Chapter III

PALEOFLOW ANALYSIS

Paleocurrent studies have received a great deal of attention by sedimentologists during the last three decades or so because of their increasing importance in basin analysis. Reconstruction of river morphology and their hydrodynamics in ancient deposits has also been engaging the attention of sedimentologists in recent years for a fuller understanding of depositional systems.

The art of paleocurrent analysis was invented by the quietessential nineteenth-century English amateur, Henry Clifton Sorby, who published his first paper on the subject in 1852. Rubey and Bass (1925, p.3) got the first credit to have actually plotted crossbedding measurements on a map. McKee (1940), Potter and Olson (1954), Olson and Potter (1954), Tanner (1955), Pettijohn (1957) and his students (Pelletier, 1958; McBride, 1962), Hamblin (1958), Wurster (1958) and others are among the pioneer workers of the paleocurrent study. In recent years Potter and Pettijohn (1963, 1974), Smith (1972), Picard and High (1973), McKee (1966), Bigarella (1970, 1971), Klein (1970) and Miall (1976, 1984, p.256) have given detailed and (or) critical accounts of this method. In India, paleocurrent studies have been undertaken in considerable details during the past decade particularly on the Late Paleozoic Lower Gondwana sequence.

However, the Mesozoic Gondwana rocks of Saurashtra have not been adequately studied so far. Preliminary work by Bhandari and Kumar (1970), based on sporadic measurements, yielded local paleocurrent directions of the Dhrangadhra Sandstone towards southwest. Casshyap et al., 1983, reported a generalised paleodrainage of Mesozoic rocks of Gujarat. It was, therefore, most appropriate that a well designed extensive work should be undertaken to determine paleocurrent over a large part of Saurashtra and other parts of Gujarat. The proposed study aims at determining the paleoflow direction of the formations constituting the Dhrangadhra Group, outcropping over an area of about 1800 sq km. The study attempts to evaluate the following aspects of sediment transport and depositional agency in relation to the various stratigraphic formations as recognised in the Dhrangadhra Group of rocks as referred to earlier:

(i) paleoflow direction through space and time,
(ii) paleoslope and shoreline distribution during Mesozoic time,
(iii) location and composition of provenance - which shall be discussed in Chapter IV.
A hierarchical sampling plan modified after Potter and Olson (1954), Potter and Pettijohn (1974), was followed to suite the object of this study. Thus instead of dividing the area into increasing sampling size from outcrop, sector, subarea, to formation, the data were recorded and treated statistically first at outcrop level, and then at formation level, after combining the data at all outcrops. To evaluate areal pattern of paleocurrents, the data from individual outcrops were pooled together for the whole formation without regard to facies, and treated graphically and statistically separately for Than, Surajdeval, Ranipat and Wadhwan formations.

Foreset dip azimuths were recorded for large- and small scale, planar- and trough crossbedding separately. Dip azimuths of planar crossbeds were recorded directly on exposed surfaces of foresets; bi-planar method of Potter and Pettijohn (1963, p.77) was followed on outcrops where a suitable single surface of planar foreset was not exposed in vertical sections (a-c plane). Trough foresets selected for measurements were those exposed in crescentric outline on bedding surface (a-b plane). About 8-32 readings from crossbedded units were recorded at each outcrop, depending upon the local variability of foreset azimuth as per sampling plan. The spacing between different outcrops was determined largely by the availability and accessibility of suitable outcrops. However, care was
taken to cover the strata both stratigraphically and laterally, as far as possible within the available means.

The paleocurrent study is based on 3542 readings of Dhrangadhra group of formations; their formation-wise break-up is given in Table 3. No tilt correction was applied to azimuthal data as dips in the study area, generally speaking, do not exceed 8 degrees.

PALEOFLOW RESULTS AND INTERPRETATION

The foreset dip azimuthal data were treated both graphically and statistically (Potter and Pettijohn, 1977, p.98) at outcrop and formation level, separately for large and small scale, planar and trough crossbedding as and where developed in each formation. Computed statistics including vector mean ($\bar{v}$) and vector magnitude in percent ($L$) is recorded in Appendix II for data at outcrop level, as also in Table 3 for those at formation level, respectively for Than, Surajdeval, Ranipat and Wadhwan formations. Standard deviation and variance were not calculated at outcrop level owing to small sample size of rarely more than 30 readings.

In view of the known genetic relationship between the primary directional features and the prevailing current system (Potter and Pettijohn, 1963), the results so obtained, indeed, can be appropriately interpreted for reconstructing paleoflow system through space and time.
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<th>TABLE 3. FORMATION LEVEL STATISTICS OF CROSSBEDDING AZIMUTHS OF THAN, SURAJDEVAL, RANIPAT AND WADHWAN</th>
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In the basal Than Formation, comprising sandstone, shale, carbonaceous shale and coal, foreset azimuthal data for large scale planar and trough crossbedding were treated graphically and statistically both at outcrop and formation level, after pooling the entire data from all outcrops.

Crossbedding azimuths display unimodal distribution in most outcrops and locally bimodal distribution as is evident from some typical samples of rose diagrams shown in Figure 25,A-B, with the principal mode directed towards west-southwest (240°-270°) through west-northwest (270°-300°); to northwest (300°-330°) in different localities; subsidiary modes of bimodal distribution are like-wise directed toward west-southwest and northwest, and secondary mode towards northwest (300°-330°) wherever developed. The arrow heads in the paleo-current map in Figure 25,A-B demonstrate vector mean (θ̅v) direction at outcrop level; its length corresponds to magnitude of resultant vector in percent (vector strength = L) as listed in Appendix II. Vector mean which are directed commonly within a range from west-southwest (268°) through west-northwest (304°), may be diagonally apart toward southwest and northwest in places of bimodal distribution especially in trough crossbedded units (Fig. 25,B).

The total pooled data for planar (127) and trough crossbedding (166) were plotted as rose diagrams at formation
Fig. 25 A set of rose diagrams showing some typical patterns of planar and trough (Sp & St) crossbedding azimuths at outcrop level in Than sandstone; A, Planar; B, Trough crossbedding.
level with computed statistics (Table 3) shown alongside (Fig. 26). The azimuthal data at formation level display unimodal distribution for planar crossbeds with modal class oriented toward west-southwest (240°-270°), but bimodal locally in the case of trough crossbeds with the two modal classes oriented transversely toward southwest (240°-270°) and northwest (300°-330°) (Fig. 26). Vector mean azimuth is 267° in the former and 243° and 321° in the latter; their variance is 1363 and 1581, respectively. Evidently, the paleoflow pattern so deduced suggests a dominant role of west-southwest directed depositional current in sediment dispersal, and a subsidiary role of northwesterly paleocurrents. The southwesterly paleocurrent system, apparently, was sea-ward directed, normal to the nearby shoreline, whereas the diagonally oriented subsidiary system toward northwest may correspond to longshore currents parallel to the inferred shoreline in the study area during the deposition of Than sediments.

**Surajdeval Formation**

The succeeding Surajdeval Formation, characterised by medium to coarse-grained, profusely crossbedded sandstone, is pink to grey, to clean white in places. As stated earlier, the formation exhibits recurring fining-upward cycles, with cross-bedded sandstone bodies forming lower part and muddy-ripple-laminated siltstone upper part.
Fig. 26 A, B: Arrows corresponding vector mean (\(\theta_v\)) of planar (A) and trough (B) crossbeds at outcrop level in Than sandstone. Rose diagrams based on total planar and total trough crossbedding data are shown alongside, respectively. Number in parenthesis indicated number of outcrop.
Frequency distribution of crossbedding azimuths for some typical outcrops of the Surajdeval sandstone for large and small scale, planar and trough crossbedding foresets, is shown as rose diagrams in Figure 27,A,B,C,D. There are some differences in the frequency distribution of planar and trough crossbeds. Large planar crossbedding commonly exhibits unimodal distribution with modal class oriented westward (240°-270°) and northward (330°-360°); locally bimodal distribution shows southerly (180°-210°) and westerly (240°-270°) modes (Fig. 27,A). Small scale planar crossbedding, however, display unimodal to bimodal distribution commonly, with primary and secondary modes directed toward west-southwest (240°-270°), west-northwest (270°-300°), or northwest (300°-330°), and in places toward north-northeast (0-30°), as shown in Figure 27,B. Similarly, large and small trough crossbedding yield unimodal to bimodal distribution with modal class directed west-southwest and northwest (Fig. 27,C,D). The bimodal distribution of planar and trough crossbedding occurs more commonly in the area around Dhaduka and Wankaner in the western part of the study area. Vector mean direction for large and small scale planar and trough crossbeds at outcrop level shows a wide span of distribution ranging from south-southwest (200°), through west (265°) to north-northwest (345°) as recorded in Appendix II, and is evident from paleocurrent maps in Figure 28,A,B.
Fig. 27 Set of rose diagrams of crossbedding foreset azimuthal data of some selective outcrops of large- and small scale planar (A, C) and trough (B, D) crossbeds of Surajdeval Formation. Number in parenthesis indicates number of outcrop.
Fig. 28 A Arrows showing vector mean azimuths of large and small scale planar crossbeds at outcrop level in Surajdeval Formation. Rose diagrams shown alongside are based on pooled data at formation level. Figures alongside arrow indicates number of outcrops.
Fig. 28 B Arrows showing vector mean azimuths of large and small scale trough crossbeds at outcrop level in Surajdeval Formation. The current roses based on pooled outcrop data. Figures by the side of arrows indicate number of outcrop examined.
The foreset azimuthal data from all outcrops lumped to yield data at formation level for large and small scale, planar and trough crossbedding, were plotted graphically as rose diagrams shown as inset in Figures 28,A,B; the corresponding statistics including vector mean, variance, standard deviation as listed in Table 3 are shown alongside. Interestingly, foreset azimuths at formation level display bimodal distribution for most large scale planar and trough crossbeds (Figs. 28,A,B), with principal and subsidiary modes oriented respectively towards southwest (210°-240°) and west-northwest (270°-300°). By contrast, small scale planar and trough crossbeds show distinctly unimodal distribution with modal class oriented toward west-southwest (240°-270°) and northwest (300°-330°), respectively (Figs. 28,A,B). Generally speaking, vector strength (L) is of high magnitude (upto 97%) at outcrop level and seldom lower than 60%, but decreases (87-62%) at formation level, signifying greater consistency of depositional system in small area of outcrop size than in large area of formation level.

The corresponding variability (variance) around vector mean direction for large and small planar crossbeds ranges from 2315-3289, and for trough crossbeds from 896-1596. For the same depositional system higher variance has been reported for planar crossbeds than for trough crossbeds (Dott, 1973) because of frequent development of different types of sand bars-transverse, diagonal, longitudinal etc. like in braided
river systems. The bimodal pattern of crossbeds in Surajdeval sandstone, lower values (60%) of vector magnitude, and higher variance may imply large azimuthal dispersion in selective areas (particularly around Wankaner and Dhaduka) due perhaps to intermixing of nearshore coastal environment including delta distributaries, tidal and longshore currents.

Ranipat Formation

Unlike the underlying Surajdeval, the Ranipat Formation predominantly consists of white, earthy to pink coarse, medium to fine-grained crossbedded sandstone and alternating thin siltstone and shale exhibiting recurring fining-upward cycle.

Roses diagrams in Figure 29A,B,C,D, show frequency distribution of crossbedding azimuth for some typical outcrops of the Ranipat sandstone for planar and trough crossbedding of large and small scale. Large scale planar crossbedding shows mostly unimodal distribution with modal class commonly oriented south-southwest (210°-240°) or southwest (240°-270°). Small scale planar crossbedding displays, however, unimodal to bimodal distribution with primary and secondary modes more or less transversely apart: toward south (180°-210°), through south-southwest (210°-240°), and west-northwest (270°-300°), respectively as shown in Figure 29A,B. Trough crossbedding of large and small scale, likewise, displays unimodal to bimodal distribution with modal class directed
Fig. 29 Some typical rose diagrams of foreset azimuth at outcrop level, including large (A, C) and small (B, D) scale planar and trough crossbeds. Ranipat Formation. Number at arrow base indicate number of outcrop examined.
southwest or north-northwest (Fig. 29,C); primary and secondary modes of bimodal distribution are diagonally to oppositely directed (Fig. 29,D).

Significantly, the south-southwest (180°-210°) or north-northwest (330°-360°) oriented modal classes are very common especially in small scale planar and trough crossbeds. Vector mean direction at outcrop level, by and large, ranges from south (203°) through west (274°) on the one hand, and north-northwest (350°) to north-northeast (7°) on the other (Appendix II), as shown in paleocurrent maps (Figs. 30,A,B,C,D).

The entire foreset azimuthal data were pooled separately for each type of crossbeds and plotted as respective rose diagrams shown as insets in Figures 30,A,B,C,D including their computed statistics as listed in Table 3. The foreset azimuths exhibit more or less a unimodal distribution at formation level for both planar and trough crossbeds of large and small scale. Modal class lies generally towards southwest (210°-240°) and west-northwest (270°-300°), as well as is directed toward north-northwest (330°-360°) in the case of small scale trough crossbeds. Vector strength (D) is commonly of high magnitude (upto 97%) at outcrop level with a few exception of lower values, but decreases to 84-54% at the formation level, signifying greater consistency of current vectors at outcrop level than at formation level. Crossbedding variability (variance) around mean for large and small planar crossbeds varies from 863-3741, and for
Foreset dip azimuth of Large-scale Planar Crossbedding

(A)
Foreset dip azimuth of Small-scale Planar Crossbedding (B)
Foreset dip azimuth of Large-Scale Trough Crossbedding (C)
Foreset dip azimuth of Small-scale Trough Crossbedding (D)
trough crossbeds from 1844-2865.

The diagonally/oppositly oriented modal classes of crossbeds at various outcrops of Ranipat sandstone are genetically significant and may correspond to ebb tidal and/or delta distributary system directed toward southwest or so, and longshore/flood tidal currents parallel to or across the shoreline toward northwest and northeast, as discussed later.

**Wadhwan Formation**

An analysis of sediment dispersal pattern of Wadhwan sandstone was carried out on a limited number of outcrops (7) of planar and trough crossbedded sandstone, because of overall paucity of exposures. The scant data on crossbedding orientation (132) provides only a generalised trend of sediment dispersal.

The vector mean and vector magnitude of crossbedding azimuth computed at different outcrops of Wadhwan sandstone (Appendix II, Table 3) and plotted in Figure 31, reveal a southwesterly pattern with a high vector magnitude (98%). The entire data from all the seven outcrops, like Than, Surajdeval and Ranipat sandstones, were lumped separately for planar and trough crossbedding and plotted as rose diagrams at formation level (Fig. 31, inset), with corresponding statistics listed alongside. The foreset azimuth display a well defined preferred unimodal distribution in either
Fig. 31 Arrows showing vector mean of planar and trough crossbeds at outcrop level of the Wadhwan Formation. Rose diagrams based on pooled data at formation level is shown in inset. Number at arrow base indicate number of outcrop examined.
case, with modal class oriented toward southwest (210°-240°). Southwesterly direction of sediment transport is genetically interesting, in that the Wadhwan sandstone locally encloses lenses of fossiliferous limestone.

**SIGNIFICANCE OF BIMODAL CROSSBEDDING**

Crossbedded sandstone showing bimodal distribution of foreset azimuth occur occasionally in all the formation of Dhrangadhra Group, as referred to above. The bimodality of crossbedding foresets in sandstone sequence calls for a detailed study in order to understand its genetic implication as is indicated earlier. One of the best outcrops showing bimodal distribution of crossbedding occurs in an outcrop of channel sandstone body in the Surajdeval Formation near Dhaduka village some 15 km on Chotila - Surendranagar road, National Highway.

A plane-table survey of the above channel sandstone body outcropping near Dhaduka village was carried out in order to map its areal pattern and geometry over a stretch of about 400 m (Fig. 32). The survey brings out a sinuous channel pattern of this sandstone body, and its dominant directional components of depositional system, as also of the underlying sequence. Some 140 readings of crossbedded foresets which are profusely developed in the given sandstone body were measured at 20 spots located in the survey figure. The rose
Fig. 32 Plane-table map of a channel sandstone body in Surajdeval, showing paleoflow by arrow heads on its upper surface and in vertical sections (A, B, and C).
diagram of grouped azimuthal data and computed vector mean
direction plotted as arrow head at each sampling locality,
indicate mean direction of the prevalent depositional system
for the upper and lower sandstone bodies of the given section.

When critically examined, the channel sandstone body and
those of the underlying section provide an example of inter­
related but distinctive depositional systems from lower to
upper part of the exposed section of Surajdeval.

Small scale planar crossbedding in the lower sandstone
beds of the underlying section exhibits a mean orientation
(θv) towards northwest (308 ± 91°), whereas large scale cross­
bedding of channel sandstone body in the upper part yields a
mean orientation toward south-southwest (191 ± 92°) as is
evident from the respective graphic plots and arrow heads
(Fig. 32,A,B,C).

The upper channel sandstone body exhibiting mean direction
of depositional system toward south-southwest may be attributed
to delta distributary and/or ebb-tidal currents, whereas, the
underlying sandstone bodies showing mean direction toward
northwest (308 ± 91°) may correspond to longshore current.
Significantly, the former sandstone display a sinuous geometry
and is buff to brown and medium to fine grained, whereas the
latter thinly bedded white, is medium grained well sorted
sandstone. A more or less similar paleoflow pattern has been
deduced in the Wankaner area some 45 km towards west where
large scale planar foresets show mean orientation towards south-southwest (221 ± 9°) and small scale planar crossbeds show mean flow toward northwest (292 ± 62°) (Fig. 33).

Associated with crossbedded sandstone and muddy laminated red shale, occasionally, occur thin beds of sandstone characterised by planar herringbone type crossbedding in the upper part of the formation; their foreset orientation roughly indicate a bimodal (334 ± 57°, 185 ± 88°) flow pattern, with corresponding means of two sub-population directed toward 185 ± 85° and 334 ± 57°, respectively. The bimodal pattern of crossbedding foresets, low values of vector magnitude (L = 57%), and high value of standard deviation (S = 57°) and variance (S² = 3289) imply large azimuthal dispersion and corroborate multidirectional current system of coastal environments (Klein, 1970, 1985).

The overlying Ranipat Formation which is characterised by white coarse, medium and fine grained crossbedded sandstone, locally interbedded with sets of herringbone-crossbedding, likewise, display a bimodal distribution of foreset azimuths with the two modal classes oriented respectively southwest (210-240°) and toward northwest (330-360°) to northeast (0-30°) in places.

CONSISTENCY OF PALEOFLOW AND PALEOSLOPE THROUGH TIME

For a temporal analysis of directional data in order to deduce the consistency of paleocurrent pattern or lack of it
Fig. 33 Rose diagrams showing mean flow orientation of large and small scale planar crossbeds in Wankaner area of Surajdeval Formation. Vertical section alongside show association of interbedded sandstone and shale.
from base to top of the Dhrangadhra Group, the entire foreset azimuthal data for large and small scale crossbeddings, were treated separately for each formation, both graphically and statistically without regard to crossbedding types. The rose diagrams and corresponding statistics in Figure 34 bring out pictorially the consistency in paleocurrent pattern in the Dhrangadhra Group from Than at the base to Wadhwan at the top.

Evidently, the unimodal paleoflow pattern as deduced from large scale crossbedding throughout the strata is consistently directed toward south-southwest \((210^\circ-240^\circ)\) and west \((270^\circ-300^\circ)\), with corresponding grand mean toward \(274^\circ, 255^\circ, 237^\circ, 224^\circ\), respectively for Than, Surajdeval, Ranipat and Wadhwan formations. However, for small scale crossbedding as recorded in Surajdeval and Ranipat modal class and mean paleoflow are directed toward west-northwest \((270^\circ-300^\circ)\), to northwest \((300^\circ-330^\circ)\). Thus, it is evident that the Mesozoic Gondwana sediments from Than to Wadhwan were brought to the basin of deposition largely by streams and/or distributaries which flowed dominantly and consistently from northeast to southwest (i.e. from land toward sea), with occasional dispersal and redistribution by northwesterly to northerly oriented longshore and/or tidal currents of the near by coastal environment, particularly so during Surajdeval and Ranipat formations, as shown schematically in Figure 34 (inset).

The consistency of paleoflow implies that the streams/
Fig. 34 Rose diagrams showing mean paleoflow through time in the various formations of Dhrangadhra rocks based on pooled data from large and small scale crossbeddings. Inset shows Mesozoic paleoslope and possible shoreline vis-a-vis study area.
distributaries of the depositional system followed a paleo-slope which, likewise, remained unchanged directed from northeast to southwest throughout the course of sedimentation in the study area. The paleocurrent study further reveals that the variance and standard deviation of depositional agency (river system) was the lowest for Than ($S^2 = 1489; SD = 38^\circ$), moderately high for Surajdeval ($S^2 = 2068-2524; SD = 45^\circ-50^\circ$), and higher still for the Ranipat ($S^2 = 1636-3274; SD = 46^\circ-57^\circ$). Pryor (1960, p.1490) has emphasized that 'probably the most important factor controlling the variance and standard deviation of dispersal pattern is the amount of slope of the depositional surfaces - the greater the amount of slope the smaller the variance and standard deviation'. By implication, it is likely that the slope of the depositional basin gradually became gentle as the sedimentation progressed from Than through Surajdeval to Ranipat, so also probably the distributary channel pattern of the depositing streams.