Seismic geomorphology – an overview

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Abstract: Seismic geomorphology, the extraction of geomorphic insights using predominantly three-dimensional seismic data, is a rapidly evolving discipline that facilitates the study of the subsurface using plan view images. A variety of analytical techniques is employed to image and visualize depositional elements and other geologically significant features. This volume presents key technical papers presented at a recent research conference – the Seismic Geomorphology Conference (10–11 February 2005), co-convened by the Society for Sedimentary Geology and The Geological Society (London). These papers cover a broad range of topics, from detailed depositional element analysis to big picture regional issues, from lithology prediction to diagenetic modification of the stratigraphic section. This discipline is only in its early stages of development and will henceforth expand rapidly in response to the growing availability to researchers of high-quality three-dimensional seismic data.

The derivation of stratigraphic insights from seismic data has its origins in the early 1970s with the advent of improved quality two-dimensional (2D) seismic data. The assumption that seismic amplitude reflections approximate geological time lines was fundamental to the development of seismic stratigraphy (Vail *et al.* 1977). The discipline of seismic stratigraphy traces its roots to the landmark publication of AAPG Memoir 26, which summarized the work of Peter Vail and his colleagues at Exxon Production Research Company (Vail *et al.* 1977). Discrete seismic reflection packages, or depositional sequences, were defined by discontinuities shown in seismic data by the downlap, onlap, truncation or toplap of seismic reflections (Mitchum *et al.* 1977). Such seismic discontinuities were interpreted to represent stratigraphic discontinuities and unconformities. Inferences with regard to lithologies were based upon internal reflection character such as reflection amplitude and continuity. These 2D-based interpretations were then mapped and the spatial distribution of depositional systems with associated lithological predictions subsequently interpreted.

Seismic reflection technology underwent significant advances in the 1980s, making these data less expensive to acquire and hence more widely available. Three-dimensional (3D) seismic reflection data comprised acquisition of closely spaced 2D seismic lines with high precision navigation, which, when computationally manipulated, yielded true 3D coverage in *X–Y–Z* space. At first, such data were interpreted as a succession of parallel 2D seismic sections. Techniques included printing the lines on translucent vellum and interpreting each section while partially seeing the immediately adjacent section through the vellum. This approach made interpretation easier from the perspective of mapping horizons but did not truly take advantage of the 'third-dimension' inherent to the 3D volume. In essence this approach resulted in little more than a tightly spaced 2D seismic analysis. By the mid to late 1980s, computer-based display and visualization of 3D data began to take hold, making true 3D interpretations possible. Methods evolved for generating horizontal and flatted slices, arbitrary traverses, wavelet attribute extractions and mapping, and rapid analysis of large complex data volumes.

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Horizontal slices, flattened time slices, and proportional slices, derived from 3D volumes, provided plan view images of amplitude and other attribute distributions that strongly resembled depositional environments. Increasing computing power enabled large volumes to be manipulated and interpreted rapidly, and visualization software increased the ability for 3D visualization of surfaces. These volumes provided map views over geological time from which depositional elements and systems could be interpreted. Such plan view images yielded data that showed buried landforms; hence the discipline of seismic geomorphology came into being (Posamentier 2000). *Seismic geomorphology* may be defined as the application of analytical techniques pertaining to the study of landforms and to the analysis of ancient, buried geomorphical surfaces as imaged by 3D seismic data. Seismic geomorphology, when used in conjunction with seismic stratigraphy, represents the state of the art approach to extracting stratigraphic insights from 3D seismic data. The following section outlines workflows for optimizing this process.

Workflow

Most workflows designed to derive stratigraphic insights from 3D seismic data involve an initial reconnaissance step. Commonly the interpreter will quickly scan through a 3D seismic volume by in-line, crossline, and time. The objective is to identify anomalous seismic features referred to as FLTs (i.e. 'funny looking things'). Typical FLTs include local amplitude brights or dims, lineaments, or in general any features that might 'look geological'. Another reconnaissance approach involves opacity rendering, whereby the 3D volume is rendered transparent except for specific amplitude values associated with a particular target, such as a channel fill deposit. Usually it is the amplitude extremes that are rendered opaque, thus allowing the targeted opaque features to stand out.

Once an FLT is identified, it becomes the focus of further detailed analysis. This analysis can take the form of: (1) horizon picking and subsequent illumination; (2) amplitude extraction along specific horizons; (3) horizon slicing or stratal slicing, whereby the volume is flattened on a key horizon and then amplitude extractions are made from time slices parallel to the key horizon; (4) proportional horizon slicing, where an interval is bound between two mapped horizons and then is unproportionally sliced between those two horizons; (5) interval attribute analysis whereby an interval that brackets the FLT is defined and then characterized seismically; (6) voxbody picking; (7) extraction of horizon-based attributes such as dip magnitude, dip azimuth, curvature and roughness; (8) extraction of volume-based attributes such as phase, coherence, and impedance; and (9) volume co-rendering, whereby two or more volume attributes are displayed simultaneously within the same volume. Examples of each will be shown in the next section.

The key to each of these analyses is to look for and recognize geologically or geomorphologically meaningful patterns in plan view as well as in section view. Such patterns can take the form of fluvial or deep water channels, slumps and slides, shelf sediment ridges, and carbonate patch reefs, to name just a few. For the geomorphological approach to seismic interpretation to succeed, it is essential for the interpreter to have a broad experience base with respect to seismic plan-view and section-view expression of a variety of depositional elements. For example, if one is not familiar with the stratigraphy and geomorphology of fluvial point bars, then features like scroll bars in plan view, and lateral accretion sets in section view may pass by the interpreter unnoticed.

A critical step in the evaluation of any seismic feature is to iterate between section and plan views. A geological feature must have an expression that is scientifically reasonable in multiple dimensions. *Analyses of section view integrated with plan view images represent the integration of seismic stratigraphy with seismic geomorphology*.

An equally critical step in seismic geomorphologic analyses is the integration of borehole data if available. These data provide critical lithologic and sedimentologic ground truth for the seismic interpretation. Modern analogues or unequivocal ancient analogues can be used to enhance the credibility of an interpretation.

Examples of seismic analytical techniques

Horizon picking and illumination. 2D or 3D displays of seismic reflections can often significantly enhance the appearance of a depositional element's external morphology. For example, a channel can appear as a seismically expressed trough; a carbonate patch reef will be recognizable by its circular, positive relief. Once a horizon or horizons bounding such an element are interpreted, various attributes can then be draped on such a surface to further enhance the appearance of the depositional element. Figure 1 illustrates an unconformity surface mapped in time illustrating the current subsurface structure on that horizon. Figure 2 illustrates an amplitude extraction draped on a horizon. In some instances merely illuminating such a horizon from different lighting angles can provide significant stratigraphic insight (Fig. 3).

Horizon parallel or stratal slicing. Several techniques exist for slicing through a 3D seismic data volume. They include time slices, dipping planar

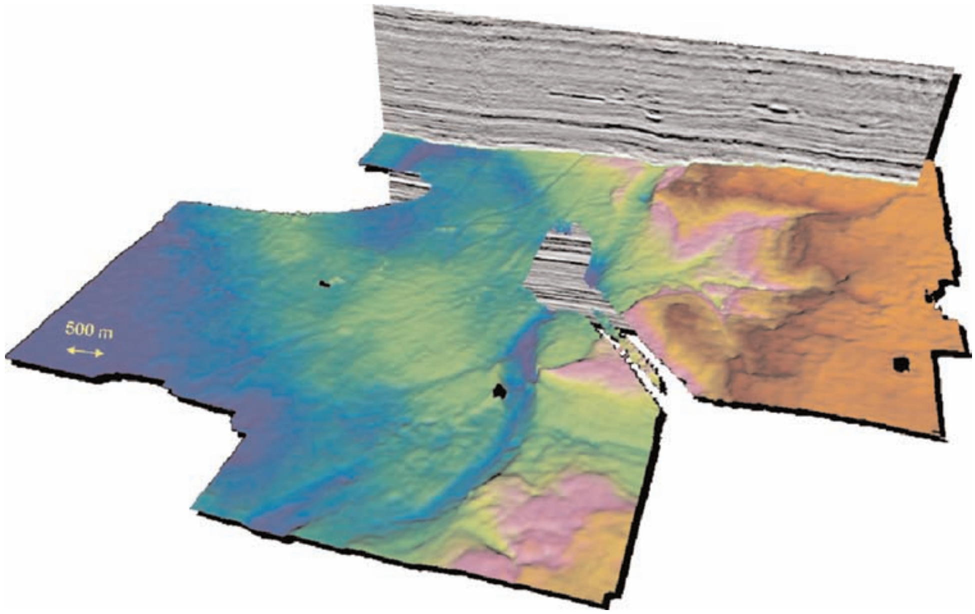

Fig. 1. Time structure draped on interpreted horizon. Base Cretaceous unconformity, western Canada basin, Alberta. Note the presence of fluvial channels on this surface.

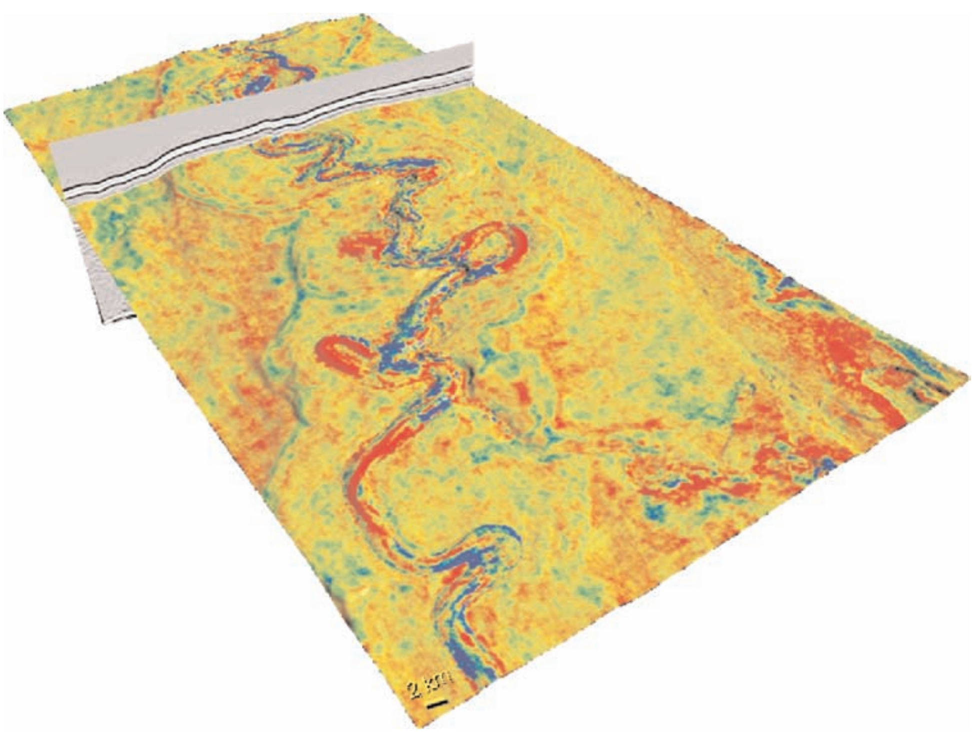

Fig. 2. Reflection amplitude draped on interpreted horizon suggesting presence of sand within deep-water turbidite channel, Gulf of Mexico.

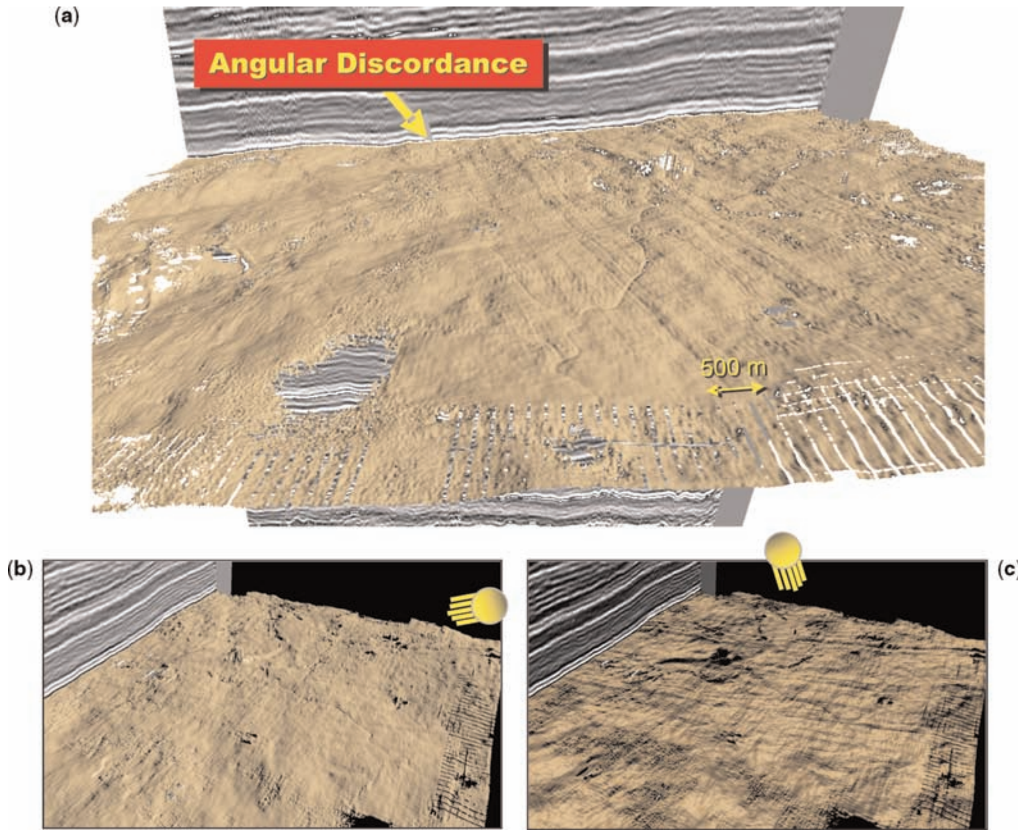

Fig. 3. (**a**) Illuminated unconformity surface in perspective view with channel and ridge-form erosional remnants (i.e. cuestas). (**b**) The same unconformity surface with lighting from the right – parallel to the trend of the ridge-form erosional remnants. (**c**) The unconformity surface with lighting from the top. Note that the ridge-form erosional remnants are far better visible when the lighting is orthogonal to the ridges.

slices, horizon-parallel slices (i.e. stratal slices), and proportional slices. Commonly, when looking for stratigraphic features, the best results are obtained by slicing as near as possible to the target interval and parallel to a well-mapped structural horizon. This technique will reduce the affects of structuring that might obscure the imaging of palaeo-geomorphic features. Where seismic reflections are parallel and nearly horizontal, then seismic time slices would suffice (Figs 4 and 5a). Where reflections are uniformly dipping, then dipping planar slices are appropriate (Fig. 5b). Where reflections are characterized by variable dip, then horizon parallel or horizon slices (i.e. stratal slices) yield the best results (Fig. 5c). In those instances where reflections are uniformly divergent, then proportional slicing would be ideal. This involves slicing between two non-parallel reflections, whereby the interval between the two reflections is proportionately divided into an equal number of slices (Fig. 6).

Horizon or slice amplitude extraction Amplitude extractions along horizons or along seismic slices can reveal the presence of depositional elements by virtue of the different impedance characteristics of the depositional element relative to the surrounding strata. For example, the deep-water crevasse splay shown in Figure 7 is apparent from the amplitude extraction along a horizon slice.

Interval attribute analysis. Seismically characterizing an interval that contains an FLT can sometimes yield superior results. Numerous interval attributes can be generated, such as maximum positive polarity amplitude, maximum absolute polarity amplitude, the ratio of positive maximum to negative maximum amplitude, total cumulative amplitude. Examples of interval attributes are illustrated in Figure 8. One interval attribute worthy of special mention is trace-shape or seismic-facies analysis. This interval attribute involves examining a sub-sample of traces

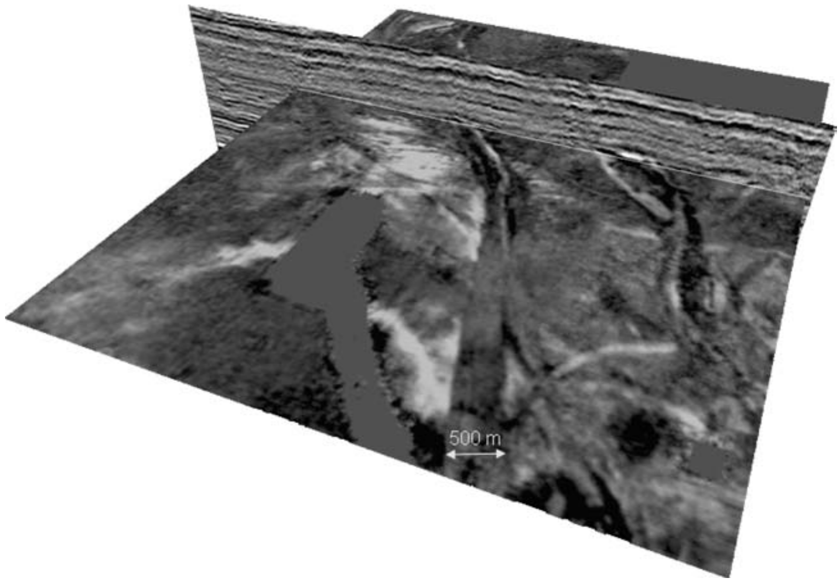

Fig. 4. Time slice amplitude extraction showing small fluvial channels, western Canada sedimentary basin, Alberta, Canada. Note that because the time slice is close to parallel with the seismic reflections, reasonable imagery of channels is achieved.

for a given area across a specific interval and then characterizing these traces according to shape. The interpreter arbitrarily determines how many classes are needed to characterize the variability of the interval in question, and then all traces are assigned to one of these classes. The result is a seismic facies map (Fig. 9a). An extension of this process is the generation of correlation maps, whereby each trace is correlated with a particular class that can yield further detail (Fig. 9b).

Voxbody picking. 3D seismic data are composed of numerous voxels, each voxel corresponding to a seismic sample along a seismic trace. Voxbody picking, also referred to as subvolume detection, involves selecting a voxel and then highlighting those connecting voxels that satisfy user-defined attribute values (most often amplitude). The connected highlighted voxels can help identify depositional elements such as channel fills or other geobodies of relatively similar attribute value (Fig. 10).

Horizon-based attribute mapping. Attributes calculated along horizons can bring to light subtleties of depositional elements not apparent in other displays. Figure 11 illustrates multiple horizon attributes calculated for a deep-water turbidite channel.

Volume-based attribute mapping. In instances where horizon slicing does not work well because no reference horizons useful for datuming can be interpreted with confidence close to the target interval, volume-based attribute analyses can be useful. One commonly used such attribute is coherence or discontinuity, whereby the similarity (or dissimilarity) between adjacent traces can be mapped. This technology, originally designed for mapping subsurface faults, is an excellent edge-detection tool and is especially useful for defining geobodies with sharply defined margins such as channels (Fig. 12).

Volume co-rendering. Where two attributes provide useful information regarding the lithofacies distribution within a geobody, co-rendering may provide the ideal display for extracting stratigraphic, geomorphic and depositional systems insights (Fig. 13). In some instances interpretations are facilitated by showing coherence in plan view and amplitude in section view (Fig. 14).

Summary

All of the techniques discussed above contribute to improving our understanding of a particular geomorphic feature or surface of interest. Critical to the success of this approach lies in the 'ground truth' calibration of lithofacies and depositional setting using borehole data. As with any other aspect of seismic interpretation, it is imperative

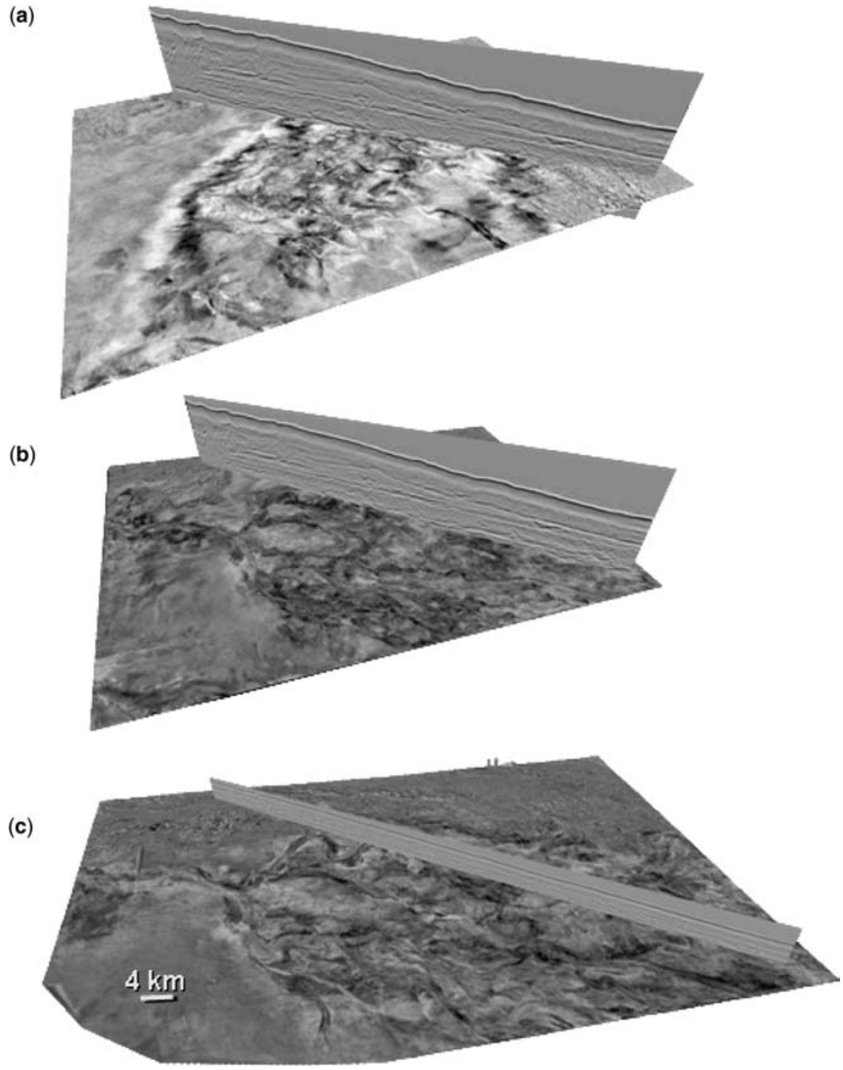

Fig. 5. (**a**) Seismic amplitude extraction along time slice through southeast-dipping reflections. Part of a frontal splay (i.e. lobe) turbidite system in the deep-water Gulf of Mexico is imaged. (**b**) Seismic amplitude extraction along dipping planar slice oriented approximately parallel to seismic reflections. More of the depositional system is imaged. (**c**) Seismic amplitude extraction along horizon-parallel slice, also referred to as horizon slice or stratal slice. This slice achieves the best possible image of the depositional system.

to be aware of pitfalls that model bias brings to the interpretation process. Moreover, the interpreter must be able to distinguish between seismic expression of actual depositional elements and geophysical data artifacts. As progressively more computer-driven analytical tools are employed, it is important that the interpreter be aware of the limitations of vertical and spatial resolution on their geologic interpretation, and how the various attributes derived and analysed in the workflow were calculated. Planform pattern recognition is a powerful addition to the interpreter's day-to-day toolkit that brings with it the need to be aware of the broader context of the features under scrutiny, and also to recognize that the planform imagery to a greater or lesser extent can be influenced by choices made by the interpreter in correlating any given horizon.

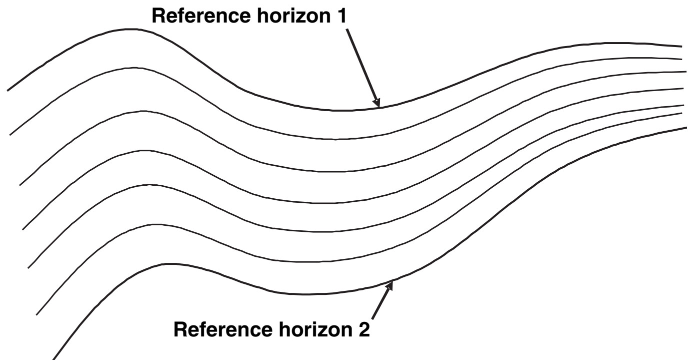

Fig. 6. Proportional slicing through divergent seismic reflections.

A look forward

Seismic geomorphology, based on interpretation of plan-view seismic images, is rapidly developing on several fronts. These are (a) understanding the development of seascapes and landscapes in clastic and carbonate settings, (b) advances in workflows directed towards lithological prediction through the integration of seismic stratigraphy and seismic geomorphology, (c) revising and improving sequence stratigraphic models, and (d) development of new and increasingly more sophisticated analytical techniques. These are all useful directions. How is seismic geomorphology poised to impact geoscience, compared for example with experimental analogue modelling and fieldwork? Where are the fundamental discoveries going to come from in the future – what new breakthroughs will be made?

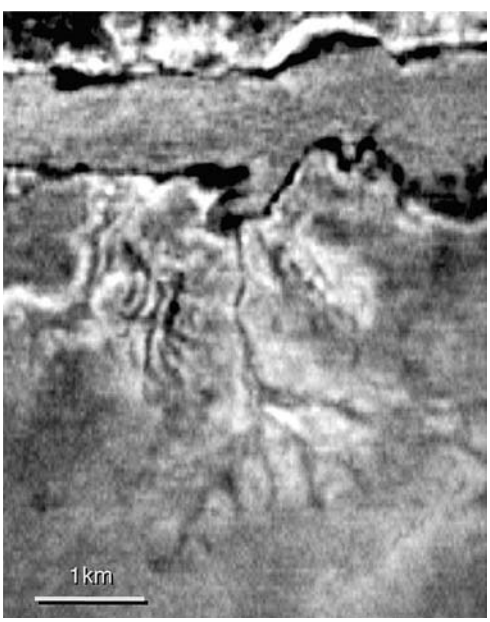

Fig. 7. Seismic amplitude extraction along a horizon slice through a deep-water crevasse splay (note the distributive channel pattern), Gulf of Mexico. Reflection amplitude suggests that the channels are sand-prone.

Palaeoceanography

Palaeoceanography is a discipline essential to the understanding of past climate change. Palaeocirculation patterns and water mass structure can be reconstructed through interpreting seismic data across contourite drift complexes. Seismic geomorphology studies of contourite drifts have been published recently (Knutz & Cartwright 2003; Hohbein & Cartwright 2006). As seismic data coverage increases in deep-water environments along continental margins, the role that these types of studies could play may become more important.

Palaeoclimatology

Newly developing techniques in morphometric analysis of seismic geomorphological features offer promise in better understanding the nature of palaeodrainage and channel discharge over geological time. The potential for reconstructing a region's rainfall and discharge history through analysis of changes in channel orientation, size, width:depth ratios and sinuosity, for example, may eventually contribute significantly to a more detailed climate history for regions than is presently achievable. In addition, critical linkages between areas such as the South China Sea and the Indian Ocean may be better understood through more detailed seismic geomorphological-derived history of the region. Such ocean-to-ocean linkages are critical for understanding the palaeo-El Nino and La Nina

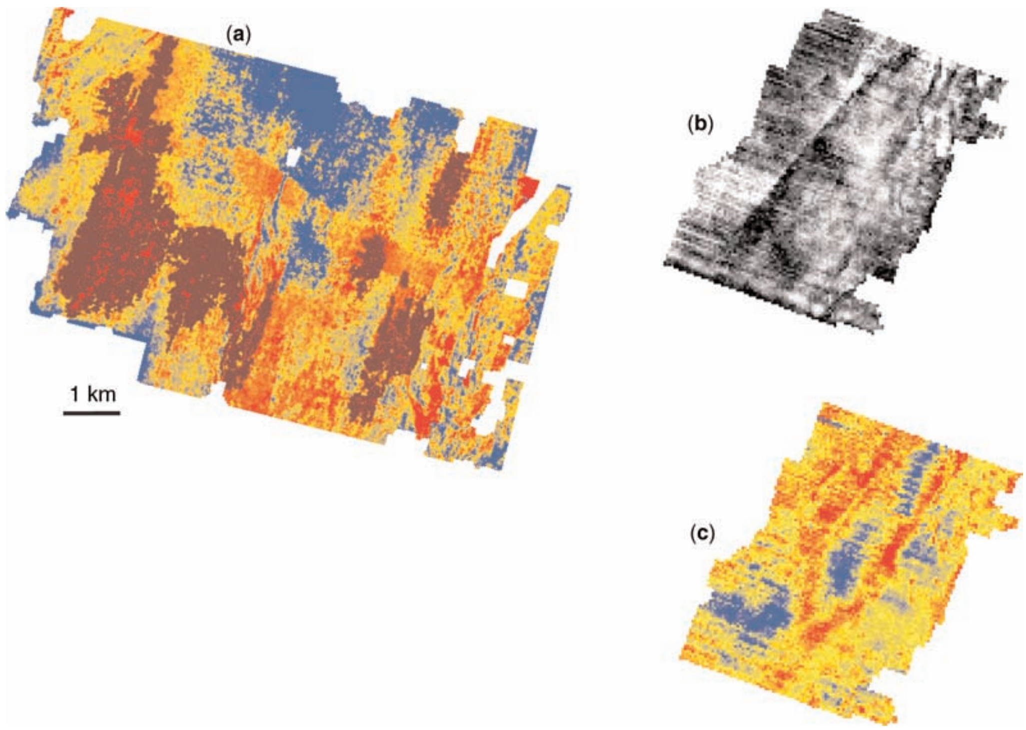

Fig. 8. Several interval attributes characterizing Miocene shelf sand ridges, offshore Northwest Java (modified from Posamentier 2002). (**a**) Interval attribute (cumulative amplitude) illustrating several sand shelf sand ridges. Note the presence of a 1 km-wide distributary channel that is imaged along with the sand ridges though it lies just beneath. (**b**) Detail of an isolated sand ridge delineated by a well-defined margin on one side (the edge of the ridge on the side that constitutes the leading edge) and a poorly defined margin on the other (i.e. the trailing edge). This attribute is the maximum negative polarity for an interval that brackets the sand ridge. (**c**) Detail of the same sand ridge as shown in (b). This attribute, a third derivative map for the same bracketing interval, highlights the presence of smaller sediment waves (large dunes?) superimposed on the larger sediment ridge.

events. A history of disruption of these linkages through sea level change is important for developing accurate palaeoclimate models.

Deep-water channel complexes

Most of the advances in understanding the stratigraphic architecture and lithofacies distributions of deep-water systems are driven by oil and gas exploration in offshore areas such as the deep Atlantic Ocean of West Africa, and the Gulf of Mexico. These systems are highly complex and variable. As seismic resolution continues to improve, some of this complexity will be more clearly imaged and consequently better understood. Such enhanced understanding is critical to the commercial success of exploration in these often very-high-cost environmental settings.

Biogeography

The growing coverage of 3D seismic data in our continental margins around the world affords us the unprecedented opportunity to understand the geomorphology of exposed shelves and shallow seaways of the world as never before. The history of exposure of regions used by palaeocultures as migration pathways, for example between mainland Asia and Indonesian archipelago, or between northern Asia and North America, is currently very poorly constrained. Seismic geomorphology (especially when applied to the near sea floor) offers an opportunity to redefine the history of lowstand shelves around the world and shed great insight into the migration routes of early cultures.

Anthropogenic hazards

The past 20 years of data collection, both seismic and borehole data, as a by-product of conventional energy exploration have brought to light a number of catastrophic processes active on margins around the world. Submarine slope failures have

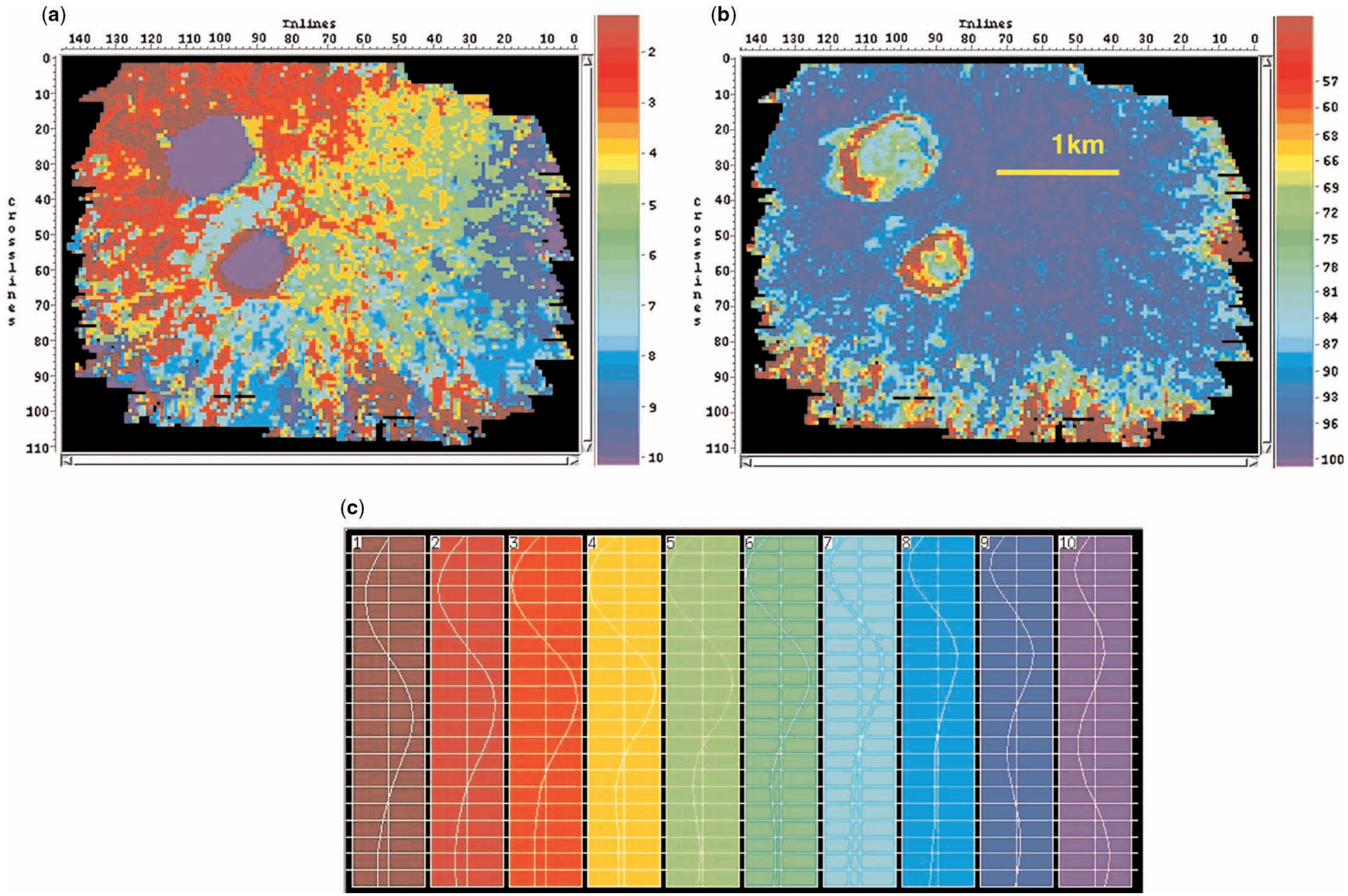

Fig. 9. Seismic facies mapping of two Devonian pinnacle reefs, western Canadian sedimentary basin. (**a**) Seismic facies map illustrating that all seismic traces within the reefs are assigned to a single facies class. (**b**) Seismic facies correlation map wherein each trace is compared with class 3 (c). Note the more detailed seismic and therefore geological expression of the reefs. (**c**) The neural-network-derived 10 seismic facies classes upon which the analysis was based (Stratimagic software by Paradigm Inc.).

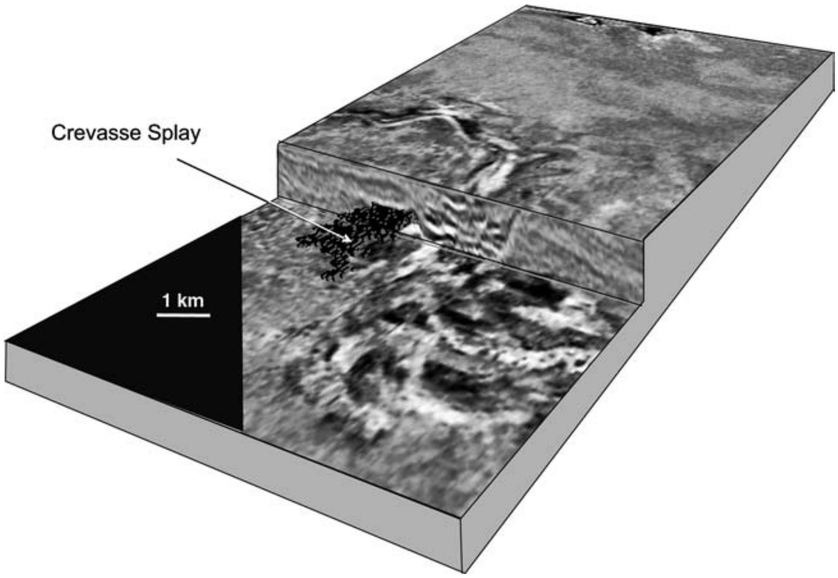

Fig. 10. Voxbody expression of deep-water crevasse splay, Pliocene of the eastern Gulf of Mexico.

been documented to generate large tsunamis in coastal regions. In addition, such mass slope failures can endanger ocean tele-communication equipment as well as engineered structures for hydrocarbon exploration. 3D seismic geomorphological analyses enable us to image and investigate these processes like never before, hopefully increasing our ability to predict and mitigate the impact of these events.

Tectonic geomorphology

This sub-discipline of geomorphology has evolved in the past decade as a result of increasing interest in Neotectonics, and the interplay of geodynamics and landscape evolution in the mountain belts (Burbank & Anderson 2001). Topics such as the structural control of river systems can easily be extended into the submarine and subsurface realm, for example, in the structural control of depositional systems on continental slopes. The seismic geomorphology of deformed surfaces is much more difficult to interpret in comparison with surfaces within simple layer-cake, unstructured successions, but with restoration techniques now available in three dimensions, the analysis of deformed surfaces is now tractable.

Igneous geomorphology

As exploration ventures into deep water, it is moving into regions of more stretched crustal type and even in some cases into basins floored by oceanic crust. Perhaps as much as 70% of divergent continental margin basins are of the volcanic type, exemplified by the northeast Atlantic margins of Greenland and Norway (Planke *et al.* 2000). Not surprisingly, therefore, more 3D surveys are acquired in areas of volcanic and intrusive activity, and this opens up potential for a wholly new approach to igneous geology, using a seismic geomorphological methodology. This approach has been defined as seismic volcanostratigraphy in the pioneering work of Planke *et al.* (2000). Studies of intrusive features such as mafic sills (Hansen *et al.* 2004) and extrusive features such as submarine volcanoes (Davies *et al.* 2002) and subaqueous lava flows (Trude 2004) are showing a host of features that have not been observed using traditional outcrop methodologies, and there is much potential for further advances in this field.

Contributions in this book

Back to basics

It is a healthy sign that, through the discipline of seismic geomorphology, some of the papers in this book go back to question some of the basic tenets of sequence stratigraphy, such as the correct placement of the sequence boundary relative to sea level. This revisited and sometimes contentious question is tackled by focusing on the late Quaternary

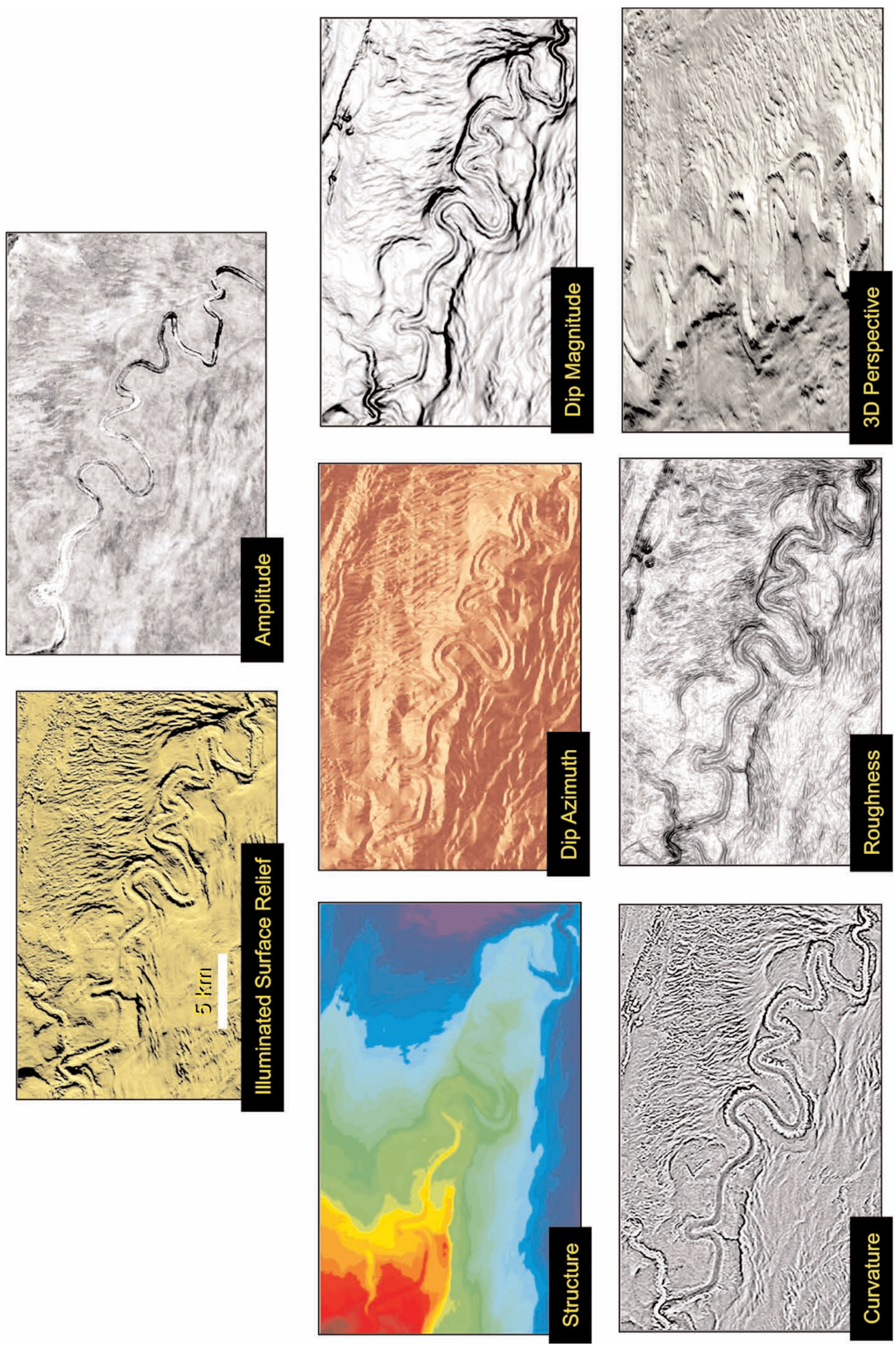

Fig. 11. Various horizon-based attributes extracted from the upper bounding surface of a deep-water turbidite channel, Gulf of Mexico. Each attribute affords the interpreter different and potentially valuable insights regarding depositional elements.

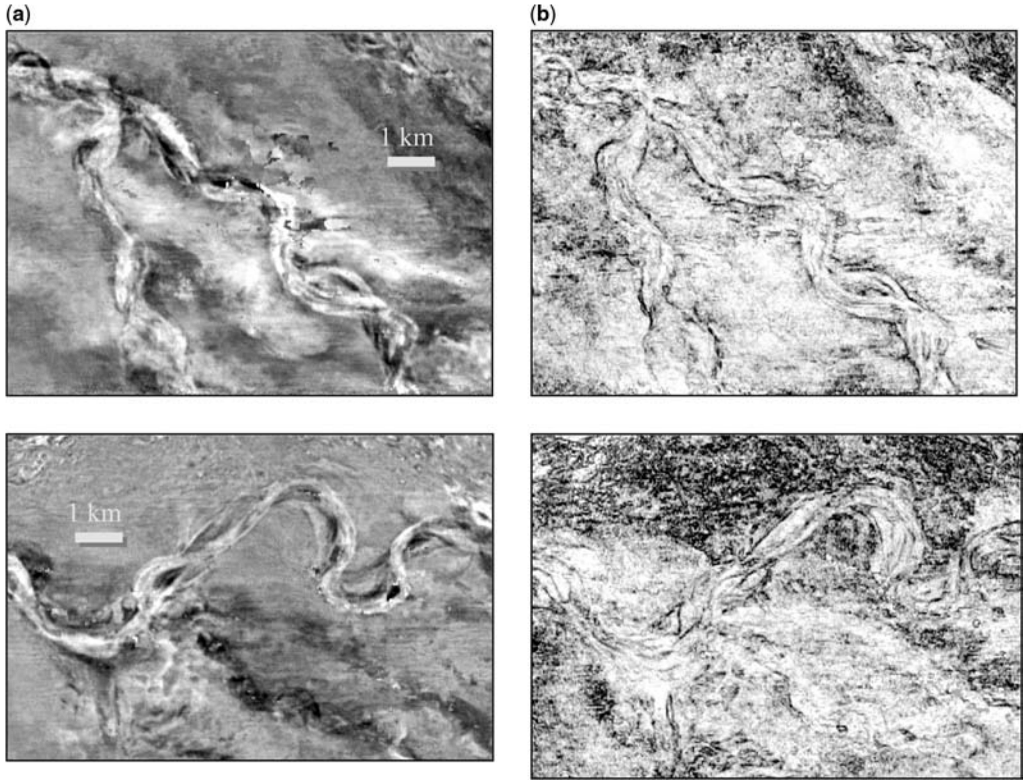

Fig. 12. Amplitude (**a**) and coherence (**b**) time slices illustrating a deep-water turbidite channel, Gulf of Mexico. The amplitude reflection attribute is an indicator of acoustic properties of the channel fill, whereas the coherence attribute highlights the edges of the channel.

geomorphology of a sequence boundary in the Gulf of Mexico, when sea-level history is well constrained through radiocarbon analyses and other chronological data (**Simms *et al.***). **Crumeyrolle *et al.*** also focus on the lowstand part of the sea level curve, using 2D and 3D seismic data to further refine sequence stratigraphic models. The datasets they employ allow them to be holistic in terms of depositional setting and cover fluvial to deepwater sediments in the Mahakam Shelf. Their approach is subsequently broadened through the use of outcrop analogues. **Hadler-Jacobsen *et al.*** take a geological long-term view, examining the stacking pattern of deepwater sediments over a 50 Ma window, and relating this to basin margin dynamics (adjustment, deformation and sediment deposition).

Data interrogation strategies

A book on seismic geomorphology would not be complete without consideration of seismic resolution, imaging quality and strategies for interrogating the data (**Zeng**). **Hart & Sagan** discuss clastic and carbonate settings from Precambrian to Late cenozoic in age, demonstrating the utility of techniques in curvature analysis. **Sullivan *et al.*** further discuss the use of seismic attributes to study karstification in the Pennsylvanian Marble Falls limestones.

Depositional elements – case studies

This book includes papers on a breadth of sedimentary environments. **Handford & Baria** illustrate how 3D seismic data are being used to re-think well-known exploration and development targets, such as the Smackover Formation, in the US Gulf Coast. They dispel the previous interpretations of the Smackover deposited as a homoclinal carbonate ramp, revealing clinoforms that they interpret to be oolitic carbonate shoreface deposits. **Rabelo *et al.*** look at fluvial depositional environments, parameterizing meander belts using 3D seismic data and seismic volumes. In the northern and the southern

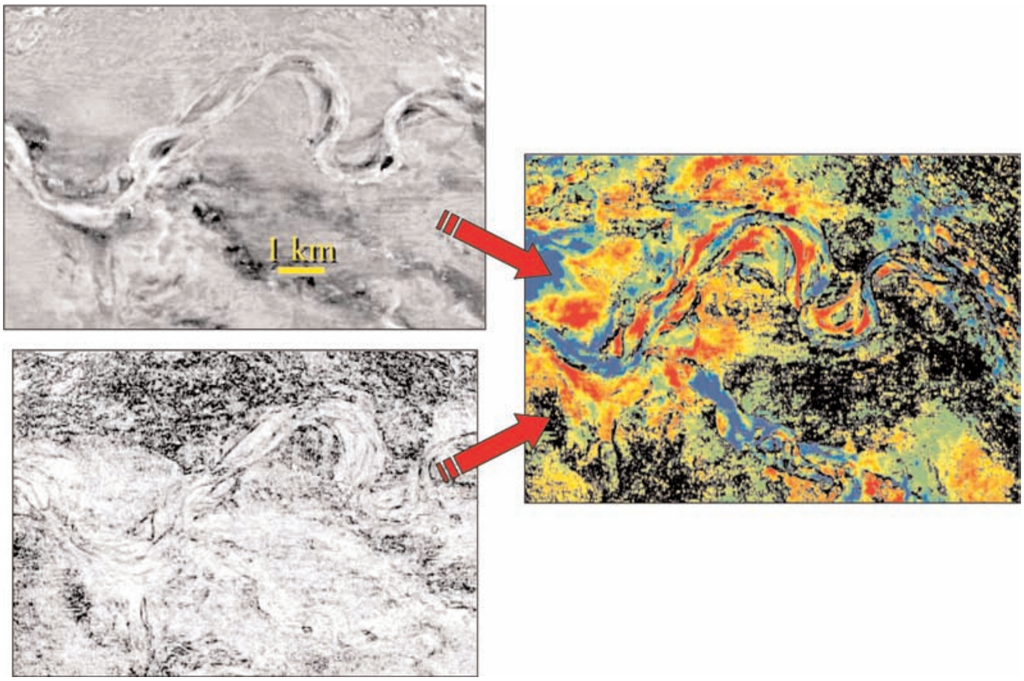

Fig. 13. Co-rendered amplitude and coherence image of a deep-water turbidite channel, Gulf of Mexico.

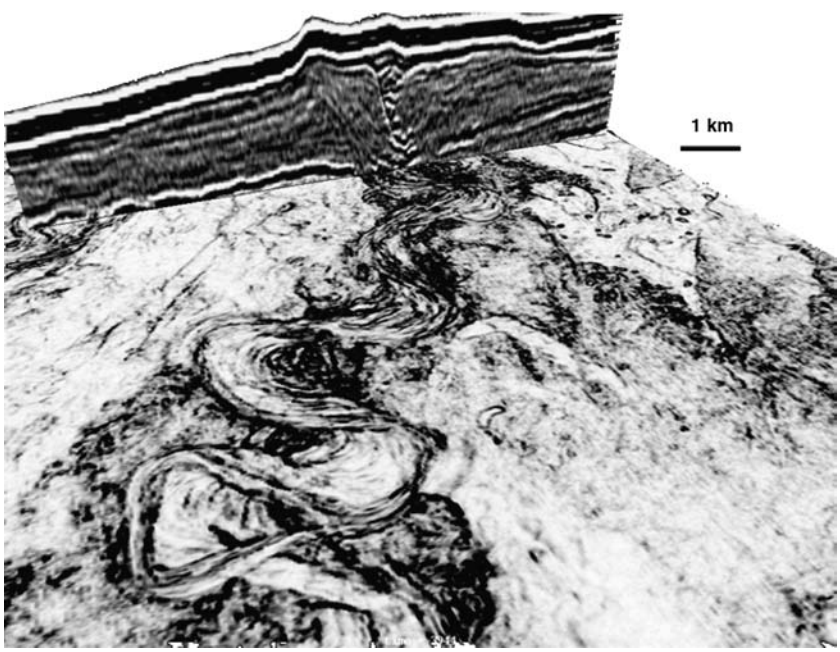

Fig. 14. Co-displayed coherence (in plan view, i.e. time slice) and reflection amplitude (in cross section view).

hemisphere the role of glacial processes in shaping landforms is particularly important. Such environments, in particular ice-streams, are investigated by **Andreassen *et al.*** using 3D seismic data from the Barents Sea.

The spectacular seismic data coming from offshore West Africa as well as other deep-water locations have revolutionized our understanding of deep-water sedimentary environments over the past 10–15 years. **Schwab *et al.*** use these data to full advantage in their analysis of a mixed turbidite-contourite system on the Mauritanian continental slope.

The scientific community is just beginning to understand the magnitude and impact of post-depositional compaction, diagenesis and sediment remobilization along continental margins. Increasingly, seismic investigations are uncovering extreme and repetitive sediment mobilization events. **Jackson** demonstrates the utility of 3D seismic data in understanding post-depositional remobilization of mud.

Conclusions

Pattern recognition, involving the interpreter being able to recognize geologically significant features in plan view on 3D the seismic data, is critical to the seismic geomorphological approach. In conjunction, it is also essential to cross reference plan view with section view images, thus integrating the geomorphology with the stratigraphy. Seismic geomorphology is a rapidly evolving discipline, benefitting from the rapidly accelerating widespread availability of 3D seismic data. Seismic geomorphological analyses address a broad range of disciplines ranging from igneous to sedimentary geology, focusing on questions ranging from lithology distribution to diagenesis to large-scale tectonic analyses. Although by no means an exhaustive treatise on this subject, this volume does present a representative cross section of applications and principles relevant to this rapidly evolving discipline.

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