Sequence stratigraphic responses to shoreline-perpendicular growth faulting in shallow marine reservoirs of the Champion field, offshore Brunei Darussalam, South China Sea: Discussion

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I do not agree with the conclusion reached by Hodgetts et al. (2001) that a deltaic shoreline in two adjacent growth fault blocks was simultaneously prograding and retrograding, for reasons explained in this article. My principal objection is illustrated in their figure 14. The block diagram and paleoenvironmental map (Hodgetts et al., 2001, figure 14c, d) show the onset of growth faulting. As the fault begins to offset the depositional surface, Hodgetts et al. (2001) argue that the greater subsidence associated with the hanging-wall (downthrown) block caused updip migration of the shoreline, while the shoreline continued to prograde in the footwall (upthrown) block. If, however, offset on the fault yielded no more than several meters of relief on the sea floor, then the delta would merely heal the surface and continue to prograde in the hanging-wall block, where the succession would be thicker than in the footwall block (overall layer thickening). This is what is observed in numerous cases in the northern Gulf of Mexico Basin (e.g., Curtis, 1970; Curtis and Picou, 1978) and the Niger Delta (Weber, 1971). Several examples that I have studied and described in publications include the Paleocene–Eocene Wilcox Group (Edwards, 1980, 1981; Winker and Edwards, 1983); the Oligocene Frio Formation (Edwards, 1995), the Eocene Yegua Formation (Edwards, 1990, 1991), and the lower Miocene (Edwards, 1994, 1995). Shoreline orientation is irrelevant because the complex traces of active growth faults at the depositional surface clearly do not have a one-to-one relationship with shoreline orientation (see, for example, Edwards [1980] and Winker and Edwards [1983], in which growth fault positions are contrasted with the orientation and location of depositional elements). Structure and interval isopach maps show that during regional shoreline progradation, minor differences in subsidence rate between fault blocks, such as observed by Hodgetts et al. (2001), were insufficient to result in localized shoreline retrogradation in a rapidly subsiding area bounded by growth faults (e.g., Edwards, 1981, 1990, 1991). In contrast, on a regional scale of depositional systems, the shoreline can simultaneously prograde and retrograde because of variations in factors such as sediment supply, subsidence. and depositional environment.

What was the reason for Hodgetts et al.'s (2001) conclusion? It may have been the misinterpretation and/or misidentification of clinoform reflectors in the seismic data (Hodgetts et al., 2001, figures 11, 12). In their discussion of the development of clinoforms, Hodgetts et al. (2001, p. 448–449) refer to parasequence stacking patterns; however, what is the relationship between parasequence stacking patterns and clinoforms? Clinoform development is commonly attributed to the lateral migration of an inclined surface, such as a prograding shoreface or delta front or, on a larger scale, a shelf margin (e.g., Winker and Edwards, 1983; Emery and Myers, 1996). In other words, the clinoform is associated with a physical stratigraphic surface capable of generating a reflector in a clinoform set. Hodgetts et al. (2001) do not link their alleged clinoforms to any surfaces in their data set. Compounding the problem is the absence of vertical scales in all of Hodgetts et al.'s (2001) seismic displays, which makes it impossible to evaluate whether the heights

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and dip angles of the clinoforms are reasonable. In the Gulf Coast Basin, clinoforms are rarely seen in growth-faulted strata (e.g., Winker and Edwards, 1983), except where the shelf margin has retrograded and subsequently filled the eroded deep-water embayment (e.g., Edwards, 1991, 2000). These clinoforms typically dip at 2–4°.

Further complicating the evaluation of potential clinoform development is the absence of references to clinoforms in Hodgetts et al.'s (2001) discussion of reservoir architecture (p. 464), seismic mapping of shoreline orientation (p. 444), and seismic to well ties (p. 440). The interpretation of clinoforms in the data set should suggest caution when using seismic amplitude extractions that are parallel to and displaced from a reference reflector (Hodgetts et al., 2001, p. 442; figure 7). The intersection of surfaces of extraction data with clinoform surfaces would result in trends that reflect the properties of clinoforms, rather than seismic amplitude data relevant to lithology, and hence shoreline orientation.

As Hodgetts et al. (2001) point out, it is important to test the seismic interpretation against the subsurface interpretation. Nevertheless, consistency in the definition of stratigraphic units should be maintained. The caption to Hodgetts et al.'s (2001) figure 8 refers to sand distribution in the E1.2 to F2.0 interval, whereas the color scale contour interval caption in the figure states that it was the E3.0 to F2.0 interval, and the text referring to this figure states that the interval was E3.0 to E2.0. No figure exists in their article that illustrates the position and significance of all of these stratigraphic units and surfaces. Looking at the mapped percent sandstone distribution (Hodgetts et al., 2001, figure 8a), I see two examples of northwest-oriented axes (one extending southeast from a concentration of wells in a light green to yellow area and a second that is parallel with the earth tones in the lower left) that were not highlighted by Hodgetts et al. How were the data contoured, how were their axes identified, and what kind of confidence can be placed in this map? Confidence in the seismic mapping of shorefaces is diminished by examination of Hodgetts et al.'s (2001) figure 6a, in which the F2.0 surface appears to cut across seismic reflectors, especially when related to the adjacent seismic markers and the thickness trends in the related cross section (figure 6b).

An important deficiency is the absence of an explanation of the lines drawn between wells in the cross section in Hodgetts et al.'s (2001) figure 6b. The caption refers to "seismically constrained parasequence correlation." Does this mean that all of the lines are parasequence boundaries? Are boundaries between facies associations also shown on this section? Are facies associations allowed to interfinger? If not, why not? The lengthy discussion on modeling (Hodgetts et al., 2001, p. 454–455) suggests that Hodgetts et al. are persuaded that tidal and shoreline facies associations in Champion field did not coexist in time, as they do along modern shorelines (e.g., Allen, 1970; Galloway and Hobday, 1983).

Virtually all geoscientists would agree with Hodgetts et al. (2001) that stratigraphic analysis using all available data is an important component of reservoir modeling. I argue against overaggressive application of "sequence stratigraphy," however, especially at the expense of other useful viewpoints, such as depositional environment modeling, seismic stratigraphy, and genetic stratigraphy. Concepts such as accommodation, parasequence sets, and sequence boundaries are complexly and nonuniquely related to more fundamental processes such as sediment supply and caliber, subsidence (tectonics), and eustasy.

To conclude, sedimentologists, stratigraphers, and, especially, sequence stratigraphers should be particularly interested in growth-faulted strata because they are a natural laboratory for investigating the complex effects of subsidence rate on sedimentation (e.g., Edwards, 1995), which are difficult to evaluate in more stable tectonic settings. Hodgetts et al.'s (2001) contribution should stimulate additional interest in this topic.

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Sequence stratigraphic responses to shoreline-perpendicular growth faulting in shallow marine reservoirs of the Champion field, offshore Brunei Darussalam, South China Sea: Reply

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We thank Edwards (2002) for his comments on our work (Hodgetts et al., 2001) and his views on the growth-faulted stratigraphy of the Gulf of Mexico. The models we presented for offshore Brunei were developed to explain observations (i.e., they are data driven), and we make no apology that the model derived from the observations is not identical with earlier models proposed by Edwards (2002) for a different part of the world. Several points are raised in Edwards (2002), and for clarity we structure our reply under the following headings: methodology and definitions; shoreline behavior during growth faulting; coeval wave-dominated and tide-dominated deposits; and sequence stratigraphy as a methodology in growth faulted settings.

METHODOLOGY AND DEFINITIONS

Our cored-well control allows confident tying of seismic reflectors to individual, coarsening-upward shallow-marine sand bodies that, from core data, have been identified as shoreface deposits, bounded by flooding surfaces (Carter et al., 1997). We refer to these units as parasequences. Because the seismic is displayed in acoustic impedance (AI) mode, the flooding surfaces tie to the zero crossover between the sand (black) and shale (orange), not the maximum/minimum value of the loop. From the seismic, we are, therefore, interpreting sand (shoreface) and shale (offshore–transition to offshore). The one-to-one tie between the AI data loops and the parasequences defined from the cored wells indicates that the vertical resolution of the seismic is 5–10 m. The nature of the AI data, the resolution of the AI volume, and how it can be tied directly to the gamma-ray log is illustrated in figure 5 of our article (Hodgetts et al., 2001). This detailed and high-resolution tie between seismic and well data allows correlations to be made using the seismic data as the lateral, interwell control, therefore giving the true well correlation and not one based on models.

We do not fully follow Edwards's (2002) points on clinoforms. We found that the majority of seismic reflectors in the Brunei data set were horizontal and not clinoformed. Although the relationship between clinoform angle and rate of accommodation space creation (average of approximately 1 km/m.y. [Sandal, 1996]) is not fully understood, our observations here indicate clinoform angle is suppressed in areas of high subsidence and high sediment supply. This is in accord with Edwards's (2002, p. 920) own observations from other areas that "clinoforms are rarely seen in growth-faulted strata." In sections of the stratigraphy, however, we do observe clinoform geometries that are proven from the well ties to represent progradational shoreface parasequences. We suspect that these intervals may represent times of lower subsidence rate, allowing the shoreline to prograde.

Edwards's (2002, p. 920) statement, "The intersection of surfaces of extraction data with clinoform surfaces would result in trends that reflect the properties of clinoforms, rather than seismic amplitude data relevant to lithology, and hence shoreline orientation," ignores the fact than the orientation of the clinoform is itself related to the shoreline orientation (particularly in the case of linear, wave-dominated shorefaces such as these) and, therefore, shares a simi-

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lar orientation to the lithological (and hence AI) variations. Edwards's (2002, p. 920) comment that the "F2.0 surface appears to cut across seismic reflectors" shows how interpreting data in two dimensions can be misleading; the interpretation shown is correct based on three-dimensional (3-D) seismic mapping and well correlation. Only by tracing events in 3-D are the correct interpretations made, particularly in seismic such as the Champion survey, which, though very high resolution, is prone to localized changes in resolution due to multiples from overlying oil-bearing rocks and modern limestone reefs at the surface that filter the higher frequencies from the seismic source. Some apparent thickness variations between the seismic interpretation and the well correlation are to be expected, owing to the seismic section being in time and the well logs in depth.

The seismically constrained parasequence correlation in Hodgetts et al. (2001) figure 6b is exactly what it says: an interpretation at parasequence scale, with shoreface sand marked in yellow, OTZ-marine shale left blank, and tidal units in purple and green. As with any shoreface parasequences, the boundaries are represented by the flooding surfaces.

All seismic displays in Hodgetts et al. (2001), apart from figures 11 and 12, have vertical scale on the log section counterpart, which is printed at the same scale as the seismic. Figures 11 and 12 are included solely to illustrate stacking patterns of sand bodies (not clinoforms). As Edwards (2002) states, we neglected to provide a vertical scale; in this case, for figure 11 (hanging wall) the seismic section is about 100 m thick and 3500 m wide, and the footwall section in figure 12 is approximately 80 × 3500 m. These sections are flattened on the overlying F20–050 flooding surface. Although the precise dip of the sand bodies depends on which surface the sections were flattened on, we estimate the maximum dip of these sand bodies to be on the order of 0.3°.

SHORELINE BEHAVIOR DURING GROWTH FAULTING

In his first paragraph, Edwards (2002) states that shorelines affected by growth faulting would not retrograde but would merely show thickening in the downfaulted block. This is indeed one possible response, and we document this in the Brunei case, where we can demonstrate thickening of seismic packages across the fault (Hodgetts et al., 2001). Well control confirms that these are thickening shoreface parasequences, bounded by the same flooding surfaces. We refer to this process in Hodgetts et al. (2001) as "layer thickening." Our data also reveal a second response to faulting: layer addition, where flooding surfaces can be followed without breaks around fault tips or down relay ramps from footwall to hanging wall. At certain stratigraphic intervals, mapping reveals one shoreface sand body between successive flooding surfaces on the footwall block and two shoreface sand bodies between the same two flooding surfaces on the hanging-wall block. We refer to this in Hodgetts et al. (2001) as "layer addition," which is the starting observation from which our figure 14 was offered as a possible, data-driven explanation. Our reasoning is that at certain times the rate of accommodation creation was greater than the rate at which sediment was supplied. When these conditions were met, the hanging-wall block behaved like any depositional system and underwent a period of retrogradation, producing a flooding surface restricted to this downthrown block.

The contour map in figure 8 (Hodgetts et al., 2001) indeed shows trends in more than one orientation, but the east-west trend is the dominant one. This is apparent not just in this interval (for which the caption is correct, but the text should read F1.2–F2.0) but in most of the other mapped intervals. Similar variations are also characteristic of gamma-ray log data (which are unfortunately subject to confidentiality restrictions) and are consistent with those derived from seismic amplitude maps.

Direct application of Gulf Coast models elsewhere in the world should be undertaken with care. Edwards's (2002) simple layer-thickening model does not explain all the features seen in the Champion field. Our model is a combination of observed data from the study area, observed data and model from analogs, and knowledge of the processes applicable to the area. We suspect that the documented layer addition may well be common in other growth-fault settings but is not always resolvable from the available seismic data.

COEVAL WAVE-DOMINATED AND TIDE-DOMINATED DEPOSITS

Our (Hodgetts et al., 2001) observations that the preserved deposits of tidal and shoreface systems are not time equivalent in the Champion area are based on the data from cored wells, tied to the 3-D seismic and mapped as distinctive seismic facies around the study area. We believe the reason for the switch between tidal and shoreface facies is controlled by a process operating on a more regional scale, perhaps movement on the main Champion Sliver fault, though without data this is obviously conjecture. Our data-driven interpretation does not preclude the larger scale existence of time-equivalent wave-dominated and tide-dominated depositional systems, as is the case in present-day north Borneo, with the Baram delta and Brunei Bay. Numerous stratigraphic analyses of ancient preserved successions around the world, however, have shown that, in general, the deposits of wave-dominated and tide-dominated coastlines are partitioned in time (e.g., examples in Van Wagoner and Bertram, 1995), which does fit with our observations.

SEQUENCE STRATIGRAPHY AS A METHODOLOGY IN GROWTH-FAULTED SETTINGS

Edwards (2002) questions the utility of sequence stratigraphy in growth-faulted sections. Sequence stratigraphy promotes the analysis of any depositional system (simple or complex) in terms of the fundamental controls on stratal architecture, such as accommodation and sediment supply. A sequence stratigraphic approach in combination with integrated analysis of a high-quality data set has assisted us in the development of a testable model for reservoir development within an accommodation/sediment supply framework. We do not agree that this is overaggressive application of sequence stratigraphy.

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