Wave forecasting and monitoring during very severe cyclone *Phailin* in the Bay of Bengal

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Wave fields, both measured and forecast during the very severe cyclone *Phailin*, are discussed in this communication. Waves having maximum height of 13.54 m were recorded at Gopalpur, the landfall point of the cyclone. The forecast and observed significant wave heights matched well at Gopalpur with correlation coefficient of 0.98, RMS error of 0.35 m and scatter index of 14%. Forecasts were also validated in the open ocean and found to be reliable (scatter index < 15%). The study also revealed the presence of Southern Ocean swells with a peak period of 20–22 sec hitting Gopalpur coast along with the cyclone-generated waves.

Keywords: Buoys, *Phailin*, tropical cyclone, swell, wave forecast.

PROVIDING accurate ocean state forecasts during tropical cyclones is challenging. However, it is also important to forewarn the users such as fishermen community, oil and shipping industry, ports and harbours, navy, coast guard and coastal communities on the possible hazardous conditions during such extreme weather events. The Earth System Science Organization (ESSO)–Indian National Centre for Ocean Information Services (ESSO–INCOIS), Hyderabad started the quantitative Ocean State Forecast (OSF) service in 2005 by issuing forecasts of vital ocean parameters like significant wave heights, remotely generated waves (swells) and ocean surface winds, seven days in advance and at three hourly intervals, with daily updates[1]. Prediction and evaluation of the wave features generated by the very severe cyclonic storm (VSCS) *Phailin* are attempted in the present study.

Phailin[2] was the only VSCS to hit the east coast of India during the last four years. The cyclone lasted for 6 days from 8 to 14 October 2013 and it made landfall on 12 October at 1700 UTC in Gopalpur, Odisha (Figure 1). During the Odisha super cyclone of 1999, no quantitative OSF system was in place for forewarning the coastal communities, but for *Phailin*, the warnings were issued five days in advance. This helped the maritime authorities and users to take maximum precautions well in advance and save lives and properties. *Phailin* also provided a unique opportunity to study instrumentally recorded extreme wave data and evaluate the forecast.

Monitoring of extreme wave fields and evaluation of its forecast (issued from ESSO–INCOIS) have been done using data from the directional wave rider buoy[3,4] (DWRB) network of ESSO–INCOIS, including off Gopalpur (19.28°N, 84.97°E at 12 m water depth), the landfall location of *Phailin*. Wave data obtained from deep-sea moored buoys BD08 (18.14°N, 89.67°E), BD11 (13.49°N, 83.98°E) and BD14 (7.03°N, 87.99°E) deployed by the ESSO–National Institute of Ocean Technology (ESSO–NIOT) have also been used for validating the forecast wave parameters (Figure 1).

The buoy measures horizontal (roll and pitch) and vertical (heave) acceleration using accelerometers and onboard compasses to give the directional displacement in

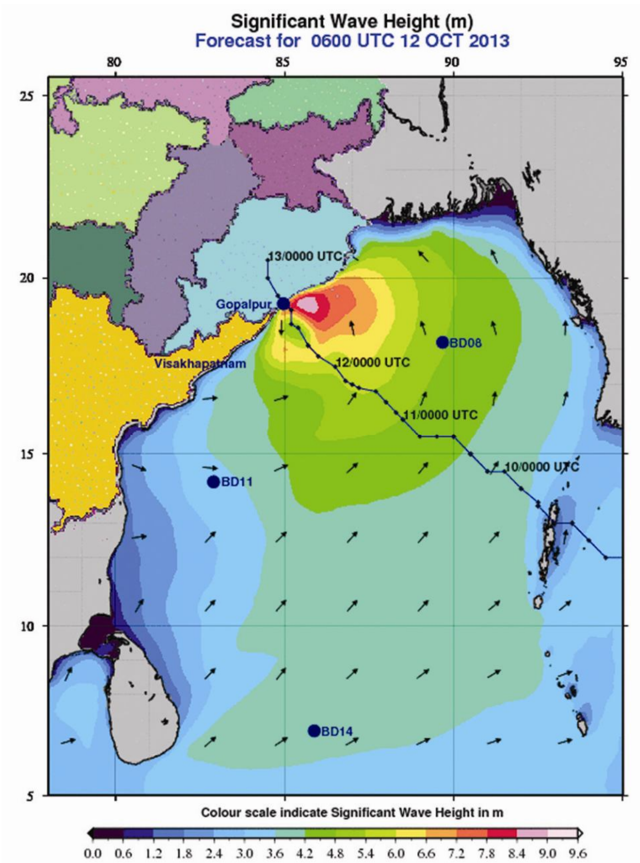

Figure 1. Snapshot of forecasted wave fields overlaid by *Phailin* track and location of buoys (Gopalpur (Odisha), BD08, BD11 and BD14) in the study area.

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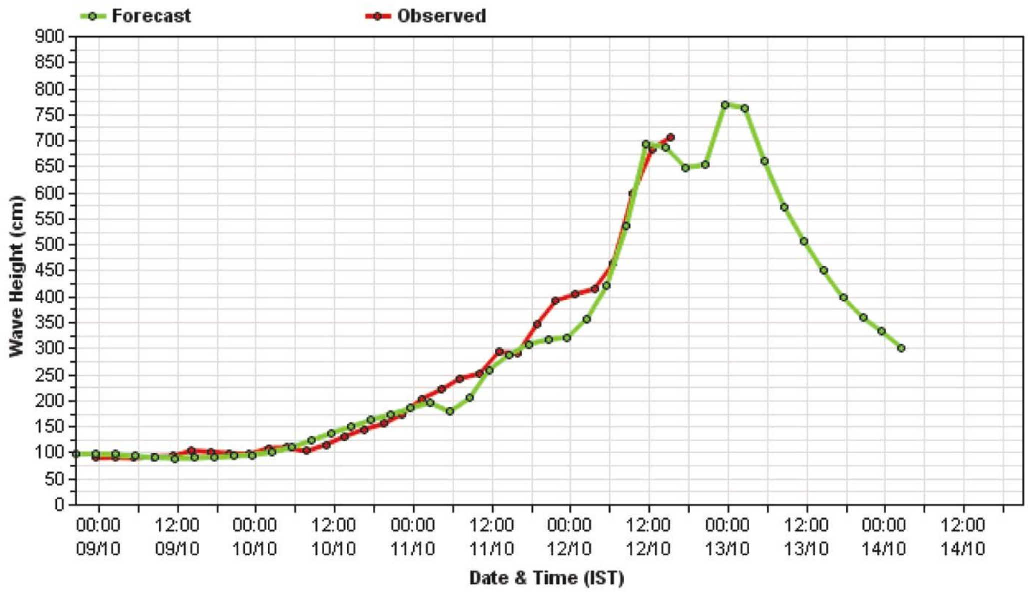

Figure 2. Real-time comparison between the forecast and observed significant wave heights at Gopalpur, during very severe cyclonic storm *Phailin*.

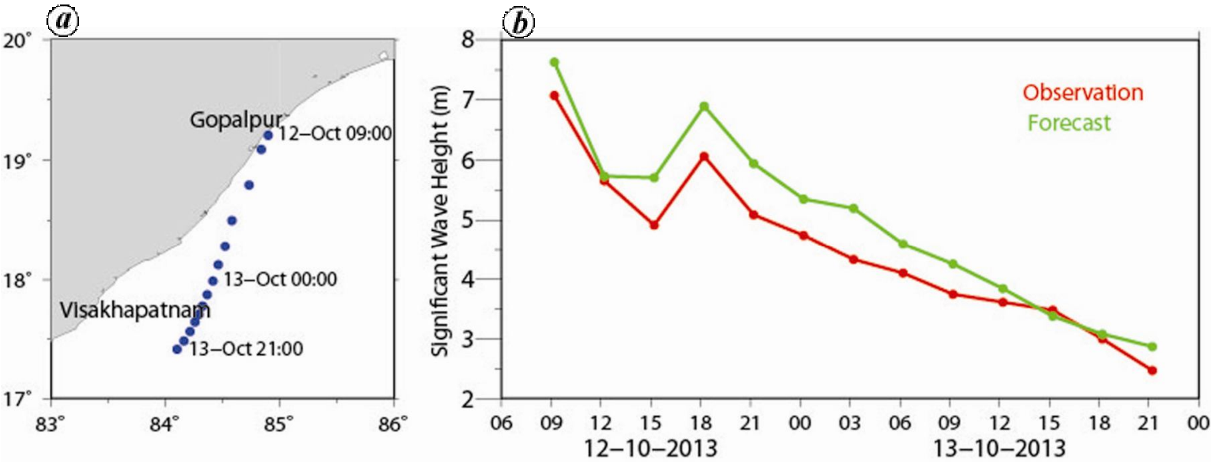

Figure 3. ***a***, Path traversed by directional wave rider buoy after detaching from mooring. ***b***, Along-track comparison of significant wave height forecast with observed data (time reported is in UTC).

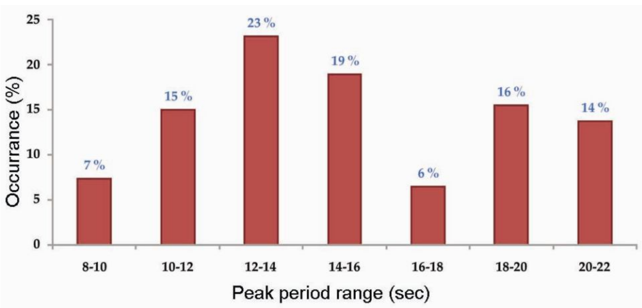

Figure 4. Percentage occurrence of waves in different peak period ranges during the cyclone period.

horizontal and vertical axes. The displacements are converted into two-dimensional wave energy spectra, which represent distribution of wave energies over different frequencies and directions. Integral wave parameters such as significant wave height (H_s), maximum wave height (H_{max}), peak wave period (T_p) and mean wave period (T_m) were derived from the wave spectrum. H_s is the average of one-third of the highest waves. H_{max} is the maximum wave height during a record. T_p (in seconds) is defined as the wave period associated with the most energetic waves in the total wave spectrum at a specific point. The data are received in real-time at INCOIS through the Indian National Satellite (INSAT) system. A state-of-the-art third-generation spectral wind–wave model (MIKE21 SW)[5,6], based on unstructured meshes, was used for forecasting the wave fields. The three-hourly forecast winds (0.25° × 0.25°) from European Centre for Medium-Range Weather Forecasts (ECMWF) was used for forcing the model. A varying resolution mesh ranging from 25 km × 25 km in the open ocean to 4 km × 4 km in the coastal areas was used for the present study.

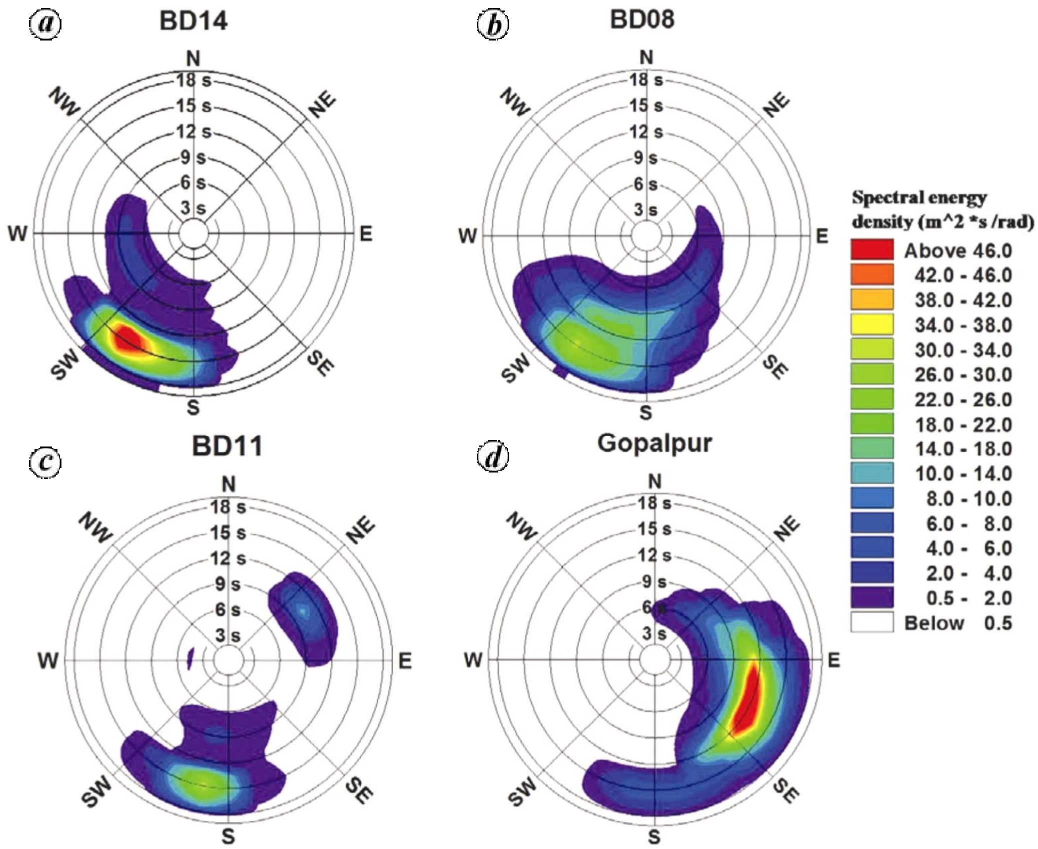

Figure 5. Model-derived two-dimensional wave energy spectra at (***a***) BD14 on 10 October 2013 at 1500 UTC, (***b***) BD08 on 11 October 2013 at 1800 UTC, (***c***) BD11 on 11 October 2013 at 1800 UTC and (***d***) Gopalpur on 12 October 2013 at 0600 UTC. The time steps are chosen in such a way that the southern swells and cyclone-generated waves are easily discernible.

Table 1. Comparison of forecast and observed wave parameters at Gopalpur on 12 October 2013 at 0900 UTC

Parameter	Observed	Forecast
H_s (m)	7.3	7.2
H_{max} (m)	13.5	13.6
T_p (s)	11.7	11.4
T_m (s)	8.6	7.8

The wave forecast (issued on 11 October 2013) indicated that high waves of 6.95 m would hit the Gopalpur coast by 0600 UTC on 12 October 2013, and the observed wave height was 6.84 m (Figure 2). Wave height forecast around 0900 UTC at Gopalpur was 7.31 m, while that observed was 7.20 m. The results reveal that the wave forecasts were highly accurate. Subsequently, the DWRB got drifted in the southwest direction from the deployed location due to high currents generated by the cyclone. Interestingly, even while drifting, the DWRB was continuously recording and transmitting wave data through INSAT. Figure 3 *a* shows the buoy's track during the drift and Figure 3 *b* shows comparison along the track. Table 1 shows excellent agreement of observed H_s, H_{max}, T_p and T_m with those forecast at Gopalpur, just before the drift of the buoy from the location. It is encouraging to note that the system could forecast H_{max} as high as 13.5 m to a good level of accuracy. The forecasts were compared with observations in real-time and published on-line in the ESSO–INCOIS website (http://www.incois.gov.in/wrbimage.jsp). The forecasts and alerts were issued in English as well as in regional languages and disseminated through various electronic media.

Figure 4 shows the frequency of occurrence of waves in different ranges of peak period at Gopalpur. This analysis manifests the presence of long-period swells (>12 sec) nearly 80% of the time during the cyclone period. It is intriguing to note that about 14% of the time, the longer period waves in the range 20–22 sec are observed to be reaching the Gopalpur location from the southerly direction. To confirm this, 2D wave spectra extracted from the numerical model at the selected buoy locations were analysed (Figure 5). The results show the presence of long-period Southern Ocean swells in all the buoy locations along with the cyclone-generated waves. Moreover, a decrease in the wave energy of this swell system could be seen as it propagated more towards

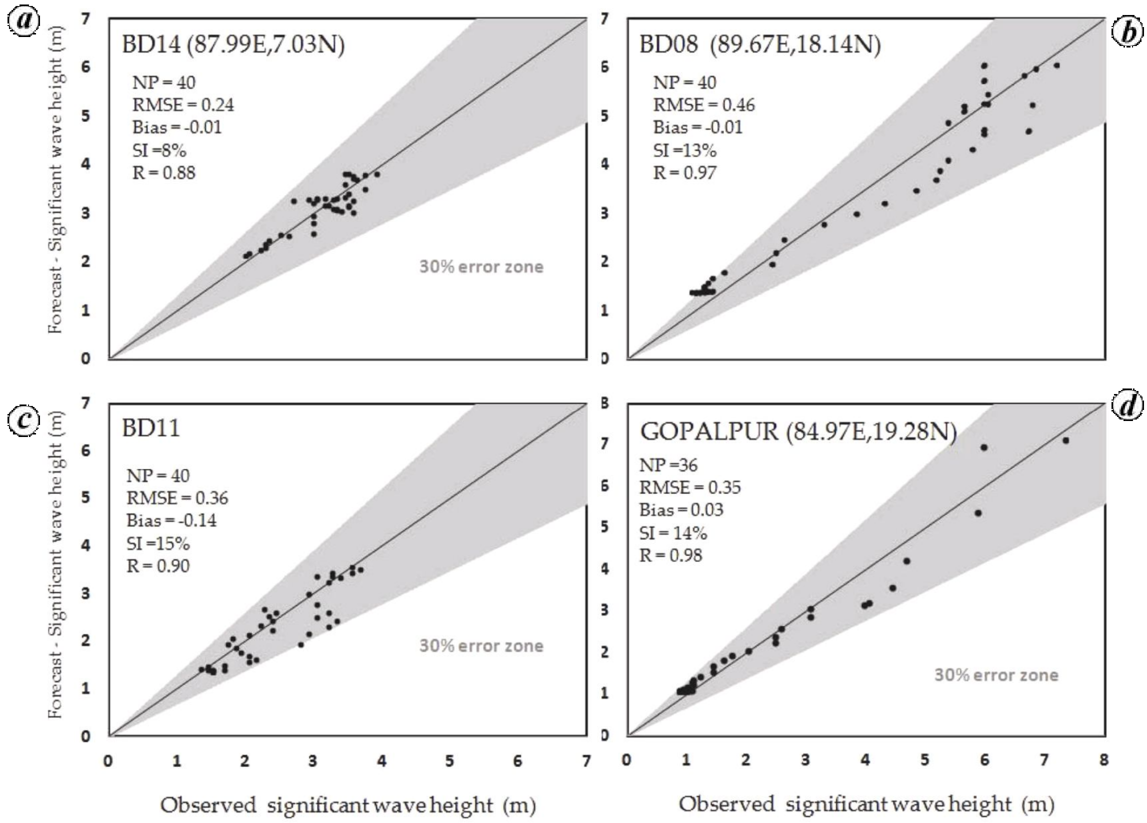

Figure 6 *a–d*. Comparison of observed and forecast H_s for the selected buoys. Shadows indicate 30% error zone, the acceptable error limit for operational wave forecasting. NP, Number of points.

north, i.e. from BD14 to Gopalpur buoy location. Careful examination of synoptic maps of the wave fields was carried out to back-track this swell system and this clearly showed that these swells were generated in the southern ocean around 50°S, 44°E as a result of a storm in that area. The significant impact of Southern Ocean swells on the north Indian Ocean wave characteristics is well known from the past studies[7]. In short, the waves observed off Gopalpur were a combination of waves generated by cyclone *Phailin* as well as the swells propagating from the Southern Ocean (Figure 5 *d*).

Further assessment of the accuracy of the wave forecast was done by computing the model error statistics[1] in terms of bias, root mean square error (RMSE), scatter index (SI) and correlation coefficient (R) at buoy locations (BD14, BD08, BD11 and Gopalpur) for the period 8–12 October (Figure 6). H_s is the most commonly used wave parameter in almost all the marine applications. Hence, we have focused mainly on this parameter for further discussions.

Figure 6 *a* shows the scatter plot of forecast H_s with observations at BD14. The low scatter index of 8% and no remarkable bias indicate the high quality of our forecast. High waves were seen at this location during 8–12 October 2013. The highest observed wave height was 3.93 m at 1500 UTC on 10 October, which was due to the Southern Ocean swells as is clearly seen from the two-dimensional wave spectrum (Figure 5 *a*). During this time, the eye of the cyclone was at 89.84°E, 15.55°N and the forecast wave height was 3.8 m. Cyclone-generated waves did not produce any impact at this location, probably because it was far south off the cyclone track.

Figure 6 *b* and *c* shows the scatter plot of forecast wave heights with observations at BD08 and BD11 respectively. BD08 lies on the right side of the cyclone tracks whereas BD11 lies on the left side. The very high correlation of 0.97, negligible bias and low SI of 13% are indicators of good forecast at BD08. As the cyclone moved in the northwest direction, the wave height started to increase at BD08 location, the highest observed H_s value was 6.27 m at 1200 UTC on 11 October. Southern Ocean swells as well as cyclone-generated waves contributed towards this, as evident from Figure 5 *b*. The Southern Ocean swells and the cyclone-generated waves approached the location from the south-southwest direction owing to the buoy location being on the right side of the track. The wave height at the location thereafter decreased monotonically as the cyclone moved further northwestwards towards the east coast. Correlation coefficient as high as 0.90 and SI of 15% at BD11 show that the model could forecast the waves to a high degree of accuracy. As in the case of BD14, wave height started increasing from 8 October onwards due to the impact of Southern Ocean swells. The cyclone-generated swells started reaching this location from the northeast direction as expected, from 11 October at 03:00 UTC onwards. This is clear from Figure 5 *c*. The location of the eye of the cyclone at this time was 11.85°N, 88.56°E (nearly 530 km away from BD14). Later, the wave height reached a maximum of 3.96 m on 12 October at 0900 UTC, when the cyclone reached near Gopalpur, due to the combined effect of Southern Ocean swells and cyclone-generated swells. As expected, the wave heights at BD08 were much higher than at BD11, as it was on the right side of the cyclone track.

Figure 6 *d* shows a comparison of measured and forecast wave heights at the Gopalpur location. Error in the forecast wave height at this location was only 14%, which reveals the reliability of the wave forecast system at ESSO–INCOIS. A high degree of correlation of 0.98 between the measured and forecast H_s was obtained at this location. The bias was negligible at this near-shore location, similar to the deep-sea buoys.

In conclusion, the evaluation once again proves that the OSF system at ESSO–INCOIS is fully poised to warn the coastal communities and offshore industries along the entire Indian coastline well in advance. The present study also suggests that the presence of Southern Ocean swells during cyclone events may enhance the complexity of the wave fields.

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Occurrence of native gold and gold–silver alloy in the olivine gabbro of layered cumulate sequence of Naga Hills ophiolite, India

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Occurrence of native gold and gold–silver alloy formed in high-temperature olivine gabbro of a layered cumulate body is reported 2 km northwest of Sutsu. It lies close to a major fault in the central part of Late Cretaceous–Eocene Naga Hills ophiolite (NHO). The amphibole-bearing olivine gabbro is composed of serpentine (MgO-28.91), anorthite (An_{93}), clinopyroxene ($En_{46}Fs_8Wo_{46}$), edenite (Mg# 76), magnesiohornblende (Mg# 78), accessory minerals, viz., chlorite (Mg# 75), epidote, sulphides (chalcopyrite and millerite) and gold. The formation of noble metals in olivine gabbro is related to partitioning of Au into intercumulus sulphides and silicates in magma and their deposition along grain boundaries and fractures. It was carried out by hydrothermal fluids by transportation and concentration of immiscible sulphide phases, and depositing these in suitable locales during final stages of crystallization. Gold mineralization in layered gabbros of cumulate bodies opens a new avenue towards primary source of precious metals in NHO. Alternative secondary source of precious metals in NHO, e.g. (i) basal conglomerate of cover sediments derived from ophiolite (Jopi or Pokhphur Formation), and (ii) placers of arterial Tizu River in Nagaland, may be considered as favourable repository.

Keywords: Anorthite, gold–silver alloy, layered olivine gabbro, ophiolite, native gold.

LATE Cretaceous mafic and ultramafic rocks are known to occur as dismembered ophiolite bodies of varied dimensions along the Trans-Himalayan and the Indo-Myanmar Ranges (IMR). They demarcate the northwestern, northern and eastern margins of the Indian plate[1], along which the Indian plate is subducting under the Eurasian plate since Late Cretaceous[2]. These mafic–ultramafic rocks once constituted a part of the ocean floor of Tethyan Sea (Upper Jurassic)[3,4], and were preserved as accretionary wedge or prism on continental margin. Exhumation of such ancient oceanic crust at the eastern Indian plate margin along the hill ranges of Nagaland and Manipur, bordering Myanmar is known as the Naga Hills ophiolite (NHO)[1]. The northern and southern edges of the ophiolite belt extend into Myanmar. The NHO is characterized by the presence of ophiolitic melange, olistostrome,

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