An underground seismic-anisotropy experiment in a salt mine

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ABSTRACT

In order to study possible seismic anisotropy due to crystal alignment in salt, we have carried out an in-situ experiment in the Devonian Prairie Evaporite about 1 km underground in the Allan potash mine, near Saskatoon, Saskatchewan. The work has been carried out using a high-resolution (~1-kHz) seismic acquisition system and a tomographic (transmission) type of experimental design. The main purpose of the study has been to establish whether or not anisotropic seismic properties in these salts, which are believed to have undergone recrystallization and thermomechanical alteration, show any promise of being useful in the mapping of such salt units.

A pillar of potash ore (roughly 30% halite and 30% sylvite) was selected for the experiment on the basis of accessibility and rock integrity. A hammer was employed as the energy source (frequencies from about 100 to 2000 Hz) and each record was obtained by vertically stacking the records from five repeated hammer blows. Geophones were affixed to one face of the pillar in three orthogonal orientations. Records were acquired in three separate steps, each with identical geometry but different orientations of the geophone polarization: first normal to the wall, then vertically tangential to the wall, and finally horizontally tangential.

We observe shear-wave splitting for many of the three-component record sets acquired in this experiment. This could conceivably be caused by cracking or fracturing in the rock as a result of destressing following mine excavation or by the alignment of salt crystals in the rock in response to the stress field prevailing at the time of recrystallization. Indications are that the anisotropy observed here is a result of crystal alignment, rather than post-excavation effects. We are led to this conclusion because the observed symmetry axes are consistent with the known trends of fracture lineaments and principal stress axes on the western Canadian plains but inconsistent with the orientations of the excavated rock faces.

INTRODUCTION

The importance of salt units and their history of dissolution and deformation in sedimentary basins has been documented by many authors (e.g. De Mille et al., 1964; Parker, 1967; Smith and Pullen, 1967; Langstroth, 1971; Lohmann, 1972; Edmunds, 1980; Oliver and Cowper, 1983; Simpson, 1984; Wilmot, 1985; Hopkins, 1987; Jenyon and Taylor, 1987; Jenyon, 1988; Anderson, 1991; Anderson and Brown, 1991a, b). Dissolution in the western Canada basin, particularly of Devonian salt units, and the subsequent differential subsidence, has helped to establish hydrocarbon reservoirs by creating structural closure in the overlying section, as well as various controls on contemporaneous or later deposition. Edmunds (1980) has stated that salt removal is perhaps the most important hydrocarbon-trapping mechanism in western Canada. Salt remnants and dissolution features can also, unless fully recognized, lead to gross misinterpretation in the subsurface in terms of reefs, basement structure, etc. By *salt* we mean primarily halite (NaCl) but potash or sylvite (KCl) often occurs together with halite and both have cubic symmetry.

Because of this important role played by salt in various exploration scenarios, and because salt crystals (halite, sylvite, etc.) have cubic symmetry and are therefore elastically anisotropic, we have been considering the possibility of using the diagnostic properties of this seismic anisotropy (such as shear-wave splitting) as an additional tool for mapping salt, in combination with the traditional well-logging tools – mainly calipre and gamma-ray logs. In order that salt units exhibit such diagnostic properties for frequencies of relevance to exploration ($f \sim 10$–10^2 Hz), salt crystals would have to be aligned throughout volumes of such dimensions. We have done some ultrasonic laboratory experiments ($f \sim 10^5$–10^6 Hz) on salt core samples, some of which have been found to exhibit shear-wave splitting (Sun et al., 1991). The present study represents the next step, i.e. to see whether in-situ salt might exhibit observable seismic anisotropy in the so-called high-resolution frequency range ($f \sim 10^3$ Hz), closer to that of exploration.

THE PROPERTIES AND CLASSIFICATION OF SALT

Salt properties may differ because of several factors such as origin, composition, and the influence of diagenesis or burial metamorphism. Sun (1993) has classified salt according to its velocity features. Salt can also be classified according to composition into two groups: pure, and impure salts. Impure salts are those in which salt crystals are mixed uniformly with clastic deposits (due to intrasedimentary growth of salt). Pure salts (Figure 1) are classified into three types: chevron-crystal, detrital and burial-metamorphic.

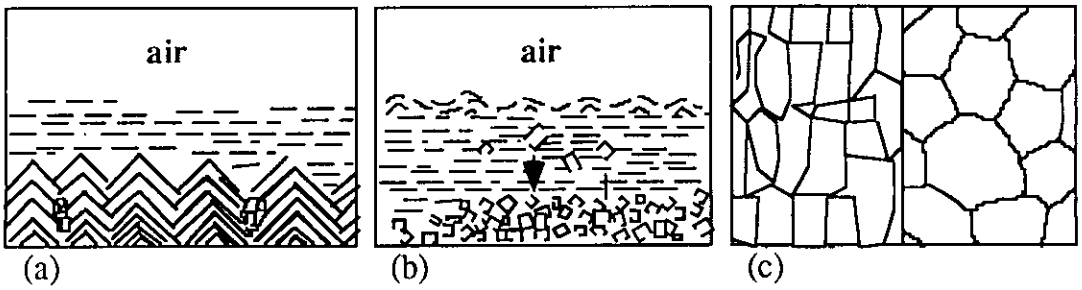

FIG. 1. Crystal framework of three major types of salt: (a) chevron-crystal, (b) detrital, (c) burial-metamorphic.

Chevron salt is produced syndepositionally in open space and has a syntaxially grown crystalline framework consisting of vertically oriented and vertically elongated crystals that exhibit cubic symmetry (Spencer and Lowenstein, 1990; Sun, 1993). It represents a stable environment (e.g. an ephemeral lake-salt pan or permanent brine body). Detrital-framework salt (Figure 1b) is produced in high-energy ephemeral environments. The framework of grains with point contacts establishes a primary detrital texture in the evaporites like in clastic rocks. The third type, burial-metamorphic (diagenetically altered) salt, may be anisotropic or isotropic. Its crystals (Figure 1c, left panel) may have a strongly preferred orientation (Skrotzki and Welch, 1983; Larsen, 1983). It may also be strongly altered by temperatures and pressures due to burial in which case it is called anhedral mosaic salt (Figure 1c, right panel).

THE HIGH-RESOLUTION EXPERIMENT

Using a 24-channel Bison GeoPro for data recording and storage, we carried out a high-resolution three-component experiment in the Allan mine of the Potash Corporation of Saskatchewan, about 40 km southeast of Saskatoon. The potash pillar consists of ~30% of each of halite and sylvite. We observed this salt to be recrystallized and thermomechanically altered (Sun, 1993). Stratigraphically, it is located in a main production zone of the Patience Lake Member of the Devonian Prairie Evaporite (Figure 2). The pillar consists entirely of recrystallized salt that has undergone some metamorphism and alteration by pressure and temperature.

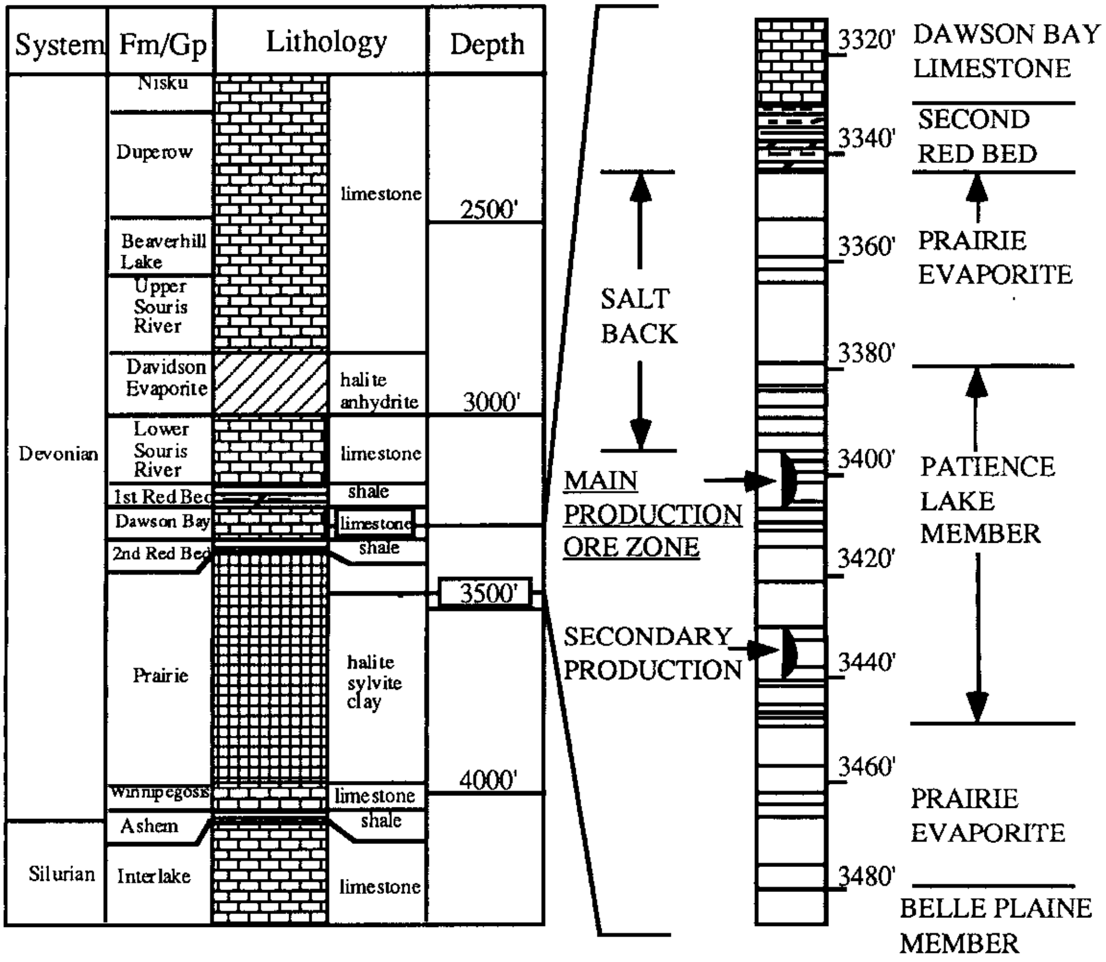

FIG. 2. A stratigraphic section of the mining zone showing the location of the experiment.

Experiments were conducted in a mining pillar that was chosen as being freshly excavated and as free of deformation (fracture, flow) as possible. However, deformation begins immediately after excavation so some such is unavoidable. A plan view of the pillar is shown in Figure 3. High-frequency geophones were rigidly attached to the wall with a small steel bracket. The geophone was screwed to one end of the bracket, which was fixed to the rock with a fastener. Fasteners are threaded Hilti bolts that were driven into the rock salt with a gun using explosive cartridges.

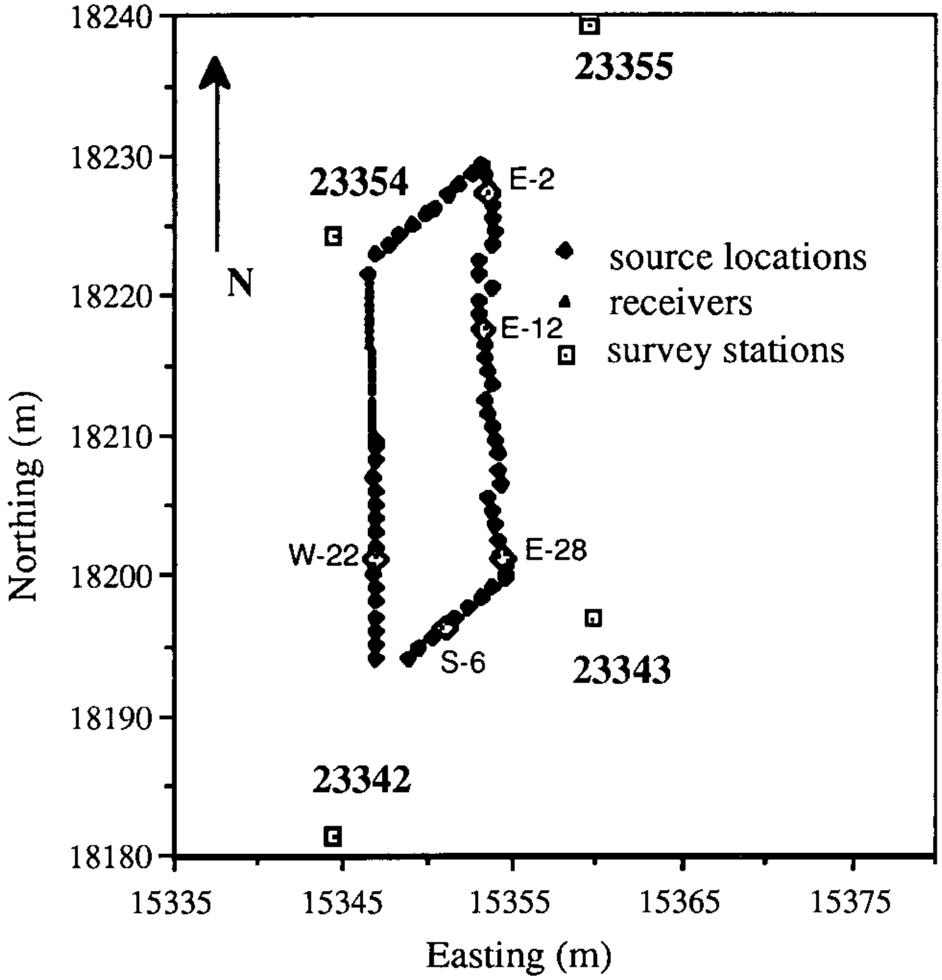

FIG. 3. Plan view of the experimental salt pillar showing source and receiver locations and mine-survey stations. Three-component record sets are displayed below for the highlighted source locations.

Table 1. Field recording parameters for all experiments.

Filters:	high-cut: 2000 Hz	low-cut: 96 Hz
Sample rate:	0.05 ms	
Channels:	24	
Samples:	1001	
Recording length:	50 ms	
AGC:	off	

The data were sampled every 0.05 ms and recorded with length of 50 ms by a 24-channel Bison GeoPro seismograph. Field parameters are listed in Table 1. There were 29 shot positions and each shot was simultaneously recorded with 23 receivers that were affixed to the northern part of the west wall at 0.5-m intervals. The sources were positioned over the rest of the pillar at 2-m intervals (Figure 3). Five hammer blows were struck at each source location for each component. Both receivers and sources were kept at the same height. The experimental procedure was as follows:

1) shots around all four sides of the pillar were recorded with geophone polarizations normal to the pillar, denoted N;
2) the geophone polarizations were changed to tangential-vertical (crossline), denoted V – everything else unchanged – and the shot series was repeated;
3) the geophone polarizations were changed to tangential-horizontal (inline), denoted H, and the shot series was carried out a third time.

Thus, for each of the 29 shots, three-component transmission records were acquired representing propagation through the potash pillar. These records have been analyzed for evidence of shear-wave splitting. In such analysis one must keep in mind the peculiar geometry of this survey (a horizontal line on a vertical rock face) compared with that of conventional reflection-seismic geometry. Here, the sagittal plane is horizontal rather than the conventional vertical; geophones recording horizontal motion normal to the pillar face (N) correspond to the conventional vertical-component phones; geophones recording vertical motion tangential to the pillar face (V) correspond to the conventional transverse or crossline horizontal-component phones, and geophones recording horizontal motion tangential to the pillar face (H) correspond to the conventional radial or inline horizontal-component phones. Figure 4 shows the variation of phase slowness and of group velocity of halite for quasishear (qS) and quasicompressional (qP) waves propagating in a horizontal symmetry plane.

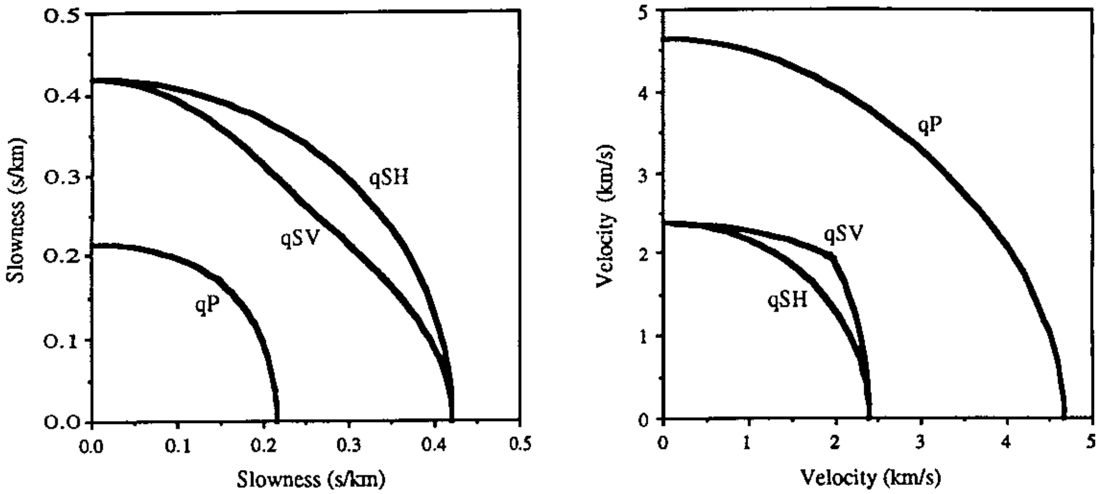

FIG. 4. The variation of phase slowness (left) and of group velocity (right) in one quadrant of a symmetry plane of halite, as determined from laboratory measurements on halite (Sun, 1993).

There is a clear relationship between polarities on the N and H components for P and SV waves, depending on where the shotpoint was located. However, there is not such a clear relationship between polarities on the V and H (or the V and N) components, since *ideally* our hammer blows should not have any net vertical component of force. For this reason, in the absence of very clear first S-wave breaks, there would be some ambiguity in correlating S1 (on N and H) with S2 (on V) for the purpose of determining split-shear time delays: one could, for example, correlate an S1 peak on N with either a peak or a trough of S2 on V.

RESULTS AND INTERPRETATION

If seismic anisotropy is observed in this rockmass, there are two possible causes that seem most likely to us. One candidate is the alignment of salt crystals, which would have occurred during recrystallization under the control of the prevailing stress regime. Another is the microcracking and fracturing that evidently initiates throughout the neighbourhood of the exposed rock faces immediately following excavation. This would be in response to the sudden release of compressive stress normal to each excavated surface (horizontal and vertical surfaces in most mines), giving rise to cracks with accordingly preferred orientations. In the former case, one would expect symmetry directions of the anisotropy to conform to those of the prevailing principal stresses. In the latter case, one would expect these symmetry directions to conform with the normals to the excavated rock faces. In either case we would expect the horizontal plane to be a plane of symmetry, i.e. the vertical direction to be a direction of symmetry, in view of the presumed maximum principal stress due to gravity and the horizontal/vertical nature of the mine cuts. We would, however, expect the two scenarios to give, in general, different horizontal symmetry directions.

Figure 4 shows the slownesses and group velocities in halite for qS and qP waves propagating in a symmetry plane of halite, presumably the horizontal sagittal plane of our experiment. Because of the unconventional geometry of this survey, the shear waves normally thought of as SV, polarized within the plane of propagation, are here polarized horizontally; and the shear waves normally thought of as SH, polarized transversely to the plane of propagation, are here polarized vertically. We therefore look for the fast shear waves, qS1 (qSV), on the N- and H-component geophones, and the slow shear waves, qS2 (qSH), on the V-component geophones.

In examining the records obtained in this survey, we find significant shear-wave splitting for many of the shot-receiver directions and little or no splitting for others. Figures 5 to 9 show the three-component records acquired for five different shot locations: S-6 (south wall, shotpoint 6), E-12, W-22, E-2 and E-28. The positions of these shots are indicated in Figure 3. Note that propagation through to the entire spread covers a range of directions. The first two of these shotpoints, S-6 and E-12 (Figures 5 and 6), have been chosen as record sets showing the least shear-wave splitting, whereas the remaining three, W-22, E-2 and E-28 (Figures 7 to 9), have been chosen as record sets showing more-or-less maximal splitting.

Directions of no splitting correspond to symmetry directions (Figure 4) so this observed pattern indicates symmetry directions roughly ENE-WSW and NNW-SSE. These do not correspond to the roughly N-S and E-W symmetry of the recording wall, but do concur quite well with directions reported in the literature for observed fracture lineament trends and for the stress regime in the western Canada basin. The observed pattern of shear-wave splitting as a function of direction appears to be incompatible with the hypothesis of excavation stress release as the cause, but quite compatible with the hypothesis of crystal alignment controlled by the prevailing stress field.

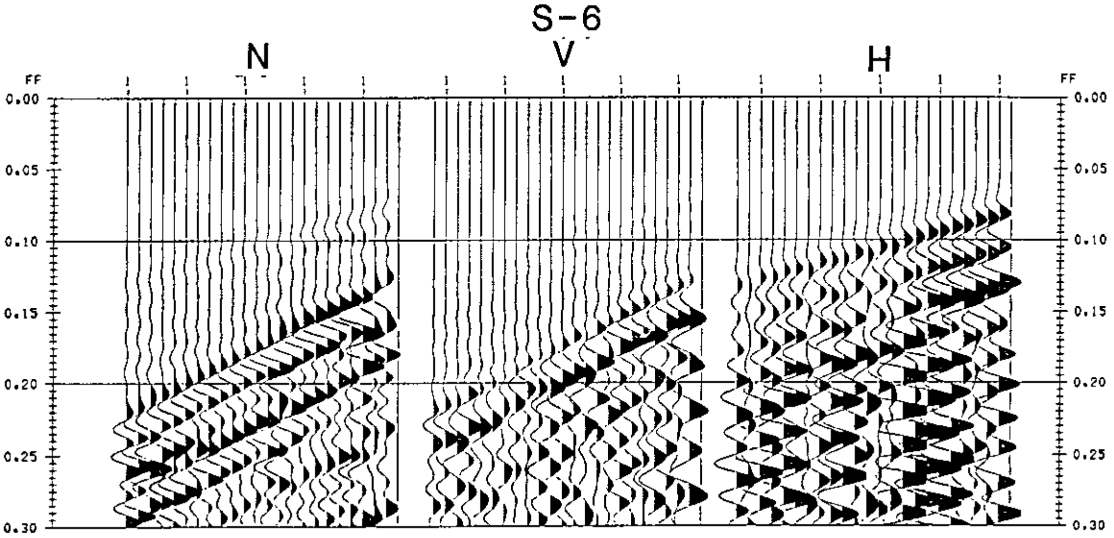

FIG. 5. Three-component record set for the shotpoint at S-6, i.e. south wall, shot location 6. There is little or no shear-wave splitting observed.

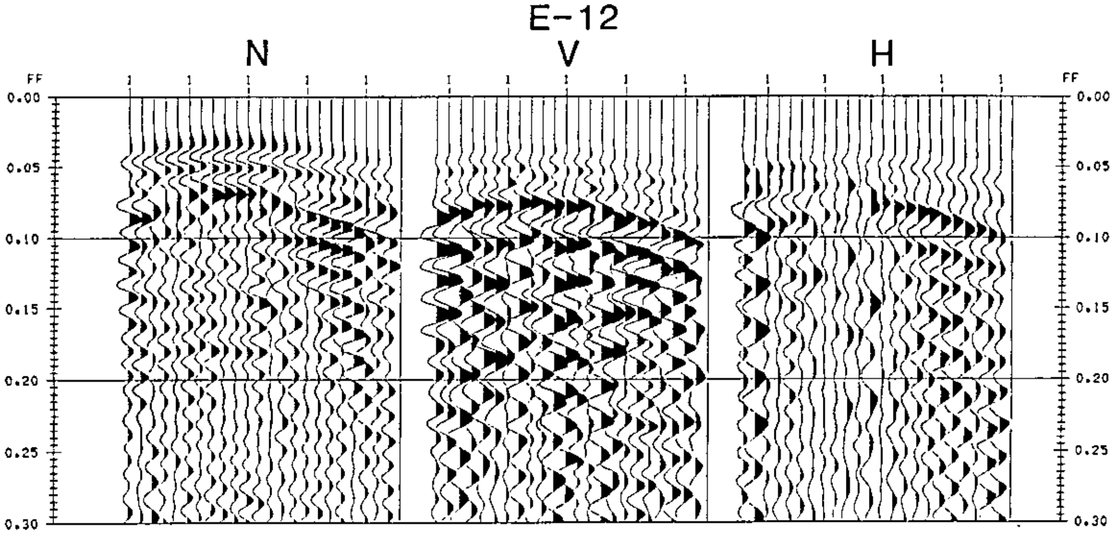

FIG. 6. Three-component record set for the shotpoint at E-12, i.e. east wall, shot location 12. There is no obvious shear-wave splitting observed, particularly on the farthest offsets.

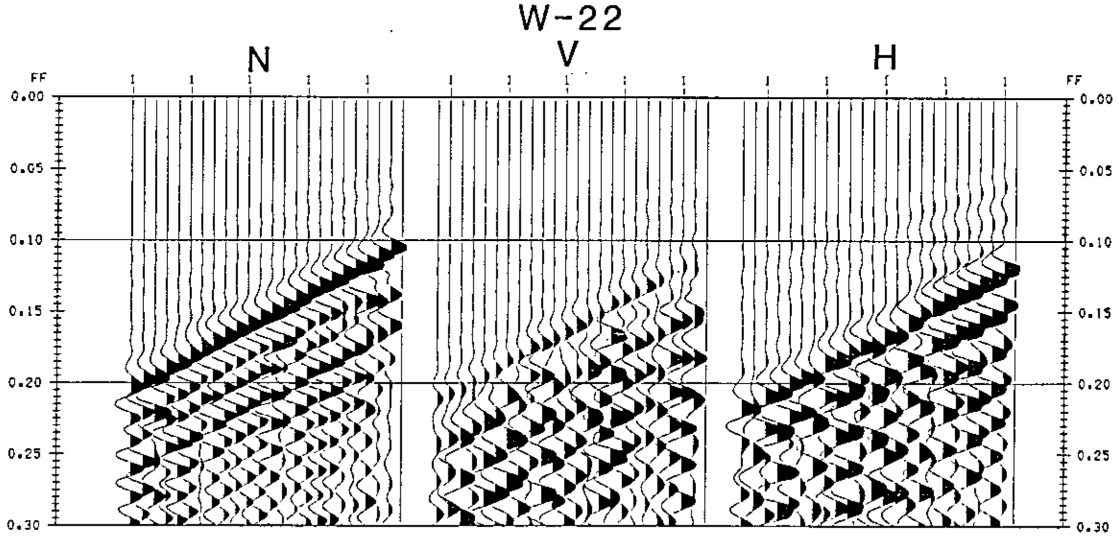

FIG. 7. Three-component record set for the shotpoint at W-22, i.e. west wall, shot location 22. There appears to be significant shear-wave splitting on all traces.

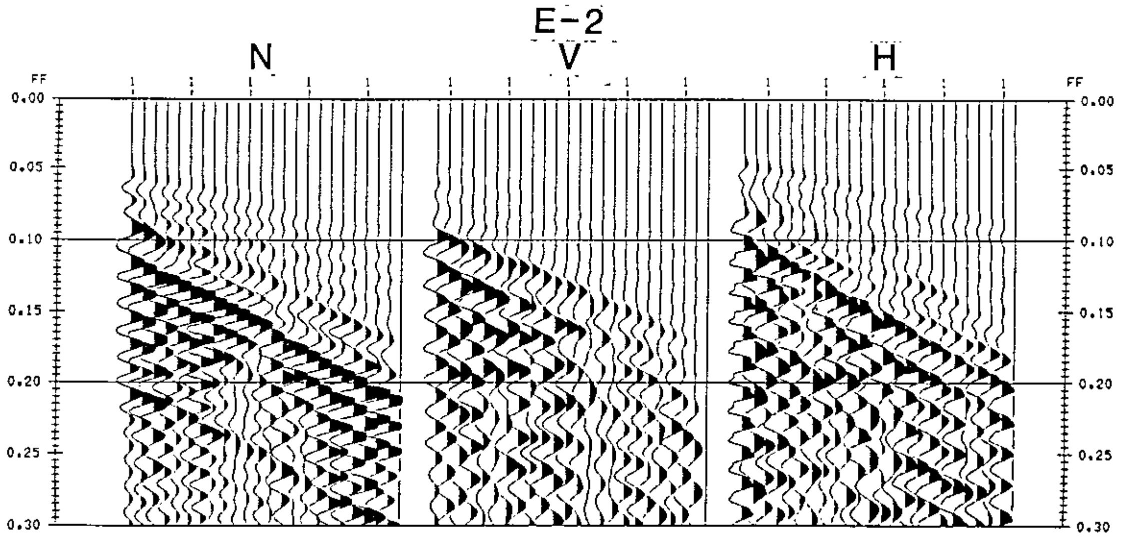

FIG. 8. Three-component record set for the shotpoint at E-2, i.e. east wall, shot location 2. There appears to be significant shear-wave splitting on all traces.

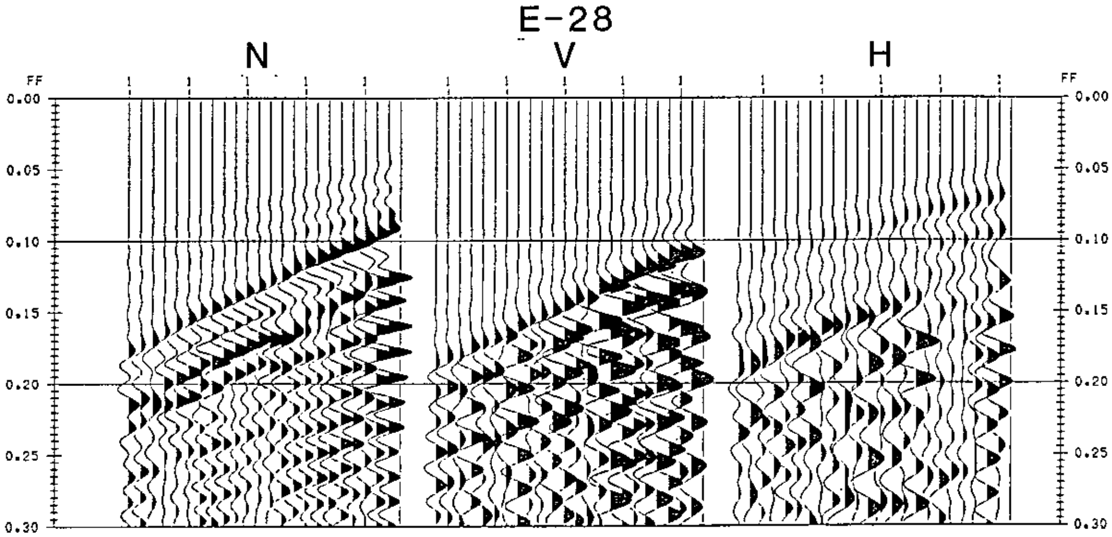

FIG. 9. Three-component record set for the shotpoint at E-28, i.e. east wall, shot location 28. There appears to be significant shear-wave splitting on all traces.

Among published studies on the western Canadian plains, Stauffer and Gendzwill (1987) document orthogonal fracture sets, consistently trending NE-SW, that they interpret to have originated in the Late Jurassic or earlier and to be related to North American plate motion. Also, Mollard (1988) reports on the results of several studies on the orientation of fracture lineaments and principal stress axes using a wide array of observations: remote sensing, photolineaments, joint sets, principal stresses from mines and from oil-well breakouts, and inferred tectonic plate motion. These studies all indicate directions close to NE-SW and NW-SE, with the inferred direction of contemporary maximum horizontal compressive stress varying locally over the plains from ENE to NNE.

We have found the hammer-impact source to be quite effective in producing shear waves, in some cases even of greater amplitude than the P waves. This effect has also been observed by D.J. Gendzwill (pers. comm.). The records shown in Figures 5 to 9 also contain spurious resonances, which could be removed by designing appropriate deconvolution filters. This ringing also contributes to the ambiguity in correlating S1 and S2, as mentioned above. Nevertheless, the compressional- and shear-wave arrivals are clear enough for one to conclude with some confidence that significant time delays exist in Figures 7 to 9 between the S1 arrivals seen on the normal (N) and the inline (H) components and the S2 arrivals observed on the crossline (V) components.

DISCUSSION AND CONCLUSIONS

The recrystallized and thermomechanically altered salt studied in this experiment appears to exhibit seismic anisotropy. The symmetry axes of the anisotropy appear to be consistent with a cause rooted in the alignment of salt crystals, perhaps of the chevron type (Figure 1). This is in accord with our expectation, on the basis of salt classification, that this type of salt could display elastic anisotropy, depending on the degree and type of alteration. The cracking and fracturing resulting from the mine excavation appears not to have been a significant factor in the observed anisotropy. This is in agreement with the findings of Holmes et al. (1993) who observe very little effect of excavation damage on shear-wave signals in an experiment in the Underground Research Laboratory of Atomic Energy of Canada Ltd at Pinawa, Manitoba.

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