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22. It is worth mentioning that the force-dipole that appears in the Oseen equation is the one relevant on large length scales. For any finite Re, this need not be the same as the actual force-dipole exerted by the swimmer. This is because, unlike the force or torque, a symmetric force-dipole is not transmitted unchanged across fluid surfaces.
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24. The absence of a volumetric displacement for a dipole field may appear to contradict Darwin's original demonstration of a net displacement for a sphere in the potential flow limit in which case the disturbance velocity field is that of a potential dipole, and therefore, fore-aft symmetric. However, as already indicated, the drift in this latter instance is of the order of the particle volume, or in the present context, of the order of the swimmer size. The Oseen analysis is, however, valid on much larger length scales – those that contribute to efficient mixing. Thus, any volumetric drift of the order of the swimmer size is not included in the analysis. In particular, a similar analysis in the potential flow limit would correspond, at leading order, to an actual potential dipole singularity rather than a finite-sized sphere, the displaced volume then being zero.
25. It may also be shown the volume displaced by a force-dipole, in the limit Re $\rightarrow 0$ grows linearly with time, much like the passive particle at finite Re; however, the smallest aquatic organisms of interest here, the zooplankton, tend to have Reynolds numbers of order unity.

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Abundance and coiling direction in planktic species *Neogloboquadrina pachyderma* (Ehrenberg) as indicators of hydrological conditions: evidence from N–S transect of Indian Ocean

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A total of 25 surface sediment samples collected along a North–South transect (from 9.69°N to 80°E and 55.01°S to 40°E) in south western Indian Ocean have been used to study recent planktic foraminifera revealing the ecological preferences of the planktic foraminifer species in the area, particularly the coiling direction patterns in the planktic species *Neogloboquadrina pachyderma* (Ehrenberg). The coiling direction and their absolute abundance can be shown to be related to ambient temperature and salinity values. Dextrally coiled forms decrease towards higher latitude, while sinistrally coiled forms increase. Similar studies should be undertaken along various transects to further establish the extent of environmental control on coiling direction in planktic foraminifera.

Keywords: Coiling direction, Indian Ocean, *Neogloboquadrina pachyderma*, seawater temperature and salinity.

COILING directions of the foraminifera have been used as a tool for both local stratigraphic correlation and palaeoclimatic studies because of their relation to palaeotemperature[1–3]. Most of these studies dealing with the relationship between the temperature and coiling direction have been spatially limited with many contradictory results[4–5] and controversies about the effect of environmental parameters on the coiling directions of foraminifera[4,6]. It has also been reported that similar species tend to show more than one response to a particular environment and the same applies to different foraminiferal species in the same geographic region[7,8]. It has further been assumed that *Neogloboquadrina pachyderma* (dextral) may be taxonomically distinct from its sinistral counterpart[9]. Recent genetic studies of modern planktic foraminifera have raised further issues which complicate the environmental interpretation of the changes in the coiling direction of planktic foraminifera[10].

In view of the contradictory reports from different regions and on different species, it appears to establish the response of individual species in specific regions, instead of making generalizations about the response of the coil-

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ing direction of any species to its ambient environmental (hydrological) conditions along geographical wide region. In the present study, we have tried to establish a relationship between coiling direction (dextral/sinistral) of the planktic species *N. pachyderma* and environmental parameters, viz. temperature and salinity along a vast geographical area covering a North–South (N–S) transect from lower latitude to higher latitude regions in Indian Ocean through an area of varied oceanographic conditions. We selected this planktic species because *N. pachyderma* occurs abundantly in polar and subpolar regions and the coiling directions and frequency and abundance of this species have been utilized to study palaeoceanography of polar and subpolar regions[11].

A total of 25 surface sediment samples (comprising Peterson grab, piston core top, gravity core top and spade core top samples) were collected during the 199C and 200th cruises of *ORV Sagar Kanya* covering a transect between lat. 9.69°N–80°E and 55.01°S–40°E in the Indian Ocean (Figure 1). The sediment samples (top 1 cm of the sediment cores/grabs) used in this study have been stained with Rose Bengal immediately upon recovery onboard and preserved in 10% formalin to distinguish living specimens of benthic foraminifers from dead ones. In the absence of exact age datings of the sediment samples, the living benthic foraminiferal specimen at the various stations were considered to reflect the modern ambient conditions at the seabed. In each station, temperature and salinity were measured from 0 to 200 m depth using conductivity temperature depth (CTD). Average salinity and temperature in the top 200 m were calculated and plotted against latitudes (Figures 2 and 3). The sediment samples were processed by standard procedures[12]. About 40 specimens of *N. pachyderma* were picked and counted for its coiling directions by using stereo-binoculars and the percentage of dextral and sinistral forms was computed. In addition, relative percentage of dextral and sinistral forms, absolute numbers of dextral form in 1 g sand fraction (> 63 μm), *N. pachyderma* in 1 g sand fraction (> 63 μm) and sinistral form in 1 g sand fraction (> 63 μm) are also plotted against the latitudes (Figure 4). Correlation coefficients were calculated using dextrality and average CTD seawater temperature (Figure 3 *a*), and average CTD seawater salinity (Figure 3 *b*).

The minimum and maximum near surface temperatures recorded in this transect were 1.55°C (at station SK 200/33) and 24.39°C (at station SK 199C/17) respectively

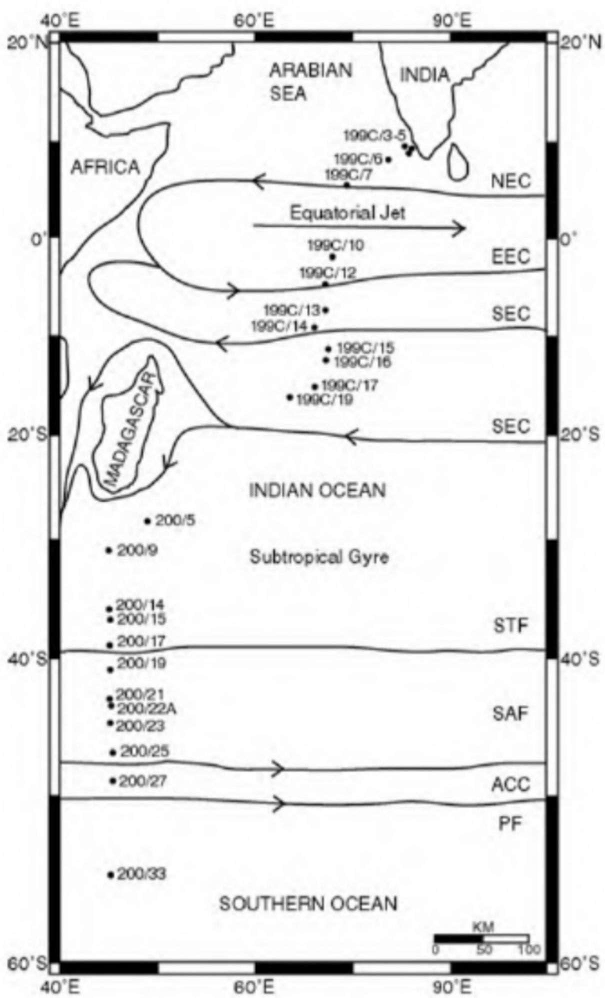

Figure 1. Location of the stations in the North–South transect in Indian Ocean with oceanographic features.

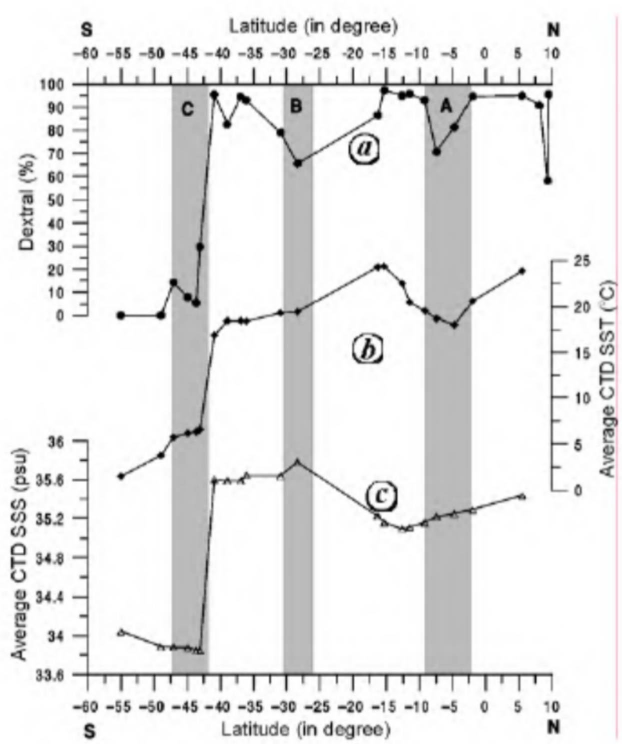

Figure 2. *a*, Latitudinal change in the percentage of dextral coiling. *b*, Sea water temperature from CTD data. *c*, Seawater salinity from CTD data.

according to CTD dataset is shown in Figure 2 *b*. Similarly, the minimum and maximum near surface salinity recorded in this transect were 33.84 psu (at station SK 200/22A) and 35.79 psu (at station SK 200/5) respectively according to CTD dataset as shown in Figure 2 *c*. The maximum values of dextrally coiled forms were encountered (97.2%) at station SK 199C/17, whereas minimum percentage values (0%) was recorded at stations SK 200/27 and SK 200/33 (Figures 2 *a* and 4 *a*) whereas the number of dextral forms in 1 g of sand fraction shows the highest value (5454) at station SK 200/23 around 45°S latitude and shows the lowest value (0) at higher latitudes (49°S to 55°S) at stations SK 200/27 and SK 200/33 (Figure 4 *b*).

The general trend emerging from the data set is the decrease of the dextrality of *N. pachyderma* towards the polar region with a strong positive correlation between dextrality, temperature and salinity along the western Indian Ocean study transect (Figures 2 and 3).

The two coiling forms of *N. pachyderma* are controlled largely by water temperature[13,14]. The left-coiling variety is abundant in the colder waters of the North Atlantic region and is absent in water with a temperature above 8°C, where the right-coiling variety dominates[15]. Hence, the alternating presence of dextral and sinistral varieties of this species can be a good indicator of alternating colder and warmer marine conditions[16]. Previously *N. pachyderma* (sinistral coiling) was reported as the most common species in cold Polar water masses between 50 and 100 m water depth with 70% abundance, among all planktic foraminifera[17]. In the modern marine regime, *N. pachyderma* sinistral predominates in the higher latitudes[18], while *N. pachyderma* dextral is found to occur in close proximity to the equatorial region[19]. It was suggested that both varieties can be used phylogenetically and morphologically as palaeoclimatic proxies, particularly for high-latitude palaeoenvironmental analyses[20].

The observed relationships between coiling directions (dextral/sinistral) and various hydrological conditions (temperature/salinity) indicate that an increase in dextral forms indicates conditions of higher salinity and temperature. Interestingly, around 10°S latitude, the profiles of the percentage of dextrally coiled forms along with temperature and salinity values show a trough (marked as A in Figure 2). Further south at around 42°S latitude, all these parameters again exhibit a trough (marked as C in Figure 2). Apparently similar pattern is exhibited in the profile of the total numbers of dextrally coiled forms in 1 g sand fraction (> 63 μm) with occasional exceptions around 35–45°S latitude (Figure 4 *a* and *b*). Such deviations in the total numbers of dextrally coiled forms in 1 g sand fraction (> 63 μm) from dextrality may perhaps be attributed to the fact that the dextrality (percentage of dextral forms) is a relative expression whereas, total number of dextral forms in 1 g sand fraction is an absolute quantity. As can be seen in Figure 4 *c* that with an overall abun-

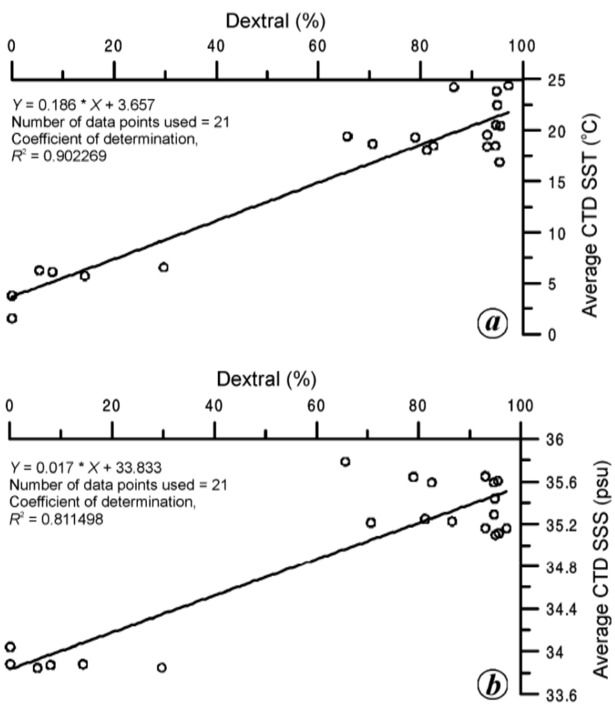

Figure 3. ***a***, Correlation coefficient between dextrality and average CTD seawater temperature. ***b***, Average CTD seawater salinity.

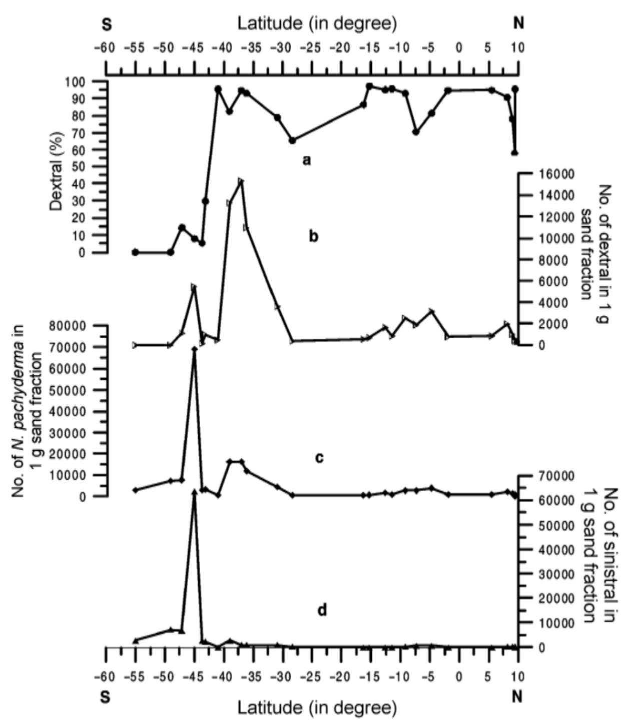

Figure 4. ***a***, Relation between the percentage of dextral coiling. ***b***, Number of dextral forms in 1 g sand fraction (> 63 μm). ***c***, Total number *Neogloboquadrina pachyderma* in 1 g sand fraction (> 63 μm). ***d***, Number of sinistral forms in 1 g sand fraction (> 63 μm).

dance of *N. pachyderma* species, absolute numbers of both dextral (Figure 4 *b*) and sinistral forms (Figure 4 *d*) have increased. Besides, nature of sediments at sampling site could be another factor influencing the absolute numbers of dextral forms in 1 g sand fraction (> 63 μm).

Such interesting trends in the profiles of dextral forms and the temperature–salinity values in the present N–S transect could be explained in terms of different oceanic processes giving rise to water regimes of relatively different properties. It is well established that along the present N–S transect, two distinct water masses occupy the thermocline of the Indian Ocean. Indian Central Water (ICW), a sub-tropical water mass forms and subducts in the subtropical convergence (STC) or subtropical front (STF) originating from the Indian Ocean sector of the STC and hydrologically ICW is identical to the South Atlantic and western South Pacific Central Water[21]. While Australasian Mediterranean Water (AAMW), on the other hand, is the tropical water mass derived from Pacific Ocean Central Water and formed during transit through the Australasian Mediterranean Sea. The large impact of AAMW on the hydrological structure of the Indian Ocean thermocline points towards a large supply of Mediterranean water outflow into the Indian Ocean, over the entire upper kilometre of the water column around 10°S latitude. The presence of AAMW is indicated by the low salinity of the out flowing water[21].

Trough A with reduction in dextral forms lies approximately within this band of low salinity (Figure 2), thereby implying that it reflects the signals of AAMW in this region. The progressive ageing (resulting in increase in salinity) of the ICW and AAMW that occupies the thermocline and larger part of the water above the thermocline in the Indian Ocean[22] may also contribute to the increasing abundance of dextral forms towards the higher latitudes. The other trough in the profiles of coiling directions of dextral at around 42°S latitude (marked as C in Figure 2) could apparently reveal the signature of the STF. The northern side of the STF is generally saltier[23], whereas south of the STF is the eastward flow of the Antarctic Circumpolar Current (ACC), found approximately between 45°S and 55°S latitude[24]. The cooler and less saline near surface water properties, differentiate the ACC water from the warmer and saltier water of subtropical regime. South of the STF, a sharp decline in salinity resulted in the decrease of dextrally coiled forms. It is intriguing to notice that though the percentage of dextrally coiled forms show decreasing values between 15°S and 35°S latitude (marked as B in Figure 2), the profile of salinity and temperature shows increasing and decreasing trends respectively, between about 15°S and 35°S latitudes. Does this nonlinear correspondence among dextrality, temperature and salinity have any link with the prevailing subtropical gyre in this region? This probably has complex dynamics and may lead to a nonlinear correspondence between coiling direction and ambient environment. In contrast, correlation coefficient between dextrality and ambient seawater properties (temperature and salinity) reveals a significant correlation through the N–S transect of Indian Ocean. The correlation coefficient between dextrality and sea surface temperature and salinity shows the R^2 value of 0.902269 and 0.811498 respectively (Figure 3 *a* and *b*). In conclusion, the data presented in the present study establishes the influential role of ambient hydrological conditions on the coiling directions of the planktic species *N. pachyderma*. These speculations can only be augmented with larger dataset covering a geographically distinct marine region. Furthermore, the inferences drawn through surface marine sediments provide the average information of several years; it is therefore recommended to study the influence of seasonal hydrographic variations on the morphological features of foraminiferal species, sediment trap at different geographically distinct locations be deployed along a N–S transect.

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Geo-archeology at Khajnawar in Western Uttar Pradesh plain

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Khajnawar village in Saharanpur district of western Utter Pradesh is inhabited over the remains of an ancient archaeological settlement. Field observations and archaeological investigation reveal two periods of settlement: settlement I with grey ware and iron objects and settlement II with painted red ware. Radiocarbon and optical stimulated luminescence (OSL) dating indicate 2600a–1400a age for settlement I and 850a–350a for settlement II. A hiatus of ~550a between the two settlements may have been caused either by an earthquake or climate change. A south-facing and NW–SE trending scarp on the southern end of the Khajnawar has been interpreted as a tectonic scarp that is a continuation of the Piedmont Fault with right-step. The scarp should have formed due to an earlier earthquake that may have caused the hiatus. Climate change can be another possibility for the hiatus, because periods of settlement and occupation seem to coincide with drier and wetter conditions recorded in the subcontinent. Collapsed and tilted walls with brick rubble and infilling by sands in the settlement II layers was probably caused by a later earthquake post-dating 350a (OSL age), suggesting that this most likely corresponds to the large $M_w > 7$ 1803 earthquake of Garhwal Himalaya.

Keywords: Active tectonics, grey and painted red ware, historical earthquake, Piedmont Fault.

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HIMALAYA is a seismically active orogenic belt that has suffered several large magnitude earthquakes $M_w > 7$ in the past. Of these, three earthquakes (viz. 1905 Kangra, 1934 Bihar and 1950 Assam) with magnitude $M_w > 7.8$ occurred within the last 105 years[1,2]. Unlike Himalaya, the Indo-Gangetic plains have no historical record of large earthquakes. However, records of some moderate earthquakes of magnitude ≥5 during 1720 (Delhi), 1956 (Bulandshehar) and 1966 (Moradabad)[3] are available. The Indo-Gangetic plains have also been impacted by the Himalayan earthquakes. The 1803 Garhwal Himalaya earthquake damaged structures in Delhi, and the 1999 Chamoli earthquake in Garhwal Himalaya produced cracks in buildings in Delhi. Palaeo-seismological studies in recent years have lead to discovery of surface rupture earthquakes, dating at AD ~1450 in northwest Himalaya[4] and AD ~1100 in central Nepal[5]. These earthquakes occurred along the Himalayan Frontal Thrust (HFT), which is a physiographic and tectonic boundary between the Himalayan front and the Indo-Gangetic plains, and a plane of active displacement[6]. Evidence of active deformation propagating further south of the Himalayan front to the Indo-Gangetic alluvial plains has also been presented[7].

In the piedmont zone (south of the Siwalik range front between the rivers Ganga and Yamuna), an active fault has been identified and designated as the Piedmont Fault (PF)[8]. Located ~15 km south of the HFT, the NW–SE trending PF has been interpreted as a footwall imbricate of the HFT. This uplifted the piedmont zone during its southward propagation. During the geomorphic surface mapping of PF and extending it to northwest towards the river Yamuna, we found an archaeological site towards the southern termination of the piedmont zone at Khajnawar (Figures 1 and 2). This site had collapsed dwelling