Stratigraphic evolution and karstification of a Cretaceous Mid-Pacific atoll (Resolution Guyot) resolved from core-log-seismic integration and comparison with modern and ancient analogues

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Abstract
Atolls are faithful recorders helping us understand eustatic variations, the evolution of carbonate production through time, and changes in magmatic hotspots activity. Several early Cretaceous Mid-Pacific atolls were previously investigated through ocean drilling, but due to the low quality of vintage seismic data available, few spatial constraints exist on their stratigraphic evolution and large-scale diagenesis. Here, we present results from an integrated core-log-seismic study at Resolution Guyot and comparison with modern and ancient analogues. We identify six seismic-stratigraphic units: (1) platform initiation with aggradation and backstepping through the Hauterivian which ended by platform emersion; (2) reflooding of the platform with progradation and aggradation through the Barremian till the early-Aptian when ocean anoxic event 1a resulted in incipient drowning; (3) platform backstepping till the mid-Aptian when the platform shifted to progradation and aggradation till the mid-Albian; (4) platform emersion; (5) reflooding with backstepping ending at the latest-Albian by platform emersion; and (6) final drowning. The stratigraphic surfaces bounding these units are coeval with some of the Cretaceous eustatic events, which suggest an eustatic control on the evolution of this atoll and confirm that several previously reported sea-level variations in the early Cretaceous are driven by eustasy. Changes in subsidence and carbonate production rates and suspected later magmatism have also impacted the stratigraphic evolution. The suspected later magmatism could lead to environmental perturbations and potentially platform demise. Contrary to previous studies, we identify two emersion events during the mid- and late-Albian which resulted in intensive meteoric dissolution and karstification. The platform margin syndepositional fractures interacted with the subaerial exposure events by focusing the dissolution which formed vertically stacked flank-margin fracture-cave system. The study gives a unique insight into the interplay between eustasy and local processes.
Isolated carbonate platforms and atolls are faithful recorders of the evolution of life on Earth, of palaeoceanographic changes, and of base-level changes (e.g. Bialik, Samankassou, et al., 2021; Harris et al., 2015; Robinson, 2011; Schlanger & Premoli Silva, 1986; Wu et al., 2020). They occur throughout the geologic record, from the Archean to the present. The low latitudes of all oceans host isolated carbonate platforms including, but not limited to, the Maldives, Chagos and the Mascarene in the Indian Ocean, the Great and Little Bahama Banks in the Atlantic, Funafuti, Bikini and Tuamotu Islands in the Pacific Ocean and Macclesfield bank in the South China Sea. They are of particular interest because their internal architecture, onset, growth, diagenetic alterations, and demise tend to be largely controlled by biotic evolution, eustasy, volcanism, subsidence and environmental conditions. Therefore, they offer better assessment of the factors controlling carbonate evolution, as they are away from clastic input (Courgeon et al., 2017).

Several drowned Cretaceous atolls are scattered throughout the Pacific Ocean, thanks to the abundance of hotspot volcanism in the region. The Mid- and Western-Pacific have been investigated by several seismic and drilling campaigns (Ocean Drilling Program (ODP) Leg 144 and 143; Figure 1; Winterer & Sager, 1995), thus offering some existing data to understand carbonate production, stratigraphic development and possible ties to eustasy in this region. In addition, these atolls are prone to subaerial exposure and karstification (e.g. Wodejebato and Limalok guyots; Arnaud-Vanneau et al., 1995), dolomitization (e.g. Resolution and Allison guyots; Röhl & Strasser, 1995) and later magmatic activity(ies) (e.g. Allison guyots; Pringle & Duncan, 1995), thus offering good natural laboratories to understand spatial and temporal evolution of diagenetic alterations such as meteoric, burial and hydrothermally induced diagenesis and island dolomite.

Despite the complex heterogeneity of carbonate platforms, our understanding of the Pacific Cretaceous atolls mostly comes from sparse well data (e.g. Arnaud et al., 1995; Jenkyns & Wilson, 1999; Wilson et al., 1998) with rare use of vintage 2D seismic reflection data (e.g. Wodejebato and Limalok guyots; Arnaud-Vanneau et al., 1995) of lower quality than modern standards (e.g. Sager et al., 1993a; Strasser et al., 1995). Hence, largely due to a lack of good seismic coverage of reasonable quality, the seismic-stratigraphic framework of the Pacific drowned Cretaceous atolls, their evolution, depositional architecture, karstification geomorphic features and potential presence of fluid venting systems are poorly resolved. Our paper presents a core-log-seismic integration study on Resolution Guyot in the Mid-Pacific Mountains and comparison with modern and ancient carbonate system analogues to shed new light on these unknowns.

Seismic Imaging of carbonate rocks has developed tremendously in the last two decades. This is reflected in the increasing number of special publications focusing on seismic imaging of carbonates (e.g. Eberli et al., 2004; Hendry et al., 2021) and seismic-based research articles (e.g. Bialik et al., 2021; Burgess et al., 2013; Clark et al., 2018; Cross et al., 2021; Fournier et al., 2005;
Huang et al., 2020; Ma et al., 2021; Paumard et al., 2017; Saller & Vijaya, 2002; Van Tuyl et al., 2018; Zampetti et al., 2004). Moreover, our conceptual understanding of carbonate systems has improved recently, thanks to satellite image and facies analyses on modern isolated carbonate platforms (e.g. Gischler, 2006; Harris et al., 2015; Jorry et al., 2016; Prat et al., 2016; Rankey, 2016; Utami et al., 2018; Wu et al., 2020). The developments in our understanding of carbonate systems and seismic imaging over the last two decades offer an opportunity to revisit the vintage seismic and well data of the early Cretaceous Mid-Pacific atolls to better understand these systems.

Deciphering the controls on the carbonate platform evolution is an ongoing question (e.g. Droxler & Jorry, 2021; Höning et al., 2017; Jenkyns & Wilson, 1999; Pomar et al., 2004; Westphal et al., 2010; Wilson et al., 1998). Considering: (1) the Cretaceous as one of the most prolific periods of carbonate sedimentation (Kiessling et al., 2003), (2) the presence of significantly different eustatic curves for the Cretaceous (Haq, 2014; Miller et al., 2005; Sahagian et al., 1996) and (3) the isolated carbonate platforms as prime targets for subsurface energy applications (e.g. Burgess et al., 2013; Esestime et al., 2016; Rusciadelli & Shiner, 2018), there is a need to better understand how the Mid-Pacific atolls functioned during the Cretaceous. This work applies seismic-stratigraphic methods to the Resolution Guyot carbonate atoll as a prime example of a Mid-Pacific early Cretaceous (Hauterivian to Albian) atoll. We integrate drilling and seismic data with examples from recently published literature of modern and ancient carbonate analogues using high-resolution seismic data and satellite images. Our objectives were to understand the following: (1) the stratigraphic evolution of the early Cretaceous (Hauterivian to Albian) carbonate atoll of Resolution Guyot to give insights into the response of Cretaceous reef builders to eustasy and global anoxia, (2) the potential karstification events as direct evidence of eustatic lowstands in the Cretaceous affecting the Mid-Pacific guyots and how the karst seismic geomorphic features are distributed and controlled, and (3) constraints on the distribution of fractures, fracture corridors and any evidence for the presence of fluid conduits.
2 | GEOLOGICAL SETTING

Resolution Guyot is a drowned atoll in the Mid-Pacific Mountains, one of the most prominent seamount chains in the Pacific Ocean (Winterer & Sager, 1995). This isolated carbonate platform is 25 × 35 km wide (Figure 1; a radius of ca. 15 km) and was originally formed at sea level, but is currently drowned and the platform top sits ca. 1200–1400 m below sea level. It has a sedimentary cover (Figure 2; Hauterivian-Albian; ca. 1620 m thickness; Winterer & Sager, 1995) resting on a volcanic edifice: it can be classified as a guyot which was originally deposited as an atoll (sensu Scott & Rotondo, 1983). It is capped by a thin pelagic cap deposited after the drowning (Winterer & Sager, 1995). Almost all our understanding of Resolution Guyot comes from ODP Site 866 near the platform margin (Figure 1), as the other two sites (i.e. 867 and 868) are very shallow.

Extensive intraplate volcanic features characterize the Pacific seafloor (Hamilton, 1956). The radiometric age of the oldest volcanic samples at Site 866 is 127.6 ± 2.1 Ma, with younger ages at 121.3 ± 1.6 Ma (Pringle & Duncan, 1995). In addition to its importance in understanding the Earth’s history, magmatic activity and associated fluid flow make major contributions to seep locations (e.g. Feng & Chen, 2015), deformation (e.g. Omosanya et al., 2017) and diagenetic alterations (e.g. carbonate dissolution, Sun et al., 2013; dolomitization, Breislin et al., 2020; silicification, Fiordalisi et al., 2021).

Based on only 1D data from Site 866 (very low average recovery of ca. 15.4%; Arnaud et al., 1995), the sequence stratigraphy of Resolution Guyot atoll can be summarized as follows: (1) Hauterivian transgression; (2) very restricted aggrading shallow marine Barremian regression sequences; (3) progressive deepening during the early-Aptian with the appearance of shallow, open-marine sediments; (4) early-Aptian transgression characterized by open-marine deposits; (5) return to shallow-marine-restricted deposits during the late-Aptian; and (6) new transgressive period during the Albian, with the development of a shallow, open-marine environment. As Arnaud et al. (1995) and Strasser et al. (1995) both highlighted that the vertical facies evolution that was used to build this stratigraphic evolution model is only applicable at the drill site and the sequence stratigraphy away from the well is unknown.

The diagenetic history of the Resolution Guyot carbonates based on core data is relatively simple including marine and meteoric diagenesis and late diagenetic dolomitization (Flood & Chivas, 1995; Röhl & Strasser, 1995). The presence of meteoric diagenesis is still debated: the irregular surface of the upper Albian carbonates below the pelagic cap observed in 3.5-kHz echo-soundings and seismic profiles is interpreted as evidence for subaerial exposure (Winterer, 1998; Winterer et al., 1995), but oxygen and carbon isotope signature of bulk carbonates and calcitic cements do not offer any supporting evidence of meteoric diagenesis (Jenkyns & Wilson, 1999; Wilson et al., 1998). This observation has raised the debate of whether the Pacific Cretaceous atolls have ever experienced subaerial exposure and karstification before their demise. This debate was reflected on the hypotheses for the demise of the Mid-Pacific atolls, which are: (1) ‘death-by-emergence-and-submergence’ (Winterer, 1998; Winterer et al., 1995) and (2) ‘death-in-tropics’ (Jenkyns & Wilson, 1999; Larson, 1991; Wilson et al., 1998).

3 | DATA AND METHODS

3.1 | Dataset

This study uses bathymetry, well and seismic reflection data (Figure 1). Bathymetry comes from Earthref website (Keizer et al., 2001) and well data come from ODP sites 866, 867 and 868 (Sager et al., 1993a, 1993b) and Deep-Sea Drilling Program (DSDP) Site 463 (Timofeev et al., 1981) (Figures 1 and 2). Site 866 penetrated 1620 m of platform interior sediments followed by 143 m of the basaltic basement. Sites 867 and 868, respectively, penetrated ca. 80 and 20 m of the platform margin. Site 463 penetrated ca. 822 m of peri-platform sediments. Well data used in this study include core images, published core descriptions (e.g. Arnaud et al., 1995; Sager et al., 1993a, 1993b; Timofeev et al., 1981) and logging data including calliper, spectral gamma ray (SGR), potassium (K), thorium (Th), uranium (U), sonic, and Formation MicroScanner (FMS).

The seismic data (Figure 1) were collected during cruise ‘Roundabout Expedition Leg 10’ (RND10WT; Nov–Dec 1988) by the R/V Thomas Washington, a programme dedicated to seismic imaging of the Mesozoic Guyots of the western Pacific. The data are single channel, 2D seismic acquired using an 80-in.3 water gun, which was processed by the Institute for Geophysics at the University of Texas including filtering (50–200), mixing (1:1:1) and automatic gain control (Marine Geoscience Data System, n.d.).

3.2 | Revised age model

Age constraints in this study are achieved by combining existing carbon- and strontium-isotope data from Jenkyns (1995) and Jenkyns et al. (1995) at Site 866. Details of our correlation methodology and calculations are provided in Table S1. Briefly, we match the δ13C data from Jenkyns et al. (1995) with the low-latitude calibrated composite
δ¹³C_carb curve (reproduced from Herrle et al., 2015, using published data from Tethyan sections of Erba et al. (1999), Gale et al. (2011), Herrle et al. (2004), and calibrated using Gradstein et al. (2012; GTS2012)). The carbon-isotope stratigraphy approach is similar to age dating of the Cretaceous Sverdrup Basin Arctic sediments by Herrle et al. (2015). Subsequently, we use the strontium-isotope data from Jenkyns (1995) and correlate their values with a recent global ⁸⁷Sr/⁸⁶Sr curve (McArthur et al., 2012, version 5B) anchored on GTS2012 (Gradstein et al., 2012) as the eustatic chart for the Cretaceous by Haq (2014) is also anchored on the same geologic time scale. The best model was obtained by iteratively moving tie points until both strontium isotope and δ¹³C constraints were honoured.

**FIGURE 2** Lithostratigraphic description of ODP Sites 866, 867 and 868 and DSDP Site 463 (adapted from Timofeev et al., 1981; Sager et al., 1993a, 1993b). The figure shows a summary of the lithological and fossil content of the different lithostratigraphic units at different drill sites along with a correlation between seismic data, logging data (SGR; Spectral Gamma Ray and U; Uranium log) and lithostratigraphic description at Site 866, showing the identified seismic-stratigraphic surfaces (SS) and units (SU) and seismic facies (SF).
3.3 | Seismic and log interpretation

Our Seismic to well tie is achieved by revising the proposed depth to seismic reflectors from Sager et al. (1993a) with integration of sonic logs at Site 866 to obtain a continuous time-depth relationship (Table S2; Figure 2). The same velocity of the first 100 m at Site 866 is applied to sites 867 and 868 to convert geological horizon depths to time so they could be identified in the seismic data. Seismic interpretation and FMS data plotting are performed using Petrel® and Interactive-Petrophysics® Software, respectively.

We have conducted our seismic interpretation using seismic-stratigraphic principles (Courgeon et al., 2016; Mitchum et al., 1977), that include (1) defining the seismic facies based on interpreting reflection geometries (internal and external), continuity, amplitude and their location within the platform; (2) tracking the key seismic-stratigraphic surfaces and associated reflection (stratal) terminations, if available. In many cases, key horizons identified within the wells (e.g. the dolomite-basement boundary; Figure 2) are not identified as distinct single reflections in the seismic data, but as boundaries between zones with differing seismic facies. Our seismic facies analysis is therefore critical to developing a seismic-stratigraphic framework for the atoll and the two interpretation steps: (i) mapping seismic facies and (ii) mapping seismic-stratigraphic surfaces are intimately linked. To groundtruth our seismic facies analysis and to overcome the issue of the low quality of the data, each seismic facies is compared with well data wherever possible and with several high-quality analogous seismic data sets from other carbonate platforms. This resulted in better understanding of what our seismic facies interpreted within these vintage data may represent away from drill sites. Seismic attributes are used to assist the interpretation including root-mean-square (RMSA), signal-envelope and variance amplitudes. Seismic-stratigraphic trends of progradation, aggradation and retrogradation are interpreted through tracing the trajectory of the platform margin using break-of-slope or mounded seismic facies features (Burgess et al., 2013). The interpretation of different seismic-stratigraphic surfaces is guided by integrating several inputs, including; (1) seismic reflection (stratal) terminations (if available); (2) marker reflections coinciding with distinct changes in reflection characteristics (e.g. sharp change across the entire atoll from chaotic to continuous reflections or high-amplitude to low-amplitude reflections); (3) core data (e.g. brecciated intervals resembling subaerial exposure and karstification); and (4) logging data (e.g. sharp peaks in SGR and U resembling flooding surface). Maximum flooding surfaces (MFS) are identified at the base of the last backstepping margin on which reflections of subsequent units downlap (e.g. Yose et al., 2006). Type-1 sequence-boundaries (Schlager, 2005) are interpreted at the top of pervasively discontinuous seismic reflections showing a rugged surface offering potential evidence of subaerial exposure (e.g. Howarth & Alves, 2016; Paumard et al., 2017; Van Tuyl et al., 2018) where sinkholes can be observed to delineate a sequence boundary (e.g. Paumard et al., 2017). Sinkhole characteristics can be summarized as (1) having V- or U-shape (e.g. Heubeck et al., 2004; Howarth & Alves, 2016), (2) showing drape or collapse of the overlying sediments (Bachtel et al., 2004) and (3) appearing as dim areas within continuous reflections and associated with bright-spot anomalous underneath (Yang et al., 2018). Type-3 sequence-boundaries are interpreted on prominent reflection surfaces representing a depositional hiatus between the highstand system tract (HST) and the immediately overlying transgressive system tract (TST) with no evidence of exposure (Schlager, 2005). These stratigraphic surfaces are interspersed with seismic-stratigraphic units each of which has certain internal seismic facies and stacking pattern revealed by tracing platform margin seismic facies (Burgess et al., 2013).

4 | RESULTS AND INTERPRETATION

4.1 | Revised age model

Ten excursion points and nine correlative intervals in between were matched (highlighted by correlation lines with the low latitude calibrated composite δ13C curve; Figure 3, Table S1) based on similar δ13C trends. In addition, 7 tie points (inflection and plateaus) were identified in Sr isotopes (Table S1):

1. At ca. 1328 mbsf (0.707449 ± σ 0.00002) corresponding to trends during the early Barremian (ca. 130.5 Ma; Bodin et al., 2015; McArthur et al., 2012)
2. At ca. 1040 mbsf (0.707595 ± σ 0.00002) corresponding to the late early-Barremian (ca. 129 Ma; Bodin et al., 2015; McArthur et al., 2012)
3. At ca. 591 mbsf (0.707334 ± σ 0.00002) corresponding to the late Aptian (ca. 121.4 Ma; McArthur et al., 2012)
4. At ca. 434 mbsf (0.707229 ± σ 0.00002) corresponding to the latest Aptian (ca. 114.8 Ma; Bodin et al., 2015; McArthur et al., 2012)
5. At ca. 250 mbsf (0.707436 ± σ 0.000031) corresponding to the mid-Albian (ca. 107.75–106.8 Ma; McArthur et al., 2012)
6. Between ca. 165 and 125 mbsf (0.707421 ± σ 0.00002, 0.707421 ± σ 0.000021, and 0.707414 ± σ 0.00002)
corresponding to the late-Albian (ca. 103.6–105.15 Ma; McArthur et al., 2012)

7. At ca. 48 mbsf (0.707458 ± 0.000024) corresponding to the latest Albian (ca. 101.3 Ma; McArthur et al., 2012).

The revised age model (Figure 3; Table S2) suggests that (1) sedimentation started above the basement at Site 866 at ca. 132 ± 1 Ma based on the projected age of the first recovered sample at 1620 mbsf, (2) the Hauterivian/
Barremian boundary lies at ca. 1400 mbsf, (3) the Barremian/Aptian boundary lies at ca. 880 mbsf, (4) the Aptian/Albian boundary lies at ca. 390 mbsf and (5) neritic carbonate production ceased in the latest Albian/early Cenomanian (ca. 100.45 Ma) based on the projected age of the last shallow marine carbonate sample recovered below the pelagic cap at ca. 19.6 mbsf.

This revised age model is anchored on the geologic time scale of Gradstein et al. (2012) giving a timespan from ca. 132 ± 1 and ca. 100.5 ± 1 Ma between onset and drowning of the carbonate platform. In Section 5.2, the updated age-model is used to compare our record with the Haq (2014) revised eustatic record and Pohl et al. (2020) carbonate production trends as they are all anchored on the same geologic time scale (Gradstein et al., 2012).

4.2 Seismic facies analysis

We identified fourteen seismic facies (Figure 4) and their palaeogeographic distributions within the atoll (Figure 5) based on seismic reflection properties including reflection patterns, continuity, amplitude and external and internal geometry. Detailed characteristics of these seismic facies are explained below along with their interpretation integrating drilling and logging data and comparison with modern examples from high-resolution seismic data sets.

Seismic facies 1 (SF1) consists of horizontal, parallel and continuous reflections of very high amplitude (Figures 4 and 5). It is found forming a tabular sheet ca. 20–60 ms TWT thick covering the upper most part of the guyot (ca. 30–90 m given our time–depth relationship, Table S2). It is also observed basinward of the toe of the slope where it onlaps the platform margin and extends for tens of kilometres (Figures 4 and 5).

Interpretation: SF1 (Figure 4) is interpreted as pelagic deposits covering the carbonate platform. This is supported by core data from Site 866 that encounter benthic fossil ooze (i.e. lithostratigraphic Unit I; Figure 2). The seismic character of SF1 matches basal deposits identified by Van Tuyl et al. (2018) in the Miocene carbonate build-ups in northwest Australia. The very high amplitude of SF1 could be explained by the underlying iron-manganese encrusted limestone (lithostratigraphic Unit II; Figure 2) representing a drowning succession similar to those identified by Eberli et al. (2010) on the Marion Plateau. Similar seismic facies was described by Mitchell et al. (2015) in other Pacific guyots.

Seismic facies 2 (SF2) consists of sub-horizontal to horizontal parallel and continuous reflections of high-to-moderate amplitude (Figure 4). It is ca. 250 ms TWT thick (ca. 420 m). SF2 is found throughout the platform interior extending for tens of kilometres. Laterally, SF2 transitions to SF6, 7 and 8 at the platform margin where the reflections become more chaotic (Figures 4 and 5).

Interpretation: SF2 (Figure 4) is interpreted as the platform interior, as it corresponds to cyclic packstone–wackestone and mudstone lithofacies (i.e. lithostratigraphic Unit III at Site 866; Figure 2). The seismic character of SF2 matches the lagoon facies identified by Van Tuyl et al. (2018) at the Miocene carbonate build-ups in northwest Australia. In our data, lagoon deposits (Figures 2 and 4) appear sometimes as transparent (ca. −2150 to ca. −2400 ms TWT) or chaotic (ca. −2400 to ca. −2800 ms TWT) which correlates to similar seismic facies observed on the Great Bahama Bank (GBB) and the synthetic seismic section of the Maiella Platform by Eberli, Anselmetti, et al. (2004).

Seismic facies 3 (SF3) is characterized by pervasively discontinuous subparallel to chaotic reflections of high to low amplitude (Figure 4). SF3 extends laterally throughout the platform (Figures 4 and 5).

Interpretation: SF3 (Figure 4) is interpreted as karst horizons. It shares similar seismic characteristics as karst horizons formed by subaerial exposure in the South Malé Atoll in the Maldives (Betzler et al., 2015), the Browse Basin, Northwest Australia (Howarth & Alves, 2016; Van Tuyl et al., 2018) and Mablesfield Bank in the South China Sea (Huang et al., 2020). Observations from cores also support karstification including (1) core recovery at Site 866 above 500 mbsf (within SF3) is ca. 8%, which decreases to ca. 1.5% above 300 mbsf (within SF3) suggesting breciation of the limestone (2) FMS Images at Site 866 (ca. 250–450 mbsf; within SF3) show intensive brecciation and abundance of vuggy porosities (Swiss cheese-like vugs; Figure 6), (3) several yellow, reddish, and brown stained calcite horizons are found at ca. 60 and ca. 220–420 mbsf (Sager et al., 1993a), (4) the drill bit at Site 867 dropped freely for 8 m interpreted as entering a cave (Sager et al., 1993b).

Seismic facies 4 (SF4) is a discrete, concave feature (a topographic depression) ca. 30 ms TWT deep (ca. 45 m) with a diameter of 1500–1750 m (Figure 4) filled with onlapping sediments. Layers below the depression are chaotic and highly discontinuous. This facies is encountered only at the seabed in the middle of the platform (Figure 5).

Interpretation: Based on observations of crater-like depressions with onlapping reflections, SF4 (Figure 4) could be interpreted as a pockmark or crater formed by sediment removal through fluid venting which is similar to category 5 pockmarks identified by Betzler et al. (2011) in the Maldives carbonate platform. Alternatively, it could be a sag structure similar to karst collapse sags discussed by McDonnell et al. (2007) in the Cambrian–Ordovician Ellenburger Group in Texas.
FIGURE 4  Main seismic facies and their reflection characteristics (internal geometries, continuity amplitude and shape) along with the corresponding well zone, if available. Their identification and interpretation are based on comparing the observed characteristics with similar examples from the literature.
| Seismic Facies | Reflection Characteristics | Lithology & Characteristics | Well Zone | Interpretation(s) | Example of Similar Seismic Facies from literature |
|---------------|----------------------------|-----------------------------|-----------|-------------------|-----------------------------------------------|
| SF8 Sigmoidal to sigmoid oblique reflections | Medium to high amplitude, semi-continuous to discontinuous, gently inclined seismic reflections. Sigmoid to sigmoid-oblique geometries. Located at the platform margin and dipping toward it | | | Platform margin clinforms | Adapted from Bachtel et al. (2004) |
| SF9 Planar high amplitude reflections with abrupt terminations | Laterally limited high amplitude reflections with abrupt terminations (highlighted by yellow triangles) and local transgression through the host rock. Planar shaped in the seismic sections. | | | Potential concordant magmatic sills | Adapted from Magee et al. (2015) |
| SF10 Disrupted chaotic zone with faint layering | Disrupted chaotic reflections of low to moderate & some times high amplitude. Gentle cliniforms, seaward-dipping-reflections (SDRs) & faint layering are present | Some soils, minor volcaniclastic rocks, brecciated & fresh basalt | ODP Site 866 Unit IX | Volcanic Basement | Adapted from Shahzad et al. (2019) |
| SF11 Chaotic variable amplitude reflections | Disrupted reflection zones characterized by chaotic reflections form which fluid flow vent system originate | It is found within the zones from -2400 to -2800 TWT ms where oolitic grainstone shifts upward to inner platform cyclic wacke/packstone | ODP Site 866 Unit VII to subunit VB | Chaotic seismic facies with fluid flow seismic pipes | Adapted from Huang et al. (2020) |
| SF12 Vertical zones of disrupted reflectivity & reduced reflection continuity | Vertical zones with disrupted reflectivity & reduced reflection continuity. Surrounded by: Tilted reflections (marked by dashed lines). Vertical extent ~500-700 ms | | | Fluid flow vents | Adapted from Hendry et al. (2021) |
Seismic facies 5 (SF5) is a vertical anomalous feature appearing as beads of high-amplitude reflections compared with the host rock. These vertical bodies have a height of ca. 15–50 ms TWT (ca. 25–90 m; mainly ca. 50 m) and a width of ca. 100–150 m (Figures 4 and 5).

**Interpretation:** The anomalous appearance of SF5 (Figure 4) is interpreted as “paleocaves” as they match the string-of-beads “paleocaves” reflections identified by numerous authors in Tahe oilfield (e.g. Zeng et al., 2020) and Tarim Basin (e.g. Yang et al., 2012) in China and many other places (Basso et al., 2018; Van Tuyl et al., 2018). The bit drop at Site 867 (at the platform margin) was interpreted as a sign of entering a cave (Sager et al., 1993b): this occurred at a drilling depth close to where we interpret “paleocaves” in seismic data. The high acoustic impedance contrast between the host rock and the “paleocaves” is due to the cave filling material which could be sedimentary deposits, collapse breccia or empty space filled with seawater (Campos Basin, Brazil; Basso et al., 2018).

Seismic facies 6 (SF6) has a broadly mounded external morphology and involves chaotic to wavy semi-continuous bidirectionally dipping low-amplitude reflections, which form bodies of ca. 60 ms TWT thickness (ca. 130 m). It is found at the platform margin between SF2 and 7 (Figures 4 and 5).

**Interpretation:** SF6 (Figure 4) is interpreted as a part of the platform margin representing shoal deposits; it corresponds to lithostratigraphic Unit V at Site 866 which is formed of planar and cross-laminated well-sorted oolitic grainstones with keystone vugs (Figure 2). SF6 seismic characteristics match shoals identified by Bachtel et al. (2004), Handford and Baria (2007), Paumard et al. (2017) and Zhang et al. (2020).

Seismic facies 7 (SF7) has convex up mounded semi-continuous to discontinuous reflections of moderate-to-high amplitude, which show bidirectional downlaps (Figure 4). SF7 is located within the platform interior, forming ca. 30 ms TWT thick (ca. 60 m) bodies with lateral extent of ca. 500 m. At the platform margin, it forms bodies of ca. 30–60 ms TWT thickness (ca. 60–90 m) with lateral extent of ca. 600–1600 m (Figures 4 and 5). Associated onlapping geometries can be observed around the mounded bodies (Figure 4).

**Interpretation:** SF7 (Figure 4) is interpreted as platform margin facies. This interpretation is supported by lithofacies at Sites 867 and 868 (Figures 2 and 5) which are located closely to SF7. Site 867 comprises peloidal and oolitic grainstones and coarse-grained rudist shell debris representing beach deposits (Sager et al., 1993a). Sites 868 comprises sponges and requieniid rudists bafflesstones and framestones interpreted as sponge, rudists and corals (subordinate) bioherms under wave and storm action alternating with coarse shell rubble layers (Strasser et al., 1995). According to Bover-Arnal et al. (2015), Özer et al. (2017), and Gili and Götz (2018), requieniid rudists are dominant in the platform margin and upper-slope settings. Therefore, SF7 likely represents a sand beach barrier with sponge and rudist build-ups that extend to the upper slope, which appear as the onlapping seismic reflections at the front of SF7. The mounded reflections with bidirectional downlaps in SF7 are similar to the shelf-margin defined by Bachtel et al. (2004). The onlapping seismic reflections behind SF7 are interpreted as a back-margin apron which matches the backreefs identified by Masaferro et al. (2004) in the Miocene build-ups of the Luconia province. This is supported by the lithology of the uppermost part of the lithostratigraphic Unit III at Site 866, which is formed of coarse-grained floatstones and rudstones with shell debris and rip-up clasts representing washover deposits.
Seismic facies 8 (SF8) consists of moderate- to high-amplitude semi-continuous to discontinuous reflections which exhibit sigmoid to sigmoid-oblique clinoformal geometries. They are located only at the platform margin (Figures 4 and 5) and are onlapped by parallel and climbing reflections.

**Interpretation:** SF8 (Figure 4) is interpreted as platform margin clinoforms, as it matches the described character of marginal clinoforms by Bachtel et al. (2004) and Van Tuyl et al. (2018). No well-based lithological controls exist but our interpretation of SF8 is supported by the exclusive location of this facies at the margin (Figure 5).

Seismic facies 9 (SF9) presents high-amplitude reflections with abrupt terminations and local transgressions exhibiting planar shapes and of distinct lateral extent (Figures 4 and 5). SF9 extends laterally from ca. 500 to 2500 m and vertically from ca. 25 to 55 ms TWT (ca. 50–120 m).

**Interpretation:** SF9’s (Figure 4) characteristics of high-amplitude reflections with limited lateral extent and abrupt terminations match described magmatic sills in numerous studies (e.g. Chen et al., 2020; Geng et al., 2020; Magee et al., 2015, 2016; Planke et al., 2005). We therefore tentatively suggest that SF9 are intruded magmatic sills, but SF9 has not been drilled at Resolution Guyot.

**FIGURE 5** Seismic profiles along with logging data wherever available (SGR; Spectral Gamma Ray and U; Uranium log) showing the palaeogeographic distribution of the different seismic facies and seismic stratigraphic units in the isolated carbonate platform of Resolution Guyot. See Figure 1 for the location of these figures. Uninterpreted seismic data are provided in the supplementary material.
Seismic facies 10 (SF10) consists of highly disrupted chaotic reflections of generally low amplitude with some zones of high amplitude (Figure 4). Gentle clinoforms (?), seaward dipping (?), and faint layered reflections were observed in some localities. This facies is only found in the deepest imaged part of the guyot (Figure 5).

Interpretation: SF10 (Figure 4) is interpreted as the volcanic basement, as it corresponds to basalts at Site 866 (Lithostratigraphic Unit IX; Figure 2). Its seismic characteristics are similar to the seamount on the Saurashtra Volcanic Platform described by Corfield et al. (2010) in terms of (1) chaotic, uneven and discontinues reflections, (2) some reflections around the margins show geometries similar to seaward dipping reflectors and volcanic clinoforms which correlates well with the suggested subaerial lava flow of the studied samples at Site 866 by Baker et al. (1995). Delineating the top volcanic basement is complicated by the similar density and seismic velocity of the volcanic basement and the overlying dolomitized limestone leading to similar acoustic impedances (Kenter & Ivanov, 1995; Figure 2).

Seismic facies 11 (SF11) consists of discontinuous, chaotic reflection zones, which are located immediately above SF10 (Figures 4 and 5). High-amplitude reflections of SF9 (intruded magmatic sills) can be observed within the chaotic zone. This facies extends laterally throughout the platform within the sedimentary succession from ca. −2400 to −2800 ms TWT (ca. 830–1620 mbsf). Qualitatively, at ca. −2675 to −2650 ms TWT (ca. 1400 mbsf), SF11 can be divided into two parts with more layered high-amplitude reflections above and less layered high-amplitude reflections and more chaotic low-amplitude reflections below.

Interpretation: SF11 (Figure 4) is interpreted as chaotic zones associated with fluid escape pipes similar to those described by Huang et al. (2020) in Macclesfield Bank in the South China Sea. At the same horizontal level of this seismic facies, the lithology at Site 866 is formed of a range of lithofacies from dolomitized oncoidal/oolitic grainstones in lithostratigraphic Unit VIII to lagoonal wacke/pack-stones in lithostratigraphic Units VII–VI.

Seismic facies 12 (SF12) presents vertical zones of disrupted and reduced reflection continuity (Figure 4). Within SF12, reflections range from upward convex or concave to more complex geometries. In some cases, SF12 is surrounded by tilted and enhanced reflection amplitudes (Figures 4 and 5). It is closely associated with SF11.
in its lower part and extends vertically for a height of ca. 500–700 ms TWT (900–1300 m).

Interpretation: SF12 (Figure 4) is interpreted as fluid vents which (Figure 2) present vertical zones of disrupted reflectivity and reduced reflection continuity cutting through layered successions similar to fluid flow pipes described in numerous studies (e.g. Cartwright & Santamarina, 2015; Hustoft et al., 2007; Moss & Cartwright, 2010). The variance attribute helps in discriminating the places affected by fluid flow pipes appearing as zones of dim to chaotic reflections relative to the well-bedded, high-medium amplitude facies of the host-rock strata (e.g. Hendry et al., 2021; Jamtveit et al., 2004; Omosanya et al., 2018). The interpreted fluid vents are surrounded by upward bending reflections potentially indicating deflection by upward fluid flow similar to fluid conduits described by Omosanya et al. (2018) in the Vøring Basin Offshore Norway and Wang et al. (2018) in the South China Sea.

Seismic facies 13 (SF13) is characterized by mounded chaotic, hummocky, subparallel and discontinuous reflections of varying amplitudes (Figure 4). It is found in basinial regions and forms lenticular bodies ca. 200–450 ms TWT thick that pinches out towards the toe of the platform edge (Figure 5).

Interpretation: SF13 (Figure 4) is interpreted as mass-transport deposits (MTDs) as the cores recovered at Site 463 (lithostratigraphic Unit IV; Figure 2) comprise clastic rubbles of limestones and radiolarian limestones (Timofeev et al., 1981) with slump structures. This matches both the lithostratigraphic descriptions (Wunsch et al., 2018) and seismic characteristics (Principaud et al., 2015) of MTDs along the slope of the Great Barrier Reef.

Seismic facies 14 (SF14) is characterized by continuous parallel reflections with amplitudes varying from low to high. It forms sheet-like bodies ca. 600–750 ms TWT thick that covers tens of kilometres in the basinal region and onlaps on the toe of the platform edge (Figures 4 and 5).

Interpretation: SF14 (Figure 4) is interpreted as contourite drifts formed of nannofossil ooze (lithostratigraphic Unit I-III at Site 463) as the seismic character matches the sheet-like drift deposits within the Inner Sea in the Maldives (Lüdmann et al., 2013).

4.3 Seismic-stratigraphic units

Based on the detailed analysis of seismic facies above and guided by the core and well-log data (SGR, U, Th, K, FMS), the sedimentary succession from the seafloor down to the basement is divided into six seismic-stratigraphic units (Figure 5) each of which has certain seismic reflection geometries, stratal stacking patterns, and bounding seismic-stratigraphic surfaces. The timespan of each seismic unit is identified using the age of the bounding seismic-stratigraphic surfaces at the corresponding depths in the revised age model at Site 866 (Figure 3; Table S1).

The top of the acoustic basement, as constrained at Site 866, appears in seismic data as the boundary between more chaotic, less layered reflections below the top basement (constrained by core data) and less chaotic, more layered reflections above (Figure 5). However, these different seismic facies (SF 10 and 11) are subtly different and are not bounded by a single reflection event, making the boundary between them difficult to constrain. Consequently, two possible interpretations of the top basement are mapped, which are (1) a flat-topped basement and (2) a flat-topped basement on the edges with doming in the centre of the guyot.

4.3.1 Seismic Unit-1: Hauterivian

Seismic Unit-1 occurs immediately on top of the basement. It is capped by seismic-stratigraphic surface 1 (SS1) appearing at ca. −2675 to −2650 ms TWT separating more chaotic and less layered reflections below from less chaotic and more layered reflections of SF11 above. SS1 (Figure 7) includes (1) a sinkhole which is visible in the seismic data as a V-shaped depression; (2) sharp peaks in SGR, K, U, Th logs at Site 866; (3) a brecciated and reworked interval in the cores at ca. 1400 mbsf. Seismic Unit-1 (Figure 5) is characterized by chaotic reflections of SF11, and platform margin mounded seismic facies (SF7). SF7 can be seen to first aggrade and then backstep to the south (Figure 8). At Site 866, Seismic Unit-1 includes a ca. 200 m thick zone of dolomitized oolitic/oncocoidal grainstone (lithostratigraphic Unit VIII; Figure 2).

4.3.2 Seismic Unit-2: Early Barremian to early Aptian

Seismic Unit-2 is capped by SS2 (Figure 7), a surface marked by a sharp change in reflection amplitude from moderate to high (SF11) below to low and transparent (SF2) above at ca. −2377 to −2388 ms TWT. In addition, SS2 appears as a surface on which internal geometries of the subsequent Seismic Unit-3 downlap (Figure 7). At Site
| Seismic stratigraphic surface | Seismic characteristics at the stratigraphic surfaces | Examples of similar seismic characteristics from literature |
|------------------------------|------------------------------------------------------|--------------------------------------------------------|
| SS5                          | Continuous reflections                               | Adapted from Howarth and Alves (2016)                 |
| SS4                          | Chaotic reflections                                   | Seismic section from Browse Basin showing: 1) characteristic discontinuous chaotic broken reflections of karst intervals; 2) sinkholes formed above the karsts in the more continuous horizons |
| SS3                          | Last backstepping platform margins (SF7)             | Adapted from Van Tuyll et al. (2019)                  |
| SS2                          | SGRIU                                                | Seismic section from Zhongsha atoll showing using the abrupt change in amplitude in delineating the bounding seismic-stratigraphic surface |
| SS1                          | Sinkhole                                             | The seismic signature of paleokarst sinkholes generated by synthetic seismic modelling |

Adapted from Huang et al. (2020)
866, SS2 (Figure 7) is characterized by dramatic sharp peaks in SGR, U, Th, and K logs associated with organic and clay-rich limestones and black shale layers between ca. 850 and 830 mbsf. Seismic Unit-2 (Figure 5) is characterized by chaotic reflections of SF11, and platform margin clinoforms and mounded seismic facies (SF7 and SF8). The platform margin (SF7 and SF8) shows first progradation from its former location in Seismic Unit-1, followed by aggradation (Figure 8). In the middle of the platform, potential magmatic sills (SF9) start to appear (Figures 5 and 8). At Site 866, Seismic Unit-2 is ca. 550–570 m thick of peritidal lagoonal lithofacies of lithostratigraphic Unit-VII to within subunit-VIA (Figure 2).

4.3.3 | Seismic Unit-3: Early Aptian to early mid Aptian (125.5 ± 1 Ma–122.8 ± 1 Ma)

Seismic Unit-3 is capped by SS3 (Figure 7) which is constrained by clinoforms near the platform edge downlapping onto the surface at ca. −2300 ms TWT. At Site 866 (ca. 670 mbsf), SS3 coincides with sharp increase in SGR, k, Th and U logs (Figures 5 and 7) and the cores show clay-rich layers. Behind the platform margin (SF7), the seismic facies (Figure 8) transitions from interpreted shoal deposits (SF6) to transparent platform interior seismic facies (SF2). Above SS2, the platform margin (SF7) is backstepping. At site 866, Seismic Unit-3 is ca. 160–180 m thick of lithofacies shifting from lagoonal cyclic pack/wacke-stone and algal laminates of lithostratigraphic subunit VIA to oolitic shoal grainstone of lithostratigraphic Unit V.

4.3.4 | Seismic Unit-4: Mid Aptian to Mid Albian (122.8 ± 1 Ma–105.15 ± 1 Ma)

The uppermost part of Unit-4 is characterized by pervasive discontinuous seismic reflections (i.e. karstification; SF3) and SS4 separates these (Figure 7) from more continuous less chaotic reflections above (at ca. −2000 to 1920 ms TWT). Some potential sinkholes are observed (V-shaped depressions; Figure 7) along SS4. At Site 866, the recovery is too low at that level, but FMS data show intermittent intervals of intensively brecciated and disrupted carbonates associated with extensive vugs at ca. 270 to 430 mbsf (Figure 6). Above SS3 (Figure 8), the trajectory of the platform margin (SF7 and SF8) within Unit-4 starts with progradation followed by aggradation. Behind the platform margin (Figure 5), seismic facies transitions from onlapping back-margin to transparent and high-amplitude platform interior reflections (SF2) with abundance of karstification facies (SF3) between ca. −2130 and ca. −1920 ms TWT. At Site 866, Seismic Unit-4 is ca. 500–510 m thick of restricted platform interior peritidal lithofacies of lithostratigraphic Unit IV.
4.3.5 | **Seismic Unit-5**: Mid Albian to late Albian (105.15 ± 1 Ma–100.45 ± 1 Ma)

The uppermost part of Seismic Unit-5 is characterized by pervasive discontinuous seismic reflections. SS5 separates them from continuous parallel reflections above (at ca. −1920 to −1850 ms TWT; SF1; Figure 7) and in the same way as SS4 some potential sinkholes were observed (V-shaped depressions) along SS5. Like Seismic Unit-4, the recovery here is low, but SS5 corresponds to a level at Site 866 above which manganese-encrusted and phosphatic limestone layers at the base of lithostratigraphic Unit-II are found. Above SS4 (Figure 8), the trajectory of the platform margin (SF7) is backstepping and behind SF7, seismic facies transitions from back-margin to platform interior (SF2) with abundance of karstification (SF3). At Site 866, Seismic Unit-5 is ca. 140–150 m thick of platform interior gastropod/dasyclad wackestone of lithostratigraphic subunit IIIA (Figure 2).

4.3.6 | **Seismic Unit-6**: age uncertain, Maastrichtian (?) to late Pliocene (?)

Seismic Unit-6 represents the last seismic-stratigraphic unit in the sedimentary succession. It is formed of aggrading laterally continuous sheets of pelagic sediments (SF1) bounded by the seabed (Figures 5 and 8). At Site 866, it is ca. 20–32 m thick composed of manganiferous limestone and foraminiferal nannofossil ooze of lithostratigraphic Units II and I (Figure 2).

5 | **DISCUSSION**

5.1 | **From seismic facies to depositional model**

The distribution of the identified seismic facies and the depositional environments we propose they represent are interpolated regionally using information from modern analogues (e.g. satellite images from the Glorieuses archipelago by Jorry et al., 2016 and Prat et al., 2016, Figure 9) to build a 3D conceptual depositional model of Resolution Guyot (Figure 9). Despite that, corals as organisms are not...
comparable to rudists, the depositional geometry of the Cretaceous carbonate platforms is characterized by: (1) small accommodation spaces typical of Cretaceous eustasy, (2) high rates of carbonate production under wave action promoting lateral progradation (i.e. prograding clinoforms), (3) dominance of autotrophic organisms (i.e. rudists), (4) backstepping during increasing accommodation and (5) rubble swept towards the inner platform and down the surrounding deeper waters (Gili & Götz, 2018; Skelton, 2003). Consequently, they tend to develop flat-topped profiles that can be compared with modern carbonate platforms. Several studies compared the depositional environments of the Cretaceous outcrop deposits and subsurface reservoirs with modern carbonate platforms (Droste et al., 2010; Homewood et al., 2007; Sena & John, 2013; Yose et al., 2006).

The distribution of seismic facies representing key depositional elements is as follows: (1) the platform margin mounded facies (SF7) extends laterally for ca. 700–2000 m, (2) the back-margin apron (onlapping reflection in the back of SF7) is at least 650 m wide, based on the distance between SF7 and Site 866 where back-margin facies were encountered in the uppermost part of Unit III (Figures 4 and 5), (3) the upper-slope facies (onlapping reflection in front of SF7) is ca. 400–800 m wide, (4) the platform interior (SF2) is ca. 20,000 m with patch reefs (SF7) of width ca. 500 m, (5) the platform margin facies (SF7) can have back shoals (SF6) which could be part of the platform margin or a back-margin apron, (6) platform slopes of the Resolution Guyot and other atolls surrounding it are prone to producing MTDs (SF13) extending for 10s of kilometres and (7) downslope contourite drifts (SF14) are surrounding the platform and extending for 10s of km.

The uncertainties in our model can be summarized in the following: (1) taking modern carbonate platforms as an analogue, the platform margin could either be continuous margin (e.g. Pigeon Atoll in South China Sea; Rankey, 2016) or discontinuous margin cut by channels and formed of faroes (e.g. Felidhoo Atoll in Maldives; Gischler et al., 2014), (2) the mounded seismic facies of the platform margin (SF7) could exhibit different facies in other sides of our platform, but no other drilling data are available to test that and (3) the platform interior patch reefs and rudist meadows could be scattered (e.g. Felidhoo Atoll in Maldives; Gischler et al., 2014) or attached together forming ridge-pond morphology (e.g. Alacranes Reef, Mexico; Purkis et al., 2015).

We can infer other depositional environments at a finer scale which are below the resolution of our seismic data by comparing well data with satellite images from the Glorieuses archipelago. Within the platform interior, drilling reports (Figure 2; Sager et al., 1993a, 1993b) mentioned the presence of floatstone and rudstone intervals comprising reworked shell debris, ooids and intraclasts with blackened material interpreted as delivered to the platform interior by storm and wave action. This could represent washover fans (i.e. part of the back-margin apron) similar to what is observed in the back-reef apron and sandwaves of the Glorieuses archipelago (Figure 9; Jorry et al., 2016 and Prat et al., 2016). Moreover, lithostratigraphic subunit VIB at Site 866 (Figure 2) consists of caprinid rudists in living position in a peloidal pack/wackestone matrix which is overlain by well-washed grainstones to rudstone containing caprinid rudists debris. The ODP party (e.g. Sager et al., 1993a) interpreted this succession as part of the outer bank and shoal deposits. We suggest an alternative interpretation for this subunit: rudist meadows within the platform interior with shell debris formed by storm events. Our interpretation is supported by: (1) the described caprinid rudists in the drilling reports (Figure 2; Sager et al., 1993a, 1993b) are in living position, suggesting that one of the valves was implanted in the wacke/packstone substrate. This is similar to elevator rudists described by Gili and Götz (2018) and interpreted as living in relatively quiet environments. And (2) an inner platform depositional environment was suggested based on the presence of caprinid rudists at other locations (e.g. Maestrat Basin; Bover-Arnal et al., 2015; the Lycian Nappe; Özer et al., 2017).

The ODP party (Strasser et al., 1995; Winterer & Sager, 1995) depositional model was based solely on the facies description at Sites 866, 867, 868 and the 3.5-kHz echo-sounder profile passing through them. They suggested that the platform rim was composed of storm beach deposits, with a lagoon and sponge-rudist bioherms behind and in front of them, respectively. As highlighted by Strasser et al. (1995), this is valid only for the location of the echo-sounder profile and the wells. Our new conceptual model overcomes this limitation by integrating the drilling data with the seismic facies interpretation and modern analogues which helps in defining a detailed depositional model for the entire guyot.

5.2 Controls on the sequence-stratigraphic evolution of Resolution Guyot and links to the Cretaceous eustasy

The initial aggradation followed by backstepping of the platform margin immediately above the basement (Seismic Unit-1) reflects a catch-up phase characteristic of the TST (Figure 8). The lithology of Seismic Unit-1 at Site 866 (lithofacies Unit VIII; oolitic/oncocoidal grainstone; Figures 2 and 8) reflects similar conditions to the current widespread oolitic shoals in the Bahamas as a response
FIGURE 9 Palaeogeographic reconstruction of the different depositional environments in Resolution Guyot carbonate atoll by integrating the interpreted seismic facies with satellite images from the Glorieuses archipelago. (a) 3D conceptual depositional model showing the different seismic facies and the corresponding facies belts. (b) Satellite image from Glorieuses Archipelago (using the descriptions by Jorry et al., 2016 and Prat et al., 2016) used to guide the palaeogeographic interpolation of the different facies belts in Resolution Guyot carbonate atoll.
to rising sea level. This phase (Hauterivian; 132 ± 1 Ma–130.8 ± 1 Ma) ended by subaerial exposure judging by the presence of (1) brecciated intervals at Site 866, (2) a sinkhole above the last backstepping platform margin and (3) sharp peak of SGR, K, U logs reflecting organic/clay-rich layer, which is thought to be deposited during exposure and subsequent reflooding.

Above SS1, the prograding and then aggrading platform margin of Seismic Unit-2 reflects a keep-up phase similar to an HST (Figure 8). This is reflected by (1) the lateral expansion of the platform, filling all the available accommodation and (2) the restricted lagoonal deposits at Site 866 with increased supratidal, sabkha, tidal flats and algal mats (lithostratigraphic Unit VII- Subunit VIA; Figures 2 and 8). Thus, we interpret SS1 as a composite surface representing both the sequence stratigraphic boundary (exposure) and a maximum flooding surface (high gamma-ray values and progradation on top of the surface). Seismic Unit-2 (early Barremian to early Aptian; 130.8 ± 1 Ma–125.5 ± 1 Ma) is capped by SS2, which represents a series of organic-rich clay layers and a 10-cm-thick black shale. These layers were interpreted by Jenkyns (1995) as OAE 1a. The previous studies showed that the carbonate factory did not shut down completely during the OAE 1a as the clay-rich and organic rich facies are alternating with lagoonal deposits reflecting peritidal settings (water depth ≤10 m; Jenkyns & Wilson, 1999). Therefore, we suggest that this interval represents an incipient drowning surface.

Above SS2, carbonate production was less than accommodation creation as the platform margin is backstepping (Figure 8). Hence, Seismic Unit-3 (early Aptian to early mid Aptian; 125.5 ± 1 Ma–122.8 ± 1 Ma) is similar to Seismic Unit-1 and is interpreted as an overall TST, while SS2 is a flooding surface (Figure 8). Above SS2, the lithofacies at site 866 shift from restricted lagoonal deposits to oolitic beach-shoals (lithostratigraphic Subunit VIA-Unit V; Figures 2 and 8). The base of Seismic Unit-4 is marked by a switch to prograding platform margin downlapping onto SS3 (interpreted as a maximum flooding surface, Figures 7 and 8). Lithofacies of the MFS (SS3) at Site 866 include a clay-rich layer with a sharp peak in SGR, K, U and Th logs.

The initial progradation of Seismic Unit-4 (Mid Aptian to Mid Albian; 122.8 ± 1 Ma–105.15 ± 1 Ma) changes to aggradation of the platform margin, reflecting a keep-up phase and this unit is interpreted as an HST (Figure 8). At Site 866, lithofacies shift from oolitic beach-shoals below SS3 to restricted lagoon pack/wacke-stone above SS3 (lithostratigraphic Unit IV-Unit III; Figures 2 and 8). SS4 is marked at the top of the pervasive discontinuous seismic reflections, suggesting a subaerial exposure and karstification event (supported by the intermittent intervals of brecciated and vuggy carbonates below; Figure 6). SS4 is thus interpreted as a sequence boundary (Figures 7 and 8).

Seismic Unit-5 represents the last phase of carbonate sedimentation (Mid-Albian to late-Albian; 105.15 ± 1 Ma–100.45 ± 1 Ma). The platform margin is backstepping (Figure 8), reflecting a catch-up phase and Seismic Unit-5 is interpreted as a TST. Apart from the very low recovery at Site 866, lithofacies from Site 868 to 866 suggest a southward shift of the platform margin (Strasser et al., 1995) supporting the interpretation of a TST. Seismic Unit-5 is capped by SS5 showing similar characteristics of karstification and potential sinkholes: hence, SS5 shows evidence for subaerial exposure (Figures 7 and 8). Following reflooding of the guyot above SS5, a thin (30 m; at Site 866B; Sager et al., 1993a) pelagic sediment cap is deposited with no record of shallow marine carbonate sedimentation. This is reflected on SS5 by manganese oxyhydroxides and phosphatized material which represents a drowning succession (Sager et al., 1993a). Therefore, SS5 may be a sequence boundary (exposure) followed by a flooding surface (drowning), or a combined type-1 and type-3 sequence boundary (Figure 8).

The stratigraphic evolution of the carbonate sequences is a consequence of several controlling factors including, but not limited to, the interplay of changes in accommodation and sediment supply, sediment transport rates and basin-margin topography. Here, an important observation is that key seismic-stratigraphic surfaces mostly match the timing of known eustatic inflections in the Cretaceous (Haq, 2014; Figure 8):

1. Sequence boundary SS1 (130.84 ± 1 Ma) and KBa1 (130.6 Ma; Haq, 2014) appear to be of similar age. KBa1 is considered a major sequence boundary with medium-amplitude eustatic changes (25–75 m, Haq, 2014).
2. Interpreted flooding surface SS2 (125.5 ± 1 Ma) and KAp1 (125.6 Ma; Haq, 2014) appear to be of similar age. KAp1 is a major sequence boundary with large amplitude of eustatic changes (>75 m, Haq, 2014). It is possible that SS2 is in fact a composite surface (sequence boundary and flooding surface), but we lack evidence in seismic to support that.
3. Interpreted maximum flooding surface SS3 (122.8 ± 1 Ma) and KAp2 (123 Ma; Haq, 2014) are of similar age. According to Haq (2014), KAp2 is a sequence boundary with a moderate amplitude of eustatic changes (25–75 m). It is thus possible that SS3 is a composite surface (sequence boundary and MFS), but we do not see seismic evidence for this.
4. Interpreted sequence boundary SS4 (105.15 ± 1 Ma) and KAl5 (105 Ma; Haq, 2014) are of similar age. KAl5 is a relatively small (<25 m) amplitude eustatic event (Haq, 2014).

5. The ages of interpreted sequence boundary SS5 (100.45 ± 1 Ma) and KAl8 (100.6 Ma; Haq, 2014) appear to be close. KAl8 is considered a major (>75 m) eustatic lowering event (Haq, 2014).

Another observation is that the trend of small- and large-scale eustatic variations in Haq (2014) may have impacted the development of the different seismic units (Figure 8):

1. The three periods of development of transgressive Seismic Units-1, -3, and -5 appear to be formed during the long-term Hauterivian rise, the short-term early-Aptian rise (between KAp1 and KAp2) and the long-term late-Albian rise (Haq, 2014), respectively.

2. The two periods of development of highstand Seismic Units-2 and -4 appear to be formed during the long-term Barremian fall and the long-term period of stasis through Aptian and early Albian (Haq, 2014), respectively.

The fact that some of the Cretaceous eustatic events (2nd and 3rd order fluctuations; from the Hauterivian to latest Albian) above match those in Haq (2014) suggests that (1) the Cretaceous eustasy plays a key role in the stratigraphic evolution of the Mid-Pacific atolls and (2) they are indeed driven by eustasy and not regional tectonic of the Arabian plate, as most of the data used in building the eustatic chart in Haq (2014) come from there.

In addition, other factors impacted the stratigraphic evolution of the atoll. Age-depth plot (Figure 3) shows rapid initial subsidence decreasing with time. The rapid initial subsidence combined with the Hauterivian long-term sea-level rise (Haq, 2014) resulted in rapid creation of accommodation facilitating the deposition of transgressive Seismic Unit-1. The study by Pohl et al. (2020; anchored on GTS2012) showed that neritic carbonates production reached the maximum between ca. 120 Ma and 80 Ma preceded by an increase in the production between ca. 130 Ma and 120 Ma. Putting this in consideration with (1) the Barremian long-term sea-level fall and the long period stasis to the late Albian and (2) the gradual decrease of subsidence with time, the available accommodation space would be limited which was reflected on thick highstand Seismic Unit-2 and Unit-4. Both transgressive Seismic Unit-3 and Unit-5 can be explained by the outpace of the early-Aptian short-term and late-Albian long-term rises, respectively (Haq, 2014). The dominance of oolitic beach-shoals in the transgressive Seismic Unit-3 above the OAE 1a is similar to the Cupido platform in Mexico, which may suggest similar impact from recovery of marine alkalinity following the acidification phase during OAE 1a (Núñez-Useche et al., 2015). Our paper shows potential presence of later magmatic activity(ies) intruding through the sedimentary succession (SF9; Figure 5). The interpreted potential sills have no age controls, as they have not been drilled (Figure 2). In general, volcanic activities could possibly impact the evolution and demise of the atoll through changing subsidence rates and causing environmental perturbations (e.g. the Neogene isolated carbonate platforms in Mozambique Channel; Courgeon, Jorry, et al., 2016; Courgeon et al., 2017).

5.3 Controls on the distribution of karstification

Our work sheds new light on the debated subaerial exposure and karstification of the Albian succession of the Mid-Pacific Mountains atolls (Jenkyns & Wilson, 1999; Wilson et al., 1998; Winterer, 1998; Winterer et al., 1995). Here, we present detailed subsurface geomorphological evidence for two karstification episodes during the Albian (Figures 6 and 10). The distribution of karst horizon seismic facies (SF3) at and directly below sequence boundaries SS4 and SS5 (Figure 10) strongly support subaerial exposure of Resolution Guyot at ca. 105.15 ± 1 Ma (marked by SS4) and ca. 100.45 ± 1 Ma (marked by SS5). Our findings of two major karstification events before the demise may support the hypothesis of ‘death-by-emergence-and-submergence’ by Winterer et al. (1995) and Winterer (1998).

The interpreted “paleocaves” (SF5; Figures 4, 5, and 11) are observed in Resolution Guyot by tracing anomalous bright spots with limited lateral extent described as “string-of-beads” by other publications (e.g. Basso et al., 2018; Yang et al., 2012; Yu et al., 2016; Zeng et al., 2020). As RMSA and signal envelope attributes are sensitive to extreme amplitude variations, they were used in delineating the lateral and vertical extension of the “string-of-beads” (Figure 11). It could be argued that these high-amplitude seismic features could also be related to non-karstic features associated with other high-amplitude seismic events and can mislead the interpretation (e.g. Basso et al., 2018); however, in our case, majority of the depths of the interpreted “paleocaves” correlate well to depths of (1) low core recovery at Site 866 along with free drop of the drill pit at Site 867 for ca. 8 m, (2) intensive brecciation and solution vugs in the FMS images (Figure 6) at Site 866 and (3) karst horizon seismic facies (Figure 10). The karst features in FMS images (i.e. intermittent zones of intensive brecciation and solution vugs) have a height of few meters up to
20 m. This vertical extension can be regarded thin beds producing a constructive tuning effect and result in high amplitudes. Multiple cave-system will ultimately form “string-of-beads” known by Loucks (1999) as coalesced palaeocave complexes (e.g. Yu et al., 2016).

The “paleocaves” are mostly encountered along the steep windward margin (Figure 11). They are stacked vertically between ca. −1950 and −2300 ms TWT. Following the “string of beads” upwards on the seismic profiles, it becomes clear that the surface expressions of these features are fractures cutting through the pelagic cap (Figure 11). We propose that these fractures are bank margin cave-fracture systems (Frost & Kerans, 2009; Mylroie et al., 1995; Smart et al., 1988; Whitaker & Smart, 1997a, b). The coexistence of fractures and “paleocaves” (Figure 11) offers a potential mechanism for the formation and control of “paleocaves” (SF5) at Resolution Guyot. In addition, we suggest that the correspondence of the high-amplitude anomalies and fractures likely mean that the interpreted “string of beads” are real geological features rather than geophysical artefacts. Carbonate platform margins are prone to synepepositional collapse, faulting and fracturing with reactivation during and post burial (Nolting & Fernández-Ibáñez, 2021; Nolting et al., 2018). Consequently, fractures can act as long-lived fluid conduits (Budd et al., 2013). At Resolution guyot, the vertically stacked “paleocaves” associated with fractures (Figure 11) may suggest that meteoric dissolution was focused on platform margin synepepositional fractures, ultimately leading to fracture-cave formation. Subsequent

FIGURE 10 (a) E-W seismic profile showing pervasive discontinuous seismic reflection (SF3) at two different levels reflecting two different episodes of karstification, (b) interpreted cartoon showing the different karstification episodes, each of which is located below seismic-stratigraphic surfaces 4 and 5 which separate them from more continuous reflections, (c) seismic profile showing potential sinkholes at the seismic-stratigraphic surfaces 4 and 5, (d) seismic profile showing potential sinkholes at the seismic-stratigraphic surface 4, (e) seismic profile from Browse Basin in Australia (adapted from Van Tuyl et al., 2018), showing similar characteristics where karst horizon is highlighted by discontinuous broken chaotic reflections. Uninterpreted seismic data are provided in the supplementary material.
exposures would lead to multiple episodes of cave development and either reactivation of existing fractures and karst (e.g. in shallow subsurface of Florida; Evans et al., 1994), or formation of new platform margin fractures and caves. The maximum vertical extent of all the stacked flank margin caves at Resolution Guyot is ca. 520–700 m. Syndepositional platform margin fractures can exceed that extent (e.g. >1000 m in the isolated carbonate platform of the Tengiz field; Narr & Flodin, 2012). The bathymetry map of Resolution Guyot shows the presence of alternating scallops and promontories (Figure 1) on the margins which may cause preferential concentration

**FIGURE 11** (a) Seismic amplitude profile along with root-mean-square and signal envelope amplitude profiles from Resolution Guyot showing the string of beads features along the platform margin interpreted as flank-margin fracture-cave system (highlighted in dashed boxes), (b) seismic amplitude profile from Tarim basin showing similar vertical stack of string of beads controlled by the fault system (adapted from Yang et al., 2012) and seismic attribute analysis showing the bright spot associated with string of beads in Tarim basin (adapted from Zhao et al., 2014). Uninterpreted seismic data are provided in the supplementary material.
of stresses and become sweet spots for fracturing (Figure 11).

We have attempted to estimate the duration of each subaerial exposure event. As highlighted by Loucks (1999), multiple cave systems reflect either a long-term exposure or multiple exposures represented by composite unconformity(ies). Due to (1) the absence of any obvious time gaps in the Sr-isotope curve (Figure 3), (2) the intermittent appearance of the brecciated and vuggy intervals in FMS between ca. 270 and 430 mbsf (Figure 6) and (3) the presence of several calcrite horizons at Site 866 (ca. 60 mbsf; below SS5 and 220–420 mbsf; below SS4; Sager et al., 1993a), we suggest that the karst horizons were formed by multiple exposures represented by composite unconformities (SS4 and SS5). In addition to the proposed multiple exposures, contribution from other freshwater fluids (e.g., the gradient from island freshwater lens and mixing zone flank margin caves; Micallef et al., 2021; Micallef, Person, et al., 2021; Mylroie & Carew, 1990; Mylroie et al., 1995) and hypogenic fluids (e.g., Zhu et al., 2017) to the dissolution features is also possible.

5.4 Fluid vents in the Mid-Pacific atolls

Vents for cross-stratal fluids are recognizable on seismic by (1) vertical zones of disturbed reflection continuity and (2) association with amplitude anomalies and seismic artefacts (Cartwright & Santamarina, 2015; Hustoft et al., 2007; Moss & Cartwright, 2010). At Resolution Guyot, we observed extensive areas (ca. 900–1300 m length; SF12) of disturbed chaotic reflections (Figure 12) cutting through almost the entire sedimentary succession associated with amplitude anomalies (e.g., sharp amplitude cut-off; Figure 12). Sharing similar characteristics, we suggest that these features represent fluid vents (SF12) for cross-stratal fluids through the Cretaceous atoll of Resolution Guyot.

Upward bending and tilted reflections surrounding the fluid vents may indicate an upward fluid flow (Behbehani et al., 2019; Niyazi et al., 2021; Omosanya et al., 2018; Wall et al., 2010; Wang et al., 2018). Fundamentally, pipes are conduits for cross-stratal magma (e.g., Huang & Jokat, 2016), hydrocarbon migration (Berndt, 2005; Cartwright et al., 2007; Maestrelli et al., 2017), fluids from overpressured layers (compaction of clays and mud rich sediments) and methane (Berndt et al., 2003; Netzband et al., 2010). Deciphering the origin of these potential fluid venting systems requires further investigations bearing in mind the quality of the seismic data and absence of drilling data close to the vents.

Fluid venting system and karstification features (e.g., flank-margin fracture-cave system, karst horizons, sinkholes) might have contributed to seawater ventilating of the Mid-Pacific atolls. These features could support geochemical analysis (Paull et al., 1995), suggesting active exchange between the atoll pore-waters and surrounding seawater.
6 | CONCLUSION

Our detailed study succeeded in identifying the carbonate system of the Cretaceous Mid-Pacific atolls including deep shelf basin (including drift deposits), slope-to-basin (including MTDs), upper-slope (including sponge & requieniid rudists build-up and reworked material from the platform margin and interior), platform margin complex (including beaches, shoals, requieniid rudists build-up, and storm deposits), back-margin (including back-margin apron, washover fans, sandwaves and shoals) and platform interior (including lagoon deposits, patch reefs and rudist meadows).

The platform evolution was controlled by the interplay between eustasy, changes in carbonate production rates and subsidence rates, and magmatism. The stratigraphic succession in Resolution Guyot is divided into two highstand units (early-Barremian to early-Aptian and mid-Aptian to mid-Albian) and three transgressive units (Hauterivian, early-Aptian to early mid-Aptian and Mid- to late-Albian). These units and their bounding surfaces are coeval with some of the Cretaceous eustatic events (major upward surge through the Hauterivian, KBa1, KAl5, KAl8; Haq, 2014) which may potentially suggest an impact from second- and third-order eustatic fluctuations on the evolution of Resolution Guyot. The initial subsidence rate was rapid with gradual decrease with time. This facilitated the Hauterivian transgression along with the Hauterivian eustatic rise. The worldwide carbonate production reached the maximum between 125 and 95 Ma. This may have acted with (1) the long-term sea-level fall through the Barremian and the long period stasis to the late Albian and (2) the gradual decrease in subsidence, which ultimately developed highstand units during the Barremian and the Albian. The recovery of marine alkalinity following the acidification phase during OAE 1a might have contributed to the short-term early-Aptian sea-level rise in developing the transgressive oolitic shoals. The long-term late-Albian rise might have outpaced the slow subsidence and high production rates facilitating the development of the transgressive unit before the demise.

The study has revealed clear evidence of two subaerial exposure events in the mid (105.15 ± 1 Ma) and late Albian (100.45 ± 1 Ma), which may support the hypothesis of ‘death-by-emergence-and-submergence’ by Winterer et al. (1995) and Winterer (1998). Syndepositional fractures at the rims interacted with the subaerial exposure events by focusing the dissolution which formed vertically stacked flank-margin fracture-cave system. In addition to karstification features, fluid vents were interpreted and both might contribute to the seawater ventilating of Mid-Pacific atolls.

Revisiting the Mid-Pacific carbonates allows us to build a much clearer image of the interplay between eustasy, changes in carbonate production rates, subsidence rate and magmatism during the early Cretaceous and their large-scale impact on evolution, demise and diagenesis in carbonate systems which can serve as an analogue for isolated carbonate platforms.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in: The Marine Geoscience Data System repository at https://www.marine-geo.org/tools/search/Files.php?data_set_uid=29456 (Seismic Data). The Division of Marine and Large Programs at https://mlp.ldeo.columbia.edu/logdb/scientific_ocean_drilling/ by searching for Leg 143 (Logging Data). International Ocean Discovery Program, JOIDES Resolution Science Operator at https://web.iodp.tamu.edu/OVERVIEW/?exp=143 (Core Images and Description). Proceedings of the Ocean Drilling Program at http://www-odp.tamu.edu/publications/leg_ndx/143index.htm (Drilling Reports, Geochemical data, Core Description).

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