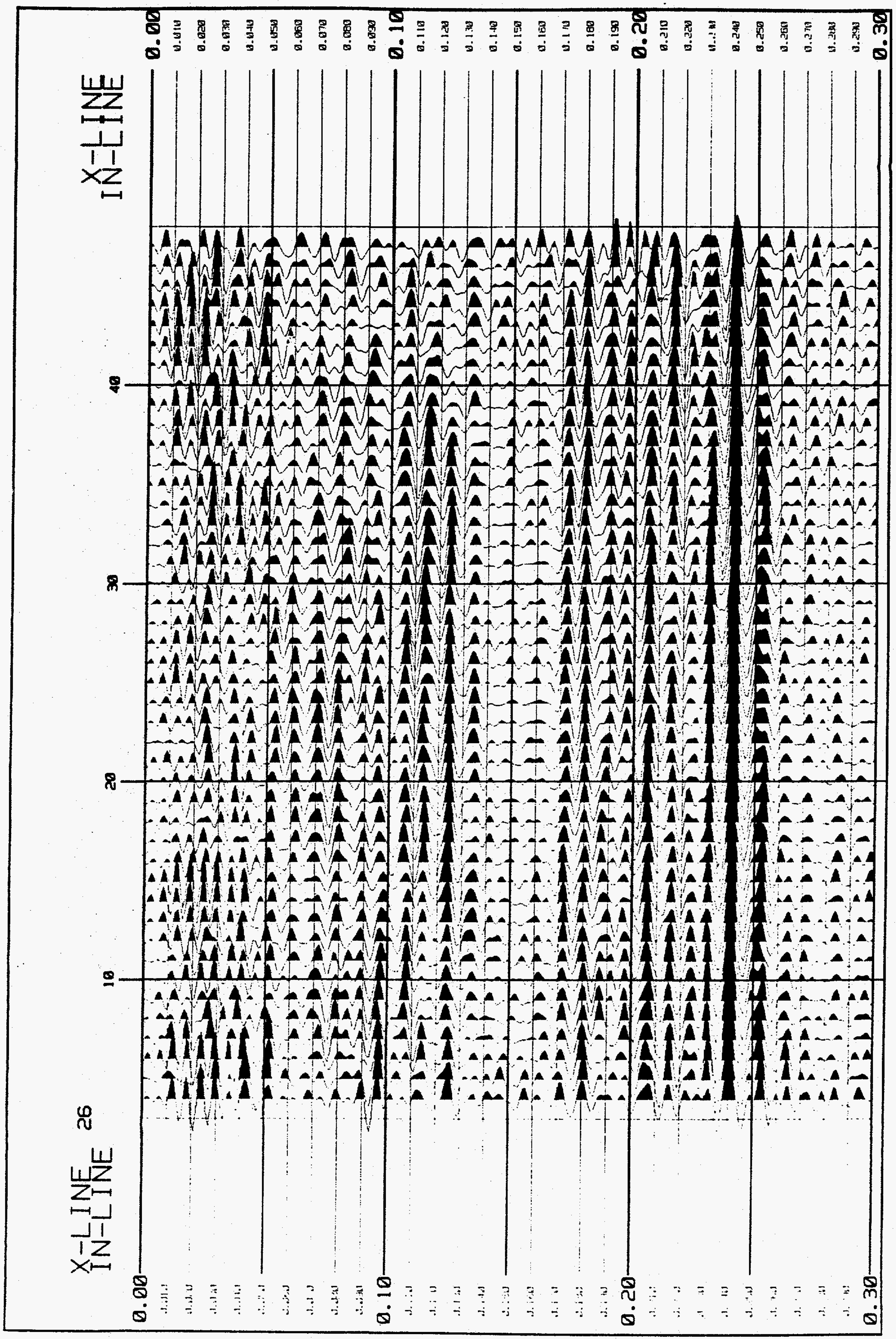
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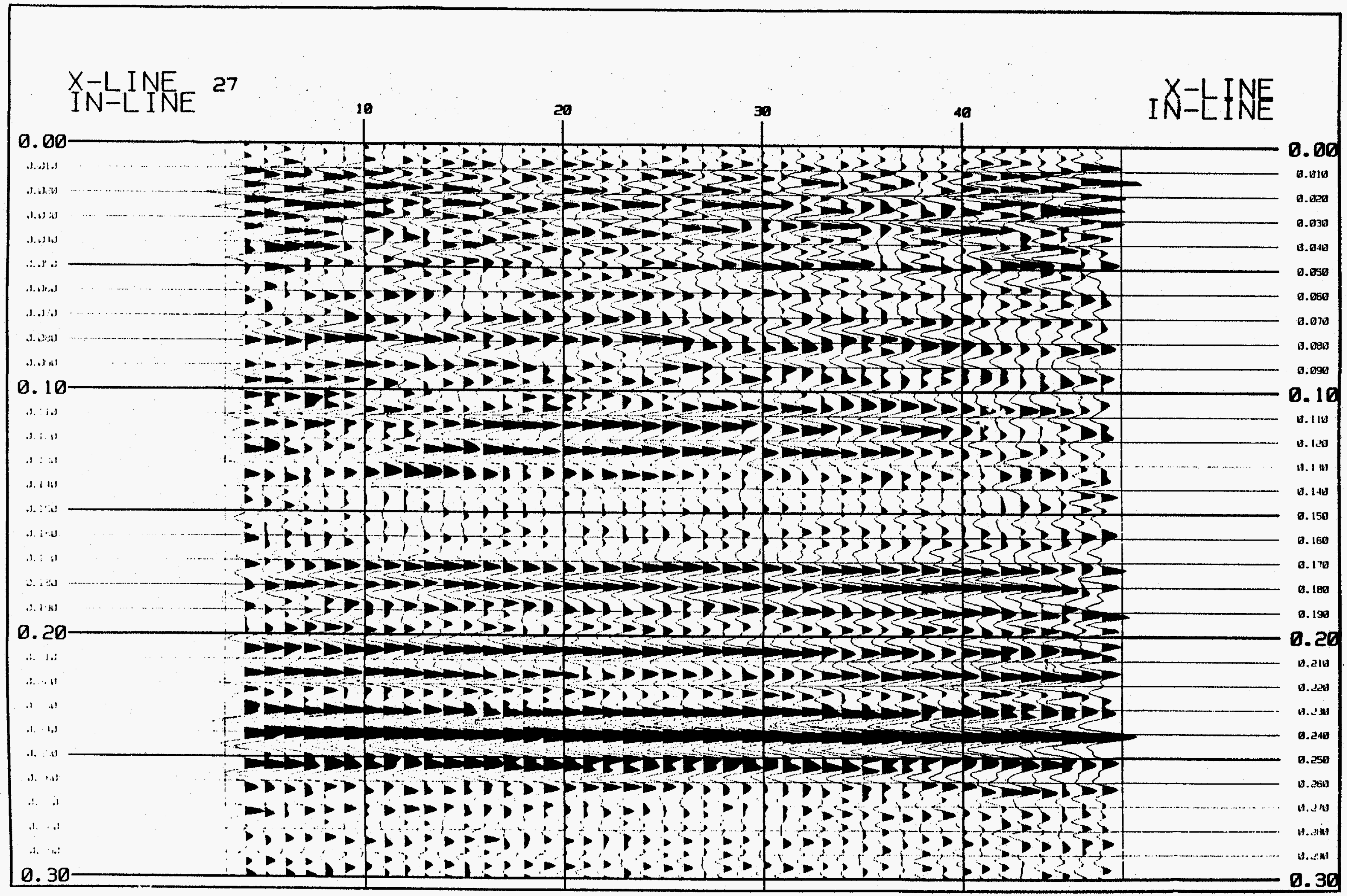
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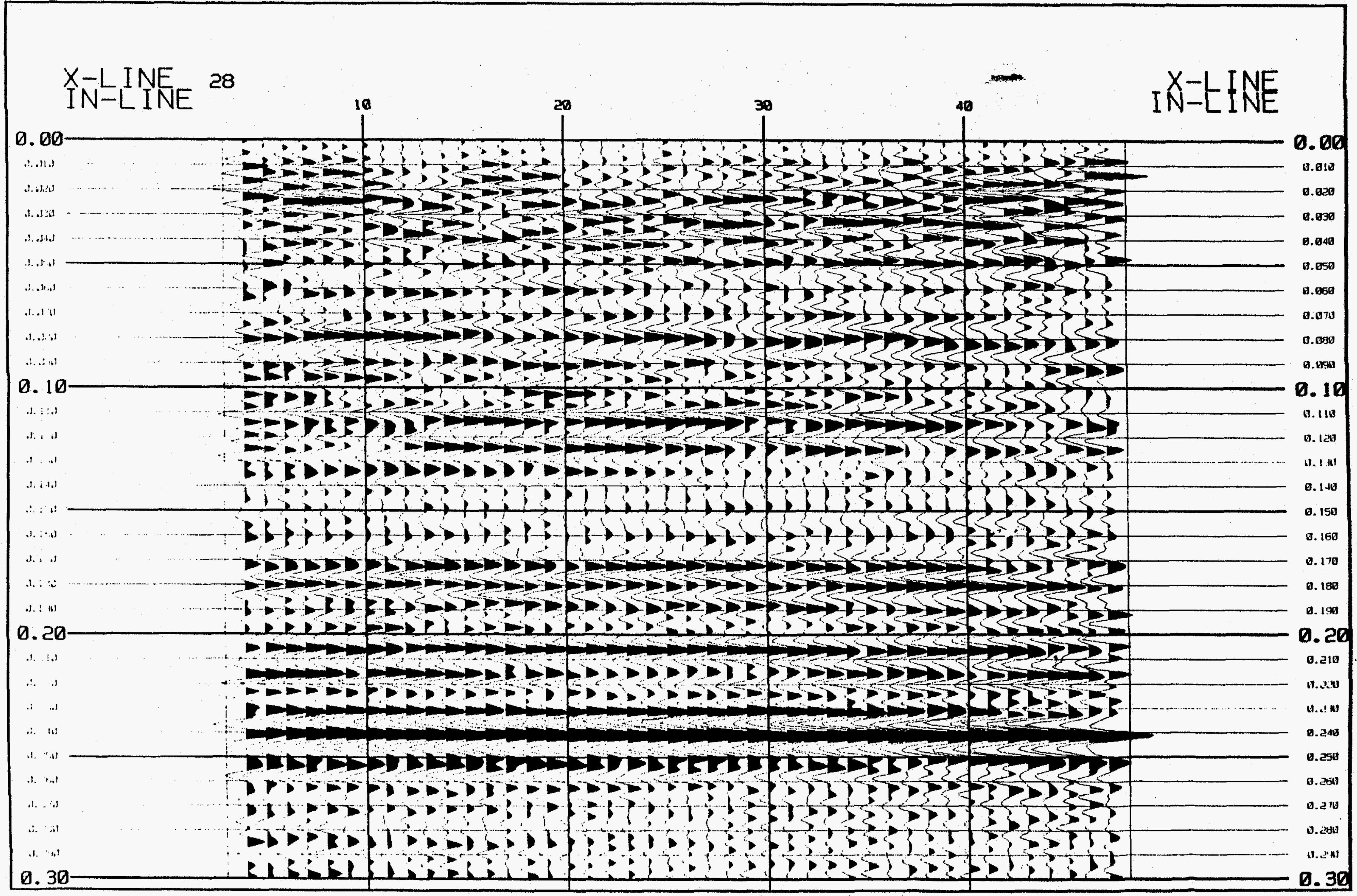
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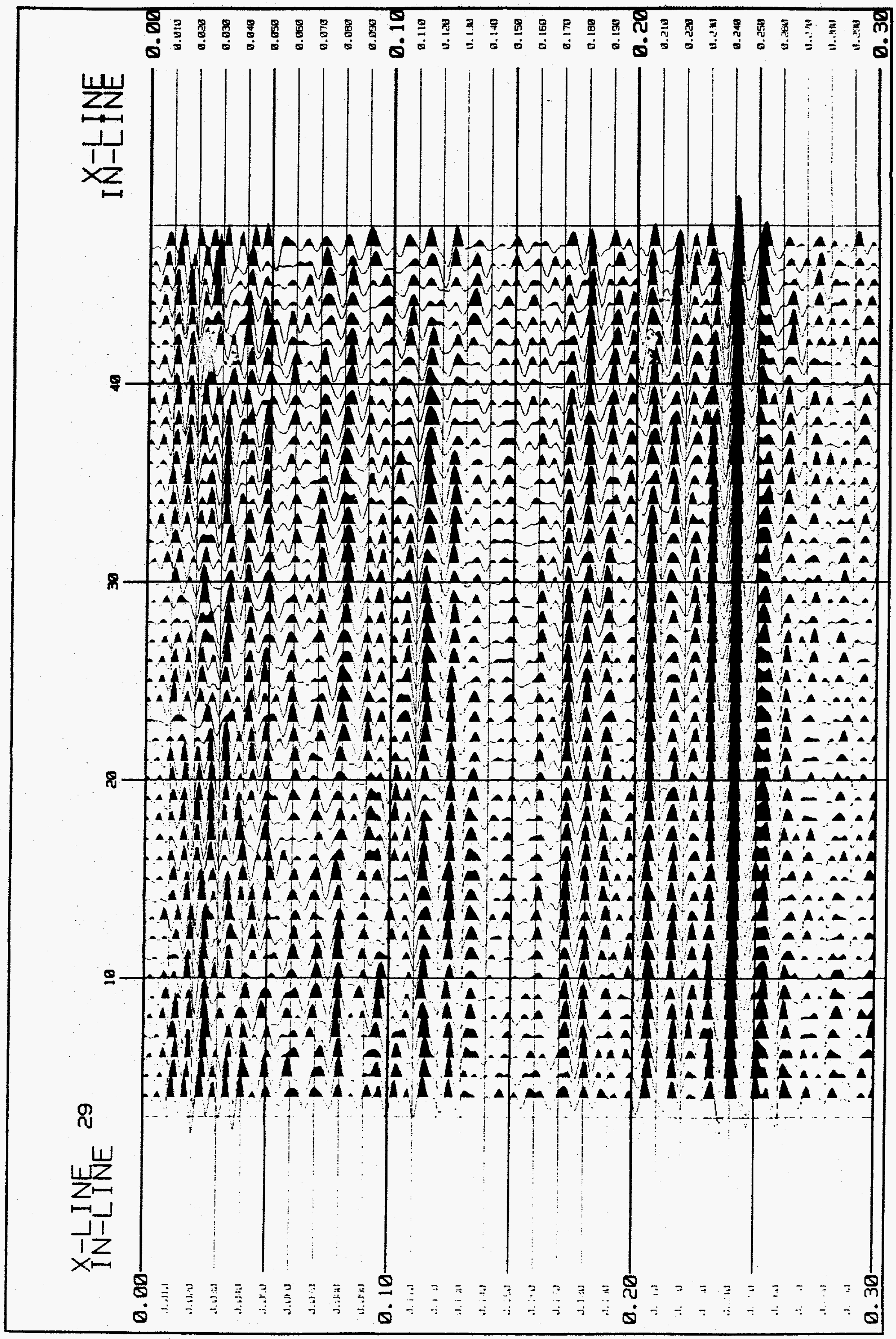
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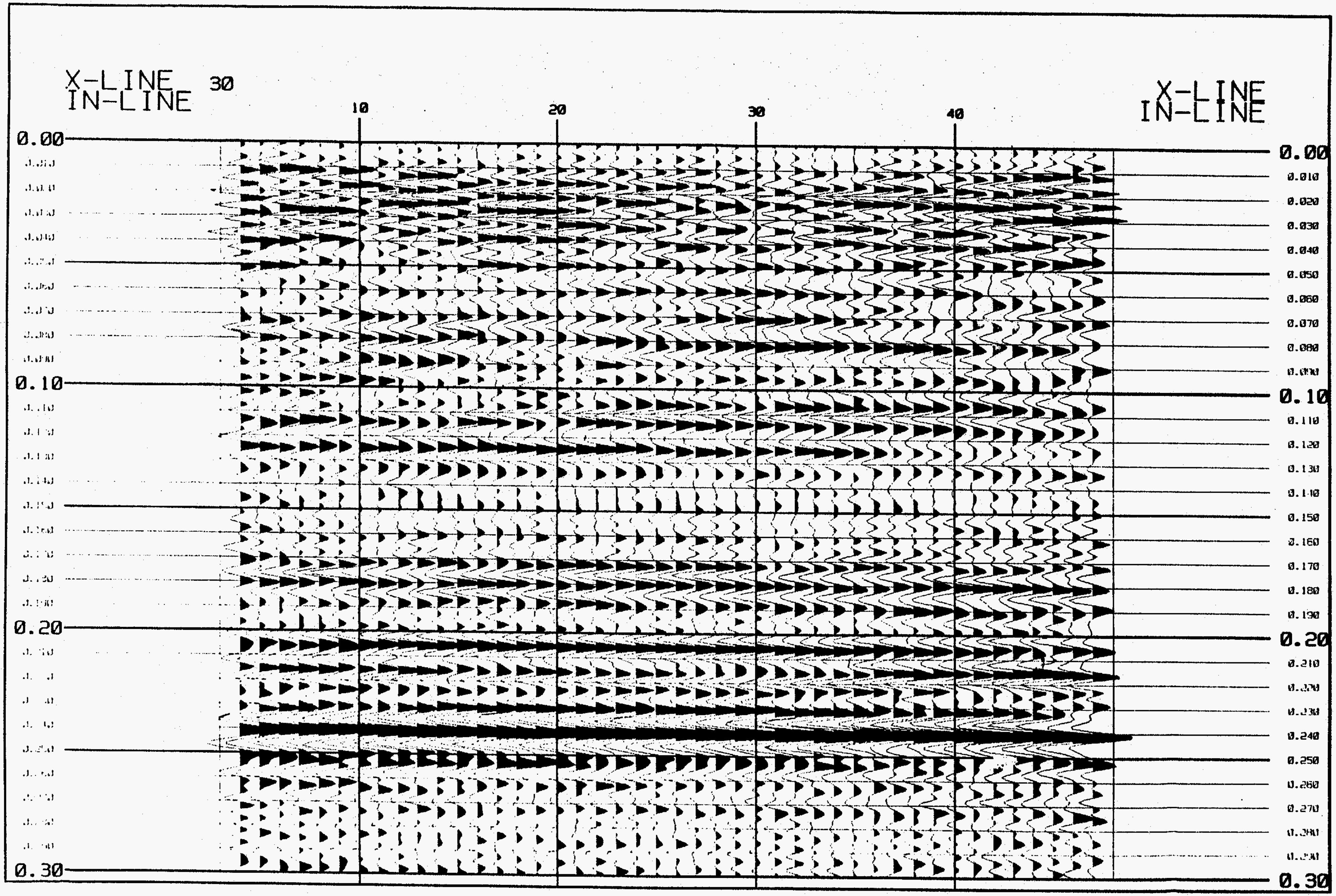
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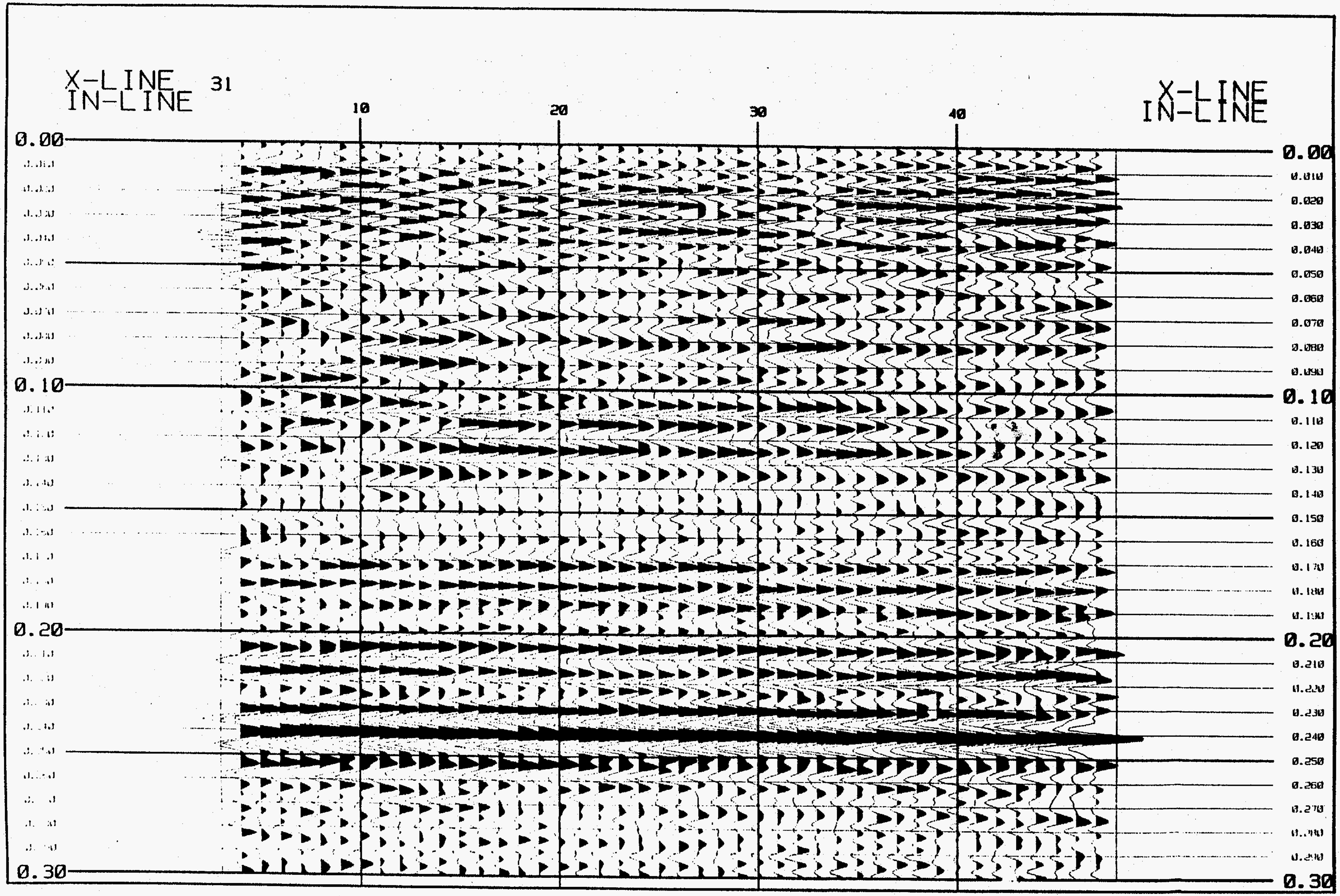
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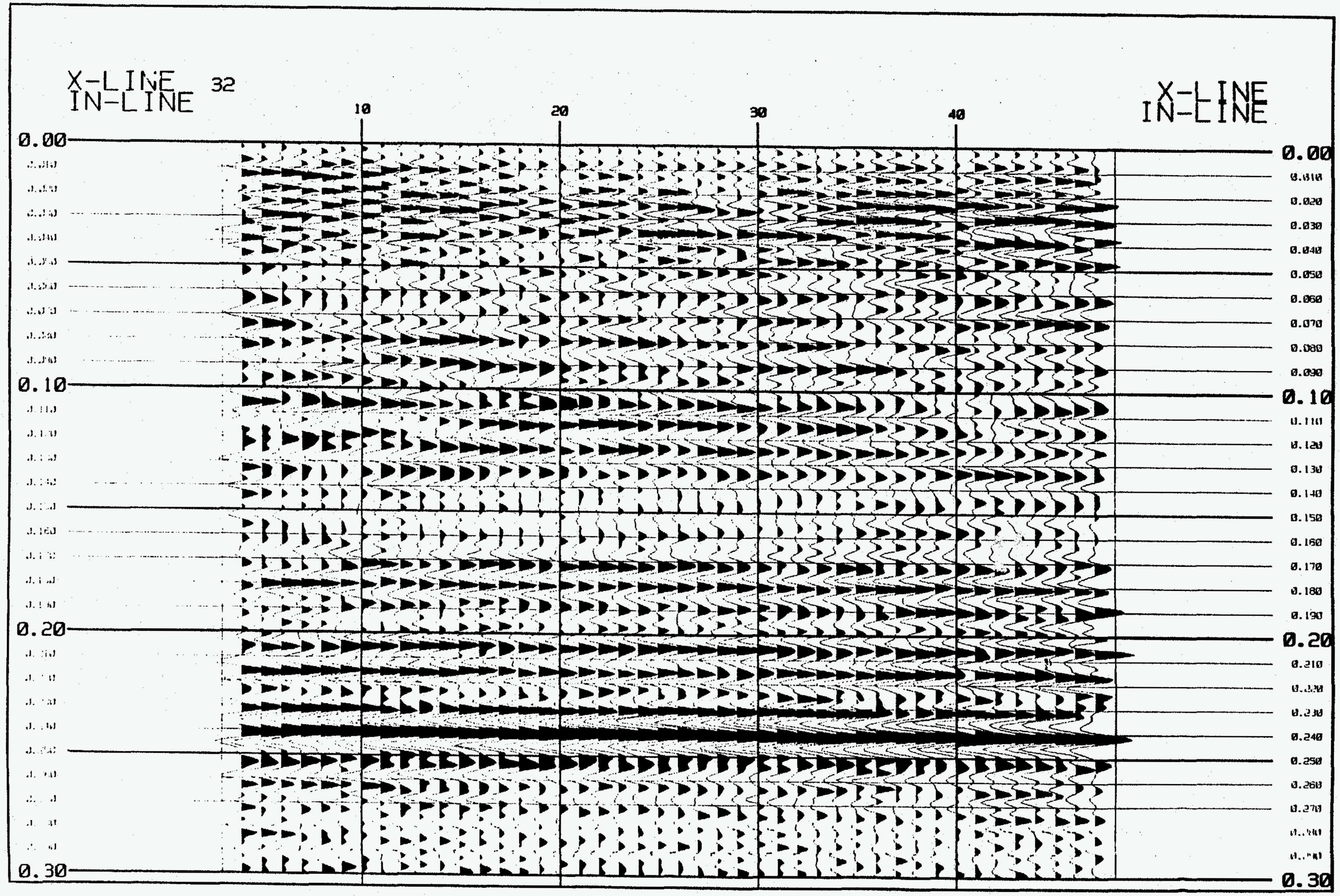
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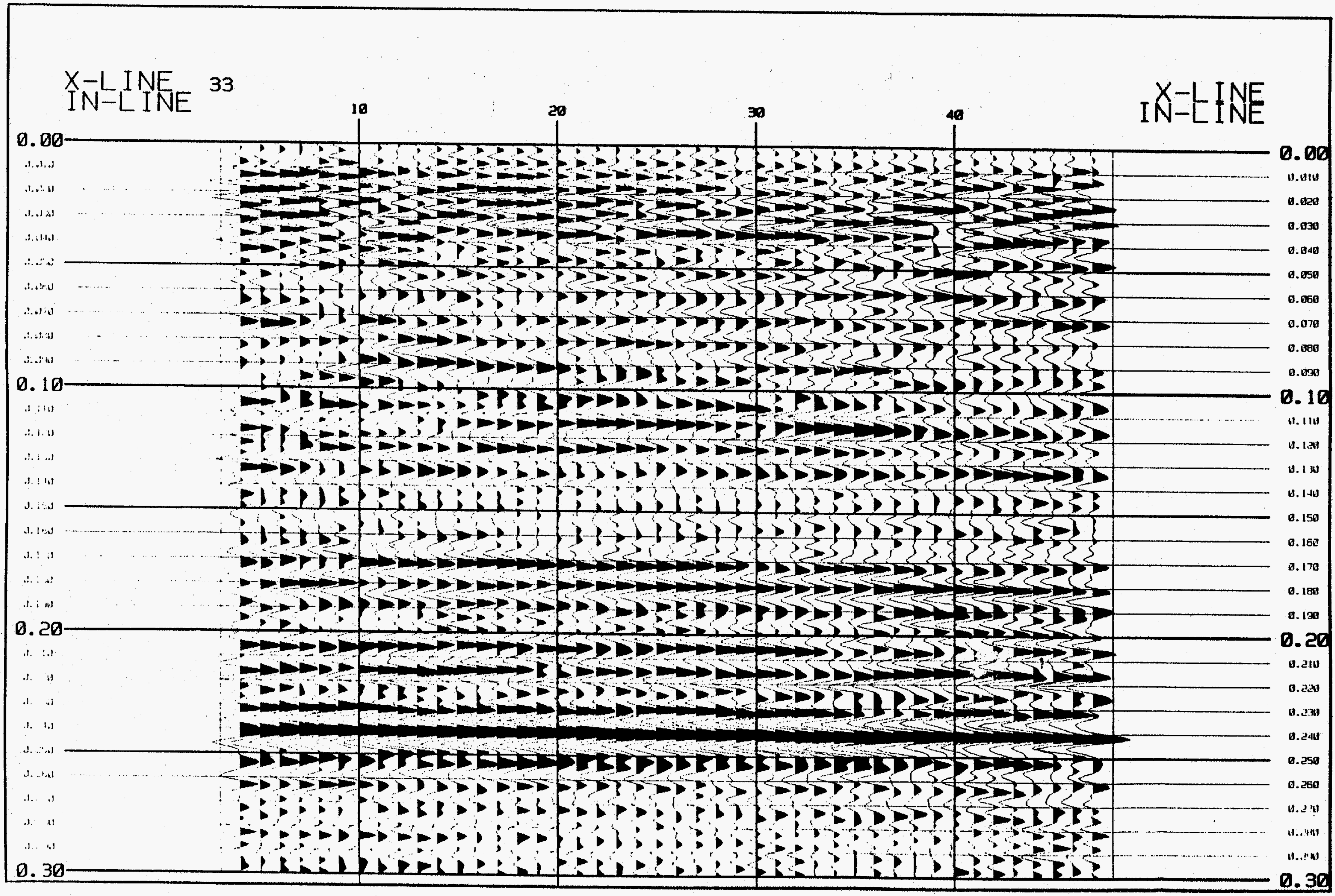
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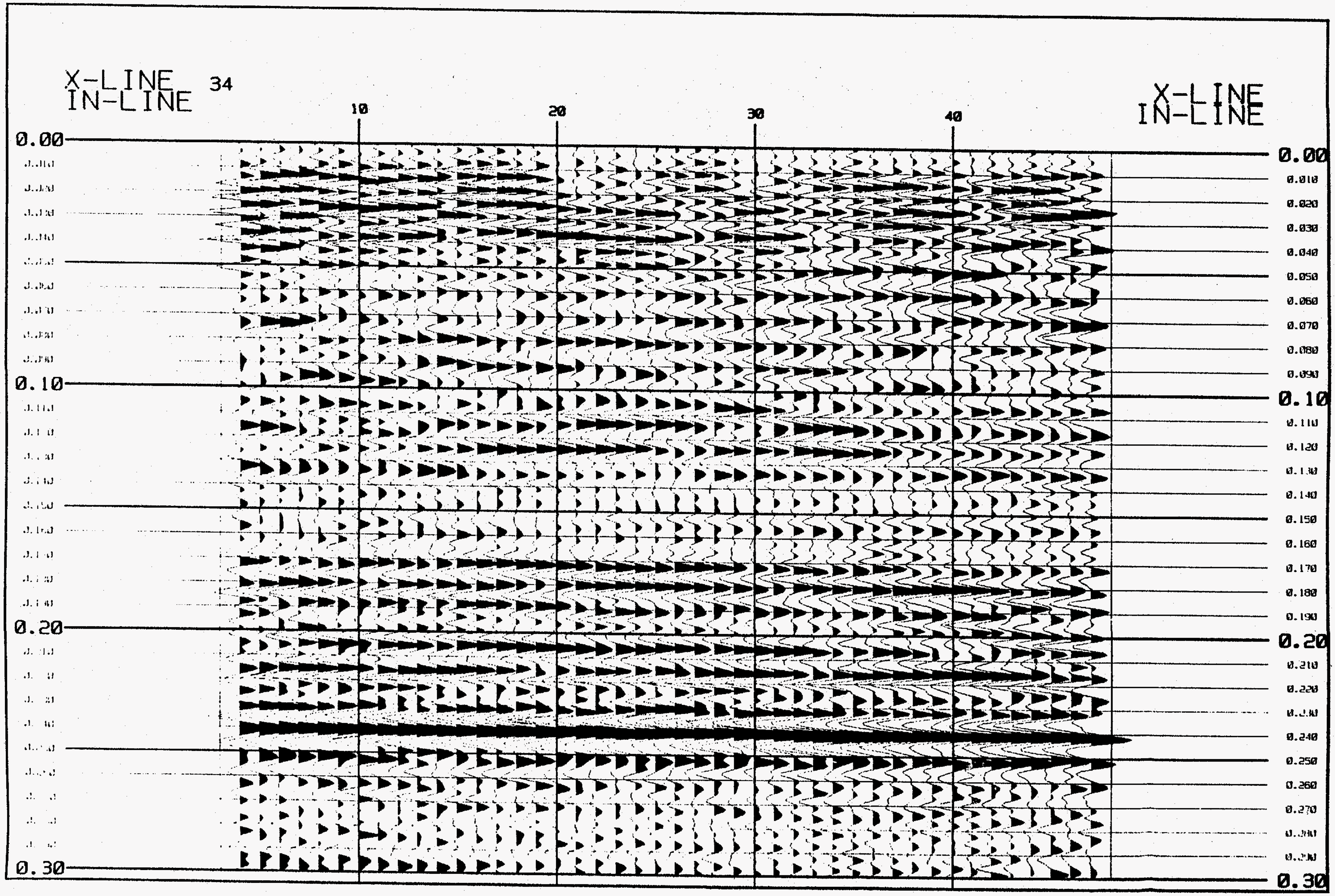
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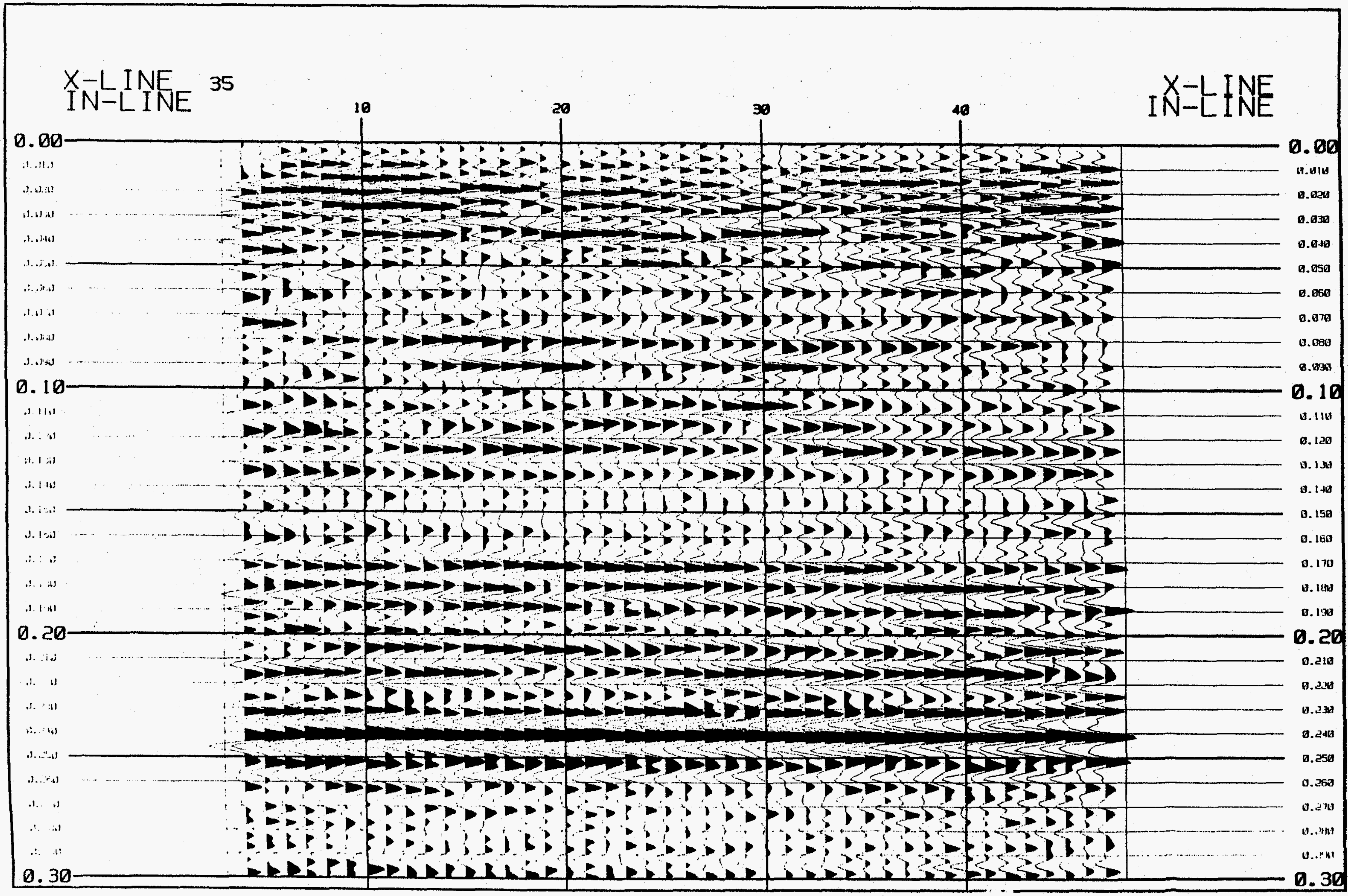

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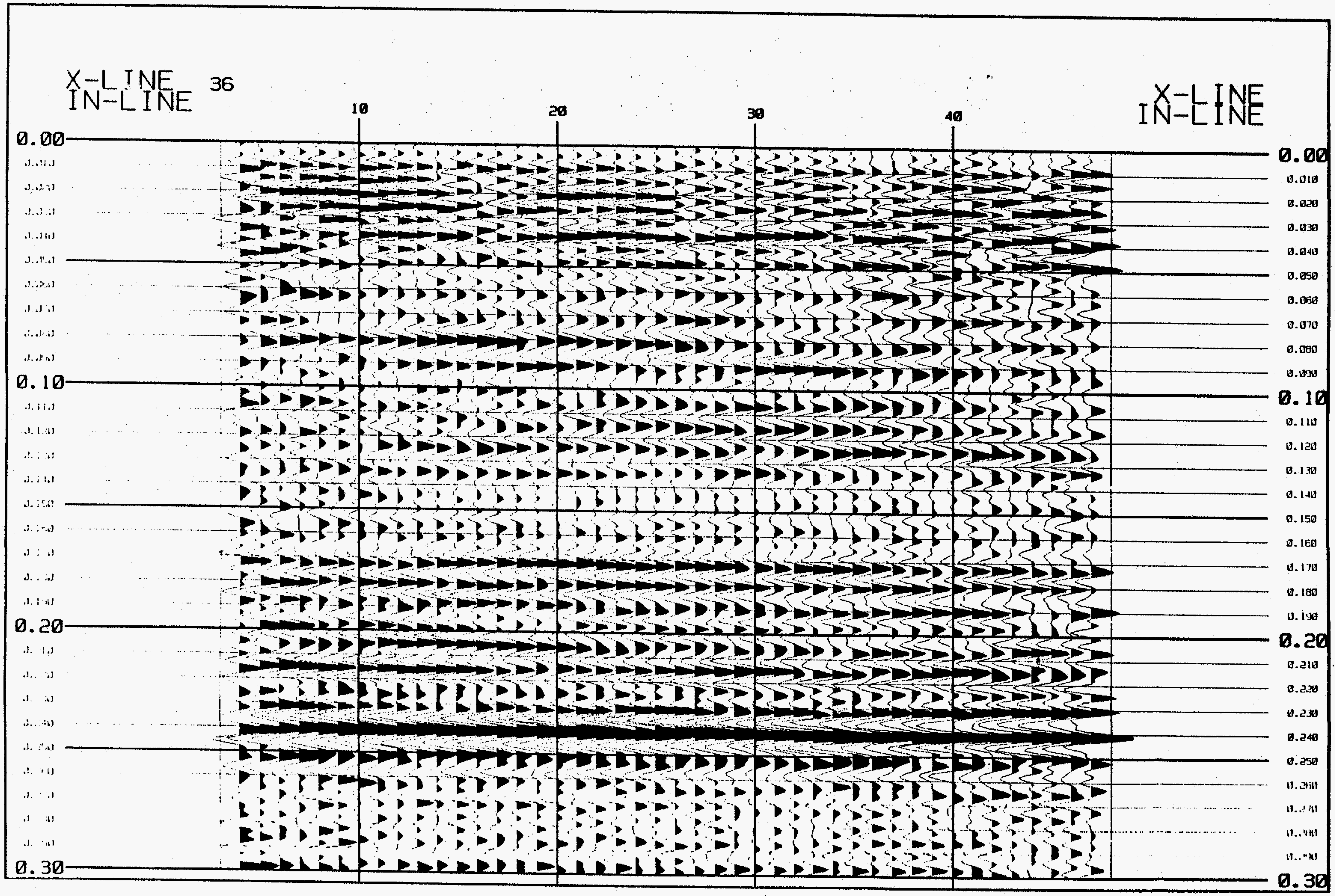
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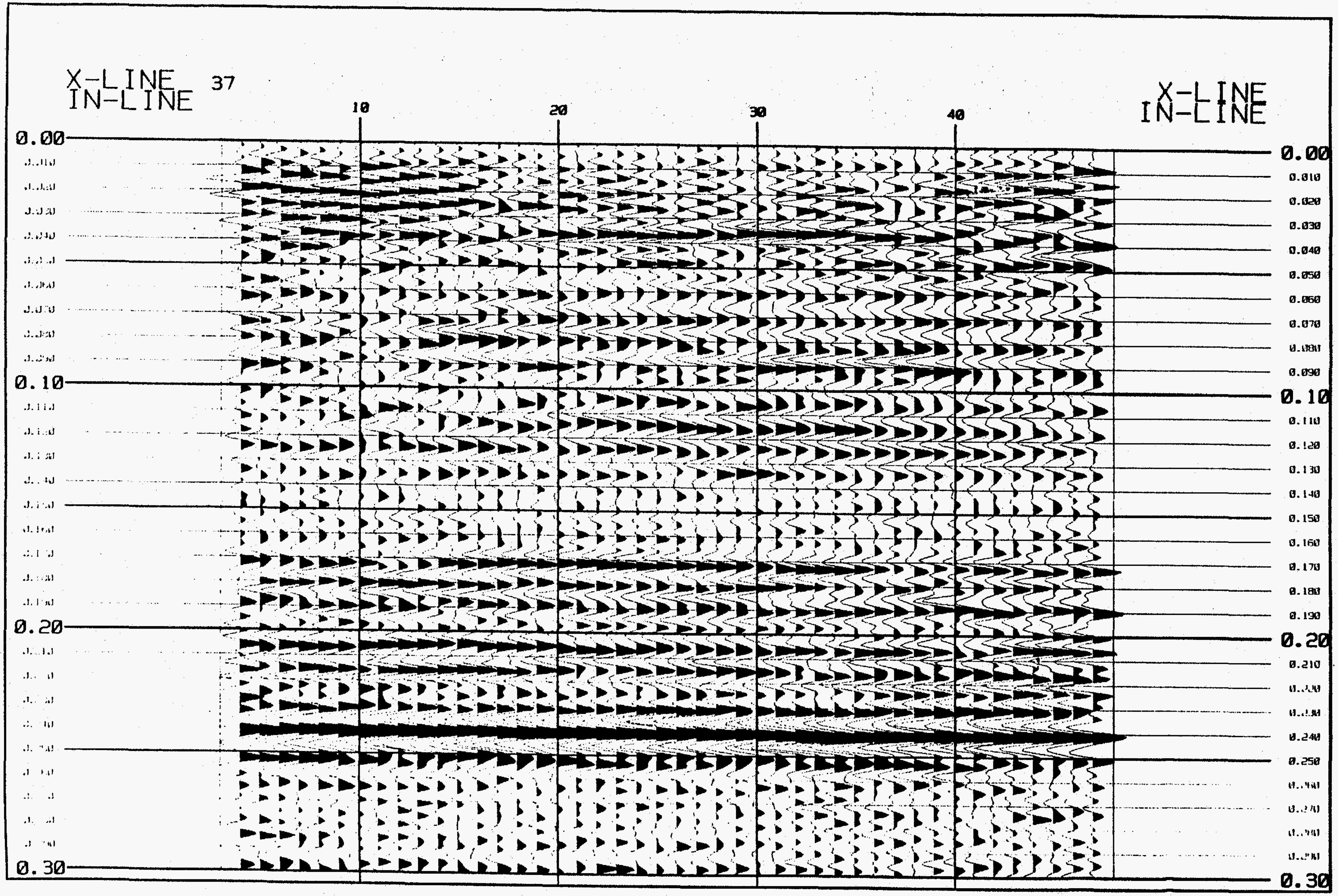
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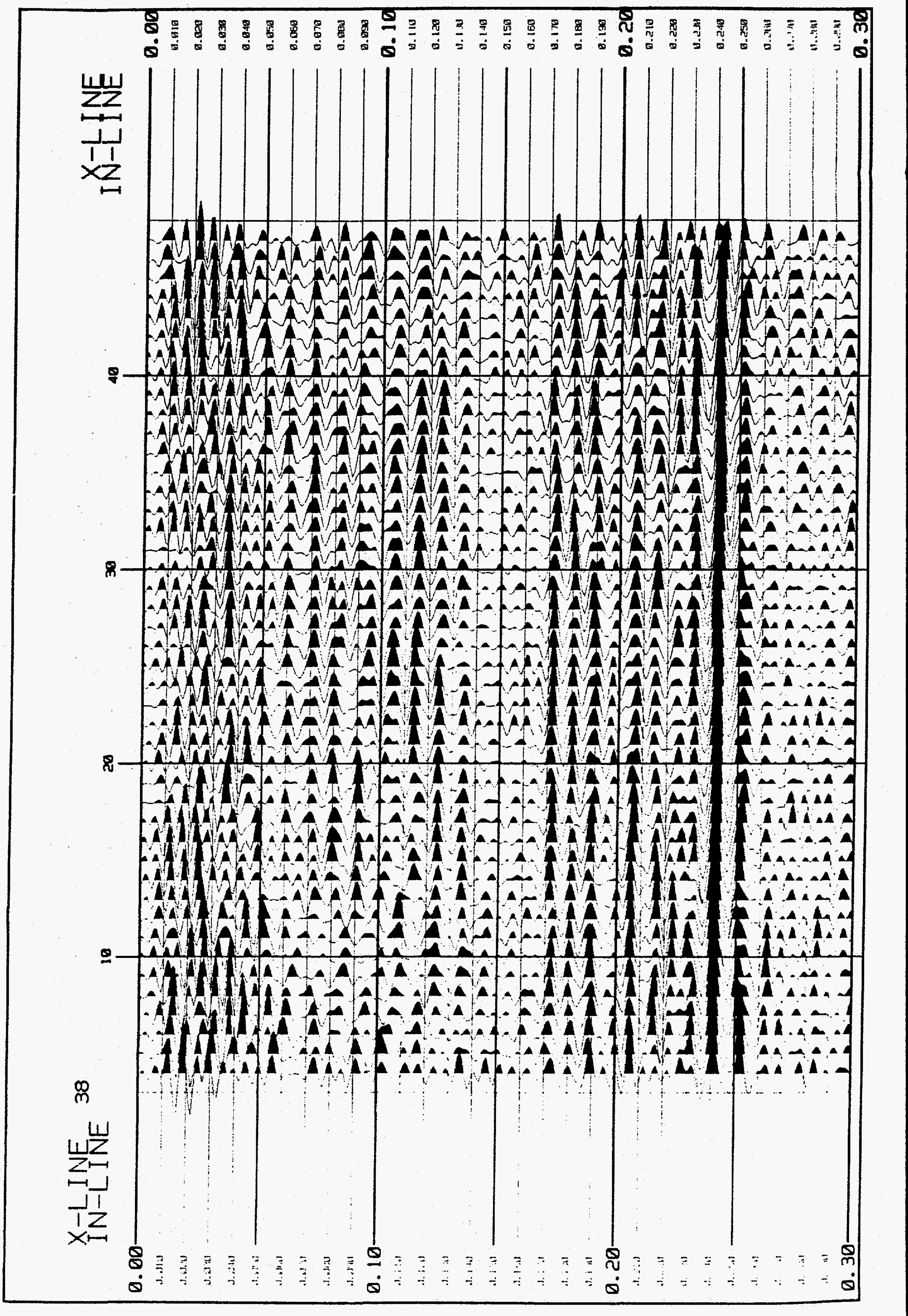
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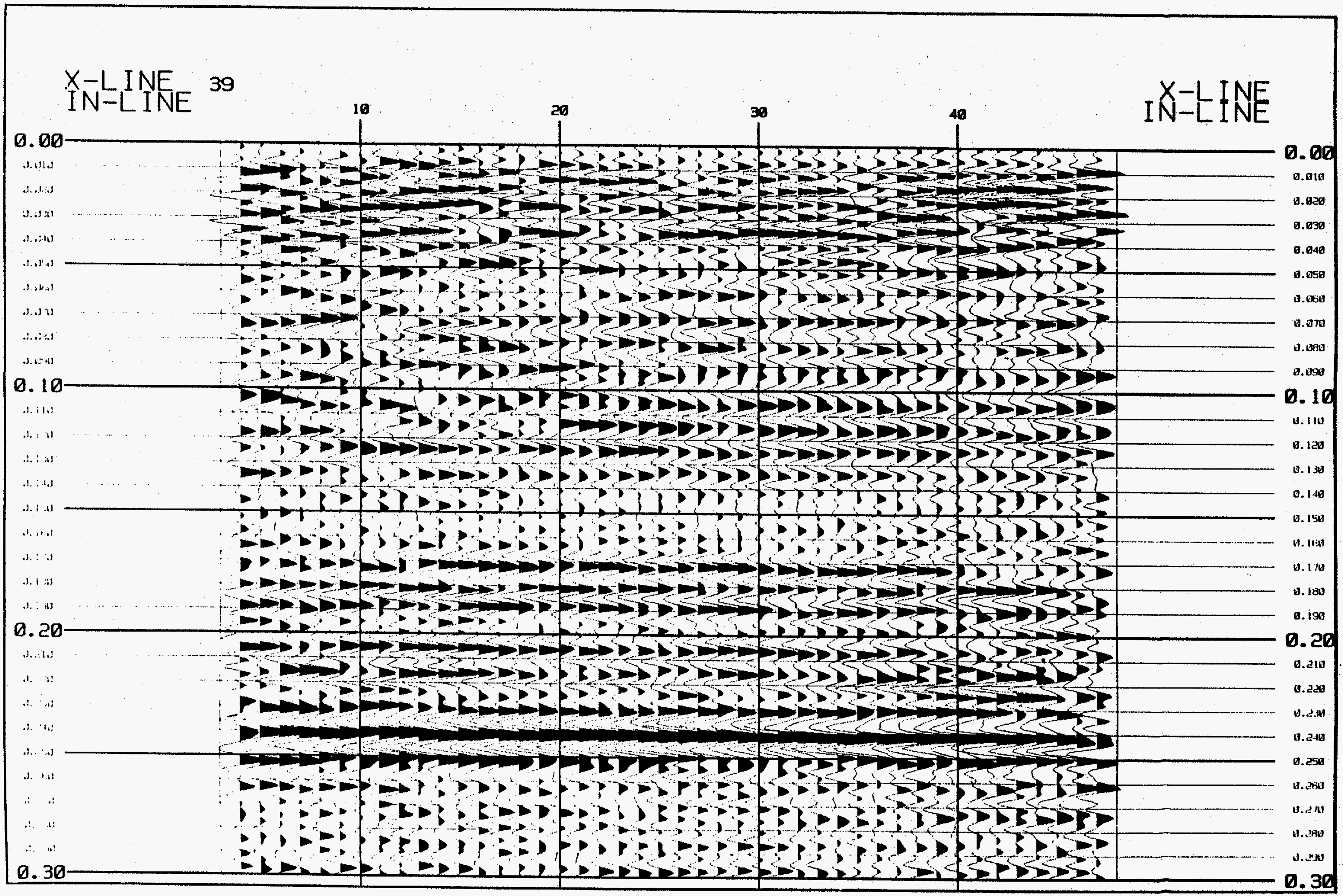
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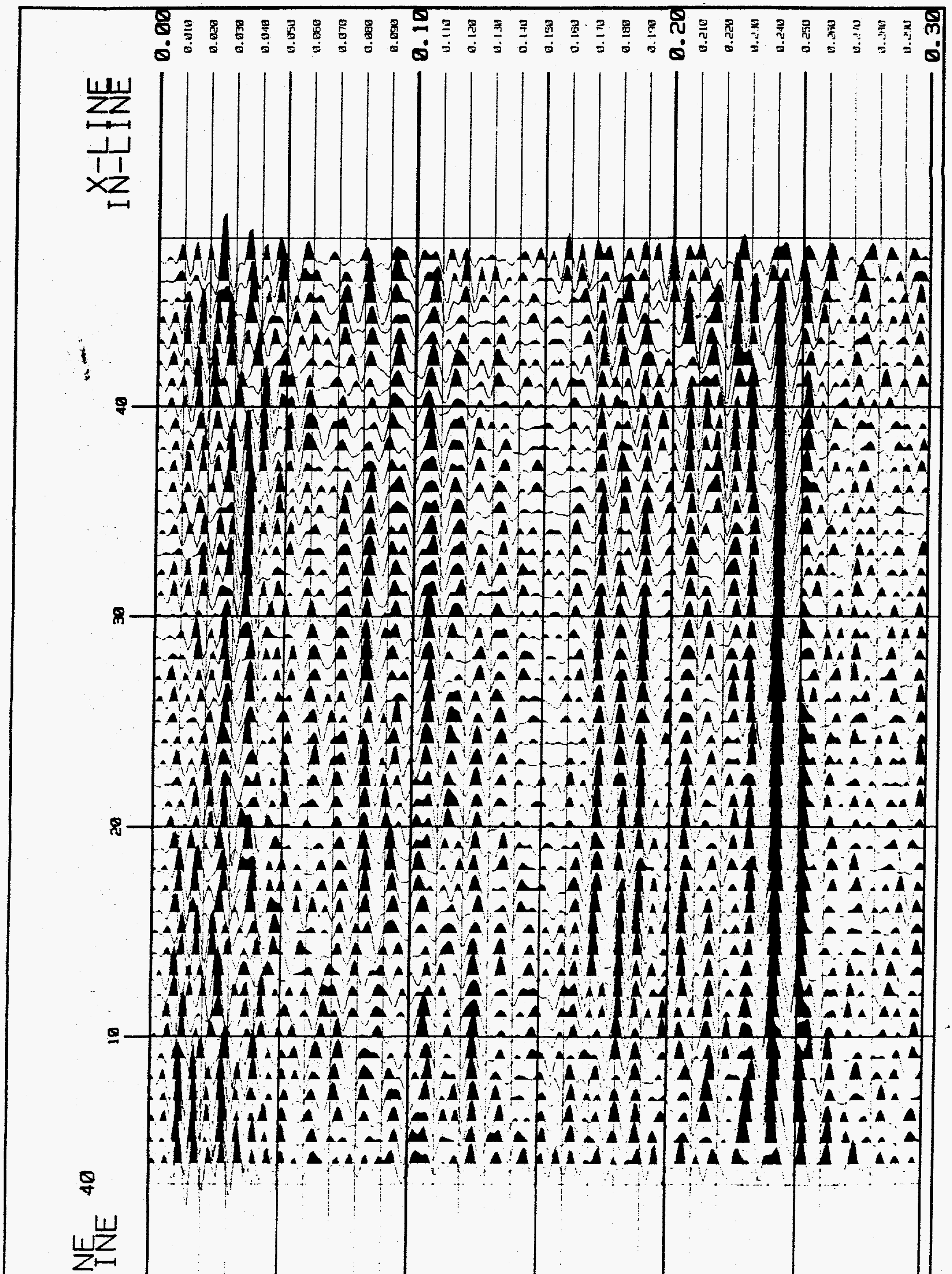

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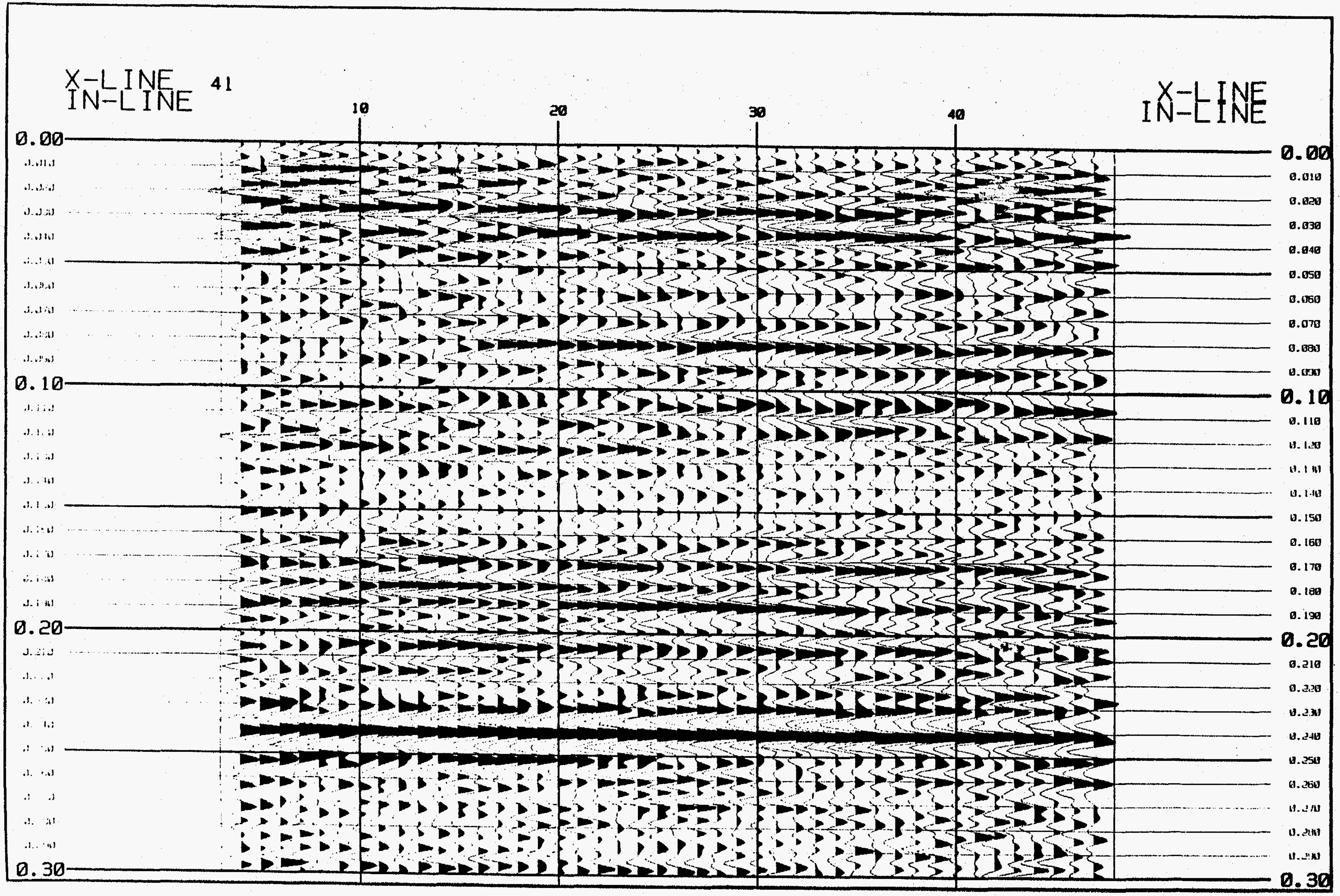X-LINE 41
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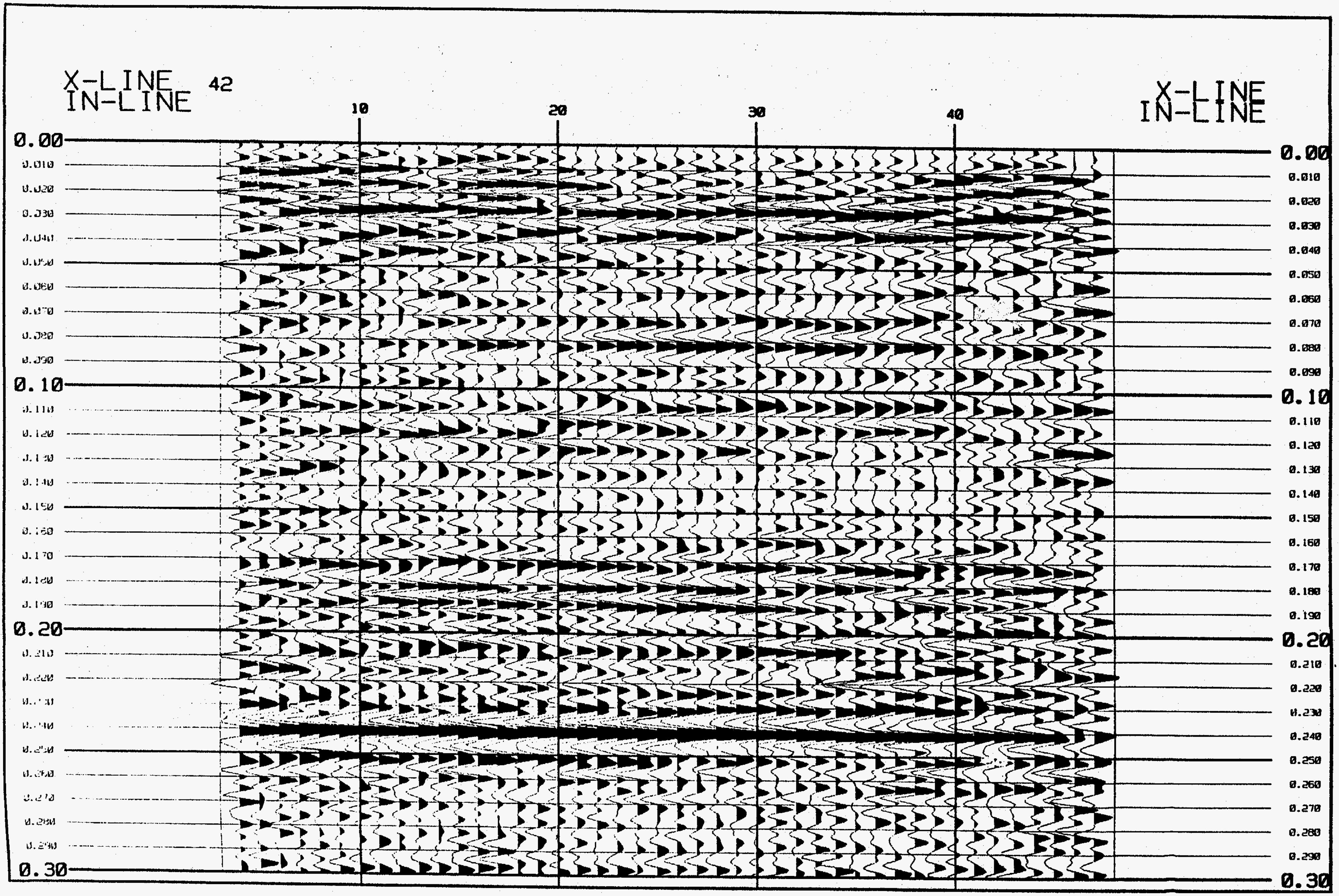
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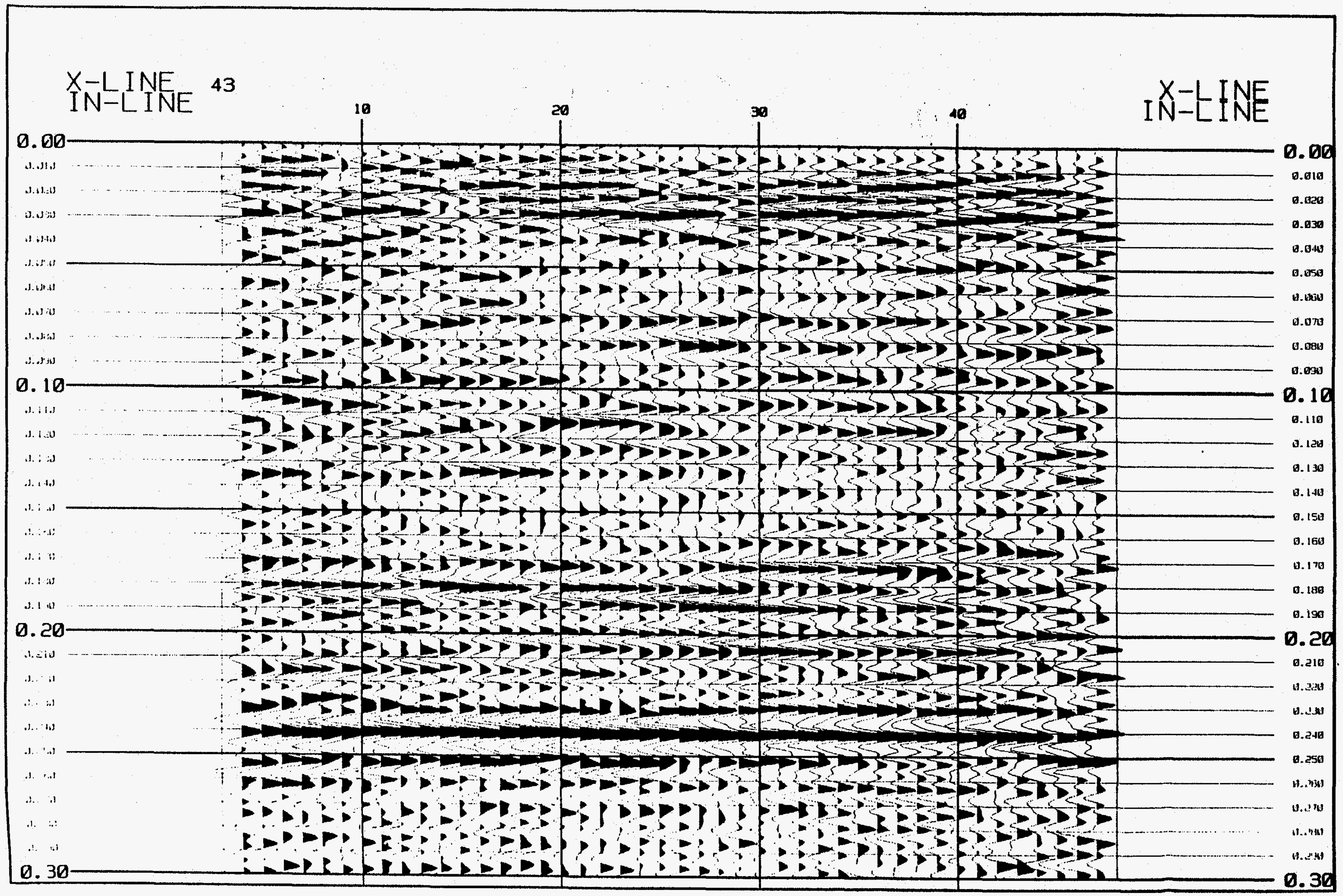
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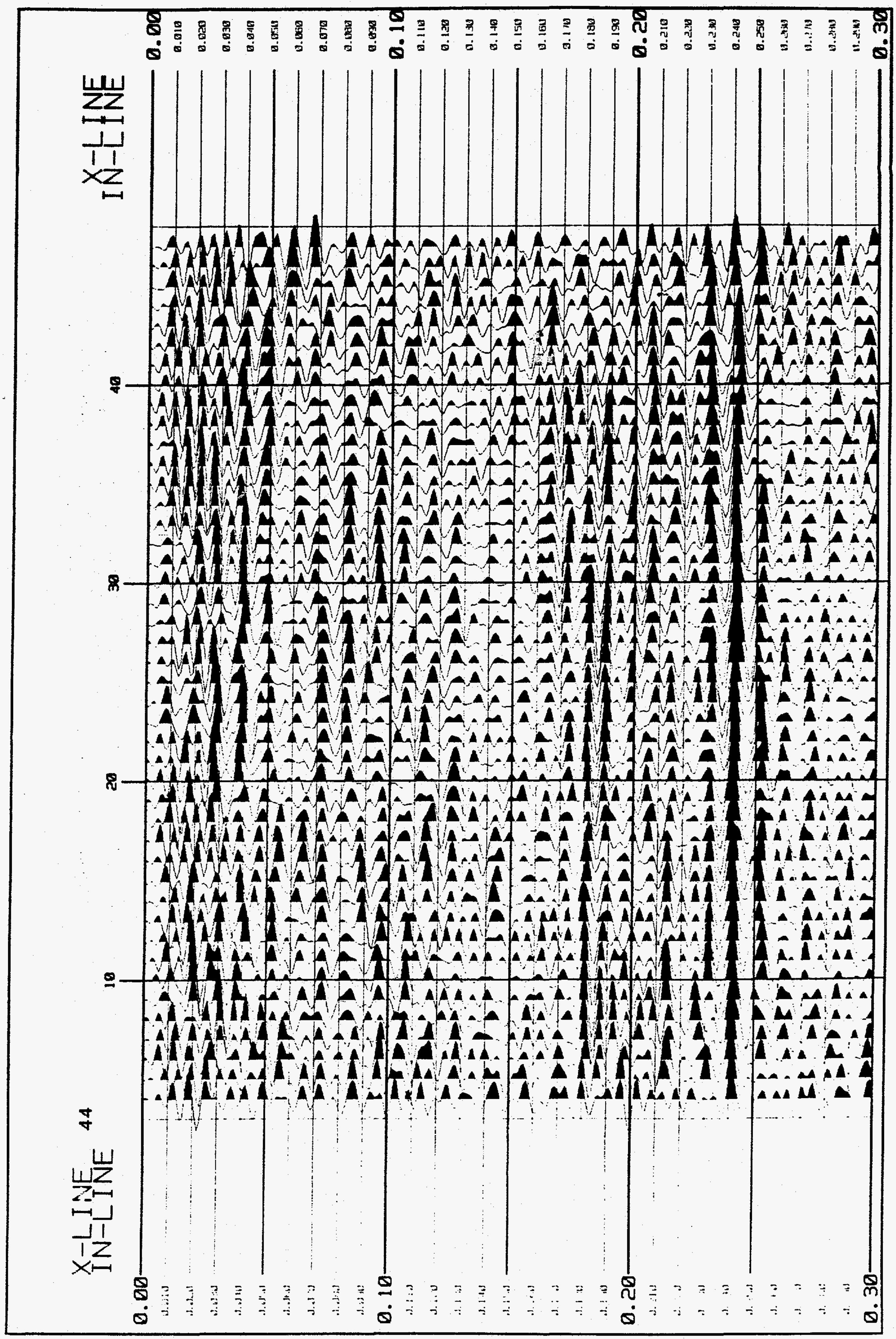
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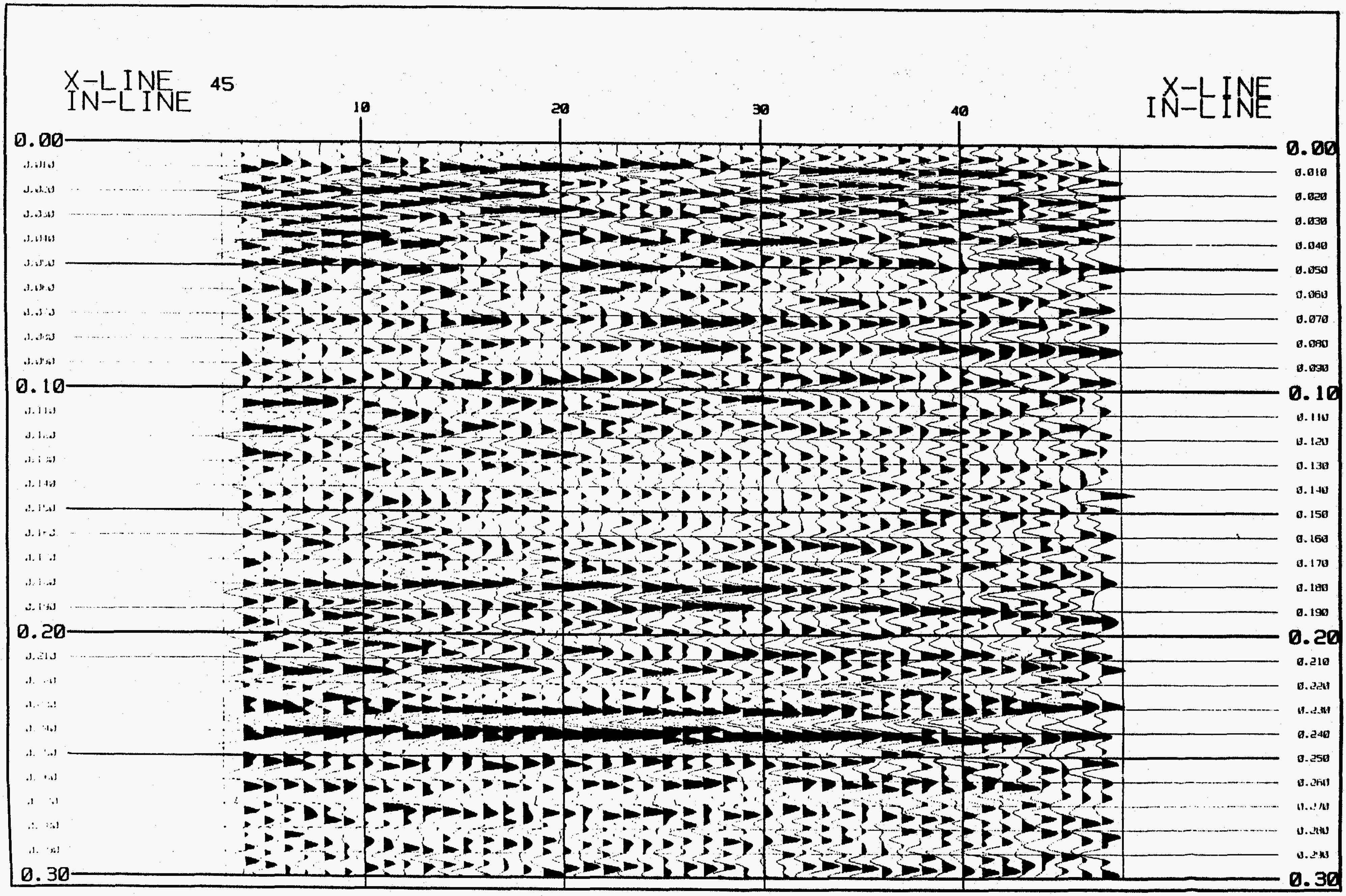
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Appendix V
Seismic Data Processing Report

PROCESSING REPORT FOR ROCKY FLATS 3D

This dataset was processed on a SUN Sparc 10 workstation, containing four CPU processors, 320 MB of RAM, and 20 GB of disk space. The software used was Geotrace Technologies, Inc. proprietary 3D high resolution processing package. Quality control of intermediate and final results was performed on a GeoQuest Interpretation workstation, loaded on a SUN Sparc II.

PROCESSING SEQUENCE

DEMULTIPLEX

SEG D format 9 track tapes
0.5 msec sample rate
96 data channels
3.0 second sweep
3.5 second uncorrelated record length
Vibroseis correlation-minimum phase correlation using auxillary channel 1 (ground force)
0.5 second correlated record length

GEOMETRY DEFINITION

The surface group intervals were 5 ft. X 5 ft. Therefore a CDP area was defined to accommodate 49 LINES (west to east) and 49 TRACES (south to north).

EDIT BAD TRACES

FK FILTER

Surgical fan belt FK filter to remove coherent, linear noise: ground roll and refractor reverberation.

SURFACE CONSISTENT DECONVOLUTION

Wavelet shaping deconvolution on shots and receivers.

Parameters are selected from running a wavelet analysis program. Operator length was 140 ms. Design window was beneath the first arrivals, extending down 220 ms. Autocorrelation functions are averaged for each shot and receiver. This program results in a constant phase output section.

GAIN FUNCTIONS

A spherical divergence correction was applied to compensate for the decrease in seismic wave amplitude due to geometrical spreading of the wavefront.

An automatic gain function was then applied with a sliding window of 150 msec.

DECONVOLUTION

A spiking deconvolution was applied to collapse the wavelet and whiten the spectrum. A 15 ms operator was used, with a design gate of 40 - 400 ms.

SPECTRAL BALANCE

The frequency spectrum is whitened and balanced by individually scaling, and then stacking, a sequence of bandpass-filtered data panels. The data was whitened from 40 to 350 Hz, using 70 Hz. frequency strips. This is a zero phase operation.

3D REFRACTION STATICS

The purpose of refraction statics is to correct for lateral fluctuations in the generally unconsolidated and variable near surface area, or weathering zone. A Generalized Linear Inversion method was used. A three dimensional near surface geological model is input to the program. Inverse modeling is performed by ray tracing first arrivals. The modeled picks are compared to the real first break picks. A discrepancy in slope is an error in velocity, and a discrepancy in time is an error in depth. Velocities and depths are solved simultaneously via least squares matrix inversions. This process is iterated several times, and the subsurface model is updated after each iteration. This process is performed interactively on a SUN workstation, with color contour displays and cross sections to evaluate the results.

For this project, the refractions statics removed some long period structure from the time sections. The time shifts were not dramatic, however, because the "weathering", or alluvial deposits overlying the bedrock, were relatively shallow.

VELOCITY ANALYSIS

Constant velocity stacks alongside color coherency semblance plots and power spectrums, picked interactively.

3D SURFACE CONSISTENT RESIDUAL STATICS

Solution of high frequency shot and receiver statics from cross-correlation functions.

VELOCITY ANALYSIS

Repick NMO velocities as before, but with the benefit of the increased resolution from the automatic statics application.

3D SURFACE CONSISTENT RESIDUAL STATICS

Solution of high frequency shot and receiver statics from cross-correlation functions.

3D NMO

Three dimensional interpolation of results from second velocity analysis.

NMO MUTE

First arrival and NMO stretch suppression.

SHOT ORDERED RANDOM NOISE REDUCTION

Spatial filter (XT domain) applied to shots records to attenuate random, ambient noise.

CDP SORT/STACK

Sort data into common depth point gathers and stack.

3D SIGNAL ENHANCEMENT

Signal to noise ratios are estimated in TAU-P domain. For each output sample, a suite of data planes extending radially (inline & crossline directions) are examined: signal is defined by the radial plane of maximum semblance; noise is determined through the use of an amplitude median/trim process within each plane. Samples surviving this median/trim process are exponentially weighted using their radial distance from the output point.

3D ONE PASS MIGRATION

FK migration using 85% of RMS stacking velocities.

BAND PASS FILTER

A filter of 35/50 - 230/260 Hz applied to the data.

SCALING

A 150 ms AGC was applied to the migrated stacked section.