

CHAPTER V

SUMMARY AND CONCLUSIONS

To understand the fate of Carbon dioxide in the northern Indian Ocean for the Last Quaternary period, two entities were assessed; the calcium carbonate content and the paleocarbonate ion content from ocean sediments. The CaCO_3 content data from ten deep-sea cores congregated from the equatorial region of the Atlantic, Pacific and Indian Ocean covering a time span of 0.6Ma was reviewed. As observed by a large number of studies, the CaCO_3 content fluctuates in a cyclic pattern through the glacial-interglacial. Largely, there are two typical patterns observed; the 'Atlantic pattern', exhibiting better preservation during the interglacials and poor preservation during glacials and the 'Pacific pattern' which exhibits poor preservation during interglacial and better preservation during the glacials. There are studies exemplifying either/both types of patterns for the Indian Ocean. The Indian Ocean carbonate fluctuations are not conclusive as to which pattern they exhibit, due to few studies. The overall patterns observed over the equatorial regions of the world oceans are attributed to changing bottom water circulation and hence changing saturation state with respect $\text{CO}_3^{=}$ concentration. Therefore, the bottom water $\text{CO}_3^{=}$ concentration is considered to be the most important factor in understanding the glacial-interglacial ocean operation.

To understand the CO_2 variations in the past it is necessary to know how the $\text{CO}_3^{=}$ concentration varied in response to the atmospheric CO_2 change. Studies with respect to paleocarbonate ion reconstruction have been extensively carried out in the Atlantic and Pacific oceans. Major thrust has been laid on using many of the available

paleocarbonate ion proxies. In this study three paleocarbonate ion proxies have been applied; 1) size index 2) planktonic foraminifera shell weights and 3) calcite crystallinity. These proxies have been applied several times in the Atlantic and Pacific oceans and therefore the shortcomings and existing gaps in knowledge are well known. In this context a few studies were carried out from the Indian Ocean to understand the paleocarbonate ion variations. In this study, before the application of any of these proxies, their validation and suitability of application to the northern Indian Ocean is evaluated. For doing this, several core top samples have been employed providing a good spatial coverage. In this endeavor the shortcomings of these major proxies have come forth. Only after clearing the major drawbacks the proxies have been applied to the northern Indian Ocean in order to understand the glacial-interglacial carbonate ion fluctuations.

This study provides a systematic basis to resolve some important aspects of the calcium carbonate fluctuations during the Late Quaternary Period. The prominent findings of this study are summarized as under:

- 1) Previous studies suggest that the CaCO_3 content in the ocean sediments fluctuated systematically in the Atlantic, Pacific and the Indian Oceans. Though these variations are influenced by three factors namely, productivity, dilution and dissolution. Out of these three factors, dissolution plays an important role in the deep seas, primarily due to bottom water $\text{CO}_3^{=}$ undersaturation. This claim is made based on the linear relation between coretops of the ten sediments cores from the Atlantic, Pacific and Indian Oceans and the carbonate ion concentration of the water bathing these coretops. The $\text{CO}_3^{=}$ concentration of bottom-waters in the major world

oceans have changed depending on the bottom-water circulation which created two distinct carbonate fluctuation patterns. These are typically christened the ‘Atlantic pattern’ and the ‘Pacific pattern’. It is believed here that the Indian Ocean displays a Pacific type of pattern due to the similar kind of bottom-water circulation prevailing in both these oceans. This highlights the importance of $\text{CO}_3^{=}$ alone in shaping the carbonate fluctuations.

- 2) To determine the carbonate ion concentrations in the past it is necessary to use certain proxies which could give a fair calculation of this entity. Three paleocarbonate ion proxies, size index, planktonic foraminifera shell weight, and calcite crystallinity, have been employed in this study. These proxies are primarily validated. In support of this the proxies have been applied to a set of core top samples from the western tropical Indian Ocean in the water depth ranges from 1086 to 4730m. All three proxies show a linear relation to one another and hence complement each other well. The significant finding here from the application of these proxies is that calcite dissolution starts to affect planktonic foraminifera from 2250 m depth onward and intense calcite dissolution begins around 3900 m depth in this sector of the tropical Indian Ocean.

To substantiate the effect of dissolution on foraminifera shells, SEM micrographs of *Globigerinoides sacculifer* from a water depth of 2250 and 3944m were compared. Apparently, shells from deeper depth show dissolution features whereas shallow depth shells show well-preserved tests. A perplexing result is that the three planktonic foraminifera species,

Globigerinoides sacculifer, *Pulleniatina obliquiloculata*, and *Neogloboquadrina dutertrei*, show wide variability in shell weights from core top sediments in the depth range of 3300 to 3400 m bathed by similar bottom water $\text{CO}_3^{=}$ concentrations. This anonymity is determined and attributed to shell calcification in surface waters which have different $\text{CO}_3^{=}$ concentrations. This study makes it apparent for the first time that initial shell weights in the tropics depend on the surface water $\text{CO}_3^{=}$ concentrations as seen for the temperate species, shown in other studies. Further, surface water $\text{CO}_3^{=}$ concentrations override milder dissolution effects experienced by samples from shallower water depths bathed by similar bottom water $\text{CO}_3^{=}$ concentrations. An important conclusion of this study is that the calcite dissolution effects are best resolved using a multiproxy approach, such that there is no indistinctness in the results.

- 3) To be certain whether the application of the proxies yields a correct estimation of the bottom water $\text{CO}_3^{=}$ concentration, it is important to understand the possible dissolution mechanisms. Two processes drive dissolution of calcite after it reaches the seafloor. First is the degree of saturation state of $\text{CO}_3^{=}$ concentration of the overlying bottom waters and the second, due to sedimentary organic matter respiration and resulting acidification of pore waters. Therefore it is necessary to examine whether the intense dissolution occurring at 3900m in the Indian Ocean is a result of undersaturation of overlying bottom waters with respect to $\text{CO}_3^{=}$ concentration. In actual conditions, the core top foraminifera are initially exposed to the benthic fluff layer at the sediment-water interface. Therefore,

this interface is perhaps a better description of the initial exposure environment in foraminifera from core tops. To understand whether dissolution taking place at 3900m water depth is due to this corrosive benthic fluff layer the $\Delta\text{CO}_3^{=}$ interface - $\Delta\text{CO}_3^{=}$ bottom water gradient was calculated and found to be + 4.2 μM which is within $\pm 10\mu\text{M}$ of bottom water, the value derived by de Villiers(2005). This suggest that there is no significant gradient in $\Delta\text{CO}_3^{=}$ across the sediment-bottom water interface at a depth of 3900m. Therefore, it is concluded that the intense dissolution along this transect in the western Tropical Indian Ocean is due to bottom water $\text{CO}_3^{=}$ undersaturation. This finding provides a boost to the application of the shell weight proxy for the northern Indian Ocean.

- 4) The suitability of two proxies, size index and planktonic foraminifera shell weights was verified with respect to understanding the temporal variations in $\text{CO}_3^{=}$ concentrations. For this purpose, size index proxy was applied to two ODP Sites 715 and 752 which were drilled above the regional lysocline depth in the Indian Ocean. The size index as measured in Site 752 and Site 715 showed significant variations, though both the sites are from shallow depths. High values of size index at ODP Site 752 and its distal location from any landmass suggest that the observed variations are due to changes in productivity of the overlying waters. Low values of size index at ODP Site 715 suggest significant dissolution has occurred throughout the core. The reasonably synchronized mismatch between size index and CaCO_3 occurring at ODP Site 715 is a unique result. Such an outcome is not noticed at ODP Site 752. The size index alone is not adequate to reason out the

observed mismatch. Therefore, the CaCO_3 content from the $<63\mu\text{m}$ fraction was studied. The CaCO_3 content from the $<63\mu\text{m}$ fraction from ODP Site 715 shows a match with the total CaCO_3 content. From the $<63\mu\text{m}$ variations it is evident that the finer fraction which is composed of juvenile forams, foraminiferal fragments and coccoliths dominates the carbonate content and holds the key to the observed variations. It is concluded here that the size index may not give a correct estimation of the carbonate ion content of bottom waters in regions dominated by coccolithophores, as encountered in the present study. *G. ruber* shells from the ODP Site 715 show an anomalous trend throughout the core which has been attributed to different morphological changes in *G. ruber* during glacial and interglacial. This study signifies that the influence of coccoliths is seen throughout the glacial period which is a major drawback in applying the size index to the glacial as a paleocarbonate ion proxy, as also confirmed by some previous studies.

- 5) Two cores are AAS9/21 from the Arabian Sea and SK218/A from the Bay of Bengal are employed to reconstruct the history of carbonate ion in these two basins for the past 25kyr. The CaCO_3 content variations from both the cores do not provide a clear picture of the fluctuations occurring during the past 25 kyr. The possible reason is the large amount of terrigenous dilution due to influx of major rivers in both these regions. In the present circumstances two important proxies are used to understand temporal variations in $\text{CO}_3^{=}$ concentrations; the size index and *G. sacculifer* shell weights. Size index application for both the cores gives an underestimation

of $\text{CO}_3^{=}$ concentration and are not consistent with the CaCO_3 content changes. Size index values in AAS9/21 which lies at shallow depth are lower as compared to the size index values in Core SK218/A. Moreover, size index results for Core AAS9/21 which lie much above the lysocline, show an increasing trend from recent to the Last Glacial Period. These results imply that the initial size distribution of the CaCO_3 deposited throughout the tropics is not uniform during present and glacial time. But, in general the high values of CaCO_3 and size index during the Last Glacial Period and lower during the Holocene reveals a Pacific type of pattern for the northern Indian Ocean.

The second proxy, planktonic foraminifera shell weights, was applied to both the cores. Shell weights from both the cores were combined with Mg/Ca thermometry, a proxy for paleotemperature. There seems to be an inverse linear close fit relation between *G. sacculifer* shell weights and Mg/Ca ratios, with higher shell weights corresponding to lower Mg/Ca ratios; indicative of lower temperatures ($R^2=0.6$). Shell weights are seen to be highest during the LGM and show a large decrease into the early Holocene. Due to the fact that shell weights are heavier during glacial time and the inverse relationship between temperature (Mg/Ca) and shell weights, suggests that the control on shell weight is carbonate ion and not calcification temperature. Such a change in shell weights during the glacial-interglacial based on the surface water $\text{CO}_3^{=}$ changes is a novel result for the tropics. This places new constraints on the coral reef hypothesis and could possibly explain the survival of reef corals on Bermuda.

- 6) The carbonate ion concentration calculated from shell weights from the Core AAS9/21 shows a good match with CO₂ measured from Antarctic ice cores for the last 25kyr. The glacial-interglacial change in CO₂ of 100ppmv registers a 45μmol/kg change in CO₃⁼ concentration as calculated from *G. sacculifer* shell weight change of 10 ± 2μg. Again, through the Holocene a shell weight change of 2μg is noticed. This 2μg change in shell weights during the course of the Holocene calculates to a CO₃⁼ concentration of 9μmol/kg and in agreement with previous work. In terms of CO₂ rise this change is of 20ppmv as measured from air bubbles trapped in an ice core from Taylor Dome, Antarctica, covering the entire Holocene. This indicates the amount of CO₂ sequestered by the Arabian Sea during the 25kyr period.

The absence of well preserved *G. sacculifer* shells in core SK218/A for the Holocene period suggests dissolution at 3307m depth in the Bay of Bengal. The minor dissolution observed at SK218/A site is attributed to pore water dissolution in this region during the glacial with the dissolution effect increasing during the Holocene period. In practice, since the planktonic foraminifera shells trace the surface water carbonate ion concentrations a correction of around 8μg need to be applied to the glacial shells (Broecker, 2003). Since there was an effect of pore water dissolution on the foraminifera shells this probably compensates for the surface water carbonate ion effect. Therefore this correction has not been applied at 3307m water depth. The CO₃⁼ concentration has been calculated for the glacial Indian Ocean using *G. sacculifer* shell weights from cores AAS9/21 and SK218/A. It is seen that the CO₃⁼ gradient was steeper during the glacial. This gradient between glacial and today is 10μmol/kg at 3307m,

whereas no such gradient exist in the water depth of 1807m. This difference of 10 μ mol/kg in the present case for the Indian Ocean implies at least a ~600m difference in the CCD which must have been at around 3900m during the glacial. The results presented here are in agreement with other studies which suggest that the CO₃⁼ gradient was steeper during the glacial. The implications of such gradients are that the waters supplying the deep sea had a greater range in density, thereby permitting stratification to persist.

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