Features in Kansas cyclothsms seen by high-resolution seismology

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Abstract: Accurate quantitative modeling of visual sequences requires verification of model results by means of comparisons with known stratigraphic intervals, and in many cases seismic data provide the best or only means toward that end. In eastern Kansas, the scale of variability within Middle and Upper Pennsylvanian units is of the order of meters. Unraveling the stratigraphy and thereby verifying models at such a scale requires high-resolution seismic data. Middle and Upper Pennsylvanian cyclic sequences (cyclothsms) are seen as just a few wiggles on standard petroleum exploration reflection seismogram sections with frequency responses of 0-80 Hz. For instance, the Kansas City and Lansing Groups cannot be distinguished. However, the use of high-resolution exploration seismology, with frequency up to 500 Hz, allows the detection of thin bed members of the individual groups and formational intervals approximately 2-5 (7-14 ft) thick. Geologic cyclicity and reflection seismology are not synonymous, and carbonate units are seen as proks and subcyclic units (mostly shales) as troughs. Seismic response becomes sensitive to phenomena such as the presence of intra-bed members of the individual groups and the nature of the shales and the surface roughness (dissimilarity of lithologic interfaces). Complex trace analysis aids in the interpretation of thin bed thickness and the nature and continuity of geologic boundaries. Reflection strength helps determine which geologic boundaries form strong reflectors and therefore have closure. The interface is instantaneous when it develops, and by emphasizing stratal reflections, indicating stratigraphic structure and sandstone channel presence, instantaneous frequency indicates (1) intra-bed structure and (2) channel presence when it displays a chaotic pattern and (3) the dominant frequency of the reflector response when it is coherent. Dominant frequency of the reflector response is frequently useful in determining bed thickness.

The verification of quantitative models that attempt to produce realistic sedimentary sequences requires the comparison of model results with high-quality stratigraphic data sets. An ideal data set could be derived from a relatively thick and continuously exposed sequence such as the Borden Group of the Coastal Plain of the United States, from which detailed stratigraphy, bounding surfaces, and stratigraphic geometry could be extracted. Unfortunately, in most settings such complete information is not available, and the modeler must rely on a combination of well log, core, outcrop, and seismic data for model calibration and verification. Of these sources of data, in many cases only seismic data can provide information regarding the continuity of stratigraphic surfaces and, by extension, stratigraphic geometry. Borehole data is basically one-dimensional. As discussed in this article, effects such as interface roughness are not seen on a well log. Furthermore, horizons are usually too far apart to derive more than a crude picture of the geometry. Reflection seismic data, on the other hand, provide a detailed continuous profile and are sensitive to both lithologic changes (vertical effects) and the condition or quality of the reflection surface (lateral effects). The seismic response is affected by an ill-defined volume about the reflector point. It is our goal here to describe from a geophysical perspective the ability of high-frequency seismic data to resolve features within the stratigraphically heterogeneous Upper Pennsylvanian strata of eastern Kansas. To effectively model at the scale of variability of these intra (meters to tens of meters), the level of detail resolvable must be maximized and spurious noise minimized. In this article we document small-scale features that are observed on a seismic seismic section over a reasonably well-known interval and relate observations on the character of a reflector to observable geologic effects.

Background

In 1968 a 70-n-m-long (230-ft-long) high-resolution seismic line was shot on the west campus of the University of Kansas. The purpose of the line was to test acquisition and computer processing techniques under development at the time; however, because the days were of higher resolution than any other previously recorded for the given geologic section, they revealed a great deal about the seismic response of Kansas cyclothsms. Details of the acquisition have been published elsewhere (Knapp, 1988; Knapp and Miitonglu, 1987; Knapp and Warne, 1987).

Seismic reflection is a differential process. That is, rather than being sensitive to lithologic processes, reflections are the consequence of changes (differences) in the acoustic impedance (product of density and velocity) of the rock. Because the seismic wavelet is band limited, the reflection from an abrupt interface is smeared or spread in time. This dispersion is defined by a vertical resolution (Knapp, 1990; Berkhourt, 1984). Likewise, limitations in lateral resolution smear the horizontal character of the reflection response (Berkhourt, 1984). Consequently, the vertical character of a
reflection is modulated according to (1) the rate of lithologic change (i.e., the vertical rate of change of the acoustic impedance) and (2) the proximity of other reflecting surfaces that produce interfering reflections.

Lateral changes in the reflector, such as faults and reflection surface roughness, likewise modulate the response at a reflection point. We report the results here. Migration, the correction of distortion resulting from reflector geometry, can correct for some of the problems of lateral interferences by removing the effects of diffracted and by moving reflectors to their correct position, but results are still strictly limited by lateral resolving power. Even migration reduces a point a little what Claerbout (1985, p. 17) terms a “focus,” that is, a point with lateral and vertical dimension. For layer-cake geology with smooth thick-bed reflectors, the reflector character is regular in amplitude and polarity repeat the change in acoustic impedance. In this case the results can be inverted to a geologic interpretation with a maximum of ease, although calibration information is required. In general, however, reflector response is the complex interference of effects resulting from vertical and lateral geologic changes. These effects limit interpretation capabilities.

Middle and Upper Pennsylvanian strata of western Kansas are characterized by cyclic lithologic sequences made up of alternating, laterally persistent limestones, shales, and sandy shales. These cycles are typically 10–30 m (30–100 ft) thick with individual members commonly less than 1 m (3 ft) thick. Local development of sand channels and coals is common in the thicker shales (Heckel, 1978; Heckel et al., 1979). Sequentially, most beds appear as thin-bed reflectors (Knapp, 1990) and are interbedded limestones and shales. Consequently, the seismic section can be processed so that the shales appear as troughs and the limestone as peaks (fig. 1). Thickness cannot be directly measured, but in some cases the thickness of a thin bed can be determined from its amplitude response (Wildes, 1973) or its frequency (Knapp, 1990). The amplitude response method requires calibration based on well log or other information and becomes unreliable when vertical or lateral changes of the reflector smear the response or when cyclothemic variation causes tuning of the reflector. The frequency method depends on the cyclothemic tuning of the reflector and, depending on the degree of tuning, may be approximate. Both methods are employed to judge the thickness of a reflector bed.

Complex trace attributes

The particular attributes or components of the seismic trace are magnitude, phase, and frequency. Each of these attributes contributes specific information to the interpretation of the seismic section, and it is frequently advantageous to separate them. The subject of complex seismic trace analysis is reviewed most thoroughly and succinctly by Taner et al. (1979). Although many of these attributes can be displayed in black and white, color adds a great deal of dynamic range and vividness to the display. For instance, on a color display yellow or orange can be quickly distinguished from red; however, on a black-and-white display the amplitude difference between the values represented might be subtle enough to require actual measurement. Color helps one see all the information in a display.

Magnitude Instantaneous magnitude (reflection strength) emphasizes the strong reflectors in a stratigraphic sequence. These are the limestones and shales that are strongly characterized by their flat reflecting surfaces and their relative thickness compared to the signal wavelength. When geophysicists model a reflecting surface, they almost always presume that the reflector is optically flat; that is, the reflector is flat compared to the highest wavelengths of the seismic source signal. Surface roughness or diffusivity is considered negligible. From inspection of the log in fig. 1, one would never suspect that the reflections from the Plattsburg Lime- stone (94 ms) and Farley–Argentine Limestone Members (102–108 ms) would be much weaker than those of the Haskell (46 ms), Stratton (84 ms), Captain Creek (88 ms), or Raytown (112 ms) Limestone Member. In fact, because they are thick, the Plattsburg and Farley–Argentine limestones are modeled as stronger reflectors. The reasons for the difference include surface roughness of the limestone-shale interfaces and interference from diffracted waves as a result of irregular overlying sand channels within the Villas and Bonner Springs Shales. Either case results in destructive interference of the limestone reflector, both (<30) or at these data simultaneously.

Thick shales (e.g., the Lane Shale, 109 ms) also cause large-magnitude reflections, manifested as troughs in this case. Such a response indicates not only that the shale is thick with flat surfaces but also that it is free of sandstone channels. Reflection strength displays alleviate the optical bias toward blackened praks. Troughs tend to be overlooked on conventional displays because they are not as visually prominent as the blackened peak.

Phase Instantaneous phase emphasizes continuity of reflectors. The beauty of instantaneous phase is that amplitude is removed as a component, and all reflectors, weak and strong, have the same display weight. Frequently it is the weaker features in intruded regions of the seismic section that are of interest, for example, structure within sandstones and shales. In fig. 1, look particularly at the Tonganoxie Sandstone Member (55–40 ms) and the Villas (90 ms) and Bonner Springs (97 ms) shales and compare them to the Lane Shale (109 ms) (remember that the shales are the troughs). Instantaneous phase enhances the small perturbations seen in the Tonganoxie Sandstone Member, which result from internal structure, and in the Villas and Bonner Springs Shales, which (perhaps) result from sandiness. The Lane Shale is massive and clean and shows no such perturbations.
Frequency

Instantaneous frequency responds to interference effects and bed thickness. Interference effects are commonly a chaotic response of all frequencies. The Tonganoxie Sandstone Member is an example where intra-bed features create such a pattern. Thin-bed cyclothems take on high frequencies, and relatively thicker bed cyclothems have to lower frequencies (Knapp, 1980). The equation is

\[
\frac{\text{interval velocity}}{\text{frequency}} = 0.25 \times \text{thickness} \leq 0.25
\]

Seismic interpretation

The seismic section and its general interpretation is shown in fig. 1. The velocity log inserted into the section is from a well approximately 10 km (6 mi) from the seismic line (Prairie Resources No. 1 Harrison, sec. 25, T. 13 S., R. 19 E., Douglas County). With the exception of an adjustment at the base of the Tonganoxie Sandstone Member, the fit is generally good. Except for the Sibley coal and the Tonganoxie Member, it is the limestones (peaks) that are identified; the shales in
between are inferred. Except for the Tonganoxie, the re-
sponse of the seismic section is of thin beds, where the
troughs correspond to shales and the peaks to limestones.
The general weakening of reflective strength with depth is due in
part to distance from the surface and increased signal-to-
noise ratio but also to a general decrease in reflection coeffi-
cient, that is, lessening geology. Note the reduced contrast of
the lithology below 150 ms, seen in the log of fig. 1.

Douglas Group (40-83 ms) Only the lower half of the
Douglas Group is represented on the seismic section. The
first reflector is the Haskell Limestone Member, which is the
basal member of the Lawrence Shale. The Haskell is 2 m (7
ft) thick and is seen as a peak at 46 ms. The remainder of
the group is the Stranger Formation, the upper third of which
has thin sandstone and two thin coals. The two coals are
the upper and lower Sibley coals. They are 0.3 m (1 ft) or less in
thickness (Bowsher and Jett, 1943), and they are resolved
seismically as two distinctive troughs at 53 ms and 60 ms,
respectively. The lower two-thirds of the Stranger Formation
is clean Tonganoxie sandstone. (See fig. 3 for the interpreta-
tion.)

The Tonganoxie Sandstone Member is a local nonmarine
channel sandstone. Beneath the city of Lawrence it is a fine-
to-medium-grained crossbedded sandstone with rare thin
slates and mudstone beds. Beneath this seismic section it has
scoured to and into the Stanton Limestone of the Lansing
Group. The nasal ridge is centered over the center of the
Tonganoxie channel valley (Linn, 1950). The thickness of
the sand is 43 m (140 ft) under the section, as measured by
core (KGS Fishpond No. 1). This is approximately the
maximum known thickness of the sandstone.

Reflection strength (fig. 2) shows the strong Haskell
Limestone Member response at 46 ms as the strongest reflector.
Two lesser magnitude events (52 ms and 60 ms) probably relate
to the upper and lower Sibley coals. It was demon-
strated by Knapp and Mulfinga, 1987 that, despite the thin-
ness of the coals, the acoustic impedance contrast is great
enough to cause a prominent reflection. Therefore the coals
should be easily detected. The lack of lateral continuity of
these two events is consistent with the interpretation (see fig.
5). The event below 80 ms is the Stanton Limestone.

Instantaneous phase (fig. 3) clearly shows the lateral
continuity of the Haskell Limestone Member, but most
important, it shows internal channel structure within the
Tonganoxie more clearly than the regular seismic sections of
fig. 1. By focusing on cross-cutting events and semicircular
events in the Tonganoxie Member, one can see the truncation
of the horizontal bed at 73 ms that occurs about two-thirds of
the way across the section (left to right).

Instantaneous frequency (fig. 4) shows, in general, a
frequency response greater than 400 Hz (purple) for the small
features within the Tonganoxie Member. The frequency
response (300 Hz, green) of the Haskell Member is consistent
with a thickness of 2-3 m (7-10 ft). The frequency response
of the upper Sibley coal is less than 100 Hz (red). The lower
Sibley coal has a higher frequency response of 300 Hz
(green). Modeling by Knapp and Mulfinga (1987) shows
that, is thickness difference is due to interference of the under-
and overbed shales. The Haskell Member and the Sibley coals are
simple thin beds that are not conducive to tuning because
cyclothemic interfing is not involved. Consequently,
attenuates to determine bed thickness will be inaccurate, prob-
ably understating thickness because tuning accentuates
high frequencies.

Kansas City-Lansing Groups (83-145 ms) Figure 5 is
the seismic interpretation of the Kansas City-Lansing Groups.
Particularly prominent on this part of the reflection strength
section (fig. 2) are the reflections of the Stanton Formation
limestones (83-89 ms) and the Lame Shale-Raytown Mem-
er combination (109 ms). Other prominent events on the
reflection strength section include the Chanute Shale (120
ms) and the Spofford Limestone-Elm Branch shale combina-
tion (135 ms). Note that reflection strength is not sensitive to
polarity. A powerful trough (shale) has the same response as
a powerful peak (limestone). The Chanute Shale event, in
particular, is not well displayed in fig. 1 because it is a trough.
It does not have the same visual impact as a peak would have.

The sandiness of the Vilas (92 ms) and Bonner Springs
(100 ms) Shales is seen on the instantaneous phase section
(fig. 3). There is a strong lack of lateral continuity in the
channel pattern of these beds. Also the breadth of these beds
is emphasized on the instantaneous frequency section (fig. 4),
where the response is less than 200 Hz (yellow to red). Other
than these two shales, the section is fairly laterally coherent to
the Pea-santon Group beneath 140 ms.

Instantaneous frequency (fig. 4) shows two points of
particular interest. The Drum Limestone (118 ms) is only 2-
3 m (7-10 ft) thick and has a high frequency response of 500
Hz (purple). The Block Limestone Member (125 ms) waxes
and wanes in strength across the section. This is because
its distribution is marginal. It represents the limit of detection
for these data. However, this interval displays good continuity
in both frequency and phase (figs. 3 and 4). In the Stanton
Limestone only the Stoner and Captain Creek Members are
detected (two peaks at 84 ms and 88 ms, respectively).
The South Bend Limestone Member and the Rock Lake Shale Member were cut out by the Tonganoxie
channel. The lack of sand in the Eudora Shale Member
(thick at 86 ms) contributes to the power of the reflector.
Figure 6 shows the flatness of the reflecting surface at the top
and bottom of the Stoner and the top of the Captain Creek. At
almost 2 m (7 ft) in thickness, the Eudora Shale Member can
be considered to be a relatively thick bed. Because the
limestone members of the Stoner are nearly twice as thick as
the Eudora Member, and because their velocity is nearly twice
as much, the wavelength thickness is equal for all three beds.
This makes the situation for tuning nearly perfect—hence the
strong, crisp result of 225 Hz. This frequency response is
consistent with a limestone thickness of 4 m (13 ft) and a shale thickness of 2 m (7 ft). This example also demonstrates the
correlation between reflector flatness and reflection strength.
Figure 7 shows the contact between the Villas Shale (92 m)
and the Spring Hill Limestone Member (95 m). Consider-
ing both the sandiness of the Villas (Figs. 3 and 7) and the
roughness of the contact between the two beds (Fig. 7), the
reflection from the Spring Hill Member is extremely weak.
Figure 8 shows the Spring Hill–Bonner Springs contact and
the presence of a sandstone channel in the Bonner Springs.

Figure 9 shows the Farley–Argentine (102–108 m) upper
contact has a rough surface. The Farley–Argentine limestone
has a weak reflection response because of the sandiness of the
overlying shale and the diffusivity of the reflection sur-
fase. Note that the Island Creek Shale Member between the
Farley and Argentine Members is considered to be of negli-
gible thickness beneath the seismic section. This is seen on all
the logs from the region.

The Lake Shale under the city of Lawrence is not as thick
as it appears in Fig. 9, but it is a clean shale with a flat contact
Conclusions

The seismic reflection response of the cyclothems of eastern Kansas is frequencies in the passband from 100 Hz to 500 Hz tends to range to the thickness of the beds. Although Middle and Upper Pennsylvanian cyclothems of eastern Kansas are basically interbedded limestones and shales and the seismic response is one of peak and trough for the cycle, the high-resolution seismic interpretation of their response is not quite that simple.

Reflection strength depends not only on rock contact type (i.e., shale-limestone) and bed thickness but also on the nature or diffusivity of the contact and/or the presence of laterally irregular sand channels in the overlying shale. Clean shales and flat contacts result in strong reflectors. In this case,
the actual strength and frequency response of the reflection depends on bed thickness. Rough contact surfaces and sand channels in the overlying shale can virtually obliterate a limestone reflector. In the Bonner Springs and Villas Shales both conditions existed at the same time, so it is difficult to separate the effects. Instantaneous phase specifically highlights lateral discontinuity, if not by showing coherent but curved channel looking features then by having a somewhat chaotic nature. In the display of instantaneous phase, internal structure within the Tonganoxie Sandstone Member is seen, and the presence of sandstone lenses within the Villas and Bonner Springs Shales is inferred. Instantaneous frequency demonstrates a realistic relationship between frequency value and thin-bed thickness when internal velocity is known or inferred.

Thus the high-resolution seismic section provides information about the quality of a shale in terms of whether or not it contains sand lenses. It contains information about the quality of the shale-limestone contact. From this, inferences can be made about whether the bed surface was exposed to
Figure 5. Interpretation of the lower Douglas, Lansing, and Kansas City Groups.

...wast development, bioerosion, or other effects that would roughen the surface.

These observations show why synthetic seismograms may fail to fit observed seismic data. Seismic data contain lateral effects, whereas synthetic seismograms do not. The effect of lateral discontinuity becomes more prominent at high frequencies (short wavelengths) because wavelength approaches the dimensions of roughness and diffusivity ceases to be negligible.

Resolution power of the section is indicated by the clear resolution of the upper and lower Sibley coals, each about 0.3 m (1 ft) thick, at depths of 50 m (160 ft) and 60 m (200 ft), respectively. Given the strength of the reflection from the 2-m-thick (7-ft-thick) Haskell Limestone Member, it is evident that reflections from limestones thinner than 1 m (3 ft) are not difficult to detect in the shallow part of the section. In the deeper part of the section, the limits of detection are defined by the marginal detection of the Block Limestone Member, which is 1 m (3 ft) thick, at a depth of about 160 m (525 ft). Wave propagation, particularly through sequences of strong cyclic thin beds like the Kansas City-Lansing Groups, is a high-cut filtering process. Frequency response diminishes...
with depth as thin beds tend to pass low frequencies and return high frequencies to the surface (Zadzikowski and Fokkema, 1986). This is seen on these data. The high-frequency response of shallow beds means that the high frequencies are being interrupted and returned to the surface. Knapp (1990) shows that for the pure cyclothems, the frequency returned is pure; consequently, all other frequencies, ostensibly lower frequencies, are passed to the deeper sections. Zadzikowski and Fokkema (1986) further point out that, as frequencies get lower in value, the probability of their being returned as a reflection diminishes. They use this mechanism to explain the observation that recorded seismograms do not contain the low frequencies of the source.

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Figure 8. Roadcut on West I-435 showing the Lansing Group (Plattsburg Limestone, Spring Hill Limestone Member) and the Kansas City Group (Bowers Springs Shale).

Figure 9. Roadcut on West I-435 showing the Wyandotte Limestone (Fairly-Argentine Limestone Member), the Lano Shale, and the Joplin Limestone (Kaysnna Limestone Member).

References


---------, 1990, Vertical resolution of thick beds and thin-bed cyclothems: Geophysics, v. 55, no. 9, p. L184-L191

Tung, M. T., Keilhan, F., and Swift, R. E., 1979, Complex seismic trace analysis: Geophysics, v. 44, no. 5, p. 1,041–1,063

Withers, M. A., 1973, How thin is it really?: Geophysics, v. 38, no. 6, p. 1,176–1,180

Ziolkowski, A., and Fokkema, J. T., 1986, Tutorial on the progressive attenuation of high-frequency energy in seismic reflection data: Geophysical Prospecting, v. 34, no. 6, p. 901–1,001