Seismic stratigraphy and small 3D seismic surveys

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The establishment of seismic stratigraphic principles in the 1970s ushered in a new era of seismic interpretation possibilities. Seismic stratigraphy spawned sequence stratigraphy (potentially applicable to seismic, log, and outcrop data), and the associated methods for defining basin evolution, reconstructing depositional histories, and making qualitative predictions of lithology. Seismic interpreters began to focus on recognizing and defining characteristic reflection terminations, seismic facies and otherwise analyzing seismic character to define sequences, systems tracts and potential drilling targets. The development of seismic geomorphology, a branch of seismic stratigraphy that focuses on plan-view images of stratigraphic features derived from 3D seismic volumes, has further enhanced interpreters’ abilities to reconstruct depositional environments and predict the lithology of the strata being imaged.

Since their inception, the principles of seismic stratigraphy have been applied in many settings and adapted to different scales of observation. Originally though (i.e., in the mid-1970s and into the 1980s) seismic stratigraphy found greatest application in the interpretation of long 2D seismic lines collected for exploration purposes. This is because these long lines had a greater probability of being able to image key stratal terminations and thereby allow for identification of sequences and systems tracts. Also, the longer lines had a greater probability of imaging different types of seismic facies, and these associations of seismic facies could be mapped and used to infer depositional systems. These types of analyses are still employed fruitfully in many basins throughout the world. The application of seismic stratigraphy to large 3D seismic surveys, particularly in the marine realm, has led to many new insights.

In this article, we use case studies to examine the application of seismic stratigraphy to the study of small 3D seismic surveys. The depositional environments we present, all from clastic settings, range from basin-floor fans to fluvial systems, and the strata include Permian and Cretaceous age rocks. As employed here, “small” is a relative term that refers to both the areal extent (measured in square miles or kilometers) and the size of the seismic survey with respect to the scale of the sequences being imaged. Small 3D seismic surveys are commonly collected on land, over relatively small producing fields for development purposes. The term might also apply to portions of larger multiclient terrestrial or marine data volumes that have been purchased for a particular development purpose. Our intent in this article is to illustrate the challenges and opportunities that may be encountered working with these data sets.

Example 1. Permian slope and basin deposits in the Delaware Basin. The first example comes from the Permian Bone Spring Formation in the Delaware Basin of the U.S. southwest (southeastern New Mexico). This thick (up to 1 km) formation consists of three carbonate-dominated intervals (the first, second, and third carbonates, in stratigraphically descending order) interbedded with three clastic intervals (first, second, and third sandstones). The alternation of clastic and carbonate units is a classic example of reciprocal sedimentation. Fine-grained carbonates were deposited on the shelf, slope, and basin floor during relative hightstands of sea level. During relative lowstands, fluvial systems or wind transported siliciclastic sediments across the exposed shelf to the shelf margin, and from density currents distributed these sediments onto the slope and the basin floor. As such, the sandstone members represent lowstand systems tracts.

The carbonate and sandstone members can be recognized on logs from slope and basin-floor locations in the Delaware Basin. Hart et al. (2000) undertook basin-scale mapping and found that the simplified stratigraphic picture presented above is complicated by the presence of allochthonous carbonate slumps and dolomitic siltstones (especially in areas distant from the shelf margin) in the “sandstone” members, thin siliciclastic units in the “carbonate” members, and gradational contacts locally between some members. Their basin-scale correlations needed to be based on careful examination of logs, paying particular attention to log facies (e.g.,
gamma-ray log shape) and lithology (derived from porosity and photo-electric factor logs).

Here we illustrate the seismic character of the third sandstone of the Bone Spring in two small 3D surveys that were collected primarily for field-scale studies of stratigraphic units above and below that unit (the Bone Spring was generally considered a secondary target). Regional mapping showed that the member could be divided into two portions, a lower basin-floor fan with locally productive channel sandstones, and an upper, finer-grained progradational package that lacked channel sandstones.

The first example is from a basinal area. The 3D seismic survey covered an area of approximately 8 square miles (20 km²), and only one well in the survey area penetrated the third sandstone. By tying the well to the seismic data via a synthetic seismogram, the tops of all members of the Bone Spring could be mapped (Figure 1a). Furthermore, it was possible to identify a reflection that corresponded to the top of the basin-floor fan of the third sandstone. Subsequent mapping was used to generate an isochron map of that stratigraphic unit (Figure 1b), and that map showed thickness trends that probably indicate the presence of channel sandstones. Areas of sandstone channel development are relatively thick because of differential compaction between them and the adjacent fine-grained intervals (the sands compacted less). This type of indirect lithology definition is commonly used in exploration for sandstones in the Permian Basin and elsewhere.

Comparison of the size of the isochron map with the scale of other modern and ancient basin-floor fans, and integration with the regional mapping, makes it clear that the seismic image is covering only a very small area of a larger fan system. As such, plan-view images such as isochron maps can be difficult to interpret. Furthermore, no distinctive reflection termination patterns (e.g., bidirectional downlap) were visible in the data, probably because of the low acoustic impedance contrasts between the channel sandstones and other lithologies of the basin-floor fan system in these Permian strata, and because of the small size of the survey. Nevertheless, by integrating the 3D seismic interpretation with the log-based regional mapping, it was possible to put the stratigraphic bodies imaged by the seismic data into a sequence stratigraphic context and thereby recognize the presence of channel forms (possible stratigraphic leads) in the sand-prone basin-floor fan of the third sandstone. The data density provided by the seismic data (bins of 55 × 55 ft) also allowed mapping of stratigraphic bodies that could not be mapped with existing well control. It should be noted that the only well penetrating the third sandstone in the 3D seismic area did not penetrate one of the channel sandstones.

The second 3D seismic volume was from a slope setting and covered an area of only approximately 6 square miles (16 km²). In this survey, the second and third sandstones lap out onto the slope and show a strongly progradational geometry (Figure 2a). The first sandstone is not present in the survey area but is present further basinward. At this slope location, characteristic reflection terminations (onlap, downlap, etc.) are present that allow sequences and systems tracts to be identified using seismic criteria.

As in the first example, by tying the logs to the seismic data it was possible to identify and map the thickness of the basin-floor fan portion of the third sandstone. The isochrons show a depositional thick in an area at the base of the depositional slope, and a possible channel leading off to the south. The thick, probably sandstone-prone, areas identified in the basin-floor fan of the third sandstone were not drilled at the time of the study and so they could not have been mapped using well control. However, the sequence stratigraphic position combined with knowledge of the effects of compaction and depositional processes and products associated with siliciclastic density currents allows these features to be identified as stratigraphic leads.

Example 2. Cretaceous channels in the Western Canada Sedimentary Basin. This example from southeastern Saskatchewan in the Western Canada Sedimentary Basin examines Cretaceous deposits of the Lower Cretaceous Mannville Group. Depositional environments include incised valley fill, fluvial, and shallow-marine sandstones and shales, and collectively the Mannville can be over 100 m thick. The study area was a tectonically quiescent interior basin during deposition of the units under consideration here. Full details of the study are provided by Sarzalejo and Hart (2006). The lower portion of the section in the study area is broadly equivalent to heavy-oil bearing sands to the northwest, although the Mannville is water-saturated in the present study area. The database consisted of a 3D seismic survey covering approximately 20 square miles (52 km²) and
Disagreement exists concerning the stratigraphy of the Mannville in southern Saskatchewan. Previous integration of log, core, and biostratigraphic information led to the establishment of a regional lithostratigraphic framework, including the recognition of unconformities (based largely on biostratigraphic control), for the Mannville. The upper portion is known to be marine, and the lower portion is channelized. Some workers have concluded that correlations based on log character alone are "highly suspect," particularly in the channelized lower portion of the group, because of the significant stratigraphic variability observed in wireline logs in this interval.

The 3D seismic-based interpretation used seismic stratigraphic criteria (reflection terminations, seismic facies, etc.) to divide the Mannville into seismic stratigraphic units. Several significant channel incisions, and many smaller channel features, were identified in vertical transects and horizon slices through the data (Figure 3). The larger channel features were associated with truncation of underlying reflections and, in places, onlapping reflections above. These patterns of reflection terminations are commonly used to define sequence boundaries. Synthetics were generated to tie log-based surfaces to the seismic data and then used the seismic data to guide well correlations. Not surprisingly, using the seismic data as a backdrop facilitated the log correlations. Gamma ray and spontaneous potential logs demonstrate that the channel-filling strata are markedly heterolithic.

Following our integrated log- and seismic-based stratigraphic interpretation, we attempted to correlate our surfaces and stratigraphic units to those that had been defined regionally (i.e., based on previous publications from areas adjacent to our study area) using lithostratigraphy and biostratigraphy. We noted a close, but not one-to-one, correlation between our stratigraphic units and those defined based on well control alone. For example, not all of the channel-like erosion surfaces (possible sequence boundaries based purely on seismic criteria) visible in the seismic data could be correlated to regionally defined unconformities. This suggests that at least some of them represent channel incision not associated with sequence boundaries or, alternatively, they correspond to previously unrecognized sequence boundaries. Also, not all of the surfaces defined regionally could be recognized as distinct reflections in the seismic data.

Figure 3. Seismic transect with gamma-ray log overlay of Lower Cretaceous Mannville Group strata from the Western Canada Sedimentary Basin. Numbered seismic horizons are identified using reflection terminations and log response. Stratigraphic units and numbered horizons are described by Sarzalejo and Hart (2006). The transect has been flattened on Horizon I. Note the variability in gamma ray log response in Unit B, which appears to be bounded by unconformities (reflection truncation below, onlap or downlap above). (Modified from Sarzalejo and Hart).

The differences between our stratigraphic correlations and previous publications could be attributed to:

1) Differences in correlation styles. The previously defined regional correlations suggested a "layer-cake" stratigraphy that was not apparent in the 3D seismic data for much of the lower and middle Mannville. We suggest that the channelized stratigraphic geometries visible in the seismic data should be used to guide log correlations in places where seismic data are unavailable. Even then, however, the correlations would need to be treated as, at best, hypothetical, especially where wells are relatively widely spaced.

2) Differences in resolution. Although the frequency content of the seismic data was relatively high at the Mannville level (dominant frequency of approximately 50 Hz), at least one of the seismically defined stratigraphic units corresponded to more than one of the stratigraphic units defined using well control and biostratigraphy.

This study illustrated the differences between well-based (logs, core and biostratigraphy) regional correlations and detailed 3D seismic and log-based correlations in a stratigraphic unit that has considerable lateral and vertical lithologic variability. Not all surfaces that might be, based on seismic stratigraphic criteria, recognized as sequence boundaries could be correlated to regional unconformities that could be recognized using log and biostratigraphic information. This discrepancy highlights one of the pitfalls of working with small 3D seismic surveys: the possibility of over-interpreting all seismic stratigraphic surfaces that can be defined within the data volume. Another limitation of working with the seismic data was associated with resolution. Not all of the log-defined units could be recognized in the seismic data. On the plus side (1) the stratigraphic geometries visible in the 3D seismic data explained the problems encountered when attempting purely log-based correlations: (2) most seismically defined surfaces could be correlated to surfaces that had been recognized regionally; and (3) the 3D seismic data could be used to image stratigraphic features (e.g., point-bar deposits in Figure 4) that could not be mapped using well control alone. It should be noted however that, due to the relatively small size of the 3D survey, the plan-form images (e.g., horizon slices) only showed...
small portions of the original depositional systems (meandering channels) and that limitation can make the identification of depositional features difficult.

Example 3. Prograding shoreface/coastal plain deposits in the Western Canada Sedimentary Basin. The final example comes from Lower Cretaceous strata (slightly younger than those examined in Example 2) of the Deep Basin of northwestern Alberta. This area, and the stratigraphic units we describe here, was used to help formulate the basin-centered gas model that has seen widespread (but perhaps somewhat indiscriminant) application in recent years. This was a relatively stable ramp-style clastic shelf during the Cretaceous that underwent repeated transgressions and regressions in response to changes of relative sea level and, perhaps, changes in sediment supply. Our database consisted of an approximately 175 square mile (450 km²) 3D seismic survey and logs for more than 670 wells in and around the 3D survey area.

The relatively dense well control in the Alberta Basin, combined with outcrops in the Rocky Mountain Foothills to the west and biostratigraphic data, has been used to define lithostratigraphic units and sequence stratigraphic interpretations for most of the Cretaceous section of the Deep Basin. Here we focus on the Peace River Formation, which is divisible into the Harmon, Cadotte, and Paddy members in stratigraphically ascending order. Each member is typically 15–20 m thick in our study area. The Harmon consists of marine shale that is overlain conformably by shoreface and foreshore sandstones and conglomerates of the Cadotte Member. In our study area, the Cadotte is overlain by nonmarine deposits that are generally assigned to the Paddy Member. Regional correlations suggest, however, that a major unconformity (possibly representing at least 1 million years) is within the lithostratigraphically defined Paddy Member (i.e., all nonmarine deposits) in our study area.

Log correlations in these shelf/shoreface deposits can be made with greater confidence than in the channelized deposits described in Example 2, especially in the marine and marginal marine strata. Based on log facies and correlations, and tying these observations to whole core, it is possible to identify flooding surfaces, maximum flooding surfaces and possible erosion surfaces/sequence boundaries within and encasing the Peace River Formation (Figure 5a). A flooding surface separates the Harmon Member from nonmarine strata of the underlying Notikewin Member of the Spirit River Formation. A maximum flooding surface (recognized as a persistent high radioactivity zone in gamma-ray logs) is present within the Harmon. The base of the Cadotte can be either gradational or sharp, suggesting deposition during a fall of relative sea level (“forced regression”). The contact between the Cadotte and Paddy members appears to be a conformable facies contact. Within the Paddy, the possible location of the unconformity can be tied to a distinct log marker in all wells within our study area. A flooding surface separates the Paddy from the overlying marine shale of Shaftsbury Formation.

As in the previous example, synthetic seismograms indicate that there is a general, but not exact, correspondence between the surfaces identified in logs and those that are visible seismically (Figure 5b). The flooding surface at the base of the Harmon (top of the Notikewin Member) corresponds to a trough in our data, and the maximum flooding surface in the Harmon corresponds to a peak. The base of the Cadotte locally corresponds to a trough and the top of the Cadotte corresponds to a zero crossing (trough to peak) in the seismic data. In reality, our synthetic seismograms and 2D seismic models indicate that the seismic expression of the Cadotte varies as a function of changes in thickness, changes in porosity in the upper part of the member, and changes in the overlying Paddy Member (e.g., presence or absence of channel sandstones immediately overlying the Cadotte). The possible unconformity in the Paddy corresponds to a trough in most of the area. The flooding surface at the top of the Paddy corresponds to a zero crossing (peak to trough). A future publication will illustrate how amplitude trends, petrographic analyses, sedimentology, and production data can be integrated to identify productive trends in the 3D seismic study area.

The stratigraphic geometries and surfaces that can be identified in the log data cannot be mapped in the seismic data, and distinctive reflection terminations that might be used to identify sequence boundaries, maximum flooding surfaces or flooding surfaces cannot be recognized. This is because: (1) the Harmon, Cadotte, and Paddy members are all near the limits of seismic resolution and so the details of their internal stratigraphy are not seismically resolvable, (2) the maximum length of the survey in the depositional dip direction, approximately 12 miles (19 km) is relatively short compared to the approximately 90 mile (145 km) distance over which the Cadotte shoreline prograded, and (3) the 3D seismic survey area is in the middle of a depositional ramp, rather than at a shelf/slope break, where distinctive strati-
Lessons learned. The areal extent of the 3D seismic surveys discussed in this article spans three orders of magnitude, from less than 10 square miles to more than 100 square miles. However, all of the surveys can be defined as "small" because of either the small geographic area being covered or because they image only a small part of the sequences we studied. Collectively, these studies illustrate several important points about the relationships between small 3D surveys in sequence stratigraphy:

1) The small 3D seismic surveys are most helpful when inte-
grated with sequences or systems tracts mapped regionally using well control or, potentially, 2D seismic coverage. This exercise is helpful for identifying stratigraphic leads or other depositional features, in addition to placing the stratigraphic features into a proper chronostatigraphic framework.

2) Not all surfaces identified in small 3D surveys have regional sequence stratigraphic significance. This is particularly true of channel erosion surfaces. Unless these surfaces can be tied to unconformities that have been mapped regionally using other data, the channel bases should (at best) be designated as “candidate sequence boundaries.” Other types of reflection termination, such as downlap corresponding to maximum flooding surfaces, can be more helpful but care would still be needed in their interpretation. For example, downlap could be produced by relative changes in sea level—a maximum flooding surface—or by autocyclic lobe switching in a deltaic succession.

3) The utility of 3D seismic surveys for identifying significant stratigraphic surfaces using reflection terminations will depend on the depositional setting and size and location of the 3D seismic data. For example, the 6 square mile 3D survey from the Permian shelf margin contained diagnostic reflection terminations whereas the 175 square mile 3D survey from the Cretaceous ramp setting did not.

4) Reflection character analysis can be critical. This is especially true when analyzing thin stratigraphic units or areas with no diagnostic reflection terminations. Well control, either from within the survey area or from potentially analogous areas, can be used to generate synthetic seismograms or seismic models that help the interpreter to understand the controls on reflection character. Vertical seismic profiles, not employed here, might also be useful.

5) Seismic geomorphology analyses (i.e., plan-view images) are useful, but interpreters need to consider the size of the survey area compared to the scale of the depositional systems being imaged. Small 3D surveys are likely to only image small parts of those depositional systems, potentially making recognition of depositional elements difficult.

6) Seismic modeling and integration of log and core data show that over the relatively short distances (e.g., several km) spanned in a small 3D survey, reflections generally correspond to lithologic contacts. Seismic reflections commonly correspond to timelines over longer distances (tens or hundreds of kilometers) that might be traced in regional 2D or 3D surveys.


**Acknowledgments:** Work on the Bone Spring Formation was undertaken while the senior author was employed at the New Mexico Bureau of Mines and Mineral Resources. Funding and data for the Mannville project were supplied by Nexen Inc. Funding for the Cadotte project was supplied by Talisman Energy, and the seismic data were supplied by Millennium Seismic. Software for all projects was supplied by Landmark Graphics Corporation through its University Grant Program.

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