The LITHOPROBE regional three-component experiment in southern Alberta

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ABSTRACT

As an augmentation of LITHOPROBE's southern Alberta transects (SALT) in general, and the Vibroseis augmented listen time (VAuLT) experiment in particular, a pair of 3-C spreads were shot with extended listen times (55 s) in mid-October 1995 near Claresholm, Alberta. Our objectives in proposing this survey were: (1) determination of crustal Poisson's ratio; (2) regional P-SV analysis of the sedimentary basin; (3) study of crustal and upper mantle anisotropy; (4) determination of crustal attenuation properties for both P and S waves. At present, only a few sample shot records have been correlated, of which two are here illustrated.

INTRODUCTION

During the summer of 1995, we proposed a three-component (3-C) augmentation to the LITHOPROBE Vibroseis Augmented Listen Time (VAuLT) experiment in southern Alberta. Our original proposal was to add transverse (crossline) and radial (inline) horizontal-component geophones to every second recording station, i.e., every 100 m, of a 170-km section of a north–south line of the Alberta Basement Transects survey. As enlarged upon below, these 3-C data would constitute an extremely valuable and, in many ways, unique dataset which we proposed to use for the following objectives: (1) determination of Poisson's ratio or, equivalently, V_P/V_S in the crust; (2) construction of a regional P-SV profile analysis of the sedimentary basin, with particular attention to lithologic properties; (3) a search for, and modelling of, anisotropy in both the crust and upper mantle; (4) study of the large-scale attenuation, or Q characteristics, of the crust for both P and S waves.

THE SURVEY

As the actual survey time approached and issues such as costs and existing contractual agreements came to bear, the actual acquisition for the 3-C add-on had to be revised and pared down. The survey was shot during mid-October near Stavely, about 15 km north of Claresholm (Figure 1), a switch from the first proposed location east of Brooks. It consisted ultimately of two stationary spreads, each 12.5 km in length with 500 2-C horizontal geophones (there was a 1000-channel recording capacity) deployed at intervals of 25 m. These were recorded from sources that consisted of eight vibrators on the N-S line (LITHOPROBE line 32) and twelve (sometimes eleven) on the E-W line (LITHOPROBE line 34).

On line 32, recording commenced about 12.5 km before the vibes reach the stationary spread and continued for about 5 km after the vibes had moved off the spread, an active shooting distance of roughly 30 km (80 shots), giving maximum source-receiver offsets of about 25 km. On line 34, recording commenced about 30 km

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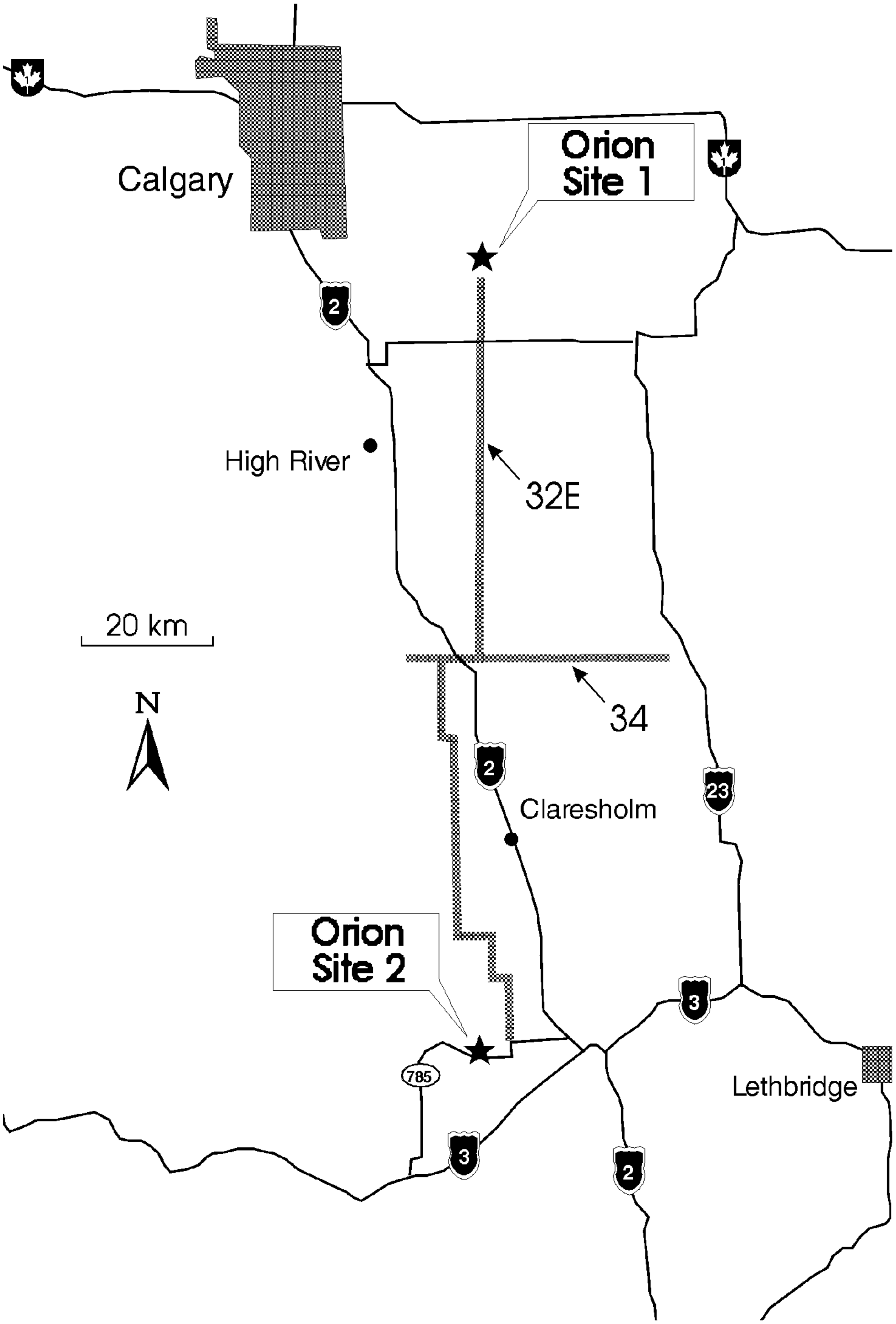

Fig. 1. Map of the area of the LITHOPROBE Vibroseis Augmented Listen Time (VAuLT) survey. The two 3-C lines were located along line 32E near Claresholm and along line 34. The Orion sites were earthquake seismometer installations used in the VAuLT survey.

before the vibes reach the stationary spread and continued for about two km after the vibes had moved off the spread, an active shooting distance of roughly 44 km (114 shots), giving maximum source-receiver offsets of some 42.5 km. The horizontal-component add-on was recorded with a 55-s listen time (after extended correlation) and an 8-ms sample interval. On line 32, vertical components were recorded with a shorter listen time, but at the same geophone interval (25 m), in earlier LITHOPROBE acquisition. For line 34, vertical components were recorded in a separate stage of the VAuLT experiment (i.e., extended listen time) but at a different geophone interval (40 m). After some interpolation, these will be combined with the two horizontals to complete the 3-C dataset.

PROPOSED RESEARCH

Crustal Poisson's ratio measurements

Coincident P-P and P-SV reflection profiles can be used to obtain estimates of the ratio $V_\mathrm{P}/V_\mathrm{S}$ (or alternatively, Poisson's ratio) in discrete stratigraphic intervals. This can be accomplished by correlating reflections observed on both profiles to obtain a set of P-wave zero-offset reflection traveltimes and a set of P-SV zero-offset reflection traveltimes. Denoting the two-way time difference between two reflections as ΔT_PP for the P-P case and as ΔT_PSV in the P-SV case, the $V_\mathrm{P}/V_\mathrm{S}$ ratio (corresponding to the stratigraphic interval between the reflections) can then be determined from the simple expression:

$$V_\mathrm{P}/V_\mathrm{S} = 2\Delta T_\mathrm{PSV}/\Delta T_\mathrm{PP} - 1. \qquad (1)$$

Poisson's ratio can also be computed from this using:

$$\sigma = 0.5\left[\left(V_\mathrm{P}/V_\mathrm{S}\right)^2 - 2\right] \Big/ \left[\left(V_\mathrm{P}/V_\mathrm{S}\right)^2 - 1\right]. \qquad (2)$$

Previous LITHOPROBE P-wave reflection profiles in Alberta, as well as donated industry datasets close to the proposed study area, have been characterized by widespread reflectivity in the lower crust and very prominent midcrustal reflections (Ross et al., 1995). In addition to P-wave impedance contrasts, teleseismic receiver-function studies (Cassidy, 1995a, b) indicate significant S-wave velocity contrasts in midcrustal reflectors (e.g., of a low-velocity zone near Edmonton). However, it is preferable to combine receiver-function studies with seismic reflection work because the receiver-function method, although sensitive to S-wave velocity contrasts, is not terribly useful for imaging P-wave impedance contrasts (J.F. Cassidy, pers. comm.).

Thus, there is strong evidence indicating that converted-wave reflections will be observed in the proposed 3-C survey that can be correlated with P-P reflections. The Poisson's ratio values computed from these measurements will provide constraints on the bulk composition of layers in the crust. As the profile will be crossing an important suture in the basement (the Vulcan structure), it may be possible to make inferences about differences in crustal composition across this suture.

Regional P-SV profile of the sedimentary basin

Recently, a number of industry template seismic profiles have led to the recognition of the importance of P-SV measurements for providing information about subsurface lithology, porosity, and pore-fluid type. P-SV seismic data can be used in conjunction with P-P data to determine other rock properties, such as V_P/V_S (or Poisson's ratio, σ). The ratio V_P/V_S is sensitive to changes in many rock properties, including porosity, pore shape, and pore fluid (e.g. Pickett, 1963; Nations, 1974; Tatham, 1982; Eastwood and Castagna, 1983; Miller and Stewart, 1990). These parameters are significant in the exploration for, and production of, oil and gas, and for mapping petroleum reservoirs. Work to date using multicomponent seismic data has been limited to relatively short 2-D profiles (on the scale of the sedimentary basin).

The LITHOPROBE program offered an opportunity to obtain long (up to ~50 km) profiles over the sedimentary basin. This would allow lithological mapping and facies analysis on a regional scale that may be related to possible controlling influences of basement-related tectonic activity during the Phanerozoic. In addition, the multicomponent experiment will provide observations of large-scale variations in P-SV reflectivity patterns and S-wave velocity structure of the sedimentary basin, as well as the deeper crust.

Anisotropy studies

The proposed 3-C profile will be oriented at an oblique angle to the known principal stress directions in the sedimentary basin. Seismic anisotropy that is induced by a preferred orientation of vertical cracks, or of pore spaces, in response to the ambient stress field will give rise to a transversely isotropic (TI) symmetry system with a horizontal axis of symmetry. For a medium that has both aligned vertical cracks and fine horizontal layering, or two orthogonal vertical crack sets, orthorhombic symmetry may arise (of which TI is a special case). Propagation of converted shear waves through the sedimentary layers should then lead to birefringence, or shear-wave splitting, with fast and slow shear waves polarized in orthogonal directions that are closely related to the directions of the principal stresses. Given the lengths of the profiles and the considerable size of the dataset, it should be possible to test such models. P-wave reflections recorded on conventional LITHOPROBE regional lines are generally insensitive to this type of anisotropy since the effects of anisotropy on P-wave moveout are much more subtle than the very diagnostic phenomenon of shear-wave splitting (e.g. Crampin, 1993).

The seismic anisotropy of the underlying crystalline basement is unknown. However, aeromagnetic anomaly trends indicate a very pronounced change from the north end of the profile (where linear anomalies strike NE-SW) to the south end of the profile, where anomaly trends are E-W. If there is a pervasive strain fabric in the crystalline basement that is oriented parallel to the aeromagnetic trends, then it might be possible to distinguish different orientations of the symmetry axes at opposite ends of the profile. In order to accomplish this, it will be necessary to remove any anisotropic effects of the sedimentary layers described above, by the process of layer stripping (e.g. Winterstein and Meadows, 1991a, b), to restore polarization directions of deeper reflected waves to the orientations they had at the base of the sedimentary section. Similarly, reflections from the Moho could potentially be used to make inferences about upper-mantle anisotropy (e.g. Guest et al., 1993), although this would require careful stripping off of the effects of the overlying layers.

Guest et al. (1993) present a plausible model of upper-mantle anisotropy for converted reflected P-S waves that have travelled only in the presumed isotropic crust but reflected off the assumed anisotropic mantle, in order to explain transverse particle motions recorded at the receivers. However, their observations may also be accounted for by lateral inhomogeneity alone, i.e., by a wholly isotropic model (crust and mantle) with a Moho that is dipping, but in a rather complex and fortuitous way. With this proposed 3-C augmentation and the deep penetration of the LITHOPROBE VAuLT experiment, we expect to see reflections representing propagation over long mantle paths, which will allow us to distinguish clearly between lateral inhomogeneity and any mantle anisotropy.

Attenuation studies

The long record length makes the proposed 3-C data ideal for estimation of the large-scale attenuation (Q) characteristics of the crust. Separate Q estimates for both P and S waves (Q_P and Q_S) would provide valuable additional information to characterize crustal lithology. It is proposed to use the spectral-ratio method (Ganley and Kanasewich, 1980) on suitably processed P-P and P-SV wave sections to simultaneously estimate Q_P and Q_S. If seismic data is processed to stack with deterministic gain procedures (i.e. no AGC) then stable spectral-ratio calculations can be made on such data, which take the known gain functions into account. If spectra are taken from windows that follow major reflectors on both sections, then interval Q estimates can be computed that are attributable to the lithology and pore fluids of the interval. Given spectral ratios from both P-P and P-SV sections, a simultaneous inversion for both Q_P and Q_S can be made. Experience has shown that Q estimates can be made on P-P data using Fourier spectra over intervals as small as 400 ms (2-ms data). A major goal of this study will be to decrease this estimation interval as much as possible using other techniques such as Burg (maximum-entropy) spectra (Claerbout, 1976).

PARAMETER SUMMARY AND PROCESSING PLAN

Number of active ground stations: 500 (each of 2 lines)

Number of channels: 1000 (each line)

Group interval: 25 m [horizontal geophones (inline and crossline) at each location]

Far offset: 25 km (line 32); 42.5 km (line 34)

Source interval: 400 m (nominally)

Number of vibrators: 8 (line 32); 12 (line 34)

Sweep length; frequencies: 40 s; 8-40 Hz

Spread configuration: fixed; shot-through

In order to enable application of an extended correlation technique to the VAuLT dataset as a whole, these data were not correlated in the field. Extended correlation of the 3-C Vibroseis data is now underway at the LITHOPROBE Seismic Processing Facility (LSPF) and two example shot records are shown here (Figures 2 and 3). We then plan to send the correlated data out-of-house for processing through to stack. Poststack processing will, in all likelihood, be done in the CREWES labs, as will specialized prestack work later on.

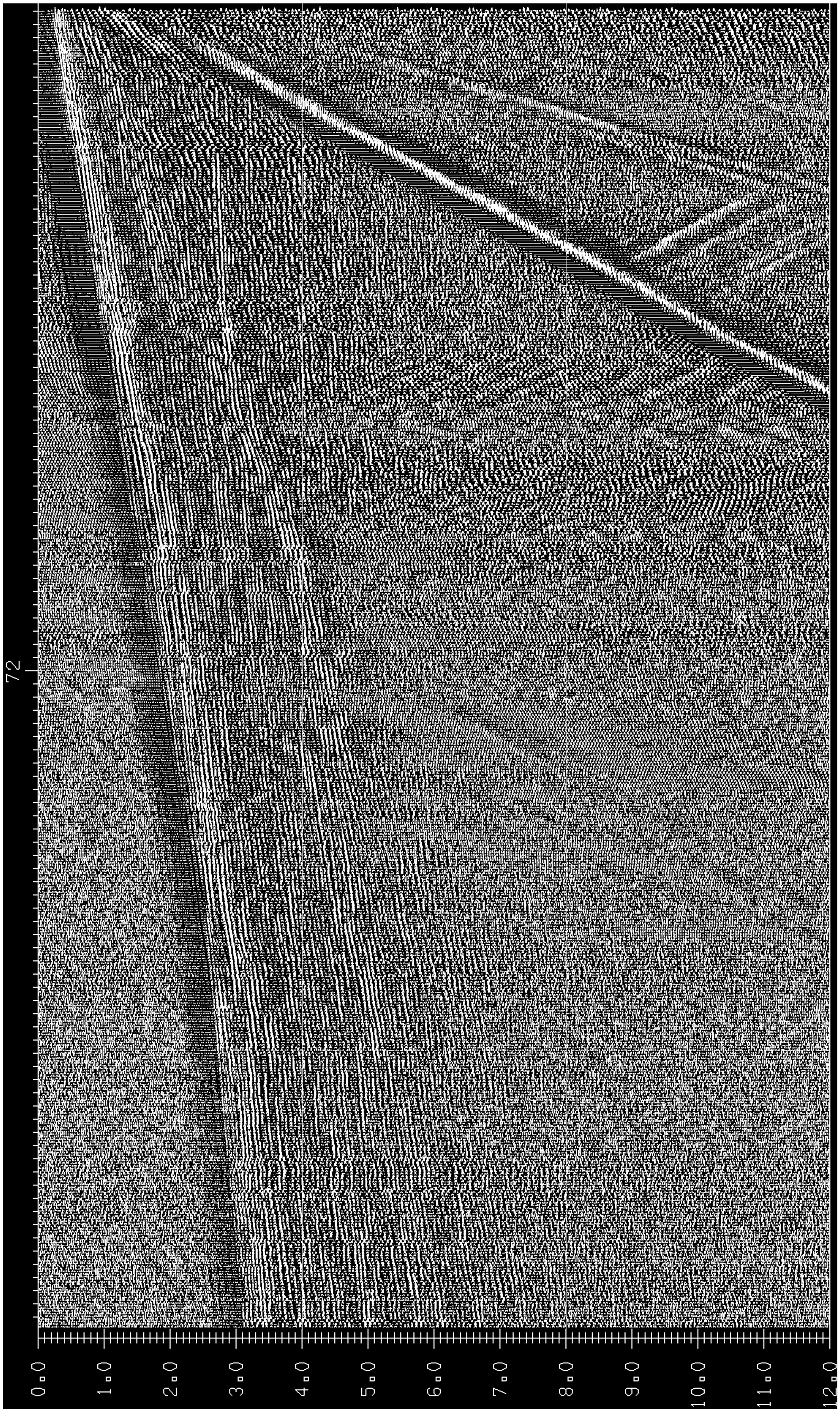

Fig. 2. Shot record (first 12 s) of the inline (radial) component of shot number 72, line 32 (north-south) from the LITHOPROBE VAuLT 3-C survey.

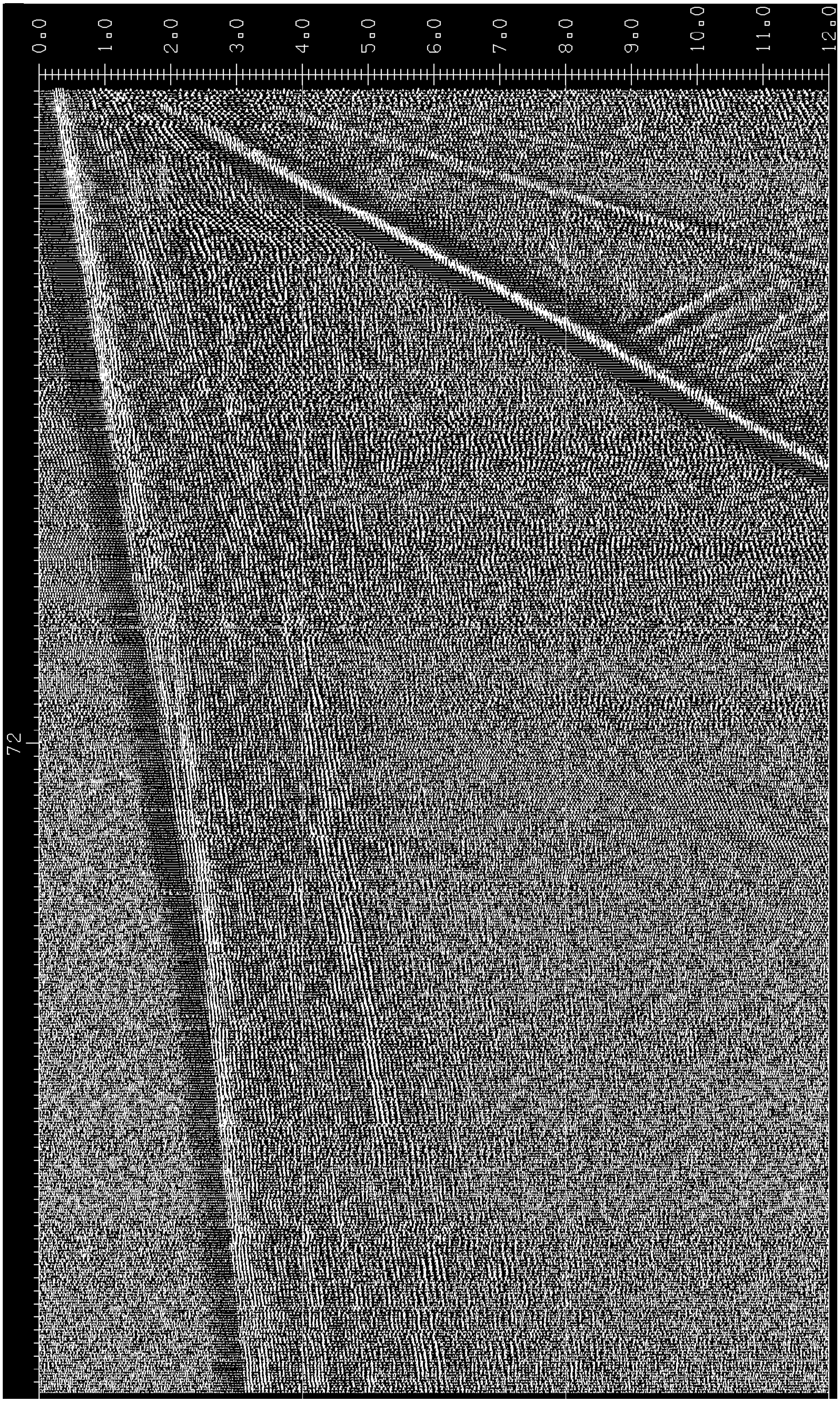

Fig. 3. Shot record (first 12 s) of the crossline (transverse) component of shot no. 72, line 32 (north-south) from the LITHOPROBE VAuLT 3-C survey.

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