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SEISMIC DISCRIMINATION OF A GEOTHERMAL FIELD: CERRO PRIETO

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ABSTRACT

Extensive reprocessing of a subset of the seismic reflection data from Cerro Prieto has been performed. The formations and faults identified in the resulting seismic profile were correlated to cross-sections constructed from well log data. The production region coincides with a zone of reflection attenuation. A detailed velocity analysis reveals a lid of high velocity events rimming the reflection attenuation zone. This may prove to be a valuable discriminant for locating a geothermal resource using seismic reflection data.

INTRODUCTION

There is strong interest in obtaining surface geophysical data to guide exploration for and development drilling of geothermal reservoirs. A variety of geophysical measurements have been utilized to identify specific anomalies associated with hydrothermal activity. Heat and mass transport of geothermal fluids, together with associated water-rock chemical reactions, generate conditions that are often manifested as anomalies in gravity, self-potential, and electrical resistivity. Unfortunately, basement highs, intrusive volcanics, porosity and salinity changes can produce the same anomalies. In addition, most inversions suffer from serious non-uniqueness problems that degrade resolution and accuracy results.

Previous investigators have noted a seismic reflection attenuation zone (RAZ) coinciding with the Cerro Prieto reservoir (Fonseca and Razo, 1979; Lyons and van de Kamp, 1980). Surprisingly, no detailed evaluation of this seismic anomaly had ever been conducted. Given the wealth of information in a broadband seismic wavefield and the RAZ associated with the production zone an examination of the seismic data seemed in order.

During the past year the Lawrence Berkeley Laboratory (LBL) has expanded its seismic reflection processing and analysis capabilities with the acquisition of a "state of the art" software package, DISCO. LBL and the Comisión Federal de Electricidad (CFE) now have the opportunity to directly investigate the seismic reflection data gathered from Cerro Prieto. This is important because the data set is of exceptional quality. The lines are long and intersecting, allowing features identified in one part of the field to be followed into another, in particular the region of geothermal activity.

A valuable first cut at data processing had been done by a commercial contractor. While the cursory processing carried out was not sufficient to obtain the detail required for fine discrimination between lithofacies, it alerted us to the potential of the data set. Our goals were two-fold. First, to use the processing capabilities now available to optimally image the seismic data into a profile of the subsurface. Second, to search for features in the seismic data that may serve as discriminants of the geothermal reservoir.

REFLECTION PROFILING

Seismic reflection profiling is a sounding technique used to locate reflectors in the subsurface. It is important to bear in mind that the features being mapped are contrasts in acoustic impedance (the product of velocity and density), rather than subsurface geology. If the reflection coefficient between two strata is relatively small, regardless of the compositional differences, their interface will not appear as a reflector. In general depositional surfaces generate reflections delineating the geometry of the bedding. The seismic reflection method allows major lithologic units to be tracked to significant depths, indicating the overall stratigraphy and structure of the subsurface, including fault orientation and vertical displacement.

The resolution problem is one of the limitations of the seismic method. Two reflectors spaced less than 1/4 wavelength apart in depth will appear as a single reflector. For a seismic wave of 20 Hz and a velocity of 8000 ft/s the resolving limit is 100 ft. This is approximately two orders of magnitude coarser than data obtained from well logs. There is also a horizontal limit to resolving power. The energy that arrives at the geophone during the first half-cycle after reflection onset comes from a region of the reflector rather than a point, resulting in a horizontal averaging of the structure. This Fresnel zone is a circle on the reflector with a radius that is dependent on the frequency of the wave. For a seismic wave of 20 Hz, a velocity of 8000 ft/s, and a two way travel time of two seconds the radius is approximately 1300 ft.

Two of the major assumptions in reflection seismology are, (1) an acoustic medium with a layered velocity structure, and (2) a near normal-incidence, high frequency wave field. Whereas these assumptions are often violated to some degree, the method is sufficiently robust to yield good results.

DATA

Eight seismic lines 120 km in total length and with a fold ranging from 24 to 97 were obtained by CFE over the Cerro Prieto area. Line B was chosen for this analysis because of its orientation to the known faults in the area, its high fold (up to 58), and its location with respect to the known reservoir (fig.1). Line B passes directly over the production zone in a NW-SE direction. Over 60,000 traces make up the data set for this line which was surveyed with the following parameters: 4 ms sampling rate, 80 ft receiver spacing, split-spread shooting, 256 channels per shot, vibroseis source, linear 14-48, 16-56, 18-60 Hz sweeps.

PROCESSING

There are many texts available on seismic reflection profiling (Al-Sadi, 1980; Waters,1978) and this is not the place to go over the details of signal processing utilized in multichannel, broadband seismic analysis. However a brief description of some of the processing that was performed is in order.

Static shifts were applied to individual traces to compensate for elevation changes along the line. The data were displayed and examined; extensive editing eliminated traces from defective geophones, traces contaminated by dominant 60 Hz signal and traces

overwhelmed by nearby cultural noise. Amplitudes were boosted to compensate for geometrical spreading. A dip filter was applied to the shot gathered data to reduce coherent source generated noise associated with surface waves. A muting schedule was designed to eliminate the primary arrival and a particularly virulent problem with air blast. The data were sorted into common depth point (CDP) gathers (ensembles consisting of traces from shot receiver pairs with a common mid-point). A preliminary velocity analysis was then performed at selected CDP's. The gathers were corrected for normal moveout (NMO, the dynamic time shift due to the horizontal separation between a source and receiver pair) and then stacked.

This first cut at the data identified regions of strong reflections, the general trend of the subsurface structure and potential problem areas. The processing then began again with the unstacked CDP ordered data. A deconvolution operator was constructed based on statistical properties of the wavefield. This compensates for the earth's filtering effect on the wavelet which selectively eliminates high frequencies reducing resolution. The operator that gave the best results was a gapped prediction operator with a gap of 24 ms and an operator length of 124 ms. A comprehensive velocity analysis utilizing constant velocity stacks and velocity spectra was performed all along the line. Again a NMO correction was applied but this time the traces were left unstacked. Surface consistent residual static corrections were computed through three iterations. The data were prepared by creating a datum plane along a dominant reflection that was then flattened to zero dip. Static shifts involving the source, receiver, and residual NMO, were performed with a maximum allowable shift of 20 ms.

The next endeavor involved translating the seismic profile from a time section to a depth section. The stacked section was migrated using a finite-difference algorithm that allowed for vertical and horizontal velocity gradients. The velocities input to the migration routine where smoothed and reduced from stacking velocities to root-mean-square (RMS) velocities. The entire section was then differentially "stretched" from time to depth by associating various time horizons with isovelocity contours.

The final stage concentrated on identifying features that could aid in later interpretation. The instantaneous frequency, phase and amplitude (quantities involved in complex trace analysis derived from the trace and its Hilbert Transform, (Taner, et al., 1979)) of the portion of the section that had a high signal to noise ratio and was free of faulting was generated for later correlation to well log data. The depth section was coherency filtered; events were passed that demonstrated prescribed levels of coherency within certain ranges of dip and lateral extent. The final displays were bandpass filtered, trace equalized and balanced in time with an automatic gain control.

RESULTS

Stratigraphy

Once the seismic data were optimally imaged the observed reflections were correlated to the well log data. Synthetic seismograms were generated for wells M-102 and T-386. Unfortunately, sonic logs were run in few of the wells, and then only over very short depth intervals. Because the sonic logs were of no use in synthetic seismogram construction, a sonic log was computed using Gardener's formula (Sheriff, 1980), which is an empirical power law relationship between density and velocity. In a region as atypical as Cerro Prieto any such synthetic seismogram utilizing a pseudo-sonic log must be used with caution. The synthetic seismogram generated from the density log at T-386 tied in well with the seismic section in the vicinity of the well down to approximately 6000 ft, the depth to the hydrothermal alteration. Below that depth correlations were difficult to obtain due to the break-down of the empirical density-velocity relationship.

The only major fault that shows up clearly is one whose trace reaches the surface near CDP 650 (fig.2). There appears to be at least one, perhaps many more smaller faults that feed into the aforementioned fault. The net vertical displacement is about 1350 ft. The identified formations are described in detail by Halfman et al. (1984) and the major fault correlates well with Halfman's H fault. There may be two or three other substantial faults to the north-west of CDP 650, but the shortage of reflectors to the north-west makes identification tentative. There are dozens of smaller (less than 100 feet of offset) faults running through the profile. The dipping events below CDP 900 (between 7000 and 9000 ft) are real and can be seen on line C as well. Near a depth of 15,000 ft to the north-west there is a reflection that may indicate basement. The interface between unconsolidated and the indurated/hydrothermally altered sediments (A/B contact) appears to be too gradual to produce reflections from the bandwidth of signal used here. A check-shot, a continuous sonic log, or ideally a vertical seismic profile would increase the confidence levels in seismic correlation with subsurface geology.

Velocity analysis

It is critical that accurate stacking velocities be chosen for processing and interpretation reasons. The advantage of high-fold reflection data is that accurate stacking velocities significantly increases the final signal to noise ratio of the stacked data. Conversely, a poor choice of stacking velocities dramatically degrades the reflection signal. The velocities used for stacking are obtained directly from the seismic data. The travel time curves for near normal incident reflections from a horizontally stratified medium display hyperbolic trajectories. This hyperbola is parameterized by the zero offset travel time, the horizontal offset between source and receiver, and the RMS velocity of the medium. Because two of the three parameters are known, the velocity can be derived directly from the data. The stacking velocities that were chosen successfully imaged reflectors down through four seconds and did not reveal any significant problem with multiples.

There are two very interesting features in the velocities derived from the seismic data. First is the gradual horizontal variation in velocities that that correlate well with the observed faults. Second is the abrupt horizontal and vertical variation in velocity that correlates well with the margin of the RAZ. This pronounced degree of velocity heterogeneity is quite unusual. There are at least three and perhaps four abrupt increases in velocity moving from the southeast to the northwest (fig.3)

Particular attention was paid to precisely mapping the the location and magnitude of these abrupt velocity changes. They closely follow the rim of the RAZ. Perhaps the most important result of this analysis is the discovery of an abrupt vertical increase in velocity as the edge of the RAZ is penetrated. The vertical jump in velocities is not a feature that is evident from a casual perusal of the data. The reflections grade out quickly upon entering the RAZ; however, there are competent reflectors from which RMS velocities can be obtained just inside the RAZ. The important feature of the interval velocities derived from these RMS velocities is that they demonstrate an anomalous increase of approximately 5000 ft/s (fig.4). The increase is rather approximate because inversion for interval velocities from RMS velocities becomes increasingly subject to error as the interval thickness decreases (within 200 ms. the velocities increase 60%). In addition, pronounced lateral velocity variations will affect the trajectory of the move-out curve. This degrades confidence levels for the interval velocity jump near CDP 930 but should not be a problem further to the north-west (near CDP's 680 and 810). The high velocity lid rimming the RAZ does not correlate directly with a single formation or with the (A/B contact), but instead appears to follow an isotherm.

REFLECTION ATTENUATION ZONE

The RAZ appears on all of the seismic lines that intersect the production zone. Unfortunately, a dearth in reflections is not a sufficiently unusual occurrence to be used as a geothermal discriminant. The absence of reflections can be caused by a number of features such as basement highs, single lithology units, wavefield scattering due to fracturing or intense faulting, high noise levels, and improperly shot data. Various hypotheses have been put forward to explain this phenomenon in a geothermal regime. One proposal is that the acoustic impedance contrasts are essentially washed out due to the intense hydrothermal alteration associated with the circulation of hot fluids (up to 370 C). Evaluation of velocities and densities from the well log data seem to indicate that the acoustic impedance contrast between sandstones and shales increases rather than decreases, which should result in reflection enhancement. In addition, if the subsurface in that region had become acoustically homogeneous the loss of reflections would be associated only with the units that had been directly altered. Unaltered units would still generate reflections that should be visible. Instead the RAZ extends to the bottom of the section.

Another hypothesis put forward for the RAZ is that the production zone is an intensely faulted and fractured medium that scatters rather than reflects seismic energy. While this cannot be ruled out, the character of the faulting in the region is such that the competence of the reflectors is maintained. Even in the most severely faulted portion of the line (near CDP 750) discrete pieces of reflectors remain in evidence. Core cuttings and dipmeter readings from wells failed to indicate significant levels of open fractures in the hydrothermally altered zone (Lyons and van de Kamp, 1980).

One possibility is that the high temperature regime of the production zone is a region of extreme seismic absorption, that the signal is essentially damped out. Unfortunately very few in situ differential attenuation studies have been attempted (Majer, et al., 1978; McDonal et al., 1958). At these frequencies interference effects, scattering from inhomogeneities, and interbed multiples all serve to make it very difficult to obtain values for intrinsic seismic attenuation. However the high fold of the data allows the possibility of a rigorous statistical investigation into the spectral properties of the wave field. A vertical seismic profile using broadband compressional and shear wave sources would be the preferred data set for such a study.

CONCLUSIONS

The first goal, optimally imaging a high fold seismic profile through a geothermal field was successful. The correct location, orientation, lateral extent and character (tied up in the waveforms themselves) of the subsurface reflectors have been enhanced by the reprocessing. This allowed the major formations and a fault across the line to be identified (although a continuous velocity control with bore hole data would significantly aid in seismic reflection processing and interpretation). The second goal, determination of seismic discriminants for a geothermal regime was also successful. The RAZ is not the result of poor processing but is a real phenomenon directly associated with the production zone. A RAZ in conjunction with a high velocity lid (that seems to be temperature related) may prove to be a strong discriminant of a geothermal system.

Additional lines from Cerro Prieto and other fields should be reprocessed with the specific intent of determining if the high velocity lid over the RAZ is a consistent feature of a geothermal regime. The indication from this subset of the data is that seismic reflection data alone may be able to image the margins of a geothermal resource.

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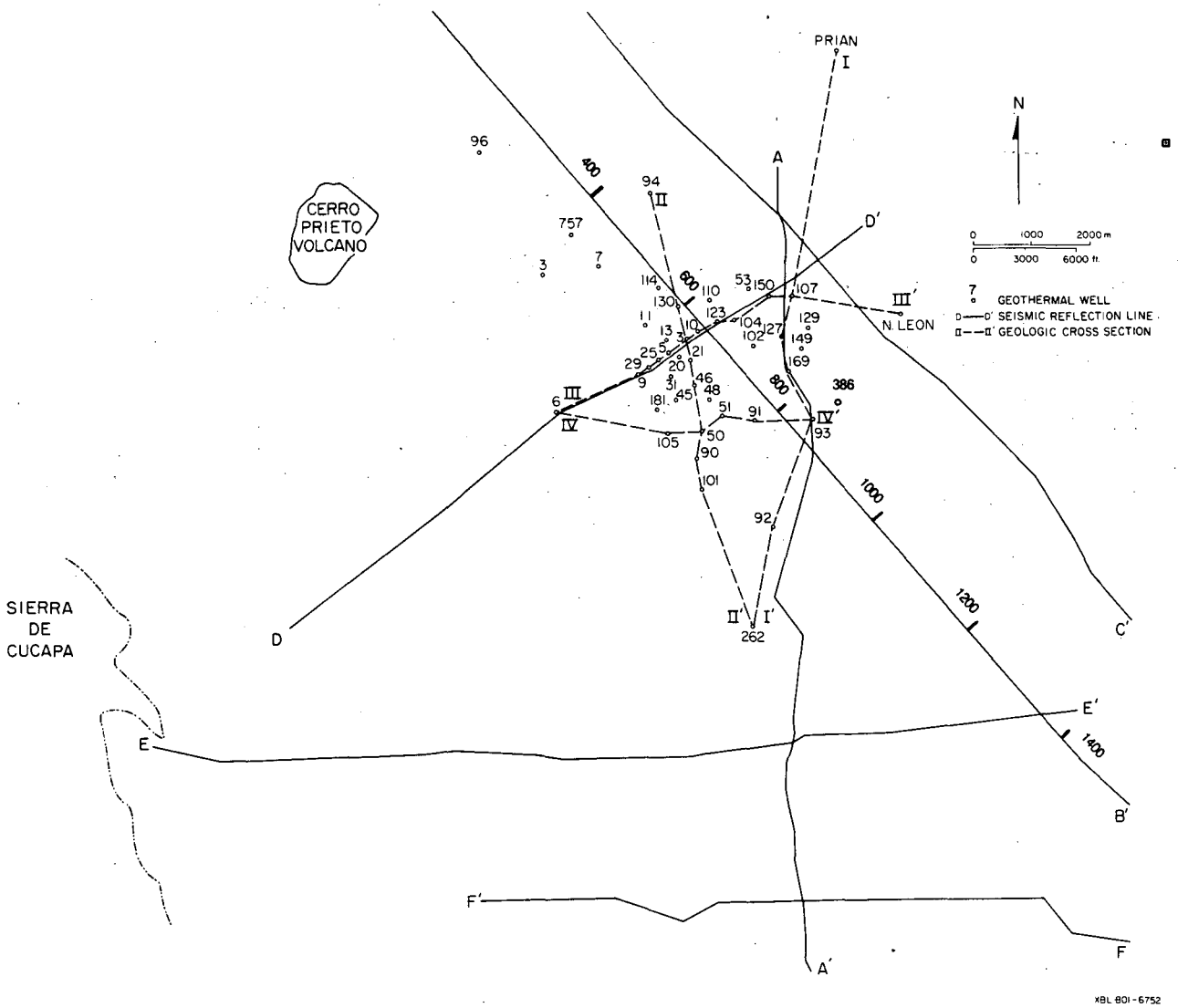

FIG. 1 — Location map of wells and seismic lines at Cerro Prieto.

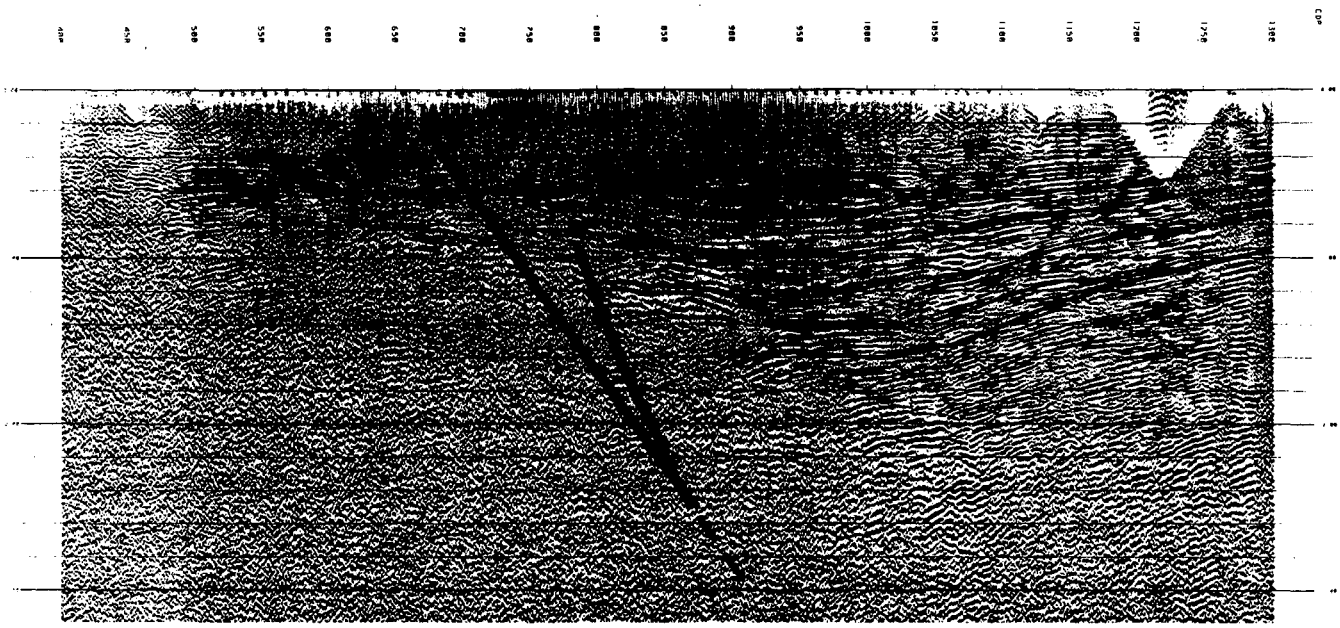

FIG.2 — Interpreted section showing H fault and formations. Formations descend from 7 to 2 with depth (see Halfman et al., 1984). The offset of formation 3 across fault H is approximately 1350 ft. Each light line is about 1000 ft. The spacing between CDP's is 40 ft.

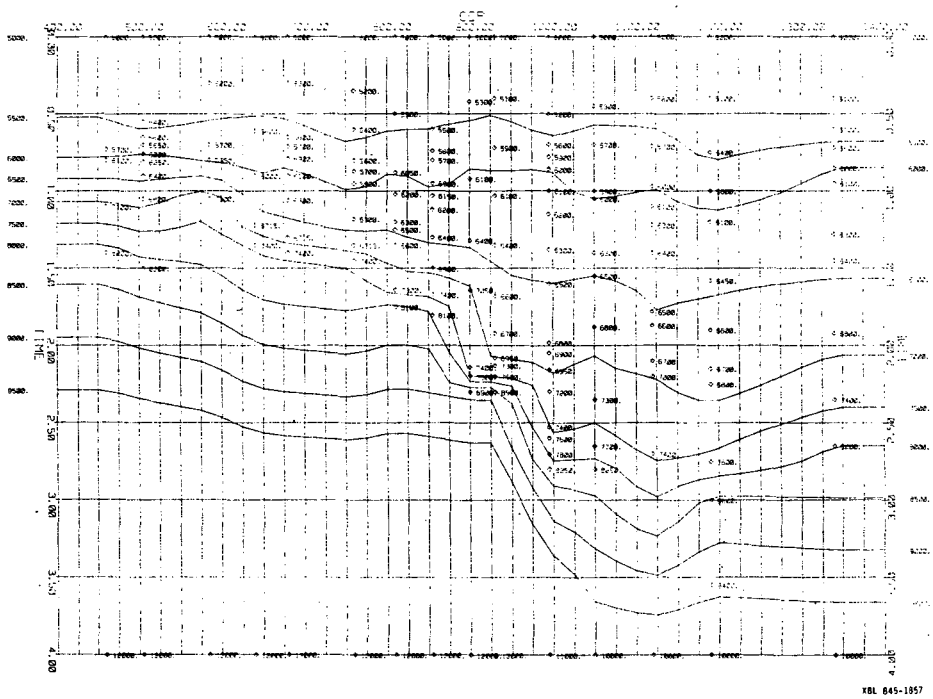

FIG. 3 — Velocities used to stack line B. The RAZ roughly corresponds to the region where no velocities were obtained. Note vertical and lateral heterogeneity. Abrupt lateral increases from south-east to north-west occur near CDP's 975, 875, 800, and perhaps 625. The vertical velocity anomaly grades out to the south-east of CDP 975. The vertical velocity anomaly is deeper than the A/B contact between CDP's 900 and 1000, apparently following an isotherm (extrapolated from M-189). Vertical units are time, not depth.

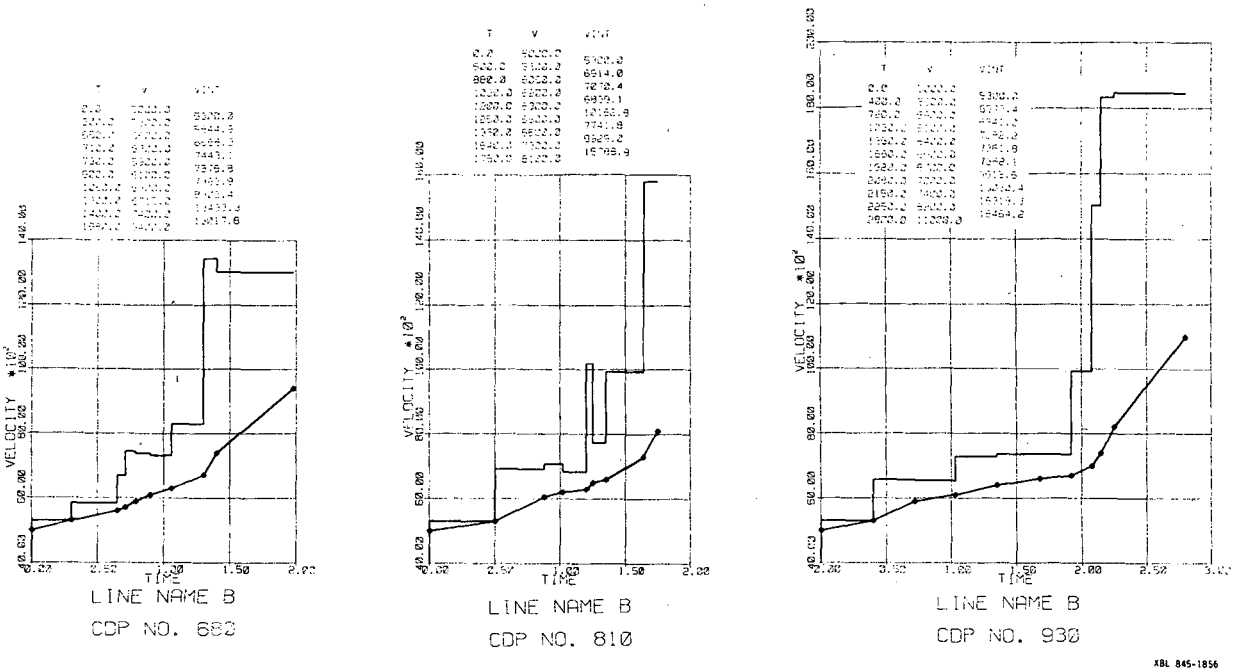

FIG. 4 — Plots of RMS and interval velocities from CDP's 680, 810, 930. RMS velocities obtained from the data are marked with the solid dots, interval velocities derived from Dix formula (Waters, 1978).

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