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CAN PLANKTONIC FORAMINIFERA HELP TO IMPLEMENT THE NEW UNITED NATIONS HIGH SEAS TREATY?

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INTRODUCTION

After two decades of planning and negotiations, the United Nations (UN) announced the passage of the High Seas Treaty on March 4, 2023. The Treaty aims to protect biodiversity in international waters, and the UN believes it will enable the enhancement and management of the ocean's resilience by allowing for the creation of marine protected areas (i.e., safe havens for fish, plants, and other vulnerable species) and the so-called "area-based management tools." Its broad intent is to support billions of people worldwide who rely on the oceans for basic needs (Kim 2023). It has been demonstrated that maintaining biodiversity is one of the key pillars to maintaining oceans' trophic levels (ocean food chain); by extension, it implies a sustainable human food supply. However, the task of selecting appropriate measures of biodiversity that have utility for international ocean management issues will require further study. For example, Harris (2007) notes that "what we now regard as the normal state of the oceans has been severely perturbed by the removal of top predators." It is also equally important to assess modification caused by unintended introduction of alien species, open ocean aquaculture, range of pharmaceuticals, anthropogenic chemicals, etc.

Consequently, these commercially valuable species are only of limited value in assessing contemporary ocean biodiversity patterns and trends. Harris (2007) further argues that "in a self-organized world where patterns arise from internal interactions, knowledge of biodiversity patterns alone is insufficient to explain what is occurring at any given time" and is an insufficient predictor of impending

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change. However, there is a light at the end of the tunnel, suggesting that assessing planktonic Foraminifera diversity may be able to overcome some of the weaknesses of the above argument and given their worldwide distributions and their preservation as a proxy for paleoenvironmental and paleoclimate indicators in ocean sediments (Yamasaki *et al.* 2022, Zeng *et al.* 2023).

The High Seas Treaty's overall mission reminded us of one planktonic Foraminifera study carried out during the Tahiti to Vancouver leg of the Hudson 70 expedition (Banerji *et al.* 1971). The entire associated unpublished 81 pages-long Bedford Institute of Oceanography (BIO) Internal Report (IR) of that leg is being reformatted for publication using the Natural Resources Canada Open File GEOSCAN reporting system. We have summarized some key observations below to widen the accessibility to broader readers and highlight the importance of planktonic Foraminifera in understanding diversity. This report describes the spatial abundance and diversity pattern of 30 planktonic Foraminifera species, within 10 genera, in three major Pacific Ocean water masses during the early summer of 1971 (Fig 1). These data are also placed with selected few subsequent studies from the equatorial and eastern Pacific Ocean to provide a broader context. As such, these data offer a potential foraminiferal biodiversity proxy signal against which future researchers can discern spatial and temporal trends in biodiversity. The value of planktonic Foraminifera as an environmental indicators is well known to link modern environmental parameters and reconstruct past environmental changes (Schiebel *et al.* 2018, Rashid *et al.* 2021, Chaabane *et al.* 2023). Most of these organisms are sensitive to environmental changes and are often restricted by a few limiting factors related to their associated water mass. Temperature, salinity, water depth, latitudinal variations, and inorganic and organic solutes in the surrounding water column are perhaps among the most important factors (Cf. Bé and Tolderlund 1971, Schiebel *et al.* 2018, Chaabane *et al.* 2023).

The Tahiti to Vancouver leg of the Hudson 70 expedition consisted of 12 sampling stations along the 150 West meridian from about 10°S to 55°N latitude (Fig 2), representing an 8334 km-long transect (Gordon 2021). Plankton tows were collected using a modified Benthos® Multiple Net Plankton Sampler fitted with 200-micron mesh nets. This type of sampler is particularly suitable for studying the vertical distribution of planktonic Foraminifera because samples

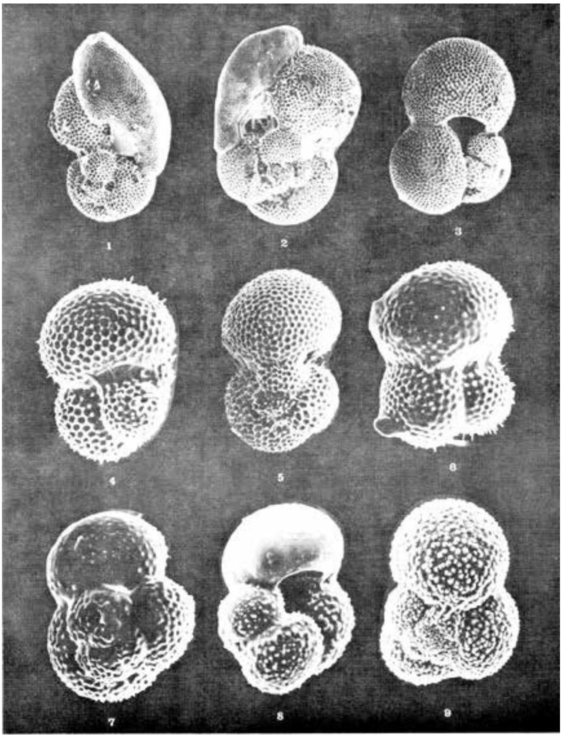

Fig 1 Electron micrographs of two genera comprising three species of planktonic Foraminifera were collected during the Hudson 70 Tahiti to Vancouver leg. Photos 1-6 are of the genus *Globigerinoides*, and 7-9 feature various views of the genus *Globoquadrina*.

can be obtained from specific depth ranges. The device was initially submerged to a depth of 25 metres and towed at a speed of about 1.5 knots for 15 minutes. Two additional tows were made during separate casts at 350 and 750-metre depths (Bé and Tolderlund 1971, Chaabane *et al.* 2023). The samples collected represent specimens resident in the 0-200, 200-500, and 500-1000 m water layers (Fig 3). For this regional survey, it was assumed that the concentration of planktonic Foraminifera remained approximately constant in the water layers sampled, not a patchy distribution, and that there was no appreciable daily change in the faunal population. The volume of water filtered through the nets was monitored using a Tsurumi-Seiki-Kosakusho flow meter® attached to one side of the triangular-shaped sampler frame. It was integrated with a Benthos® Model 1023 acoustic tele-

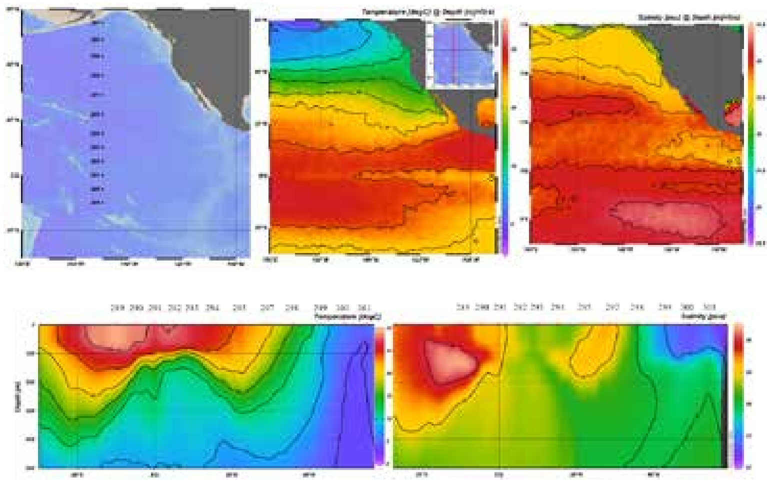

Fig 2 **Station locations for the Tahiti-Vancouver leg of the HUDSON 70 expedition. The 12 sampling stations covered three major Pacific Ocean water masses. The modern climatology suggests that mean May temperature and salinity produce two distinct isotherms and isopycnals. The bottom left panel illustrates one broad temperature cell with 24°C isotherm cropping out on both sides of the equator; however, two distinct cooler cells with 12°C isotherm are found at 300 m water depth. In contrast to the temperature, three isopycnals with 36, 35, and 33 psu cells were found within the stations covered by the survey.**

metering unit that signaled the water depth of the sampler and the closing and opening of nets during each deployment. On board, the samples were washed from each net and preserved in a 10% formalin solution buffered with hexamethylene tetramine.

PREVIOUS STUDIES

The first systematic study of living planktonic Foraminifera in the Pacific Ocean was conducted by Brady (1884) and Murray (1895). Bradshaw's (1959) classic work on the ecology of living planktonic Foraminifera in the north and equatorial Pacific Ocean represented a major breakthrough in a long gap of research quiescence. The author studied the Foraminifera from over 700 plankton samples collected in the north and equatorial Pacific. Twenty-seven species were identified and grouped into four biogeographic faunas, including cold, transitional, central, and equatorial. Their faunal boundaries coincided with hydrological divisions based on temperature and salinity data.

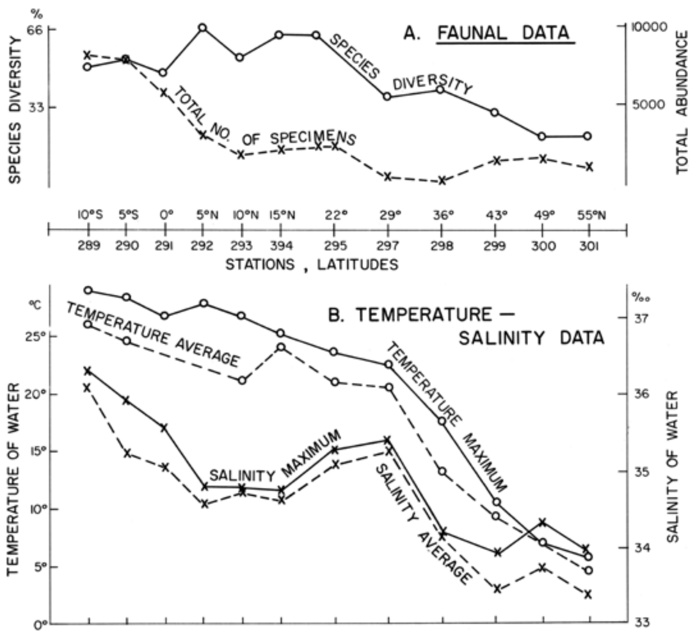

Fig 3 Maximum and average temperature-salinity values of surface waters at various stations in relation to their respective foraminiferal species diversity and total number of specimens.

One interesting observation by Bradshaw (op. cit.) was that the most abundant populations of planktonic Foraminifera per unit volume of water occurred in the subarctic water mass and at limited localities in the equatorial region. Parker (1960) extended Bradshaw's study towards the equator and South Pacific by noting the distributional patterns of 16 of the more common planktonic Foraminifera species. The author concluded that temperature may be more important than salinity in controlling the Foraminifera distribution. In a later publication, Parker (1962) discussed the systematics of all the planktonic species recorded from the South Pacific. In the following six decades, numerous subsequent studies built on the works of Bradshaw (1959) and Parker (1960) further updated and refined data about the seasonality of Foraminiferal blooms, temperature and salinity, genetic variations, and diversity from the eastern and equatorial Pacific (Schiebel *et al.*, 2018). Further, the increase in interest in understanding the dynamics of surface currents and the evolution of the El-Nino southern oscillation (ENSO) led to the setting up of sediment traps in the eastern equatorial Pacific, particularly in Panama Basin, California Borderland, and Guaymas Basin in the Gulf of California (see Davis *et al.* 2019, for a review) were important.

SPECIFIC OBSERVATIONS

The entire equatorial and northern Pacific regions sampled during this study along the 150-meridian line may be divided into three water masses based on their physical and chemical properties. Water masses from south to north are designated as Southern, Central, and Northern, or Subarctic (Fig 2). The boundaries dividing these three water masses coincide approximately with latitude 32°N and latitude 46°N. The northernmost end of the southernmost boundaries could not be defined due to incomplete coverage. In any event, aII 29 plankton tows contained Foraminifera specimens. Fundamentally, the observed faunal composition is similar to that of Bradshaw (1959). Most of the species were found to be separated into restricted horizontal latitudinal zones and vertical depth categories. Four groups are recognized based on their associations with certain ranges of water temperature. A warm water species group thrives in the equatorial waters bounded by the 20°C isotherm (Yamasaki *et al.* 2022). Within this group, two faunal subgroups can be defined: 1). A Warm Tropical Species Subgroup exists around the equator to 15°N where the average sea surface temperature (SST) is approximately 25°C. Its indicator species include *Candeina nitida* (D'Orbigny), *Globigerina calida* (Parker), *Globigerinoides trilobus* (Reuss), *Globigerinoides ruber* (D'Orbigny), *Globoquadrina conglomerata* (Schwager), and *Globorotalia tumida* (Brady), 1). b somewhat cooler Warm Temperate Species Subgroup that thrives further north to latitude 30°N and coincides with an SST of 20°C. Species common to this subgroup include *Globorotalia inflata* (D'Orbigny) and *G. hirsuta* (D'Orbigny). Finally, a Cold Temperature Group in which six species thrive in this water mass including (in order of abundance): *Neogloboquadrina pachyderma* (Ehrenberg), *Globigerinita glutinata* (Egger), *Turborotaliata quinqueloba* (Natland), *Neogloboquadrina dutertrei* (D'Orbigny), *Globigerina bulloides* (D'Orbigny), and *Globorotalia inflata* (D'Oribgny).

Members of this Group thrive in waters from the equator to latitude 43°N, and their northern boundary coincides approximately with the ten °C isotherm. Last, there is a Cosmopolitan Species Group designated as the third group. *Globigerinita glutinata* (Egger) is the only true cosmopolitan species present in all the water masses of the northern and equatorial Pacific. At the same time, *Globorotalia inflata* (D'Orbigny) is present in the subsurface waters at most of the stations. Using seven-year sediment trap data from the Guaymas Basin of the Gulf of California almost five decades later, Davis *et al.* (2019) also concluded the annual presence of the *Globigerinita glutinata*. In comparison to this study, *G. inflata* appears to reflect dwelling in divergent water masses in the North Atlantic, e.g., it lives at the base of the seasonal thermocline (~100-200 m depth) in south of Iceland (Sahoo *et al.* 2022) while it is also found in the mixed-layer (~10 m) of subtropical waters associated with the warm North Atlantic Current (Schiebel *et al.* 2018, Zeng *et al.* 2023).

At most stations, three plankton tows were successfully retrieved and are designated here as Surface (S), Intermediate (M), and Deep (D). Broad groupings of faunal abundance at various depths and with respect to different water masses are evident. Since Hudson 70 data are derived from only one set of samples taken during the 1969 summer, these species do not lend themselves to broad generalizations for the entire year (see Schiebel *et al.* 2018 for a review). However, it may be stated that, for the 8334 km-long transect sampled, the abundance of planktonic Foraminifera decreases rapidly in the three successively deep-water levels (between the upper 200 m and the 500-1000 m levels) at an approximate abundance ratio of 5:1. This decrease in faunal abundance with increasing depth has been observed by various workers studying the characteristics of different oceanic water masses in various oceans (Kucera *et al.* 2005, Chaabane *et al.* 2023). Lohman (1920) was perhaps the first to give a quantitative estimation of the variations in the total abundance of specimens concerning depth in Atlantic waters. Subsequently, plankton tows and sediment traps data confirmed those findings. The author's data also show a pronounced decrease in specimens at depths > 200 metres. Bradshaw (op. cit.) determined that the highest concentrations of planktonic Foraminifera occurred between 6-30 metres in most tows and that the greatest decrease in number per M3 was noticed between 50-100 metres during his study of the northern Pacific. Hudson 70 survey observations in equatorial and north Pacific water masses revealed an almost uniform reduction in specimen abundance from the three depth categories sampled at most stations (Fig 4), consistent with the findings of numerous subsequent studies (Schiebel *et al.* 2018, Davis *et al.* 2019, Yamasaki *et al.* 2022). The depth limit of photosynthesis, in general, has been determined to be 120 metres in clear tropical waters, 40 metres in shelf waters, and 15 metres in turbid waters in temperate latitudes (Sigman and Hain 2012). It is well known that phytoplankton are one possible food source for planktonic Foraminifera (Kucera *et al.* 2005). Thus, the direct dependence on photosynthetic organisms as a food source may strongly control the bathymetric distribution of living planktonic Foraminifera.

Correlation analysis of the 29 Pacific planktonic Foraminifera samples from all depths indicated strong but almost equal effects of temperature and salinity on absolute abundance and species diversity (Banerji *et al.* 1971). Species diversity and specimen abundance correlate inversely with latitude and positively with temperature (maximum and average values) and average salinity. Nutrients (phosphates and nitrates) correlations are comparatively less significant; however, an inverse correlation of second order of importance was noted. Oxygen appears to be an insignificant factor; its presence in minor amounts is essential for organic metabolism.

Latitudinal variation in the composition of planktonic Foraminifera may most easily be explained using species diversity data. Species diversity (Ds) is defined as the number of species found in a sample and is generally expressed as:

$Ds = \frac{S}{TS} x100$, where Ds = diversity percent; S = number of foraminifera species observed at a particular station, and TS is the total number of species. Species diversity may be expressed either in actual numbers of species or as the relative percentage of species present in an assemblage. The Southern Water Mass includes that part of the equatorial warm-tropical to warm-temperature belt extending from south of the equator to latitude 30°N of this study. Stations within this water mass include 289, 290, 291, 292, 293, 294, 295, and 297 (Fig 2). Temperature and salinity values of its surface water vary from 22°C to 30°C and 34.6 to 36. 16 ‰, respectively. Species diversity varies from 50-66.70% in the surface waters, whereas the minimum diversity of 20% was noticed in the subsurface water of station 290 (at 05°S). All stations within this water mass show a relatively high frequency of dominant warm water Foraminifera. These Foraminifera are divided into warm-tropical and warm-temperate species subgroups. The plot of species diversity concerning latitude illustrates a uniform decrease in diversity from the equator to the higher latitudes, as confirmed by numerous subsequent studies (Cf. Bé and Tolderlund 1971, Yamasaki *et al.* 2022). Certain unexplainable anomalies have been noted at a few stations. Plankton tows taken south of the equator (e.g., stations 289 and 290) are comparatively rich in foraminiferal specimens compared to the north. Warm-tropical species range from the equator to latitude 15°N, where the surface temperature is approximately 25°C. The species thriving in this area in order of their abundance are *Globigerinoides ruber* (D'Orbigny), *Globigerinoides toilobus trilobus* (Reuss), and *Globoquadrina conglomerata* (Schwager), which are relatively abundant, followed by *Globorotalia tumida* (Brady). The ratio of total specimens to species number decreases rapidly at northern stations. A Central water mass that lies between the Southern water and Northern or Subarctic water masses and includes a narrow zone bounded by 30°N and 45°N. Two stations (No. 298 and 299) were sampled to 900 metres depth on May 31 and June 2, 1970, and the maximum temperature and salinity were 17.6°C and 34.3‰, respectively. These two stations are located in a part of the Northern Pacific with intricate circulation patterns. Changes in the faunal assemblages are frequent due to the complexity of the circulation pattern, i.e., the mixing of the Southern warm water with the Northern cold water mass. Hence, the samples from this water mass have yielded dominantly warm and cold water species. Species diversity in this area is lower than that of Southern water and varies from 30 to 40% at all depths.

In general, faunal data of both the Southern and Subarctic waters are intermixed in the Central Water Mass so that the dimensions of the Central water mass vary depending upon the distance from the original faunal province and the degree of mixing. The faunal association within the Central Water Mass is characterized by the first appearance of *Neogloboquadrina pachyderma* (Ehrenberg) and the continued increase in *Globigerina bulloides* D'Orbigny specimens to the north. Mixing warm water from the south and cold water from the north has a pronounced effect on the distribution of a few less tolerant species in samples collected from two stations in the Central water mass. The Bering Strait separates the Northern or Subarctic

Water Mass from Arctic waters, beyond the collection coverage in 1971. The boundary separating it from the Central water mass runs approximately along latitude 45°N. Only two stations (No. 300 and 301) in the Central Water Mass were sampled on June 4 and 5, respectively. The maximum temperature and salinity of the water were 7.2°C and 34.35‰. The most interesting feature of the associated fauna in this area is the low but uniform value of 20% species diversity, which characterizes most of the plankton samples, and relatively higher specimen-to-species ratios compared to other areas. *Globorotalia cavernula* Bé has been recorded in amounts of up to 3% of the total fauna from the subsurface sample at station 301 (at 55°N). The change in the abundance of *Neogloboquadrina incompta* (Cifeli) living in Central water to *Neogloboquadrina pachyderma* (Ehrenberg) in subarctic water is a significant factor in delineating the boundary between these two water masses.

DISCUSSION

Scrutiny of the 81 pages of the BIO internal report (IR) demonstrates the somewhat "noisy" aspect of planktonic Foraminifera biodiversity when viewed at regional scales. However, the proxy indicator utility of these protozoans appears to offer a good starting point for addressing the High Seas Treaty ocean management mission for comparison to regional and seasonal changes. Nevertheless, it will likely require decades of inter-seasonal baseline monitoring along with biodiversity trends revealed in fossil assemblages preserved in seafloor sediments to reach the level of reliability needed for a regional-scale proxy indicator of changing environmental conditions of the earth's vast ocean space. For a start, a more practical approach might be to initially test the concept in just one of the four major oceans to confirm planktonic Foraminifera's suitability, reliability, and limitations as proxy indicators of natural and anthropogenic-driven environmental changes. Finally, we must never forget the teachings of Graham Harris (2007), whose writings repeatedly remind both researchers and the Treaty's management that the success of the High Seas Treaty approach "rests primarily on situations where the science is not in dispute, and where a strong lobby for political action exists." Harris argues further that although certain global prediction models can offer useful insights into future ocean environment trends, one thing that they will probably not be able to do reliably for ocean environment change is to predict "sudden state shifts, hysteresis effects, and tipping points." For time scales on the order of months to years, measuring planktonic Foraminifera biodiversity trends may be the best and most cost-effective approach for detecting environmental impacts.

CONCLUSIONS

Five groups of living planktonic Foraminifera species were distinguished in the equatorial and northern Pacific. These groups include a warm-tropical (equator to 15°N), warm-temperate (up to 30°N), cold-temperate (up to 43°N), cold water (north of 43°N), and a cosmopolitan group. Factors such as temperature and nutrients appear to be most important in controlling the geographical limits of these groups. The population density of planktonic Foraminifera in Pacific waters decreases rapidly with increasing depth. The abundance ratio of specimens on the surface compared with subsurface waters during the period of this investigation was approximately 5:1. The decrease in the foraminiferal population with a depth of water is probably closely related to the degree of light penetration in seawater, which, in turn, controls phytoplankton distribution. There is a uniform decrease in species diversity from the equator to the higher latitudes in this part of the Pacific. A simple direct relationship seems to exist between the temperature and salinity of water and the absolute abundance and species diversity of Foraminifera populations in the Pacific.

The UN's High Seas Treaty proponent nations must recruit a worldwide cadre of biologically trained experts and affiliated institutions that can contribute spatial and temporal data germane to the Treaty's biodiversity-related objectives. As such, living planktonic Foraminifera monitoring appears to have a major role to play in the overall effort needed for cost-effective ocean space environment management decision-making that lies ahead.

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