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SHALLOW STRUCTURE FROM A SEISMIC-REFLECTION PROFILE ACROSS THE BORAH PEAK, IDAHO, FAULT SCARP

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Abstract. A short 12-fold CDP seismic-reflection survey was performed along the road to Doublespring Pass across the fault scarp formed by the October 28, 1983, magnitude-7.3, Idaho earthquake. This high-resolution reflection survey was conducted to determine the feasibility of using reflection seismology to delineate shallow structures in a fault zone. Field-recording parameters were designed to optimize seismic reflections in the 30-150 msec range corresponding to 10-100 m in depth. A modified 30-06 hunting rifle was used as the energy source. Single 100-Hz geophones at 1.5-m group intervals in conjunction with 220-Hz low-cut recording filters (24 dB/octave) provided dominant frequencies above 150 Hz on field records. As would be expected from geologic considerations, the processed data suggest the existence of faulting in the subsurface. Strong events between 30 and 80 msec on the upthrown side of the scarp are of distinctly different character and frequency than those on the downdropped side at similar times. This indicates different geologic units are present at approximately the same reflection time on opposite sides of the fault zone. The northeastern edge of the scarp may not represent the true subsurface boundary of the upthrown block. Projection to the surface of the northeasternmost edge of the seismically determined subsurface graben is 10-15 m farther northeast than expected from surface faulting. High-frequency energy present within the subsurface expression of the graben is primarily noise and is related to the deformed and incoherent nature of materials within the graben.

Introduction

On October 28, 1983, an earthquake of $M_S = 7.3$ ruptured the ground surface at the base of Borah Peak near Mackay, Idaho [Crone et al., 1984]. The fault scarp measured 36 ± 3 km long with a maximum displacement of 2.7 m on the western base of Borah Peak. During the earthquake an anti-thetic graben was formed as shown in map view in Figure 1.

During late November 1983, the Kansas Geological Survey and the U.S. Geological Survey engaged in cooperative seismic-reflection studies across the fresh fault scarp using the MiniSOSIE recording technique [Skipp and Harding, 1984]. As an experimental sidelight, we acquired much shallower, higher-resolution, seismic-reflection data using a 30-06 rifle. The 30-06 rifle source produces sufficient seismic energy at frequencies above 100 Hz to detect beds shallower than 30 m. Higher-frequency data improve thin-bed resolution [Widess, 1973]. Data from the 30-06 rifle source and single 100-Hz geophones routinely image features at depths between 10 m and about 30 m compared to depths of 50-650 m for MiniSOSIE data. They both are good locators of major faulting. The two reflection techniques are sufficiently different in resolution that, except for imaging the major faults, practically no overlap in the depth range of the results would be expected.

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Seismic Reflections and Fault Studies

Fault detection by seismic-reflection methods at depths of several hundred to several thousand meters is well established [for example, Crone and Harding, 1984]. In order to successfully detect faults at depths of a few tens of meters, however, recording frequencies of a few hundred Hz are required [Knapp and Steeples, 1986]. Resolving power of seismic techniques is directly proportional to frequency of the seismic waves (assuming the bandwidth of the signal is at least 1-1/2 to 2 octaves). Most of the published land seismic-reflection data involves energy at frequencies less than 100 Hz. A few notable exceptions to that frequency range include Farr [1979], Steeples and Knapp [1982], Doornenbal and Helbig [1983], and Hunter et al. [1984]. The keys to recording the needed high-frequency energy include a careful choice of energy source, recording equipment, field methods, and processing techniques. The use of seismic reflection to image subsurface faulting shallower than 30 m has never been documented in the literature. Therefore, the use of high-resolution seismic reflection over the Borah Peak fault scarp with a target depth range of 10-30 m is a demonstration of a potentially powerful new application of a well established technique.

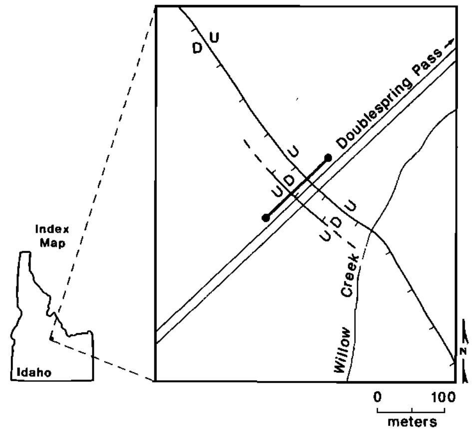

Fig. 1. Base map of field site in central Idaho. The seismic profile completely traversed the graben as indicated by the dark line northwest of the road, which is represented by a double line that crosses the figure from southwest to northeast. The relative movement of the main normal fault is clearly up on the range side and down on the basin side.

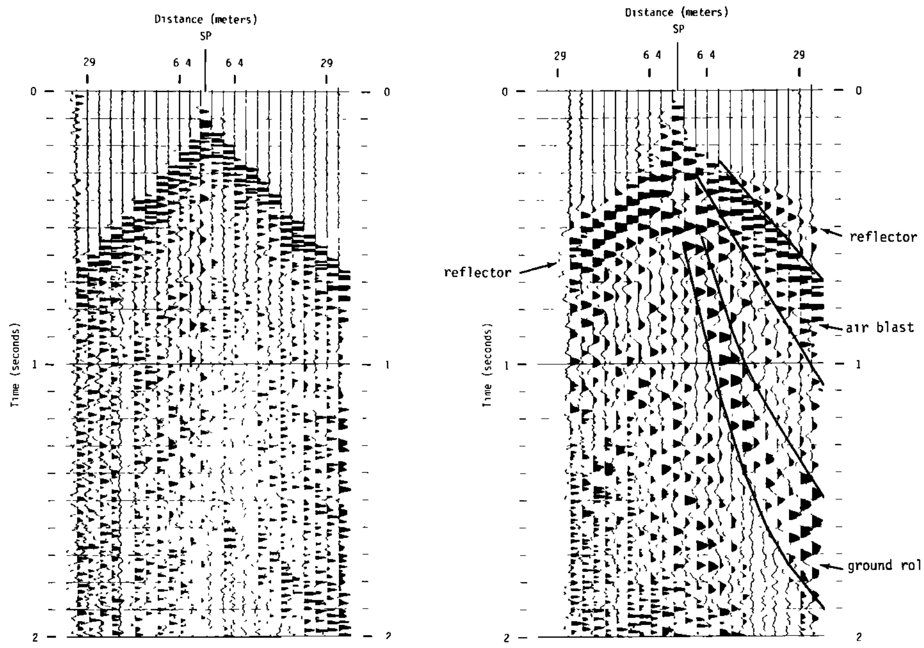

Fig. 2. The field seismogram on the left was obtained from a shot fired within the graben, while the field seismogram on the right was recorded on the range-front side of the upper fault scarp. Indicated on the right seismogram are the two prominent reflecting events (one at 40 msec and one at 60 msec). The air-blast and ground-roll wave trains are identified on the right seismogram.

Field Methods and Data Processing

The very high resolution 30-06 data were obtained over the 1983 Borah Peak earthquake scarp where it crosses Doublespring Pass road (Figure 1). An Input/Output, Inc. DHR-2400 seismic-recording system was used to amplify, filter, digitize (word size 11 bits plus sign), and record the data on digital tape in the field. Severe analog low-cut filters (220 Hz with 24 dB/octave rolloff) were used to increase the dominant frequencies, improving the detail and the eventual resolving power of the resulting CDP seismic section. As previously mentioned, a modified 30-06 hunting rifle was used as the source to shoot into a split-spread geophone geometry with source-to-closest-receiver distance 4.6 m. Receivers were single 100-Hz geophones forced into frozen ground 1.5 m apart. Due to the scarcity of subsurface geologic information near the reflection line, little is known about the types and exact depths of the rocks that underlie the surveyed area. The surface material consists of unsorted, unconsolidated sediments ranging in size from silt to boulder.

Data processing was done on a 32-bit Data General computer at the Kansas Geological Survey. The software used is a proprietary set of algorithms that is in standard use on TIMAP seismic systems marketed by Texas Instruments. The processing flow was very similar to that used on seismic data for petroleum exploration except more detail and emphasis was placed on near-surface velocity analysis, and extra care was exercised in muting refracted arrivals.

Results

Amplitude, frequency, and wavelet-character differences distinguish data recorded within the graben from data obtained totally outside the graben (Figure 2). Seismic reflections, refractions, the air-coupled wave, and ground roll can be identified directly on the field plots from outside the disturbed area associated with the graben (right half, Figure 2). Identifiable seismic energy is absent from field plots when the source was within the graben (left half, Figure 2). Field plots recorded above the northeastern edge of the upper fault scarp show prominent reflectors at 40 msec and 60 msec (right half, Figure 2). Data recorded below the southwestern edge of the lower fault scarp show hints of reflected energy between 30 and 70 msec. Data from outside the graben showed distinct air-coupled waves and ground-roll arrivals on the field plots. These distinctly arriving noises were easily separated from the reflection events. This is in contrast to data from within the graben where the air-coupled wave with its characteristic high-frequency (>400 Hz) wavelets inundate the seismogram. Apparently the near-surface earth materials within the graben are sufficiently fractured that coherent signal is not returned.

The reflections observed on the field plots can be followed through the processing flow to coherent events on the stacked 12-fold CDP seismic profile (Figure 3). Reflection energy is present on both the upthrown and downdropped sides of the fault. The area directly under the graben, however, is void of any coherent seismic waves. The high-frequency wavelets within the graben on the section are primarily air-coupled waves, as evidenced on the field plot in Figure 2.

The reflecting events on the northeast end of the stacked section are drastically different in frequency, wavelet character, and stacking velocity than those on the southwest end (Figure 3). These differences strongly suggest rock units at

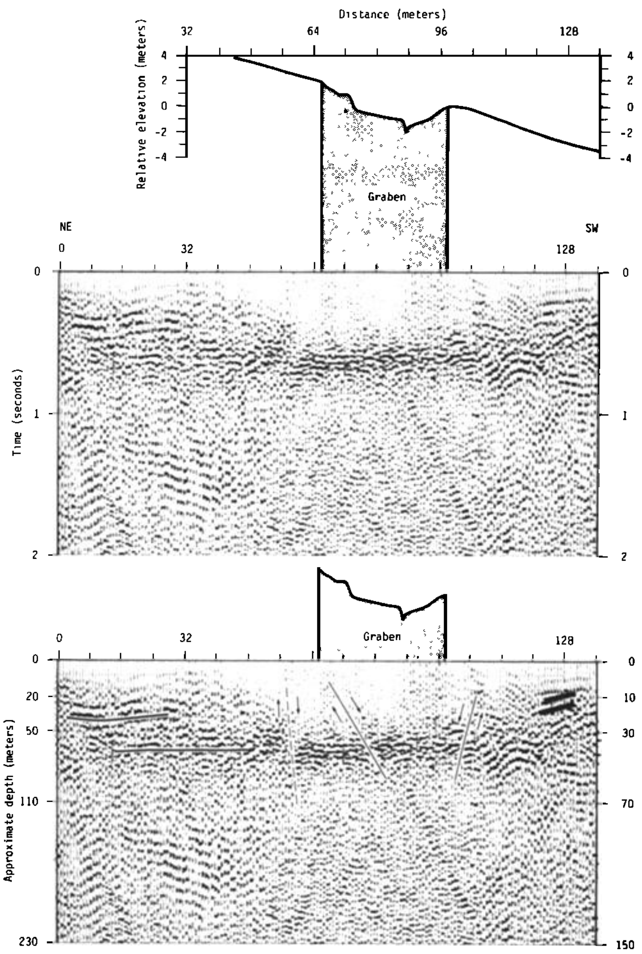

Fig. 3. Processed and stacked 12-fold CDP seismic section, interpreted seismic section, and relative-elevation diagram are plotted with the same horizontal scale. The surface expression of the graben can be tied to each seismic section from the relative-elevation diagram at the top. The main fault scarp is at 67 m and the antithetic fault scarp is at 98 m on the horizontal-distance scale. The approximate-depth scales (which were calculated from stacking velocities differing by 500 m/sec) are not equivalent on opposite sides of the fault. The subsurface expression of the graben can be seen from the faulting interpreted on the lower seismic section. Interpreted reflectors on opposite sides of the fault are from different geologic units.

equivalent reflection times on opposite sides of the fault plane are lithologically different. The approximate-depth scales on opposite sides of the interpreted section on the lower portion of Figure 3 are nonsymmetric about the graben. These approximate depths were determined using stacking velocities of 1250 m/sec on the upthrown side and 750 m/sec on the downdropped side.

Normal faults observed at the surface can be extrapolated into the subsurface on the seismic section (Figure 3). The interpreted faults show the graben in the subsurface and also give some indication that the northeasternmost normal fault may not extend all the way to the surface. This interpreted fault is between 10 and 15 m northeast of the range-front edge of the scarp.

Determining more than just structure from the seismic section requires detailed stratigraphic information such as drill-sample or logging data between about 10 m and 40 m of depth on both the upthrown and downdropped side of the fault. To our knowledge, no detailed stratigraphic information is available in this depth window in the near proximity of this seismic-reflection profile. Hence, attempting to correlate reflections from the seismic section to possible geologic units would be speculative on our part.

Conclusion

Presence of faults in the subsurface can be identified on the seismic section (Figure 3). Substantial differences in frequency, amplitude, and wavelet character of data recorded inside the graben, as opposed to outside, may be a key to locating other faults for prospective geologic studies such as trenching. The section also suggests subsurface normal faulting northeast of the present surface expression of the fault. This implies long-term (i.e., millions of years) displacement has occurred across a fault zone and not just one individual fault. Therefore, pre-Holocene fault scarps also may be present on the basin side of the present surface fault. Seismic detection and subsequent geologic study of old scarps could prove beneficial in understanding the mechanism and recursion interval of this faulting environment.

Based on this initial study at a fault reactivated during the 1983 Borah Peak earthquake, we believe that shallow, very high resolution seismic reflection surveys may be a useful tool in fault-zone studies. The technique has potential to provide acoustic imaging in the depth range below that of trenching and ground-penetrating radar, but shallower than the depth range of MiniSOSIE and other standard seismic-reflection techniques.

It is important to realize that seismic-reflection methods had not been used for depths shallower than 30 m prior to 1982 [Steeples and Knapp, 1982]. The technique is a powerful tool that is rapidly decreasing in cost as computer time decreases in cost and as engineering-seismograph capabilities improve. Theory and interpretation techniques have developed over the past 60 years, and applications to shallow problems will benefit greatly from the vast experience of deeper, lower-resolution surveys.

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References

Crone, A.J., and S.T. Harding, Relationship of late Quaternary fault scarps to subjacent faults, eastern Great Basin, Utah, Geology, 23, 292-295, 1984.

Crone, A.J., M.N. Machette, M.G. Bonilla, J.J. Lienkaemper, K.L. Pierce, W.E. Scott, and R.C. Bucknam, Characteristics of surface faulting accompanying the Borah Peak earthquake, central Idaho, in Proceedings of Workshop XXVIII on the Borah Peak, Idaho, Earthquake, A, National Earthquake Prediction and Hazard Programs, U.S.

Geological Survey Open File 85-290, 43-58, 1984.

Doornenbal, J.C., and K. Helbig, High-resolution seismics on a tidal flat in the Dutch Delta—acquisition, processing, and interpretation, First Break, May, 9-20, 1983.

Farr, J.B., High-resolution geophysics as an aid to the engineer, in Proceedings of a conference on site exploration in rock for underground design and construction, National Technical Information Service, Springfield, VA, report no. FHWA-TS-79-221, 1979.

Hunter, J.A., S.E. Pullan, R.A. Burns, R.M. Gagne, and R.L. Good, Shallow seismic reflection mapping of the overburden-bedrock interface with the engineering seismograph--Some simple techniques, Geophysics, 49, 1381-1385, 1984.

Knapp, R.W., and D.W. Steeples, High-resolution common depth point seismic reflection profiling, field acquisition parameter design, Geophysics, 51, 283-294, 1986.

Skipp, B., and S.T. Harding, Preliminary report on geology of Borah Peak area, Idaho, including interpretation of seismic and gravity data, in Proceedings of Workshop XXVIII on the Borah Peak, Idaho, Earthquake, A, National Earthquake Prediction and Hazard Programs, U.S. Geological Survey Open File Report 85-290, 657-671, 1984.

Steeples, D.W., and R.W. Knapp, Reflections from 25 feet or less, in SEG 52nd Annual Meeting Expanded Technical Program Abstracts with Biographies (Exp. Abs.), Society of Exploration Geophysicists, Dallas, TX, 469-471, 1982.

Widess, M.B., How thin is a thin bed?, Geophysics, 38, 1176-1180, 1973.

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