CHAPTER 6

PALEOCURRENT ANALYSIS

Potter and Pettijohn (1963, p. 226 & 228) have said that the knowledge of the current system is essential in understanding distribution, orientation and make-up of the sedimentary bodies which constitute the basin fill. They have further stated that 'there is a close relationship between the arrangement of major sedimentation elements in a basin and directional structures in as much as both are a product of a common dispersal pattern'. Pettijohn (1962, p.1468-69) has also emphasized the importance of paleocurrent studies in understanding the sedimentary basin as a whole.

The paleocurrent data collected from the various formations has been classified according to the four stratigraphic units. A total of about 1,260 paleocurrent readings were taken covering the entire Wagad area. Observations were made in sets of 2 to 9 readings with an average of 4 to 5 readings per set, each set pertaining to a small stratigraphic interval usually representing a good single outcrop. The author has utilised the paleocurrent data to determine patterns of current flow, sediment transport, and to develop paleogeographic and environmental ideas regarding the basin. In this chapter, the author has given the distinctive characters and description of the various paleocurrent features, and their variations. The interpretation aspects of the study have been included in another chapter (Part IV, Chapter 10).

The sedimentary structures studied include cross-bedding both small scale and medium scale, symmetrical and asymmetrical ripple marks, sole marks, flute clasts, scour and fill structures, erosional trucations and load casts etc. Quantitative and statistical work was, however, carried out only for cross-bedding and ripple marks. Table 6.1 shows total number of readings etc. taken for

TABLE 6.1

Number of paleocurrent observations taken (structurewise)

	Cross bedding	Ripple Marks	Sole Marks	Flute Casts
Number of readings	893	349	18	10
Number of sets of readings	204	82	5	3
Average reading per set	4.5	4.4	3.5	3.3

TABLE 6.2

Number of paleocurrent directions (sets of readings) obtained from sedimentary structures in various formations of Wagad hills

Formation	Cross bedding	Ripple Marks	Sole Marks	Flute Casts
Gamdau	40	20	1	2
Upper Kanthkot	33	15	3	1
Lower Kanthkot	109	27	1	-
Washtawa	22	20	-	-

different structures, and Table 6.2 shows the formation-wise distribution of sets of readings.

NATURE AND DISTRIBUTION OF SEDIMENTARY STRUCTURES

Following is a brief description of the important structures studied and their distribution in the area.

Cross-Bedding

Cross bedding is by far the commonest of all the sedimentary structures developed in the area. This structure is fairly well distributed vertically as well as laterally within the various formations, and commonly shows both tabular and trough patterns (Potter and Pettijohn, 1963, p.69, fig. 4-1). Good development of cross-bedding is usually seen within thickly bedded or massive and friable sandstones.

The core of the Washtawa dome which exposes the sandstones of the Kharol Member, shows good cross-bedding of tabular type. Outcrops of cross-bedded sandstones are also encountered along the southern limb of Dedarwa dome, within the Chitrod sandstone Member of the Washtawa Formation. The Fort Sandstone Member of the Kanthkot Formation shows the most prolific development of cross bedding.

PLATE 13

Tabular cross bedding in sandstones of the Washtawa Formation. Locality: Southern flank of Dedarwa anticline.

PLATE 14

Cross bedding both small and medium scale in Lower Kanthkot Sandstones. Locality: about 1/2 mile N of Kidianagar.

PLATE 15

Trough cross bedding in Fort Sandstone Member. Locality: Bhuj-Rapar road, about 1.5 miles N of Khirai.

Accessible outcrops showing good structures comprise the Fort Hill proper, the Ramwao cliff (S of Ramwao village), the core of the Adhoi anticline, the Chitrod cliff, the Bhuj-Rapar road cuttings near village Khirai, cliff sections around Bhutakia and Bhimasar and the nala section N of Kidianagar. Though both tabular and trough patterns are common, it observed that trough type is more predominant in the eastern half of the area.

Cross-bedding is also seen within the Adhoi Member but it is not as abundant as in the Fort Sandstone Member. A few good outcrops of the sandstones of the Adhoi Member showing cross-bedding can be cited as the northern flank of the Adhoi anticline, the Bharodia nala, the core of the Kakarwa anticline, the Mae and the Wamka domes. Within the Gamdau Formation, the best cross-bedding outcrops are those towards the NW of the village Mae and Halrae, as well as, to the N of Wamka dome and around Torania village within the Gamdau syncline.

Table 6.3 shows the formationwise distribution of cross bedding azimuths.

Ripple Marks

Though not as common as cross bedding, ripple marks too are found in all formations. Both symmetrical and asymmetrical types are seen. They are usually confined to the flaggy sandstone units of the different formations.

In the Washtawa Formation, a few outcrops showing good ripple marks are seen on the southern flank of the Washtawa dome and within the Chitrod dome. The ripple marks here are mostly symmetrical in nature.

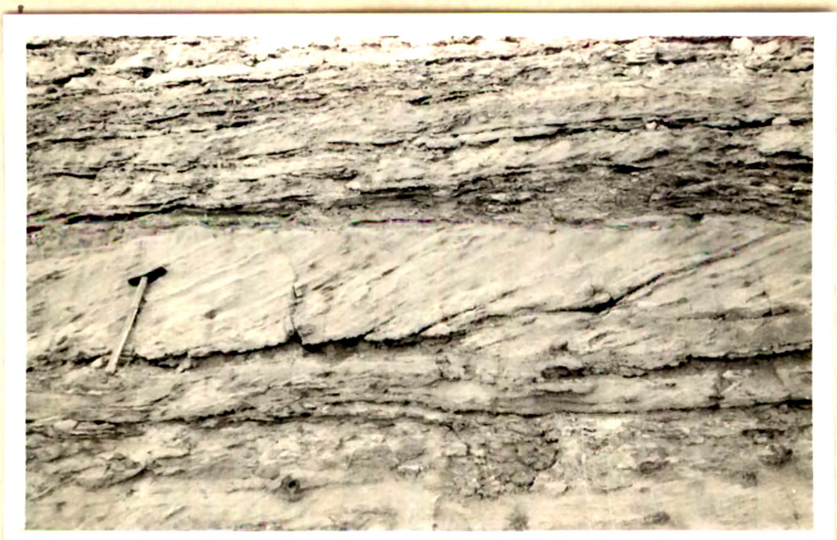
The Lower Kanthkot Formation exposes good outcrops of ripple marks within the Adhoi anticline, N of the Kanthkot Fort and near Dabunda village. The outcrops near Dabunda shows giant size ripple marks with wave lengths varying from 2' to 3' and amplitudes of about 3"-4". A few good and easily accessible outcrops of ripple marks in the Upper Kanthkot Formation include those within the Kakarwa anticline and the Mae dome, and those a little S of the village Bharodia.

Ripple marks are also quite common in the Gamdau Formation. The best locations showing this structure in the Gamdau rocks are N of Wamka dome, SE of Torania,

PLATE 16

Sporadic development of tabular cross bedding in Fort sandstone. Locality: Fort hill.

PLATE 17



Small and medium scale tabular cross bedding in sandstone of Adhoi Member. Locality: Adhoi anticline.

PLATE 18

Asymmetrical ripple marks in Fort sandstone. Locality: Southern flank of the Washtawa dome.

PLATE 19

Asymmetrical ripple marks in Fort sandstone. Locality: Fort hill.

PLATE 20

Large size, asymmetrical ripple marks in Fort sandstone. Locality: northern flank of Dedarwa anticline.

PLATE 21

Large size symmetrical ripple marks in Fort sandstone. Locality: northern flank of Dabunda dome.

PLATE 22

Cuspate ripple marks in sandstone of the Gamdau Formation. Locality: about 1 mile N of Wamka dome.

and around Mae dome. The area N of Wamka dome shows a good development of transverse ripple marks and ripple drift structures, while those SE of Torania are of giant size with crests measuring 2' to 3' apart.

Sole Marks

As most of the strata of the Wagad hills are horizontal to gently dipping, sole marks are not very easily recorded and this structure has been encountered only in a few localities within the Kanthkot and the Gamdau Formations, where the strata shows high dips.

The steeply dipping beds of the southern flank of the Adhoi dome near the South Wagad fault exhibit good outcrops of the sole marks within the Upper Kanthkot Formation. One such outcrop lies just S of village Adhoi. Here the sole marks are seen as long linear markings over hard calcareous, flaggy sandstones.

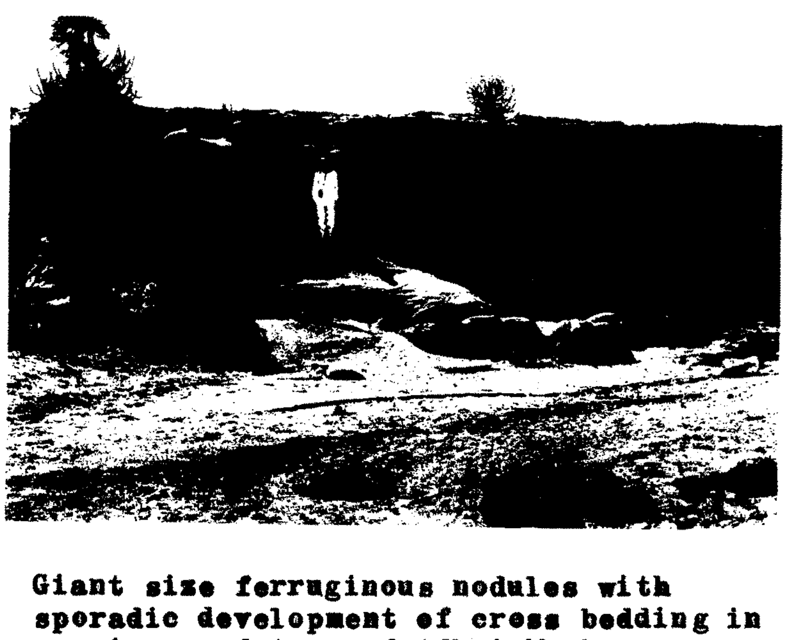
Flute Casts

Flute casts are not very common and only occasionally met with. The author came across a few occurrences within the Gamdau Formation. One good outcrop of flute casts is noted just N of the Kakarwa anticline. The casts are about 5" to 6" in length and indicate a westerly current direction.

PLATE 23

Slightly asymmetrical ripple marks in sandstone of the Gamdau Formation. Locality: about 1/2 mile N of Wamka dome.

PLATE 24



Giant size ferruginous nodules with sporadic development of cross bedding in massive sandstone of Adhoi Member. Locality: about 1/2 mile S of Bharodia.

Scour and Fill Structures

The author has recorded several 'scour and fill' structures in the eastern part of the area in the Lower Kanthkot Formation around Tindalwa, Pragpur, and Bhutakia. The structures show scouring action on basal sandstone, followed by deposition of younger sandstone unit over it. Scour and fill structure is also noted at a few places within the Gamdau Formation N of Halrae and Wamka. In the other formations this structure is not seen.

Erosional Truncations

Erosional truncations are also confined in the eastern parts of the Lower Kanthkot Formation. These indicate local unconformities. Good outcrops showing this structure are seen in the area around Bhimasar-Bhutakia within the Lower Kanthkot Formation.

Load Casts

A few examples of load casts were recorded in a nala just N of Kidianagar in a cross-bedded, fine grained, light grey sandstones of the Lower Kanthkot Formation.

DATA COLLECTION

The general methodology of sampling and their processing followed is that as suggested by Potter

PLATE 25

**Scour and fill structure in Fort sandstone.
Locality: Rapar-Kidianagar road, about
2 miles S of Pragpur, Eastern Wagad.**

and Pettijohn (1963, p. 252-277).

Though the various sedimentary structures exposed in the area were carefully studied, the statistical work was done only for cross-bedding and ripple marks.

Sample Distribution

For the purpose of data collection, the area was divided into different arbitrary grids of 2 x 2 miles dimensions. Within every grid, three to four outcrops depending on the availability, were studied and paleocurrent readings at each outcrop were recorded. The observations, as far as possible, were equally distributed within the grids. Since all over the Wagad area, the structural dips are quite low, this scheme afforded good coverage to the entire stratigraphy. However, the actual amount of data collected and the selection of their locations was influenced by the frequency of the development of cross-bedding and ripple marks and the availability of good outcrops. These facts have led to certain deviations from the scheme.

Besides a few vertical sections, representative of the various formations and showing good cross-bedding developments were studied with a view to know the vertical variations of the paleocurrent data.

Spot Measurements

(i) Cross Bedding: The attitude (dip, strike and dip direction) of a foreset laminae of cross bedding was worked out from its trace on different planes, since it is quite rarely that the entire foreset lamination is exposed. For the measurement of true azimuth and dip of the foreset laminae, dip and azimuth of the trace of foreset laminae on at least two or three different planes along with attitudes of planes of measurements were recorded, and from these readings the true attitudes of foreset laminae was calculated. Azimuth measurements in case of trough cross-bedding is quite difficult due to the shape of the foreset. The possibility of azimuth measurement being not parallel to the plunge direction of the trough is quite high. However, wherever the outcrop conditions permitted, direct measurement of the true foreset dip and its azimuth in case of tabular cross-bedding and plunge direction in case of trough patterns of cross-bedding were recorded.

Besides these, thickness of every cross-bedded unit as well as the attitude of the parent beds were also recorded.

(2) Ripple Marks: Measurements of the strike of the symmetrical ripple marks and the strike as well as the direction of the steeper side of the asymmetrical ripple marks were made. Besides, the wave lengths and the amplitudes of the ripple marks were also recorded.

For both, cross bedding and ripple marks, about 2 to 9 observations were recorded at each outcrop studied with an average of 4 to 5 readings (Table 6.1).

Since the structural dips of the strata are quite low, usually below 10° wherever the paleocurrent observations were made, none of the data warranted any tilt correction.

DATA PROCESSING

All the data obtained was processed on high speed IBM 1401 computer and for every outcrop i.e. for each set of azimuthal readings, vector mean, vector magnitude of resultant vector in terms of both length and percentage as well as variance and standard deviation was calculated. The following formulae as suggested by Potter and Pettijohn (1963, p.252-277) were utilised in calculating these factors:

(1) <u>Vector Mean</u>:

$$\bar{x} = \text{arc tan } \frac{W}{V}$$

where $$W = \sum_{i=1}^{n} n_i \sin x_i$$

$$V = \sum_{i=1}^{n} n_i \cos x_i$$

x_i = the mid point azimuth of the ith class interval

n_i = number of observations in each class

n = total number of observations

$\bar{x}$ = azimuth of resultant vector.

(2) <u>Vector magnitude in terms of length:</u>

$$R = (V^2 + W^2)^{\frac{1}{2}}$$

(3) <u>Vector magnitude in terms of percent</u>:

$$L = (R/n) \, 100$$

(4) <u>Sample variance</u>:

$$S_x^2 = \sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{(n-1)}$$

Where S_x^2 = sample variance.

$\bar{x}$ = vector mean

x_i = individual azimuth

n = number of observations.

(5) <u>Standard Deviation</u>:

$$S_{\bar{x}_n} = \frac{S_x}{\sqrt{n}}$$

The vector means as computed above for each set of readings were treated as data level for the directional part of the study, as Barrett (1970, p.398) has rightly pointed out that they are the best estimate of the current direction during the deposition of the sampled interval at that locality.

Besides, as stated by Barrett (Ibid, p.398), though the mean of each set is computed vectorially, the standard deviation is computed about the vector mean as if the data are linear.

RELIABILITY OF STRUCTURES

The study of the standard deviations and variances reflects the reliability of different structures as direction indicators, Barrett (1970, p. 399-400) has tabulated different sedimentary structures according to their reliability as direction indicators based on the median values of standard deviations.

The standard deviations for all the four stratigraphic intervals (i.e. the Washtawa Formation, the Lower and Upper Kanthkot Formations and the Gamdau Formation) are shown in the form of histograms for both cross bedding and ripple marks (Figs. 6.1 and 6.2). It is seen that the majority of standard deviations for all the formations for ripple marks is quite low as compared to that for the cross bedding, and thus obviously the ripple marks appear to be more reliable paleocurrent indicators as compared to the cross bedding. Barrett (1970, p.400) has also arrived at similar conclusion regarding the paleocurrent data of Permian and Triassic Beacon rocks of Antarctica. A major percentage of standard deviations for the cross beddings in different formations also show low values between 30 and 60.

Some of the observations which show more than 90° of standard deviations were rejected. Also the observations showing high variances i.e. more than 12000 and which contained only a few readings were also not considered.

PREPARATION OF PALEOCURRENT MAPS

Potter and Pettijohn (1963, p.272) have emphasized the desirability of presenting the actual data at several levels of factual generalisation as well as in the form of a completely interpretative map. Accordingly, the paleocurrent maps representing the Washtawa, the Lower and the Upper Kanthkot as well as the Gamdau Formations have been prepared. These maps show the observed pattern of current direction at individual outcrops. At each outcrop the vector mean for the particular structure has been plotted.

The cross bedding observations have been displayed by showing arrows. The tips of these arrows represent the actual location of the outcrops. The length of the arrow is a measure of the vector magnitude in terms of percent.

Besides, the paleocurrent maps prepared have been divided into different sub-areas according to the number of observations and the exposed area of particular formation. For each sub-area, a percentage current rose diagram has been prepared. This has been constructed by grouping the total number of cross-bedding azimuthal data into 12 class intervals viz. 0-30, 31-60, 61-90, 91-120, 121-150, 151-180, 181-210, 211-240, 241-270, 271-300, 301-330 and 331-360, and the percentages of azimuths falling in each class have been calculated. On azimuthal population in each class have been prepared, for cross beddings.

Table 6.3 shows the total number of cross bedding arimuths falling in each class for the different formations.

The strike of the symmetrical ripple marks has been shown by a line parallel to the strike with a solid circle representing the actual location of the outcrop. In case of the asymmetrical ripple marks along with the strike directions, the steeper side of the crest have been shown by an arrow indicating the current direction.

Observations of both the structures viz., the cross-bedding and ripple marks have been shown together on the maps.

VERTICAL VARIABILITY OF STRUCTURES

A study of the vertical variability of the structures was undertaken to examine the variability of paleocurrent directions in time.

With a view to study the vertical variability of the sedimentary structures several sections of all the formations were examined.

Though the cross bedding development through a vertical column at several locations was found to be fairly good, ripple marks did not show any such consistent development. However, it was observed that within all the formations ripple mark development has taken place only in a few closely spaced stratigraphic horizons, and as such the majority of the ripple mark data presented on the maps represent only a small stratigraphic interval of the respective formation.

Figure 6.3 shows the vertical variations in cross bedding for the Washtawa, the Lower Kanthkot and the Gamdau Formations. It is seen that the cross bedding azimuths do not appreciably vary for the Washtawa Formation. They mainly show WSW and WNW current directions. The total variation for a section of 250' is about 160°.

Similarly the Lower Kanthkot Formation rocks of the Fort Hill show variations of the current directions between W and S, however, a few northeasterly azimuths are also noted in the upper part. The cross bedding directions of the Lower Kanthkot Formation exposed at the Lilpur Hill predominantly show variations from NW to SSW.

The Gamdau hill section of the Gamdau Formation, shows variations from SW to WNW, in the cross bedding directions.

It is thus seen that the paleocurrent system of the Wagad Hills, though represents varying energy and physical environments through time, shows consistency in regional directions. Wilson, Watson, and Sutton (1953, cf. Pettijohn, 1962, p.1481) have observed cross bedding in a 12,000 foot sequence in Moine Series of Great Britain which displays uniformity of orientation throughout the course of their deposition. Pettijohn (1957, cf. Pettijohn, 1962, p.1481) also found no significant variation in cross bedding orientation in the 7000' thick Lorrain Quartzite Formation of Lake Superior region.

REGIONAL VARIATION IN PALEOCURRENT DIRECTION

The Washtawa Formation

The Figure 6.5 shows the paleocurrent directions observed in the Washtawa Formation. The cross bedding directions for this formation at the Dabunda and the Narada domes are seen to be due SW and W. The same in the Dedarwa-Mewasa area in the south eastern part are bimodal with NE and SW azimuths. In the Chitrod dome the direction shows a southerly swing, while in the Nara and Washtawa domes in the south central part of the area, the cross beddings show predominantly south westerly azimuths with a few readings towards W and SE.

The thickness of the cross bedded sets do not show much variation within the Washtawa outcrops (Fig.6.4). Both the Dabunda and the Narada dome shew the thickness variations of the cross bedded sets from 1' to 2' while the same is measured about 1' to 1½' in the Washtawa-Mewasa area in the south central and south eastern parts.

Rose diagrams which represent cross bedding population show a trimodal pattern for the western half while the same for the eastern half show a bimodal pattern with the modes roughly 180° apart.

The ripple marks are mostly of transverse oscillation type with a few current types. The average wave length measured within the Washtawa dome is about 6" to 9" with an amplitude of about 1". The strike of the ripple marks within the Dabunda and Narada dome is roughly N-S. In the Dedarwa-Mewasa-Chitrod area it is seen to be either NNW-SSE or NNE-SSW, while the same in the Washtawa dome is predominantly NE-SW. In the Sarasla area in the W, a few readings taken show E-W trend. The ripple marks are mostly of symmetrical to slightly asymmetrical type. The current direction is interpreted to be either in the direction of the steeper slopes of the crests or perpendicular to the strike directions nearer to the cross bedding azimuths (in case of symmetrical ones). The resolved current directions are roughly towards W, NW and SW, which are in conformity with those revealed by the cross bedding data.

The Lower Kanthkot Formation

Figure 6.6 which represents the paleocurrent map for the Lower Kanthkot Formation, shows strong preferred orientation of cross beddings towards SW and SSW directions in the eastern and the northern parts of the area, between Rapar, Sai and Bhimasar. Both trough and tabular patterns of cross beddings are extensively developed in this part. However, it appears that the trough pattern predominates over the tabular one. In the SE, around Kidianagar-Mewasa the cross stratifications show westerly and west north westerly azimuths. However, around Khirai-Chitrod-Badargadh in the south central part of the area, it is predominantly westerly and south westerly. In the north central part around Tramau-Ramwao the cross bedding orientations are towards SW and SSE, while the same is towards SSW in the Kanthkot area of western Wagad. The Adhoi anticline in the south western part displays bimodal pattern of cross bedding with SSW and NNE current directions.

The rose diagrams represent the four sectors of the map viz., NE, SE, NW and SW. The north eastern part shows a strong unimodal current pattern while the south eastern part shows three modes with a prominent west north westerly mode. The north western area also depicts three modes with a southerly grand mean while the south western part shows a bimodal nature with modes roughly in NE and SW directions and opposite to each other. As such, regionally the entire area represents SSW and SW current patterns and the grand mean being towards S39°W.

Variations in the thicknesses of cross bedded sets show an interesting pattern (Fig. 6.4). It is generally seen that the eastern parts of the area show thicker cross bedded sets, the thicknesses varying between 1½' to 2½'. In the western and south western parts around Kanthkot and Adhoi, the average thickness values are about 1/2' to 1'. Thus it can be broadly generalized that the thicknesses of the cross bedded sets have decreased along the paleocurrent directions.

The ripple marks occurring in the E around Rapar-Dabunda-Bhimasar area are usually of transverse current type and broadly show a N-S strike with steeper parts of their crests dipping towards W. In the Chitrod

Mewasa area, ripple marks display E-W to NW-SE strikes, while in the western Kanthkot area the predominant strike is E-W. In the south western Adhoi-Wamka area the orientations of the ripple mark strike vary between WNW-ESE to WSW-ENE directions. In the Kanthkot area the ripple marks are mostly of oscillation type. But for a few anomalous ripple mark observations, in this area, in most cases they show good regional conformity with cross bedding data.

The Upper Kanthkot Formation

The paleocurrent pattern map for the Upper Kanthkot Formation which mainly occurs in the western half of the area is shown in the Fig. 6.7.

In the northern part around Bharodia, Jaseda-Ramwao, the cross beddings consistently show south westerly azimuths. The area between Bharodia-Kakarwa as well as the south western area between Mae and Adhoi shows two directions of cross beddings, NE and SW. This bimodal nature of currents is quite prominent in this area. The tabular patterns of cross bedding is more predominant.

The thicknesses of the cross bedded sets do not show much variations areally. It is observed that thicknesses in the Bharodia-Jaseda area in the N are about 1' to 2' while in the western and southern areas around Kakarwa-Wamka-Adhoi it varies between 3" to 1'. On an average the cross bedded sets show about 9" of thickness in the Adhoi area.

The two rose diagrams which represent the total cross bedding observations for the northern and the southern parts of the Upper Kanthkot Formation show bimodal pattern of current system with roughly NNE and SSW modes.

The ripple marks of the Upper Kanthkot Formation are mostly of oscillation type. The predominant strike is NW-SE. At a few locations, E-W and NE-SW strikes are also noted especially around Adhoi and Kakarwa. The average wave length is about 4" to 6" with amplitudes of about 1" to 1½".

In this formation too the resolved current directions perpendicular to the ripple marks strikes show a conformity with the cross bedding azimuths.

The Gamdau Formation

Both trough and tabular types of cross bedding are common in the Gamdau Formation. Figure 6.8 represents the paleocurrent direction map.

In the southern parts of the area around Torania-Gamdau, the rocks of this formation occur as an elongated syncline with WNW-ESE axis. A most striking feature of the cross beddings is that their orientation shows some genetic relationship with the synclinal structure. The cross bedding azimuths in this area show either NW or SW orientations towards the synclinal axis, while in the farthest eastern parts of the syncline NE of Adhoi, the cross bedding show WNW azimuths, parallel to the axis. Significance of this relationship is discussed in the Chapter 10.

In the western parts around Mae-Manfara, the azimuths display westerly, northwesterly and northerly orientations.

The rose diagram for cross bedding for the entire area, shows a unidirectional current pattern with a grand mean towards N56°W.

The thicknesses of the cross bedded sets vary from 1/2' to 3' with majority between 1' to 1½' (Fig.6.4).

The ripple marks show both current and oscillation patterns though current types are more common. In the Gamdau syncline area, their strikes show strong preferential orientation towards NE-SW directions with the steeper sides of their crests pointing towards NW. In the western Mae-Manfara area, the N-S as well as NNW-SSE strike directions are noted.

Though the average wave length of the ripple marks varies between 3" to 6", at a few places e.g. SE of village Torania, giant size ripple marks showing 2' to 3' of wave lengths are also recorded.