Evolution of deep-water synkinematic sedimentation in a piggyback basin, determined from three-dimensional seismic reflection data

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ABSTRACT

Three-dimensional seismic data have revealed the interaction between synkinematic deposition and active folds in a deep-water piggyback basin. Background aggradational deposition is punctuated by debris flows and/or landslides, channels, canyons, fans, and degradation complexes. Gravity-driven hummocky strata-bound folds hundreds of meters to 2 km in wavelength, with tens of meters amplitude developed on the unstable slopes of large fans. At the base of the debris flows and/or landslides, long, curved, erosive furrows indicate flow transport direction and help demonstrate changing flow directions as the basin evolved. In flows that traversed several anticlines and synclines, sediments were transported as sheet-type flows in the syncline and focused back into narrow channels or canyons at anticline-related topographic ridges. Basin evolution is characterized by early synkinematic sedimentation, where growing folds are in a distal position to gravity flows and display a relatively intact antiformal geometry. Flows entering the basin tend to be axial, either from the southwest or northeast. Anticline growth triggered instability on the fold crests and caused local landslides. Later flows entering the basin perpendicular to the anticlines and crossed the seafloor ridges by either exploited weak points at the crests, e.g., overpressured mud/flow pipes, or structurally related low points, e.g., saddle regions where two plunging anticlines linked along strike. At the exit point of some anticline-traversing canyons, high-relief fans developed where deposition locally exceeded subsidence rate. Such fans can ultimately block and divert flow from the original fan feeder canyons to other piggyback-basin entry points.

INTRODUCTION

The interaction of growing folds and deep-water sediments has been largely documented from outcrop data, particularly in the back-arc troughs of Japan, and Alpine fold belts of Europe and North Africa ( Mutti et al., 1988, 2000; Martin-Martin and Martin-Algarra, 2002; Ricci-Lucchi, 2003; Sinclair and Tomasso, 2002; Lucente, 2004; Takano et al., 2005), or in the subsurface from two-dimensional (2D) seismic reflection lines (e.g., Bally, 1989; Faugeres et al., 1999; Ajakaiye and Bally 2002). In a continental setting, the rugged topography and commonly remote nature of fold-and-thrust belts, coupled with surface static problems, and complex subsurface structure make 3D data too expensive and difficult to acquire except over small areas. Even 2D data are commonly acquired on a widely spaced grid (several kilometers) and are of poor quality. Offshore fold-and-thrust belts in an accretionary prism setting have been imaged by 2D seismic data acquired for research (e.g., Taira et al., 1992; Cowley et al., 2004). Such settings are not typically very hydrocarbon prone, and are at water depths that are too great for drilling. Consequently, models for the interactions between folds and sedimentation in deep-water basins are largely based on outcrop data, high-resolution sonar images of the seafloor, and 2D seismic reflection data (e.g., Mutti et al., 1988; Normark et al., 1993; Barnes and de Lepinay, 1997; Sinclair and Tomasso, 2002). These data provide a good perspective on deep-water sedimentary processes, but not the complete 3D aspects of how basins have evolved through time.

Folds and thrusts growing in the deep-water environment develop structurally controlled seafloor topography, where the highs are anticlines and the hanging walls of thrusts, and the synclines and thrust footwall regions form elongate depressions (usually subparallel to the continental slope). The depressions trap synkinematic sediments, and are carried along on the tops of thrust sheets; hence they are commonly called piggyback basins. In terms of general evolution, slope piggyback or minibasins were described by Prather et al. (1998), Booth et al. (2000), and Sinclair and Tomasso (2002) as evolving through the following stages: (1) complete trapping of flows due to high initial structural relief; (2) with diminishing relief due to deposition infilling, the basin “fill and spill” cycles or partial trapping and flow stripping occur (Prather et al., 1998; Booth et al., 2003; Sinclair and Tomasso, 2002); and finally (3) when the accommodation space is filled, flows bypass the area and incise the basin on their passage to depocenters further downslope.

The gap in high-resolution temporal as well as spatial data coverage has now been resolved because the ability to explore for hydrocarbons in water depths of as much as 2–3 km has resulted in high-quality marine 3D surveys across fold belts on continental slopes (Nissen et al., 1999; Hooper et al., 2002; Posamentier and Kolla, 2003; Booth et al., 2003; DePaule et al., 2003; Heinio and Davies 2006). The tectonic setting tends to be passive margin fold-and-thrust belts associated with gravity deformation (e.g., Nissen et al., 1999; Hooper et al., 2002; Booth et al., 2003). Much work on slope deposition in minibasins has come from the Gulf of Mexico (e.g., Winkler, 1996; Booth et al., 2000, 2003); however, this is an area of complicated salt and shale tectonics, and does not represent a

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classic fold-and-thrust belt. Few detailed studies of sedimentation in piggyback basins associated with fold-and-thrust belts based on 3D seismic data have been published. However, several such publications exist for offshore Brunei, including Demyttenacre et al. (2000), McGilvery and Cook (2003), and Ingram et al. (2004). These papers show details of the modern depositional setting, and range of sedimentary geometries, but have not documented in detail how structure and sedimentation have varied with time.

In this paper 3D industrial seismic reflection data from the deep-water area of Brunei Darussalam, northwestern Borneo, are used to describe in detail one piggyback basin where the feedback loop between how sedimentation styles and transport pathways have evolved in response to fold geometry and evolution, and how folds have been modified by active sedimentary processes can be determined. The piggyback basin studied is ~40 km along strike (northeast-southwest) and 25 km in the dip direction (Fig. 1).

**GEOLOGICAL SETTING**

The northwestern margin of Borneo (Fig. 1) has been extensively explored for hydrocarbons, and consequently the shelf and upper slope areas of Brunei, Sabah, and Sarawak are well known from drilling and seismic reflection data. Several books summarizing the data have been published (James, 1984; Sandal, 1996; Petronas, 1999). The shelf is dominated by prograding shallow-marine sequences, of early Miocene–Holocene age, that attain thicknesses in excess of 10 km in places. The sequences are deformed by growth faults, shale diapirs, and anticlines located over inverted growth faults (Morley et al., 2003).

The northwestern Borneo fold-and-thrust belt is developed on the slope in the deep-water equivalents of the early Miocene–Holocene shelfal sequences (Figs. 2 and 3). The slope dips between 1º and 3º into the deepest region of the South China Sea, the northwestern Borneo trough (Fig. 1). Until recently the fold-and-thrust belt was only known through sparse industrial and academic 2D seismic lines (James, 1984; Hinz and Schluter, 1985; Hinz et al., 1989; Sandal, 1996; Schluter et al., 1996; Pin Yan and Hailing Liu, 2004). The 2D seismic data show that the slope is affected by an extensive train of folds spaced between 5 and 15 km apart and commonly 50 km to several hundred kilometers long, that verge offshore (Figs. 2 and 3). They appear to be mostly located at the leading edges of imbricate faults that at depth sole out into one or more detachments. The 2D seismic data have shown that the northwestern Borneo trough is the site of inactive subduction where the oceanic crust of the proto–South China Sea was subducted during the early Cenozoic. The subduction zone became jammed in the latest early Miocene by the entry of thinned continental crust of the Dangerous Grounds block (Hinz et al., 1989; Levell, 1987; Hall, 1996, 2002). The present-day fold-and-thrust belt appears to be largely of Pliocene–Holocene age (Sandal, 1996; Ingram et al., 2004); therefore, the
Figure 2. Regional edge map derived from water-bottom maps of three-dimensional seismic reflection surveys. I—X are numbers assigned to different anticlines for reference. A–E are reference points for important channels in the upper slope. Numbers: 2, 3, 4, 8, and 15 are locations where gravity flows cross anticlines from one minibasin to another; 13 is location where flows pass around plunging nose of anticline; 16 is area of seafloor ridges associated with a landslide, whose breakaway cliff is marked by 17. See Figure 1 for location. Note that the complete set of locations from 1 to 18 is not shown in this figure.
deformation is unrelated to subduction. Instead, deformation may have resulted from regional stresses related to Australia-Sundaland collision, or local gravity-related stresses associated with uplift of Borneo, or a combination of both (Hall and Morley, 2004). Shortening across the fold belt is localized above the ancient subduction zone, which is a major zone of weakness in the crust.

The piggyback basin discussed herein exhibits the best transition from channel systems to fans and debris-flow deposits in the offshore Brunei area (Fig. 2). The basin was mapped in detail to show the depositional geometries of the deep-water mass movement deposits. The area of the detailed study is the broad piggyback basin that is between anticlines VIII and V (Fig. 4), two very prominent anticlines that are highs at the seafloor today (Fig. 5). The basin is internally subdivided by en echelon anticlines VI and VII, which join along an oblique-trending saddle. Seafloor edge and amplitude maps show that today there are two large fans fed by channel and canyon systems that breach anticline V at locations 3 and 8 (Figs. 2 and 4). The intermedi- ate anticline trend (VII and VI) is in the process of being covered by the fans. This study investigates how the fan and channel systems evolved through time and interacted with growing folds. The evolution is documented through isochron, difference, and amplitude maps, integrated with the cross-sectional geometry of seismic data.

**METHODOLOGY**

The three-dimensional (3D) seismic data set used in this study is clipped at 1 s below the seafloor; this would be approximately equivalent to 0.8–1 km depth of section, of predominantly Pliocene-Holocene age (calibrated with data from Sandal, 1996; Ingram et al., 2004). Seismic interpretation was conducted using

![Figure 3. Regional seismic lines showing the regional setting of the study area (see Fig. 2 for location). TWTT—two-way traveltime. (A) Typical dip line along the western part of the area. (B) Arbitrary line along a sediment transport path down the slope. Note the difference in seafloor topography between the two lines. This figure shows the regional horizons A–D discussed in the text. II, III, IV, V, VI, VIII, and IX define different anticlines; 3, 4, and 13 are locations of canyons crosscutting anticlines; D and A are upper slope channel systems. Location of lines a and b and alphanumerical locations are given in Figure 2.](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/4/6/939/3336925/i1553-040X-4-6-939.pdf)
Landmark software. In this study, five horizons (A–E; Fig. 6) were picked on a 10 × 10 line and trace grid, with extra infill, sometimes down to a 2 × 2 grid, where the auto-picker was unable to properly infill the data within the 10 × 10 grid. The main criteria for choosing the horizons were to find reasonably distinctive, high-amplitude, continuous reflections that could be carried through most of the area. Figure 5 illustrates the locations of the mapped horizons on dip lines across the area. Two of the regional horizons from an unpublished regional study were used and picked in greater detail (regional horizons A and B; Fig. 3), and three new (local) horizons were picked. The local horizon A = regional horizon A, local horizon E = regional horizon B (Fig. 3). From this point onward in this paper all horizon references are to the local horizons, unless regional horizon is specifically stated. The aim of the detailed seismic picking and extra horizons was to bring out the details of the sedimentary system geometries, in particular to (1) obtain isochron maps to show how the depositional features have changed location with time (Fig. 7), (2) generate high-quality images of erosional furrows developed at the base of the gravity deposits (Figs. 7, 8, and 9), (3) locate channel and canyon features with respect to growing structures, and (4) define features developed at the surfaces of the fans.

To determine the sedimentation patterns and fault patterns in map view from amplitude anomalies, two methods were used: (1) the

Figure 4. Edge map of the seafloor of the study area showing many features of the structural and depositional style of the area. Locations 2, 3, 4, 8, and 15 are canyons cutting across anticlines; 5 is fan A; 12 is fan B; 1, 9, and 13 are channels within the piggyback basin areas; 4, 7, and 15 are curvilinear large-scale hummocky topography developed on slopes with high sediment transport; 10 and 11 are areas of local channels coming off anticline V; 6 and 16 are areas within the slumped and remobilized debris flow; 17 is cliff separating the margins of a giant debris flow and/or landslide complex to the west and the smoother less disturbed sediments to the east; 14 and 18 are high regions of piggyback basin. IV to X are numbers assigned to different anticlines for reference. LS—landslides associated with anticline growth. Circular features around canyon 3, and anticlines V, V1a, and V1b are shale pipes and associated mud volcanoes. Locations of seismic lines in Figure 5 are labeled a-f at the top of the figure. See Figure 2 for location.
Anticline VI displays relatively large amplitude and sub-divides the minibasin. Anticline VIII displays relatively low amplitude (saddle region between two linked anticlines), and this is a region where a canyon system cuts across the fold. The separated sub-basins A1 and B lie at very pronounced different levels, that are not seen further to the west. The way the sub-basins are offset and tilted resembles a normal fault bounded tilted fault block setting. The section above horizon D in sub-basin A1 is expanded considerably with respect to sub-basin B. This is not the case further west.

Sediment pathway (4, Figs. 2 and 4) across anticline VI in this part of the basin.

Anticline VI imposes a small barrier to sedimentation in the middle of the piggyback basin.

Mini basin A2 is a broad depocenter little affected by anticlines VI and VII, passing eastwards the mini basin becomes sub-divided by anticline VI into depocenters A1 and B. At area 17 the seafloor is irregular and bounded by cliffs up to 20m high. Fan B is built from prograding debris flows 1, 2, 3 and 4.

Near sediment entry point E and saddle between linked anticlines VI and V II.

Area 16 is a region of creep on the fringe of a major debris flow to the east, the breakaway area is seen at location 17 section d. The area is breaking up into curvi-linear ridges and sliding WSW, down plunge and down slope, parallel to anticline VIII. Debris flows 3 and 4 have amalgamated in this section.

Anticlines X and VII subdivide the mini-basin into three sub-basins. Transparent units become thicker. In places a strong reflection shows the inferred debris flows of the transparent unit are composed of several stacked flows. To the SW all these internal divisions of the transparent unit disappear, probably due to post-depositional re-mobilization of the units.

Fan A
Hummocky folds above thick chaotic unit

Figure 5. Examples of three-dimensional data dip lines across the piggyback basin. See Figure 4 for location. The piggyback basin is subdivided by anticline VI into subbasins A and B. Subbasin A is divided into the northeastern area (A1) and southwestern basin (A2). IV, V, VI, and VIII are labels for anticlines. In D, numbers 1–4 denote mappable units within fan B.
Figure 6. Oblique three-dimensional views of the time-depth structure maps on seismic horizons: A = water bottom, B = horizon A, C = horizon B, D = horizon C, and E = horizon D. Locations 2, 3, 4, 8, and 15 are canyons cutting across anticlines; 5 is fan A; 12 is fan B; 1, 9, and 13 are channels within the piggyback-basin areas; 4, 7, and 15 are curvilinear large-scale hummocky topography developed on slopes with high sediment transport areas; 10 and 11 are areas of local channels coming off anticline V; 16 is an area within the slumped and remobilized debris flow; 17 is cliff separating the margins of a giant debris flow and/or landslide complex to the west and the smoother less disturbed sediments to the east; 18 is a current high region of piggyback basin. See Figure 5 for locations of horizons on seismic data and Figures 2 and 3 for location maps.
amplitude of the auto-picked horizon and (2) the root mean square (RMS) of anomaly values for a 10 ms window of data sampled above or below the picked horizon (the grid infilled by auto-picking) using Landmark’s StratAmp software. All amplitude maps shown are RMS for a 10 ms window above the picked horizon. However, results were broadly similar for all methods. Changes in rate of curvature of mapped surfaces are used to detect subtle structural and stratigraphic signatures of comparatively minor features such as channels, scarps, craters, and small faults. These derivative images of the dip or strike characteristics of time-structure maps are known as edge, difference, and azimuth maps. It was found that difference and edge maps gave the best images, and they are the ones presented in this paper. For details of the theory and

Figure 7. Isochron maps (i.e., interval thickness maps in time) derived from time-structure maps of the mapped seismic horizons. (A) Horizons A to water bottom. (B) Horizons B to A. (C) Horizons C to B. (D) Horizons D to C. (E) Horizons E to D. Fan A = A, Fan B = B. Location 1 indicates saddle between anticlines VI and VII; 2, 3, 4, 8, and 15 are canyons cutting across anticlines; 5 is fan A; 12 is fan B; 9 and 13 are channels within the piggyback-basin areas; 10 and 11 are thick areas of fan B; 4, 7, and 15 are curvilinear large-scale hummocky topography developed on slopes with high sediment transport areas; 17 is cliff separating the margins of a giant debris flow and/or landslide complex to the west (16) and the smoother, less disturbed sediments to the east.
Figure 8. Difference maps derived from time-structure maps of the seismic horizons. (A) Horizon A shows blocky character at the top of fan B, and hummocky folds associated with fan A. (B) Horizon B shows furrows at the base of fan B and hummocky folds affecting the eastern part of the basin (both linear and arcuate). (C) Horizon C shows prominent hummocky folds and fan-shaped bodies. Note dewatering pockmarks at the northern edge of the basin. Locations for seismic lines that illustrate the hummocky fold geometry are given in Figures 11 and 12. On right, enlargements i and ii are two examples of smaller chaotic units with furrowed bases. Locations are given in A. Lines a–d show locations of seismic lines in Figure 11.
Elongate fan geometry in transport direction

10 km

Villa

VI

VII

X
Figure 9. Root mean square amplitude maps for a 10 ms window above the mapped seismic horizon. (A) Horizon A. The amplitude map shows many characteristics similar to the water-bottom amplitude map (see Fig. 13). Mixtures of axial and transverse flow directions are present, and restricted channels traversing anticlines expand to broader flows in less restricted areas. (B) Horizon B follows the base of fan B, and shows the furrows at the base of the fan expanding out of canyon 8 and curving around to a general northwestward transport direction. Hummocky strata-bound folds are between 4 and 13. (C) Horizon C amplitude pattern predominantly shows hummocky folds around developing fans. (D) Horizon D; a dark gray pattern indicating unit 1 (see Figs. 15 and 16) was fed from a transverse canyon crossing anticline VI, and turned to a northeast direction. (E) Horizon E. It is difficult to see any significant sedimentary patterns in the amplitude map. IV to X are numbers assigned to different anticlines for reference. Numbers refer to seafloor features shown in Figure 4. Locations 2, 3, 4, 8, and 15 are canyons cutting across anticlines; 5 is fan A; 12 is fan B; 1, 9, and 13 are channels within the piggyback-basin areas; 4, 7, and 15 are curvilinear large-scale hummocky topography developed on slopes with high sediment transport areas; 10 and 11 are areas of local channels coming off anticline V; 6 and 16 are areas within the slumped and remobilized debris flow; 17 is cliff separating the margins of a giant debris flow and/or landslide complex to the west and the smoother, less disturbed sediments to the east; 14 and 18 are current high region of piggyback basin.
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structural configuration of the piggyback basin

The piggyback basin investigated in this study is not a simple synformal basin, but instead is a basin bound by two long continuous anticlinal trends (V–IV and VIII) and internally subdivided by three anticlines (VI, VII, and X; Figs. 2 and 4). In the eastern half of the piggyback basin anticline VI separates the basin into two. The eastern part of the fold VI is high; the forelimb rises ~350 m above the piggybackbasin floor and the backlimb rises ~150 m above the piggyback-basin floor (Fig. 5A). Thus the fold forms a barrier to sediment transport across the basin. Fold amplitude abruptly decreases to the southwest (between locations 4 and 13; Figs. 2 and 4), and only forms a partial barrier to sediment transport. In Figure 5C the anticline forms a smaller cliff ~75 m high, with a narrow backlimb dipping southeast. Figure 5B shows the area around location 4 (Fig. 4) where the canyon system cuts across anticline VII, indicating no relief at the seafloor associated with the fold. As fold amplitude increases, terracing of adjacent basins and the dip of the fold backlimb results in the basin geometry resembling a large normal fault offsetting two basins: e.g., in Figure 5, from lines d to a, the piggyback basin A1 is increasingly offset downward with respect to piggyback basin B, and the A1 basin fill also expands in thickness toward the anticline. Southwest of location 13 anticlines VI and VII plunge toward each other to form a low saddle region (Fig. 6), where the piggyback basin is effectively undivided post-horizon D.

The 3D views of time-structure maps also give an impression as to how the basin has filled and anticline geometries been modified by erosion with time. Horizon D (Fig. 6E) shows a smoothly folded surface except for anticline V, which is deeply dissected in places, indicating that surface erosional features have penetrated deeper than horizon D. It is apparent that the early fold geometry developed a deep synclinal depocenter (A1) between anticline VII and VIII, while the depocenter between anticlines V and VI–VII was narrower and shallower. By the time of horizon B, the two synclines had been infilled considerably and the plunge direction of depocenter A1 reversed from the earlier northeast direction to a southwest direction. The present-day water-bottom map shows that the older synformal geometry of depocenter B has largely been eliminated and now is a region of northwestward dip dissected by channels.

ages of the section investigated

There is no well control, so correlation of lithology to seismic character cannot be undertaken. Shallow cores of the seafloor indicate that the section, at least today, is very mud prone with few sand samples recovered. Ingram et al. (2004) reported at least seven episodes of turbidite fan deposition (associated with sandstone hydrocarbon reservoirs) from the neighboring area of Sabah that affected the northwestern Borneo margin and that range in age from middle Miocene to early Pliocene. Some approximate age dating can be made based on the seismic character of the seismic section shown in Ingram et al. (2004) compared with adjacent seismic data offshore Brunei, and depth of section in the synclinal areas. The dating can also be confirmed by correlating horizons with wells high on the slope, offshore Brunei (Sandal, 1996). The youngest fan discussed by Ingram et al. (2004) (Lingan fan, 5.6–4.1 Ma) is below the horizons defining the piggyback basin fill discussed in this paper. Time-averaged sedimentation rates for a 9 m.y. time period using data in Ingram et al. (2004) yielded average sedimentation rates of 0.28 mm yr⁻¹ for the center of a syncline, suggesting that the depocenters of sequences investigated here (the upper 400–500 m of section) could be ~1.8 m.y. old. It is clear that applying time-average sedimentation rates to sequences composed of thick rapidly deposited bodies, that shift location with time, interbedded with thin units representing long-term background sedimentation, is not ideal, but at least gives an idea of the time span of the units discussed in this paper. Thus each of the five isochron units (Fig. 7) probably represents deposition that occurred over hundreds of thousands of years.

seismic reflection character

The seismic character of reflection packages in the deep-water data is commonly distinctive and the 3D geometry of the bodies can be mapped. Although lithology cannot be determined with confidence, the geometries of the different components of the system can be described in considerable detail. The reflection packages can be divided into two basic types (Figs. 5 and 10): (1) long continuous reflections of semibasinwide extent that are the main reflections used to generate regional maps, and (2) areas of discontinuous, low-amplitude reflections that appear as chaotic or transparent units on the seismic sections. The characteristics of these two types of reflection package are further subdivided and described in detail in the following.

Long continuous reflections can form stacked sets of subparallel reflections, particularly deeper in the section (Fig. 10). However, often the reflections are more complex than simple subparallel sets; variations include the following.

1. Hummocky to wavy internal geometries that are not associated with erosion of the substratum (Figs. 11 and 12). The synformal base of the hummocks forms either a weld-like geometry above a single thin underlying low-amplitude unit, or hummocks overlie a thick underlying low-amplitude unit (Figs. 5, 11, and 12). In both cases the underlying unit is not horizontal but inclined, and the folds verge down-dip. The underlying unit is always a transparent low-amplitude, commonly chaotic package. The geometry is of a strata-bound package of folds. Generally the fold packages involve a section that on seismic data is one to three peaks and troughs thick (15–60 ms, i.e., ~15–55 m). The folds typically have wavelengths of several hundred meters, but range to 2 km, and have amplitudes of ~15–55 m. Unfolded reflections cap the folded package (Fig. 11). This geometry indicates that the folding developed after only small amounts of burial (perhaps 10–30 m). In map view between anticlines V and VI there are north-south–trending ridges that give a rippled appearance to the data; this rippled appearance can also be seen on isochron map c (Fig. 7). Hummocky folds are very pronounced features of the isochron pattern, and can also be seen on the amplitude and edge maps of the mapped horizons D and C (Figs. 8 and 9). The fold form in map view is arcuate around the fan located in area 5, and linear along the west-plunging syncline between anticlines V and VI. These patterns indicate that the folds are a response to gravity and slope direction; they also developed shortly after deposition. The strata-bound folds are interpreted to represent a shallow loading phenomena, where the transparent unit is probably overpressured, or contains a high percentage of fluid (in the case of mud, fluid content could be as high as 60%–70%), and so has flowed in response to differential loading. Hence the hummocky geometries appear to be large-scale load structures linked with gravity-driven slope instability. Ercilla et al. (2002a, 2002b) described wave geometries of similar dimensions associated with turbidite systems, and noted their relationship to slope dip. These waves were described as large bedforms responding to turbidite currents. Ercilla et al. (2002a, 2002b) also recognized that similar geometries could be
Figure 10. Strike lines across the basin. See Figure 4 for location. Location 17 is seafloor cliff (see Fig. 4). Numbers 1–4 indicate the units (debris flows) that can be mapped within fan B. Numbers i, ii, and iii are continuous, strongly reflective packages that separate debris flows.
produced by other mechanisms including creep folds. The constant thickness of the folded high-amplitude layer and the association with pinch and swell structures in the underlying transparent unit in the examples described here preclude the folds as originating as current-related bedforms. Probably these folds are associated with shallow dewatering and bear some similarity to giant dewatering features from the Niger Delta described by Davies (2003). The Niger Delta features have hummocky shapes, are 30–50 m in amplitude, and are 200–1500 m wide. The more linear geometry of the hummocks described here compared with more typical circular-oval dewatering features is attributed to the gravitational instability and setting on a fan with a low-angle radial dip pattern, compared with the channel setting described by Davies (2003).

2. Hummocky to wavy internal geometries where there is erosion of the underlying units (Figs. 10 and 11). The synformal bases of the wavy units can lie on any unit (not a single unit such as 1 above). The underlying units can be of any type (high amplitude and low amplitude-transparent). The geometry tends not to be a simple strata-bound fold package, but is instead a complex zone of braided or anastamosing reflection packages. This type of package is interpreted to represent a region that commonly underwent sediment bypass and erosion. A modern example is the backlimb slope of anticline VIa, which on seismic reflection data shows a wavy erosional character (Fig. 11); the edge maps of the seafloor show slightly sinuous channels or scour extending down the backlimb slope (Fig. 4). These channels are adjacent to canyon 3 and probably developed by flows exiting the canyon, running up the backlimb, losing energy, then reversing and flowing back down the slope.

The transparent packages display a range of characteristics. The following are the main types.

1. Units with a top characterized by a rugged, irregular blocky character and by disrupted internal reflections. These internal reflections can be seen to range from straight undisturbed units that separate stacked transparent units (Figs. 10 and 12) through folded and imbricated geometries (Fig. 10) to short coherent sections separated by chaotic segments (Fig. 10). The unit that best displays this type of character covers a very extensive region of the seafloor today in the western half of the offshore Brunei deepwater area (Fig. 2). The rugged, blocky nature

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**Figure 11.** Details of hummocky, strata-bound folds; see Figure 8C for location.
of the seafloor is very apparent in the amplitude and edge maps of the water-bottom reflection (Figs. 2, 4, and 13). Sometimes a similar geometry can be identified from mapped subsurface horizons (Figs. 8A and 9A). McGilvery and Cook (2003) interpreted the rugged seafloor topography with associated transparent units as debris flows. The debris flows appear to have deformed both during emplacement and postemplacement. The later deformation resulted in amalgamation of stacked debris flows. It is noticeable that where strong reflections separating debris flows abruptly terminate, there is either a marked decrease in thickness of the amalgamated unit with respect to the separated units (Fig. 10), or in the case of the youngest debris flows, there is a cliff developed at the seafloor that in map view separates ridged topography to the southwest from a smooth seafloor to the northeast (Fig. 4, location 17). Seismic lines across the cliff (Figs. 10A, 10B, location 17) show that it is not related to any fold or fault at depth. The cliff is a shallow feature related to the shallowest debris flow. The stacked multiple debris flows seen in Figure 10B indicate that amalgamation of flows is associated with compaction and volume loss, which in turn points to a loss of fluids. Hence at least in part the postemplacement motion of the debris flows is related to overpressured fluids and consequent dewatering. Mechanisms that trigger postemplacement motion include rapid loading by the arrival of younger debris flows and fast and slow creep downslope as growing folds steepen bedding dips and consequently cause gravitational instability. Particularly at the edges of large debris flows, there is breakup of once coherent section by downslope creep or landslides that results in short transport distance slides (as seen southwest of location 17, Fig. 4).

2. Transparent units with strike sections that display a fairly flat top, and an irregular concave-upward base (Fig. 10). The geometry of these transparent units as defined by isochron, amplitude, and difference maps (Figs. 7, 8, and 9) can range from a fan shape to smaller bodies that fill existing bathymetry and consequently are highly elongate in the transport direction (Fig. 14). In the study area the basal section of fan B contains at least four stacked transparent units separated by thin internal continuous reflections (Fig. 10). In a dip direction

Figure 12. Dip line illustrating the seismic character of the piggyback-basin fill and different stages of basin development. TWTT—two-way traveltime. Stage 1—flow ponding of predominantly axially transported flows. Stage 2—flow ponding of flows transported transverse to folds. Stage 3—basin starvation due to temporary filling of transverse channels to the basin across anticline VI, and a shift of sedimentation to the western half of the basin. Stage 4—mixed areas of deposition and erosion (mixed flow stripping and flow bypass; terminology of Sinclair and Tomasso, 2002). A–E are the five local horizons mapped around the piggyback basin. See Figure 8C for location.
these internal markers show progradational geometries, dipping to the northwest, as successive transparent units built out to the northwest (Fig. 5D). In particular the lowest unit (1, Fig. 5D) is not of great extent in a dip direction, because it filled in the most pronounced structural topography. Bases of the transparent units show erosional troughs that are as much as several hundred meters wide and meters to a few tens of meters deep (Fig. 10). On difference, isochron, edge, and time-structure maps these erosional troughs or furrows range from straight to curvilinear (not meandering) (Figs. 7, 8, and 9) and appear to define flow directions at the base of the unit. These furrows occur at the base of every unit that shows downcutting geometries.

The furrows are influenced by the slope direction; they flare out from constricted canyons (Fig. 14) that traverse anticlines and show the influence of topography by curving into the synclinal axis (Figs. 8B and 9B). The absence of a meandering channel pattern suggests that the furrows are erosional features developed during a single phase of transport at the base of a flow.

Figure 13. Water-bottom root mean square amplitude map (A) and time-depth map (B) of the study area. See Figure 2 for regional location. Locations 2, 3, 4, 8, and 15 are canyons cutting across anticlines; 5 is fan A; 12 is fan B; 1, 9, and 13 are channels within the piggyback-basin areas; 4, 7, and 15 are curvilinear large-scale hummocky topography developed on slopes with high sediment transport areas; 10 and 11 are areas of local channels coming off anticline V; 6 and 16 are areas within the slumped and remobilized debris flow; 17 is cliff separating the margins of a giant debris flow and/or landslide complex to the west and the smoother, less disturbed sediments to the east; 18 is current high region of piggyback basin. B is mud volcano on anticline VIb.
Figure 14. Root mean square amplitude map of base of fan B illustrating furrow geometry expanding from canyon 8.
rather than an established channel system. Gee et al. (2005) described similar features related to a submarine landslide offshore Angola. Blocks carried along at the base of the flow are thought to be responsible for many of the furrows (Gee et al., 2005). Experimental subaqueous debris flows also showed reworking of the substratum to the debris flow despite exhibiting hydroplaning at the head of the flow (Toniolo et al., 2004). These units may possibly be a turbidite sandstone complex with some channels. However, the amplitude and difference maps of the top of the transparent units show a very irregular blocky character (Figs. 8A and 9A), similar to the seafloor geometry of the giant debris flow unit (see package 1 above). Consequently the interpretation preferred here is that the stacked transparent units represent debris flows where flow in a canyon traversing an anticline expands laterally upon reaching the piggyback-basin floor. There are many examples of individual transparent units with the overall geometries discussed above, with furrows at the base that are not stacked. Instead they appear to be infilling depressions between the two major fans in the piggyback basin. This indicates that the fans had built sufficient seafloor topography that debris flows and/or turbidites were deflected around the high areas to infill the intervening lows.

3. Fan A is the only example of a transparent unit that is significantly different in characteristics from packages 1 and 2 above, both of which appear to be variants on large and intermediate size debris flow geometry. The key differences are (1) overall geometry; fan A has a flat base and convex upward top (Figs. 12 and 15); (2) there are no furrows or erosional features at the base of the fan (Fig. 16); and (3) from proximal to distal locations the fan progresses from predominantly transparent and/or chaotic reflections with occasional gull-wing shapes, to more continuous and higher amplitude reflections. Consequently, for fan A the geometries are more suggestive of turbidite fan deposits than fan B. The chaotic fill is interpreted to correspond with channelized and overbank deposits, while the more continuous reflections are lobes.

EVOLUTION OF SEISMICALLY DEFINED UNITS IN THE PIGGYBACK-BASIN

Much of the description of the infill of the piggyback basins is based on the vertical thickness variations in time of units shown by isochron maps (Fig. 7). Generally the maximum thickness variations across the isochron maps for individual units are ~200–240 ms. Interval velocities in the water-rich, shallow sediments are slow, between 1700 m/s and 2000 m/s;
consequently, the largest changes in thickness discussed here are on the order of 100 m. The smaller scale features picked out by abrupt changes to the next color band mark thickness contrasts of ~10 m. Hence the resolution of features shown in Figure 7 would approximate the largest features that could be determined from extensive, well-exposed outcrops.

Isochron map e (Fig. 7E) shows the early stage of the piggyback basin fill; the isochron pattern is fairly unremarkable. Area 1, the area where the plunging noses of anticlines VI and VII meet, is a pronounced high region. Two main synclinal depocenters are present, between anticlines VIII and VI and between VII and X. The RMS amplitude maps on reflections e and d also show no really distinctive sedimentary geometries (Figs. 9D, 9E). The impression given by the data is that there was relatively quiet aggradational infilling of the structural lows, and major mass flow deposition was either blocked or just the distal portions of mass flow deposits entered the basin.

Isochron map d shows a considerable change from isochron map e (Fig. 7). Note that in the western area of the isochron map d (location 6, Fig. 7D) the predominantly yellow color is a chaotic area on seismic (interpreted to be a debris flow) and unmappable. For the syncline between anticline V and anticlines VII there is simple expansion of the section toward the synclinal axis. Conversely, the area of greatest sediment thickness (location 5, Fig. 7D) has a shape that is narrower in a northeast-southwest direction, and longer in a northwest-southeast direction than the syncline in Figure 7E. This change in shape is not structurally controlled, but marks the deposition of sediment in a pronounced fan-like geometry. The seismic characteristics of fan A on seismic lines (Figs. 5A, 5B, and 10A) is described above (transparent reflections type 3).

In the vicinity of area 4 (Fig. 7D), there is a feeder canyon to fan A; this canyon is linked with canyon 3, which traverses anticline V. The location of canyon 4 occurs at a point where anticline VI has much lower relief and lower amplitude passing southwestward (Figs. 5 and 10B), a feature that has persisted at the seafloor today (Figs. 4 and 13). Feeder canyon 2 is located at a low point between anticlines IV and V, while canyon 3 is located where anticline V was weakened by the presence of a large mud pipe intrusive complex (Fig. 4). In area 7 a smaller fan is present and appears to have developed by sediment being transported around the plunging nose of anticline VI (Fig. 7D). Hence there is strong structural control on the entry points for the fan feeder systems. The locations of fans on the isochron maps are highlighted by the arcuate hummocky pattern indicative of loading water-rich fans and the resulting movement downslope (see seismic reflection characteristics above).

Isochron map c corresponds with a generally thin unit characterized on seismic reflection lines by predominantly high amplitude, high continuity reflections (Figs. 5 and 7C). The unit drapes and infills the fans, and hummocky folds of the underlying sequence d, and is also eroded by the transparent units that compose fan B (Figs. 7C, 10B, and 10C). Isochron c shows a considerable reorganization in depositional pattern. The syncline between anticlines V and VI shows only thin sediments. In area 5 there is no longer a thick fan; instead, deposition shifted to the northwest and southwest (Fig. 7C). The shift in deposition is due to the mounted seafloor geometry of fan A that forced younger turbidites and debris flows to be deposited around the fan, not on top of it (see Figs. 7C and 10). The feeder canyons 2 and 4 do not appear to have transported much sediment into the system during isochron c, while canyon 3 kept operating. Probably during isochron c time canyon 8 was present, but what is shown on the isochron map (Fig. 7C) is the effect of fan B (formed during isochron b time) eroding into sequence c.

Isochron c is characterized by relatively quiet background sedimentation, while isochron b shows the development of a new fan system (location B, Fig. 7B). The fan system represents a shift in feeder canyon location and breaching of anticline V at location 8 (Fig. 4). The geometry of erosional curvilinear furrows or channels at the base of the fan complex can be seen on both amplitude and edge maps of horizon B (Figs. 8B, 9B, and 14), and isochron map c (Fig. 7C; the same furrows and channels also imposed a scratchy, fine linear pattern on isochron b). All these maps show erosional furrows expand from feeder canyon 8 and turn both northeast-southwest and northwest-southeast to

![Difference map, base fan A](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/4/6/939/3336925/s1553-040X-4-6-939.pdf)

![Difference map, base unit 1](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/4/6/939/3336925/s1553-040X-4-6-939.pdf)

Figure 16. Difference maps for the base of fan A, and the underlying unit 1 (see Fig. 15 for seismic cross section). The base of fan A is smooth, while curved furrows characterize the base of unit 1. Pma is pockmark.

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extend for a short distance subparallel to the forelimb of anticline V. These channels then curve around to a northwest-southeast direction, giving a tulip-like geometry to the basal erosional features. As these furrows approach the southeast-dipping topography of the backlimb to anticline VIII, they curve sharply to the west and southwest, clearly following the extant bathymetry. Fan B is broken into three separate depositional thicknesses (Fig. 7B). The amplitude and edge maps for horizon A (Figs. 8A, 9A), show that the top of fan complex B has a very blocky character indicative of debris flow deposits. As discussed in the section on seismic reflection characteristics, transparent reflections type 2, the units composing fan B appear to be predominantly debris flows, and have a different seismic character from fan A. In particular the presence of the erosional furrows in fan B and their absence in fan A suggests a different style of emplacement. To the east of fan B between locations 3 and 13 there is a smaller depositional system fed from canyon 3 that is also associated with basal furrows (Fig. 8).

Isochron map a (Fig. 7A), is the interval from seismic horizon A to the seafloor, and represents another considerable variation in depositional geometry. Fan B built a broad mounded topography largely from stacked debris flows. This topography has forced channel systems to flow around the margins of the fan, as seen in Figures 8A and 13. Figure 17 is a perspective diagram with the horizon A RMS amplitude map and four seismic lines. The coincidence of the fan B geometries with the mounded profiles on seismic data and the thick accumulations of the seismically transparent units are evident. The feeder canyon across the anticline at location 8 has been filled by subhorizontal sediment, unlike the erosional canyons farther to the northeast along the anticline (Fig. 16). Isochron a (Fig. 7A) also shows that fan B, which was so active during isochron b, became an area of thin section and even some erosion during isochron a. The depositional pattern shows a return to maximum fill in the northeastern half of the area. The isochron, amplitude, and edge maps for horizon A (Figs. 7A, 8A, 9A) show channel systems flowing from canyon 3 around the plunging nose of anticline VI (location 13) and into the syncline between anticlines VI and VIII. In addition, flows also entered the syncline farther northeast through canyon 4; both systems found the low point in anticline VIII (which is the linkage point between two plunging anticlines), giving rise to the two canyons at location 15 (Fig. 4).

The study area just includes the corner of the massive landslide that dominates the surface sedimentology of the deep-water Brunei area (Fig. 2; Gee et al., 2007). This corner area demonstrates some of the postdepositional processes that affect the debris flows. In Figure 10 it can be seen that debris flows separated by high-amplitude, high-continuity reflections laterally amalgamate into a single thick transparent unit. In particular in Figure 10B three reflection events (i, ii, and iii) separate four landslides and/or debris flows; to the southwest these flows amalgamate into one unit. The amalgamation of the debris flows is marked by a pronounced drop in the seafloor bathymetry, indicating that amalgamation is accompanied by volume loss, most likely related to dewatering. Another feature of the debris flows is a northeast-southwest-trending cliff (location 17) seen in the water-bottom edge (Fig. 4), amplitude, and bathymetry (Fig. 13) maps. This cliff marks the abrupt termination of high-amplitude, high-continuity reflections to the east, and the transparent to chaotic reflection signature of a debris flow to the west. West of the cliff the water-bottom edge map shows a triangular shaped area of troughs and ridges within the debris flow (area 16; Figs. 4 and 13). The geometry of the structures fits with a locally mobilized unit that has begun to slump and break up. The ridges and troughs remain strongly linear, and probably are controlled by listric normal faults accommodating downslope movement. The transport distances are probably short (tens to hundreds of meters), and the cliff is the region of breakaway. Hence the region is one where locally transported units are becoming chaotic and incorporated into the

Figure 17. Perspective view of amplitude map for horizon A (Fig. 9A) with seismic lines illustrating the way cross-section views of the fan geometries and canyons relate to the amplitude map. Locations 3, 8, and 13 are channels and canyons; V and VI are anticline locations (see Fig. 4).
DISCUSSION

Sinclair and Tomaso (2002) used outcrop-derived data from the Tertiary Alpine basins to characterize the infill of confined turbidite basins by four stages: (1) flow ponding, where incoming flows are completely trapped, and thick sheet-like sand-mud couplets are deposited; (2) flow stripping, where the more dilute portions of the flow escape beyond the confining topography, thus increasing the sand/mud ratio within the basin; (3) flow bypass, where the basin is filled, consequently flows traverse the basin, and the basin is either incised or abandoned; and (4) blanketing of the basin and surrounding topography, where the basin topography is completely lost and the area is covered, usually by meandering channel-levee complexes. Similarly for a minibasin in the Gulf of Mexico, Booth et al. (2003) identified a sequence of early confinement by topography, then diminished relief, with fill and spill cycles, and finally incision and bypass of basins further down the slope. However, such stages are not necessarily a simple progression and may instead show cyclical stacking (Sinclair and Tomasso, 2002).

The piggyback basin studied shows elements of the cycles described above, particularly early flow ponding, and later communication to basins further downslope suggesting mixed flow stripping and flow bypass (Fig. 12); the basin has not progressed as far as blanketing and infill. Figure 12, stage 1, shows flow ponding of predominantly axially transported sediments. The transparent units below horizon E are of basinwide extent and have slightly erosive bases. Mostly continuous, subparallel, high-amplitude reflections lie between the transparent units. The lower part of the sequence marks a period of mostly axial basin transport (southwest to northeast) and relatively distal sedimentation with the section being fully ponded by anticlines VIII and VI. In the upper part of the sequence, transverse transport starts to dominate (Figs. 12 and 17).

Stage 2 is representative of flow ponding of sediments transported transversely to folds. Instead of flat-topped transparent units, the mounded fan geometry created surface dips, and hummocky folds developed due to gravity instability and dewatering. Stage 3 is one of basin starvation due to temporary filling of transverse channels to the basin across anticline VI, and a shift of sedimentation to the western half of the basin. Stage 4 shows mixed wavy, high-amplitude reflections (local unconformities and channels), with some erosive-based chaotic units. Mixed areas of deposition and erosion are present, i.e., mixed flow stripping and flow bypass in the terminology of Sinclair and Tomasso (2002).

The basin size relative to flow size is large enough that individual flows do not fill the entire basin and there are multiple entry points for flows to enter the basin. Consequently the timing and style of the cycles will vary from area to area. Other than eustatic effects, the types of stages identified by Booth et al. (2003) and Sinclair and Tomaso (2002) may vary laterally and through time within a basin due to (1) changing rates of folding, and accommodation space creation laterally or with time, (2) the location of sediment source areas changing with time, and (3) the size of the flows entering the basin. Hence when applied to larger piggyback or minibasins, the classification of Sinclair and Tomasso (2002) is perhaps better thought of as processes rather than stages. For example, in the study area flow ponding is clearly occurring through pathways 2–4–15 and 3–13–15 (Figs. 4 and 13), yet the basin has remaining topography, and at times is capable of completely ponding flows in some places (e.g., fan B area). Flow stripping will operate in other places (such as the location 18 area), but with part of the flow exiting the basin via location 15 (Fig. 4). The giant landslide complex that dominates the western half of offshore Brunei (Fig. 2) illustrates the great range in flow sizes affecting the piggyback basins, and that some gravity flows are large enough to undergo only minor influence by the structural topography. In addition, repeated large flows may have more rapidly removed the effects of structural topography in some areas compared with others.

The location of the giant landslide corresponds with the entry point of the Baram delta onto the shelf. The landslide indicates that at times in the western half of offshore Brunei large-scale sedimentary processes have smoothed out any effects of folding. For the eastern half of offshore Brunei the picture is different. There is no single major fluvial system entering the margin, and the transport directions for smaller flows down the continental slope are strongly controlled by structural location. In particular the linkage points of anticline tips that plunge toward each other (saddle areas), mud pipe complexes, and en echelon anticline transfer zones are the locations for feeder canyons in the study area (Fig. 18). These entry points can be at least temporarily plugged or reduced in efficiency by the growth of fans that back fill into the canyon region. Through time basins fill up both as a consequence of fold growth and accommodation space development, and by switching of sediment supply direction related to canyon plugging. For example, backfill geometries and isochron data around canyon 8 (Fig. 7B) indicate that flow through the canyon was reduced or inhibited by deposition of fan B, which built up back into the canyon. Consequently, the majority of subsequent flows entered the minibasin farther to the northeast, in particular passing through canyon 13 (Fig. 13).

More regional effects also influence entry points to the piggyback basin. During isochron d there is little indication of lateral transport of gravity flows across the anticlines. Any flows were probably axial (Fig. 18E). During isochron d the overlapping transfer zone between anticlines 4 and 5 was the main entry point (2, Fig. 18D). More regional mapping than the data presented here shows that the transport directions in the eastern deep-water area prior to isochron d tended to be parallel to the folds (i.e., northeast-southwest and southwest-northeast; with reference to Fig. 2 from area E, across C to canyon 2). Consequently the northeast-southwest–trending transfer zone between the anticlines was well oriented to funnel flows into the piggyback basin. This system, and flows from the northeast (Sabah), fed fan A (Fig. 18D). However, as anticlines updp of the piggyback basin started to be breached, flows began to arrive at anticline V transported in a southeast to northwest direction (Fig. 2, 18C). This placed the northeast-southwest transfer zone at a less than ideal orientation. Probably the initial flows from areas B and D (Fig. 2) hit anticline V adjacent to canyon 3 and were forced to turn into canyon 2, but eventually they created a straighter path (Figs. 18A, 18B, and 18C). This straighter path was facilitated by the instability and increased erosion associated with shale pipe...
Figure 18. Transparent overlay of isochron maps (Fig. 8) with edge maps providing a summary of the way sediment transport paths and fan locations have changed with time. (A) Interval horizon A to water bottom, edge map for horizon A. (B) Interval horizons B to A, edge map for horizon B. (C) Interval horizon C to B, edge map for horizon C. (D) Interval horizon D to C, edge map for horizon D. (E) Interval horizon E to D, edge map for horizon E. i, ii and iii show schematic summaries of the types of interaction between flows and anticlines seen in the actual data (A–E). Locations 2, 3, 4, 8, and 15 are canyons cutting across anticlines; 5 is fan A; 12 is fan B; 1, 9, and 13 are channels within the piggyback-basin areas; 4, 7, and 15 are curvilinear large-scale hummocky topography developed on slopes with high sediment transport areas; 10 and 11 are areas of local channels coming off anticline V; 6 and 16 are areas within the slumped and remobilized debris flow; 17 is cliff separating the margins of a giant debris flow and/or landslide complex to the west and the smoother, less-disturbed sediments to the east; 14 and 18 are current high region of piggyback basin. IV to X are numbers assigned to different anticlines for reference.
emplacement at the crest of anticline V (location 3, Fig. 3). As an analogue for the erosion process, anticline Vla shows dip-parallel erosional channels on the backlimb (Fig. 4), which suggests erosion by flows running up and collapsing back down the backlimb. It is this kind of erosion that probably ate away at the anticline topography in the vicinity of location 3 once flows from upslope broke through and began to arrive perpendicular to the anticline. At location 8 there is an en echelon transfer zone between two plunging anticlines (Fig. 2); this structural low in the anticline would appear to be an ideal entry point for gravity flows into the piggyback basin, yet it was only activated late during isochron b, and resulted in the development of fan B. The failure to exploit the seemingly ideal structural location earlier strongly suggests that (1) the flow direction relative to structural trend is important in terms of erosive power (i.e., the southwest to northeast flows exploited canyon 2 in preference to canyon 8), and (2) the northwest-southeast feeder system following path D-3 (Fig. 2) was established earlier than feeder system A-C-8 (Fig. 2). Two types of fan have been built in the piggyback basin. Fan A is a flat-based, mounded fan, with weak but in patches coherent, internal reflections. Unlike fan B, no distinct subdivision of fan A into separate flow events is possible. The base of the fan shows no furrow development. The characteristics indicate a fan composed predominantly of stacked subseismic resolution flows, probably turbidites that can be subdivided into lobes and channels, based on seismic character. Fan B is composed of four chaotic units separated by high-amplitude events that prograde basinward with time (Fig. 5C) and show pronounced furrowing at their bases. Each unit tends to have a broadly u-shaped base and flat top. However, stacking of units produces an overall mounded geometry to the fan. Possibly the depositional geometry of the fans is dictated by the nature of the transport pathway. Fan A is fed by a sinuous, indirect, and relatively long transport pathway, while fan B is associated with a fairly direct northwest-southeast transport direction from the upper slope, and displays a highly erosive base, with numerous furrows. It is presumably this difference in transport path and consequent energy of the flow upon reaching the piggyback basin that resulted in the different scales of deposit and the considerable erosive power of the fan B–type deposits, and the flat, monotonous base to fan A.

At the seafloor (Fig. 4) true channel systems in the synclinal areas seem to occur for short distances in laterally restricted areas. Beyond these areas flows appear to abruptly spread out into more sheet-like flows. On the piggyback-basin floor the best-developed channels are located in areas 9 (flowing around the margin of a high related to fan deposition) and 13 (flowing around the backlimb of anticline Vla). At location 15 canyons are restricted to the anticline, and are absent in the basins updip and downdip. These features indicate that flows at least in their lower reaches rapidly broaden in the flatter parts of the basin, and focus into channels and canyons only where forced to do so by surface topography. This broadening and narrowing of the flow can occur several times passing down the slope.

The sediments discussed in this paper are poorly lithified, and near the seafloor probably contain 60%–70% water. The rapid burial by turbidites and debris flows means that the water-rich sediments are highly unstable. A range of dewatering features is present at the scale of the seismic data, including large-scale pockmarks and collapse chimneys, and amalgamation of debris flows. After deposition the fans were affected by gravity and movement downslope, probably associated with dewatering. This has resulted in strata-bound hummocky folds, with hundreds of meters to ~2 km wavelength, and an amplitude as much as 50 m being developed on top of transparent units (probable debris flows). The poorly lithified nature of the sediment is also highly significant for the resistance of antilines to erosion. The growth of antilines creates significant gravitational instability, and the seafloor edge map (Fig. 4) shows numerous examples of local landslides from the crests of antilines, and minor extensional faulting. Despite the impressive height of some surface antilines that are hundreds of meters higher than the piggyback-basin seafloor, the weak lithologies composing the antilines also means that flows arriving perpendicular to the antilines are rapidly able to exploit weak points and carve canyons across growing antilines.

The horizons mapped show the progressive change from a fold-dominated influence of basin geometry and isochron thicknesses, to a mixed sedimentary and fold influence. As breaching of the antilines by fold-perpendicular channels and canyons progressed, so the influence of sedimentary process on basin architecture changed and became more pronounced. The filling in of the fold geometry and erosion of the antilinal crest resulted in the basins in the northwestern area, where they are divided by anticline VII (Fig. 5A), developing a geometry resembling that of a tilted normal fault block.

CONCLUSIONS

Interpretation of five horizons and the water-bottom reflection from 3D seismic data has provided detailed information about the evolution of ~500 m of synkinematic section that accumulated in a large, complex piggyback basin associated with fault propagation folds. Key characteristics of the flows that can be imaged from seismic data are as follows. (1) Repeated instances of trains of hummocky, strata-bound folds (hundreds of meters to 2 km wavelength, tens of meters amplitude) developing on slopes, above transparent units, particularly mimicking fan geometries. These are inferred to be gravity-driven folds enhanced by dewatering. (2) Repeated occurrence of long, curved furrows indicating erosion and flow transport direction at the base of inferred debris flows (chaotic units). (3) Two different fan geometries have been identified with internal reflection characteristics, suggesting that fan A is built from turbidites, while fan B is composed predominantly of debris flows. (4) Depending upon seafloor morphology, the flows abruptly spread out when unconfined, then when constrained by topography focus back into narrow channels or canyons, a flow entering the piggyback basin may have three areas of topographic constriction (anticlines V, VII, and VIII) and two areas of expansion (the synclinal depocenters).

Piggyback basin fill appears initially to be dominated by fold-parallel (axial) flow. Flows created by en echelon fold transfer zones are exploited as entry paths to basins downslope (the en echelon transfer zone between anticlines V and IV, location 2, Fig. 18). Later flows arrive transverse to the anticlines due to filling and spilling from upslope piggyback basins. The transverse gravity flows erode the antilines and exploit points of weakness to enter piggyback basins further downslope. Fold crests weakened by local landslides and emplacement of overpressured shale pipe complexes can ultimately become traversed by canyons (location 3 on anticline V, Fig. 18). The topographically low saddle region where two laterally propagating collateral antilines meet is another common sediment entry point for transverse flows (anticline V, location 8, Fig. 18).

The location of entry points across antilines is not just structurally controlled: deposition as flow wanes upon exiting anticline-traversing canyons can permanently or temporarily backfill the canyon system (e.g., anticline VI) and divert flows. Canyon blockage occurred at anticline VI, which forced flows farther west and created a new entry point at 8 and the formation of fan B (Figs. 18A, 18B).

The different stages of piggyback basin fill identified by Booth et al. (2003) and Sinclair and Tomasso (2002) are influenced by (1) changing rates of folding, and accommodation space creation with time or laterally, (2) the location of sediment source areas changing with time, and (3) the size of the flows entering the basin. Hence when applied to larger piggyback...
or minibasins, the different stages of Sinclair and Tomasso (2002) can occur laterally across a basin at the same time.

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