with a height of about 3800 m, about 1.3x greater than Benham, located at the northeast end of the plateau. Based on dredge samples on Vinogradov, the age of this seamount is at most 26 My (Shcheka *et al.* 1995). Both the Benham and Vinogradov seamounts are interpreted as late-stage magmatic features, but the latter formed during the dying stage of magmatism of the hotspot (Barretto *et al.* 2020) and is, therefore, younger and possibly more silicic than the Benham volcano. In terms of morphology, it can be inferred that – unlike Benham Bank – the rest of the seamounts do not host a significant amount of carbonate accumulation. For example, the Bayog and Kalantas Seamounts, located within the plateau, are defined by steep rugged morphology and breached cones, indicative of collapse structures in volcanic terranes (Figure 3).

Sub-bottom Geometry

The more than 160-km long seismic profile reveals a few moderate to weak-amplitude hyperbolic internal reflectors and irregular clinoforms within the platform interior but mostly discontinuous due to sonar signal attenuation in carbonate structures. At the platform margins where there is greater signal penetration, high-amplitude hyperbolic reflectors are imaged. Selected seismic chirp profiles displaying the architecture of Benham Bank are described below.

Seismic Chirp Profile 2. This profile is a southwest-northeast trending profile that cuts across the east rim and other shallow terraces (Figure 4). At the northern end, there is a series of hyperbolic transparent facies (pink solid line) interspersed with sediment fill units that can be observed outcropping as terraces and mound structures. Although the reflectors are weak and discontinuous, the facies are interpreted as partially buried reefs whose gaps are infilled by sediments. Toward the west, the platform is composed of transparent facies interpreted as sediment infill overlapping an irregularly oscillating low-amplitude surface (pink dashed line) between 70–100 m. This surface could be interpreted as a karstic surface formed during low sea level. Lastly, a sediment wedge is observed initiating at

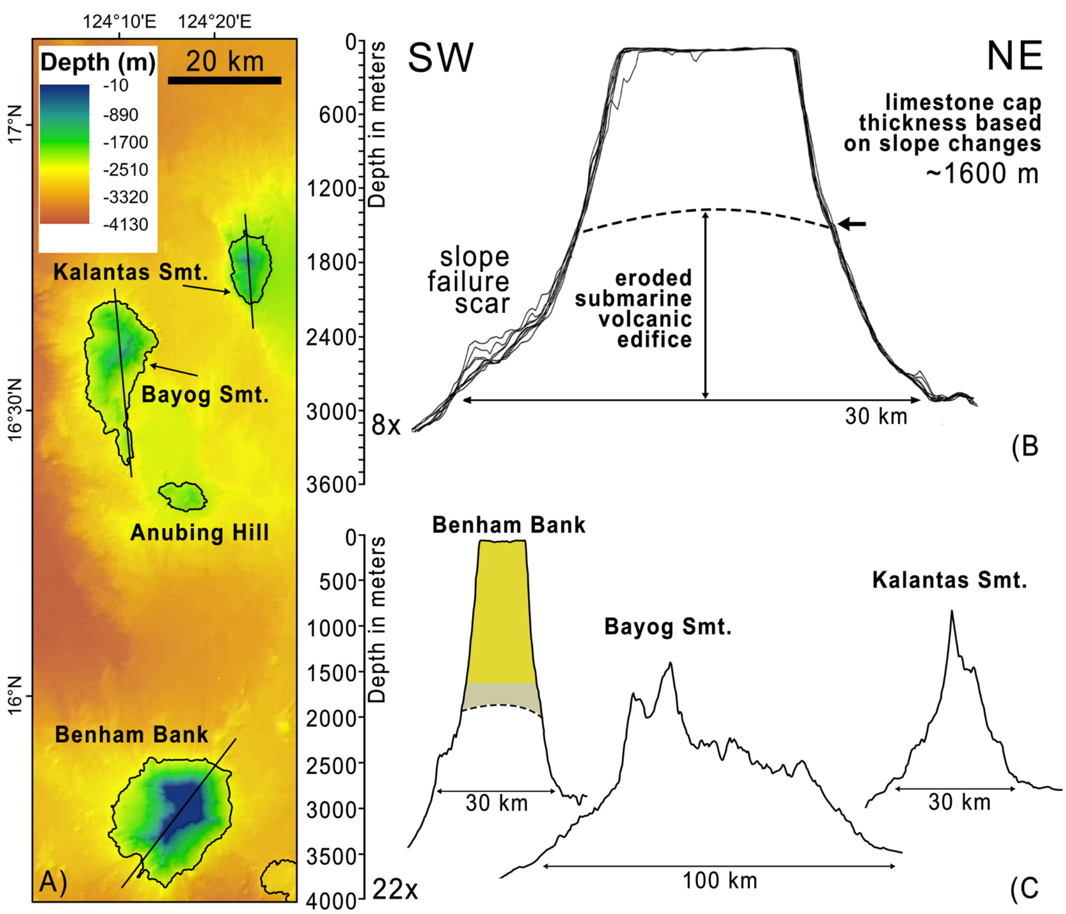

Figure 3. [A] Bayog and Kalantas Seamounts and Benham Bank bathymetry. [B] Visual estimate of carbonate thickness based on stacked cross-sections of Benham Bank acquired parallel to the long axis as shown in A. [C] Comparison of height, basal depth, and morphology of the Bayog and Kalantas Seamounts with Benham Bank along cross-sections shown in A. The height of the residual volcanic edifice (dashed line) is estimated to be 1150 m.

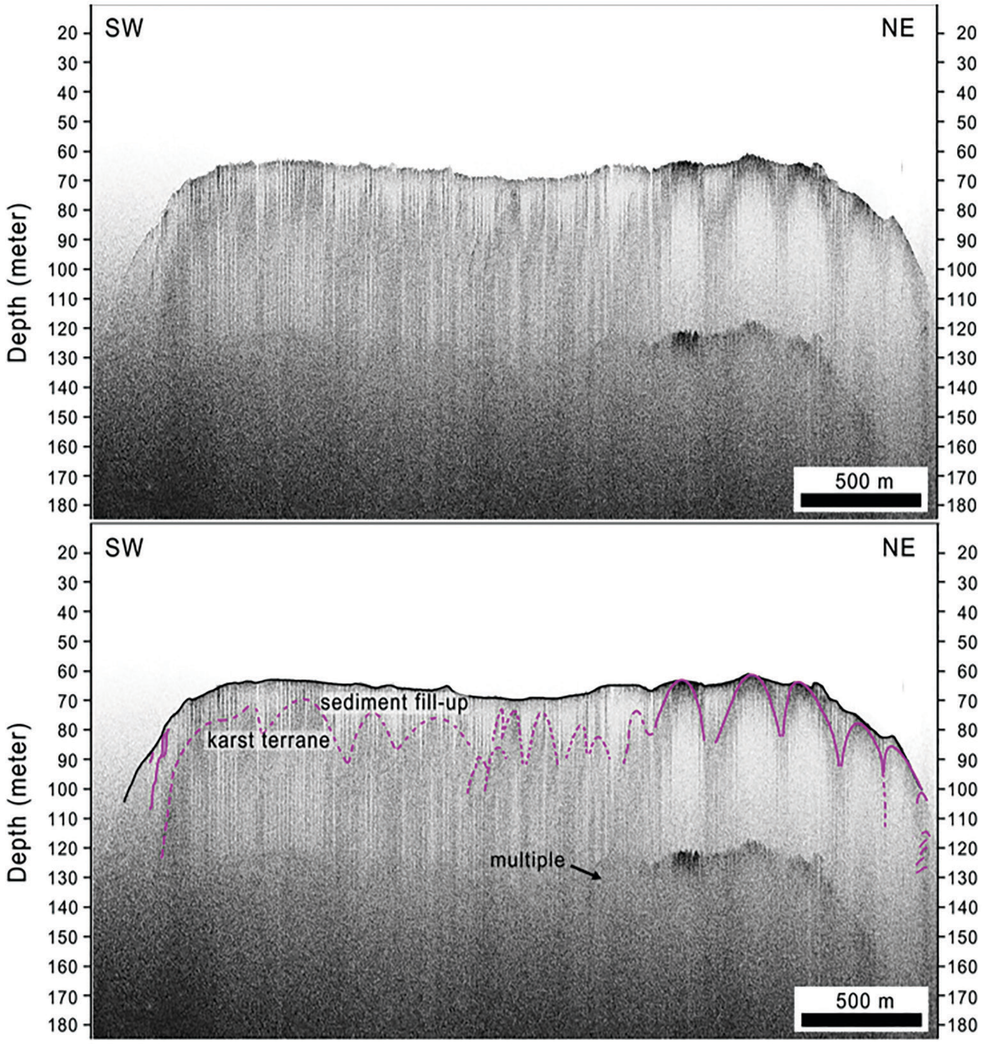

Figure 4. Seismic Profile Line 2. The southwestern end of the profile has a relatively smoother seafloor surface underlain by about ten meters thick sediment fill-up on a highly irregular and low amplitude reflector corresponding to the antecedent karst topography on the sub-bottom up to 70 m below the seafloor. Meanwhile, the northeastern end reflects a more rugged seafloor with high-amplitude hyperbolic reflectors at the sub-bottom (see Figure 1 for location).

a depth of ~ 80 m on the southwestern end of the profile.

Seismic Chirp Profile 4. This profile is an east-west trending profile across the central portion of the bank (Figure 5). Towards the east, the sub-bottom is characterized by an irregular high-amplitude surface (pink dashed line) interspersed with transparent facies. These are interpreted as buried to partially buried reefs that are overlain by or intercalated with sedimentary infill units. At the east margin, a sediment wedge also initiates from a depth of ~ 85 m and thickens with depth towards the steep upper slopes. Towards the west, the buried reefs are discontinuous and marked by a weak amplitude surface.

Seismic Chirp Profile 20. This profile displays the northwest slopes of Benham Bank (Figure 6). The slopes are defined by steep parallel medium to high-amplitude reflectors, which are sediment wedges deposited on gentle slope breaks within the slope that pinch out basinward. Along the slope, sediment wedges initiate at a depth of ~ 800 m. Low-amplitude hyperbolic reflectors that represent former atoll rims are imaged at the northern sub-bottom slopes up to a depth of ~ 1300.

DISCUSSION

Long-term Subsidence and Lateral Migration of Benham Bank

The translation of the Benham Rise away from the hotspot led to the thermal cooling of the crust and

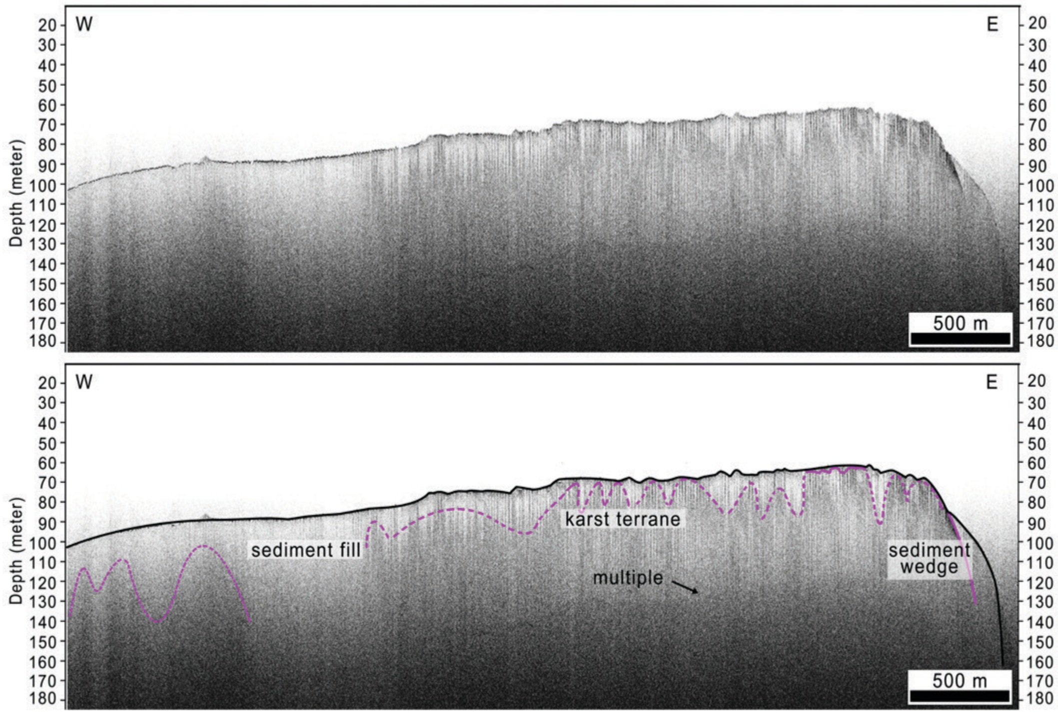

Figure 5. Seismic Profile Line 4. The western end illustrates a gently downsloping surface underlain by tens of meters of sediment fill. Towards the east, the seafloor is defined by a rugged seafloor texture whose sub-bottom shows irregular high-amplitude reflectors of the antecedent karst topography up to 30 m below the seafloor. At the eastern edge, a sediment wedge initiates at a depth of about 85 m (see Figure 1 for location).

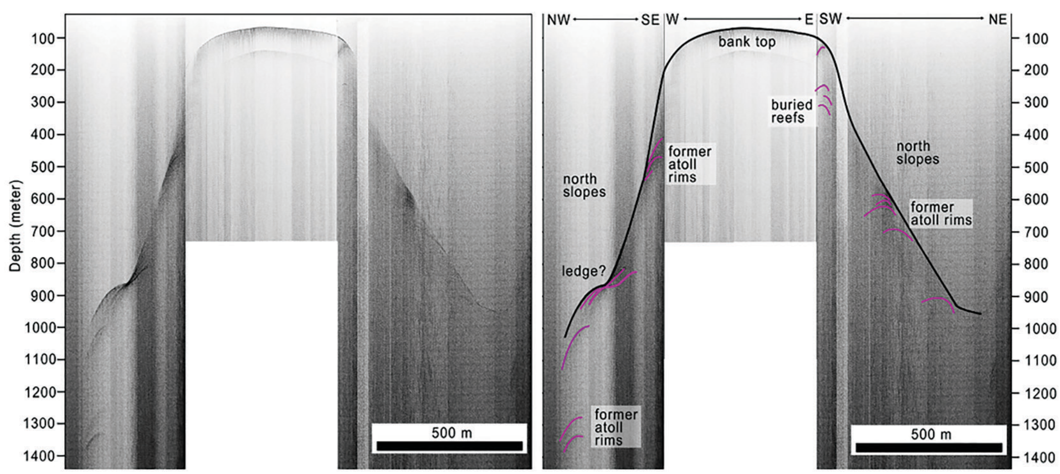

Figure 6. Seismic Profile Line 20. The profile shows a bank-to-slope profile, revealing hyperbolic reflectors or former atoll rims as deep as more than 1300 m below the seafloor. Buried reefs are also identified around 250 m below the seafloor. The ledge of the northern slope is found at a depth range of 800–900 m (see Figure 1 for location).

therefore subsidence since its formation between 40 Myr ago (Barretto *et al.* 2020) and 47 Ma (Deschamps and Lallemand 2002). By Pliocene (3.2 Myr), the Benham Rise collided with the East Luzon Trough (Bautista *et al.* 2001), and this led to the reversal of vertical motions of Benham Bank when it was subjected to the lithospheric forebulge of the subducting slab along Philippine Trench [*e.g.* Dickinson (2013)]. The amplitude of the crest of the forebulge is about 400 m high, while it is located almost 200 km east of the trench. These measurements were derived from offshore cross-sectional profiles that transect the southern areas of the trench not influenced by a bathymetric high like the Benham Rise. For comparison, in the case of the New Hebrides Trench, the crest of the forebulge is about 105 km away from the trench axis and 150 m higher than the seafloor of the trailing edge

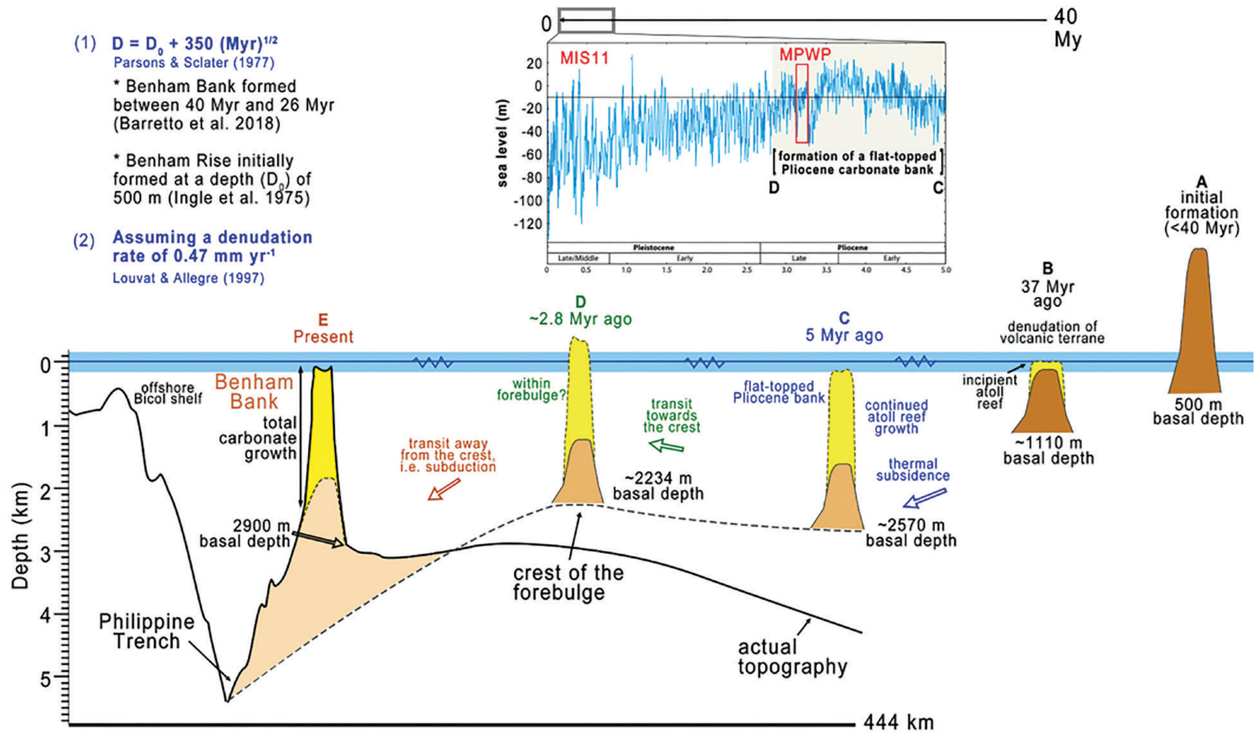

Figure 7. Schematic diagram summarizing the long-term evolution of Benham Bank from an emergent post-caldera feature that formed about 40 Myr at the latest (Barretto *et al.* 2020) to a submerged carbonate bank with at least 1600 m thick carbonate accumulation. The light blue box indicates the range of sea level fluctuations between –120 m and +150 m above the present sea level represented by the blue line at 0 m. The thick black line is an actual cross-section of the Bicol Shelf–Benham Rise. The inset graph shows sea level fluctuations in the last 5 Myr (Miller *et al.* 2020; Droxler and Jorry 2021), wherein the time period between scenarios C and D is indicated by a filled box. The illustrated depths assume 40 Myr as the upper age limit for Benham Bank. The equation by Parsons and Sclater (1977) and a denudation rate of 0.47 mm yr^{-1} (Louvat and Allegre 1997) were used in the illustration. The horizontal distances between A and B and B and C are not to scale.

(Dickinson 2013; Dubois *et al.* 1977). The difference in their dimensions may be attributed to their different tectonic histories and, therefore, rheology.

Based on the vugular texture of basalts recovered in Site 292 of the Deep Sea Drilling Project Leg 31, it has been estimated that Benham Rise may have extruded under shallow water conditions, possibly at a depth of 500 m or less (McKee 1975; Ingle *et al.* 1975). If the depth of formation of the plateau was 500 m below sea level, but Site 292 presently lies at about 2900 m depth (Table 1; A in Figure 7), then the Benham plateau due to thermal cooling must have undergone net subsidence of at least 2400 m.

The Hawaiian-Emperor seamount chain can be used as an analog to illustrate the subsidence of hotspot volcanoes. The presently active hotspot volcano, Mauna Loa, is an emergent volcano that is more than 4000 m above the present sea level. In contrast, the average depths of the older seamounts located on the northwestern end of the chain range between 2000–3000 m, with the deepest up to 4000 m below sea level (Moore and Decker 1987). The subsidence of Hawaiian volcanoes is due to both the lithosphere's thermal cooling and the crust's volcano-isostatic response (Clague and Dalrymple 1987).

The depth of Benham Bank (D In formula 1) at certain crustal ages (Myr in formula 1) is roughly estimated using the equation by Parsons and Sclater (1977), which is:

$$D = D_o + 350\,(Myr)^{½} \qquad (1)$$

This formula can be applied to Benham Bank since the bank formed in the dying stage of magmatism and did not undergo subsequent reheating. In the case of Benham Bank, which is underlain by an oceanic crust with an age between 26–40 Myr (Barretto *et al.* 2020) and initially formed at depths of 500 m (D_o in formula 1) (Ingle *et al*. 1975), subsidence due to thermal cooling predicts that the bank should be found presently at depths between 2200–2625 m (Parsons and Sclater 1977). At present, the basal depth of Benham Bank is 2900 m. This discrepancy may be due to certain assumptions made in the calculation, specifically the initial depth of formation of 500 m, which is largely unconstrained (Ingle *et al.* 1975). This depth was only estimated based on the texture of the basalt and cited fossil evidence on the sediment strata directly overlying the basalt unit (Ingle *et al*. 1975). Possibly, the depth of formation of Benham Bank could have been deeper since the main body must have already undergone subsidence when Benham Bank formed during the late-stage volcanism phase of the rise (Barretto *et al.* 2020). However, if this assumption is correct, it could imply that the age of Benham volcano is older than previously estimated. Barretto and co-authors (2020) state that Benham Bank is a post-caldera feature that formed at the intersection of faults by magmatism after about 40 Myr. Through the Parsons and Sclater (1977) formula, the basal depth of Benham Bank would require an age of about 47 Myr, which falls on the shield-building phase of Benham Rise (Deschamps and Lallemand 2002; Barretto *et al.* 2020). This hypothesis can only be confirmed by dated core samples of the Benham Bank volcanic basement.

Another possible reason for the discrepancy between the computed and actual depth of Benham Bank is the position of Benham Bank with respect to the forebulge. At present, the Benham Bank – based on the actual cross-section of the seafloor morphology (solid line in Figure 7) – is already located on the subsiding slope of the subducting slab towards the trench (E in Figure 7). Its incipient subduction down the Philippine Trench could explain why the underlying crust of Benham Bank is deeper than the theoretical subsidence curve due to thermal cooling.

In relation, the present dimensions of the Philippine Trench forebulge and the subduction rate of 7 cm yr^{-1} along the Philippine Trench (Seno 1977) can be used to further reconstruct the migration of Benham Bank through time along the forebulge. It is estimated that the Benham Bank may have reached the crest of the flexure around 2.8 Myr ago (D in Figure 7). With sea level fluctuations of about 60 m and a mean sea level lower by about 30 m than the present sea level (Droxler and Jorry 2021), the Benham Bank would have been emergent during this period since it would also be uplifted by 400 m at the forebulge crest.

Thickness and Timing of the Formation of the Carbonate Bank

Chirp seismic profiles on Benham Bank and its morphology indicate that the total thickness of carbonate accumulation on the Benham Bank guyot is at least 1300 m (Figure 6). This thickness is equivalent to more than a third of the total height of the guyot. In multi-beam bathymetry, the inferred total reef thickness is about 1600 m based on a sharp slope break in the eastern slope of Benham Bank, where steep and almost vertical structures signify reef morphology (Menard 1983) (Figure 3). This estimated thickness is comparable with the deep drilling results in the Maldives, which recovered at least 2100-m-thick limestone that has grown since the Eocene times (Droxler and Jorry 2021). Submerged seamounts or atolls in Hawaii such as the Koko Seamount and Midway Atoll also have limestone caps that are at least 600 and 500 m thick, as observed in seismic reflection profiles and deep drilling cores, respectively (Ladd *et al.* 1970; Davies *et al.* 1972). In terms of vertical accommodation space, the thickness of at least 1600 m of carbonate sequence could have been developed over a period of about 36 Myr, which is equivalent to the time it would take for the cooling crust of Benham Bank to subside at the same magnitude. At the time when the Benham Bank was at the forebulge, *i.e.* uplifted, it can be expected that karstification would have reduced its height, producing the highly irregular pattern seen in the chirp profiles (D in Figure 7). Combined with lowstands, karstification may have occurred at prolonged periods so differential dissolution led to a central lagoon and elevated rims (Liu *et al.* 2022). Renewed significant accretion on Benham Bank would have taken place during its re-submergence (D–E in Figure 7) while it passed the forebulge because of the continued subduction of the plate.

The 1600-m-thick carbonate sequence grew on top of a volcanic edifice whose original height must have been likely much taller than 1300 m, considering the erosion of the emergent volcanic island as it was subsiding. Denudation of the Benham volcanic island may have significantly reduced its original height. Denudation rate estimates range from 0.04–0.19 mm yr^{-1} in Hawaii (Li 1988) and 0.47–3.43 mm yr^{-1} in Reunion Island in the Indian Ocean (Louvat and Allegre 1997). Using 0.47 mm yr^{-1} as the rate, the height of the volcanic edifice may have been reduced by up to 1410 m after 3 Myr since the formation of the Benham volcano (B in Figure 7). In terms of subsidence, the basal depth of Benham volcano around this period is about 1110 m [using Parsons and Sclater (1987)] (B in Figure 7). If the assumed original height of Benham volcano is 2400 m, following the height-to-basal-width ratio of Vinogradov Seamount; given that they are both post-caldera features (Barretto *et al.* 2020), it can be estimated that Benham volcano was already submerged by more than 115 m below sea level around 37 Myr ago after accounting denudation and subsidence. In terms of reef development, atolls may have already formed earlier than 3 Myr since the formation of the volcano (B in Figure 7). However, if the actual height of Benham volcano is less than 2400 m, full submergence of the volcano and therefore atoll reef development would have occurred much earlier. Due to the translation of Benham volcano away from the hotspot center, there was also a decline in volcanic activity and, therefore, volcanic inputs that would have hindered optimal conditions for reef growth.

Influence of Sea Level and Climate on Reef Growth

The Benham volcanic island underwent rapid and large-magnitude subsidence due to thermal cooling and, therefore, relative sea level rise (Parsons and Sclater 1977; Buchs *et al.* 2014). At the same time, short-period

(10^6 yr) sea level oscillations ranging from 15–30 m were riding on an overall eustatic sea level decline (Miller *et al.* 2005). Higher frequency sea level changes would have led to alternating accretion during an overall rise of sea level and karstification during lowstands. During submergence, continued reef growth would produce well-developed atolls (Hopley *et al.* 2007). If carbonate sediment production was also high, the lagoon of the atoll may be filled with carbonate materials (Hopley *et al.* 2007). In seismic profiles, a completely filled Benham Bank lagoon is indicated by the occurrence of sediment wedges from all sides of the bank (Figures 4 and 5).

In terms of climate, the Benham Rise has been located within the tropical latitudes since its formation (Hall 2002) and, therefore, the general environmental conditions are ideal for carbonate growth, although the more recent climate events are possibly more significant in the carbonate accretion on the bank. During the Pliocene, an unusually warm interval marked by low-amplitude sea level cycles kept the climate relatively stable for about 80 kyr. This was called the mid-Pliocene Warm Period (Draut *et al*. 2003), during which the sea level was up to 25 m above the present (Dowsett *et al*. 1999) (Figure 7). During the migration of Benham Bank towards the lithospheric forebulge that started around 5 Myr ago, the bank was led to relatively shallower areas to form a flat-topped bank (C in Figure 7). The timing of scenario C in Figure 7 was based on potential subsidence due to crustal cooling (Parsons and Sclater 1977) and the derived dimensions of the forebulge. Together with much higher sea levels and a warm climate during the Pliocene, this period was very advantageous for carbonate growth on the bank. From the late Pliocene to the Holocene, the eustatic sea level trend is on a decline but marked by 30–60-m sea level fluctuations that pace the growth and decay of Antarctic Ice Sheets (Miller *et al*. 2005).

Alternating cycles of accretion and karstification eventually led to the development of at least 1300–1600-m-thick carbonate sequence on the bank. The internal karst topography identified on seismic profiles may represent the antecedent Pleistocene foundations that served as hard substrates for subsequent Holocene carbonate growth.

CONCLUSION

The Benham Bank is a carbonate bank that consists of at least 1300-m-thick carbonate accumulation based on the deepest remnant atoll rim observed in seismic profiles and about 1600 m thick based on slope changes in multi-beam bathymetry. This thick carbonate sequence grew on top of a former Benham volcanic island, which has been subjected to both subsidence due to thermal cooling and subaerial erosion. It is estimated that an initial Benham atoll developed as soon as 3 Myr or earlier after the formation of the Benham volcano. If the Benham plateau formed at a depth of 500 m (Ingle *et al*. 1975) and the Benham Bank basal depth is at 2900 m, then subsidence due to thermal cooling could account for 2400 m. However, the present depth of Benham Bank may be also influenced by its position with respect to the lithospheric forebulge of the Philippine Trench. Based on an actual seafloor cross-sectional profile, it can be deduced that Benham Bank is already located on the subsiding slope of the subducting slab towards the trench. Sea level and climate directly contributed to the growth of the carbonate sequence on Benham Bank. A Pliocene flat-topped bank similar to Droxler and Jorry (2021) can also be adapted for Benham Bank, though this remains to be confirmed by more data. A warm, relatively stable climate and higher sea level during the Mid-Pliocene Warm Period (Draut *et al*. 2003) would have completely filled Benham Bank and allowed the formation of at least 1600 m of carbonate sequence, although the emergence of the upper portions of Benham Bank when it was at the crest of the lithospheric forebulge subjected the bank to more frequent accretion and karstification cycles due to sea level fluctuations. Likely, this led to karstification and reduced the height of the carbonate sequence. Towards the transit of Benham Bank to its present position, re-submergence would allow continued reef accretion on the bank.

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