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## Deep water geomorphology of the mixed siliciclastic-carbonate system, Gulf of Papua

Jason M. Francis,<sup>1,2</sup> James J. Daniell,<sup>3</sup> André W. Droxler,<sup>1</sup> Gerald R. Dickens,<sup>1</sup> Samuel J. Bentley,<sup>4</sup> Larry C. Peterson,<sup>5</sup> Bradley N. Opdyke,<sup>6</sup> and Luc Beaufort<sup>7</sup>

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[1] The Gulf of Papua (GoP) has become a focal point for understanding the deposition and accumulation of siliciclastic and carbonate material along and across a low-latitude continental margin. Although studies have addressed submarine geomorphological features on the inner and middle shelves, as well as processes that may have led to their formation, the seafloor of adjacent slope regions remains poorly documented. This study presents and interprets results from approximately 13,000 line-km of multibeam bathymetry, 9500 line-km of 3.5 kHz seismic, and 122 sediment cores that were collected from the GoP shelf edge and slope, primarily on two cruises (PANASH and PECTEN). Bathymetric maps, in conjunction with the seismic profiles and cores, were used to make extensive observations, descriptions, and interpretations of seafloor geomorphology and begin to address several key issues regarding the delivery and accumulation of sediment. This study divided the GoP slope region into physiographic regions including intraslope basins: Ashmore Trough, southern Pandora Trough, northern Pandora Trough, Moresby Trough and intraslope plateaus/platforms: carbonate platforms and atolls and Eastern Plateau. Ashmore Trough contains a very linear northern margin capped by a drowned barrier reef system. This shelf edge is also defined by a broad promontory with channels extending from its apex, interpreted as a relict shelf-edge delta. Southern Pandora Trough is characterized by pervasive slope channels and slump scars extending down slope to a thick depocenter and an extensive mass-transport complex. In contrast, northern Pandora Trough has few visible slope channels. Seismic observations reveal a wedge of sediment extending down slope from northern Pandora Trough shelf edge and filling preexisting bathymetry. Large fold-and-thrust-belt ridges are also present on the seafloor in this region and may act to divert and/or catch sediment, depending on sediment transport direction. Moresby Trough contains a large axial submarine channel that extends almost the entire length of the intraslope basin. In addition, an extensive system of canyons lines the NE margin of Moresby Trough. Mass-transport deposits have been fed from the canyons and in one case deposited a large ( $\sim 2000 \text{ km}^2$ ) mass-transport complex. Fold-and-thrust-belt ridges also extend into Moresby Trough. Here they trend perpendicular to slope and catch gravity flow deposits on their updip side. GoP carbonate platforms/atolls all display very pronounced scalloped-margin morphology, which may indicate pervasive mass-wasting processes on carbonate margins. Northwest Eastern Plateau is dominantly carbonate and displays the characteristic scalloped margin morphology; however, most of the plateau is characterized by parallel seismic reflectors. These seismic observations in conjunction with core data indicate that accumulation on Eastern Plateau is primarily mixed pelagic and hemipelagic sediment. Observations and interpretations of the bathymetry have revealed the deep water GoP to contain very diverse geomorphology and suggest it is a dynamic system influenced by a variety of sediment transport processes, particularly mass wasting and other gravity flow processes.

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## 1. Introduction

[2] The Gulf of Papua (GoP) lies between northeast Australia and southern Papua New Guinea (Figure 1). The continental margins along this embayment represent the northern extent of the largest modern tropical mixed siliciclastic-carbonate system. A series of major rivers, notably the Fly, Kikori, and Purari, discharge some 200–400 megatonnes (Mt) per year of siliciclastic material onto the inner shelf [Harris *et al.*, 1993; Milliman, 1995]. Neritic organisms, which inhabit the northern Great Barrier Reef (GBR) and atolls on isolated carbonate platforms (Ashmore Reef, Boot Reef, Portlock Reef, and Eastern Fields Reef), produce and export abundant carbonate sediments [Francis *et al.*, 2006; Francis, 2007; Carson *et al.*, 2008; Jorry *et al.*, 2008]. Siliciclastic and carbonate material ultimately mix across the region [e.g., Brunskill *et al.*, 1995] and accumulate over geologic time, responding to and shaping a complex depositional system [Davies *et al.*, 1989; Pigram *et al.*, 1989; Symonds *et al.*, 1991; Sarg *et al.*, 1996; Tcherepanov *et al.*, 2008]. The MARGINS source-to-sink (S2S) Initiative for the GoP aims to develop an understanding of sediment transport and accumulation within this region [NSF MARGINS Office, 2004].

[3] Broadly defined, the GoP comprises a ~150,000 km<sup>2</sup> area south of Papua New Guinea (PNG), east of Torres Strait, north of Bligh Canyon, and west of Moresby Canyon (Figures 1 and 2). The seafloor of this region can be divided into ~40,000 km<sup>2</sup> of shelf between 0 and 70–125 m depth and ~110,000 km<sup>2</sup> of slope between 70–125 and 3500 m depth. The shelf is wide (~200 km) in the west and northwest but narrow (~10–30 km) in the northeast. For the purposes of this study, the shelf also includes shallow reefs and lagoons (atolls) on the isolated carbonate platforms. The “slope” comprises a large region between the shelf edge and two major submarine canyons: Moresby Canyon in the southeast and Bligh Canyon in the southwest. Lower portions of the slope lead to the deep (~3500–5000 m) Coral Sea Basin through these two major canyons [Winterer, 1970]. The slope is divided into four intraslope basins (Ashmore, Bligh, Pandora, and Moresby Troughs) and a broad intraslope plateau (Eastern Plateau). Throughout this publication the terms “intraslope basin” and “trough” will be used interchangeably.

[4] Regional sedimentology on the modern GoP shelf is fairly well understood, especially for siliciclastic material [e.g., Harris *et al.*, 1993; Wolanski and Alongi, 1995; Walsh *et al.*, 2004]. Nominally, 100 Mt/a of the total siliciclastic discharge from rivers accumulates in a large prograding delta system, much of which lies in extensive clinofolds on the inner part of the broad northwest shelf [Harris *et al.*, 1993; Walsh *et al.*, 2004]. A clockwise current along the shelf moves excess sediment to the northeast, eventually extending the clinofolds to the shelf edge in the north central GoP [Wolanski *et al.*, 1995; Wolanski and Alongi, 1995; Keen *et al.*, 2006]. Here, some quantity of siliciclastic sediment, estimated to be minimal (<5 Mt/a), escapes to the

slope [Brunskill *et al.*, 1995; Walsh and Nittrouer, 2003; Muhammad *et al.*, 2008]. Relatively small rivers draining the Papuan Peninsula feed additional amounts of siliciclastic sediment to the much narrower eastern shelf. Carbonate sedimentation in the GoP has not been thoroughly examined: there are limited studies for the northern GBR [Harris *et al.*, 1996; Harris *et al.*, 2005], but no studies of the isolated platforms. However, by analogy to segments of the northeast Australian margin to the south, neritic organisms probably produce 10–20 Mt/a of carbonate, with approximately half accumulating in shallow water and half shed to the slope [Ryan *et al.*, 2001; Dunbar and Dickens, 2003].

[5] For more than half of the last 450 thousand years (ka), sea level has been between 70 and 125 m lower than at present [e.g., Lea *et al.*, 2002; Labeyrie *et al.*, 2003]. Given the depth of the GoP shelf, the production, delivery, and storage of sediment on this margin must have been much different in the past [Harris *et al.*, 1993]. During intervals of low sea level, particularly extremes such as the Last Glacial Maximum (LGM) ~19–23 thousand years ago (ka), the shelves were subaerially exposed; major rivers extended to the outer shelf or shelf edge; sediment previously deposited on inner and middle shelves was mobilized; major reef systems shut down and became karstified.

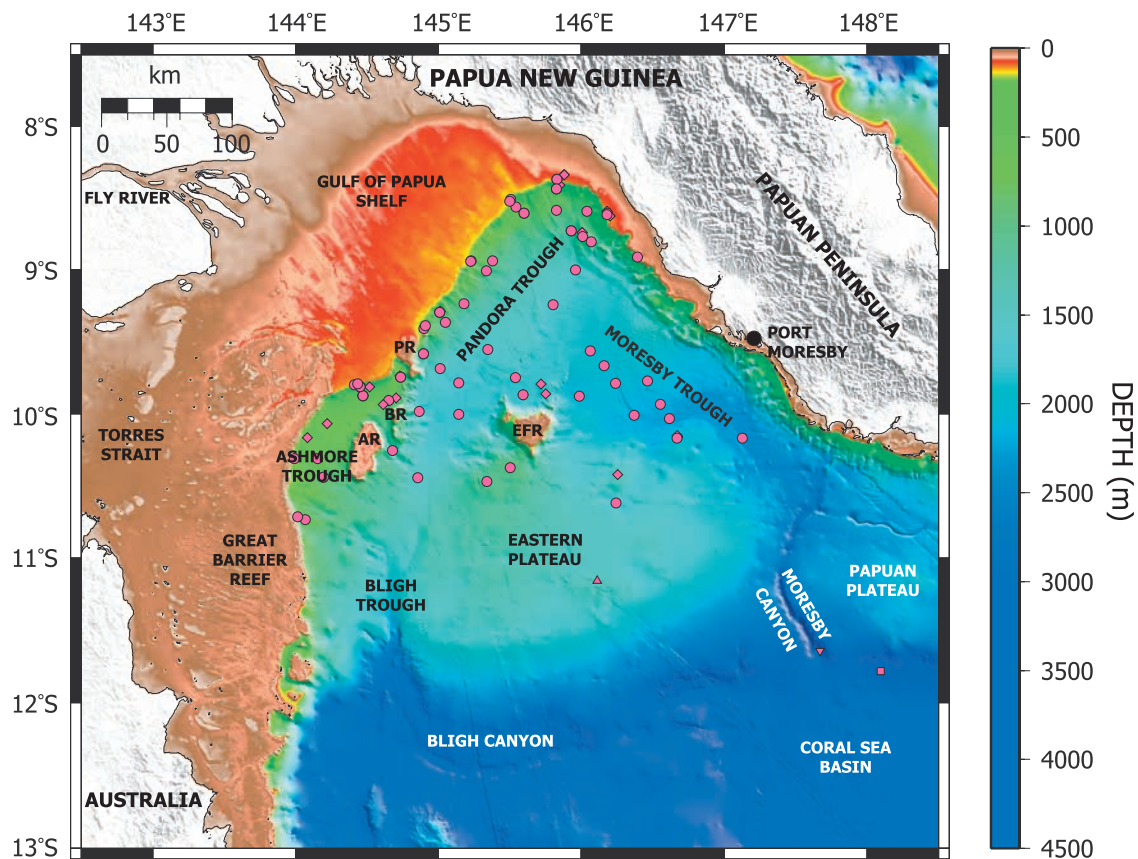
[6] The shelf break and slope regions of the GoP should contain a record for the evolution of this continental margin. However, even the bathymetry and geomorphology of this area remain poorly documented [Winterer, 1970; Davies *et al.*, 1989; Symonds *et al.*, 1991]. In this study, we present and discuss new bathymetric maps of the GoP seafloor from the outer shelf across the slope, including intraslope basins (i.e., troughs) and the intraslope plateau, with constraints from recently acquired 3.5 kHz seismic data and well-dated sediment cores [see also Daniell, 2008]. This enables us to make new observations and interpretations of seafloor geomorphology and begin to address several key issues regarding the delivery, transport, and accumulation of sediment at present and over portions of the late Quaternary.

## 2. Gulf of Papua

### 2.1. Regional Tectonics

[7] The GoP region has undergone a complex tectonic history since the Paleocene [e.g., Hamilton, 1979; Milsom, 1985; Cooper and Taylor, 1987; Pigram *et al.*, 1989; Sarg *et al.*, 1996; Quarles van Ufford and Cloos, 2005; Tcherepanov *et al.*, 2008]. Although researchers disagree on the number and style of deformation events, two points important to our work appear uncontested.

[8] A series of troughs and ridges, some exposed and some buried beneath the shelf, dominates the physiography of the region. This overall structural fabric was created during the opening of the Coral Sea Basin in the Paleocene when blocks of continental crust were rifted from the Australian/Papuan continent [Davies *et al.*, 1989; Pigram *et al.*, 1989; Symonds *et al.*, 1991; Norvick *et al.*, 2001]. Plateaus in the region, including Eastern Plateau located in



**Figure 1.** Gulf of Papua regional bathymetry. Major physiographic features are labeled. AR, BR, PR, and EFR indicate Ashmore Reef, Boot Reef, Portlock Reef, and Eastern Fields Reef, respectively. Core locations are depicted in pink, with circles for *Melville* cores, diamonds for *Marion Dufresne* cores, triangle for *Franklin* core, inverted triangle for *Vema* core, and square for *Sonne* core. Land is pictured in white and shades of gray.

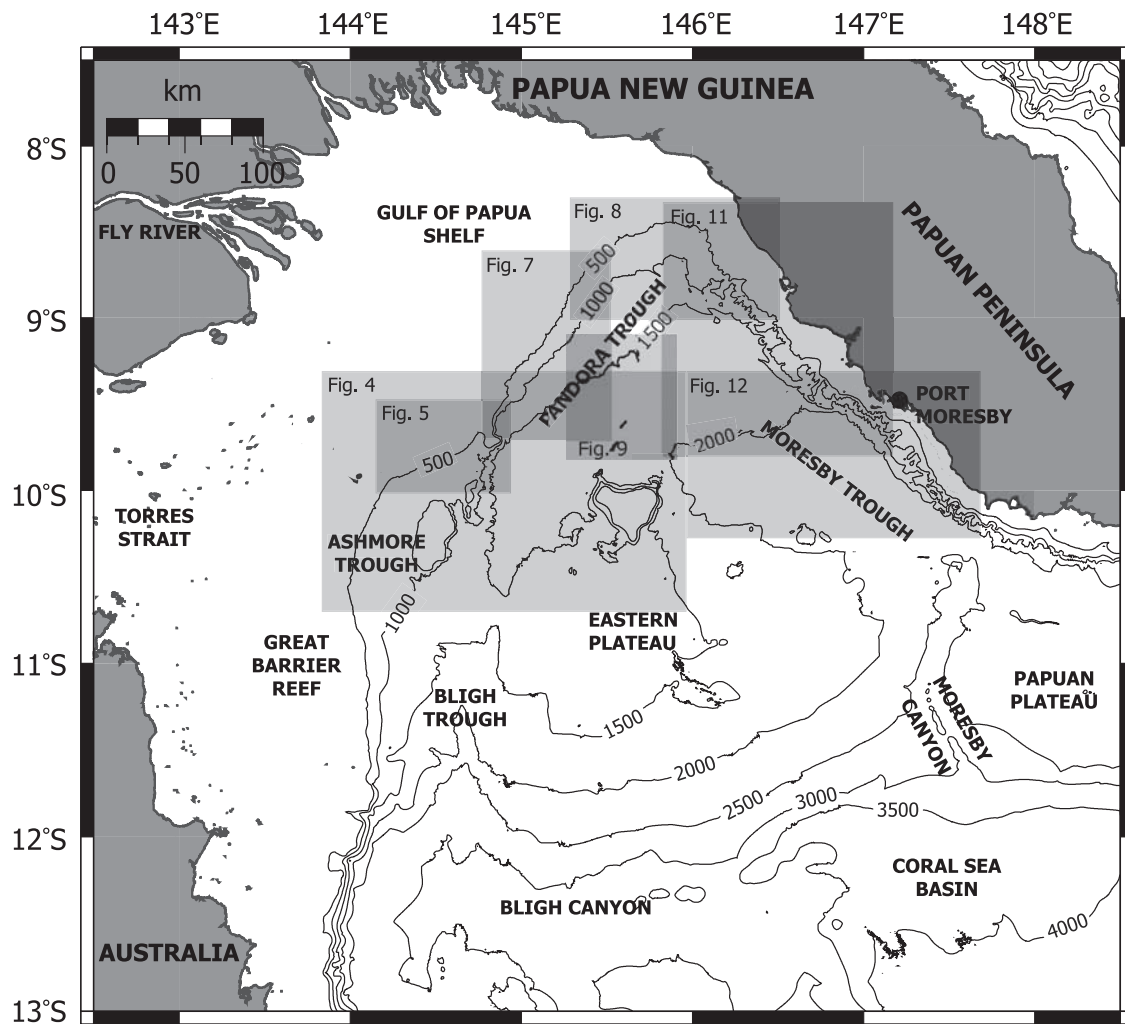
southeast GoP, and Papuan Plateau on the eastern end of the gulf, are therefore relict ridges of thick continental crust [Symonds *et al.*, 1991; Sarg *et al.*, 1996; Norvick *et al.*, 2001; Jablonski *et al.*, 2006]. By contrast, the intraslope troughs are regions underlain by thinned continental crust [Symonds *et al.*, 1991; Sarg *et al.*, 1996; Norvick *et al.*, 2001]. Farther south, in the Coral Sea, oceanic crust forms basement [Symonds *et al.*, 1991]. Since the late Oligocene and Miocene, the NE-SW trending ridges have served as bathymetric highs on which carbonate platforms have become established [Davies *et al.*, 1989; Symonds *et al.*, 1991; Sarg *et al.*, 1996; Tchernepanov *et al.*, 2008].

[9] There have been at least two major collisional orogenies during the Cenozoic. The first occurred during the Oligocene (~35–30 Ma) and was limited to eastern New Guinea [Quarles van Ufford and Cloos, 2005, and references therein]. However, the second event, which began in the latest middle Miocene, constructed the Central Range of PNG [Quarles van Ufford and Cloos, 2005]. Together, these orogenies have created the steep mountains that supply large amounts of siliciclastic sediment to the GoP [Davies *et al.*, 1989; Sarg *et al.*, 1996]. The southwestern front of the fold-and-thrust belt is subvertical, revealing outcrops of late Oligocene-early Miocene sedimentary rocks on coastal Papuan Peninsula [Davies and Smith, 1971].

## 2.2. Shelf Physiography and Sediment

[10] The modern shelf varies significantly across the region (Figure 1). However, for sake of discussion, it can be divided into four general areas: southwestern, middle to outer western, inner northwestern, and eastern.

[11] Carbonate platforms have developed across much of the southwestern GoP. The GBR, extending from northeast Australia to ~9.5°S, covers a large portion of the southwestern GoP shelf. It contains an almost continuous, well-developed shelf edge barrier reef system and a broad lagoon with additional reefs. Less extensive barrier reefs are also present on the shelf edges north of Ashmore Trough and southwest of the Papuan Peninsula. There is also Portlock Reef, an atoll nearly incorporated into the GoP shelf edge. Eastern Fields Reef, Ashmore Reef, and Boot Reef are atolls on isolated carbonate platforms. These atolls each have central lagoons (40 to 55 m water depth) surrounded by rings of shallow reefs. Like all modern tropical reef systems, including the GBR and isolated platforms along northeast Australia [e.g., Ryan *et al.*, 2001; Dunbar and Dickens, 2003], they undoubtedly produce neritic aragonite and high-magnesium calcite [Francis *et al.*, 2006; Francis, 2007; Jorry *et al.*, 2008]. A portion of this material is shed from the shelf and isolated platforms to surrounding slopes



**Figure 2.** Gulf of Papua figure location map. Major physiographic features are labeled. Land is pictured in gray. Semitransparent boxes indicate bathymetry figure locations. Bathymetric contours are labeled in meters below sea level.

[Francis *et al.*, 2006; Francis, 2007; Carson *et al.*, 2008; Jorry *et al.*, 2008].

[12] The broad middle to outer shelf in western GoP has a hummocky seafloor ranging from 50 to 120 m water depth. Harris *et al.* [1996] has described this region as an incised valley zone, and the irregular topography may represent a transgressive ravinement surface yet to be covered by the prograding delta system [Crockett *et al.*, 2008]. Tidally scoured depressions, as deep as 220 m, may also have contributed to erosion on the outer shelf [Harris *et al.*, 2005]. As revealed by dated cores, very little sediment has accumulated in this region over the Holocene [Harris *et al.*, 1996]. The limited sediment primarily consists of mud-poor, carbonate bioclasts [Harris *et al.*, 1996].

[13] Much of the inner shelf of the northwestern GoP is <50 m deep and characterized by prograding packages (clinoforms) of siliciclastic material [Harris *et al.*, 1993; Walsh *et al.*, 2004]. These deposits form where multiple fluvial sources enter the GoP [Walsh *et al.*, 2004] and interact with wind-driven waves and tidal currents [Wolanski and Alongi, 1995]. A clockwise gyre circulates water in the northern Coral Sea [Wyrki, 1962; Andrews and Clegg, 1989],

which facilitates net northeastern transport of sediment along the shelf [Wolanski *et al.*, 1995; Wolanski and Alongi, 1995; Keen *et al.*, 2006]. As a consequence, the modern GoP clinoforms reach the shelf break where the shelf narrows in the northeast [Wolanski and Alongi, 1995]. This region of the shelf edge serves as a modern entry point for siliciclastic delivery to Pandora slope and beyond [Brunskill *et al.*, 1995; Walsh and Nittrouer, 2003; Muhammad *et al.*, 2008].

[14] Overall, very little work has been done on the narrow (<20 km) and shallow (<50 m water depth) eastern shelf. The presence of rivers and carbonate reefs clearly indicates that the eastern shelf receives both siliciclastic and carbonate sediment. Siliciclastic sediment is supplied from numerous relatively small rivers that drain the Papuan Peninsula. Carbonate input is from a relatively continuous barrier reef on the southern portion of this shelf (north to ~9°20'S).

### 2.3. Slope Physiography and Surface Sediment

[15] The GoP continental slope can be divided into seven major regions: four intraslope basins, Ashmore Trough, Pandora Trough, Moresby Trough, and Bligh Trough; two major submarine canyons, Bligh Canyon and Moresby

Canyon; and one intraslope plateau, Eastern Plateau (Figures 1 and 2). Ashmore Trough, Pandora Trough, Moresby Trough, and Eastern Plateau constitute the main focus of this study.

[16] At nominally  $\sim 8000 \text{ km}^2$  and  $< 1000 \text{ m}$  water depth, Ashmore Trough in the western GoP is the smallest and shallowest of the intraslope basins. This SSW-NNE trending feature is rimmed by active carbonate reef systems on two sides. The northern extension of the GBR forms a fairly continuous system to the west. To the east, Ashmore Reef, Boot Reef, and Portlock Reef, in addition to some drowned platforms between these active carbonate platforms, form a discontinuous chain dissected by one major and several minor passages. The southwest GoP shelf edge delineates the northern boundary of Ashmore Trough and a broad outlet to the south leads to Bligh Trough. Surface sediment in Ashmore Trough is dominated by carbonate material (80 to 95%), principally a mixture of pelagic microfossils and neritic material shed from surrounding reef systems [Francis *et al.*, 2006; Francis, 2007; Carson *et al.*, 2008].

[17] Pandora Trough underlies  $\sim 20,000 \text{ km}^2$  of the middle GoP. This SSW-NNE trending basin is confined by Portlock Reef, Boot Reef, and Ashmore Reef to the west, by Eastern Plateau to the southeast, and by the shelf edge to the northwest and north. The two ends of the trough differ significantly. Southern Pandora Trough is a semienclosed basin ( $\sim 1700 \text{ m}$  deep) without a clear modern outlet. By contrast, northern Pandora Trough is open to the east, where it connects to Moresby Trough at  $\sim 2000 \text{ m}$  water depth. Surface sediment in Pandora Trough ranges from carbonate rich ( $> 50 \%$ ) in the south, proximal to the carbonate platforms [Patterson *et al.*, 2006; Jorry *et al.*, 2008], to carbonate poor ( $< 20 \%$ ) in the north, where modern siliciclastic sediment escapes the shelf edge [Brunskill *et al.*, 1995; Febo *et al.*, 2008; Muhammad *et al.*, 2008].

[18] Moresby Trough includes  $\sim 20,000 \text{ km}^2$  of the eastern GoP seafloor with water depths reaching  $\sim 3000 \text{ m}$ . Unlike the other troughs, it trends NW-SE and is bordered by the Papuan Peninsula and its narrow shelf to the northeast and by Eastern Plateau and Eastern Fields Reef to the southwest. The trough extends downdip into Moresby Canyon, the eastern pathway to the Coral Sea Basin [Winterer, 1970; Symonds *et al.*, 1991]. Recent sediment in Moresby Trough is dominantly siliciclastic material with abundant turbidites [Patterson *et al.*, 2006].

[19] Eastern Plateau is an extensive ( $\sim 25,000 \text{ km}^2$ ) bathymetric high in the southern GoP that borders eastern Bligh Trough, southern Pandora Trough, Moresby Trough, and Moresby Canyon. To the south, Eastern Plateau has a steep slope dropping into the W-E trending Bligh Canyon. Eastern Fields Reef crowns the northeastern end of Eastern Plateau and contributes modern carbonate sediment to the surrounding seafloor. However, siliciclastic material dominates surface sediment on the plateau ( $\text{CaCO}_3 < 50 \%$ ) in some places [Dunbar, 2000; McFadden *et al.*, 2006].

### 3. Cruises, Data, and Methods

#### 3.1. PANASH and PECTEN Cruises

[20] Data used in this study were collected primarily on two research cruises. The PANASH cruise, conducted on *R/V Melville* in March and April 2004, acquired about

8000 line-km of multibeam bathymetry and 3.5 kHz seismic profiles. The PECTEN cruise, conducted on *R/V Marion Dufresne* in June and July 2005, collected about 1500 line-km of multibeam bathymetry and 3.5 kHz seismic profiles. Additional multibeam data, about 2500 line-km, was collected by other MARGINS S2S cruises of *R/V Melville* during the multiple transits between Port Moresby and GoP shelf areas. The PANASH and PECTEN cruises also retrieved 122 sediment cores from the GoP, some of which are discussed in this work.

#### 3.2. Multibeam Data

[21] The *R/V Melville* used a SeaBeam 2000 system to acquire multibeam bathymetry data. This system was composed of 28 hull-mounted transducers and a hull-mounted hydrophone array of 84 elements. The transducers insonify the ocean floor with a 12 kHz sonar. The  $15^\circ$ -wide beam allows a swath width approximately three times the water depth. The SeaBeam 2000 can resolve seafloor features at a scale  $\sim 1\%$  of water depth. The *Marion Dufresne* uses a Thomson Marconi TSM 5265 system with similar specifications. Multibeam surveys of the GoP inner and middle shelf were done on the *R/V Melville* using a Simrad EM3000 system. Specifications of the Simrad EM3000 system are detailed in the work of Crockett *et al.* [2008].

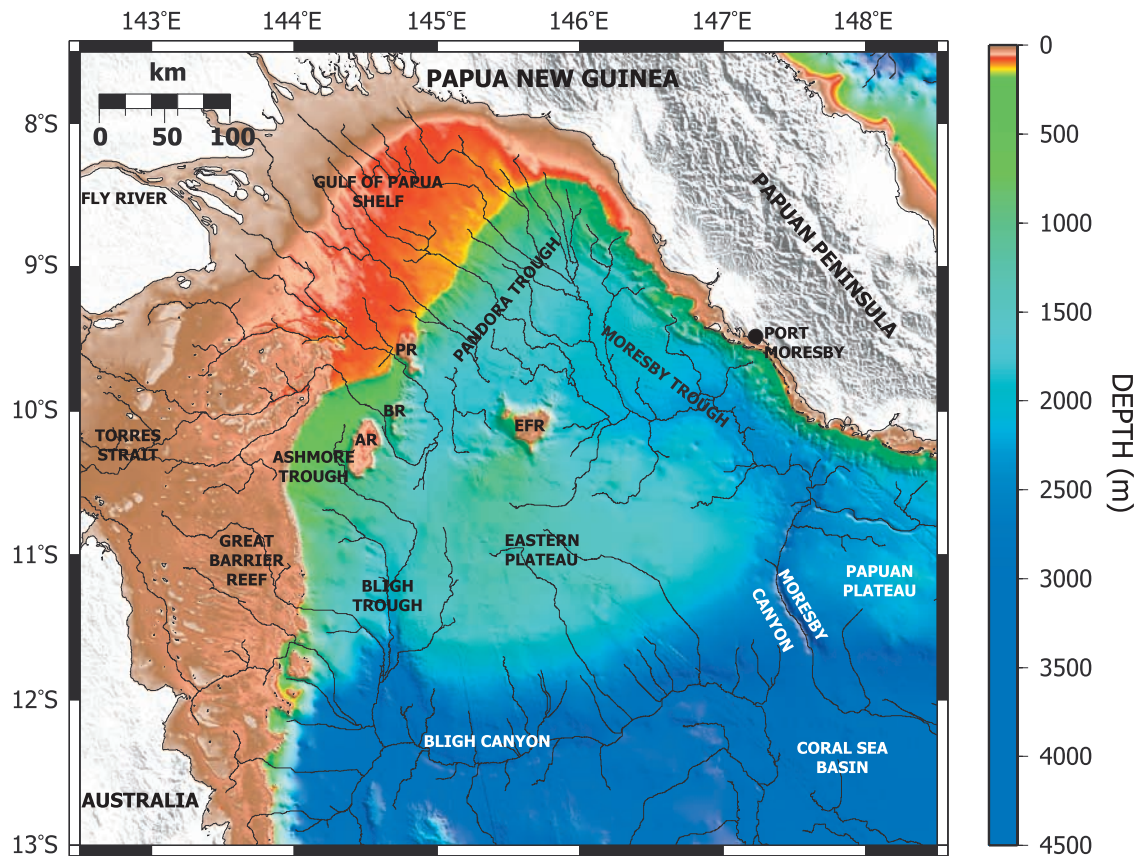
#### 3.3. Bathymetry Grid

[22] A bathymetry grid was created for the area encompassing  $140^\circ\text{--}150^\circ\text{E}$ ,  $6^\circ\text{--}14^\circ\text{S}$  with a  $3.6''$  (seconds) cell size ( $\sim 110 \text{ m}$ ) [Daniell, 2008]. The interpolated bathymetry grid was created using the ANUDEM software [Hutchinson, 1989]. Generic Mapping Tools (GMT) [Wessel and Smith, 1998] were then used to generate figures. The bathymetry grid incorporates data from multiple sources: multibeam sonar data, Landsat data, Australian Hydrographic Service fairsheet and survey data, Geoscience Australia OZMAR shiptrack data, and several miscellaneous sources [Daniell, 2008]. In areas without data, surfaces were interpolated. The data gaps often give the appearance of segmented features, such as segmented channels, when these features can be quite continuous. Data coverage for the GoP region can be viewed in a companion paper [Daniell, 2008].

[23] The GoP bathymetry grid was also processed using RiverTools software to determine drainage paths across the seafloor (Figure 3). RiverTools allows for the extraction of drainage patterns using digital elevation models, like the GoP bathymetry grid [Peckham, 1998; RIVIX, 2004; Patterson *et al.* 2006]. Today, some sediment is transported through features reaching the middle shelf [Crockett *et al.*, 2008]. However, sediment transport on the modern shelf is largely independent of identified channels, which probably represent palimpsest features [Harris *et al.*, 1996]. The drainage network map may, however, give a fairly accurate representation of sediment flow paths in slope settings where gravity-flow transport can dominate.

#### 3.4. Bottom Seismic Profiling

[24] Echosounder data was acquired on *R/V Melville* using a Knudsen Engineering Limited system. This system contains a 320B/R transceiver unit capable of 10 kW output in 3.5 kHz mode. The Knudsen system also contains sixteen Massa TR1075A 3.5 kHz transducers arranged in a  $4 \times 4$



**Figure 3.** Gulf of Papua seafloor drainage system. Major physiographic features are labeled. AR, BR, PR, and EFR indicate Ashmore Reef, Boot Reef, Portlock Reef, and Eastern Fields Reef, respectively. Land is pictured in white and shades of gray. Bathymetric map is overlain by a seafloor drainage network calculated by RiverTools software.

array. This array is located immediately starboard of the centerline, just forward of the multibeam receiver array. On the PANASH cruise, standard operating settings were a 12 ms chirp in shallow depths and a 24 ms chirp in deeper water. For all depths, a receiving range of 200 m and gain settings between  $\sim 80$  and 130 were used.

### 3.5. Sediment Cores

[25] The PANASH cruise retrieved 33 jumbo piston cores (JPCs) up to 14 m in length, 29 trigger gravity cores, 4 individual gravity cores, 30 multicores, 4 box cores, and 5 rock-dredge samples. These sediment samples come from the shelf edge and slope; they span water depths between 65 and 2300 m (Figure 1). The PECTEN cruise retrieved 22 CALYPSO, CASQS, and gravity cores ranging from 8 to 47 m in length. These cores come from a similar range of settings and water depths (Figure 1). Some of these cores, including their ages and composition, are discussed in companion papers [Francis *et al.*, 2006; Patterson *et al.*, 2006; Francis, 2007; Carson *et al.*, 2008; Febo *et al.*, 2008; Jorry *et al.*, 2008; Muhammad *et al.*, 2008]. Used in conjunction with multibeam and 3.5 kHz data, they place crucial constraints on the location, composition, and timing of sediment accumulation during the last sea-level cycle.

### 3.6. Methods

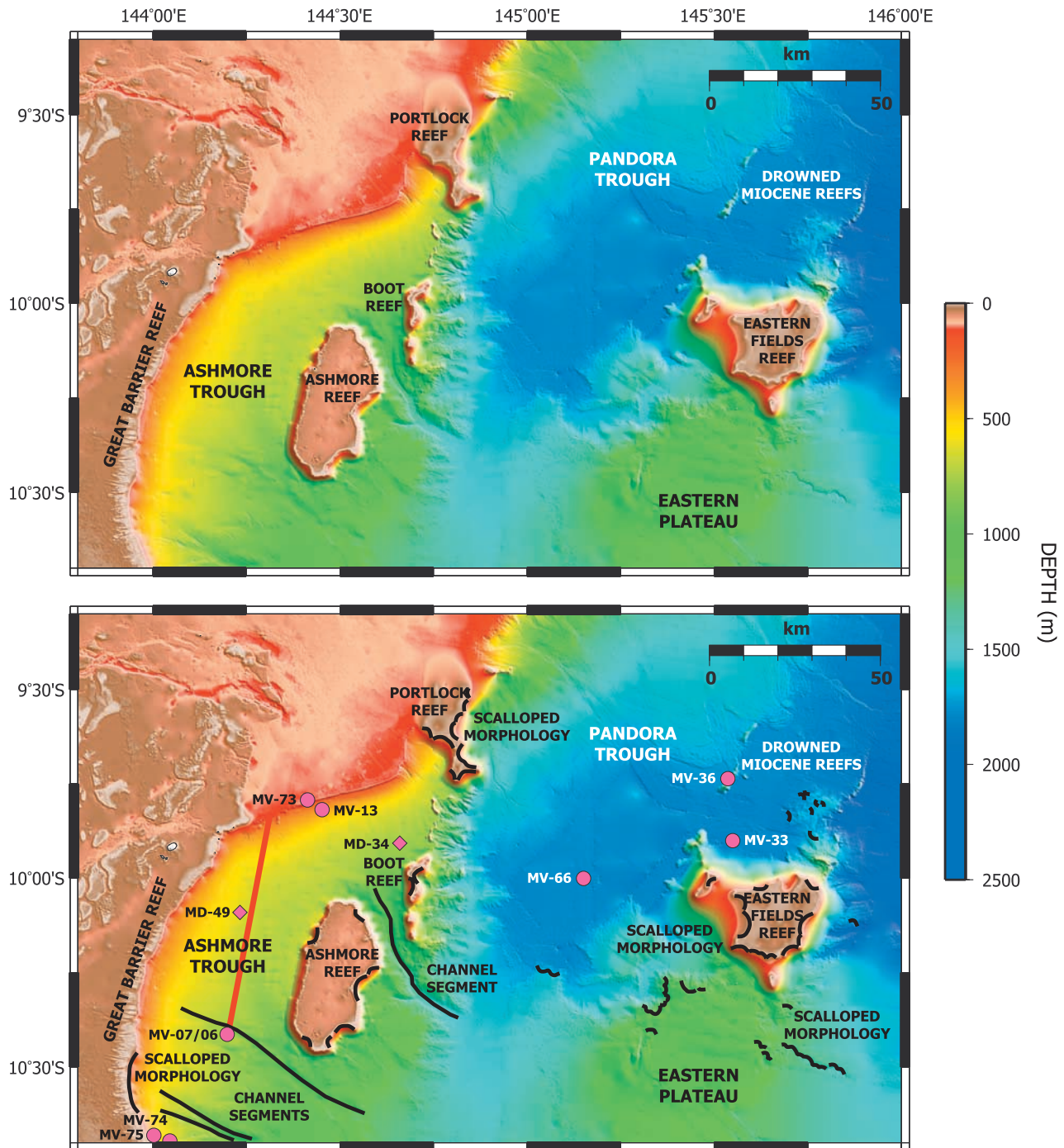
[26] This research utilized primarily multibeam bathymetry data and the bathymetry grid and to a lesser extent seismic

profiles and sediment cores to make observations of bathymetric features. The observations were then compiled into original descriptions of seafloor geomorphology. Sedimentological and stratigraphic interpretations were made of the geomorphology to the extent that the data allowed. In many cases multiple interpretations of bathymetric features can be made.

## 4. Geomorphology of the Shelf Edge, Slope, and Intraslope Troughs

### 4.1. Overview

[27] The GoP shelf edge, slope, and intraslope basins/troughs vary considerably with respect to depth, morphology, and sediment type. Water depth varies from sea level to  $\sim 60$  m water depth along sections of the GBR, the PNG barrier reef, and the ring reef atolls of Ashmore, Boot, Portlock, and Eastern Fields Reefs. However, along nonreef areas the shelf edge is approximately 120 m water depth. Shelf-edge morphology also varies from very linear along northern Ashmore Trough to highly irregular along sections of the carbonate platforms and the western Papuan Peninsula. Similarly, slope morphology varies from smooth and homogeneous along portions of Ashmore Trough and northern Pandora Trough to highly channelized and/or incised along southern Pandora Trough and Moresby Trough. Modern sediment composition across the shelf



**Figure 4.** Gulf of Papua reefs. This figure contains uninterpreted and interpreted bathymetric data with shaded relief. Sun-illumination is from the NE. Core locations are depicted in pink, with circles for *Melville* cores and diamonds for *Marion Dufresne* cores. Scalloped morphology is labeled and highlighted with black crescent shaped lines. Black lines indicate submarine channels in southern and central Ashmore Trough. Red line indicates the location of 3.5 kHz seismic line displayed in Figure 6.

edge and slope changes significantly from nearly pure carbonate on and around the carbonate platforms to nearly pure siliciclastic material along northern Pandora Trough [Febo et al., 2006].

**4.2. Carbonate Platforms and Atolls**

[28] Although not directly examined during our cruises, the complex lagoons, rimmed margins, and steep upper

slopes of carbonate platforms (Figure 4) certainly influence sediment accumulation in surrounding intraslope basins. Water depths across carbonate platforms approach or are at sea level along platform rims. Neritic carbonate material is primarily produced from atoll rims, accumulates in the enclosed lagoons ranging in depths between 40 to 55 m, and is partly exported to adjacent slope and intra-slope basin environments [Brunskill et al., 1995; Francis et al., 2006;



Francis, 2007; Carson *et al.*, 2008; Jorry *et al.*, 2008]. GoP carbonate platforms display steep gradients along their margins, particularly in the upper 100 m. For example, the northeast Eastern Fields Reef slope ranges in depth from sea level to ~2000 m over a distance of 2 km (i.e., 45°). Slopes with steep gradients are common features along platform margins [e.g., Emery, 1948; Stoddart, 1962; Ball *et al.*, 1969]. Such steep gradients can be conducive to margin failure [e.g., Grammer *et al.*, 1993; Zampetti *et al.*, 2004], generating significant volumes of material that accumulate in deep water environments adjacent to carbonate platforms. Evidence of margin failure can be preserved as “scalloped margin” morphology [Mullins and Hine, 1989].

[29] Scalloped margin morphology was originally described on the Florida escarpment [Mullins *et al.*, 1986]. Similar features have been found along margins of the Gulf of Mexico and the Caribbean region [Mullins and Hine, 1989; Hine *et al.*, 1992], as well as along ancient margins in the rock record [e.g., Franseen *et al.*, 1989; Bosellini *et al.*, 1993; Stewart *et al.*, 1993; Zampetti *et al.*, 2004]. These features have been interpreted by the above authors as scars from large-scale mass wasting or slope failure events. Suggested triggers for failure include earthquakes, sediment loading, erosion of lower slopes by deep water currents, and carbonate dissolution through sea-level fluctuations [Schlager *et al.*, 1984; Sarg, 1988; Mullins and Hine, 1989; Handford and Loucks, 1993].

[30] The isolated carbonate platforms of Eastern Fields Reef, Ashmore Reef, and Boot Reef exhibit scalloped margins (Figures 4). These are margins characterized by large (up to tens of kilometers across), irregular embayments, similar to those described by Mullins and Hine [1989]. Portlock Reef also displays scalloped margins, particularly on the south side where it has not yet been surrounded by siliciclastic sediment and extends into water depths exceeding 600 m. The seaward margin of the GBR contains the largest scalloped feature in the GoP, a broad 20 km wide embayment at 10°30'S on the southwestern margin of Ashmore Trough (Figure 4). From the abundance of scalloped margin morphology it is inferred that mass-transport processes are an important mechanism of sediment transport along GoP carbonate margins. However, there is little evidence to confirm this inference, with the exception of occasional calciturbidites in Pandora Trough [Jorry *et al.*, 2008].

### 4.3. Ashmore Trough

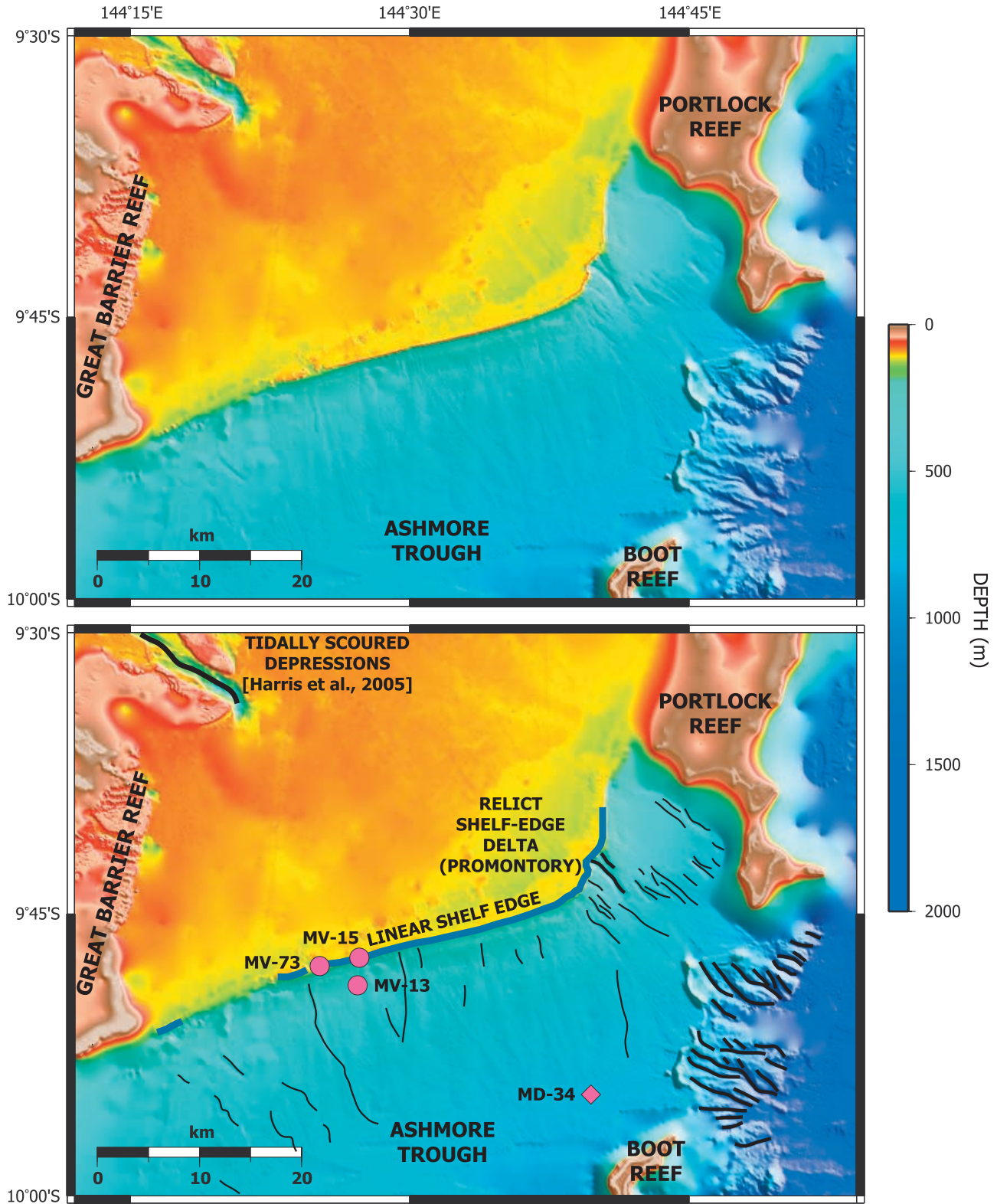
[31] The shelf edge of northern Ashmore Trough has several noteworthy features (Figure 5). First, the shelf edge is very linear between 144°15'E and 144°40'E with water depths ranging from ~60 to 125 m. This complex shelf edge extends into a broad submarine promontory adjacent to Portlock Reef. The promontory is centered at approximately 9°40'S and 144°35'E with water depths of ~110–120 m, and covers >200 km<sup>2</sup>. The northern shelf edge contains a drowned barrier-reef system, initially documented by Harris *et al.* [1996] and described by Mallarino *et al.* [2004] and Droxler *et al.* [2006]. The nearly continuous reef structure extends for approximately 30 km from 144°25'E to 144°40'E. Less continuous stretches of reef continue west, although with the exception of four pinnacles, no reefs are found on the western shelf edge of

northern Ashmore Trough. Submarine channel segments are found on the northern Ashmore upper slope. The largest channel (~1 km wide and ~30 m deep) originates at the apex of the promontory and extends SE downslope for >5 km. Below 500 m water depth, the channel disappears, perhaps due to sediment infilling. Channels are relatively narrow (<500 m) and shallow (4–20 m) features of variable length (1–20 km) that trend from NNW to SSE on the central margin and from NW to SE on the eastern margin. Slope channels are more densely spaced adjacent to the promontory along the upper slope.

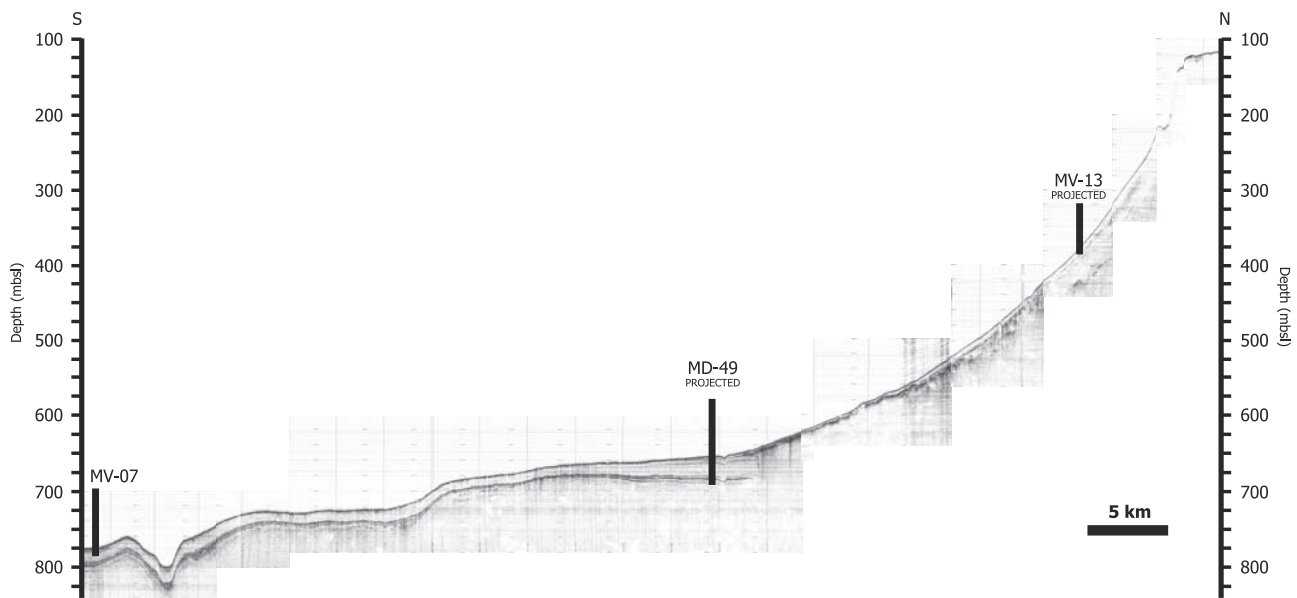
[32] A smooth, regular seafloor characterizes much of the lower slope across Ashmore Trough. However, channels are present in several places (Figures 4 and 5), particularly in northern Ashmore Trough. At the southern end of the trough, southwest of Ashmore Reef, three large channels begin at ~500 m water depth adjacent to the GBR and trend SE (Figures 4). They are ~2 km wide and 20–40 km long. Another major NW to SE channel begins at ~1200 m water depth and extends between Ashmore Reef and Boot Reef. It is 3–5 km wide and 40 km long. Between Portlock Reef and Boot Reef, the character of the seafloor changes dramatically. This area contains a series of small drowned carbonate platforms [Tcherepanov *et al.*, 2008] divided by a set of W to E trending channels.

[33] The linear shelf-edge along northern Ashmore Trough is unique within the GoP (Figure 1). Core MV-73 was taken in order to determine the composition and depositional environment of the shelf-edge sediment. Specifically, this core targeted a small embayment in the drowned barrier reef to determine the nature of the underlying sediment. The piston core penetrated the shelf edge at 125 m water depth (Figure 5) and recovered 8.43 m of sediment dominated by ~15–18 ka siliciclastic material deposited in an upper and lower shoreface environment [Mallarino *et al.*, 2004; Droxler *et al.*, 2006]. The siliciclastic-dominated coastline formed during lower sea-level when the shelf edge coincided with the coastline [Mallarino *et al.*, 2004]. Consequently, the short-lived barrier reef established itself on this paleocoastline during the last sea-level transgression [Mallarino *et al.*, 2004; Droxler *et al.*, 2006]. A similar feature can be found along the western Gulf of Mexico shelf edge, offshore Corpus Christi [Belopolsky and Droxler, 1999]. Moreover, the Belize barrier reefs have been inferred as growing on top of siliciclastic ridges and lowstand shelf edge deltas during sea-level transgression [Choi and Holmes, 1982; Ferro *et al.*, 1999; Droxler *et al.*, 2003].

[34] The linear shelf edge/paleoshoreline changes in character to the east. The shelf edge extends seaward as a broad promontory. This morphology may represent a relict shelf edge delta, formed when sea level was lower and large masses of fluvial sediment extended to the shelf edge. Seismic data from this shelf edge displays clinofolds [Symonds *et al.*, 1991; Tcherepanov *et al.*, 2008] often associated with prograding deltas [e.g., Posamentier and Vail, 1988; Porebski and Steel, 2003]. The submarine channel originating from the presumed delta apex also supports this inference. Several modern rivers (e.g., Mississippi, Rhone) have relict delta systems near the shelf break with submarine canyons or channels extending from their apices [Porebski and Steel, 2003]. The submarine



**Figure 5.** North Ashmore Trough. This figure contains uninterpreted and interpreted bathymetric data with shaded relief. Sun-illumination is from the NE. Core locations are depicted in pink, with circles for *Melville* cores and diamonds for *Marion Dufresne* cores. Channels are highlighted with black lines. Blue line highlights barrier reef at the shelf edge. Promontory at eastern shelf edge is interpreted as relict shelf edge delta.



**Figure 6.** Seismic profile of northern Ashmore slope. N–S oriented seismic profile extending from northern Ashmore shelf edge to trough floor. Line location is marked on Figure 4.

canyons or channels are thought to have been most active during sea-level regressions and lowstands, when rivers discharged sediment directly into the slope incision [Porebski and Steel, 2003].

[35] The smooth bathymetry of the lower slope and trough floor results from pelagic and hemipelagic sedimentation, which is the dominant mode of recent sediment transport [Francis *et al.*, 2006; Francis, 2007]. Seismic profiles show a wedge of sediment extending across Ashmore Trough, thickest along the northern and western sides of the trough (Figure 6). This “sediment wedge” is semitransparent and overlies a mass transport deposit on the lower slope. The wedge varies in thickness, from ~20 m on the upper slope to negligible thicknesses on the lower slope. Seismic facies change dramatically downdip. Southern and central Ashmore Trough contains a very continuous seismic facies bounded on the top and bottom by high-amplitude reflectors. This change reflects a difference in the long-term sediment processes between northern and southern/central Ashmore Trough [Francis *et al.*, 2006; Francis, 2007].

[36] Carbonate platforms may play a role in the origin and location of major channels in Ashmore Trough. First, the only major scallop along the GBR side of the trough is at the southern end of the trough adjacent to the series of channels (Figure 4). This supports the assertion that mass wasting may form scalloped-margin morphology and sediment conduits downdip. Next, channels are associated with (Figures 4 and 5) the NNE-SSW reef trend that extends from Ashmore Reef north to Portlock Reef and even into the subsurface of the GoP shelf [Sarg *et al.*, 1996; Tcherepanov *et al.*, 2008]. Here ridges and channels have formed between and adjacent to Boot and Portlock Reefs. Last, the large channel running between Ashmore and Boot Reefs likely represents a major sediment conduit.

[37] The trends of seafloor channels have important implications for sediment delivery and accumulation. The dominant trend of submarine channels is from NW to SE or

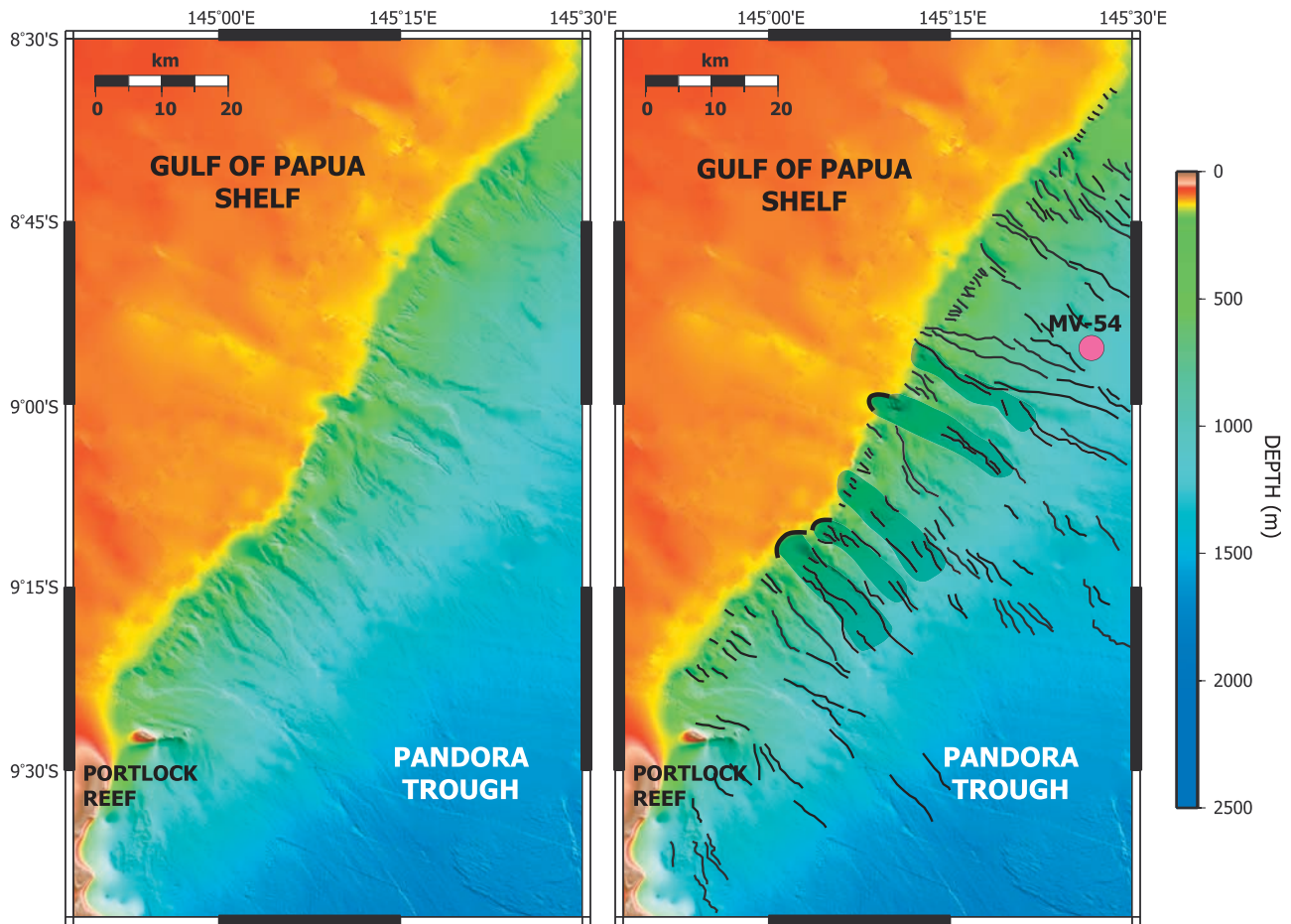
directly east (Figure 5). This implies that some fraction of sediment, probably significant, has bypassed Ashmore Trough. Some of that sediment accumulated in southern Pandora Trough [Francis, 2007; Jorry *et al.*, 2008] and some probably traveled south toward Bligh Trough and the Coral Sea Basin.

#### 4.4. Southern Pandora Trough

[38] Seafloor morphology changes significantly along the shelf edge, slope, and intra-slope Pandora Trough (Figures 7 and 8). From Portlock Reef at 9°30'S to ~8°40'S, relatively deep (~120 m) waters cover an undulating shelf edge, and numerous NW-SE trending channels dissect the upper slope. To the north, however, the outer shelf of Pandora Trough is shallower (~70 m water depth) and slope channels are significantly less common (Figure 8).

[39] Morphological characteristics can be identified along the shelf edge of southern Pandora Trough at various scales (Figure 7). At large scale, the shelf edge has a broad, shallow promontory between 8°50'S and 9°10'S. At smaller scale, the shelf edge appears scalloped, although incomplete multi-beam coverage precludes a full description of these embayments. The upper slope contains broad slump scars (5–10 km wide) that originate from scalloped morphology at the shelf edge (Figure 7). The slope channels are relatively straight and narrow (<500 m wide), shallow (4–20 m), with variable segment lengths (1–25 km), although this range may again reflect incomplete multibeam coverage. The channels start on the shelf edge at ~120 m water depth and extend downslope to ~1500 m.

[40] The morphology of the intraslope basin floor also varies significantly across southern Pandora Trough (Figures 4 and 9). In the southeast, the seafloor is generally smooth and flat. In the central trough, however, large sediment deposits extend down the slope and onto the floor of Pandora Trough. The features have variable geometries but are mostly elongate down the slope. At their termini, they contain internal compressional ridges that generally



**Figure 7.** South Pandora Trough. This figure contains uninterpreted and interpreted bathymetric data with shaded relief. Sun-illumination is from the NE. Core locations are depicted in pink. Channel segments are highlighted with black lines. Many of the channels appear to be highly segmented due to gaps in the multibeam bathymetry data as discussed in section 3.3 bathymetry grid. Slump scars are highlighted by gray semitransparent polygons. Scalloped morphology is highlighted with black crescent shaped lines.

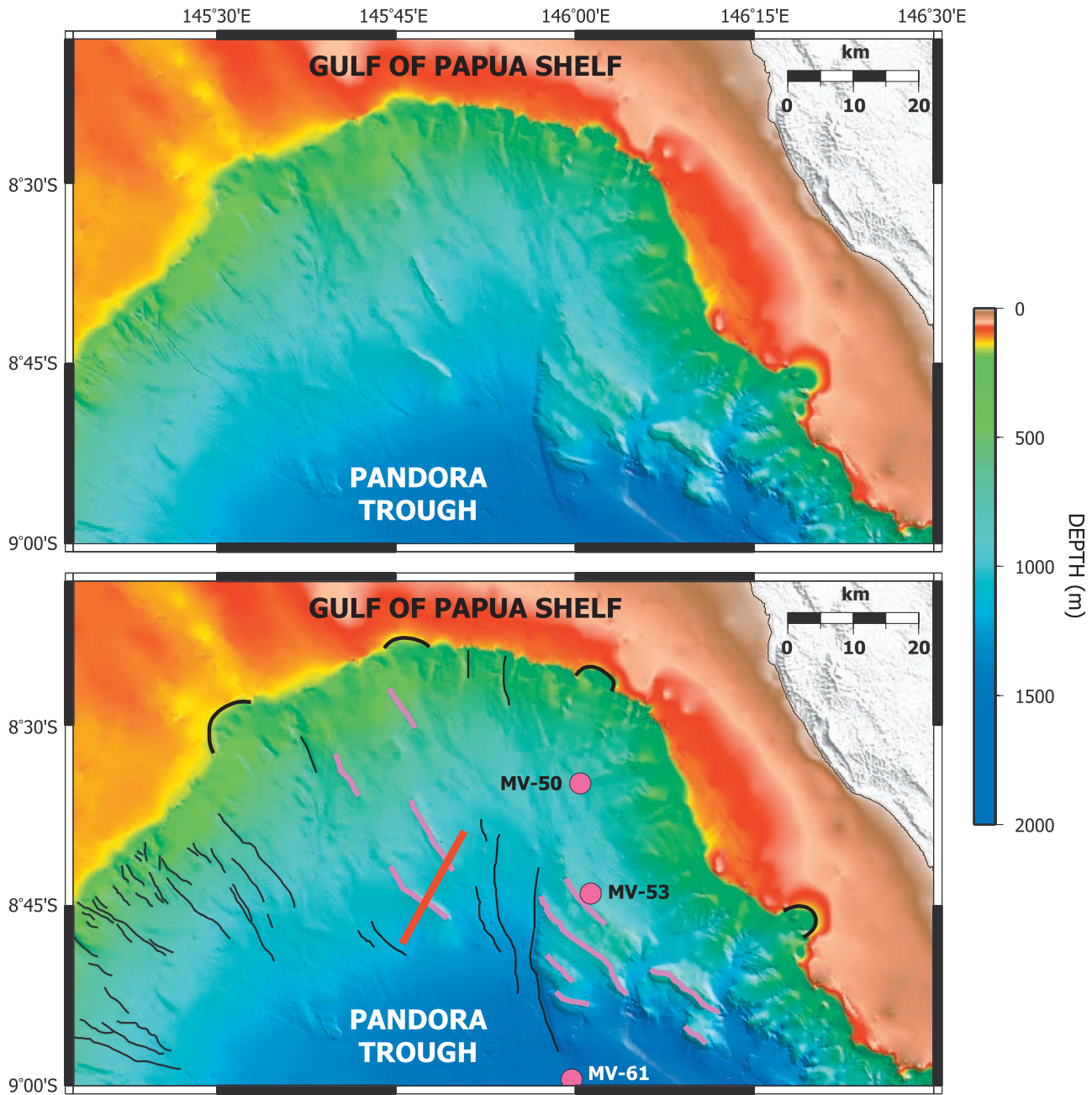
curve updip toward the edges of the deposits [Martinsen, 1989; Stow *et al.*, 1996]. Subbottom profiling shows these sedimentary bodies to display minimal internal stratigraphy (Figure 9). However, the stratigraphy that is evident has undergone deformation (Figure 9).

[41] Morphological elements found along the slope of southern Pandora Trough are common to deep water environments elsewhere, often adjacent to river systems (e.g., Indus, Mississippi, and Amazon Rivers) [e.g., Kolla and Coumes, 1984; Weimer, 1990; Flood *et al.*, 1991]. Moreover, the large scallops, slump scars, canyons, and channels collectively indicate a margin strongly impacted by failures and gravity flows. The significance of scalloped morphology was discussed earlier in regards to carbonate platforms. In dominantly siliciclastic settings, like the shelf edge of southern Pandora Trough, similar scalloping occurs, and again may indicate mass wasting [e.g., Mutti, 1985; Martinsen, 1989; Reading and Richards, 1994]. Scalloped morphology can mark the updip extent of slump scars where material has been removed from the shelf edge/slope. Downdip slump scars can continue as broad erosional

scours and may transition into mass transport deposits (MTDs) (Figure 7).

[42] Seismic data reveals the smooth and flat southern basin floor of Pandora Trough to contain a thick (>50 m) pile of laterally continuous strata of alternating turbidite and hemipelagic deposits (referred to as central Pandora Trough in the work of Jorry *et al.* [2008]). Downcore, southern Pandora Trough contains a sequence of lowstand turbidites [Patterson *et al.*, 2006; Jorry *et al.*, 2008], and the central slope contains an early transgressive sequence >8 m thick [Febo *et al.*, 2008]. Clearly, Pandora Trough has undergone a complex history of sedimentation.

[43] The large sedimentary bodies found in central Pandora Trough are interpreted as MTDs or collectively these stacked or shingled MTDs are generally referred to as a mass transport complex (MTC). Both are dominated by relatively cohesive gravity-flow deposits from slides, slumps, and debris flows, although turbidites and hemipelagites may be present. The character of MTD internal stratigraphy depends on the cohesion of the flow and can preserve original bedding and lamination or undergo com-



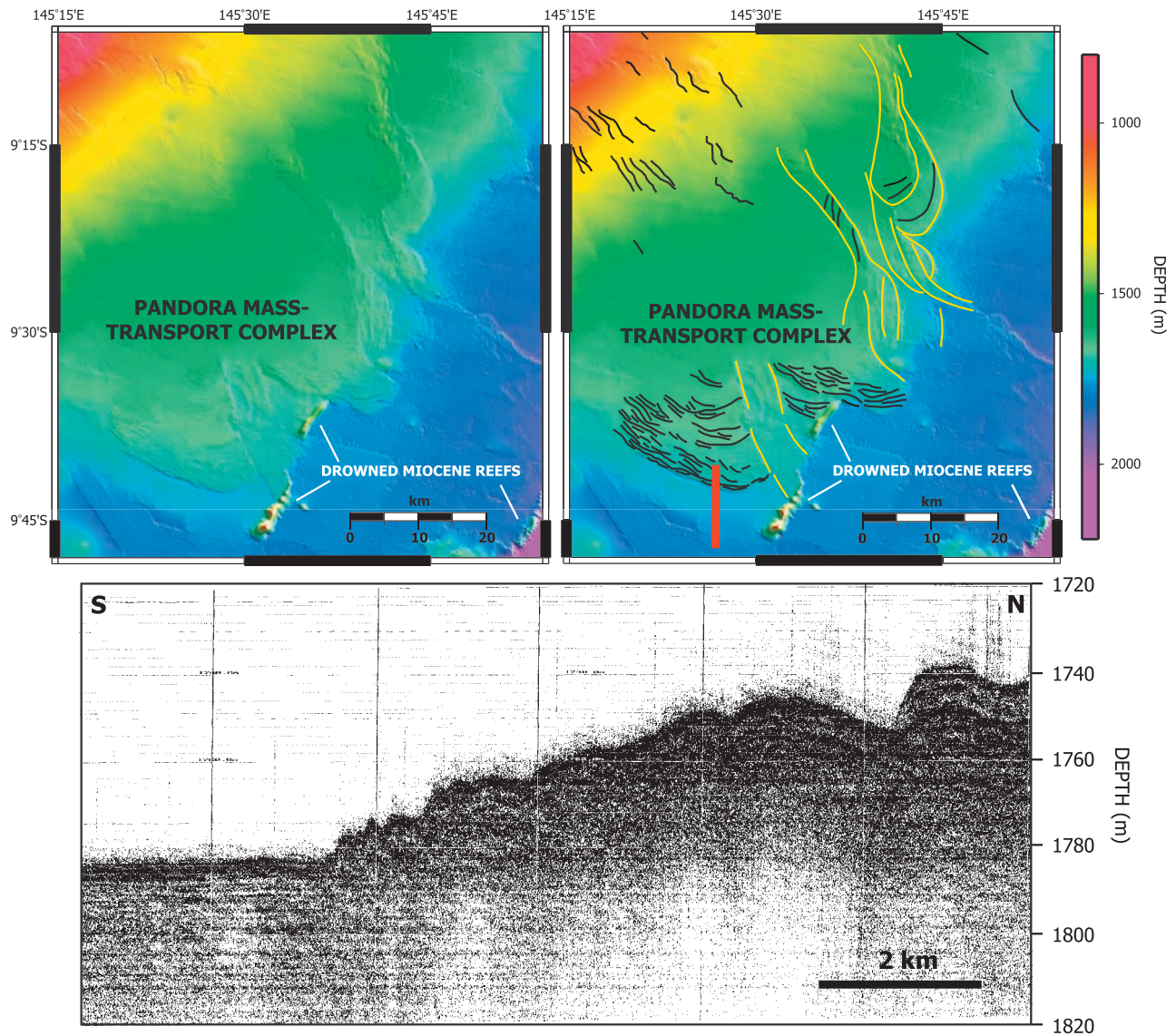
**Figure 8.** North Pandora Trough. This figure contains uninterpreted and interpreted bathymetric data with shaded relief. Sun-illumination is from the NE. Land is pictured in white and shades of gray. Core locations are depicted in pink. Channels are highlighted with black lines. Scalloped morphology is highlighted with black crescent shaped lines. Pink lines highlight tectonic ridges. Red line indicates the location of 3.5 kHz seismic line displayed in Figure 10.

plete internal deformation [Stow *et al.*, 1996]. Regions updip of MTDs are generally characterized by extensional structures or slump scarring and downdip compressional structures such as folds and thrusts are pervasive [Stow *et al.*, 1996]. Compression forms “pressure ridges” on the toes of MTD, normal to flow direction. Ridges within a MTC may also be formed by multiple MTDs overlapping and stacking.

[44] “Pandora MTC” occupies a large area in Pandora Trough from approximately 9°00’S–9°45’S and 145°15’E–145°45’E (Figure 9), likely originating from the slump scars

present updip, on the shelf edge and upper slope of Pandora Trough (Figure 7). Several MTDs show dip-oriented changes in morphology. They are relatively confined updip (<5 km wide) and spread laterally downdip (>10 km wide). The toe of the MTC is well defined by pressure ridges and shingled MTDs. Pressure ridges indicate NW to SE transport, supporting a central Pandora shelf edge/upper slope source.

[45] Sediment gravity flows can also be influenced by irregular seafloor morphology. In Pandora Trough, several drowned carbonate platforms have been discovered that



**Figure 9.** Pandora mass-transport complex. This figure contains uninterpreted and interpreted bathymetric data with shaded relief as well as a seismic line. Sun-illumination is from the NE. Narrow black lines highlight sedimentary ridges associated with mass-transport complex on lower slope and channels on upper slope. Yellow lines highlight the boundaries of individual mass-transport deposits. Red line indicates the location of 3.5 kHz seismic line displayed in this figure. Seismic line shows internally deformed mass-transport complex deposited in Pandora Trough.

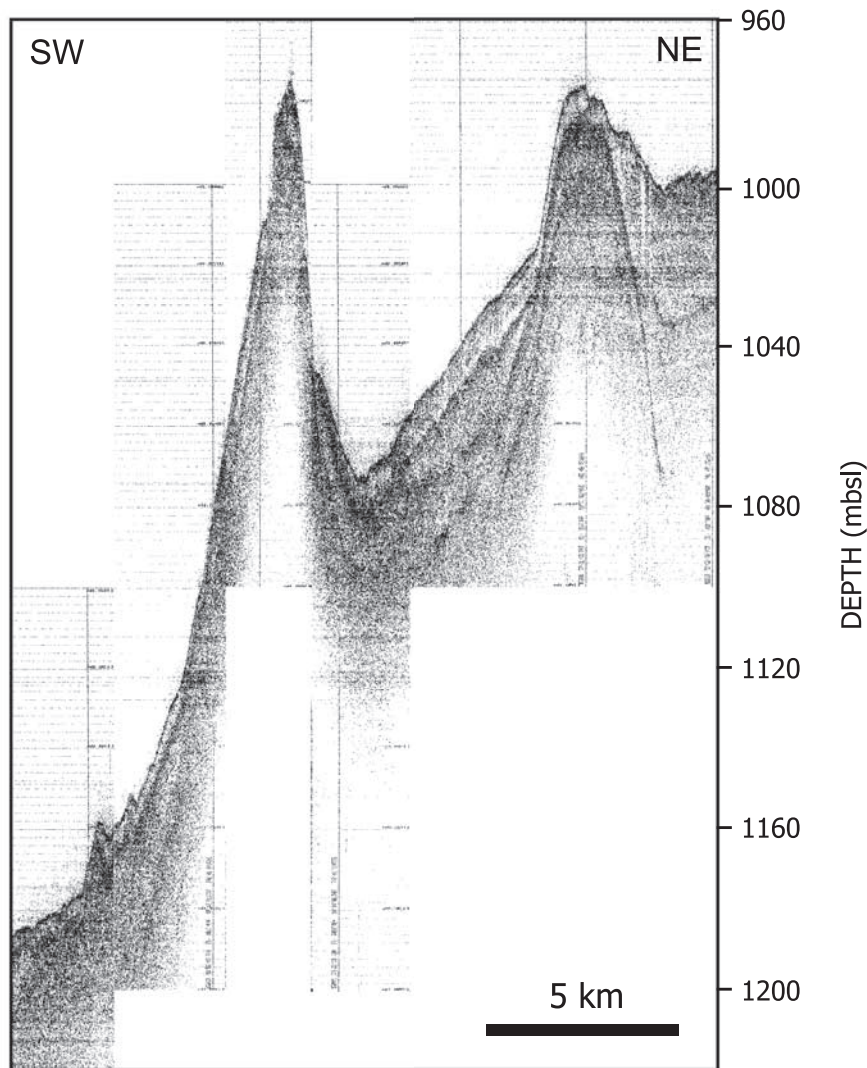
acted as seafloor barriers to catch and divert mass transport events during downslope transport (Figure 9). The drowned platforms are ridges exposed in the water column with steep sides and several hundreds of meters of relief. A dredge sample from one of these platforms determined its age to be early Miocene ( $\sim 20$  Ma) [Tcherepanov *et al.*, 2008].

#### 4.5. Northern Pandora Trough

[46] The shelf edge of northern Pandora Trough, between  $145^{\circ}30'E$  and  $146^{\circ}10'E$ , is semicircular (Figure 8). Scalloped morphology is abundant with three major ( $>5$  km) and several minor ( $<5$  km) embayments. In contrast to southern Pandora Trough, however, channels or slump scars

on the slope are less pronounced. The few obvious channels are  $\sim 1$  km wide, 4–14 m deep, and between 5 and 10 km long. Seismic data show this region to contain a sediment wedge extending from the shelf edge to the lower slope. Other distinct features in northern Pandora Trough are a series of NW–SE trending ridges that exhibit several hundred meters of relief from the surrounding seafloor (Figures 8, 10, and 11).

[47] Scalloped morphology may again indicate that mass wasting has been an important process. However, the seafloor in this region shows little morphological evidence of MTDs, such as elongate dip-oriented sedimentary build-



**Figure 10.** Tectonic ridges in North Pandora Trough. Seismic line across two tectonic ridges on Pandora Trough slope. Note the onlap of sediment onto the ridges particularly on the northeastern ridge. Line location is marked by red line on Figure 8.

ups or pressure ridges. Either gravity flow processes are less prevalent on this part of the GoP margin or gravity flow processes have been important in the past, but subsequent sedimentation has buried the resultant features. Seismic profiles confirm that some channels are partially filled in this area.

[48] Unlike the shelf edge of southern Pandora Trough, thick, prograding packages of sediment extend to the shelf edge along northern Pandora Trough, as noted in previous

work [Walsh *et al.*, 2004] and clearly documented by 3.5 kHz seismic data from the PANASH cruise [Dickens *et al.*, 2006; Muhammad *et al.*, 2008]. On the outer shelf, these clinoforms are >20 m thick. The shelf edge clinoforms indicate that siliciclastic material currently escapes to the slope in this region [Muhammad *et al.*, 2008]. Similar seismic facies, associated with very young deposits [Muhammad *et al.*, 2008], have thicknesses <20 m on the upper slope and pinch-out downslope ~50 km from the

**Figure 11.** North Moresby Trough. This figure contains uninterpreted and interpreted bathymetric data with shaded-relief. Sun-illumination is from the NE. Land is pictured in white and shades of gray. Core location is depicted in pink. Canyons and channels are highlighted with black lines. Scalloped morphology is highlighted with black crescent shaped lines. Pink lines highlight tectonic ridges. The pink lines on land highlight Oligocene-early Miocene outcrops described by Davies and Smith [1971]. Narrow black lines highlight sedimentary ridges associated with Moresby mass transport complex and other mass transport deposits.

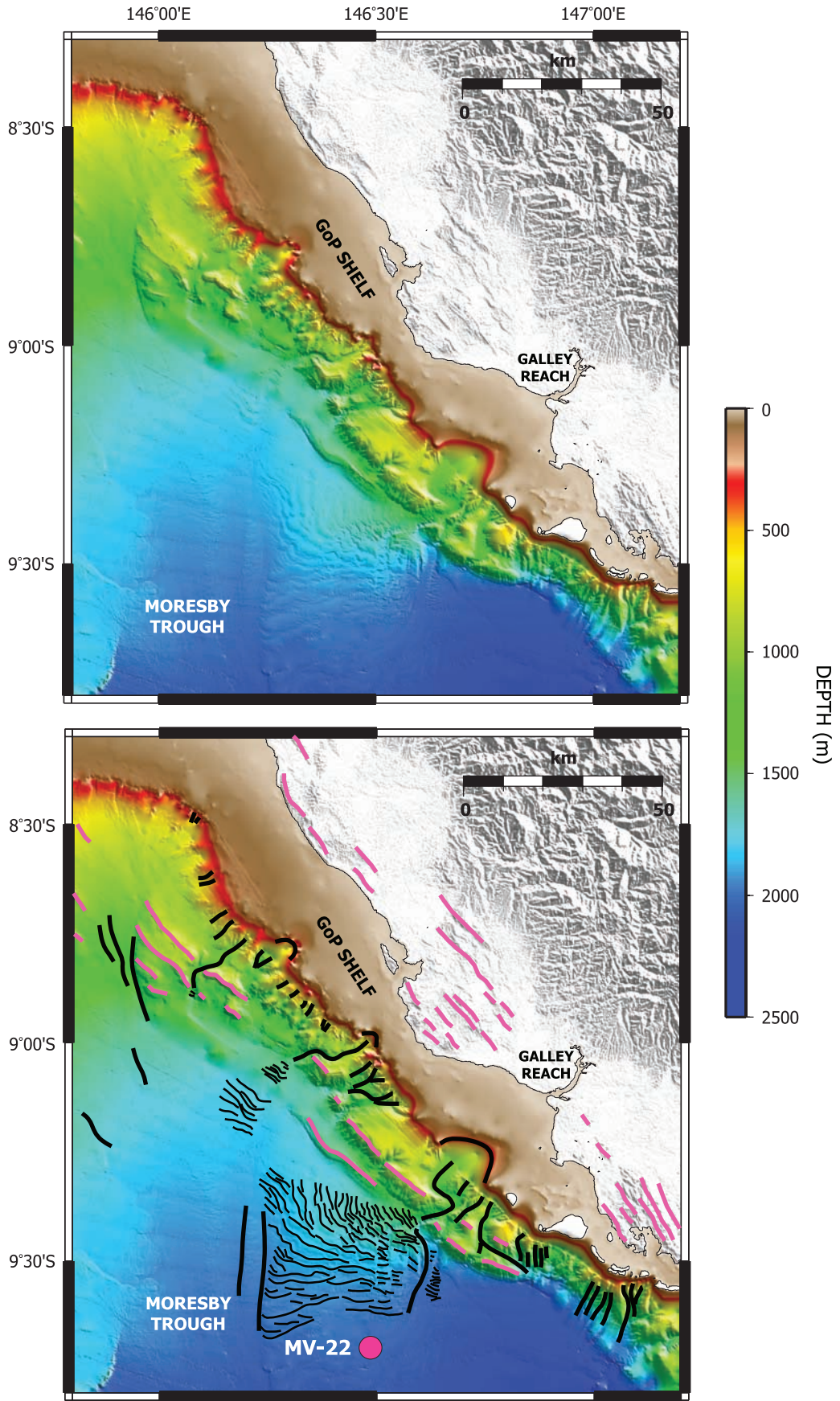


Figure 11



shelf edge. Studies of cores support this assertion, showing relatively high rates of siliciclastic accumulation ( $\sim 2$  mm/a) in cores from the slope of northern Pandora Trough [Walsh and Nittrouer, 2003]. Cores MV-50 and MV-53 (Figure 8) have Holocene siliciclastic accumulation rates of  $\sim 1$ – $3$  mm/a, according to  $^{210}\text{Pb}$  measurements [Muhammad *et al.*, 2008].

[49] The NW–SE trending seafloor ridges located across much of northern Pandora and Moresby Troughs are interpreted here as tectonic in origin, resulting from a Miocene compressional event. Tectonic extension and collision is a major control on the long-term physiographic and stratigraphic evolution of the GoP. The topography of New Guinea also records the Neogene collisional event as a NW–SE trending fold-and-thrust belt that forms the mountainous central highlands [Quarles van Ufford and Cloos, 2005]. In the coastal lowlands, the fold-and-thrust belt reveals itself as a series of parallel to subparallel ridges (Figure 11). Research conducted on ridges in the vicinity of Port Moresby has determined them to be overthrust Oligocene/Miocene carbonates [Davies and Smith, 1971]. Seafloor ridges in Pandora and Moresby Troughs are subparallel to the Papuan fold-and-thrust belt and resemble the tectonic ridges present on the Papuan Peninsula. Seismic observations also reveal these features to be compressional faults in the subsurface [Jablonski *et al.*, 2006]. These seafloor ridges clearly represent the foreland front of the Papuan fold-and-thrust belt.

[50] The slope ridges play an important role in controlling gravity-flow transport direction by acting as barriers and catchments for sediment shed from the shelf edge. The tectonic ridges on the western side of the North Pandora slope affect gravity-flow sediment transport less than the ridges on the eastern slope. This is due to their orientation relative to the direction of slope. On the west, the ridges run parallel to the slope gradient. Therefore they do not act as a barrier as much as they assist in funneling sediment. To the east, the ridges are perpendicular to the slope gradient and intersect sediment that is transported downslope. Bathymetry and 3.5 kHz profile data reveal that many of the ridges on the east side have sediment piled on the updip side (Figures 8, 10 and 11).

#### 4.6. Moresby Trough

[51] The shelf edge and slope between Papuan Peninsula and Moresby Trough (Figure 11) contrast with other GoP margins. First, the shelf is narrow, varying in width from 10 km to 30 km. South of  $9^{\circ}30'S$ , the outer shelf also hosts an almost continuous barrier reef system, although much less extensive than the GBR in the western GoP. Drowned carbonate buildups have been observed at  $\sim 8^{\circ}45'S$  [Droxler *et al.*, 2006]. Pervasive scallop morphology marks the shelf edge, and numerous major canyons dominate the slope,  $\sim 1$ – $5$  km wide and  $\sim 2$ – $20$  km long (Figure 11). Along the northern Moresby slope, the canyons are irregularly spaced, whereas along the southern slope, they have a regular spacing of  $\sim 10$  km. Some of the canyons appear to be diverted by the NW–SE trending ridges. These ridges extend from northern Pandora Trough along the strike of the continental slope into Moresby Trough. They block some canyons but have occasional breaks, from which diverted canyons continue down the slope. Some of the

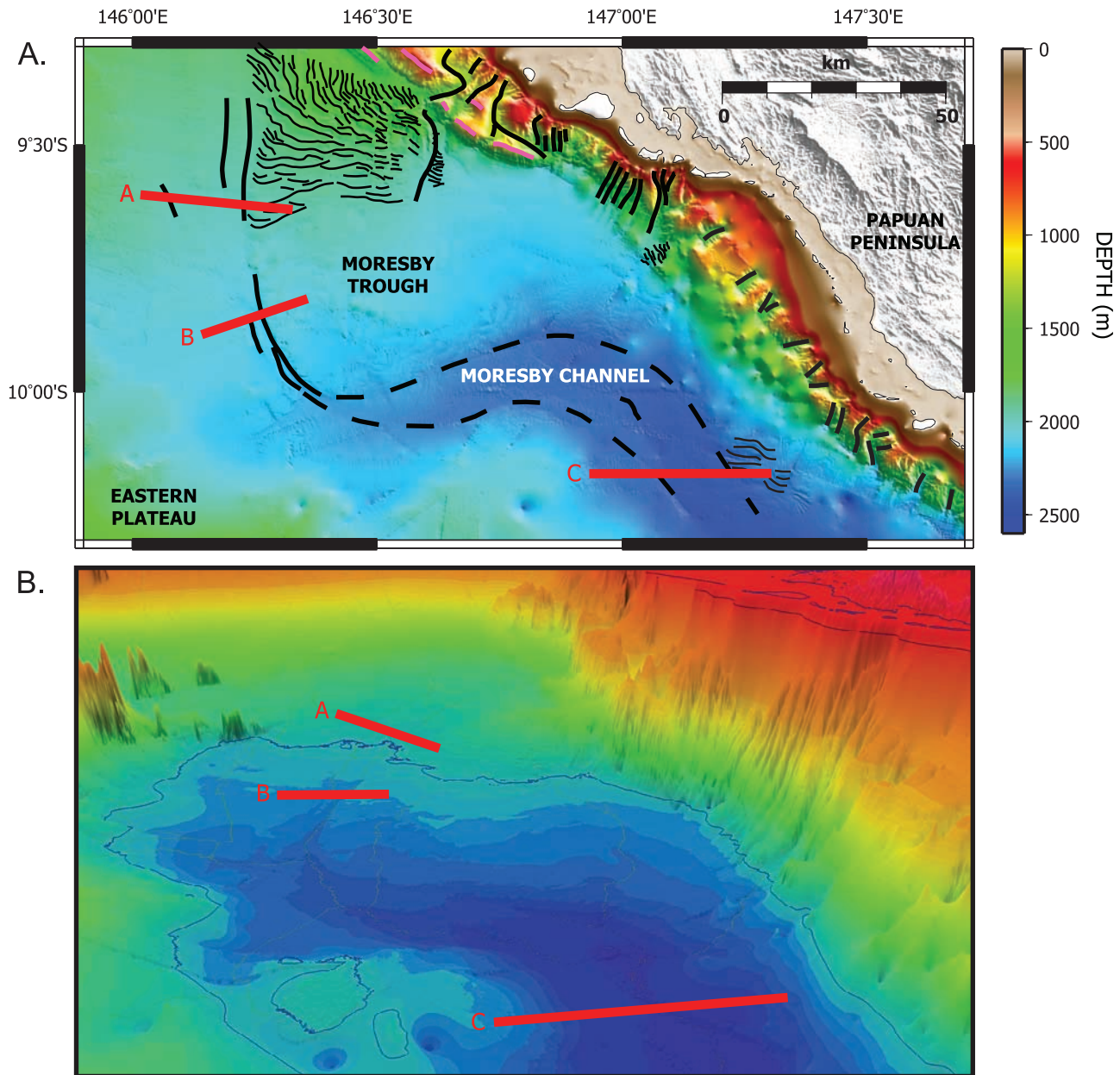
largest canyons extend from large scallop morphology on the shelf edge.

[52] Two prominent features dominate the seafloor of Moresby Trough: a fan and a channel. On the central eastern side, between  $9^{\circ}15'S$  and  $9^{\circ}45'S$  latitude and  $146^{\circ}15'E$  and  $146^{\circ}40'E$  longitude, is a large ( $\sim 2000$  km<sup>2</sup>) sedimentary deposit with an overall fan shape containing sedimentary ridges (Figures 11 and 12). The deposit appears to be fed from one or two of the canyons noted above. The ridges radiate perpendicularly from the canyon mouth and are composed of deformed strata (Figure 13). Moresby Trough also contains a large, well-developed submarine channel (Figures 12 and 13). This channel, fed by several secondary canyons and channels, originates in northern Pandora Trough, and continues into Moresby Trough and Moresby Canyon.

[53] In Moresby Trough the tectonic ridges are also important to understanding the regional sedimentology because they can trap sediment and redirect sediment transport pathways. Anomalously shallow bathymetry on the updip side of several large tectonic ridges (Figures 8, 10, and 11) highlights their trapping effect. Evidently, mounds of sediment have accumulated against the ridges, preventing material from being delivered to Moresby Trough. The best example of the latter effect is the canyon that feeds the large sediment body in Moresby Trough. The canyon head is located at a site of possible shelf edge mass wasting and the canyon extends southwestward downslope until it intersects a ridge. The canyon then heads southeastward and joins another canyon trending southwestward downslope.

[54] The large sedimentary deposit found on the basin floor is interpreted as a MTC, hereafter called “Moresby MTC,” based on morphology, seismic character, and core data. It has an overall fan shape with sedimentary ridges that radiate perpendicularly from a canyon mouth (Figures 11 and 12). Seismic data show the ridges to be composed of faulted and folded strata (Figure 13). They may be either pressure ridges, created by internal compression, or shingled MTDs, where the toe of one flow has moved over an older flow [e.g., Lewis, 1971; Dingle, 1977; Martinsen, 1989; Martinsen and Bakken, 1990; Stow *et al.*, 1996]. Core MV-22, retrieved from distal Moresby MTC, contains sandy siliciclastic turbidites with mineralogy indicative of a Papuan Peninsula source, confirming gravity flow transport from the eastern GoP shelf [Patterson *et al.*, 2006]. The MTC appears to be supplied from a large scalloped margin at the shelf edge (Figure 11). The limited multibeam coverage along the shelf edge leaves the morphology of the scalloped margin poorly constrained.

[55] Moresby MTC differs from Pandora MTC in two notable ways. First, Moresby MTC appears fed from one primary canyon, whereas Pandora MTC seems to be derived from failure at multiple points along the adjacent slope. Consequently, Moresby MTC is more confined at the canyon mouth and has a fan-like morphology and amalgamated MTDs. Pandora MTC, by contrast, is a broad, poorly confined sedimentary body with partial overlap of individual MTDs. Second, Moresby MTC has better defined internal stratigraphy than Pandora MTC (Figures 9 and 13). This may be caused by the type of gravity flow deposits within each MTC. Moresby MTC may be comprised dominantly of turbidites, imaged as well-developed strata,

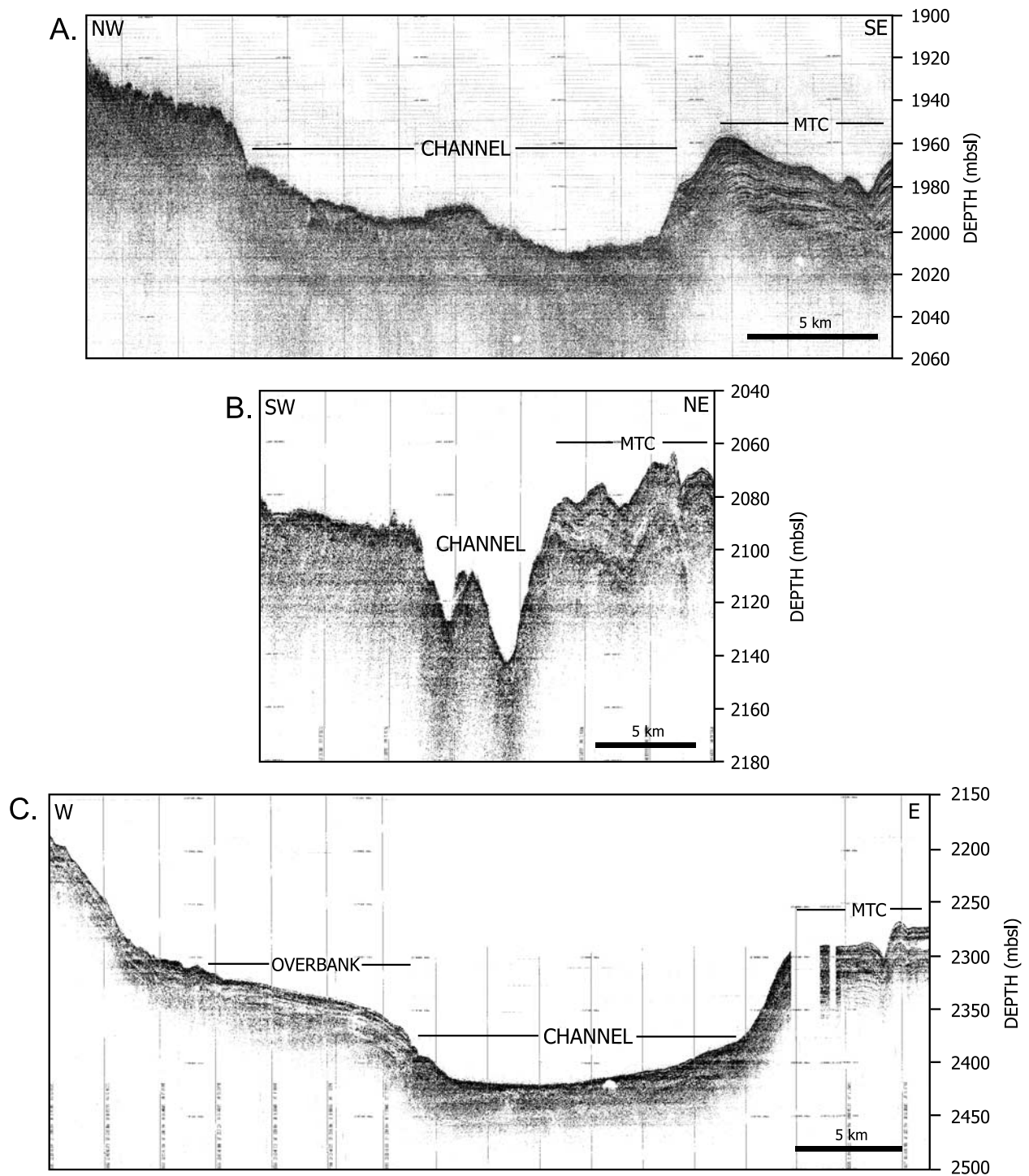


**Figure 12.** Moresby Channel. (a) This figure contains interpreted bathymetric data with shaded relief. Sun-illumination is from the NE. Major physiographic features are labeled. Land is pictured in white and shades of gray. Canyons and channels are highlighted with thick black lines. The boundaries of lower Moresby Channel are dashed to indicate a low angle gradational channel boundary. Narrow black lines highlight sedimentary ridges associated with Moresby mass transport complex. Pink lines highlight tectonic ridges. Red lines indicate the locations of 3.5 kHz seismic lines displayed in Figure 13. (b) This is a NW perspective view of Moresby Trough and Moresby Channel. Blue contour in Moresby Trough indicates the 2000-m isobath. Red lines indicate the locations of 3.5 kHz seismic lines displayed in Figure 13.

while Pandora MTC may be slumps and debris flows, imaged as an internally disorganized mass. However, this cannot be verified with the available data.

[56] The large channel that trends SE down the axis of Moresby Trough is referred to as “Moresby Channel.” It is best developed in southern Moresby Trough and changes character as it extends down the trough, apparently due to changes in gradient (Figures 12 and 13). At ~9°30’S, the channel is 15 km wide and ~50 m deep, and consists of two

parallel subchannels separated by a 10-m bathymetric high. With a slope gradient of ~0.007, Moresby Channel is erosive in this area, downcutting into antecedent topography. In particular, Moresby Channel erodes into the large MTC discussed above (Figures 12 and 13). Farther down-dip, the slope gradient increases to ~0.010, channel incision increases to ~70 m, and channel width becomes confined to 5 km. The master channel remains divided into two subchannels, and the eastern channel shows more erosion than



**Figure 13.** The 3.5 kHz Seismic cross sections of Moresby Channel. Major sedimentary bodies are labeled. Labels A, B, and C relate to line locations on Figure 12, where MTC refers to mass transport complex.

the western channel. At 10°00'S, the channel changes dramatically from a straight N–S trending feature to a channel with a large meander. The slope gradient also flattens to ~0.001, allowing the channel to widen to 20+ km and deepen to ~100 m. It is unclear if the meandering

of Moresby Channel is driven exclusively by the gradient change or if Eastern Plateau has acted as a barrier to influence the change in channel course. This lower segment of Moresby Channel also contains what appears to be a 50+ m overbank deposit on the west side of the channel.

[57] Moresby Channel undoubtedly has served as a major conduit for transporting siliciclastic sediment from the shelf through Moresby Trough and, ultimately, to the Coral Sea Basin. At 50–100 m deep and 5–20 km wide, it is the largest deep water channel in the GoP. The seafloor drainage network indicates that Moresby Channel could potentially be the primary output of gravity flows to the Coral Sea Basin (Figure 3). Thick sequences of siliciclastic sediment (turbidites) confirm that large volumes of sediment have bypassed the slope and were deposited in the Coral Sea Basin. Sediment transported in Moresby Channel is likely fed from the shelf edge adjacent to Pandora Trough and Moresby Trough (Figure 3).

#### 4.7. Eastern Plateau

[58] Most of the seafloor across Eastern Plateau is smooth (Figures 1 and 4) with parallel poorly defined semitransparent seismic reflectors. The smooth bathymetry indicates the long-term accumulation of pelagic and hemipelagic material. MV-63 confirms this with ~280 ka of mixed sediment ranging from 10% to 44% carbonate content [McFadden *et al.*, 2006]. However, regions of the seafloor south and southwest of Eastern Fields Reef display scalloped morphology, similar in size to the scalloped shelf edges of nearby carbonate platforms.

[59] Scalloped morphology can be caused by mass wasting on both carbonate and siliciclastic dominated margins; however, two considerations suggest that these features are likely formed on a carbonate margin. First, Eastern Plateau is not connected to the shelf, precluding rivers from building large accumulations of siliciclastic sediment on the plateau. Second, the scalloped morphology lies along the NE–SW carbonate reef trend that dominates the GoP [Symonds *et al.*, 1991; Sarg *et al.*, 1996; Jablonski *et al.*, 2006; Tcherepanov *et al.*, 2008]. These considerations and the similarity to scalloped morphology along GoP carbonate platforms support the conclusion that, at least, part of Eastern Plateau may be a drowned carbonate platform [Davies *et al.*, 1989; Tcherepanov *et al.*, 2008]. Eastern Fields Reef is likely the segment of the broader platform that was able to grow upward rapidly enough to compensate for sea level change and crustal subsidence. This assertion is supported by seismic data showing drowned and buried reefs north and south of Eastern Fields Reef [Symonds *et al.*, 1991; Tcherepanov *et al.*, 2008]. Fossils from dredge MV-36 were used to approximate an early Miocene drowning of a reef north of Eastern Fields Reef [Tcherepanov *et al.*, 2008] (Figure 4).

## 5. Conclusions

[60] This study presents a wide range of geomorphological features found in deep water environments across the GoP margin. Bathymetric maps were used in conjunction with seismic profiles and cores to describe and interpret the seafloor geomorphology of six GoP slope regions, including intraslope basins: Ashmore Trough, southern Pandora Trough, northern Pandora Trough, Moresby Trough, and the intraslope platforms/plateaus: general carbonate platforms and atolls and Eastern Plateau. Each slope region contains geomorphological elements unique to that area, as well as elements common to the deep water GoP as a whole.

[61] Ashmore Trough, located in the southwestern GoP, contains a very linear northern margin capped by a drowned barrier reef system. This shelf edge is also defined by a broad promontory with abundant slope channels originating from its apex. Geomorphologic data was combined with findings from previous studies [Mallarino *et al.*, 2004; Francis, 2007] to interpret this feature as a relict shelf edge delta. Three large submarine channels, ~2 km wide and 20–40 km long, extend across southern Ashmore Trough. These channels originate along the GBR margin, proximal to scalloped margin morphology, and trend SE toward Bligh Trough. Additional channels are common between carbonate platforms on the eastern edge of this intra-slope basin. In general, the orientation of submarine channels suggests Ashmore Trough has undergone significant sediment bypass.

[62] Southern Pandora Trough, lying to the north of Ashmore Trough, is characterized by a very irregular shelf edge with extensive scalloped morphology and slump scars that extend down the upper slope. Additionally, the slope is marked by pervasive southeastward trending slope channels that extend to the intraslope basin floor. Here, a large portion of the Pandora trough floor is occupied by a mass-transport complex, identified by characteristic pressure ridges. The remaining intra-slope basin floor is relatively smooth and filled with extensive turbidites [Jorry *et al.*, 2008]. Overall, the southern Pandora Trough upper slope has undergone extensive mass-wasting and mass-transport processes, transporting and accumulating sediment in the intraslope basin floor depocenter.

[63] Northern Pandora Trough has scalloped margin morphology but differs from southern Pandora Trough in that there are few visible slope channels. Seismic observations reveal that clinoforms prograded to the northern Pandora Trough shelf edge and fed a wedge of sediment that extends down slope and fills in the preexisting bathymetry. These observations in conjunction with rapid Holocene siliciclastic accumulation rates of ~1–3 mm/a [Muhammad *et al.*, 2008] support the idea that slope channels may be buried features along northern Pandora Trough. This region is also characterized by a series of NW-SE oriented ridges representing the foreland front of a Papuan fold-and-thrust-belt. These ridges can act to divert and/or catch gravity flows depending on sediment transport direction. In summary, the seafloor geomorphology of northern Pandora Trough is dominated by recent sediment accumulation which fills in the preexisting bathymetry and is additionally influenced by tectonic ridges which partially control sediment transport.

[64] Moresby Trough, along the western GoP, is characterized by several prominent features. The Papuan Peninsula shelf edge, NE of the intraslope basin, is marked by some of the largest scalloped morphology in the GoP. Downdip from this shelf edge is an extensive system of slope canyons, many of which are intersected by fold-and-thrust-belt ridges. Similar to Pandora Trough, these ridges act to catch gravity flows and in some instances divert flow direction. Along Moresby Trough, the ridges trend perpendicular to slope and collect deposits supplied from the Papuan Peninsula shelf and slope. Individual mass transport deposits and a large mass transport complex (~2000 km<sup>2</sup>) are located on the floor of Moresby Trough. These features have distinct NW-SE trending pressure ridges, supporting a

NE source. The geomorphology suggests these mass transport deposits originated from the scalloped features of the Papuan Peninsula shelf edge and were transported to the intraslope basin floor through the slope canyon system. Moresby Trough also contains a large axial submarine channel that extends from northern Pandora Trough along almost the entire length of the intraslope basin, potentially supplying sediment to Moresby Canyon. In summary, sediment accumulating in Moresby Trough is transported from the GoP shelf to the NW, as well as the Papuan Peninsula to the NE. A well-defined axial channel suggests that some material bypasses Moresby Trough and may ultimately accumulate in the Coral Sea Basin.

[65] Carbonate platforms/atolls within the GoP are all characterized by high-gradient margins and very pronounced scalloped-margin morphology. For example, slope gradients up to 45° were measured along Eastern Fields Reef. The scalloped morphology may indicate pervasive mass-wasting processes along the GoP carbonate margins.

[66] Distinct scalloped margin morphology is also observed along the dominantly carbonate northwestern portion of Eastern Plateau. Most of the plateau is characterized by parallel seismic reflectors, suggesting, in conjunction with cores data, that accumulation on Eastern Plateau is primarily mixed pelagic and hemipelagic sediment.

[67] This study describes diverse morphologies found in the GoP related to spatial and temporal differences in sediment transport and accumulation. Features found along the GoP shelf edges, slopes, and intraslope troughs indicate distinct alternations between regions and intervals dominated by gravity flow processes and suspended sediment deposition. Pervasive gravity flow processes led to mass wasting of the shelf edge, slump scars, canyons, channels, mass transport deposits, and the accumulation of large amalgamated gravity flow deposits (Pandora and Moresby Mass Transport Complexes). This contrasts regions and intervals of relative quiescence in which material was delivered to the deep water primarily as suspended sediment, leading to sediment drapes, sediment wedges, and regions of more diffuse sediment input. This study provides an important preliminary understanding of recent deep water processes, as well as the long-term margin evolution across the Gulf of Papua.

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