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Research paper

Seismic architecture of a Miocene isolated carbonate platform and associated off-platform strata (Central Luconia Province, offshore Malaysia)

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ABSTRACT

Rather than being homogeneous and isotropic, many isolated carbonate platforms in the geologic record include internal heterogeneity and complex geometric relations with off-platform strata on their flanks. To better understand stratal architecture of a Miocene isolated platform (Central Luconia, offshore Malaysia), this study integrates core, log and seismic data, revealing stratal terminations and geometries that define several seismic stratigraphic units. A thick in the basal seismic unit, the initial deposits of the carbonate buildup, is 4–5 km across. This thick includes abrupt thinning to the west and east, with onlap onto its flanks, but continues outside of the survey area to the north and south. Above a mappable surface, a less extensive (2 × 5 km) seismic unit represents a backstepped isolated platform (Platform Stage 1). Across a pronounced normal fault on the east/southeast margin of the platform occur marked isochron and seismic character changes, with thicker carbonates on the downthrown (western) block. The northern and western margins are not faulted. A third seismic unit, representing a smaller, elongate (< 1 × 3 km), N-S trending carbonate platform (Platform Stage 2), reflects a second backstep. The top of this unit in core is associated with karst, suggesting subaerial exposure; the surface can be traced off the platform and across the fault, to an (upthrown) area with irregular amplitude and similarity, interpreted to represent karst. These strata – and several other reflectors that dim and decrease loop duration away from the buildup ("wings") - sit atop one of a series of north-prograding clinoforms (siliciclastic "wedges"). In turn, two chronostratigraphically distinct wedges that onlap and thin away from the thick of Platform Stage 2 are interpreted to be carbonate (platform stages 3 and 4), and are onlapped by another succession of off-platform clinoforms (interpreted as siliciclastic). All of these strata are capped by another elongate (< 1 × 2 km) seismic unit (Platform Stage 5), before the platform is covered with siliciclastics.

The most marked stratigraphic theme within the isolated platform is the successive backsteps, but the pattern is complicated by interactions with the basinal strata. Superposition and cross-cutting relations document that isolated platform-sourced flanking beds ("wings") interfinger with basinal clinoforms ("wedges"), as defined by geometries on the margins and flanks of platform stages. The platform evolution also was influenced markedly by syndepositional structural activity, although structural trends changed from the initial buildup to later platform stages. The results, and comparison with other isolated platforms, demonstrate the complex controls on carbonate platform growth and interactions with basinal siliciclastics.

1. Introduction

Many Holocene carbonate accumulations form flat-topped edifices that include shallow blue-green lagoons rimmed by reefs or shoals, and surrounded by dark blue, deep open-ocean water. This 'simple' geomorphic arrangement evident in hundreds of Holocene isolated carbonate platforms belies the complex stratigraphic architecture evident through the initiation, expansion, and demise of their ancient relatives in the geologic record. This complexity reflects time-integrated impacts of the variable influences that can shape the origin, transport, and accumulation of carbonate sediment.

The Central Luconia Province of offshore Malaysia (South China Sea) is particularly well endowed, with more than 200 carbonate platforms of Oligocene to Recent age. The area represents a natural laboratory to explore isolated platform systems, in part because many of these accumulations form proved hydrocarbon reservoirs, and thus

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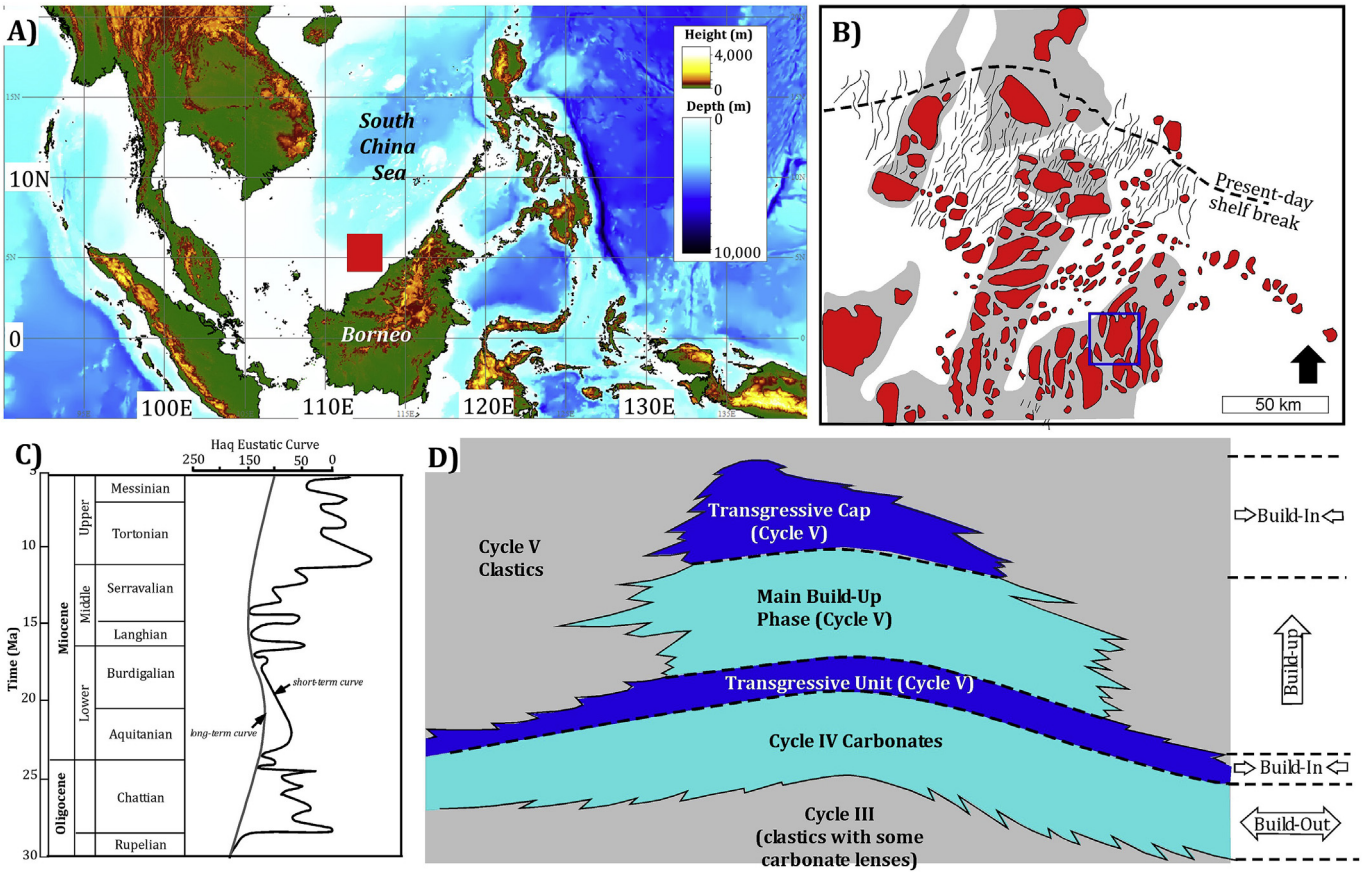

Fig. 1. General setting, Central Luconia carbonates. A) Map illustrating the location of Central Luconia, South China Sea, offshore Borneo, in the red square B) General Middle Miocene paleogeographic map of Central Luconia. In this area, general structural highs (greys) and lows (unshaded) set the framework for almost 200 isolated carbonate platforms (red shades). Similarly, a number of faults (black lines), related to the overall structural setting and generally oriented NE-SW, appear to have influenced the growth and development of many isolated platforms. Field EX lies within the blue-outlined square. Compiled from Ting et al. (2011), Menier et al. (2014), and Koša et al. (2016). C) Miocene sea-level curve. Modified from Haq et al. (1987). D) General conceptual model for growth patterns of a generalized, idealized Central Luconia buildup, after Epting (1980). Of note is the interpretation of general growth stages and the interfingering between platform carbonates and off-platform siliciclastics. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

have a wealth of data across a range of settings. As such, regional summaries of Central Luconia carbonates have emphasized the end-member differences in the growth patterns of isolated platforms and their relations to contemporaneous basinal siliciclastic sediment (e.g., Epting, 1980; Vahrenkamp et al., 1998; Koša et al., 2016).

An important key to unraveling the growth patterns of isolated carbonate platforms in the subsurface is identifying and mapping seismic stratigraphic variations, defined using stratal terminations, superposition, and seismic geometries. In this context, the purpose of this paper is to describe details of the architecture of a Middle to Upper Miocene isolated carbonate platform of Central Luconia and its interactions with adjacent siliciclastic strata using seismic stratigraphy. Integrated seismic data, two cores, and well log suites of this succession provide the basis for interpreting its seismic stratigraphy and architecture, and evaluating controls on its growth and demise. Results reveal that although many parts of the isolated platform appear to have broadly tabular geometry, syndepositional structural deformation and interaction with adjacent basinal siliciclastics created complex geometries near the margins and flanks of the platform throughout its evolution. These data, and comparison with other isolated platforms, reveal that although patterns and trends among these platforms are evident, the detailed stratigraphic record of each is shaped ultimately by local and regional contingencies.

2. Background

2.1. Terminology

Numerous publications have described and used various terms to describe large scale accumulations of carbonate sediment, leading to some inconsistencies (for example, compare Wilson, 1975; Read, 1985; Tucker and Wright, 1990; James and Kendall, 1992; Blendinger et al., 2004; Bosence, 2005; Wilson and Hall, 2010; Burgess et al., 2013). This paper follows Wilson (1975), who originally defined a carbonate buildup as a "body of locally formed (laterally restricted) carbonate sediment which possesses topographic relief," a general term that includes carbonate accumulations with broad spectrum of morphologies. Herein, this term is used in a broad sense of a carbonate accumulation with no explicit implications in regards to size, relief, or depositional gradients. In contrast, isolated carbonate platforms are a specific subset of carbonate buildups, defined as detached, broadly flat-topped shallow-water carbonate accumulations surrounded by deeper water (cf. Wilson, 1975; Read, 1985; Handford and Loucks, 1993). As used herein, isolated carbonate platforms also include a diverse range of facies, an attribute that distinguishes them from features such as patch reefs, but have no predefined lateral or vertical scale (cf. Wilson, 1975; Wilson and Hall, 2010; Burgess et al., 2013). At greater detail, the flanks of these isolated platforms include reflectors that extend outward, into the surrounding basinal strata, colloquially termed stringers or wings (e.g., Burgess et al., 2013; Koša et al., 2016). These reflectors

can downlap, lose amplitude and loop duration, or both, away from the platform.

2.2. Geologic framework

The Central Luconia Province is a broad and generally stable part of the 200–300 km wide shelf in the Sarawak Basin, offshore Borneo. The present-day seafloor slopes gently away from the shoreface of Borneo, and the Central Luconia region lies in water depths of 60–140 m. It passes to the north-northeast into the continental slope, and ultimately the abyssal South China Sea.

At the largest scale, the area was shaped by regional extension and sea-floor spreading in the South China Sea to the north, starting in the Oligocene (Taylor and Hayes, 1983; Hall, 1996). This extension established a regional pattern of horst and graben structures, and although the age of the end of sea-floor spreading is debated (Taylor and Hayes, 1983; Hall, 1996), it is generally considered to persist into the Early Miocene. By the Middle Miocene, compressional phases, perhaps associated with the Sabah Orogeny of the Balingian Province to the south (Lunt and Madon, 2016), sporadically influenced Central Luconia. These extensional and compressional phases are manifest in the Lower Miocene strata of Central Luconia as regional faults, and associated highs and lows (Fig. 1B). This bathymetric and tectonic differentiation, coupled with long-term relative changes in sea level during the Early to Middle Miocene (Fig. 1C) and variable siliciclastic input, influenced the initiation, growth, and demise of carbonate buildups at several scales (Fig. 1; Epting, 1980; Taylor and Hayes, 1983; Ting et al., 2011; Jamaludin et al., 2014).

During the Middle Miocene, a relative rise in sea level (Fig. 1C) and a decreased rate of siliciclastic influx to Central Luconia led to initiation of carbonate production in over 200 carbonate buildups across the province. Important north-to-south differences are evident, however, including: 1) the carbonate platforms to the south (e.g., the area of this study) are thinner (< 500 m), include less depositional relief, and terminated earlier than the thicker (some approach 3000 m), higher-relief isolated platforms to the north (e.g., Epting, 1980; Vahrenkamp et al., 1998; Bracco Gartner et al., 2004; Masaferro et al., 2004; Vahrenkamp, 2004; Zampetti et al., 2004); 2) Middle-Late Miocene siliciclastics sourced from NW Borneo and the Baram deltas interact with and ultimately cover the Miocene isolated platforms to the south, whereas younger (Latest Miocene to Pleistocene) northward-prograding siliciclastics covered younger isolated platforms to the north and northwest, although some remain uncovered still, and form bathymetric highs on the seafloor today.

Regional Sarawak stratigraphy has been subdivided into 8 regional 'cycles,' numbered from I through VIII, that range in age from Eocene to Present (Ho, 1978; Doust, 1981; see review in Lunt and Madon, 2016). Although the exact nature and significance of these cycles is still debated (Lunt and Madon, 2016), they provide a stratigraphic framework that has been tied into the area of Field EX (Fig. 1B), and reveal that the Miocene strata on which this study focuses include carbonates of Cycle IV and Cycle V (Fig. 1D).

Early publications (most notably the seminal paper of Epting, 1980) on carbonate buildups of the area described much of the essence of their stratigraphy, by reference to various stages of development. These stages include build-out (rate of carbonate production and accumulation greater than rate of sea-level rise), build-up (rate of carbonate accumulation similar to rate of sea-level rise), and build-in (rate of production and accumulation less than the rate of sea-level rise), the latter including a backstepping stage and a drowning stage (cf. Kendall and Schlager, 1981; Schlager, 1992). These general attributes were captured in a conceptual model of typical growth patterns evident in Central Luconia buildups (Fig. 1D, from Epting, 1980).

EX represents the first Central Luconia gas field, discovered in 1971 with well EX-1. After drilling the vertical appraisal wells EX-2 and EX-3, numerous deviated development wells were drilled. The field is a stratigraphic trap, with a carbonate buildup reservoir encased in shales. The field has been the subject of numerous geological and seismic studies, including Epting (1980), Bracco Gartner et al. (2004), Zampetti et al. (2004), and Jamaludin et al. (2014).

2.3. Well and seismic data

The data available and utilized for this study include cores from two wells that partly penetrate the succession, wireline log suites for three wells, and a seismic volume. The facies and stratigraphy of the cores will be described in detail elsewhere, such that here only the highlights relevant to seismic interpretation are discussed.

Seismic data (processed last in 2004, central frequency 22 Hz) from Field EX provided the basis for seismic stratigraphic interpretation. Seismic data include 272 inlines and 582 crosslines in an area of ~28 km^2. Data were processed to zero phase, SEG normal polarity, such that a downward increase in acoustic impedance is a peak (red on figures herein, unless noted). The inlines are spaced at 25.0 m and crossline spacing is 12.5 m. These data included acquisition, processing, and geological (including gas effects) artifacts that limited quantitative analysis, and even stratigraphic interpretation in parts of the survey.

Well-log data indicate that sonic velocity varies vertically and laterally, related to changes in rock type (siliciclastic, carbonate), and within the carbonates, due to changes in porosity and mineralogy (limestone, dolomite). To a first approximation, given the dominant frequency (22 Hz) and assuming an average velocity of 3750 m/s in the carbonate succession, vertical resolution of these data is roughly 43 m. This velocity also is used to estimate thicknesses in the descriptions below (thickness = velocity * TWT/2), with TWT noted parenthetically.

The seismic interpretation workflow in Kingdom Suite subdivided the succession into seismic units separated by surfaces defined based on stratal terminations, including toplap, downlap, onlap, and erosional truncation (Mitchum et al., 1977). As documented by seismic-well ties (see below), some horizons (e.g., top carbonate, a downward increase in impedance) are carried on amplitude peaks; others within the carbonates are mapped on amplitude troughs, reflecting a downward decrease in impedance (lower density, velocity) related to either higher porosity or more argillaceous material. In the basinal succession off the platform, each peak and several high-amplitude continuous troughs provided markers that were carried throughout their extent. Surfaces were carried on an orthogonal grid with spacing of 5 lines, but locally interpreted line-by-line, then interpolated.

Seismic units and seismic stratigraphic surfaces defined by stratal terminations include varied character, as reflected in distinct isochron, local gradient, amplitude, time structure, and quantitative seismic attributes. Platform margins and off-platform areas have limited available well penetrations in this survey; additionally, even some seismic units that comprise the platform are not penetrated by cored wells. As a result, geological interpretation of these areas is only partly constrained.

To evaluate the geological significance of individual reflectors, the two cored vertical wells with sonic and density logs that penetrate the platform were tied to the seismic volume via synthetic seismograms. Although reflectors are caused not solely by one interface, but rather represent a composite impact of many interfaces, this approach provides a means to integrate the different scales of data. This study used Kingdom Suite SynMod to extract wavelets, calculate reflection coefficients, and generate the synthetics; each well had check shots through the interval and at the base of the well.

3. Strata and sediment

The three vertical wells, two of which have cores, illustrate a large-scale zonation of the field (Fig. 2). The thickest well penetration, in EX-1, includes a largely carbonate succession in excess of 1800 ft. (~550 m) thick, but it is not cored. The other two wells include 1190 ft

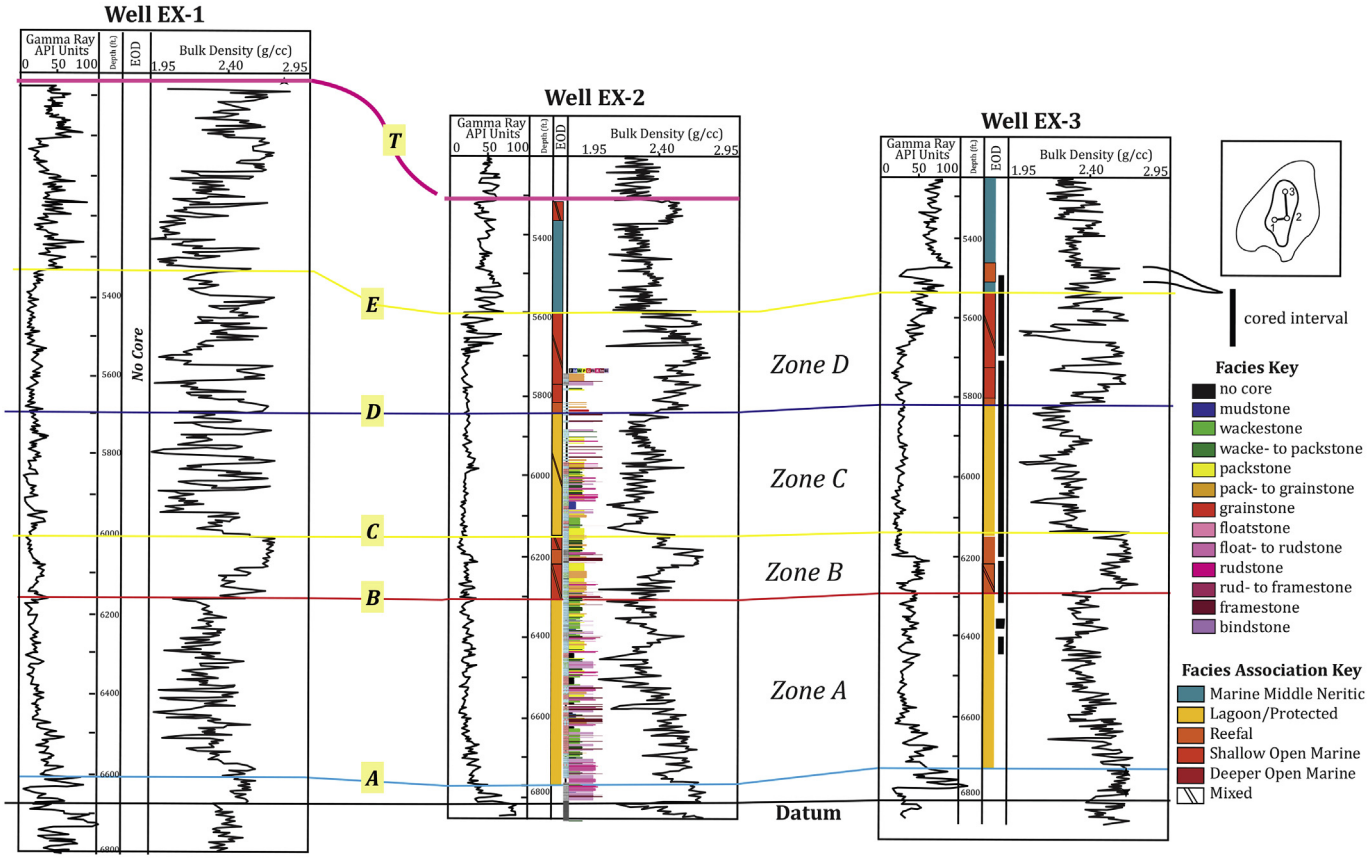

Fig. 2. Well-log cross section through EX field, modified after Ali (2013). The well logs, as calibrated to core, indicate several zones of alternating high-density and low-density intervals. The tops and bases of these zones are noted by alphabetical names (A, B, C, D, E, and T), with each zone named on the basis of the underlying surface. These zones are correlative among the wells, except the uppermost zone (above E). Facies are from our core descriptions, facies associations are from Ali (2013). See text for discussion.

(~362 m; EX-3) and 1180 ft. (~360 m; EX-2) successions of carbonate (both limestone and dolomite) with a few units of argillaceous carbonate. Details of facies and diagenesis will be documented elsewhere; only the first-order trends are illustrated here.

Below the carbonates of cycles IV and V lies a thick succession of mixed carbonates and siliciclastics of Cycle III. Although not described in detail as part of this study, these deposits have been described as "thinly interbedded calcareous/dolomitic claystone and argillaceous floatstone and rudstone with thin intervening calcareous shale/claystone and argillaceous bindstone/bafflestone" (Ali, 2013, p. 238). These deposits were interpreted to represent shallow inner shelf environments.

At the largest scale, the cored carbonate succession can be subdivided into six reservoir zones in these wells, with zones of lower impedance alternating with intervals of higher impedance. The basal, low impedance interval (Zone A; Fig. 2) ranges in thickness between 439 and 463 ft. (134–141 m). It's base corresponds with the Horizon 1 of Zampetti et al. (2004). This interval is cored completely in well EX-2, where it includes a succession that passes upward from an interval with dominant coral rudstone and floatstone (Fig. 3A and B), to a succession of more common wackestone and packstone that include abundant benthic foraminifera and coralline red algae. This interval is more dolomite-prone than younger strata, and also includes the gas-water contact.

Zone B, a higher impedance interval, is between 145 and 164 ft. (44–50 m) thick in the wells. It is cored in both EX-2 and EX-3, and both cores reveal fewer rudstone, floatstone, and grainstone strata than Zone A, and more abundant foraminiferal and red algal wackestone and packstone strata (Fig. 3C and D), and an argillaceous interval in EX-2. At the base of this zone (~6300 ft depth, 1920 m) in well EX-2, unpublished PETRONAS biostratigraphic reports (Mohamed and Hasan, 2000) document planktonic forams, larger benthic forams (*Cycloclypeus* spp., *Miogypsina* spp. *Miogypsina thecideaformis*, and *Lepidocyclina* spp.), and smaller benthic forams including rotaliids and miliolids. Nonetheless, the stratigraphic position of the upward increase in density and velocity (e.g., the impedance contrast at base of Zone B) appears to have been impacted by diagenesis, and is ~15 m lower than the argillaceous zone evident in core (as suggested by Zampetti et al., 2004). In well EX-3, strata of Zone B (from 6246 to 6164 ft, 1904–1879 m) include *Cycloclypeus* spp. and *Lepidocyclina*, fauna, and this interval locally (6175 ft, 1882 m) includes common planktonic foraminifera; the fauna and facies of these strata were interpreted to represent "a transgressive event" (Mohamed and Hasan, 2000). In well EX-2, the top of Zone B is picked at ~6143 ft. (1872 m), a level roughly coincident with the Middle to Late Miocene contact, which was identified biostratigraphically at 6129 ft. (1868 m), and is the approximate position of Horizon 2 of Zampetti et al. (2004).

Zone C represents a thick lower impedance interval, of thickness between 304 and 319 ft. (94–97 m), that is cored in both EX-2 and EX-3. This zone includes a lower succession (< 150 ft. (46 m) thick) of wackestone to packstone with common foraminifera and coralline red algae, strata that locally are dolomitized. These deposits pass upward into deposits with more abundant floatstone and rudstone with some framestone (Fig. 3E), and less common dolomite. This interval is the most consistently coarse-grained part of the entire succession.

An abrupt upwards increase in impedance defines surface D, the base of Zone D. The succession is incompletely cored in well EX-2, and more continuously cored in EX-3. Both wells consists of a succession of

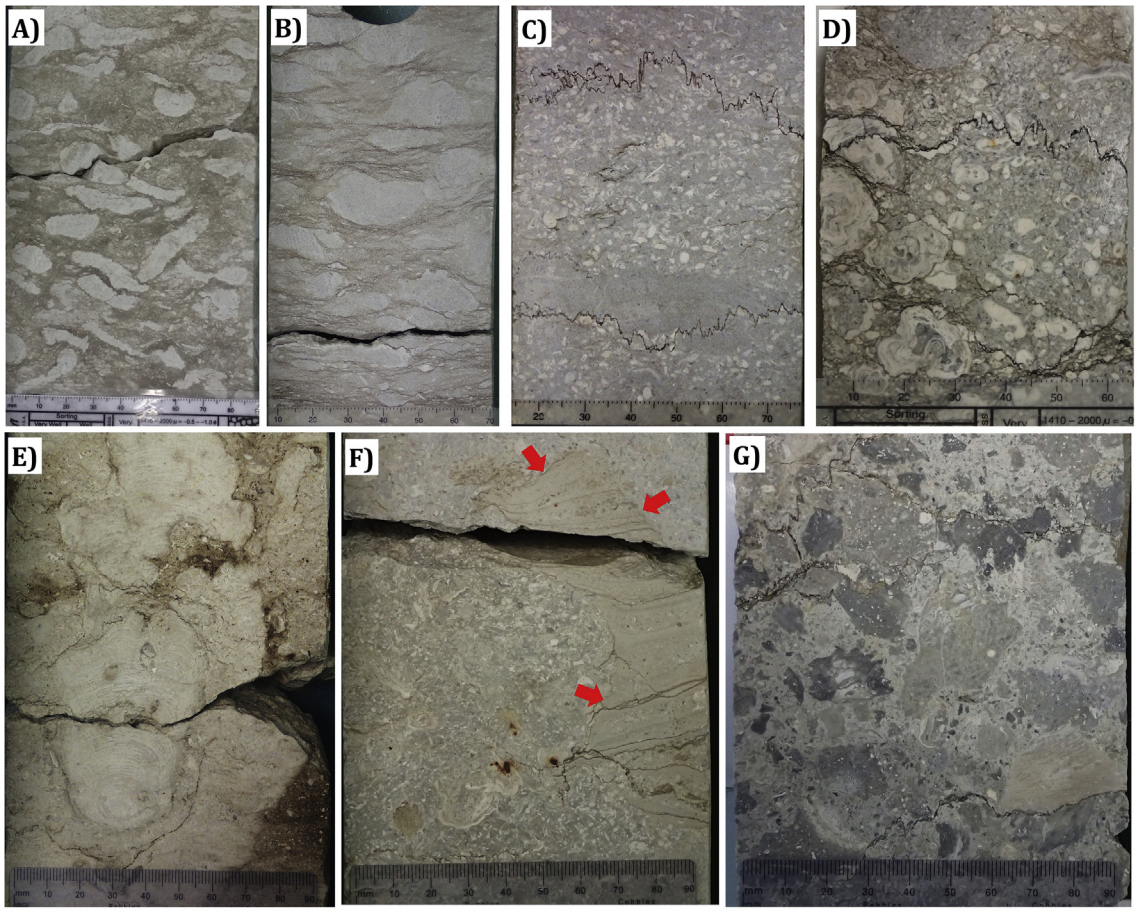

Fig. 3. Core photographs of representative facies. A) Dolomitized coral rudstone. EX-2, 6775 ft. (Zone A); B) Dolomitized coral floatstone with wackestone to packstone matrix. EX-3, 6370 ft. (Zone A); C) Tight skeletal packstone. EX-3, 6269.5 ft (Zone B); D) Tight red algal-foram-skeletal floatstone with packstone matrix, EX-3, 6250 ft. (Zone B); E) Coral framestone with skeletal packstone matrix, EX-3, 5921 ft. (Zone C); F) Skeletal packstone, abrupt truncational contact with later laminated wackestone (red arrows), EX-3, 5579 ft. (near top Zone D); G) Intraclast-lithoclast breccia, EX-3 5540 ft. (above Zone E). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

wackestone to packstone, with some grainstone, but generally are muddier and include much less dolomite in Zone D than in the older zones. The gamma-ray readings increase upward within this section in the wells, and this unit includes considerable variability in density (Fig. 2). In well EX-2, the interval above surface D documents planktonic foraminifera (*Globigerinoides* and *Orbulina*) and *Cycloclypeus* spp., interpreted to represent "a general transgressive trend" (Mohamed and Hasan, 2000). In Zone D (5768 - 5588 ft depth, 1758–1703 m) in well EX-3, elevated gamma ray and the foraminifera were interpreted to suggest an "overall transgressive trend" (Mohamed and Hasan, 2000). Nonetheless, a pronounced karst interval is evident in core of well EX-3 below the top of carbonates (Fig. 3F).

Well EX-1 penetrates 542 ft. (165 m) of additional carbonate strata above zone D, an interval not present in the other two cores. This succession is uncored in this well, so textural and biostratigraphic details are unknown, but it appears to include two distinct zones. A basal, low density (porous dolomitic) interval 311 ft. (95 m) thick is overlain by a 231 ft. (70 m) zone of higher impedance and higher gamma ray, perhaps reflecting a tight argillaceous carbonate interval. The carbonates are abruptly overlain by shale. Carbonate stringers above Zone D are cored in well EX-3, where they include coarse intraclast-lithoclast rudstone (Fig. 3G).

In addition to these vertical wells, well reports from a number of deviated development wells provide additional information on stratal attributes. Because these wells include no core, are deviated, do not have checkshots, and (many) occur in areas of steep flanks with possible migration issues, these data were used only qualitatively.

4. Seismic character

4.1. Seismic-well tie

In the survey area, the only available two vertical cored wells with sonic and density data were the EX-2 and EX-3 wells, both of which penetrate the buildup; the third well (EX-1) includes logs but no core. No log data were available for off-platform or platform-marginal areas, hence the precise nature of those strata is much less well constrained.

Construction of synthetic seismograms aids in understanding the nature and controls on seismic reflections. Given the relatively low frequency of the available survey (22 Hz), the first-pass interpretation used the large-scale reservoir zones to subdivide the strata. Synthetic-to-seismic ties are qualitatively reasonable (Fig. 4).

These synthetics reveal that the base of low-impedance reservoir zones (base of zones A, C, and E; downward transition from soft to hard) are manifest as peaks, the tops of these zones (hard to soft) occur as troughs. Comparison with Zampetti et al. (2004) suggests that the base of Zone A corresponds with their Horizon 1, the base of Zone C is their Horizon 2, and the top of Zone E is their Top Carbonate reflector at location of wells EX-2 and EX-3. As illustrated above (e.g., Fig. 2) and below, and as recognized by Zampetti et al. (2004), the top of carbonate is not a chronostratigraphic surface across the area.

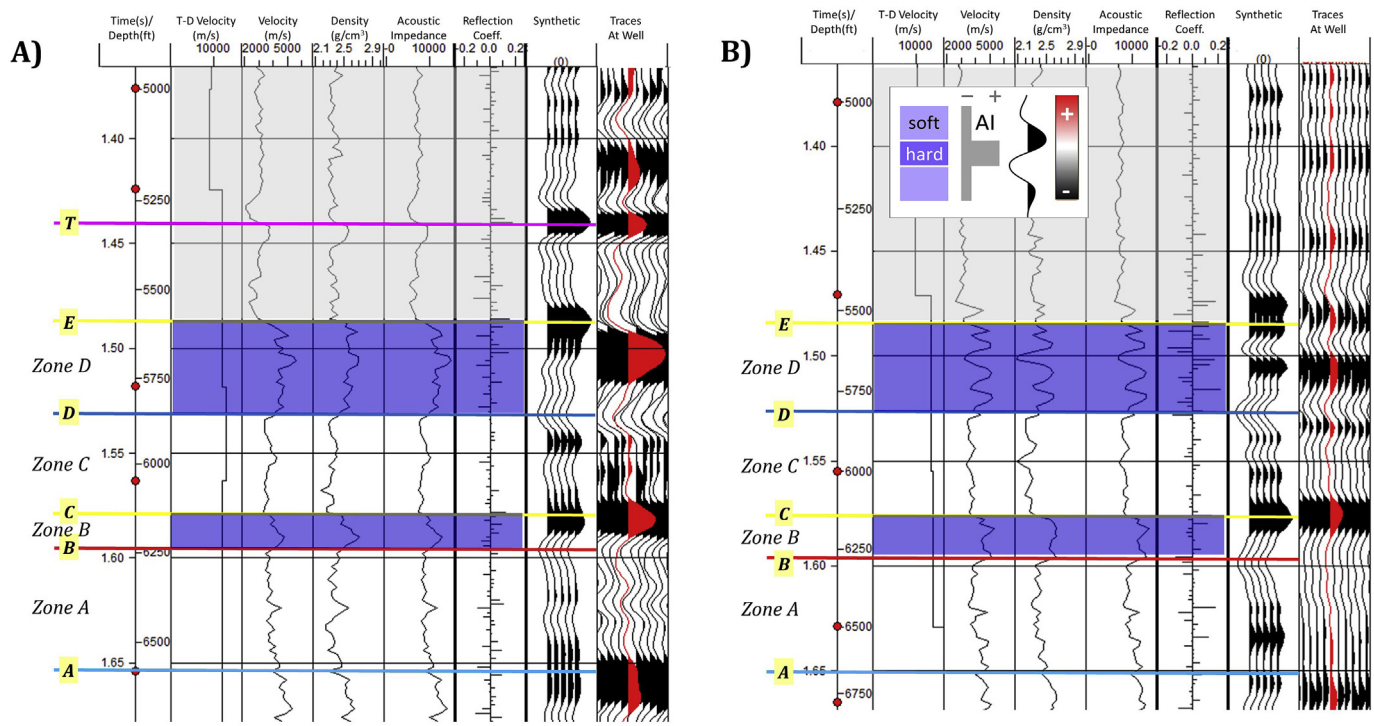

Fig. 4. Seismic-well tie for the two vertical wells with sonic and density logs. A) Well EX-2. B) Well EX-3. Note that the tops of low density and low velocity (low impedance) zones (e.g., surfaces B and D) correspond to troughs, whereas the tops of high density and high velocity intervals (e.g., C and E, shaded dark blue) are peaks. Note the qualitatively robust synthetic-to-seismic tie. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4.2. Seismic stratigraphy

The extension of the synthetic-well ties to the seismic data reveal a carbonate accumulation that consists of several distinct seismic stratigraphic units, defined by stratal terminations. Carrying these horizons off the platform shows their relations to associated basinal strata.

Seismic Unit 1 is underlain by Horizon A (a peak; blue on figures), capped with Horizon B (a trough) (Fig. 5A). Calibration to the synthetic reveals that Horizon A corresponds to the shift from mixed carbonate-siliciclastic to dominantly carbonate strata, and Horizon B approximates the top of the lower, porous dolomite-prone reservoir zone. Horizon A is cut by numerous, steep (dominantly) normal faults that trend north-south to northeast-southwest, and include offsets of up to 56 m (30 ms TWT) (Fig. 5B). Most faults do not extend completely through the entire unit, but instead terminate within Seismic Unit 1 (Fig. 5A), with a few important exceptions (described below).

Thicknesses of Seismic Unit 1 range from less than 37–168 m (< 20 ms–90 ms TWT) (Fig. 5A,C), with a well-defined north-south trend of thicker strata which define a stratal body with extent of up to 4–5 km across. The eastern margin of this thicker package corresponds with location of faults locally. Nonetheless, the fault that extends through Seismic Unit 1 (and above) with the largest offset (Fig. 5A) is not associated with changes in stratal thickness (Fig. 5C). Internal seismic character of Seismic Unit 1 is highly variable in amplitude and continuity, and some lines include hints of stratal geometries within Seismic Unit 1, but they are not readily mappable.

Interpretation. Based on the core characterization and biostratigraphy, Seismic Unit 1 corresponds with the Stage IV buildup (termed the "Mega Platform" or "Megabank" by earlier workers such as Vahrenkamp, 1998, and Koša, 2015; cf. Epting, 1980). The stratal thinning associated with onlaps in overlying strata on the east and west flanks of the thick is interpreted to reflect depositional shelf margins of a north-south oriented carbonate buildup. The location of the sharp change in isochron on the eastern margin of the buildup corresponds to the location of mapped faults, suggesting a possible fault control, at least locally (Fig. 5A,C). Although there are faults which cut Horizon A near the western margin, orientations are distinct and they are not associated with stratal thinning, and hence do not appear to have exerted similar control.

Seismic Unit 2 is underlain by Horizon B (a trough), includes Horizon C (the first peak above Horizon B; yellow on figures), and is capped by Horizon D (a trough; dark blue with white dashes on figures) (Fig. 6A). Both Horizon B and Horizon C are parallel and continuous across the survey. The synthetic-well ties indicate that Horizon C represents the top of a denser and less porous zone, and it appears that it is this surface which is onlapped as Seismic Unit 1 thins. Horizon D is restricted to a less extensive (*ca* 2 × 5 km) area than the megabank of Seismic Unit 1; it downlaps onto Horizon C.

Thickness of Seismic Unit 2 averages ~75 m (40 ms TWT), but reaches up to 118 m (63 ms TWT), with subtly thicker areas in excess of 113 m (60 ms TWT) on the north flank, and around the rim (Fig. 6B). Although parallel, continuous, low to high amplitude reflectors are most common seismic facies within Seismic Unit 2, geometries include sigmoidal clinoforms and subtle, low-angle downlaps onto Horizon B (Fig. 6C).

The northern and western flanks of the thick part of Seismic Unit 2 are unfaulted. At the east and southeast extent of the thick, patterns are complicated by a pronounced ~ north-south trending normal fault. This fault, which offsets strata locally in excess of to 165 m (88 ms TWT), parallels the east/southeast margin of the isochron thick. Stratal thinning (due to non-deposition or erosion) across the fault can exceed 50 m (26 ms TWT), with thicker strata of Seismic Unit 2 always on the downthrown (western) block.

Interpretation. Seismic Unit 2 is interpreted to represent an isolated platform (Platform Stage 1) that retreated several kilometers from the margins of the thick buildup of Seismic Unit 1. The basal strata (between horizons B and C, Zone B in the log cross section) include tight, dense, and locally muddy deposits. These strata likely represent the

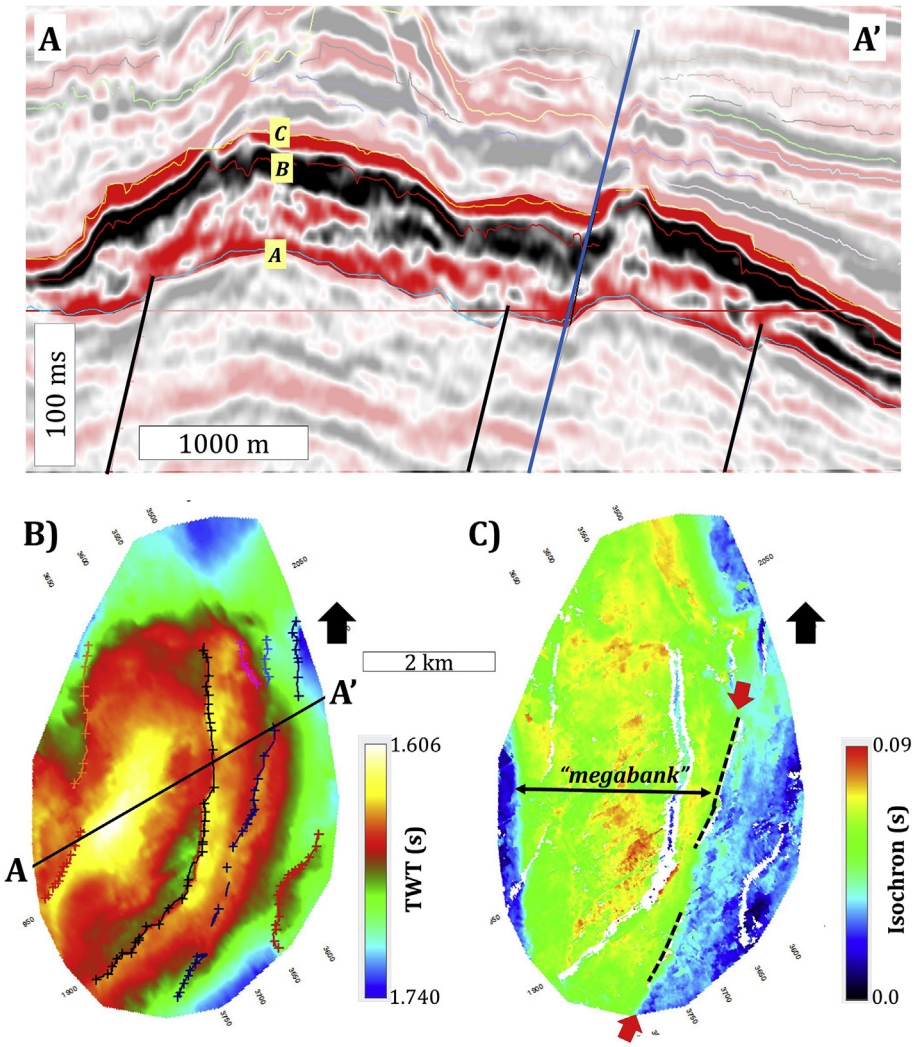

Fig. 5. Seismic character of Seismic Unit 1. A) Inline through the volume. This line illustrates that several of the faults which offset the lower surface terminate within this unit, but a major fault (here shown in blue) that cuts through appears to have no change in stratal thickness or character across the fault. This line also exhibits the low-amplitude, discontinuous reflectors common in this unit, and the marked thickening on the left side of the line, overlain by onlapping strata. B) Map of time to base of Seismic Unit 1. Note the numerous faults that offset this horizon. C) Isochron of Seismic Unit 1. Note a thick that trends north-south, with abrupt margins on the west (unfaulted) and east. The eastern flank appears to coincide with the location of mapped faults (dashed lines, emphasized by red arrows). Note as well that no major isochron changes occur across the curved fault (black in part B, blue in part A). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

initial flooding (a "build-in" phase of Epting, 1980). Nonetheless, Zampetti et al. (2004) document intense cementation in this zone such that Horizon B is stratigraphically lower (by ~15 m) in the seismic relative to the argillaceous layers in the core. In turn, the more porous overlying strata with abundant red algae, forams, and corals between Horizon C and Horizon D (Zone C in the log cross section) are interpreted to represent the more areally restricted re-establishment of shallow-water carbonate sedimentation that constructed the isolated platform. Syndepositional relief on the margins of the platform locally may have exceeded 94 m (50 ms TWT).

The stratal offset and marked thinning of Seismic Unit 2 across the normal fault suggests that the fault was active during, or immediately following, the development of the platform. The observation that the carbonate strata are thicker on the downthrown side of the fault is counter-intuitive, as carbonates generally favor more prolific growth on depositional highs due to greater light intensity and higher energy conditions (James, 1983; Schlager, 1992). Two possibilities may explain this apparent anomaly: 1) the upthrown footwall provided only limited accommodation to the east, and hence only thin deposits accumulated. This scenario would predict prolific sedimentation on the highs, with platform expansion to the east and west into downdip areas, with more accommodation (e.g., Bosence, 2005). Such evidence (e.g. clinoforms dipping away from the fault) is absent, however. 2) The eastern block was uplifted and eroded after deposition. This possibility cannot be ruled out with available data, although if marked erosion did occur, we might expect to see evidence in the form of slumps, blocks or debris downslope (to the east) (e.g., Janson et al., 2010, 2011), features that are not evident in the seismic in this interval. On the other hand, if uplift were accompanied by intense chemical weathering (which might be expected given the tropical wet climate during this time period), the absence of a downdip wedge may not be surprising.

Seismic Unit 3 is underlain by horizons D (in the central area) and C (on the flanks of the area) and includes reflectors that downlap, onlap, or are conformable-parallel to the top of Seismic Unit 2. This package is comprised of a complex of shallow-water strata (capped by Horizon E), and basinal strata (overlain by a series of toplapping reflectors: E′, E″, G, and H).

In areas of thick Seismic Unit 2 (e.g., on top of the carbonates of Platform Stage 1), Horizon E is defined by onlap onto its eastern and western margins (Fig. 7A). This reflector marks the top of a less extensive elongate (< 1 × 3 km) north-south trending body up to 152 m (81 ms TWT) thick (Fig. 7B). Internally, it includes a basal high-amplitude continuous peak (black horizon on Fig. 7A) overlain by parallel reflectors of much lower amplitude. Amplitude from this internal high-amplitude peak to the top of this seismic unit illustrate elevated positive amplitude on the north and west flanks, relative to the east and south flanks of the feature (Fig. 7C).

On the east side of the thick of Seismic Unit 2, Horizon E can be traced off the thick into the basinal areas (cf. Fig. 7A, D). In one such area in the center of the survey, the surface can be carried across the fault (as reflector E′), into a region in which this upthrown side includes reflectors with high but irregular amplitude, apparently reversing

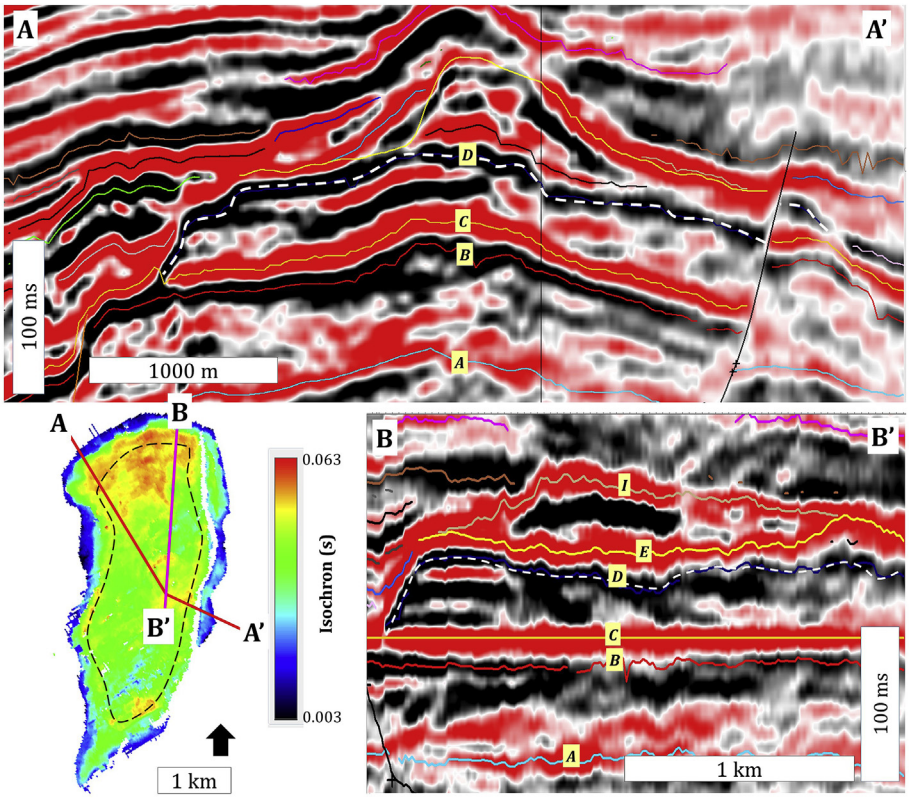

Fig. 6. Character of Platform Stage 1. A) Representative arbitrary line (location illustrated in part B). This line illustrates the generally tabular overall geometry and variable amplitude and continuity of internal reflectors in this interval. Note as well the fault on the SE part of the line that offsets this unit, with marked thickening on the downthrown side. B) Isochron of Platform Stage 1. Note the subtly thicker isochrons around the rim (indicated by the dashed black line), most notably in the north of the pinnacle. C) Representative north-south line, illustrating high amplitude, parallel doublet peak, flanked to the south (generally platformward) by possible subtle inclined reflectors of lower amplitude. Geometries such as these are apparent on several lines, but cannot be mapped confidently. The along-strike, lozenge shape of the strata between Horizons E and I are evident in this figure as well (Platform Stage 3, discussed below).

phases, and low similarity (Fig. 7D–F). Time slices through amplitude and similarity volumes indicate irregular circular features. This more chaotic reflector passes laterally eastward and southward into reflector (Horizon E″), a moderate amplitude, more continuous peak. [To be clear, the E-E′-E″ trio are interpreted to be the same horizon, simply noted differently to reflect their very distinct character.]

This horizon (Horizon E″) in turn can be traced around the area. In the southern extremity of the survey, it overlies (e.g., is younger than) Platform Stage 1 (Fig. 8A). Yet, as this reflector is traced north, its elevation relative to the top of the strata of Platform Stage 1 decreases (Fig. 8B), and other similarly dipping reflectors in turn overly it.

Interpretation. Seismic Unit 3 is interpreted to include both shallow-water carbonates and basinal siliciclastics, and to record their complex interactions. Calibration with core and log character illustrate that the thick strata (above Platform Stage 1) between Horizon D and Horizon E are largely shallow-water carbonates (Platform Stage 2). The seismic geometry and more limited aerial extent of these carbonates reflect a backstep from the previous isolated platform area; the upward trend into less grainstone-prone deposits evident in core may reflect this backstepping.

Platform Stage 2 is interpreted to have shed debris that interfingers off-platform with a succession prograding from the south and east. Although the lithology is unconstrained by a well in the survey area, the directions of transport (oblique to the platform, towards the north and then to the west) of these clinoforms (underneath E-E′-E″) is inconsistent with a platform source, which would be expected to thin away from the platform. Instead, they are interpreted to include dominantly siliciclastics (consistent with regional information, e.g., Epting, 1980; Koša, 2015; Koša et al., 2016) ultimately derived from rivers draining off Borneo to the south and southeast.

The presence of karst in the core near Horizon E in EX-3, and the highly irregular character of the correlative basinal reflector (Horizon E') on the upthrown side of the fault, is consistent with an interpretation that those areas were subaerially exposed. As noted, however, the cores penetrated strata off the thickest part of Platform Stage 2, and the irregular seismic is present even further downdip and basinward. The interpreted karst on the east (upthrown) side of the major fault may represent uplift and subaerial exposure of off-platform strata shortly after deposition.

Seismic Unit 4. In off-platform areas, a pronounced reflector (F in Fig. 8C) present only north of Platform Stage 2 includes amplitude and duration decreases away from the platform edifice of Platform Stage 1. This reflector downlaps onto Horizon E″, and does not toplap. This reflector (Horizon F) is overlain conformably by two toplapping reflectors broadly akin to Horizon E″, that form successive shingles around, and successive onlaps of, Platform Stage 1 (Fig. 8B and C). The steepest parts of these clinoforms have changes in thickness that suggest depositional gradients of 3–4°. These reflectors (horizons E″, G, and H) are capped by a surface of toplap (Fig. 8B). Viewed on individual 2D lines oriented normal to the margin of Platform Phase 1, several of these onlapping reflectors decrease in amplitude and loop duration away from the margin (e.g., G and H in Fig. 8C; H in Fig. 7A), but geometric constraints (onlaps, toplaps and downlaps) document that they post-date both Platform Stage 1 (Seismic Unit 2) and Platform Stage 2 (Seismic Unit 3).

On the northeast flank of the isochron thick of Platform Stage 2 lies a laterally discontinuous wedge, capped by Horizon I (Figs. 7A and 9). This wedge is up to 113 m (60 ms TWT) thick, extends 2.2 km along strike (Fig. 6C) and up to 750 m across (Fig. 9B). It includes an internal (unnamed) reflector that onlaps Horizon E (see Fig. 7A), and the upper surface (Horizon I) lies lower than, and onlaps, the flank of Platform Stage 2; that is, this wedge does not completely cover Platform Stage 2. Horizon I is in turn onlapped by several reflectors, including horizons J, K, and L (Fig. 7A; these reflectors are discussed further below); where Horizon I is not present, these reflectors (J, K and L) onlap Platform Stages 1 and 2.

Interpretation. The seismic architecture of Seismic Unit 4 documents complex platform-basin stratal relations. The horizon that caps Platform Stage 2 (Horizon E) is correlative to a horizon (E″) that represents but one of a succession of north-to west-prograding reflectors

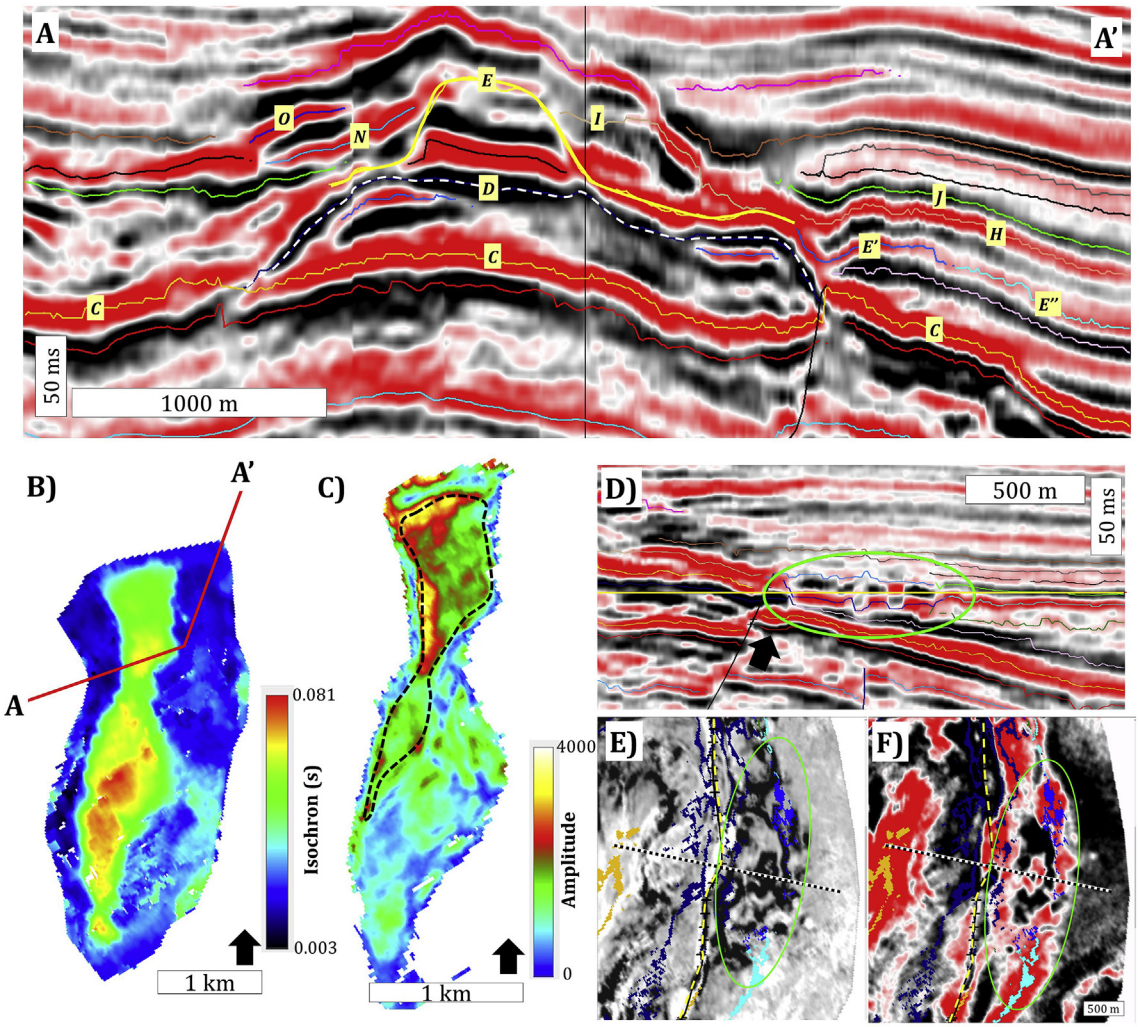

Fig. 7. Character of Platform Stage 2 and associated strata, as well as aspects of stages 3 and 4. A) Representative seismic line, illustrating the smaller aerial extent of Platform Stage 2 (between D and E) relative to Platform Stage 1 (between C and D). Note that Horizon J lies stratigraphically above both Horizon E (Platform Stage 2) and Horizon I (Platform Stage 3) on the right side of this line, and below horizons N and O (Platform Stage 4) on the left side. B) Isochron of Platform Stage 2. C) Map of amplitude of quadrature phase data between horizons D and E (Platform Stage 2). Note the high amplitudes in the north-northwest part of the buildup. D) Seismic line showing character of reflectors across the fault; note to the east of the fault, Horizon E′ has a chaotic, bursty amplitude (circled). Position of the time slices in E and F are indicated by the horizontal yellow line. E-F) Time slices illustrating semblance (E) and amplitude (F) changes across the fault (dashed yellow and black line). These data show that the eastern, upthrown side includes numerous circular features (broadly encircled by the green oval). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

in off-platform areas (including horizons F, G, and H). Overall, these strata are interpreted to represent a series of generally siliciclastic sediment wedges sourced from the south and east.

On vertical profiles, these reflectors appear as features broadly comparable to "wings," *sensu* Koša et al. (2016), with decreasing amplitude and loop duration away from the buildups. They could reasonably be interpreted to represent carbonate debris shed from the laterally adjacent Platform Stage 1, due to their onlapping geometry and seismic character (e.g., Fig. 8C). Yet, 3D mapping documents that they all post-date that platform, and that those strata above Horizon E'/E'' (including horizons F, G, and H in Fig. 8C) are younger than even Platform Stage 2. The changes in seismic amplitude and duration away from the platforms suggest that it is possible (probable?) that they (at least locally) include carbonate debris, but if so, it would have to be shed from a platform younger than that which they onlap.

The younger platform interpreted to be the source is the wedge bound below by reflector E and above by reflector I, or Platform Stage 3. This stage is present only on the northeastern flank of Platform Stage 2. The onlapping reflectors and absence of evidence that it directly overlies the thickest parts of Platform Stage 2 document its limited extent. Although it is present only on the downthrown side of the major fault, it is thickest closer to the crest of Platform Stage 2, and does not thicken towards the fault. These observations suggest that the source of sediment was not the upthrown side of the fault, but rather nearer the previous platform thick. These strata, not penetrated by a cored well, are interpreted to represent a small reef system on the flank of the previous (and previously subaerially exposed) pinnacle.

Seismic Unit 5 is underlain by Horizon J and is overlain by Horizon P (Fig. 10); like Seismic Unit 4, it includes strata in both paleotopographic highs and in more basinal settings. The basal reflector, Horizon J, is a prominent trough that can be carried across the survey, except where it onlaps the highs of Platform Stage 2 (Horizon E) or Platform Stage 3 (Horizon I) (or where data quality issues preclude confident correlation). In basinal areas, Horizon J overlies the toplapping clinoforms of horizons E″, G, H, and it is in turn downlapped or onlapped by several different reflectors.

In areas to the southeast of the thick parts of platform stages 1 and 2, a southeast-dipping Horizon J is parallel to Horizon E″ and reflectors

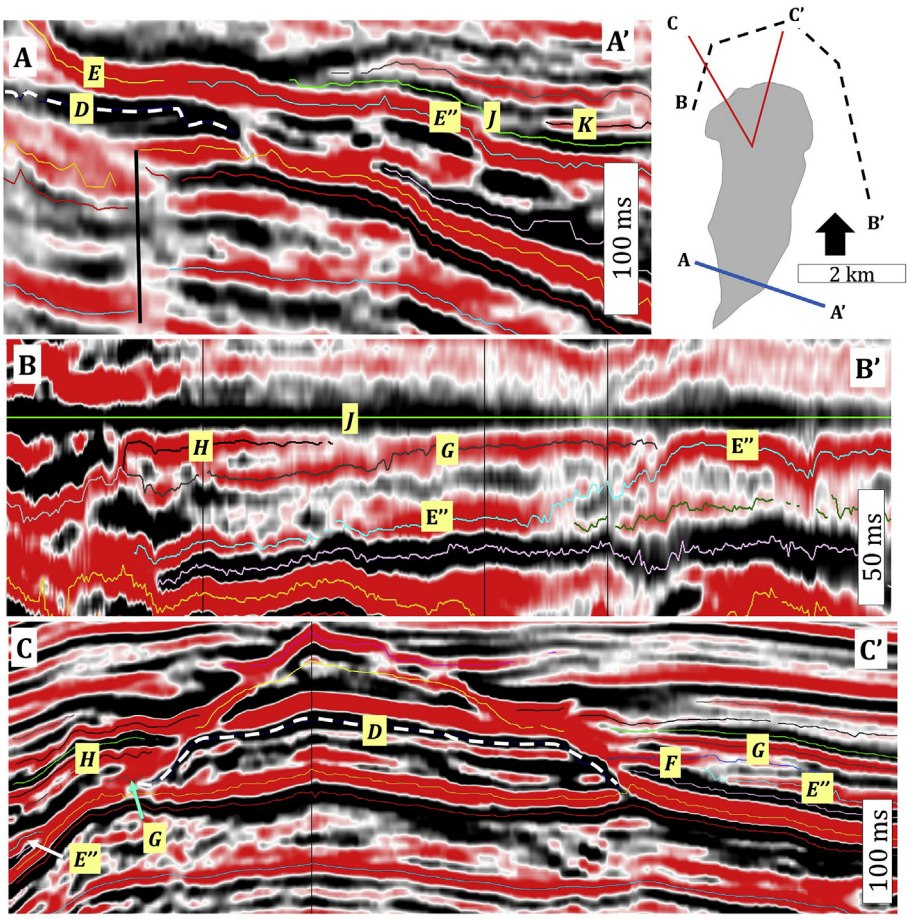

Fig. 8. Character of off-platform (basinal) strata, and relation to platform stages. A) Line from southern part of Platform Stage 2, illustrating an area that the fault does not offset Horizon D or above. Here, Horizon E can be traced directly to Horizon E″, suggesting time-equivalence. B) Arbitrary line wrapping around from the east to north of Platform Stage 1, flattened on Horizon J. This line illustrated that a series of reflectors (E″, G, and H) form several clinoforms dipping to the north, and then west, around the pinnacle. C) Arbitrary line that extends from the basin, to the platform, then back into the basin. This line illustrates how several of the clinoform reflectors (part B) onlap the flanks of Platform Stage 1, appearing as "wings" off the platform. Superposition (e.g., Part A) illustrates that all of these reflectors post-date this platform stage, and many even are younger than Platform Stage 3; they are not flank beds contemporaneous with Platform Stage 1, as interpretation based on one line, or ignoring basinal geometries, would suggest.

below it, but is onlapped by several overlying reflectors (e.g., Fig. 8A). In another area farther north, off-platform strata between horizons C and H (the southward-prograding clinoforms; cf. Fig. 8B) successively onlap Platform Stage 1, yet are folded in an area with four-way closure (Fig. 10B). Each of these reflectors (older than and including Horizon J) are offset by a down-to-the-east normal fault at the edge of the survey, with isochron and amplitude changes across the fault. In marked contrast, rather than being conformable, the overlying reflector (Horizon K) onlaps Horizon J radially on the crest of this anticlinal structure.

Horizon K itself includes distinct spatial trends. Present only in the northern part of the survey, Horizon K overlies or onlaps platform stages 2 (Horizon E) and 3 (Horizon I) on their northeast flanks (e.g., Fig. 10A), but onlaps Horizon J to the north and northeast (Fig. 7A). It includes greatest loop duration and highest amplitude in the northwest, near, but paleotopographically lower than, the thick of Platform Stage 2. Amplitude and duration decrease away from this area, to the west, north and east (Fig. 10C and D); similarity is highly variable in the area west of the platform (Fig. 10E) and includes several circular features. Unpublished well reports suggest that this interval includes tight limestone. Above Horizon K, a reflector (Horizon L), limited largely to the east side of the survey, loses amplitude and loop duration as it appears to onlap reflector K from the east (Fig. 10A), and northwest (Fig. 10C, cf. left side of Fig. 6A).

On the west side of Platform Stage 2, both horizons J and K are

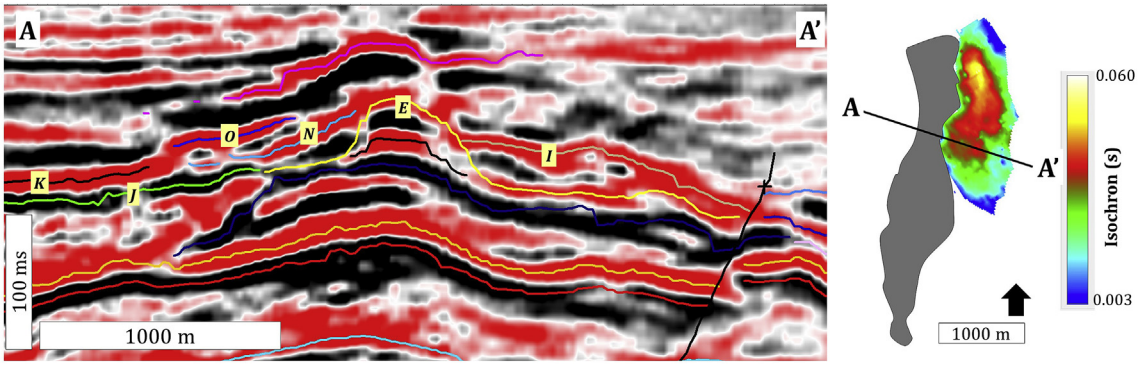

Fig. 9. Platform Stage 3. A) Representative seismic line across the platform, illustrating Platform Stage 3 onlapping Platform Stage 2, and occurring in a position below its crest. This body also has a discontinuous distribution along strike (cf. Fig. 5C). B) Isochron of Platform Stage 3 (colors) relative to Platform Stage 2 (grey body). Note that this stage has an extent limited to the northeast flank of Platform Stage 2. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

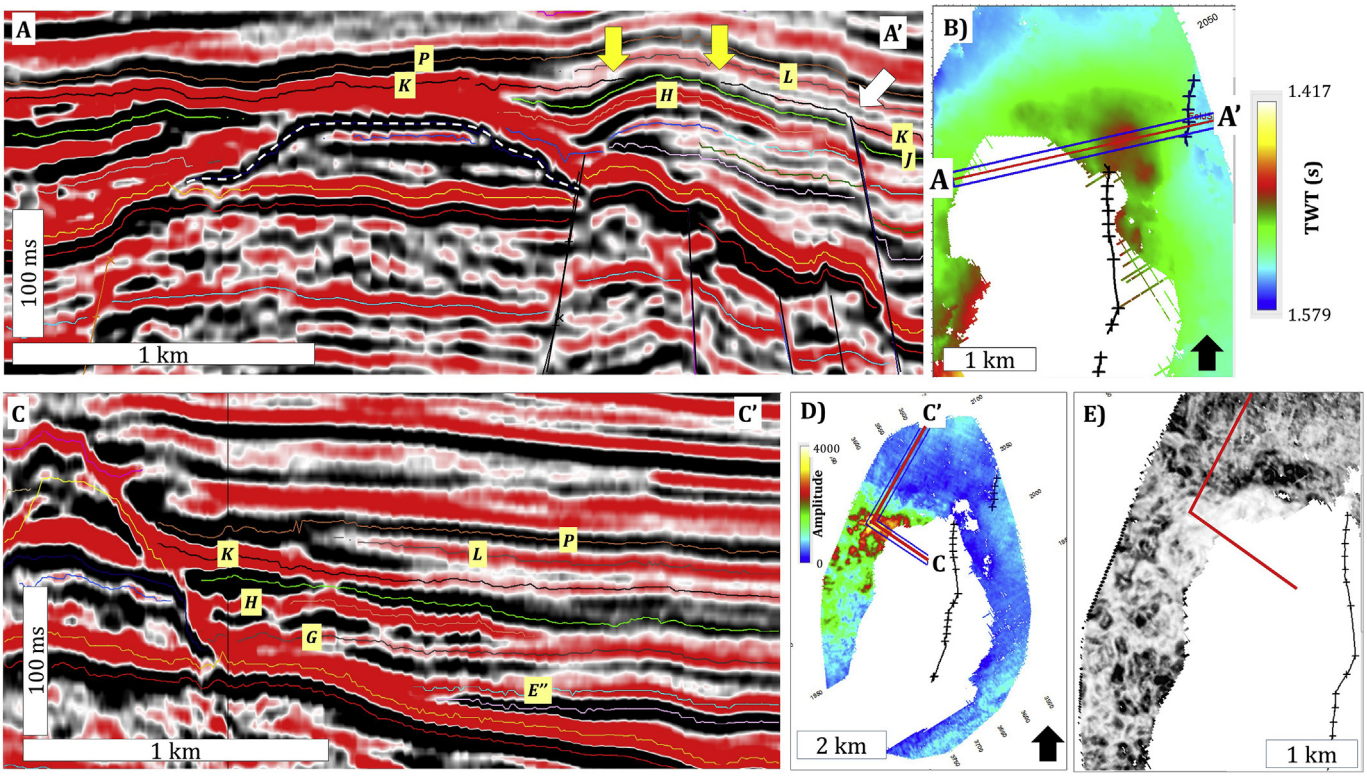

Fig. 10. Seismic character of flank and basinal strata. A) Illustrative line across northern tip of Platform Stage 1. In the area to the east of the isolated platform (to the right), strata below Horizon J that form the succession of clinoforms dipping north in this area appear to be broadly warped. Horizon K onlaps the crest of this structure (yellow arrows). Similarly, across a fault (white arrow), the horizons below K include isochron and amplitude changes. B) Time structure map (Horizon J), illustrating that this structure forms a general dome with 4-way closure (in time); recall that this structure is radially onlapped by Horizon K. C) Arbitrary line illustrating decrease in loop duration and amplitude away from where it onlaps Horizon E (Platform Stage 2). This geometry alone could suggest these are debris flows from Platform Stage 2, akin to reflectors H and G that onlap Platform Stage 1. Yet, the basinal reflector equivalent to Platform Stage 2 is actually Horizon E'' (cf. Fig. 7A), which onlaps Horizon C, low on the shelf in this area. D) Map of amplitude of Horizon K, illustrating highest amplitude to the west of the buildups. E) Map of semblance, Horizon K, showing irregular circular discontinuous character in some of these areas. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

downlapped by a series of west-dipping reflectors (Figs. 7A, 10A and 12B). These reflectors (Horizons M, N, and O) are continuous along strike for several km, and collectively form a wedge up to 115 m (61 ms TWT) thick, 750 m across, generally broader to the south-southwest (Figs. 10 and 11). Geometrically, the oldest reflector (M) in this set occurs to the south, and is overlain by reflectors (horizons N and O) that successively build further north (Figs. 10 and 11) as they offlap to the west. These reflects each onlap the flank of Platform Stage 2, but none continue to lie stratigraphically above it. Although this interval is not cored, an unpublished report from a development well that penetrates part of the succession documents "tight (argillaceous) limestone with and chalkified/mouldic limestone" with a thick (> 80 ft; 24 m) shale.

This succession is in turn overlain by Horizon P, which onlaps various horizons (E, I, M, N, and O), representing Platform Stage 2 and younger strata. It is otherwise continuous across the area.

Interpretation. Horizon K onlaps Platform Stage 1, and it onlaps platform stages 2 and 3 near the base of their flanks. Thus, it occurs in paleotopographically low regions. Loop duration is greatest to the northwest, where it includes and its highest, but variable, amplitude and irregular similarity.

The omnidirectional onlap of Horizon K onto Horizon J (e.g., Fig. 10A) suggests syndepositional paleotopography. These onlaps overlie the succession (horizons E″, G, H) that includes southward progradation (Fig. 8B), and these lower horizons are continuous and parallel in this immediate area, suggesting they were not impacted at the time of their deposition. This onlap - with no evidence for thinning or thickening in underlying strata - suggests that the topography was created by deformation just prior to deposition of Horizon K. East of this area, faulting associated with isochron and amplitude changes (Fig. 10A) to Horizon J and the unit that it caps suggests it was active and influenced deposition as well. [The "main" fault continues in some areas through this time as well; see Figs. 6A and 9.]

Horizons J and K both onlap Platform Stage 3, and are downlapped by horizons M, N, and O. Thus, superposition principles mandate that the wedge defined by horizons M, N, and O is younger than both the laterally adjacent Platform Stage 2 and the Platform Stage 3; that is, like Platform Stage 3, it is chronostratigraphically distinct, and does not represent syndepositional flank strata. The westward-offlapping geometries document a source to the east, from the area near or above the west flank of Platform Stage 2. These clinoforms could reflect *in situ* production and accumulation (e.g., Koša et al., 2016). In this scenario, the top of Platform Stage 2 still could be subaerially exposed and these shingles represent prolific production on the flank of this island complex. The offlapping geometries are consistent with limited accommodation, and transport into adjacent off-platform areas. Alternatively, they may represent deposits downdip of the youngest carbonate strata (e.g. that directly overlie Platform Stage 2). In this scenario, the onlap of horizons M and N below and to the west of the crest of Platform Stage 2 would reflect production on the high, and bypass to lower in the slope. Although observations that conclusively rule out this latter possibility are not evident, these dipping reflectors do not extend above the top of Platform Stage 2, or contain geometric evidence of interfingering with the strata above it. Thus, although the data are not clear, the succession of horizons M, N, and O are interpreted to represent a Platform Stage 4.

Seismic Unit 6. Reflector P forms the base of a succession with

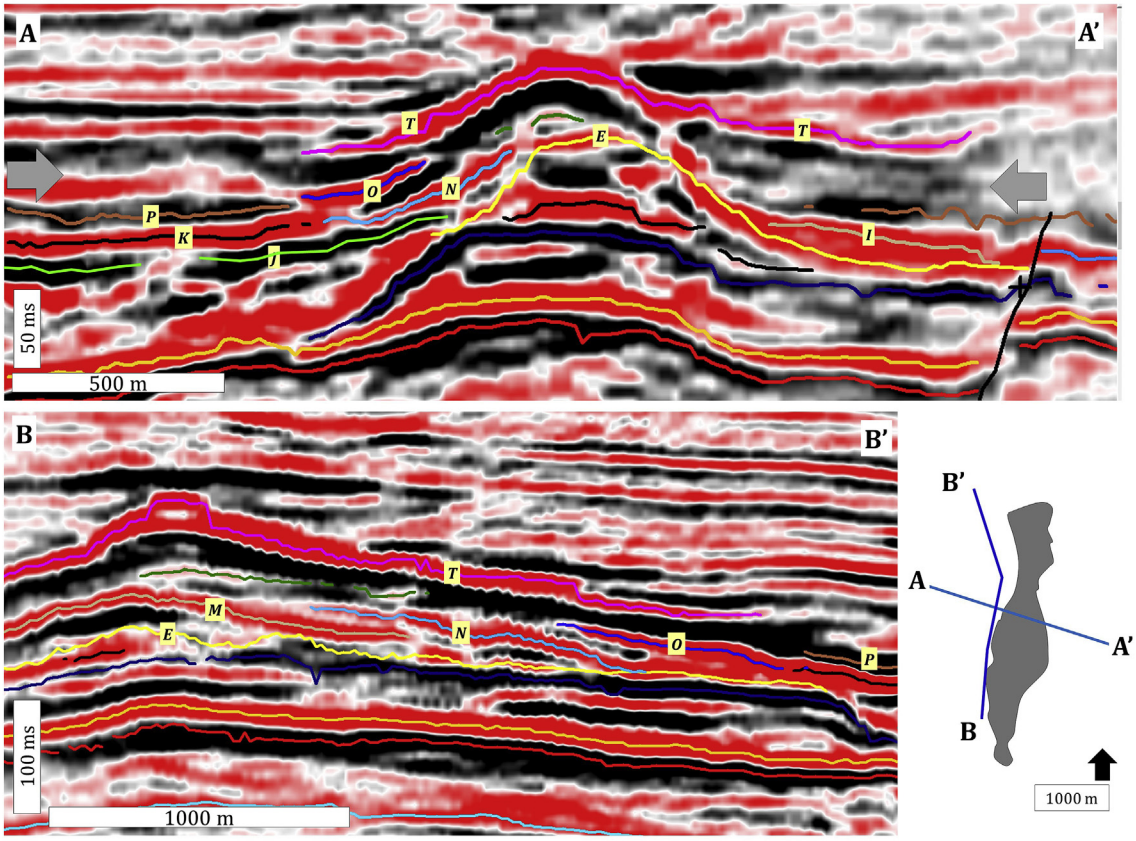

Fig. 11. Seismic character of Platform Stage 4. A) Dip line. Note that these reflectors (N and O) offlap to the west of Platform Stage 2. Reflector N downlaps (is younger than) Horizon J. Siliciclastics (below Horizon T) are indicated by the grey arrows. These strata clearly post-date Platform Stage 2 (Horizon E) and Platform Stage 3 (Horizon I), and pre-date Horizon T (top carbonate) as discussed in the text, but their geometric relationship with strata between horizons O and T is ambiguous. B) Strike line, illustrating that the offlapping shingles (M, N and O) also built successively to the north. Inset location map indicates location of seismic lines, relative to isochron thick of Platform Stage 2.

discrete characteristics in the basin and on the platform. To the flanks of the highs of platform stages 2–4, in basinal (off-platform) areas, a low- to moderate-amplitude section includes a series of peaks dipping north- to northeast at low angles (Fig. 12A and B). These reflectors downlap Horizon P, and are overlain (at least locally) by Horizon T, which can be traced to the top of the carbonate succession, as described below. These reflectors onlap the carbonates of platform stages 2, 3, and 4 (e.g., Figs. 8C and 9), or simply lose amplitude (e.g., Fig. 11A, right side), a dynamic which masks termination patterns in these data.

Above platform stages 2, 3, and 4, a low amplitude section (with a discontinuous peak overlain by a trough) is capped by a high-amplitude peak (Horizon T). The weak internal reflectors between horizons E and I and Horizon T suggest downlap onto platform stages 2 and 3, and onto reflectors M, N, and O (cf. Fig. 6). This thick succession is penetrated by well EX-1, and includes a thick (544 ft, 166 m) succession of carbonates; log character suggests that parts are dolomitic and others are argillaceous (Fig. 2). Gamma-ray values of greater than 30–50 API in this well suggests an increase in abundance of argillaceous material upwards. This carbonate package, capped by Horizon T, defines a northeast-southwest oriented, convex-up thick (up to 175 m, 94 ms TWT), roughly 1 by 2 km in size. The highest area of Horizon T includes a small ($\ll$ 1 km^2) doublet (cf. Fig. 11B). Horizon T can be tracked off the thick, and to location of well EX-2. At that well, the synthetic-well tie indicates that the peak represents the top of a high-impedance carbonate stringer 50 + ft. (15 + m) thick that overlies, and is overlain by, siliciclastics of lower impedance (see Figs. 2 and 4).

Interpretation. This succession is underlain by Horizon P, onto which several reflectors downlap, suggesting that it is a regional flooding surface. Tie to well EX-2, and reports from several development wells document that the low-angle reflectors are part of a succession of siliciclastics. The geometries suggest progradation to the north. Reflector T is interpreted to represent the top of Platform Stage 5, which is thickest on the highs of Platform Stage 2 and 4 (Platform Stage 3 sits a bit lower). Above this horizon, the succession is largely siliciclastic, reflecting the drowning of the platform.

5. Discussion

Throughout the expanse of geologic history, innumerable reefs and isolated carbonate platforms have stood proud, towering above the surrounding lows. Yet, the vast majority of these edifices have struggled, perished, and been interred by younger siliciclastic, evaporite, or basinal carbonate strata.

The Central Luconia Province, with its numerous buildups, has provided a natural laboratory for understanding the initiation, growth, and demise of carbonate platforms. With the advent and utility of 3D seismic data, recent efforts have recognized Central Luconia buildups as more regionally variable and complex individually than the initial conceptual model offered by Epting (1980) (e.g., Vahrenkamp et al., 1998; Bracco Gartner et al., 2004; Zampetti et al., 2004; Masaferro et al., 2004; Ting et al., 2011; Koša, 2015; Koša et al., 2016). A representative line and interpreted seismic stratigraphy (Fig. 13) illustrates the evolution of this platform and adjacent basinal strata, and reveals the complicated story of the carbonates of Field EX, in terms of phases of growth, the influence of tectonics, and the nature of platform flanks.

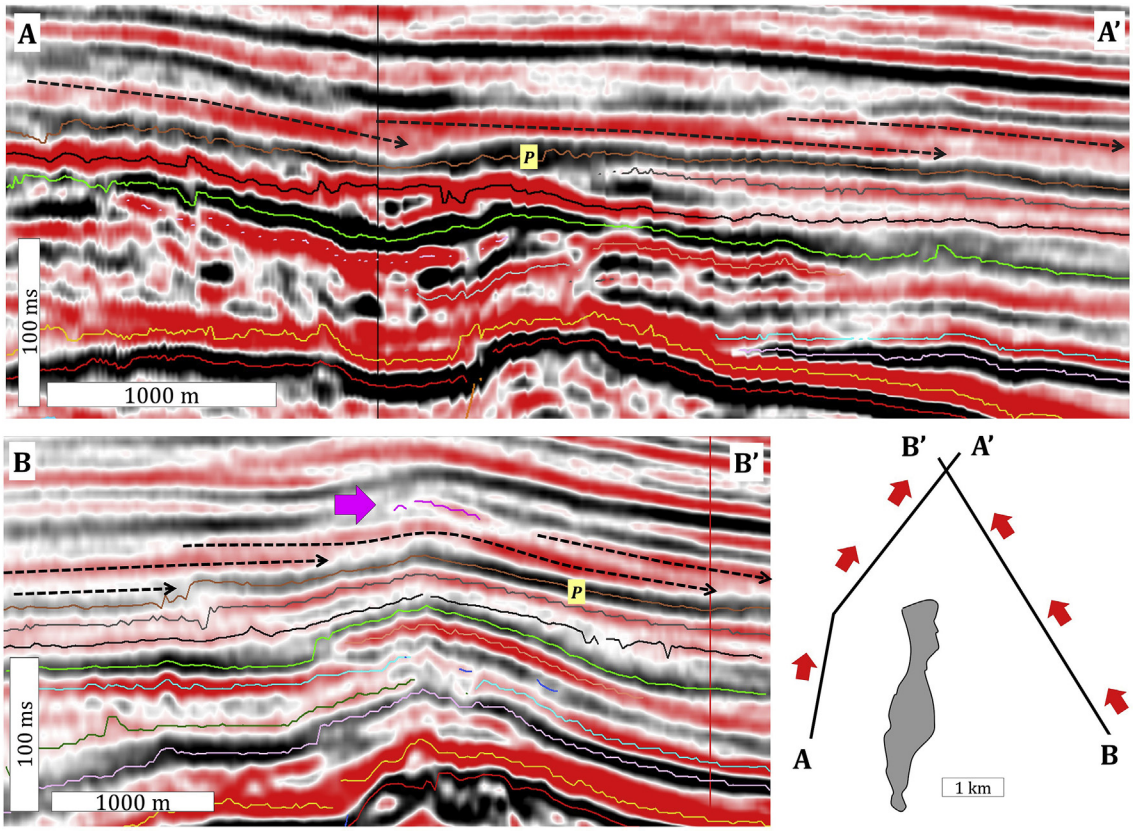

Fig. 12. Character of basinal siliciclastics that post-date Platform Stage 4. A-A′) Arbitrary line to the east of Platform Stage 2. Note the low-gradient reflectors that offlap northward, and downlap Horizon P. These predate the top-carbonate reflector (pink arrow). B-B′) Arbitrary line to the west of Platform Stage 2. This succession also includes low-angle clinoforms, dipping to the north/northeast, which downlap Horizon P. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

5.1. Phases of carbonate growth

In the Epting (1980) conceptual model, a basal build-out phase is overlain by a transgressive build-in unit. Strata above this backstep include an aggradational build-up phase overlain by a transgressive (build-in) phase, with interfingering between platform and basinal strata throughout the history of the platform.

The carbonates of Field EX include six distinct phases of platform growth, as well as complex interactions with basinal strata (summarized in Fig. 13). Seismic data reveal that the oldest carbonates (Cycle IV) include a basal build-out phase that consists of the most laterally extensive carbonates ("megabank stage") evident in the survey, and that included defined shelf margins. Subsequent flooding is indicated by a shelf-margin backstep and a reduction in the areal extent of carbonates into a north-south elongate platform (Platform Phase 1).

Above Platform Stage 1, Platform Stage 2 represents another stepback into a narrow, elongate isolated platform; termination of this isolated platform occurred as a series of basinal wedges prograded northward and may have been tectonically enhanced. Platform Stage 2 is flanked by onlapping carbonate deposits; those to the east (Platform Stage 3) appear more aggradational, whereas strata to west (Platform Stage 4) prograde to the west and north. These strata (stages 3 and 4) are temporally distinct, however, as defined by stratal terminations and superposition relations. These strata all are overlain by a second northward-prograding basinal siliciclastic succession, and the capping Platform Stage 5, above which the platform drowns. These patterns of carbonate isolated platform evolution and the details of their interaction with siliciclastics are broadly consistent with - but more complicated than - the more generalized Epting conceptual model (e.g., compare Figs. 1C and 13).

5.2. Role of tectonics in platform evolution and architecture

Following Epting (1980), numerous studies of Luconia platforms have de-emphasized the influence of active tectonics on platform dynamics. For example, Vahrenkamp (1998, p. 7) suggested that "… *considering the several thousand feet thick carbonate sections and the lack of major faulting and tectonic activity it is likely that Luconia platform growth was governed by eustatic sea-level fluctuations and not by autocyclicity … or some changing tectonic regimes*." More recently, Koša (2015) noted what he interpreted as a "relatively uneventful structural history," at least regionally.

In contrast, other regional studies had demonstrated the role of tectonics in shaping the location and orientation of Miocene faults, and structural horsts and grabens, in Central Luconia (Ho, 1978; Hall, 1996; Taylor et al., 1997). Through their influence on paleo-bathymetry, these blocks in turn controlled nucleation sites favorable for carbonate platforms, and hence shaped the regional distribution and orientation of platforms (Ting et al., 2010, 2011; Ali, 2013).

Given this regional structural setting that generated regional fault-bounded blocks, syndepositional tectonics have been interpreted to have influenced depositional patterns and stratigraphic architecture of individual platforms as well (Ting et al., 2011; Menier et al., 2014; Jamaludin et al., 2018). Consistent with these considerations, several stages of Miocene tectonic activity and syndepositional deformation are evident from the seismic data in Field EX (red bars on right side of Fig. 13B). Although the dominance of normal faults reflect the broadly extensional setting, these stages of syndepositional faulting include distinct timing, orientation, and offsets.

The first stage included numerous north to northeast-oriented, down to the west faults that offset Horizon A, the base of the megabank.

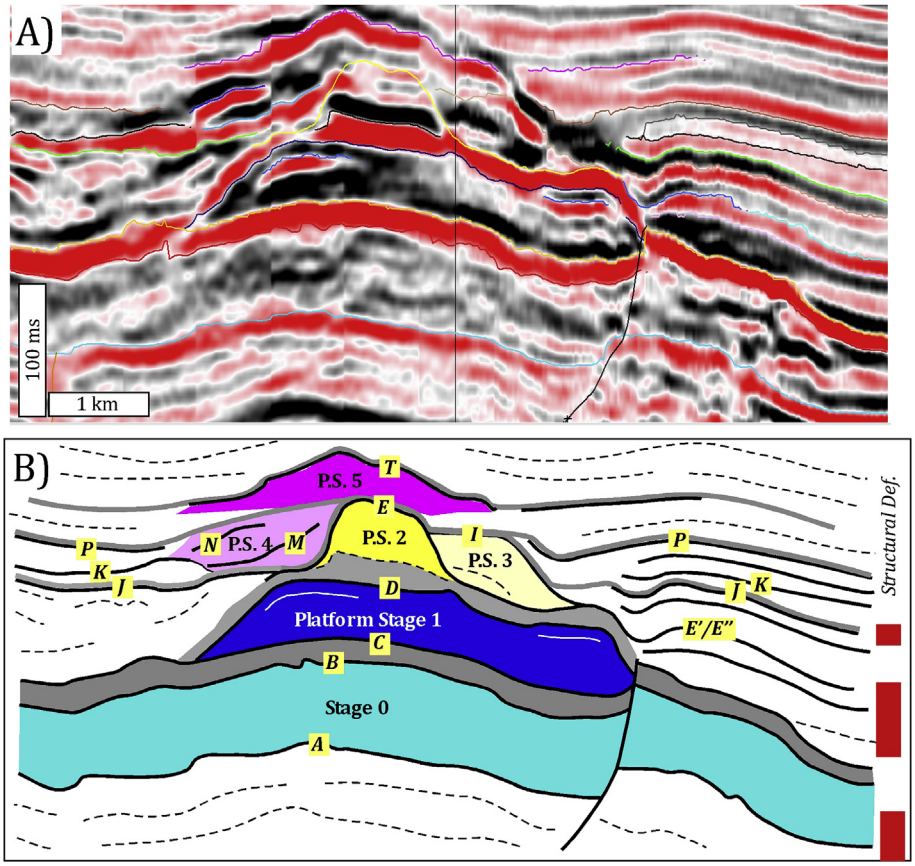

Fig. 13. Summary of geometric evolution of Field EX. A) Arbitrary, quadrature-phase seismic line with interpreted seismic horizons. B) Interpretive representation of line in part A, illustrating the various platform stages. Grey colored intervals are interpreted transgressive stages. Some of these are comparable to build-in phases of Epting (1980), others are defined based on downlaps. Red bars represent are intervals of interpreted structural deformation. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

These faults, and related highs and lows, may have (likely?) influenced nucleation of the platform, although unambiguous evidence is absent in the seismic data illustrated here. The coincidence of the eastern terminal margin of the megabank with faults is consistent with an interpretation of a structural influence on growth, with downthrown side including thinner strata. Seismic data suggest that many of the faults which offset Horizon A terminate within the megabank and do not offset Horizon B, illustrating that they were inactive by that time.

A second, distinct stage of structural activity occurred following deposition of Platform Stage 1 (Horizon D), and lasted at least through deposition of Platform Stage 3 (offsetting Horizon J; Fig. 10). Strata below Horizon C include no pronounced isochron changes across the most pronounced of these normal faults (e.g., Figs. 5 and 6A), and thus they appear to have been inactive during the first structural stage. This second stage markedly impacted Platform Stage 1, however, with a normal fault on east side of isolated platform complex dropping the thickest parts of the buildup down to the west; this fault offsets off-platform strata above the backstep above Horizon D, at least as young as Horizon J. Similarly, a second normal fault offsets basinal strata through at least Horizon J, with isochron and amplitude changes across the fault (Fig. 10A), suggesting it was active through deposition of this unit as well.

A possible final stage of syn-depositional deformation is indicated by folding in one area to the northeast of the platform succession (Figs. 10A and 13B, upper red arrow). This folded strata were interpreted to be drift deposits by Bracco Gardner et al. (2004), based on three 2D lines, although they had noted in the abstract that "*an alternative is folding during tectonic deformation ….*" In the 3D data, the clinoforms prograding northward through the area are folded (below Horizon J), and these folded strata are overlain by omnidirectional onlap of the overlying horizon (K), demonstrating subtle depositional topography. This final stage suggests subtle compression, unlike the others, which are extensional.

5.3. Nature of flanks and relations to off-platform strata

Regional studies of platforms in Central Luconia have recognized carbonate stringers or "wings," regional changes in their distribution and character, and their importance (Koša et al., 2016; cf. Epting, 1980, 1989). Where present, these wings are recognized on the margins or flanks of the carbonate platforms, where they generally interfinger with basinal siliciclastics. The initial observations, based largely on 2D data, suggested continuous interfingering (e.g., Fig. 1D), although a later intepretation (Epting, 1989) subtly modified this conceptual model to suggest that some platform margins interfingered with basinal strata, others did not.

Using three generally north-south oriented 2D seismic lines from Field EX, Bracco Gartner et al. (2004) interpreted platform debris interfingering with basinal shales, but noted spatial asymmetry in the geometric character and distribution of debris deposits. Their 2D data suggested that the southern margin included bypass throughout deposition followed by later onlap, whereas the northern margin had both bypass and interfingering throughout the succession. In all, however, they interpreted less interfingering than the Epting (1980) conceptual model. Zampetti et al. (2004) extended these concepts using 3D seismic data from Field EX, emphasizing slope failure and slumping, perhaps accentuated by syndepositional faulting, in the genesis of off-platform carbonates. Thus, both studies suggest some time equivalence between platform and basinal strata, but neither mapped basinal strata in detail.

In contrast, recent study focusing largely on regional 2D lines (Koša et al., 2016) envisioned more complicated interactions at the margins. Their data clearly illustrated regional differences in morphology of margins; southern areas of Central Luconia (as Field EX) were interpreted to have been characterized by elevated rates of siliciclastic influx deposited in low-relief deltas in off-platform areas (cf. Figs. 8B and 11), such that these southern platforms never towered high above surrounding deep-water basins. Koša et al. (2016) suggested that these

deltaic deposits (in relatively shallow water) formed substrates on which carbonates could be deposited *in situ* as "*thin, short-lived carbonate platforms established in the vicinity of exposed carbonate buildups during sea-level falls and marine transgressions* …" (p. 2066).

The seismic interpretation of Field EX re-emphasizes several concepts, and clarifies several others related to carbonate-siliciclastic/platform-basin interactions. First, stratal terminations document that beds that abut platforms may, or may not, be temporally equivalent with the platform they flank, in contrast to the continuous intercalations inferred by Epting (1980). For example, there is no seismic evidence for interfingering between megabank or Platform Stage 1 strata (e.g., below Horizon D) and siliciclastics. Instead, these strata are onlapped by later, northward-prograding clinoforms of siliciclastic material. In sharp contrast, however, the later platform stages include geometries that suggest a close association, and at least broad temporal equivalence, with basinal siliciclastics.

Second, the geometries and terminations suggest that syndepositional relief varied through time. The greatest relief (in excess of 90 m) appears to have existed following deposition of Platform Stage 1, before faulting and influx of basinal siliciclastics that prograded and subsequently filled much of the relief. Strata of Platform Stage 2 built up on the highs of Stage 1, and included pronounced relief (at least 100 m), but relief was subdued by the basinal siliciclastics and platform stages 3 and 4. These platform stages (3 and 4) are in a sense flank beds that onlap the sides of a previous edifice, but do not grow on top of the previous platform stage. In this regard, these stages may be analogous to the shallow *in situ* platforms that grew as previous platform deposits were emergent, a dynamic suggested by Koša et al. (2016). Nonetheless, there are no core data to test this interpretation.

A third concept emphasized by these results is the important role of the siliciclastics on the nature of flank beds. As discussed above, for at least parts of the succession, the off-platform siliciclastics formed the foundation on which carbonate wings were deposited (e.g., Figs. 8C and 10C). The data reveal, however, that the depositional patterns in the siliciclastics contrast with those in the carbonates, and even appear out of phase. For example, in off-platform areas, above Horizon D lies a succession of northward-prograding clinoforms (including reflectors E″, F, G, and H) which successively toplap (Fig. 8C). Yet, a carbonate buildup (Platform Stage 2) appears to grow, and be terminated, in the middle of this prograding succession (e.g., capped by Horizon E/E'/E″). This platform is in turn onlapped by another carbonate succession (Platform Stage 3) that is also younger than the flooding surface above the prograding clinoforms. Thus, what appears in the basin as a prograding succession (Fig. 8B) corresponds to two phases of platform growth. Yet, few clastics are evident in the carbonates. Indirectly, and arguably, these observations could be interpreted to suggest that the siliciclastics therefore did not drive the platform drowning and backstepping (recall as well that siliciclastics were not present in the off-platform areas until after Platform Stage 1, which was itself a backstep from the megabank stage).

In contrast, following Platform Stage 4, the off-platform areas appear to have been filled at least in part by northward-prograding siliciclastics (Fig. 11). This fill may have favored the broad wings of Platform Stage 5 (the stringer evident in the cored well, EX-2) (Figs. 2, 11 and 13). Thus, instead of favoring drowning, these siliciclastics also may have facilitated platform expansion.

5.4. On the role of eustasy

Middle Miocene is considered a period of general eustatic rise (Fig. 1C), and the base of Cycle V has been interpreted to be coincident with a 200 + km landward shift in the position of the coastline (Koša, 2015). In field EX, this interval (just above Horizon B) is accompanied by a pronounced stepback, from the megabank to Platform Stage 1, and a lack of resolvable siliciclastics in the off-platform areas until after termination of Platform Stage 1. After that time, however, various considerations regarding tectonics and the nature and timing of siliciclastic accumulations suggest that although eustatic change surely influenced the stratigraphic succession in the buildup of field EX, it was not a primary control (cf. Koša, 2015). Although detailed evaluation awaits improved chronostratigraphic resolution, several lines of evidence are in consistent with a eustatic control.

First, structural deformation clearly impacted the platform during its growth after Platform Stage 1, with apparent offsets in excess of 50 m, locally greater than 100 m. Changes in accommodation of this magnitude, and differential structural segmentation of the shelf locally, partitioned this area into highs and lows, with different accommodation trends.

Second, given the pronounced local relative changes in sea level, it might be expected that patterns in this area diverge from regional trends that have been interpreted to represent a largely eustatic signal (Koša, 2015). In his regional review, Koša (2015) documented that in the upper part of Cycle V many buildups are characterized by platform expansion, and in some cases, coalescence with adjacent platforms. This pattern of platform expansion is precisely the opposite of that evidenced in the platform stages of Field EX, which are dominated by backstepping. The divergence is inconsistent with a eustatic control, but again suggests a more pronounced structural control.

Finally, the patterns of accumulation between the siliciclastics and carbonates appear contradictory and even out of phase. Regionally, Koša (2015) noted the "… intercalation of carbonates and clastics at major stratigraphic surfaces, and the demise of the carbonate platforms coincidental with stratigraphic breaks in the clastics" (p. 45). The seismic stratigraphic patterns of Field EX appear more complex in parts of the succession, however. For example, off-platform strata of reflectors below Horizons E' through Horizon I include a succession of toplapping geometries. During this time, however, carbonates include a platform backstep (Platform Stage 2) capped with a subaerial exposure surface (Horizon E), and this horizon is in turn onlapped by another succession (Platform Stage 3).

5.5. Comparison with other isolated carbonate platforms

The carbonate platform that forms Field EX is but one of several hundred platforms in Central Luconia, and one of innumerable buildups in the geologic record. Comparisons among these platforms indicate both broad similarities and contrasts with Field EX, in terms of size and thickness (Fig. 14) and controls.

Cenozoic Buildups, Southeast Asia – The seismic character of the carbonate platform in Field EX shares similarities and differences with other Cenozoic buildups in the south China Sea and southeast Asia more broadly. For example, Masaferro et al. (2004) documented aspects of a Middle Miocene buildup from Central Luconia that lies farther offshore than Field EX. This buildup is roughly 2.5 × 4 km in size, and is elongate in a north-south direction. The external form includes no evidence for carbonate stringers or interfingering between the carbonates and basinal siliciclastics; that is, it has a "closed wing" geometry (Koša et al., 2016). Internally, the buildup includes several reservoir zones that are defined based on the distribution of tight zones, related to the presence slightly argillaceous flooding intervals. Seismically, these tight zones appear as continuous, parallel high-amplitude reflectors. In contrast, each reservoir zone includes distinct internal seismic geometries. Seismic facies included mounds, sigmoidal clinoforms, and shingled clinoforms, most of which prograde platformward, or towards the platform interior. These patterns were interpreted to reflect a reef that grew first, followed by excess production and platformward expansion of the reef sand apron. Masaferro et al. (2004) interpreted the ubiquitous mounded facies on the west/southwest platform margin to reflect better-developed reefs on the paleo-windward flank.

Also located in the northern part of Central Luconia, a second platform, Jintan, is a much larger (30 × 50 km in extent), thicker (1.2 km-thick), Middle Miocene buildup (Vahrenkamp, 2004; Ting

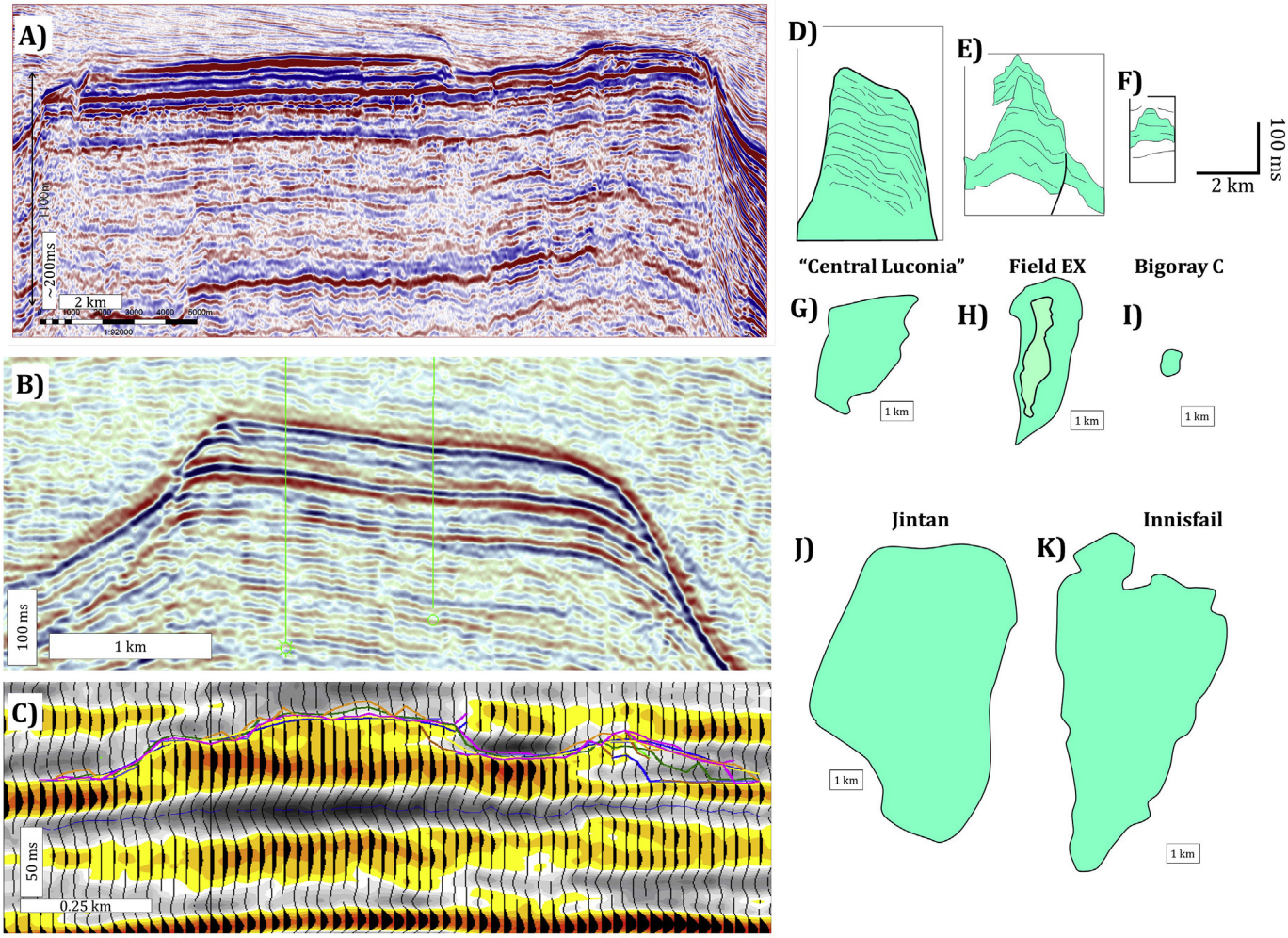

Fig. 14. Comparison of architecture and scale of illustrative Miocene and Devonian buildups. A-C) Seismic lines, A – Jintan, Central Luconia, modified from Ting et al. (2011) [line is in depth, time is estimated using 3750 m/s average velocity]; B – "Central Luconia Field", Masaferro et al. (2004); C – Bigoray C Field (Devonian), Rankey and Mitchell (2003). D-F) Sketches of seismic lines, plotted at same scale as Jintan (part A). D – "Central Luconia Field" Masaferro et al. (2004); E – Field EX, this study. Plotted are Platform Stage 1 (medium blue) and Platform Stage 2 (light blue); F – Bigoray C Field, Rankey and Mitchell (2003). G-K) Map-view outlines of buildups, all plotted on the same scale. G - "Central Luconia Field" Masaferro et al. (2004); H – Field EX, this study; I – Bigoray C Field, Rankey and Mitchell (2003). J-Jintan, Ting et al. (2011); K – Innisfail Field, Atchley et al. (2006). See text for discussion. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

et al., 2011). Like EX, Jintan nucleated on structurally controlled high, and as in EX, syndepositional faulting has been interpreted to have markedly influenced depositional patterns and stratigraphic architecture (Vahrenkamp, 2004; Ting et al., 2011; Menier et al., 2014). Most of the thick platform is aggradational, although it is capped by a succession of several backsteps that gradually reduced the size of the platform and ended with several smaller pinnacles on top of the larger edifice. Regional correlations show that basinal siliciclastics post-date and onlap the platform margins, and it includes no wings; it appears to have included greater syndepositional relief than EX. Internally, several horizons (both in seismic and in core) include evidence for pronounced karst.

These platforms and their seismic character provide several contrasts to that imaged in Field EX. First, these northern fields include closed-wing geometry and greater syn-depositional relief than in the EX pinnacle. This observation is consistent with that of Koša et al. (2016), who suggested the differences relate to later siliciclastic influx (e.g., deeper waters around platforms) in the northern area, depths that inhibited infill and progradation of carbonates. In contrast, prograding siliciclastics created shallower off-platform areas around EX, and facilitated development of wings, as discussed above. Second, although tight zones (flooding intervals) in each of these fields form continuous, high amplitude reflectors, the architecture of porous zones is distinct. The northern field (Masaferro et al., 2004) includes mounded geometries near the margins (especially the western margin), and evidence for platformward progradation; in contrast, in the seismic data of Field EX, no unambiguous evidence for mounding or clinoforms are apparent within the carbonates, with the exception of Platform Stage 4, whose clinoforms prograde basinward. Nonetheless, greater isochron and higher amplitude on the northern and western margins of platform stages 2 (Figs. 6B) and 3 (Fig. 7C) potentially could reflect better developed reefs on those areas. These reefs could be favored by high wave energy from those directions, as inferred in the northern field. Third, Field EX includes pronounced backsteps at several stratigraphic levels (e.g., horizons C, D), and onlapping carbonate packages on its flanks (e.g., platform stages 3 and 4). In contrast, the northern fields tend to be more aggradational overall, but Jintan does include several platform backsteps in the youngest strata. Understanding why these patterns occur will depend on accurate age constraints among these platforms (an on-going project).

Devonian, Western Canadian Sedimentary Basin – Devonian strata of the Western Canadian Sedimentary Basin include numerous isolated

carbonate buildups. Among the best studied of these deposits include strata of the Frasnian Nisku Formation (Chevron Standard Limited, 1978; Watts et al., 1994). Although most Nisku reefs are small (less than 2.5 km^2 in area, Watts et al., 1994), they collectively include over 500 million bbl of oil and 500 billion ft^3 of gas. Many Nisku pinnacle reefs initiated on a shallow, gently dipping carbonate ramp, but segregated into isolated buildups which largely built vertically, flanked by deeper off-platform argillaceous carbonates and shale, due to relative rise in sea-level. The pinnacles in the West Pembina area occur in a 10–30 km wide trend that roughly parallels depositional strike on a northwest-dipping ramp, including numerous pinnacles that occur at what has been termed an "outer shelf margin" (Anderson and Machel, 1989). They have been interpreted to include 10s of m of depositional relief, constrained by tongues of silty and argillaceous off-platform strata up to 15 m thick that locally interfinger with pinnacle strata, but total carbonate thicknesses reach up to 100 m. The reefs in these buildups are comprised of stromatoporoids, corals, calcareous algae, and calcimicrobes, as well as cement. The highest reservoir quality occurs in dolomitized strata (Watts et al., 1994), wherein porosity can average 11% and is mostly secondary (moldic, vuggy, intercrystalline, fracture porosity; Anderson and Machel, 1989). The silty and argillaceous flooding intervals can form permeability baffles or barriers within reservoirs, akin to Luconia buildups.

A seismic line through one of these buildups (Rankey and Mitchell, 2003) illustrates the seismic character of one of these buildups. This line illustrates the broad, low-relief buildup near the resolution of the (~20 Hz) seismic data. As with many of these buildups, the greatest uncertainty in seismic interpretation lies in the flanks, as illustrated by the various interpretations in those areas (Fig. 14C). In these data, stratal terminations and geometries are insufficient to subdivide the succession into seismic stratal units. In contrast, Schwab et al. (2004) examined and seismically modeled an older Redwater reef. Field data illustrated both basinal onlap onto the platform margin and interfingering between platform and basin. Nonetheless, they noted that seismically the platform margin is most readily recognized by a sharp change of seismic facies, related to lithologic changes between basin and platform.

Other successions are better constrained by extensive well-log and core data, and provide additional perspectives on platform-basin dynamics. For example, a study of Beaverhill Lake buildups (Wendte and Uyeno, 2005) recognized differences in character of interactions across the shelf. Areas near the siliciclastic source include abundant fine clastics that infilled much of the topography. These clastics and westerly, leeside shedding of lime mud off the shallow platforms favored basin infilling, and leeward platform progradation during slower base-level rise, or actual falls. In contrast, in areas farther from clastic source, the basin remained unfilled, such that carbonate platforms prograded only by building over their own debris into deeper basins. This dynamic hindered progradation or expansion of isolated pinnacles, and as a result, most platforms in these areas are backstepping.

Atchley et al. (2006) documented stratigraphic details of a slightly younger (Leduc Formation, Woodbend Group) buildup using seismic data constrained by 109 wells and 26 cores at Innisfail Field. Their study documented a ~220-m thick succession of platform carbonates that nucleated on a paleotopographic basement high. Facies range from platform margin reefs and coarse grainstone shoals to finer packstones of the platform interior, arranged into several 5–20-m thick high-frequency sequences bounded by surfaces of subaerial exposure. The stratigraphically lower, more aggradational sequences include platform-margin stromatoporoid barrier buildups, whereas upper, more backstepping sequences have more stromatoporoid shoal deposits; the shelf margin progressively backsteps several km. All facies are dolomitized, but the platform-margin association includes the highest porosity, permeability, and fracture density. Although a number of less-permeable sequence boundaries and flooding intervals are evident, they do not markedly limit flow, largely because of the influence of fractures.

Comparison of the stratigraphic and seismic character of these Devonian platforms reveal similarities and differences with the Miocene of Central Luconia and Field EX. One similarity is that many Devonian pinnacles (Keg River, Swan Hills, Leduc, Niksu) generally formed during longer-term transgressive phases (e.g., Potma et al., 2001; Wendte and Uyeno, 2005). The regional study of Ali (2013) reached a broadly comparable interpretation regarding the major carbonate growth phases of isolated buildups of Luconia, suggesting that the regional middle to late Miocene (Cycles IV-V) transgression was associated with regional tectonic tilting. This tectonic activity in Central Luconia also established the regional structural highs and lows, and movement on faults that provided nucleation sites for individual platforms and impacted their growth patterns (Doust, 1981; Ting et al., 2011; Ali, 2013; Menier et al., 2014; Jamaludin et al., 2018; this study); such widespread evidence for tectonic influence on the WCSB Devonian buildups is absent.

A second similarity is the ubiquitous (but not universal) backstepping and retrogradation evident in both Miocene and Devonian buildups (e.g., Vahrenkamp, 1998; Vahrenkamp, 2004; Potma et al., 2001; Atchley et al., 2006). This pattern is not surprising, given their genesis during transgressive phases, and their ultimate shared fate, drowning. Yet, the scale of platforms (Fig. 13) and their backstepping appears distinct. Many Devonian buildups, for example, are less than 200 m thick, and individual high-frequency sequences (5–20 m thick) document the backstepping (Potma et al., 2001; Atchley et al., 2006). In contrast, Miocene examples can be in excess of 1000 m thick, and seismically discernible backstepping units appear to be greater than 50 m thick, although higher-resolution sequences can be defined in core and logs (Schlaich, unpub. data, 2018). These distinctions may be related to the overall subsidence rate (greater in Central Luconia) and global climate setting (Miocene icehouse, Devonian greenhouse).

A final similarity is the dynamics between the basinal siliciclastics and the platform carbonates. In both Devonian and Miocene examples, those platforms nearer the clastic source had a shallower basin floor in which to shed carbonate sediment, and thus are characterized by more intimate interfingering (wings within the siliciclastics). Other, more distal platforms had greater water depths, and in many cases did not interfinger but rather were onlapped by later siliciclastics. Nonetheless, many Devonian and Miocene buildups met their ultimate common demise (drowning), and were buried by basinal silciciclastics.

General considerations – The seismic data from Field EX illustrate numerous features consistent with the criteria outlined by Burgess et al. (2013) for identifying carbonate buildups. Specifically, geometries such as localized thickening (Fig. 5), onlap of overburden (Fig. 7), and depositional wings (Figs. 8, 10C and 11A), geophysical signatures including velocity pull-up (Figs. 6A and 9) and high-amplitude capping reflector (Fig. 11), and seismic geometries of stacking patterns (Figs. 7A and 9) and possible karst-related features (Fig. 7D) all are well-captured in the data.

6. Conclusions

Seismic characterization of a Miocene isolated platform succession and the adjacent off-platform siliciclastics reveal a complex evolution and interactions. A basal, laterally extensive carbonate buildup (with an extent not documented in the 3D survey area) is overlain by a flooding interval and platform stepback (Platform Stage 1), with minimal debris in off-platform areas, and an absence of siliciclastics. This isolated platform is deformed by a major fault. A second flooding surface is overlain by a second backstepped isolated platform (Platform Stage 2), and subsequently by a thick succession of northward-prograding siliciclastics. These siliciclastics onlap Platform Stage 1, and interfinger with carbonate debris shed off of Platform Stage 2, and the younger Platform Stage 3. A pronounced flooding surface that overlies the prograding siliciclastics is in turn downlapped by another carbonate

succession (Platform Stage 4), and is structurally deformed locally. These strata are capped by another succession of northward prograding siliciclastics, and a final platform (Platform Stage 5), before the platform is drowned.

The seismic stratigraphic architecture document the influence of syndepositional structural deformation on platform evolution. Complex patterns of interactions between platform and off-platform strata suggest that whereas some platforms developed marked relief in excess of 100 m and flanked basins with minimal sediment influx, others were more intimately associated with basinal siliciclastics. Comparison of the nature, dynamics, and scales of this platform with other Miocene platforms of Central Luconia, and platforms of other geological ages, highlights the complexity of isolated carbonate platforms and the variables that control their internal heterogeneity.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpetgeo.2019.01.009.

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