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Sequence Stratigraphy Past, Present and Future, and the Role of 3-D Seismic Data

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Abstract

In the twenty-five years since the landmark publication of AAPG Memoir 26 and later, SEPM Special Publication 42, the concepts of sequence stratigraphy have evolved rapidly. This discipline, an outgrowth of seismic stratigraphy, has spread far beyond applications to 2-D seismic data alone. Sequence stratigraphy has seen applications embracing data sets ranging from biostratigraphic to geochemical to physical oceanographic, and from borehole to outcrop, and finally, coming full cycle, to 3-D seismic data. Initially the domain of industry geoscientists, sequence stratigraphy has gained widespread acceptance among geoscientists in all professions, having been recognized as an approach that facilitates integration of a broad range of disciplines.

The evolution of sequence stratigraphic concepts is far from complete. In particular, recent increased availability of high-quality 3-D seismic coverage promises to provide insights that will lead to further fine tuning of sequence concepts. In addition to enhanced 2-D profiles, 3-D seismic data afford exceptional plan views of the subsurface that in the past could only be inferred. These plan view images now comprise a fundamental starting point from which geologic analyses and interpretation can begin. Such images depict paleo-landscapes, which can be analyzed using time-honored principles of geomorphology, leading to the development of the discipline of *seismic geomorphology*. When used in conjunction with seismic stratigraphy, seismic geomorphology can significantly enhance sequence stratigraphic interpretations.

The identification of depositional elements such as channels, valleys, shore faces, shelf ridges, *etc.*, in plan view, can be integrated with seismic stratigraphic analyses of associated seismic profiles to calibrate profile reflection patterns and refine analyses of basin fill histories. Systematic seismic geomorphologic analysis of 3-D seismic volumes can bring to light spatial and temporal relationships of successive depositional systems. Moreover, recognition of these systems and analyses of their succession can help in the identification of possible missing facies tracts. This approach, coupled with direct and indirect recognition of unconformities, comprises an integral aspect of sequence stratigraphic interpretation.

Introduction

Since the 1970s, the concepts of sequence stratigraphy have become widely accepted by the geological community and have been applied to a broad range of data bases, including conventional and high resolution seismic data, wireline logs, outcrops, cores, paleontologic, and geochemical data. Much has been written recently about sequence stratigraphy, and numerous papers in the recent literature have applied these concepts or a variation of them (*e.g.*, Einsele *et al.*, 1991; MacDonald, 1991; Posamentier *et al.*, 1993; Dalrymple *et al.*, 1994; Johnson,

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1994; Weimer and Posamentier, 1993; Saito *et al.*, 1995; Van Wagoner and Bertram, 1995). The sequence stratigraphic approach has been applied to rocks ranging in age from Proterozoic (Christie-Blick *et al.*, 1988) to the modern (Posamentier *et al.*, 1992).

Modern sequence stratigraphic concepts can be traced to the work of the European stratigraphers who in the late 19th century subdivided sedimentary rocks into discrete units separated by surfaces representing abrupt changes or breaks in sedimentation. These rock successions were formally defined as unconformity-bounded stages. At about the same time, Suess (1904) introduced and expounded on the concepts of eustasy and global controls on unconformities.

Subsequently, Wheeler and Murray (1957), Wheeler (1959), Weller (1960), and Sloss (1962, 1963), recognized the significance and utility of correlating time synchronous surfaces across geological sections and further refined these concepts. Their application of chronostratigraphy to stratigraphic analysis in many instances yielded better insights than those available from the more conventional lithostratigraphic approach prevalent among stratigraphers at that time. Many of the notions that these workers developed can readily be re-cast into what we now refer to as sequence stratigraphy.

The approach Wheeler, Weller, and Sloss championed did not take root with the geologic community to the extent that modern sequence stratigraphy has, because they were missing one critical ingredient that did not become available until the late 1960s and 1970s. This ingredient was high-quality, multi-channel seismic reflection data. With these data, geoscientists could obtain continuous physical stratigraphic images of the subsurface that allowed them to minimize some of the major leaps of faith previously required of stratigraphic correlations. Thus was born modern seismic stratigraphy.

The Past

Seismic stratigraphy involves the stratigraphic interpretation of seismic data. In the landmark publication AAPG Memoir 26, Peter Vail and his colleagues at Exxon Production Research Co. (Vail *et al.*, 1977) observe that detailed stratigraphic information could be interpreted from seismic data. In fact, relatively sophisticated stratigraphic insights could be gleaned from such data. The fundamental assumption upon which Vail and his colleagues based their work is that seismic reflections approximate time correlative surfaces (Vail *et al.*, 1977). They argue that since seismic reflections follow time lines, then seismic data depict stratal architecture, albeit at low resolution. Patterns of stratal discontinuities as defined by seismic reflection terminations are interpreted, and their geologic significance is established through integration of available borehole data. Seismic facies interpretation is based on observations of seismic reflection terminations as well as reflection character (*e.g.*, continuity, amplitude) from 2-D seismic reflection data (Fig. 1).

These seismic stratigraphic observations suggested that a distinct cyclicity was present within lithologic successions, and moreover, that similar patterns of cyclicity existed within the same chronostratigraphic intervals in different sedimentary basins around the world. They argued that to account for such apparent global synchroneity of events, a globally effective causal mechanism must be active. It was proposed that this mechanism comprised cyclic variations in global sea level; *i.e.*, eustatic cycles. Hence, the first seismic-based global eustatic curves were published (Vail *et al.*, 1977). At this time also, Pitman (1978) observed that the *rates* of sea-level change exerted significant control on stratal architecture. These global sea-level curves were characterized by cyclicity at several different orders of magnitude. The global synchroneity of stratigraphic cycles, however, has been the subject of debate in recent years and remains a matter of some disagreement (Miall, 1992, 1994, 1995).

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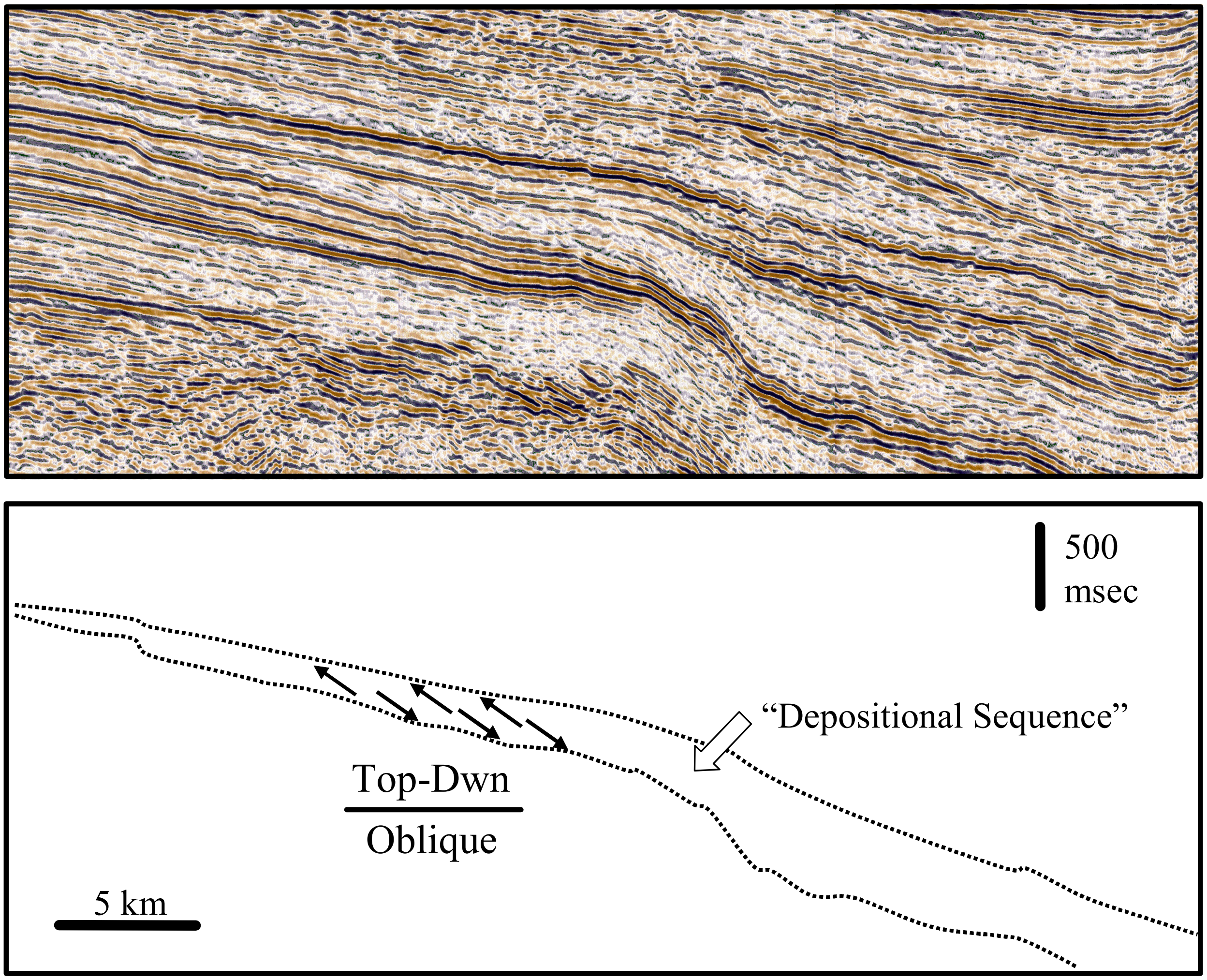

Figure 1. Dip-oriented seismic reflection profile across a delta plain. Toplapping and downlapping reflection terminations define depositional sequence boundaries in the sense of Vail *et al.* (1977).

The cyclic deposits that formed the basis for the interpretation of sea-level cyclicity were referred to as *depositional sequences* (Mitchum, 1977). The surfaces that were chosen to define the boundaries of these sequences were stratal discontinuities defined by seismically-expressed reflection terminations (*i.e.*, onlap, downlap, toplap, and erosional truncation)**.** These discontinuities were inferred to represent unconformity surfaces. This approach was consistent with the ideas of the early European stratigraphers (e.g., Stille, 1924). Where a sequence boundary was traced laterally to a point where no hiatus exists (*i.e.*, the strata are concordant *and* conformable) a correlative conformity marked the expression of the sequence boundary (Mitchum *et al.*, 1977). The emphasis of Vail *et al.* (1977) was on regional as well as global correlations of discrete cyclic stratigraphic units and their relationship to eustatic change. Less emphasis was placed on lithologic predictions within depositional sequences.

The authors of initial publications on seismic and, later, sequence stratigraphy selected unconformities and their correlative surfaces to subdivide sediment cycles into depositional sequences (Vail *et al.*, 1977); such cyclic stratigraphic units were given the name "sequence." This usage was consistent with that proposed by Sloss (1962), although Sloss's sequences were commonly significantly larger in scale and did not include the notion of the correlative conformity.

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The Present

The next quantum jump was the introduction of *sequence* stratigraphy with the publication of the SEPM Special Publication 42 (Wilgus *et al.*, 1988), wherein the link between the stratal architecture of sequences and relative sea-level change was analyzed (Cross, 1988; Jervey, 1988; Plint, 1988; Posamentier *et al.*, 1988; Posamentier and Vail, 1988). These papers also argued that sequence stratigraphic concepts, built around the notion of the interaction of sediment supply and sediment accommodation (*i.e.*, the space available for sediment to accumulate) applied not only to conventional seismic scale data but also to smaller-scale data sets such as outcrop and borehole data (Fig. 2). The applicability of sequence concepts to outcrop, borehole, and core data was subsequently demonstrated in Van Wagoner *et al.* (1990).

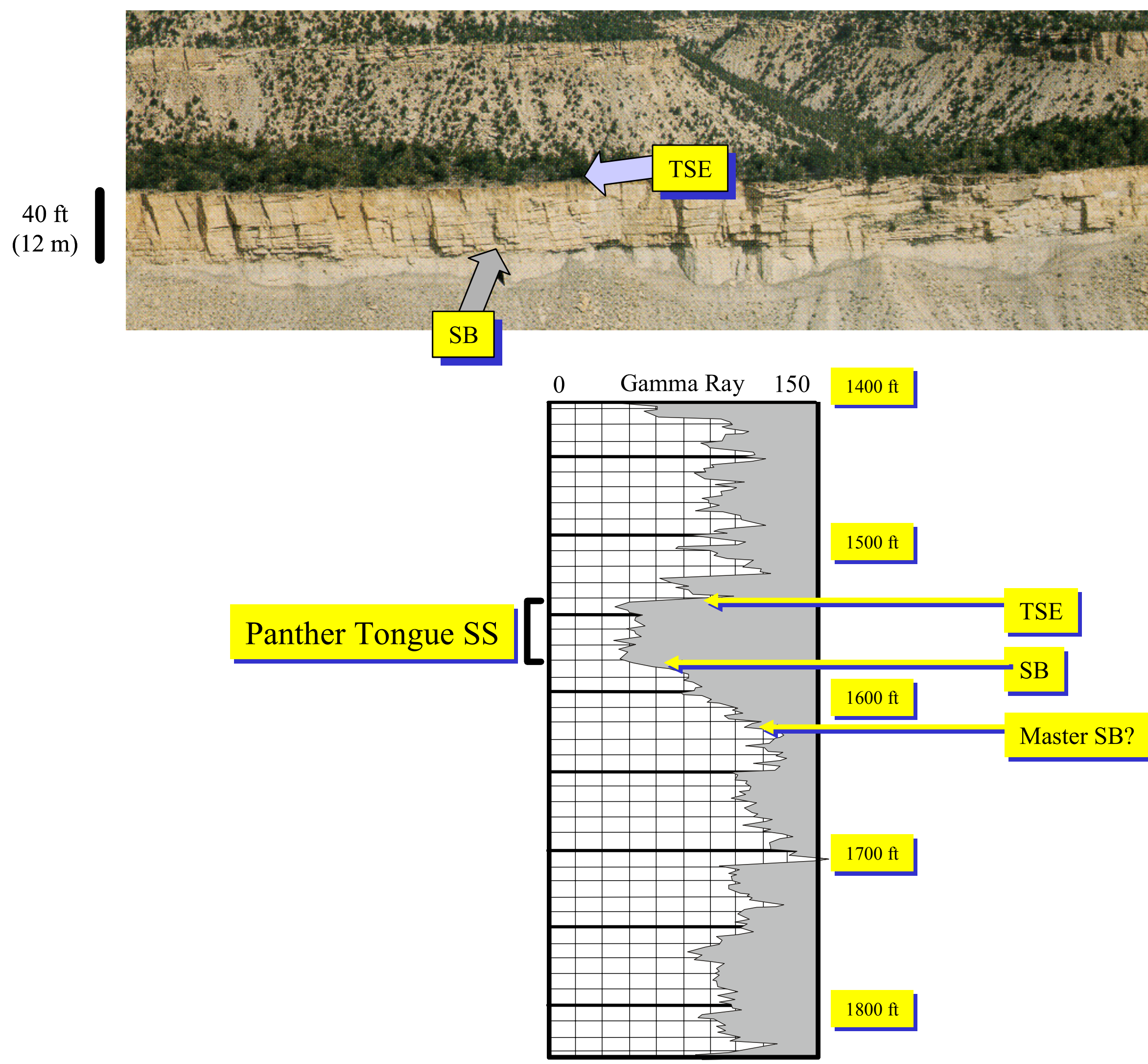

Figure 2. Sequence stratigraphic interpretation of the Panther Tongue Member of the Star Point Formation near Helper, Utah. The sequence boundary and transgressive surface of erosion are annotated on both the outcrop photo as well as the wireline log. The stratigraphic unit bounded by these two surfaces constitutes part of a lowstand systems tract.

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The focus of sequence stratigraphy shifted more to prediction of lithology using integrated data bases, and less towards age model prediction. Subsets of sequences (*i.e.*, systems tracts) were defined and quantitatively related to variations of relative sea level, sediment flux, and physiography (Fig. 3). Many variations on the general sequence stratigraphic theme were recognized, such as the concept of forced regression and the application of sequence stratigraphic concepts to fluvial deposits and deep-water settings were presented.

Integration of data sets has become the hallmark of sequence stratigraphic analyses (e.g., Fig. 2). The use of small scale models as well as modern analogs has further improved the understanding of how depositional systems evolve under the influence of changing sea level and sediment flux (Fig. 4).

The Future

Sequence stratigraphy is and always will be grounded in rock data. The comprehensive integration of core, outcrop, and borehole data, with seismic data long has proven to yield the best overall geological interpretations. With the advent of widely available 3-D seismic reflection data geoscientists have been able in many instances to move the accuracy of such interpretations to a new and higher level. 3-D seismic volumes yield plan view images of the subsurface to complement 2-D vertical profiles and consequently bring a different perspective to bear on geologic investigations. Plan view images can comprise seismic reflection horizon attributes, such as amplitude, time/depth structure, dip azimuth, dip magnitude, curvature, and roughness. Or, they can be of interval attributes such as amplitude distribution, frequency, and seismic waveform facies. Images can be displayed as a two-dimensional map or as a three-dimensional perspective view. These images depict depositional elements in map view and, when interpreted in conjunction with seismic profiles, yield valuable insight as to lithologic distribution, and temporal and spatial relationships of stratigraphic units. Missing facies tracts can be inferred, and stratigraphic compartmentalization can be predicted. Under certain circumstances, new exploration play types can be identified.

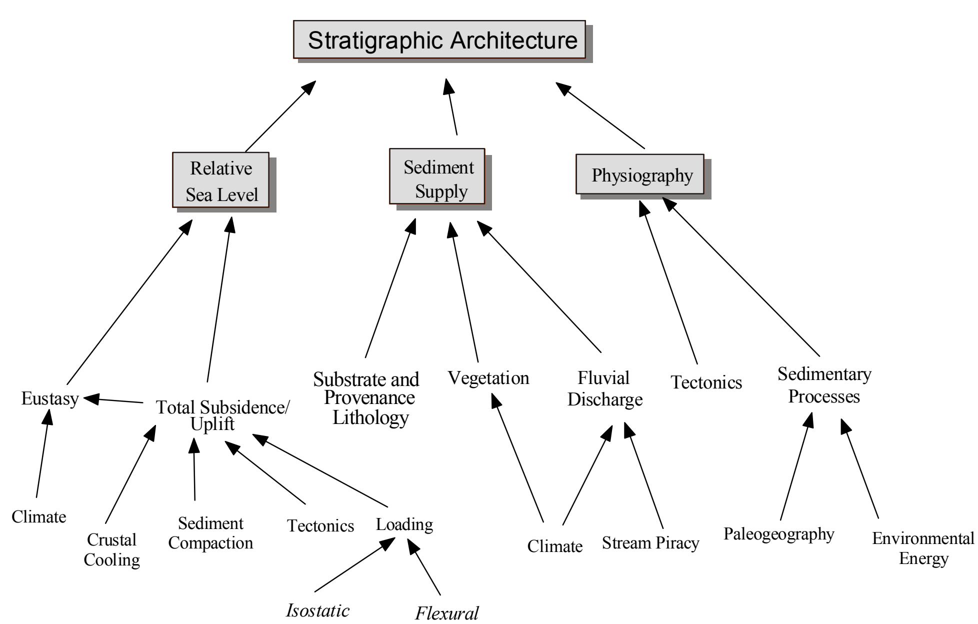

Figure 3. Interrelationships of key parameters associated with basin-fill architecture (Posamentier and Allen, 1999).

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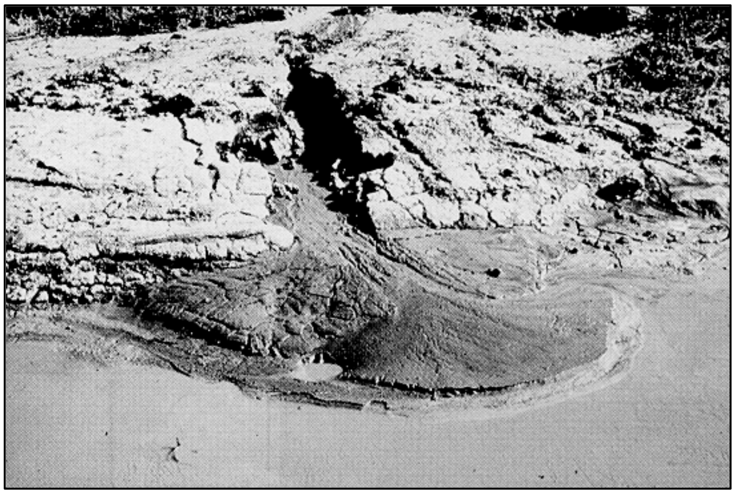

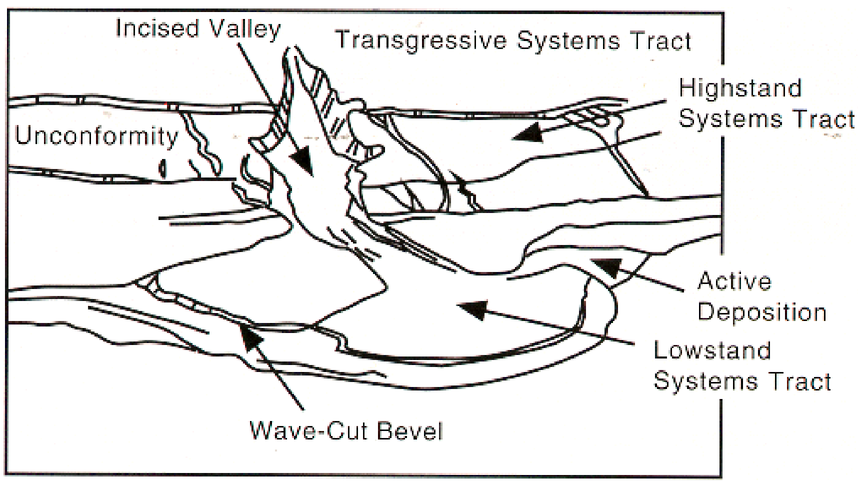

Figure 4. Small-scale deltaic system illustrating the effects of "sea-level" fall. When "sea level" was high, an inner shelf highstand delta formed; when "sea level" was low, an incised valley linked with an outer shelf delta formed. During time of lowstand, sediment bypass characterized the inner shelf (from Posamentier *et al.*, 1992).

Horizon Attributes

Seismic reflections, or horizons, can be characterized on the basis of their reflection amplitude and their structure. Reflection amplitude maps represent the seismic response primarily to variations of lithology and fluid type, and, to a lesser extent, bed thickness. Where sharp lithologic edges exist, discrete depositional elements can be imaged (Fig. 5). Depositional elements with gradational edges, such as the trailing edge of a migrating shelf ridge (Fig. 6), are more difficult to identify. Horizon slices, which are produced by flattening on a reference horizon and then generating a time slice volume, can yield valuable insights where discrete reflections within an interval of interest lack sufficient continuity and therefore can be difficult to correlate regionally with confidence (Fig. 7).

Time structure maps can effectively recreate the "lay of the land" in the absence of post-depositional tectonic movements, and highlight the relief associated with discrete depositional elements (Fig. 8). The same surface, when examined in 3-D perspective view can yield additional insights (Fig. 9). Figure 10 illustrates a section and 3-D perspective view of an unconformity surface highlighting the presence of a fluvial system there.

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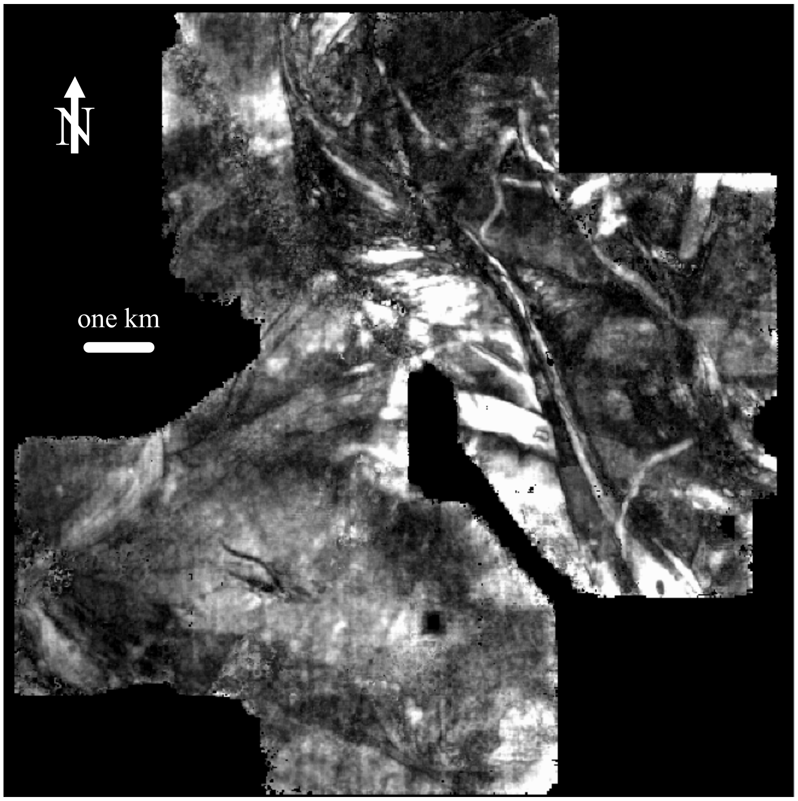

Figure 5. Network of Cretaceous channels, southern Alberta, imaged on amplitude extraction from seismic horizon slice. Channel edges are well defined in response to sharp lithologic contrasts that characterize the channel fill/over bank contact. The timing of channel formation can be determined from analysis of cross-cutting relationships.

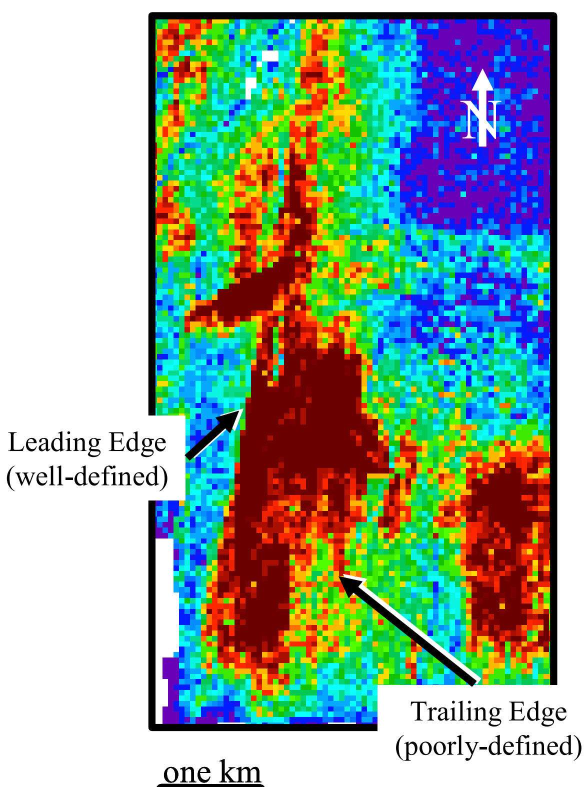

Figure 6. Amplitude extraction of seismic reflection illustrating shelf ridge characterized by steep, sharply delineated leading edge, and poorly delineated trailing edge. Migration direction across the transgressed sea floor inferred to be from east to west (Posamentier, 2002).

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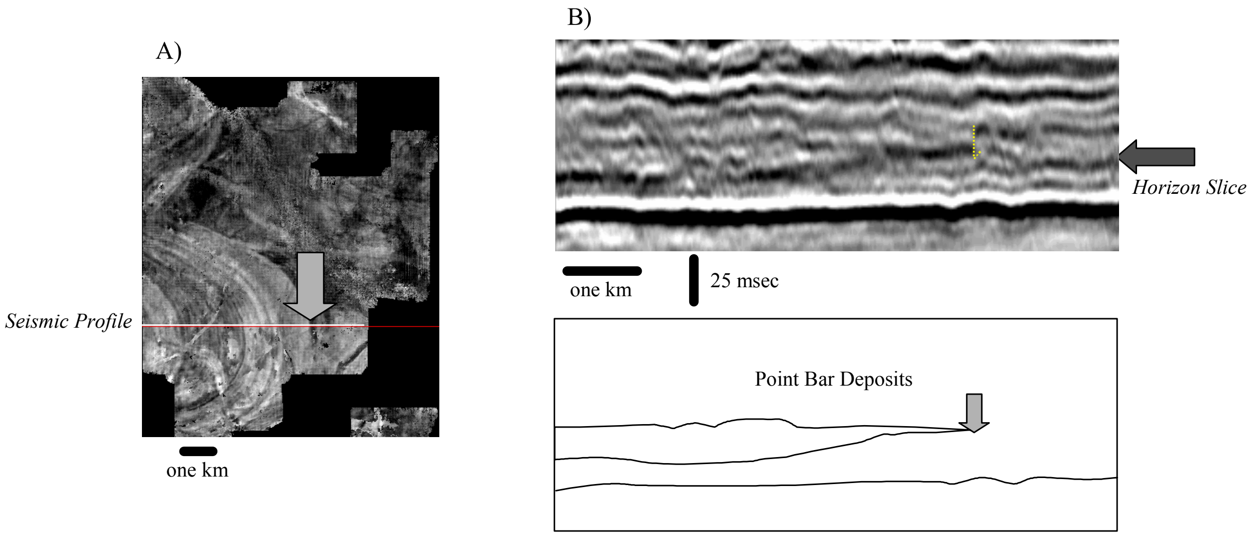

Figure 7. (A) Amplitude extraction from seismic horizon slice across Cretaceous-aged high-sinuosity fluvial meander scroll bars. (B) Seismic reflection profile across fluvial meander scroll bars.

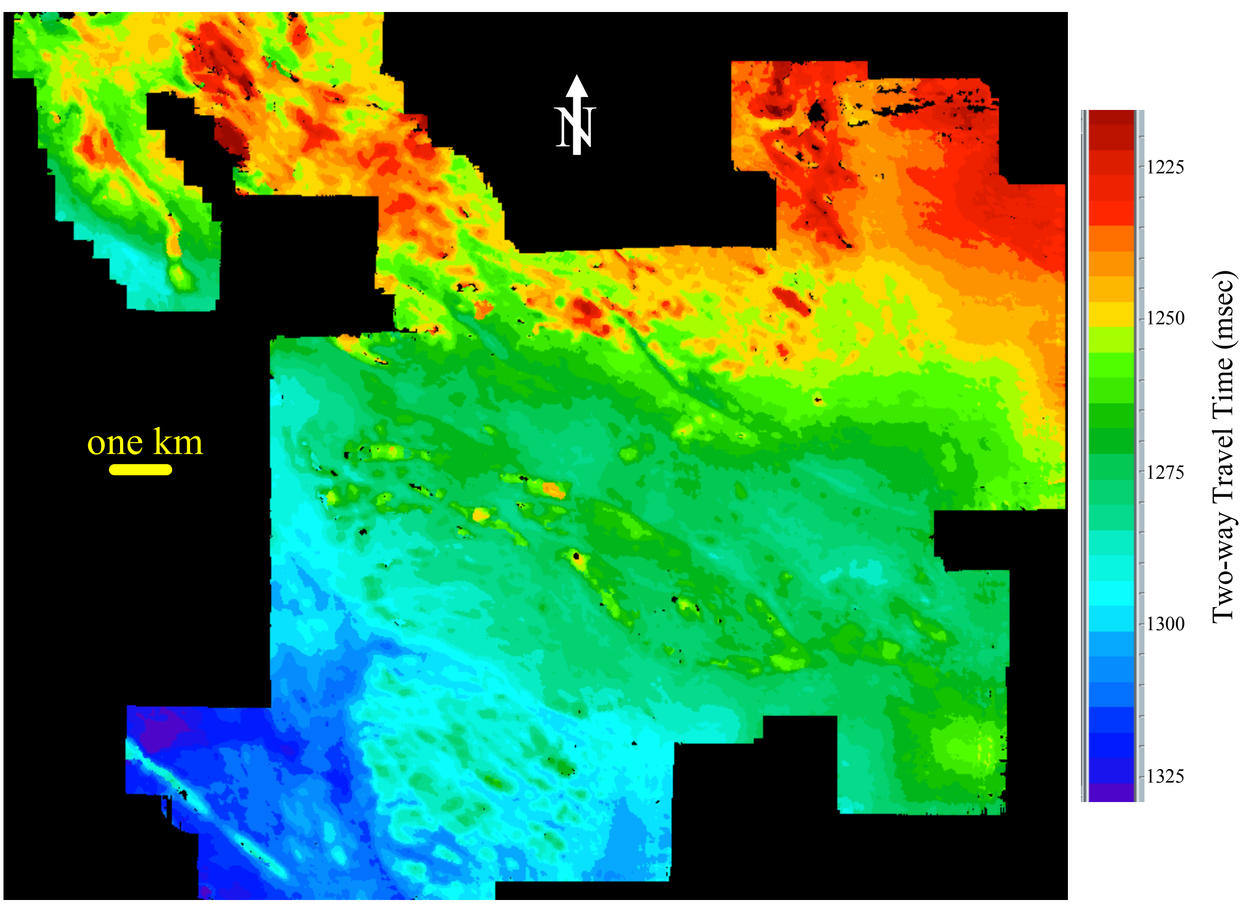

Figure 8. Seismic reflection time structure map on small carbonate buildups of Devonian age.

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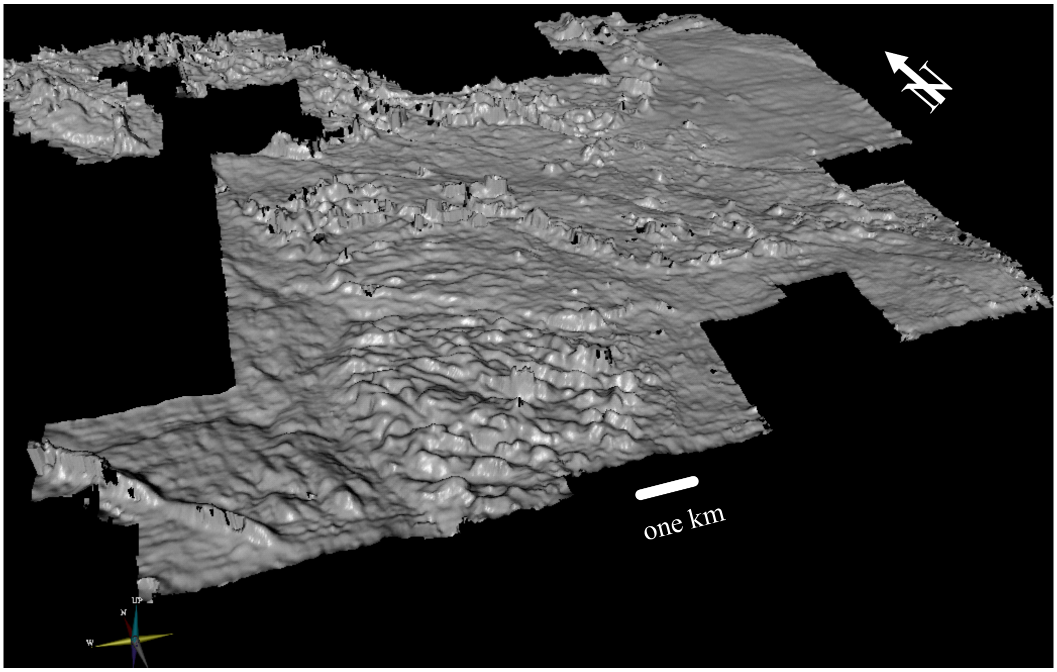
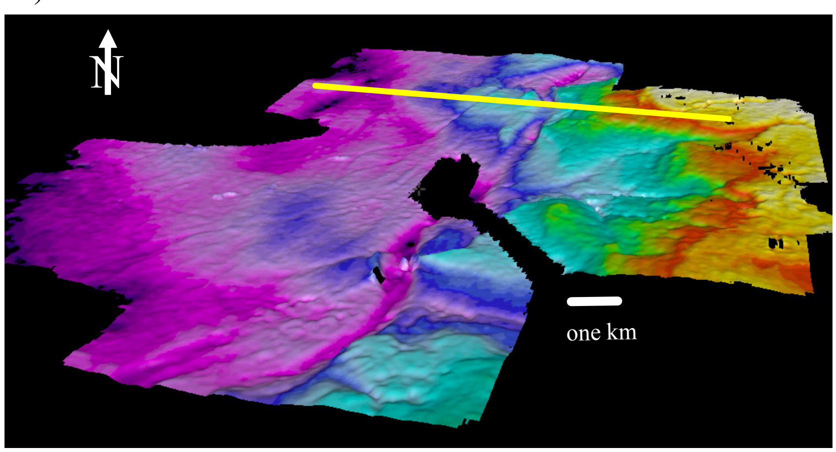


Figure 9. 3-D perspective view on carbonate buildups shown in Figure 8.

A)



B)

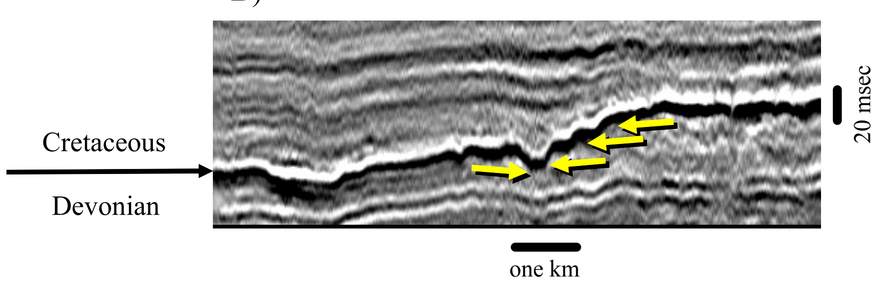


Figure 10. 3-D perspective view (A) and seismic section (B) across base Cretaceous unconformity separating Cretaceous clastic sediments from underlying Paleozoic carbonate sediments, south-central Alberta. Note the fluvial drainage system etched into the Paleozoic carbonates.

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Note that although the presence of an unconformity could be readily determined from the reflection terminations apparent in the section view, the plan view image details the depositional elements that overlie this surface. Analysis of dip magnitude and dip azimuth can emphasize the physiography and the structural grain respectively (Fig. 11). In these images, the dip magnitude map depicts the angle of dip across each 3 x 3 (in-line and cross-line) area, and the dip azimuth map depicts the direction each 3 x 3 area faces, yielding a pseudo-relief map. Another view of the same depositional features is illustrated in Figure 12, where surface curvature and roughness are shown. Curvature maps describe the magnitude of curvature across each 3 x 3 area and the roughness map describes the degree of irregularity across each 3 x 3 area. Each of these attributes shows the same features but each highlights different nuances, the combination of which yields the most robust interpretation.

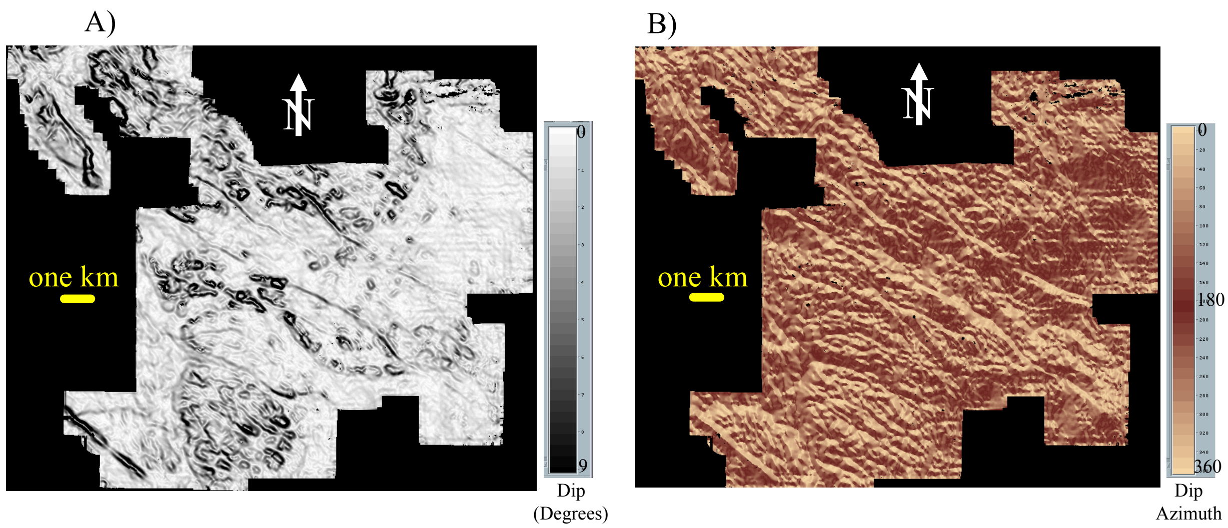

Figure 11. Dip magnitude (A) and dip azimuth (B) maps on seismic refection at top of carbonate buildups shown in Figure 8 (compare with Fig. 12).

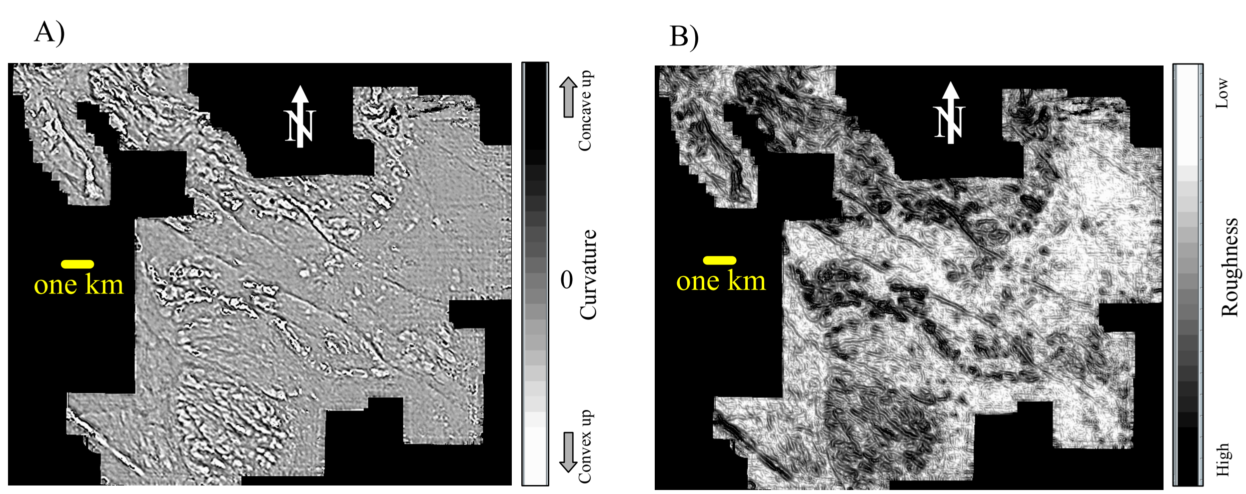

Figure 12. Reflection curvature (A) and roughness (B) maps on seismic refection at top of carbonate buildups shown in Figure 8 (compare with Fig. 11).

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When used in conjunction with 2-D profiles, 3-D perspective views (Fig. 13A) can be powerful tools for interpreting a succession of depositional events. Figure 13 illustrates a Pleistocene shelf to slope transition. A shelf edge protuberance can be observed on a time slice (Fig. 13D) and a progradational geometry can be observed on a dip transect (Fig. 13B). The linear features oriented parallel to dip (Fig. 13A) are interpreted as mass transport grooves, and their presence at the basal boundary of overbank levees (Fig. 13D) suggests that mass transport processes were active just prior to levee formation within a single deep-water depositional episode.

Interval Attributes

Interval attributes describe the acoustic characteristics of a seismic interval. Two examples of interval attribute maps are illustrated in Figures 14 and 15. Analyses of interval attributes are especially useful for imaging features that are associated with discontinuous, difficult to correlate seismic reflections. Where seismic reflections are discontinuous, an interval bracketing potential features of interest can be created using horizontal time slices or horizon slices referenced to more readily interpretable seismic reflections, and then amplitude, frequency, waveform attributes and other acoustic characteristics can be analyzed.

Seismic facies mapping using 3-D seismic data bears little resemblance to seismic facies mapping based on 2-D seismic data (Fig. 16). With 3-D seismic data it is possible, through neural network algorithms, to classify individual traces into groups (*i.e.*, seismic facies classes) based on similar waveform characteristics. Figure 17 illustrates a seismic facies map of a Miocene distributary channel offshore northwest Java. The facies mapping highlights the heterogeneity of the channel fill. This heterogeneity is subsequently calibrated by borehole information tied to the seismic data. Figure 18 illustrates another seismic facies map of a porosity trend. In this instance, the facies map cannot discriminate between the poor porosity of the eastern part of the trend from the excellent porosity of the western part of the trend. Both areas belong to the same facies class (*i.e.*, facies class 10). However, mapping the correlation between each individual trace with seismic facies class 2 brings out the contrast between excellent and poor porosity facies.

Utility of 3-D-Based Seismic Geomorphological and Stratigraphic Analyses

Prediction of lithology as well as reservoir compartmentalization is greatly enhanced as a result of 3-D seismic analyses. 3-D seismic volumes enable the direct recognition of depositional elements through the integration of plan view images with vertical seismic profiles. The best imaging of depositional elements will be at shallow burial depths where seismic resolution is relatively high. With increased depth of burial, seismic resolution diminishes and depositional elements are progressively more difficult to clearly image. Consequently, seismic geomorphological and stratigraphic analyses have a dual purpose: (1) well-imaged depositional elements at shallow burial depths provide excellent analogs for more deeply buried exploration targets, and (2) direct imaging of depositional elements at exploration depths help mitigate risks associated with prediction of reservoir and seal lithologies. Examples of shallow-buried analogs are shown in Figure 19.

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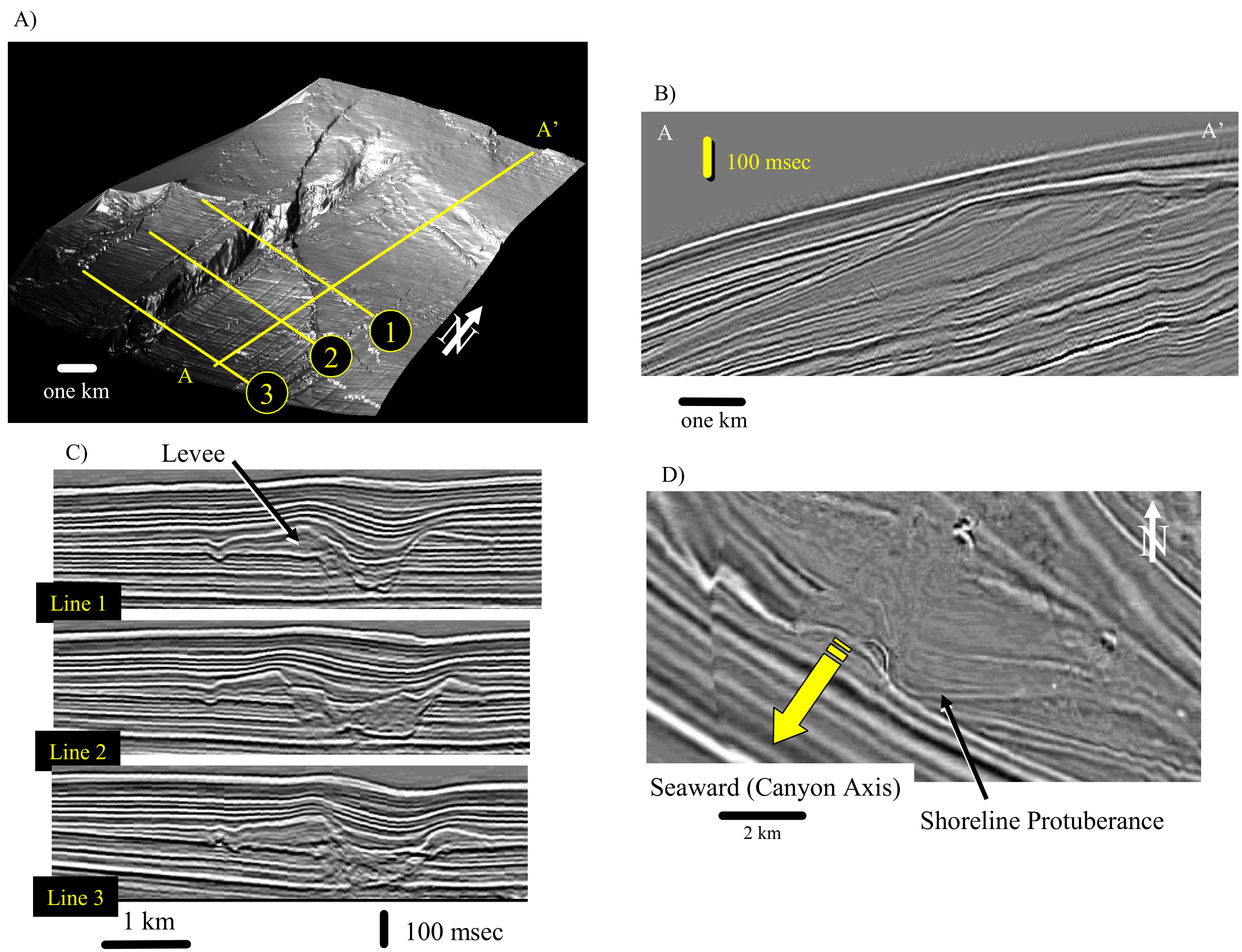

Figure 13. 3-D perspective view of outer shelf and upper slope offshore Louisiana (A), with time slice (D) and vertical profiles (B and C). A linked shelf edge delta and deep-water channel can be observed. The delta is characterized by a shoreline protuberance (D) and clinoform reflection geometry (B). The deep-water system is characterized by a channel-levee complex (C). The grooves at the base of the levee (C) are oriented parallel to dip (A) and are interpreted to be caused by mass movement processes.

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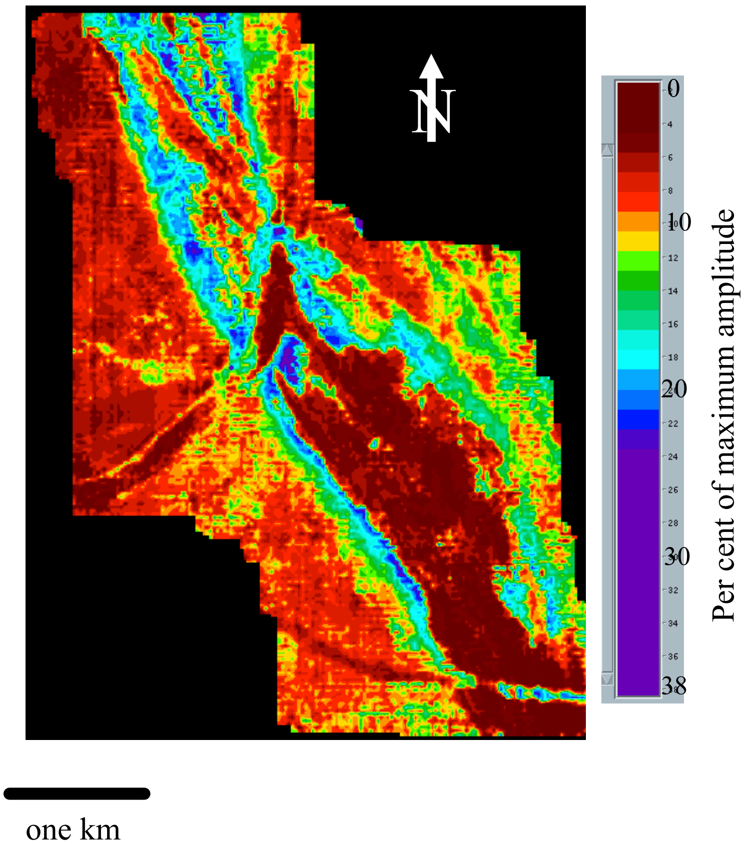

Figure 14. Interval attribute map illustrating cumulative amplitudes across a Cretaceous distributary channel in south-central Alberta. This attribute is a measure of the amplitude strength of an interval and the extent to which the total amplitude is weighted towards the upper or lower boundary of the interval selected. The lineaments within the channel are interpreted as side bars within the channel. Well data indicates that the channel is filled with up to 35 m of sandstone. Two smaller channels can be observed to crosscut the larger NNW-SSE oriented channel and are interpreted to be younger in age.

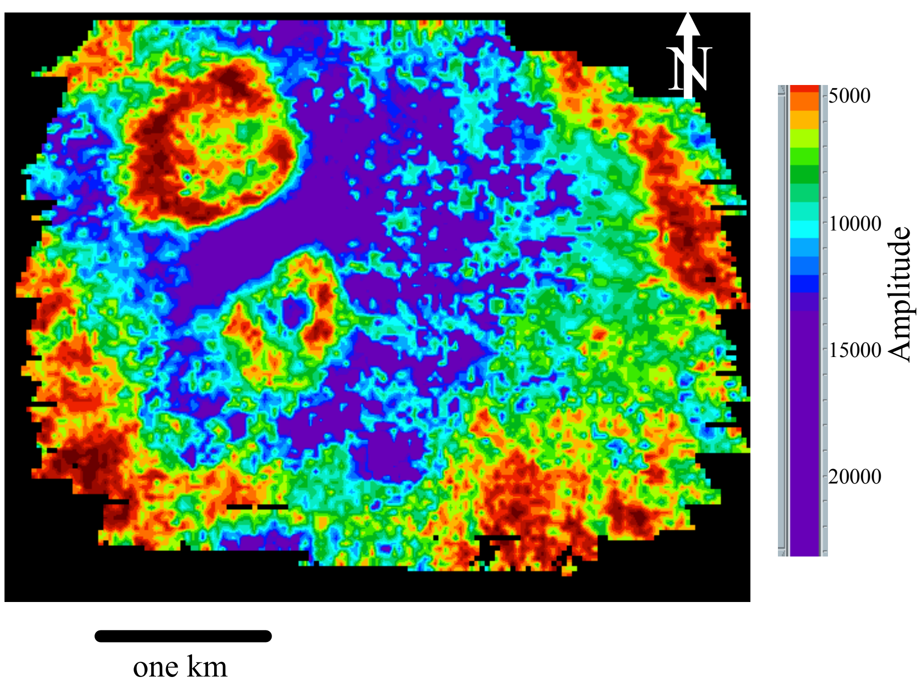

Figure 15. Interval attribute map illustrating peak amplitudes from an 80 msec interval across two small Devonian-aged pinnacle reefs from southern Alberta.

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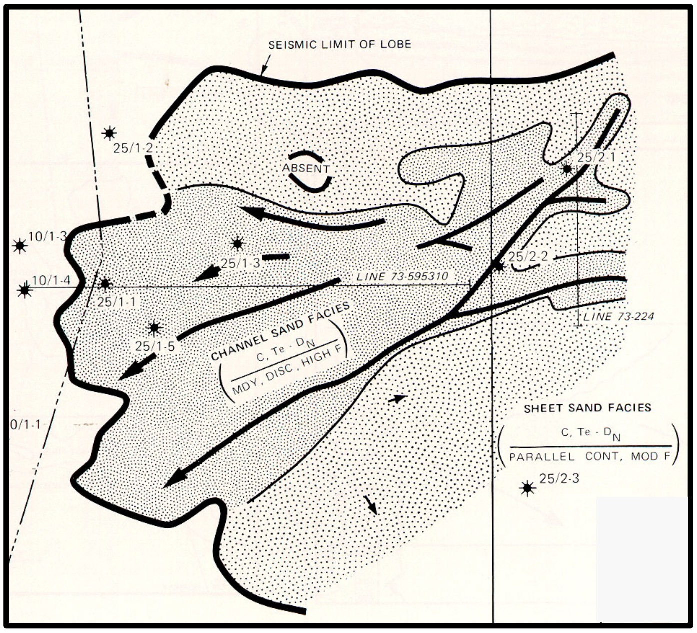
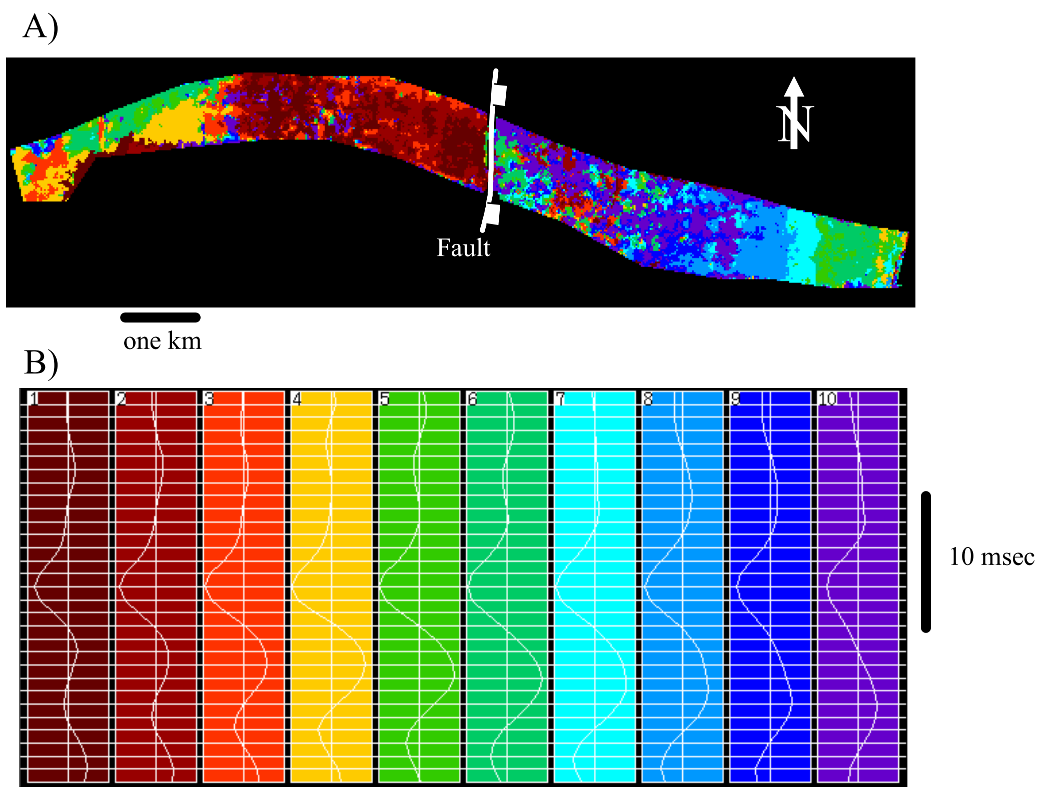


Figure 16. Seismic facies map based on 2-D seismic data from Frigg Field, North Sea (from McGoveny and Radovitch, 1985).



Seismic Facies Classes

Figure 17. Seismic facies map (A) and associated facies classes (B) of a 30 msec interval across a Miocene distributary channel offshore northwest Java. Colors represent facies classes. Facies analysis was conducted along the isolated channel trend only. The seismic facies distribution within the channel suggests a heterogenous lithofacies. The fault crossing the channel seems to have had an influence on channel fill as illustrated by the marked change from predominance of classes 1-3 on the west side of the fault to classes 7-10 on the east side.

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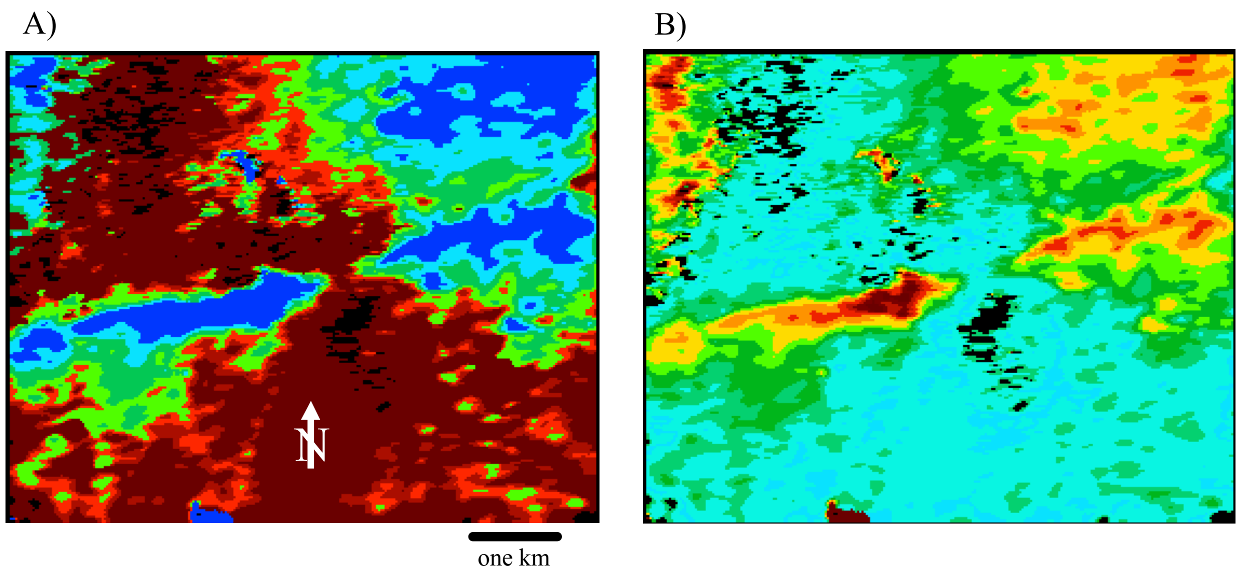

Figure 18. (A) Seismic facies map for an interval across a linear porosity trend. Colors represent facies classes. (B) Map of correlation values between each individual trace and class 2. Hot colors represent high correlation values; cold colors represent low correlation values. The porosity is better developed on the left side of the linear trend. However, whereas the seismic facies map does not allow for differentiation of porosity between the left and right portions of the trend (A), the correlation map does (B), highlighting the highest porosity areas on the left side of the trend.

Conclusions

Revitalization and continued evolution of sequence stratigraphic concepts will occur through the integration of such disciplines as seismic geomorphology, seismic stratigraphy, biostratigraphy, and chemostratigraphy. Because of the inherent flexibility imbedded into the sequence stratigraphic concepts, sequence stratigraphy remains evergreen and continually evolving. With the advent of widely available 3-D seismic data, spatial and temporal relationships between depositional elements will become clearer resulting in enhanced geologic interpretations. The emphasis on plan view imagery enables the development of seismic geomorphology as a discipline to be used in conjunction with more classical stratigraphic analyses. Interpretation techniques such as seismic facies analysis have taken on new significance when applied to 3-D seismic volumes. In some instances, sequence stratigraphic models will be modified and improved (Posamentier, 2001; Posamentier, 2002). In this way, seismic stratigraphy and sequence stratigraphy will benefit from seismic geomorphological analyses and will be elevated to new levels. The development of scientific analyses based on new types of data, which we cannot even now anticipate, assures us that sequence stratigraphy will continue to evolve and be refined well into the future and remain a backbone for the study of sedimentary rocks.

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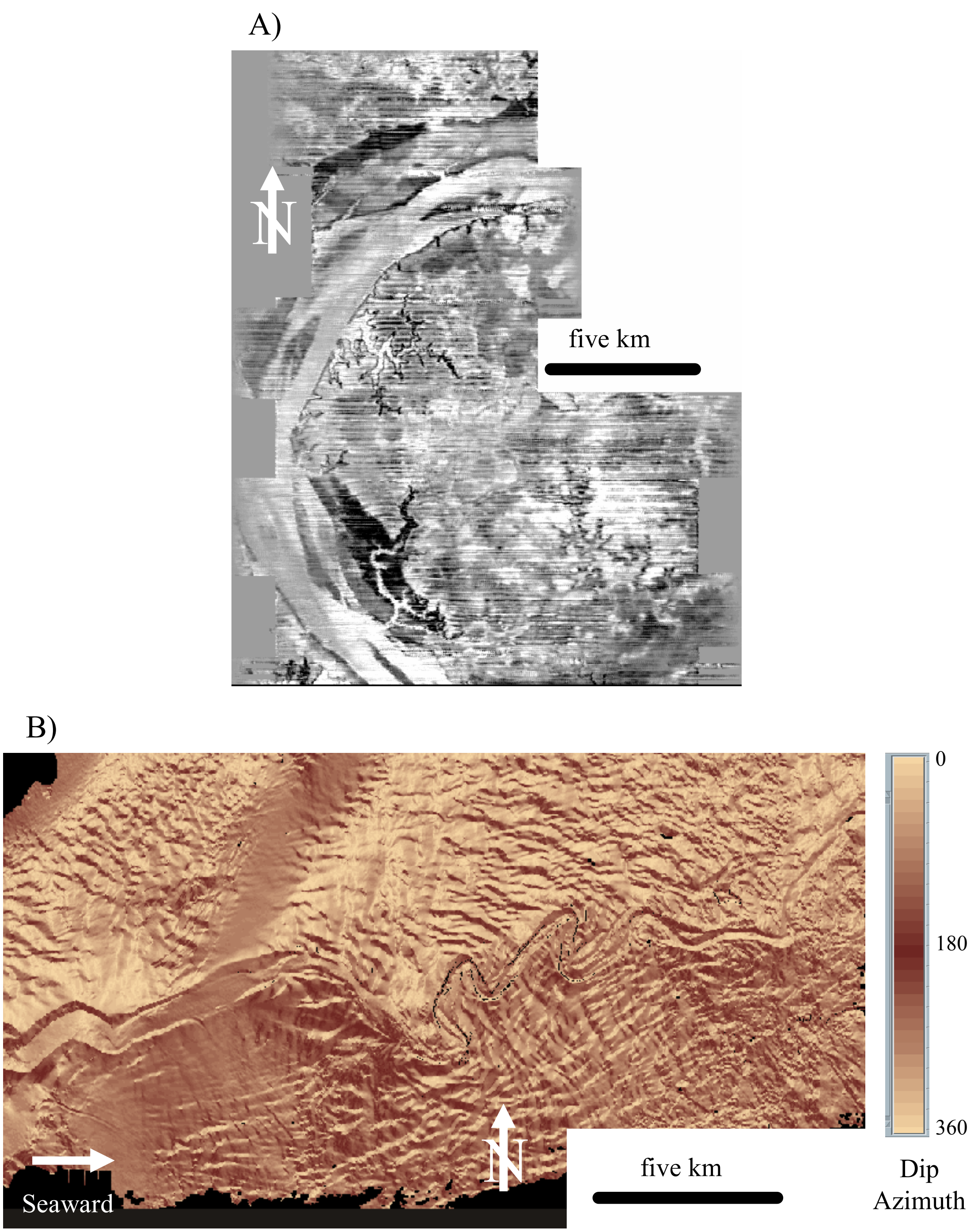

Figure 19. (A) Amplitude extraction from seismic time slice of Pleistocene incised valley with fluvial system at base, offshore northwest Java (Posamentier, 2001). Tributary incised valleys can be observed cutting into associated interfluve settings. (B) Dip azimuth map of seismic reflection from top of Pleistocene channel-levee complex at shallow burial depth in ultra-deep water offshore Borneo, Makassar Strait, Indonesia. Channel and associated levees with sediment waves can be observed.

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