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Benham Bank: a Thick Carbonate Bank on the Philippine Rise, West Pacific

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Little is known about Benham Bank, a guyot with a highly diverse coral reef ecosystem expanse. The Benham Bank is one of several seamounts in the Philippine Rise, a ~ 48-Myr ocean island basalt complex. Recently acquired high-resolution continuous seismic profiles and existing multi-beam bathymetry reveal its internal architecture, overall morphology, and history. Benham Bank is capped by at least 1300–1600-m-thick limestone that grew on top of the former Benham volcanic island, whose development varied with the lateral and vertical tectonic motions of Benham Bank in geologic time. The former Benham volcanic island underwent subsidence of at least 2400 m due to thermal cooling since its formation around 40 Myr ago. Intense denudation may have also significantly reduced the height of the Benham volcano, so that by about 5 Myr after it became inactive, the initial Benham atoll had already formed. The 1600-m minimum thickness of the carbonate sequence may have been attained about 4 Mya during the Pliocene. A warm relatively stable climate and higher sea levels during this period may have caused progradation and complete fill-up of the lagoon. Further westward migration of the Benham Bank towards the Philippine Trench positioned the bank at the crest of the topographic forebulge and led to its emergence. During this period of emergence, karstification may have reduced the carbonate cap of the Benham Bank. The present submergence of Benham Bank associated with its incipient subduction along the Philippine Trench provides vertical space for continued reef growth.

Keywords: atolls, Benham Bank, Benham Rise, carbonate bank, submerged reefs

INTRODUCTION

Carbonate banks are thick sequences of shallow-water carbonate rocks and sediments. This term describes an isolated stratigraphic feature that rises from the deep sea with marginal reefs forming a rim on its top such as the Great Bahama Bank (Bosence 2005). The global geographic distribution of documented low-latitude isolated carbonate banks approximates the location of shallow bathymetric highs in the Pacific, mostly submerged volcanoes (*e.g.* Hawaiian Seamount Chain and Caroline Islands) (Vecsei 2004). The distribution of banks on tropical and subtropical latitudes and their settlement on shallow foundations reflect the importance of warm sea surface temperature and light penetration for carbonate growth.

The subsidence hypothesis, first proposed by Charles Darwin, is a well-accepted mechanism for the formation of very thick reef sequences, as supported by deep-sea drilling results in the Pacific atolls [*e.g.* Midway Atoll; Ladd *et al.* (1970)]. On a subsiding oceanic crust, the evolution of fringing to atoll reefs reflects the subsidence of the volcanic basement towards greater depths that occur in a span of millions (10^6) of years (Hopley *et al.* 2007). Later, new hypotheses evolved where large sea level oscillations and

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differential dissolution are the main drivers of the classic "empty bucket" atoll morphology (Toomey *et al*. 2013). At least for Quaternary atolls, the improved antecedent karst model proposes that the volcanic basement no longer directly influences the development of thick reefs since they grew on top of flat-topped Pliocene banks (Droxler and Jorry 2021). In this model, the glacial-interglacial sea level oscillations served as the main driver of vertical reef growth, since the magnitudes of eustatic sea level rise and fall are larger than that of subsidence. During subaerial exposure, a karst topography defined by elevated margins or rims and a central depression is formed, which serves as a "template" for the morphology of modern atolls (Droxler and Jorry 2021).

These models propose different levels of importance of various processes that contribute to the formation of thick reef sequences that compose atolls and carbonate banks. Generally, both tectonics and sea level oscillations are known contributors to reef development, though they may vary in significance at different scales. For reefs growing on a volcanic basement, subsidence on a scale of 10^2–10^3 m would be significant since it provides accommodation space for vertical reef growth (Buchs *et al.* 2014). In an idealized schematic diagram, volcanic islands that host fringing reefs subside due to the thermal cooling of the lithosphere and eventually become seamounts that host a thick carbonate bank (Woodroffe 2002). Once seamounts arrive at subduction zones, they may undergo uplift associated with the topographic bulge of the subducting plate, before entering deep trenches (Dickinson 2013). Meanwhile, large sea level changes on a scale of 10–10^2 m could easily interrupt reef build-up on volcanic features such as lowstands that may expose reefs and lead to their demise. These instances show that the role of sea level oscillations interplaying with tectonics remains important in the formation of thick stacks of reefs that serve as building blocks for much thicker limestones on carbonate banks.

Offshore on the eastern coast of the Philippines, the Benham Bank is a guyot that hosts mesophotic reefs, which serve as an important natural marine resource for the Philippines and the general west Pacific region (Figure 1). The first published survey results on benthic habitats on Benham Bank are by Nacorda and co-authors (2016), which reveal that at mesophotic depths of about 55 m, the eastern rim of the bank hosts a very high coral cover. Together with reef-building and free-living corals, an assemblage of soft corals, arborescent sponges, and macroalgae are found on the

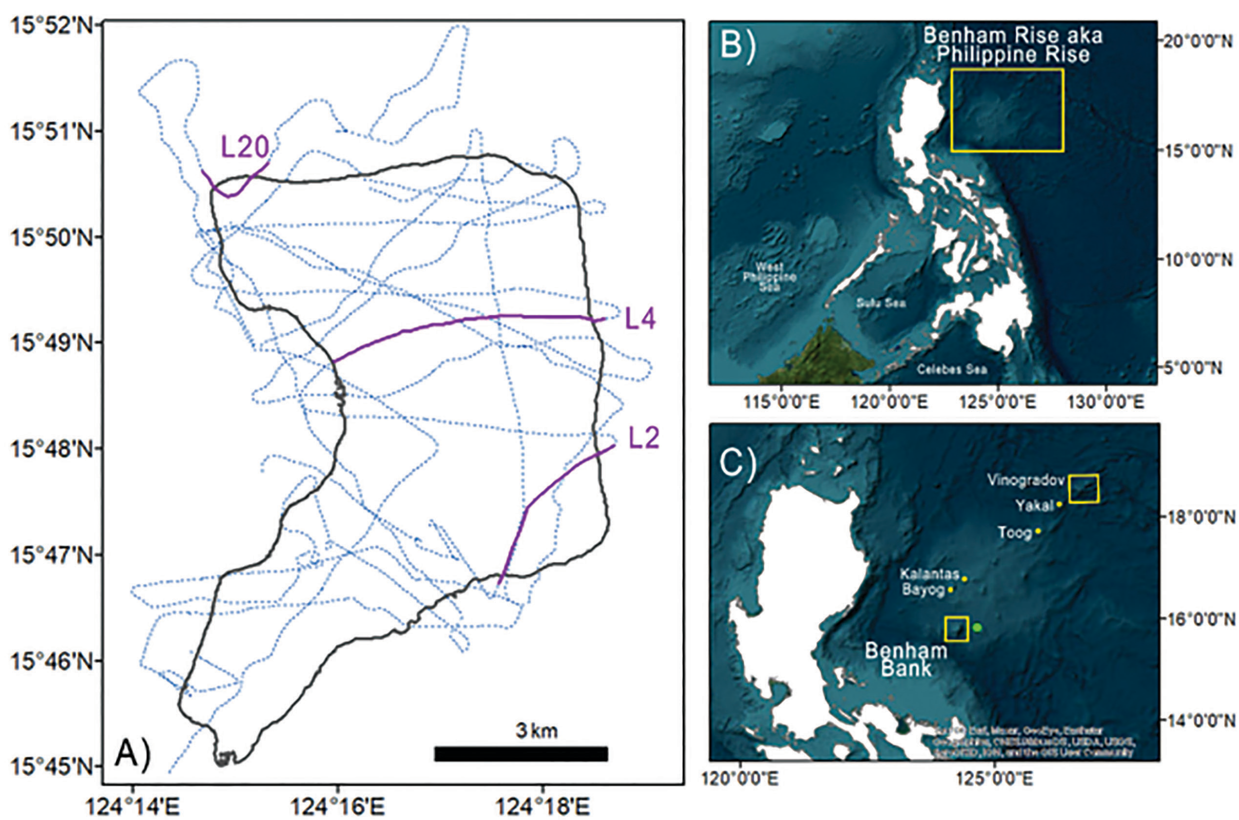

Figure 1. Location map: [A] representative seismic lines 2, 4, and 20 on various areas of Benham Bank; [B–C] inset maps showing the general location of the study site and other seamounts within Benham or Philippine Rise. Site 292 corresponds to the green dot in C.

eastern rim. However, the extent of these benthic habitats has yet to be established. This study aims to determine the origin of the bank by characterizing its internal architecture and overall morphology.

Geologic Setting of Benham Bank

The geologic setting of Benham Bank is tied to the regional history of the Benham Rise. The Benham Rise is a prominent submarine plateau, located immediately east of mainland Luzon island. The rise was formed by hotspot volcanism at a triple junction due to the spreading and opening of the West Philippine Basin (Deschamps and Lallemand 2002). It is composed of the main body and three spurs – namely, the Narra, Molave, and Loro Spurs – which overlie a 15-km thick crust (Barretto *et al.* 2020). Recently, it has been proposed that the crest of Benham Rise is an extinct caldera, named thereafter *Apolaki* Caldera, whose shield-building phase occurred between 48–43 Myr ago (Barretto *et al.* 2020). Subsequently, this suggests that Benham Bank is one of the post-caldera features that formed between 40–26 Myr ago (Barretto *et al.* 2020). Site 292 of the Deep Sea Drilling Program Leg 31 core sample acquired at depths of almost 3000 m represents a biostratigraphic reference section of the Benham Rise (Ingle *et al.* 1975). The thick basalt flow at the basement of the plateau is overlain by almost 370-m-thick nannofossil ooze and chalk deposited from the Eocene up to the Holocene. The Site 292 sample also shows that the underlying crust is oceanic in nature, composed of a thick extensive sequence of vugular tholeiitic basalts, suggesting that it was deposited under shallow marine conditions at an estimated depth of 500 m (Ingle *et al*. 1975; Karig 1975; Mrozowski *et al*. 1982). Presently, the basement of Benham Rise is found at depths of 5000 m.

The Benham Rise is a buoyant feature that resists subduction along the East Luzon Trough, which is said to be causing a sharp bend in the eastern Luzon coastline (Bautista *et al*. 2001). The Benham Rise is considered an aseismic ridge and relatively stable compared to other oceanic areas in the vicinity of the subduction zones east of the Philippines (Vogt *et al.* 1976). The collision of the Benham Rise along the East Luzon Trough is placed at 3.2 Myr (Pliocene) (Bautista *et al.* 2001).

MATERIALS AND METHODS

Multi-beam Bathymetry

The multi-beam bathymetry dataset used in this study was acquired by the National Mapping and Resource Information Agency (NAMRIA) in 2004. The bathymetry data covers the area bounded by latitudes 15° 23’N to 16° 5’N and longitudes 123° 41’E to 124° 38’E. Their survey tracks are spaced 300 m on the bank and 3–5 km outside the bank. The density of data points during acquisition varies in the whole survey area depending on sea conditions, speed and movement of the vessel, and prevailing depth in the area. The “Point to Raster Tool” in ArcGIS was used to produce a bathymetry grid model with a pixel resolution of 30 m on the bank and 100 m outside the bank but with noisy peaks at greater depths. This resolution is the finest output that is free from gaps that may be generated by raster interpolation.

Seismic Chirp Profiling

Continuous seismic profiling was employed on Benham Bank by deep towing the EdgeTech SB–216S vehicle about 7 m below the sea surface aboard M/Y Panata in May 2022. During acquisition, the EdgeTech system was set at a frequency range of 2.0–10.0 kHz with a ping rate between 1–3 Hz, depending on seafloor depth, whereas the vessel was traveling at a mean speed of 5 knots. More than 160 km long high-resolution seismic chirp profiles were collected over 5 d. For processing, the Hypack software was used to adjust the time-varying gain and frequency filter to enhance the imaging of sub-bottom reflectors. The software uses a default sound speed of 1500 ms^{-1} to convert the two-way travel time to depth. Seismic profiling was done to determine the internal structure of the bank. Since the seismic profiles are finer in resolution than the multi-beam bathymetry data, they were also used to identify features on the seafloor. The maximum sub-bottom penetration of the acquired profiles is 45 m, which varies with the nature of the substrate and sub-bottom material. In general, soft and finer sediment particles allow greater penetration than hard and coarse substrates like the skeleton of hard corals. The depth recorded in the seismic profiles was corrected for the tow depth of the vehicle during acquisition.

Multi-beam bathymetry shows that the Benham Bank steeply rises almost 2900 m above its surrounding seafloor with a depth of 3000 m and has a diameter of 30 km from its base (Figure 2). It is a guyot characterized by a broad flat summit that terminates to almost vertical flanks on all its margins. Its basal depth of 2895 m is measured at the slope inflection point between the seafloor and the slopes. In planar view, the summit is marked by numerous scalloped margins, indicating multiple marginal platform collapse events of varying ages and sizes. The summit of Benham Bank ranges from 100–48 m in depth, where the shallowest portion forms a ridge on the eastern margin that hosts diverse mesophotic coral assemblages (Nacorda *et al.* 2016). The summit has a surface area of 52 km^2 and a general length and width of 8 and 6.5 km, respectively. The platform top is gently sloping upward towards the east at 0.012°, derived from the vertical relief of the bank spread over its long axis distance. This drastically differs

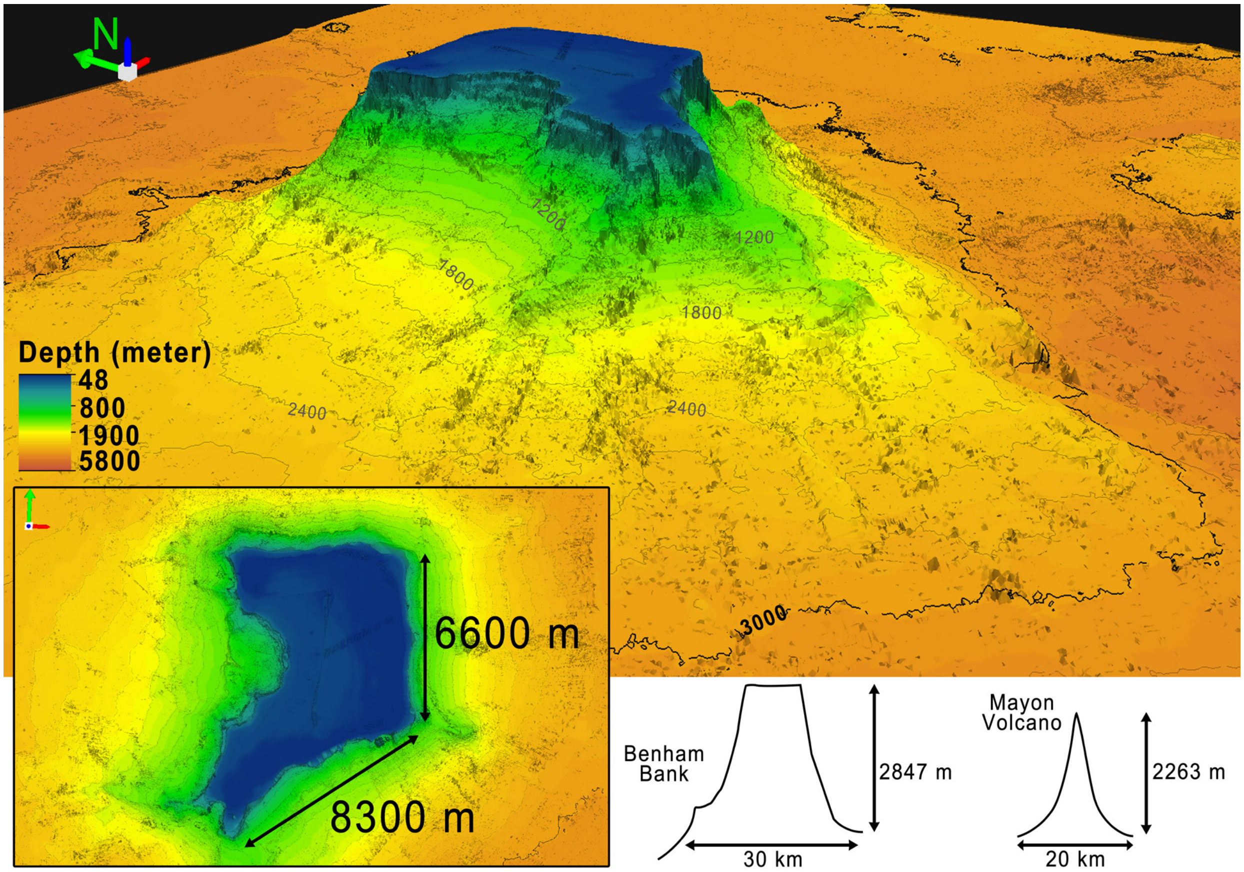

Figure 2. The Benham Bank has a distinctly flat summit with scalloped margins and almost vertical upper slopes. The 3D visualization is vertically exaggerated 2x. The 3000-m contour is represented by a thick line to approximate the basal depth of Benham Bank. A comparison of the cross-sections of Benham Bank and Mayon Volcano along their long axes is provided for reference.

from the upper slopes of the flank, whose slope angle ranges from 60–80°. The Benham Bank morphology is unique among at least 19 bathymetric high features on the Benham plateau as identified in the official GEBCO database of undersea features. Among these features, at least six can be classified as seamounts based on a minimum 1000-m relief defined by the International Hydrographic Organization (see Table 1). A comparison of the summit depth, basal depth, and height, with the basal diameter and cross-section of Benham Bank with other seamounts on the plateau, is presented in Table 1 and Figure 3, respectively. The names Toog, Yakal, Bayog, and Kalantas Seamounts were adapted from the IHO-IOC GEBCO Gazetteer of Undersea Feature Names, as proposed by NAMRIA (2019) and Vinogradov Seamount from Shcheka and co-authors (1995).

The height of Benham Bank is around 2900 m, which includes its carbonate portion. By using the change in slope as a reference (Menard 1983), it can be estimated that the limestone cap initiated at a depth of 1600 m (Figure 3B). The Benham Bank height is greater than those of Bayog, Kalantas, and Toog (which are all around

Table 1. Benham Bank dimension vs. other volcanic features.

Name of feature	Summit elevation (m)	Basal elevation (m)	Height (m)
Benham Bank	–48	–2895	2847
Bayog Seamount	–941	–2846	1905
Kalantas Seamount	–722	–2761	2039
Toog Seamount	–2269	–4276	2007
Yakal Seamount	–2407	–5108	2701
Vinogradov Seamount	–1160	–5000	3840
Mayon Volcano	+2460[a]	+197[b]	2263

[a]From Moore and Melson (1969); [b]measured from Google Earth

2000 m tall) and Yakal Seamount (which is about 2700 m tall). The larger size of Benham Bank compared to other shallow features within the plateau has been attributed to more silicic volcanism forming at an intersection of faults (Barretto *et al.* 2020), but accretion due to carbonate growth now appears to be a significant component of the size of Benham Bank. The tallest feature is Vinogradov