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INFLUENCE OF EOLIAN PROCESSES ON PRECAMBRIAN SANDSTONES OF THE GODAVARI VALLEY, SOUTH INDIA

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ABSTRACT

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The shallow marine Precambrian Pakhal sandstones (Middle Proterozoic, about 1400 Ma) of the Godavari valley are composed of first-cycle terrigenous grains derived from the crystalline Basement Complex. The sandstones include a large number of rounded and well rounded grains of quartz and feldspar. The rounded grains, without exception, occur in intimate association with angular grains. The sandstones are also characterised by several other types of textural inversions.

Relative effectiveness of several processes with regard to the development of roundness of the Pakhal sands has been considered. Simple sedimentary differentiation fails to explain the high degree of roundness of the first-cycle sands. Solutions rich in organic matter cannot be considered effective in rounding Proterozoic sands. Chemical action is inconsistent with the presence of fresh grains of feldspar. Beach processes also fail to explain the presence of large numbers of feldspar grains. The roundness of these sands is best explained by eolian processes, that can effectively round grains of quartz as well as feldspar.

The textural inversions of the Pakhal sandstones can be attributed neither to mixing of sands derived from multiple sources nor to mixing of materials coming from different environments. They possibly resulted from mixing of sands with contrasting mechanisms of transport, viz., eolian and aqueous, in a common area of sedimentation.

Eolian transport and abrasion processes probably played a more significant role during the time of Pakhal sedimentation than at present, because of the absence of protective vegetation in Proterozoic time.

INTRODUCTION

The Precambrian Pakhal sandstones belonging to the Purana Supergroup of the Godavari Valley are characterised by the occurrence of a large number of rounded and well-rounded grains of quartz and feldspar which, without exception, occur in close association with angular and sub-angular grains. A dual source for the sediments would explain the textural inversion, but available evidence suggests derivation of all the clastics from a single crystalline source. The present study aims at an evaluation of the different processes that could be responsible for rounding of terrigenous grains during transportation, and demonstrates the possibility of the generation of highly rounded, first-cycle sands directly from a crystalline source. It also appears from the present study that the influence of source or of environmental processes, or both, on rounding have probably been overemphasized in explanations of textural inversions of sandstones. An alterate hypothesis explains the textural inversions in sediments derived from the same source and deposited in similar environments, as being due to different transportation mechanisms.

ROCK FORMATIONS AND DEPOSITIONAL ENVIRONMENTS

The Purana sedimentary rocks of the Godavari Valley (age about 1400 Ma, Middle Proterozoic, Vinogradov et al., 1964) occur in two narrow, linear belts, about 240 km long, bordering the younger Gondwana sediments (Fig. 1).

These rocks are slightly metamorphosed and highly deformed in the southeastern end of the valley, but northwestward they are unmetamorphosed and undeformed. This belt of sedimentary rocks is, however, affected by a large number of steeply dipping to near-vertical faults. Large, gently plunging open folds or broad warpings have developed in places. Regionally, these rocks on both sides of the valley strike in a north-west to south-east direction and dip towards northeast to north-northeast at low angles normally ranging from 10° to 20°.

The generalised stratigraphic succession of the unmetamorphosed Precambrian formations around Ramgundam (18°45′ N; 79°26′ E), the area of the present study, is given in Table I.

TABLE I

Lithostratigraphic succession of the Purana Supergroup around Ramgundam (Chaudhuri, 1970b)

Cretaceous—Carboniferous	Gondwana Supergroup			
Late Proterozoic		Sullavai Group		
	Purana Supergroup		Mulug Subgroup	Rajaram Limestone Ramgundam Siltstone Ramgundam Sandstone Ramgundam Conglomerate
Middle Proterozoic		Pakhal Group		
			Mallampalli Subgroup	Pandikunta Formation Damla Gutta Formation
Early Proterozoic or Archaean (?)	Crystalline Basement Complex			

TABLE II

Summary of lithology, primary sedimentary structures and depositional environments of Pakhal sedimentary rocks

Rock sequences (with maximum thickness)	Generalised lithology	Primary sedimentary structures	Depositional environment
Damla Gutta Formation (49 m)	1. Sandstone: mainly bimodal quartzarenite with calcareous mud matrix. 2. Limestone: micrite and algal biolithite (dominant) with penecontemporaneous dolomite.	1. Thin plane beds dominant, small-scale ripple marks and cross-beds common. 2. Thin horizontal algal laminations, shrinkage cracks, small-scale cross-beds, ripples, birdseye structures.	1 and 2. Tidal flat environment.
	Contact gradational		
Pandikunta Formation (314 m)	1. Limestone: micrite and algal biolithite (dominant), with penecontemporaneous dolomite and subordinate oomicrite facies. 2. Glauconitic sandstone and siltstone.	1. Algal stromatolites, limestone-pebble conglomerate, shrinkage cracks, climbing ripple lamination, ripple marks, cross-beds, worm burrows and birdseye structures. 2. Structureless and massive in general, sometimes shrinkage cracks and cross-beds in fine-grained facies.	1. Mainly supratidal and intertidal zones. 2. Low subtidal environment
	Unconformity		
Ramgundam Conglomerate (914 m)	1. Bedded chert (5 m—10 m) at the base. 2. Conglomerate: clayey arkosic groundmass, framework pebbles of quartz, quartzite (dominant).	1. Thin plane beds. 2. Thin or moderately thick plane beds (dominant). Cross-bedding, rare, in basal part, graded bedding.	Along deep coast line; below active wave base.
	Sharp contact		
Ramgundam Sandstone (107 m)	1. Clayey arkose and subarkose. 2. Silica-cemented subarkose and quartzarenite.	1. Thin or moderately thick beds with some thick beds. 2. Profusely cross-bedded and ripple marked. Ripples: symmetrical, asymmetrical, flat-topped and interference types.	1. Low-energy regime of shallow and moderate depth. 2. Barrier island beach dune complex.

The Pakhal Group consists primarily of sandy and calcareous sedimentary rocks, deposited in shoreline environments of a shallow marine embayment (Chaudhuri, 1970b). The Pakhal sedimentary rocks of the area under study are replete with various types of primary sedimentary and biosedimentary structure. Algal stromatolites, dolomitised micrites, shrinkage cracks, birdseye structures, worm burrows and intraformational limestone conglomerates indicate a tidal-flat origin for the Pakhal carbonates (Chaudhuri, 1970a). The lithology and the primary structures, e.g., cross-stratifications and different types of ripples, indicate a more or less similar shallow marine origin for the sandstones (Chaudhuri, 1970b).

The sandstones of the Damla Gutta Formation, later referred to as the Damla Gutta Sandstone, are deposits of a typical carbonate—orthoquartzite facies and were deposited on a mature, peneplained Archaean basement, in a moderately agitated, shallow, near-shore environment. The glauconitic sandstone of the Pandikunta Formation records phases of slightly greater submergence within the tidal flats and was deposited in quiet water below wave base. The Ramgundam Conglomerate was also deposited beneath wave base, along a steep coast. The lower part of the Ramgundam Sandstone was deposited in a low-energy depositional regime of shallow or moderate depth, but during the deposition of the upper part the low-energy regime was replaced by a high-energy regime, presumably of a barrier island-beach dune complex (Chaudhuri, 1970b). A summary of the lithology, primary sedimentary structures and depositional environment of the four basal Pakhal Formations in the Ramgundam areas is given in Table II.

PETROGRAPHY OF THE PAKHAL SANDSTONES

Compositionally the Pakhal sandstones range from arkose to quartzarenite, with the latter being dominant only in the Damla Gutta Formation. All the sandstones are characterised by the presence of large amounts of matrix, either clay or lime mud. The lime-mud matrix that occurs as micrite is inferred to have been deposited mechanically, simultaneously with terrigenous sand and silt components (Chaudhuri, 1970b). These sandstones, in many beds, contain significant amounts of secondary cement (secondary quartz, secondary feldspar, chert and sparry calcite) that was formed by replacement of either micrite or clay matrix (Chaudhuri, 1970b). This suggests that in most of the beds the original amount of matrix was significantly greater than the amount now present.

SOURCE OF THE PAKHAL SANDSTONES

The Pakhal sands are inferred to have been derived directly from the immediately underlying granitised Basement Complex that occupies the marginal areas south and southwest of the depositional areas (Fig. 1). The first-cycle

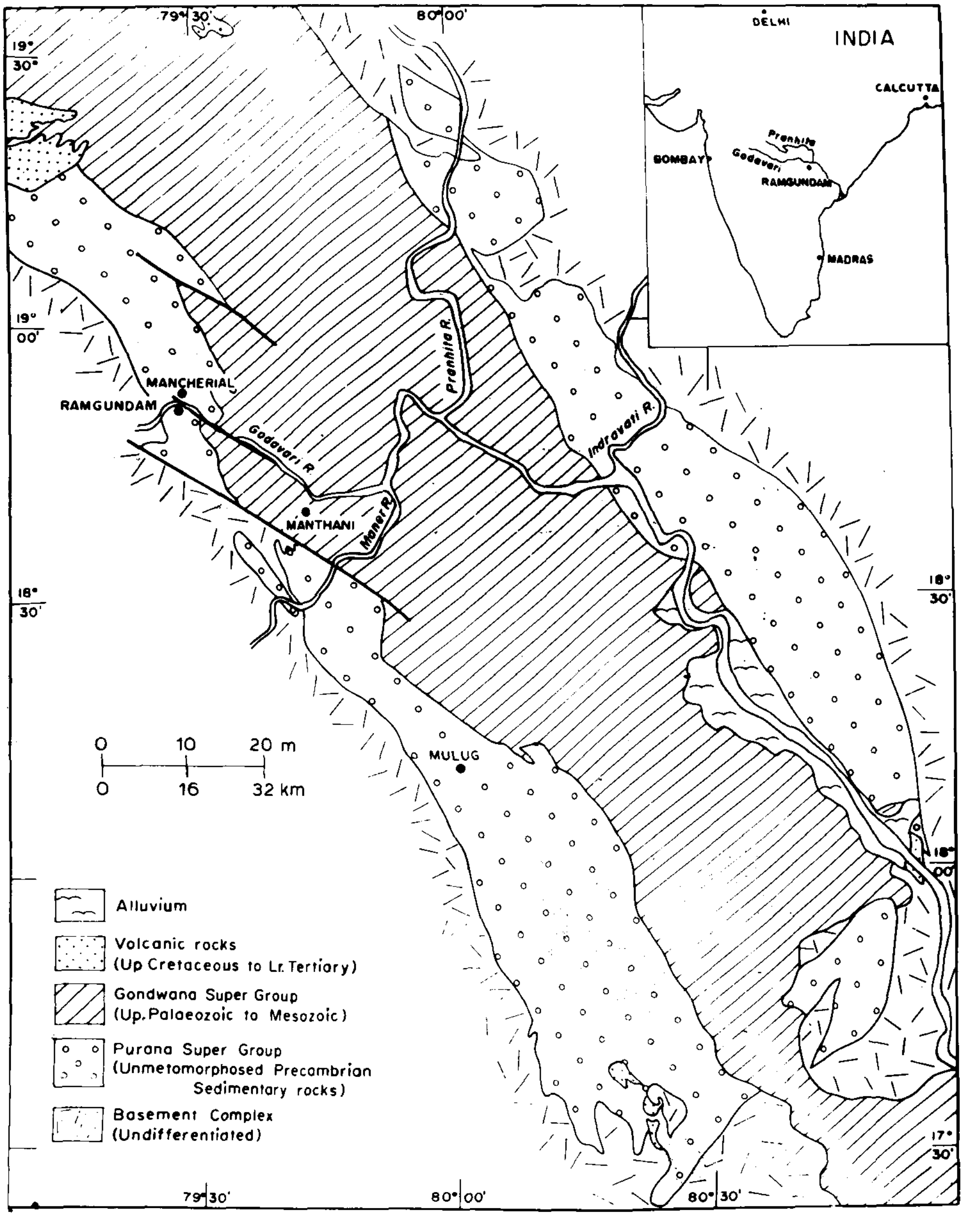


Fig. 1. Geological map of a part of the Godavari valley (modified after King, 1881). Inset map shows the location of Ramgundam.

sediments were derived from a linear source bordering the southern margin of the Pakhal exposures (Chaudhuri, 1970b). Abundance of fresh grains of potassium feldspar, vein quartz, myrmekitic intergrowths, and the presence of fragments of granite and granite gneiss strongly suggest derivation of the

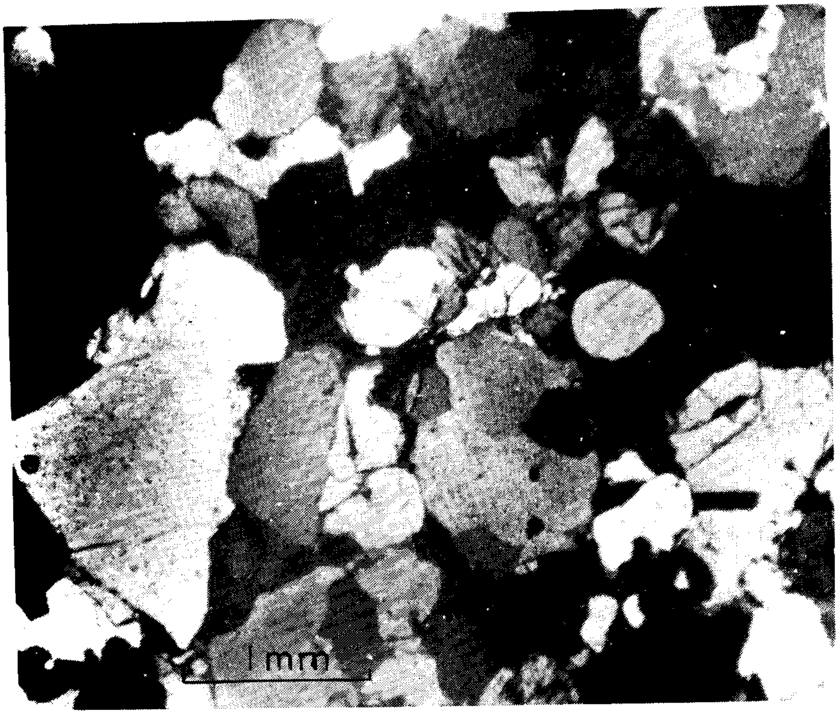


Fig. 2. Close association of rounded and angular grains. Note the presence of small rounded and large angular grains. (Crossed nicols)

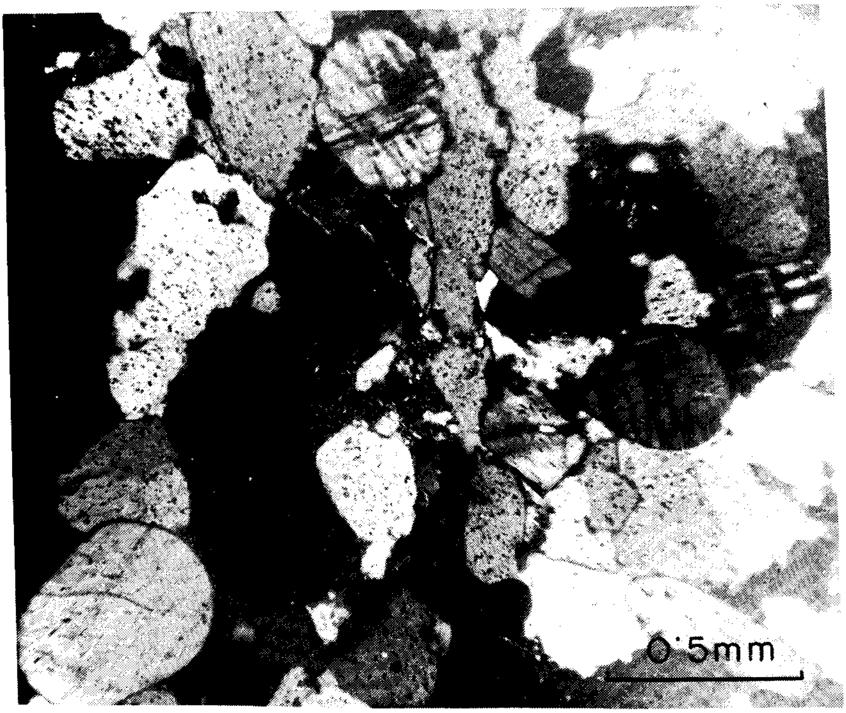


Fig. 3. Bimodal roundness in the same size grade. Note the relationship of roundness and mineral species; feldspar-rounded, quartz-angular. Well rounded fresh feldspar grains. (Crossed nicols)

Pakhal sands from a granite source. Recycled grains with broken and abraded overgrowths are not known from the Pakhal rocks. Apart from the underlying Basement Complex, there are no other known older source rocks for the Pakhal sands.

GRAIN ROUNDNESS AND TEXTURAL INVERSIONS

The sandstone horizons of the Pakhal Group are characterised by the ubiquitous presence of large numbers of rounded and well-rounded grains (Figs. 4—7; roundness measured by visual comparison with Powers' scale, 1953). Also ubiquitous is the presence of different types of textural inversions, viz., abnormal size-roundness relationship, incongruous mixture of angular and rounded grains, incompatible grain roundness—matrix relationships or mixture of well-sorted grain populations of different sizes. The salient features of the roundness distribution and of the textural inversions of the Pakhal sandstones are as follows:

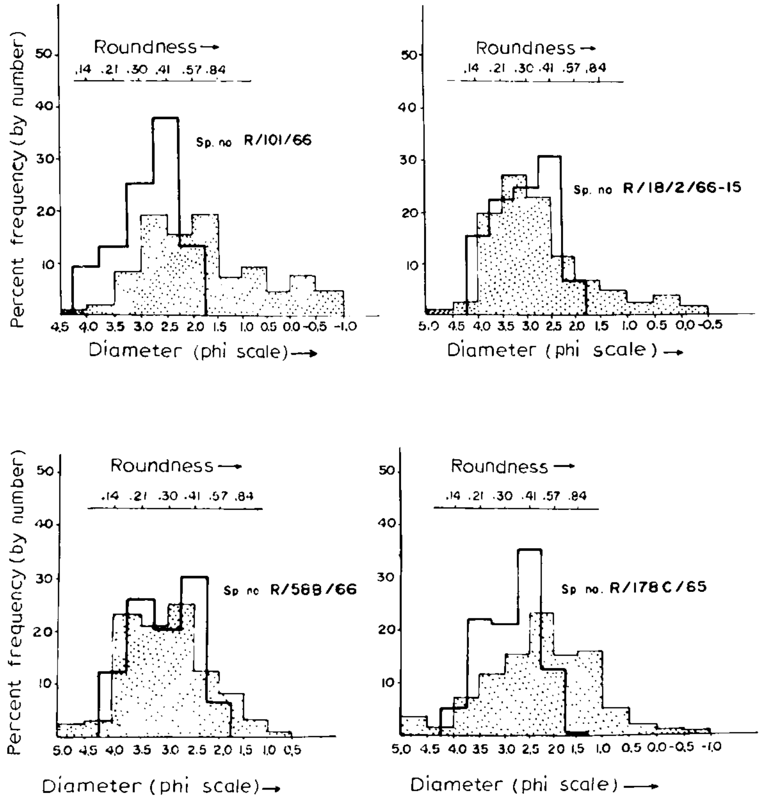


Fig. 4. Histograms showing grain-roundness and grain-size distributions of the Damla Gutta Sandstone. (Grain size histograms — stippled)

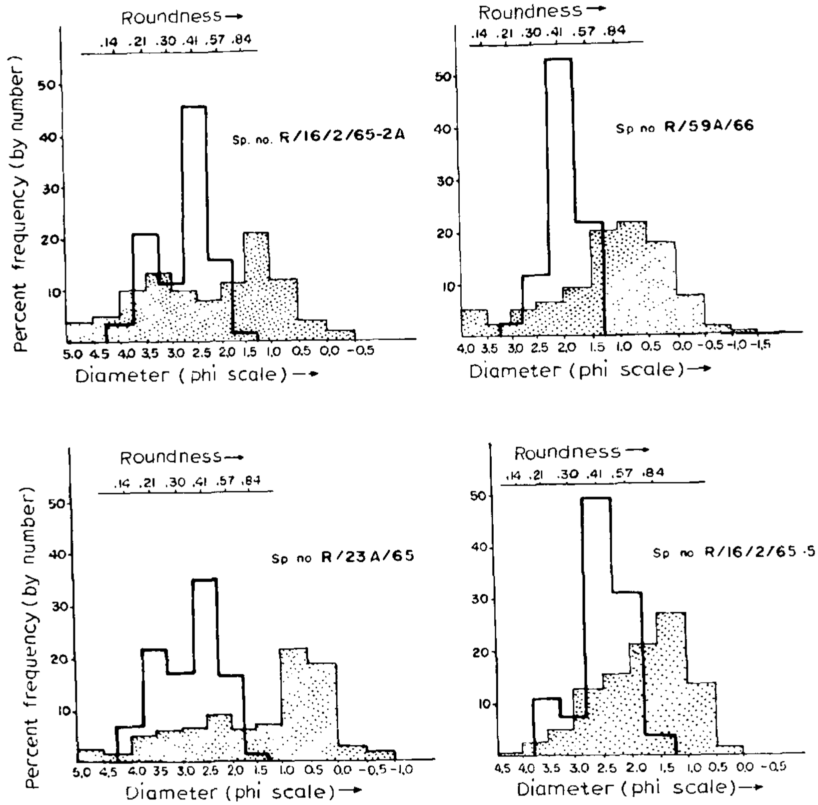


Fig. 5. Histograms showing grain roundness and grain-size distributions of glauconitic sandstone. (Grain-size histograms— stippled)

1. All the Pakhal sandstones are characterised by high modal roundness (Figs. 4—7).
2. Individual thin sections show close association of rounded and angular grains (Figs. 2, 3), and in most of the samples, the roundness histograms show a fairly well defined break near roundness value 0.30 (subrounded) (Figs. 4—7).
3. Size and roundness are two independently variable parameters. The roundness histograms exhibit well-defined inflections which may be completely absent in the grain size histograms (Figs. 4—7). The scatter plots (Figs. 8—10) also demonstrate the absence of any significant correlation (linear or otherwise) between size and roundness.
4. Degree of grain roundness and frequency of occurrence of rounded grains are independent of the matrix content of the rocks and the grain mineralogy (Figs. 11 and 12). Moreover, rounded grains are equally abundant in both arkosic and quartzose rocks (Fig. 13). Hence, roundness is independent of mineralogical maturity.

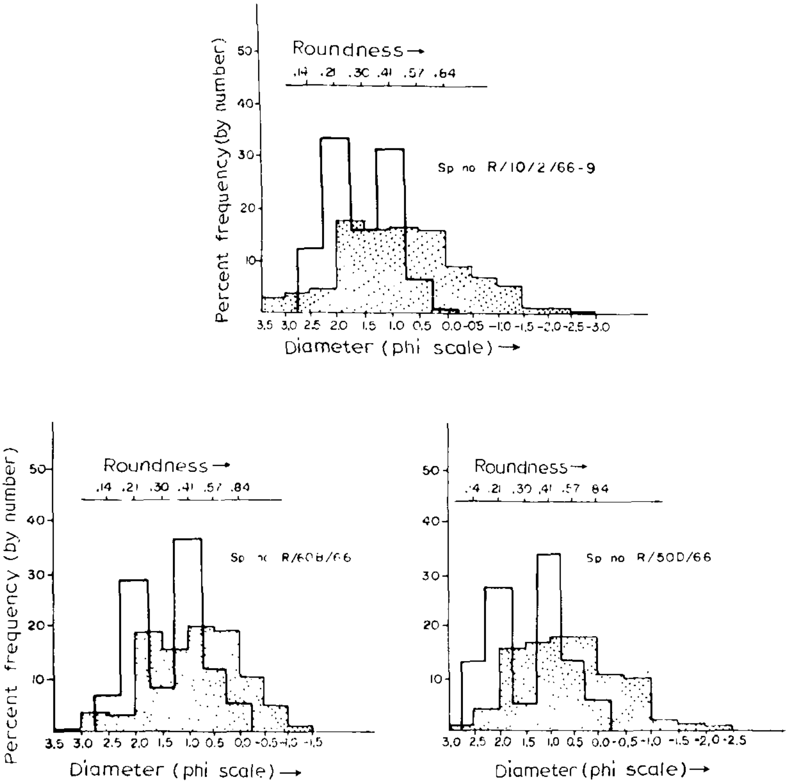


Fig. 6. Histograms showing grain-roundness and grain-site distributions of the sand fraction of the Ramgundam Conglomerate. (Grain-size histograms — stippled)

5. Roundness patterns of both quartz and feldspar grains follow analogous trends. Inflections in the roundness curves for both minerals also appear in the same position (Fig. 14) indicating that roundness is independent of grain mineralogy.
6. There is no appreciable size difference between rounded quartz and feldspar grains (Fig. 15).
7. The most rounded feldspar grains are almost always fresh, though large numbers of angular and subrounded grains are in different stages of alteration and staining by iron (Fig. 3).
8. In the Damla Gutta Formation, the sandstones are characterised by a texture that consists of two major modes of distinctly different grain sizes. Typically, the texture is a mixture of well rounded and fairly well sorted coarse sand with fine and very fine sand, the finer fraction containing a few grains of intermediate size (Figs. 16 and 17).

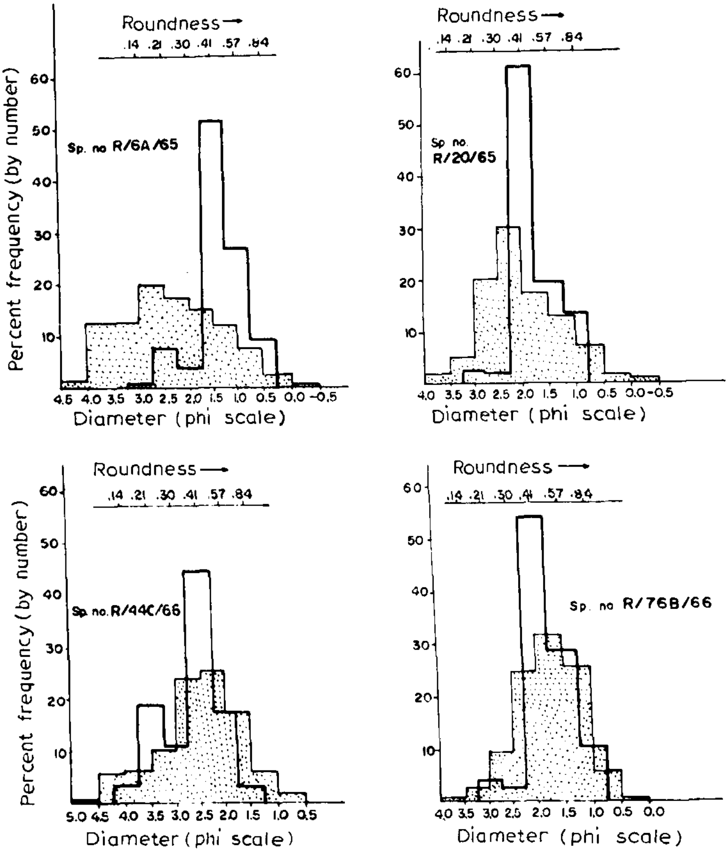


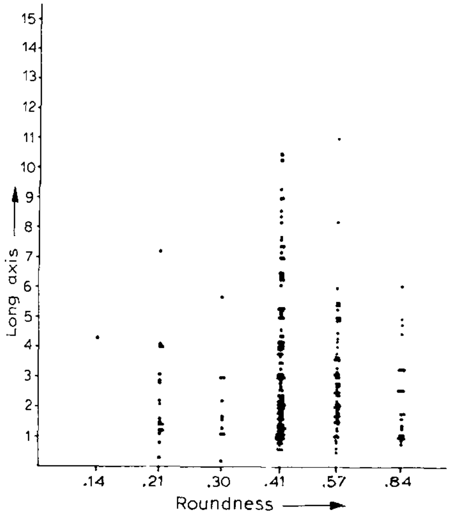
Fig. 7. Histograms showing the grain-roundness and grain-size distribution of the Ramgundam Sandstone. (Grain-size histograms — stippled)

EXPLANATION OF THE HIGH DEGREE OF ROUNDNESS OF THE PAKHAL SANDS AND THE INTERPRETATION OF THE TEXTURAL INVERSIONS

Previous work on grain rounding

The effects of fluvial transportation on sand rounding are, in general, not considered to be of much significance (Russell and Taylor, 1937; Russell, 1939; Twenhofel, 1945; Pollack, 1961; Kuenen, 1959a,b), and the rounding of sand grains has been attributed mainly to one of the following four causes: (1) sedimentary differentiation, (2) chemical solution, (3) beach processes and (4) eolian processes.

Beach action, although advocated by Russell (1939) and Folk (1960), is considered ineffective in rounding sand grains by others (Twenhofel, 1945; Kuenen, 1959b). Modern beach deposits do not contain more rounded grains



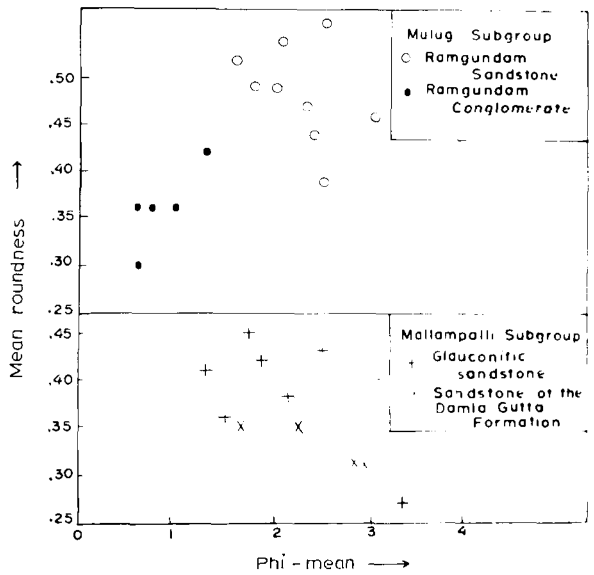


Fig. 8. Scatter plot of roundness versus size of sand grains of a sample of the Ramgundam Sandstone (each point corresponds to the roundness and the long axis of the same grain). Note absence of correlation between the two variables.

Fig. 9. Scatter plot of mean roundness versus mean size. Each point corresponds to mean size and mean roundness of one sample. Note absence of significant correlation between the two variables.

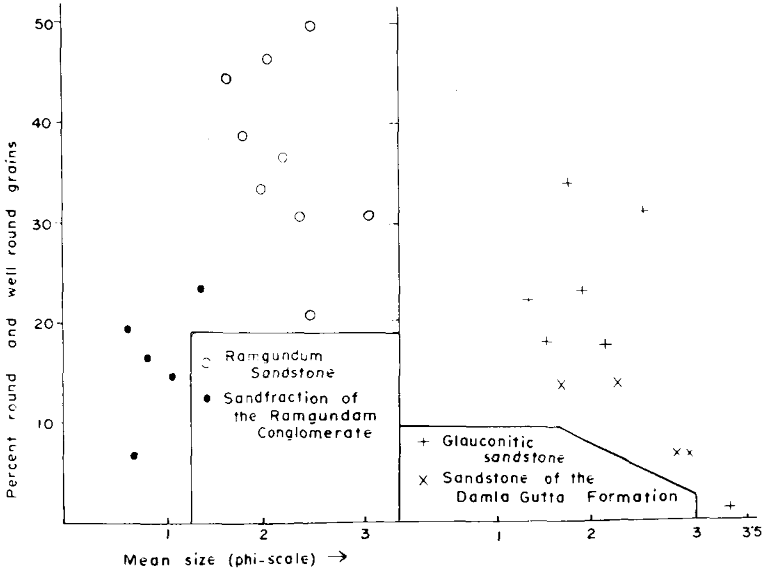
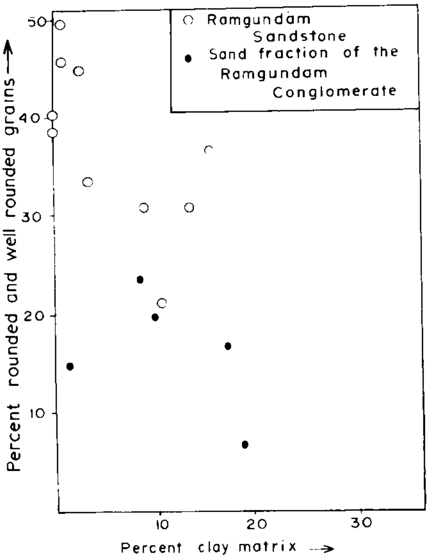


Fig. 10. Scatter plot of mean size versus percent frequency of rounded and well rounded grains. Each point represents one sample. Note absence of significant correlation between the two variables.



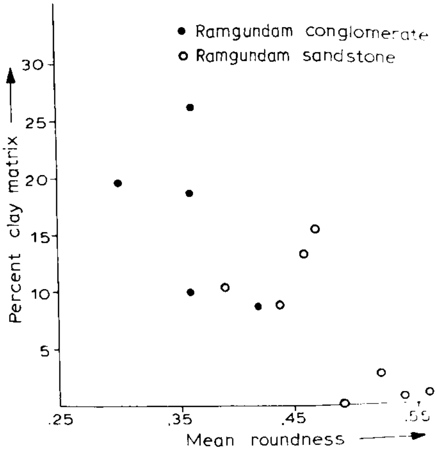


Fig. 11. Scatter plot of percent clay matrix versus percent frequency of rounded and well rounded grains. Each point represents one sample. Note absence of significant correlation between the two variables.

Fig. 12. Scatter plot of mean roundness versus percent clay matrix. Note absence of significant correlation between the two variables.

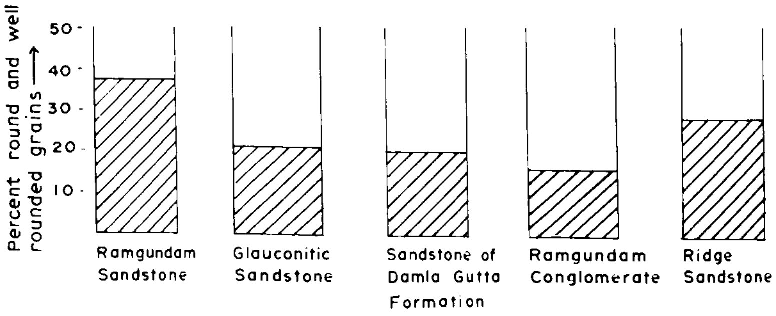
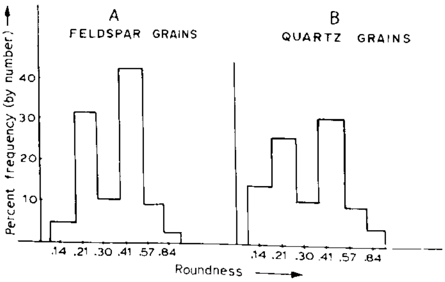


Fig. 13. Frequency (%) distribution of rounded (0.57) and well-rounded (0.84) grains in different sandstones.



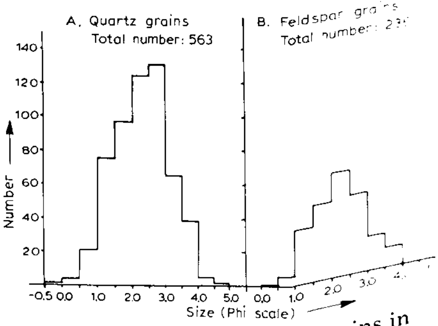


Fig. 14. Histograms showing the roundness distribution of quartz and feldspar grains in the sand fraction of the Ramgundam Conglomerate. Note the similarity of the distributions.

Fig. 15. Histograms showing the size distributions of rounded (0.57) and well-rounded (0.84) grains of quartz and feldspar from nine samples of the Ramgundam Sandstone.

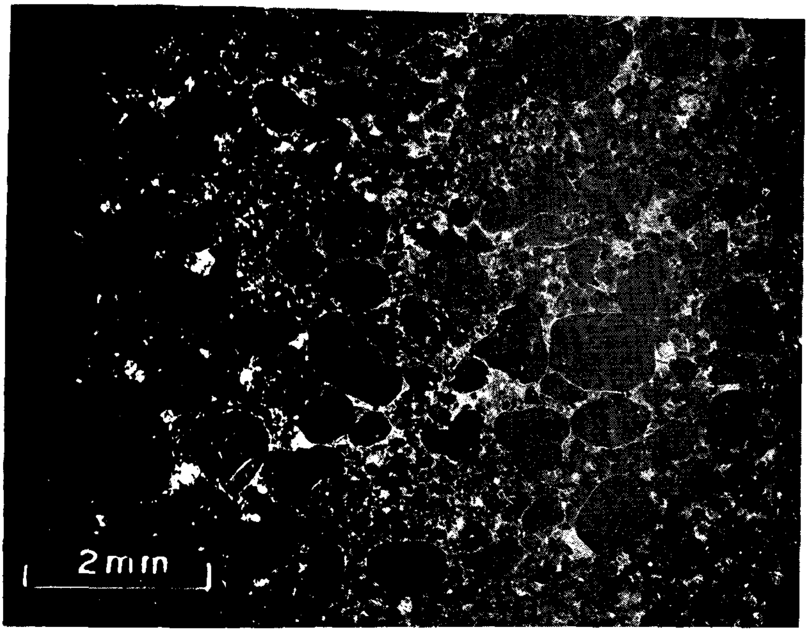


Fig. 16. Polymodal quartzarenite in a lime mud base, Damla Gutta Formation, Ramgundam. Two fairly well sorted modes of coarse and fine sands with a minor mode of intermediate size. Note high degree of roundness of the coarser grains.

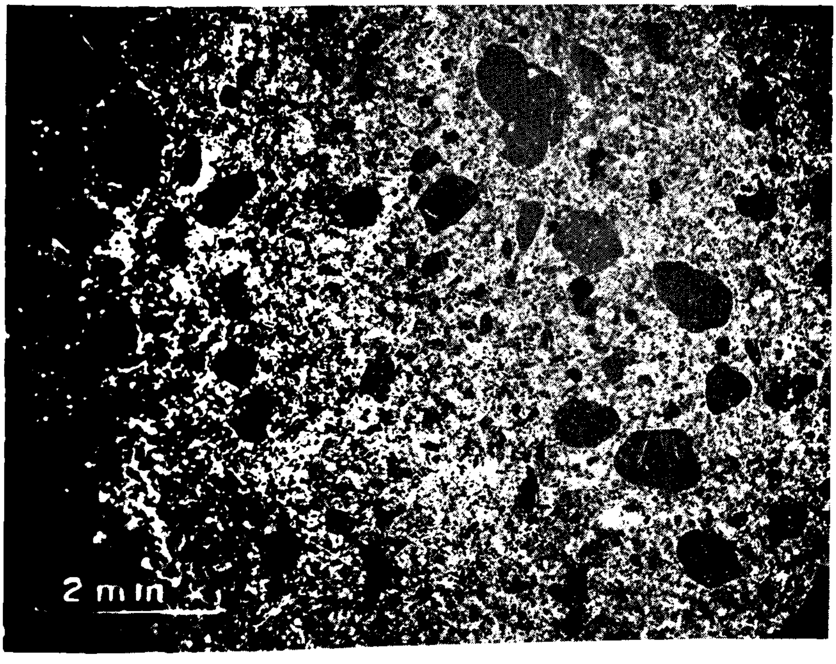


Fig. 17. Bimodal quartzarenite in a microcrystalline calcite matrix, Damla Gutta Formation Ramgundam. Note high degree roundness of the coarser grains.

than their inferred continental counterparts (McCarthy, 1933; Pettijohn and Lundahl, 1943; Pettijohn et al., 1972). The effects of chemical action on sand rounding, in general, are not considered significant (Galloway, 1919; Kuenen, 1959b, 1960), even though Crook (1968) suggested that solution-rounding during weathering may play an important role in shaping quartz grains. Eolian action is more commonly accepted as most effective in rounding sand grains. This idea is based mainly on observations on recent eolian sands (McCarthy, 1933, 1935; Twenhofel, 1945; Beal and Shepard, 1956) and on experimental studies (Kuenen, 1959b, 1960), but only rarely on observations from ancient eolian deposits (Dake, 1921; Shotton, 1937).

It is, however, generally agreed that sand particles round extremely slowly (Anderson, 1926; Russell, 1939; Twenhofel, 1945; Kuenen, 1959b) and that mature sandstones cannot be produced in large volumes directly from crystalline rocks. Sediments with a high degree of grain roundness are normally attributed to inheritance from pre-existing sedimentary rocks (Potter and Pryor, 1961).

Relative role of different processes in rounding Pakhal clastics

Sedimentary differentiation

If it is assumed that sedimentary differentiation is the most acceptable mechanism for the development of the high roundness of sand grains, then sediments with coexisting populations of rounded and angular grains such as the Pakhal rocks can be interpreted to have originated from two different sources, (1) a sedimentary source producing recycled, rounded grains, and (2) a crystalline source yielding first-cycle angular grains. This explanation of dual source of sediment supply would also be compatible with the textural inversions referred to earlier. However, in view of the presence of large numbers of rounded feldspar grains, this assumption appears suspect. Though rounded quartz grains could conceivably have been inherited from pre-existing sedimentary rocks, it is unlikely that grains of fresh feldspar, a mineral that is readily susceptible to chemical weathering, could have survived several cycles of sedimentation (Kuenen, 1959b). The Pakhal rocks studied here are all considered to be first-cycle sediments, derived from the same quartz-feldspar terrain. The highly rounded grains in Pakhal sands, therefore, cannot be attributed to recycling. The observed textural inversions cannot be explained by mixing of sediments from two sources, although Pettijohn (1957) asserts that the absence of normal size-roundness relationship is a virtual proof of dual source of sediment supply.

Chemical solution

Modification of the shape of the quartz grains by solutions rich in organic matter during weathering has been emphasised by Crook (1968). The morphology of the rounded grains of the Pakhal sandstones, however, is distinctly different from that of the chemically rounded grains which are characterised by ubiquitous linear or curvi-linear re-entrants and protruberences (Crook, 1968). Significant chemical dissolution would also be incompatible with the presence of fresh, rounded feldspar grains. The stratigraphic continuity of the different sandstone horizons and the distinctive character of the various beds indicate that the distribution of the rounded sands in the Pakhal rocks is related neither to the present day erosional surface nor to any palaeosol. Had the solutions rich in organic matter been potentially effective in rounding sand grains, Precambrian sands, in general, would have been relatively less rounded than their Phanerozoic counterparts, as action of solutions enriched in organic matter is expected to be more intense in Phanerozoic time than in the Proterozoic. However, there are no data to substantiate such a postulate or to show any correlation between roundness of sand grains and organic matter.

Eolian and beach processes

The high degree of rounding of the Pakhal sands is, probably, attributable either to eolian processes or to abrasion in high-energy depositional regimes, e.g., beach. Neither eolian transport nor any other process would by itself account for the observed close association of highly rounded and angular grains. The association may be explained by two different modes of transportation of the terrigenous grains, or by deposition of the grains in two different environments, after transportation by the same agency (Fig. 18). The latter process would call for subsequent mixing of sands deposited in the high-energy (e.g., beach) and low-energy (e.g., estuarine or neritic) environments. Mixing of materials belonging to different populations is also suggested by the grain-size analyses of the total sand fraction that exhibit sharp inflections in the cumulative frequency curves (Figs. 19 and 20). Such a mixing could explain the observed textural features of the Pakhal sandstones, namely, close association of highly rounded and angular clastic grains and presence of

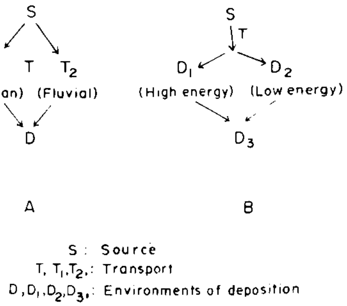


Fig. 18. Schematic diagram showing the possibilities to explain the close association of rounded and non-rounded grains:
A: two different modes of transportation, with subsequent mixing in a near-shore environment.
B: deposition in two different environments after transportation by the same agency and subsequent mixing.

rounded grains in poorly washed, muddy sandstone (Folk, 1964, p. 104), but fails to explain the survival of fresh, highly rounded feldspar grains.

In the Silurian sandstone of West Virginia Folk (1960) found evidence to suggest that appreciable rounding takes place during a single cycle of sedimentation, the well-rounded grains being inferred to be of beach origin and the less-rounded ones of estuarine origin. Balazs and Klein (1972) thought that prolonged abrasion during long-distance bedload transport within the limited geographic extent of the intertidal zones can convert very angular sands, particularly quartz sands, into supermature, highly rounded sands during a single depositional cycle.

Vigorous beach action, however, would probably tend to reduce the feldspar content of a sand (Pettijohn, 1957, p. 125). Though it is possible that feldspar may occur in beach deposits (Pettijohn and Lundahl, 1943), rapid mechanical destruction of feldspar during transportation along beaches is clearly shown by Martens (1931). Mechanical destruction of feldspar, with less than 80 km of bedload transport has also been demonstrated by Pittman (1969). Highly rounded, first-cycle Silurian beach sands of West Virginia are all supermature quartz sands; feldspar originally present in these sands had been completely eliminated by rigorous abrasion in beach environments (Folk, 1960). Even if well-rounded, fresh feldspar grains are retained in beach environments, they are usually much finer than the accompanying, rounded quartz grains, and occur in the fine and very fine sand range (Folk, 1964, pp. 81, 107). Prolonged abrasion during bedload transport in intertidal environments also results in size reduction of feldspar grains, so that the feldspar grains are finer and less rounded than the associated quartz sands (Balazs and Klein, 1972).

The presence of large numbers of rounded and highly rounded feldspar grains and the absence of any significant size difference between these grains and the associated rounded quartz grains (Fig. 15) therefore contradicts the assumption of grain rounding in high-energy environments.

Paucity of feldspar in the Damla Gutta Sandstone and in the upper part of the Ramgundam Sandstone may lend support to the idea of beach rounding. Virtual elimination of feldspar from the upper part of the Ramgundam Sandstone, along with a few other textural changes, viz., almost complete elimination of matrix and fairly uniform high degree of rounding of most of the grains (Figs. 11, 12; Fig. 7, samples 20 and 76B/66) strongly suggest vigorous reworking by surf action in barrier island-beach dune environments (cf. Table II). Probably some grain rounding took place in this environment of high kinetic energy. This perhaps also resulted in the homogenisation of the sharp difference of roundness between the two populations of grains (Fig. 7, sample 20, 76B/66) in the upper part, in contrast to the lower part (Fig. 7, samples 6A/65, R/44C/66) where it is so prominent. However, the elimination of feldspar from the Damla Gutta Sandstone cannot very reasonably be attributed simply to surf action, because feldspar is absent from both the round and the angular populations. Also, the high matrix content of these rocks and the presence of a relatively large number of angular and subangular grains compared to rounded and well-rounded grains (Fig. 4) do not support the hypothesis of final deposition in an environment of high kinetic energy. Causes of the elimination of feldspar from this texturally inverted quartzarenite of typical orthoquartzite-carbonate facies are, therefore, to be ascribed to processes other than reworking by surf action. Feldspar loss may have been caused by intense chemical weathering of the source rock under very stable tectonic conditions (Pettijohn, 1957, p. 300; Pettijohn et al., 1972, p. 227).

Surf action might have accomplished some grain rounding during part of the deposition of the Pakhal sands, but this idea cannot be invoked to explain the high grain roundness typical of all the Pakhal sand deposits.

A possible alternative explanation of the textural inversions and the high degree of grain roundness is the mixing of rounded and angular grains in a common area of deposition, after transportation by two different agencies, one causing a high degree of rounding of quartz and feldspar grains, and the other affecting them to a lesser degree (Fig. 18B). Elimination of chemical solution and surf action as possible rounding agencies leaves eolian transportation as the most probable single agency responsible for the high degree of rounding of first-cycle quartz and feldspar grains of the Pakhal sands. Uniform high degree of rounding of sand grains is a characteristic feature of Recent eolian sands (McCarthy, 1935; Twenhofel, 1945) and also of ancient eolianities (Dake, 1921; Shotton, 1937). Experimental studies (Kuenen, 1960) proved the effectiveness of wind action in rounding sand grains, even those up to fine sand grade (grain diameter 0.5—0.4 mm). In this study, rounding by eolian action is shown to be independent of the grain composition. Rounding by eolian action is achieved mainly during non-aqueous transportation and is independent of the processes operating at the final site of deposition, and unrelated to the degree of roundness of the grains in sediments brought to the same site by other non-eolian (possibly aqueous) agencies. Such a process of eolian rounding of the sand grains and their final deposition in an aqueous environment together with water-transported sediments, therefore, is capable of explaining the presence of well-rounded grains, including fresh feldspar grains, in texturally immature rocks.

Discussion on the mode of grain rounding in the Pakhal sandstones

The mineral grains of Pakhal sedimentary rocks are considered to have been rounded by wind action during eolian transportation to the site of deposition. It is probable that during Middle Proterozoic time, eolian processes were more effective, and played a far more important role, than they do to-day, because of the absence of vascular plants (Pettijohn et al., 1972, p. 507).

The grain-size analyses of these rocks indicate that except in the Damla Gutta Sandstones, rounded and well-rounded grains plot on a straight line on probability paper (Figs. 19, 20), probably indicating that they belong to a single population. The curves for the total sand fraction and the less round grains, however, show inflections, suggesting admixtures of more than one

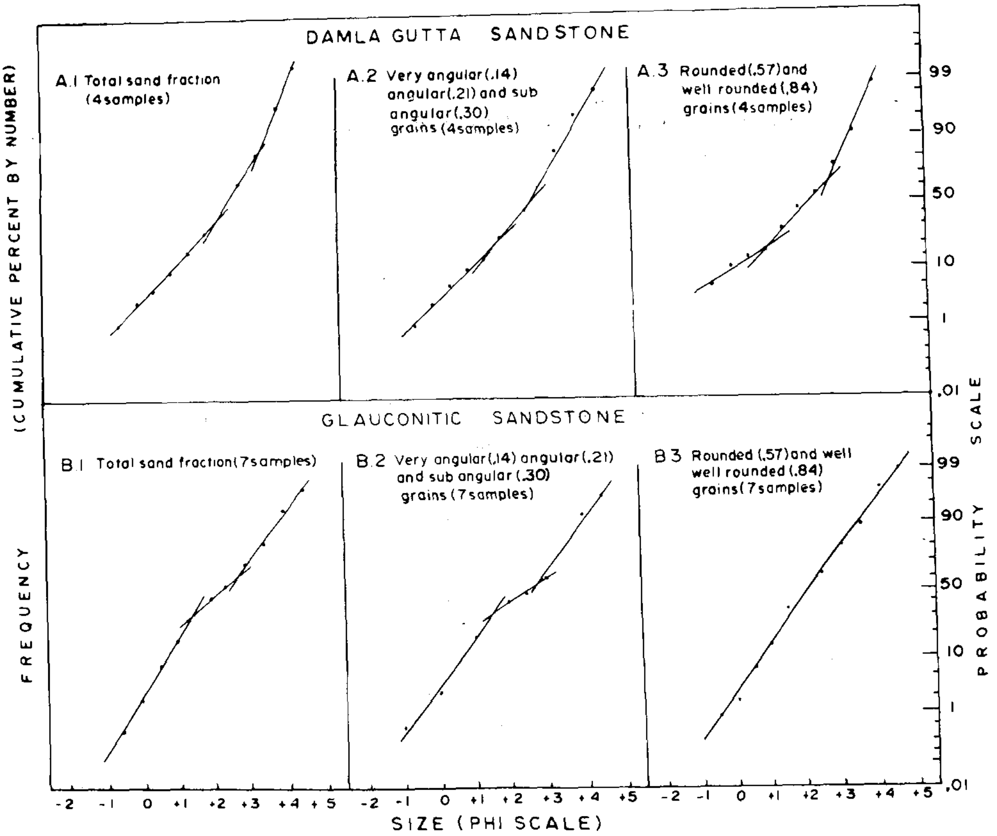


Fig. 19. Cumulative grain-size frequency curves for:
A: Damla Gutta sandstone.
A. 1: total sand fraction.
A. 2: very angular (.14), angular (.21) and sub-angular (.30) grains.
A. 3: rounded (.57) and well rounded (.84) grains.
B: Glauconitic sandstone.
B. 1: total sand fraction.
B. 2: very angular (.14), angular (.21) and sub-angular (.30) grains.
B. 3: rounded (.57) and well rounded (.84) grains.

population of grains. The unimodal grain-size distribution and fairly good sorting of the round grains also suggest eolian transport. The size distribution of the rounded grains of the Damla Gutta Sandstone, however, are polymodal and are very similar to those for either the total sand fraction or the less rounded fraction (Fig. 19). These polymodal size distributions (Figs. 16, 17) closely approximate size distribution patterns of desert flat deposits produced by deflationary eolian processes (Folk, 1968, figs. 2, 4; Pettijohn et al., 1972, pp. 218, 224).

The orthoquartzite—carbonate association, presence of glauconite, algal stromatolites, mud cracks, flat-topped ripple marks, interference ripple marks,

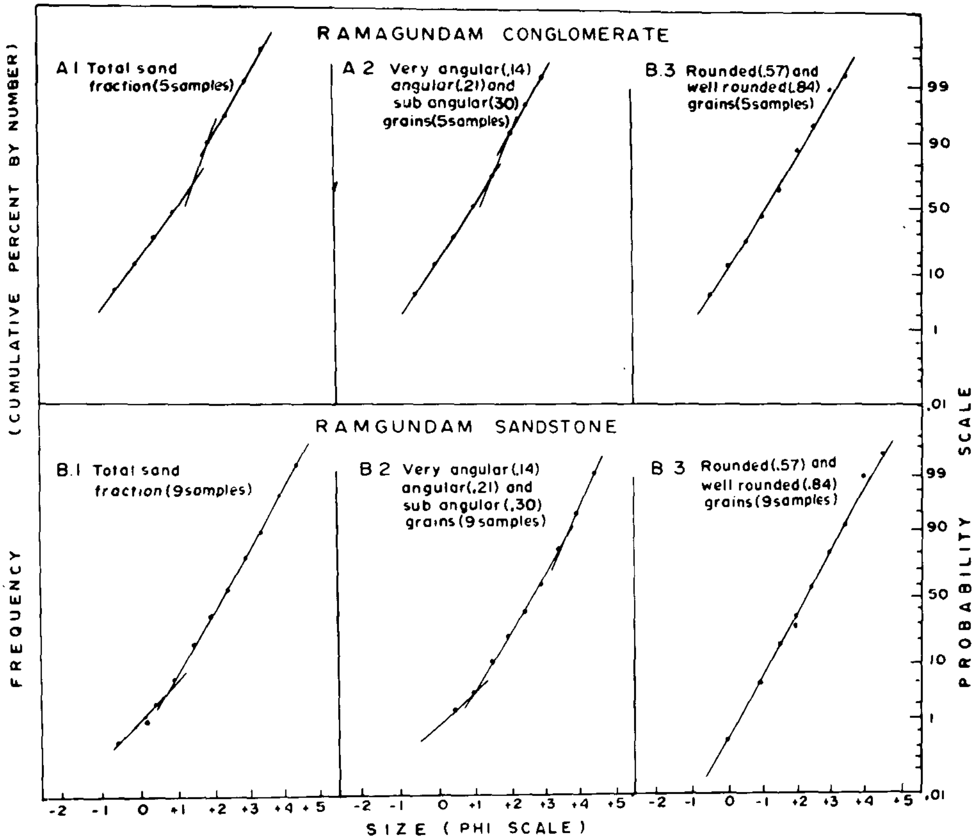


Fig. 20. Cumulative grain-size frequency curves for:
A: Sand fraction of the Ramgundam Conglomerate.
 A. 1: total sand fraction.
 A. 2: very angular (.14), angular (.21) and sub-angular (.30) grains.
 A. 3: rounded (.57) and well rounded (.84) grains.
B: Ramgundam Sandstone.
 B. 1: total sand fraction.
 B. 2: very angular (.14), angular (.21) and sub-angular (.30) grains.
 B. 3: rounded (.57) and well rounded (.84) grains.

ripple-drift-laminations, penecontemporaneous limestone pebble-conglomerates etc., suggest that the original Pakhal sediments are essentially shallow-water, shoreline deposits (Chaudhuri, 1970b). The air-borne clastics were deposited in these near-shore environments and were mixed with less well-rounded grains transported as aqueous load. The polymodal sands of the Damla Gutta Formation probably formed as deflationary desert deposits, in areas marginal to the depositional sites, and were preserved through incorporation into shallow marine deposits by the slight, repeated transgressions of the sea (Folk, 1968). The rounded grains of the other three sandstone sequences, however, represent the saltated fraction and were blown into the marginal sites of deposition. The absence of other properties of eolian sand is explained by the eventual sub-aqueous condition of deposition and by reworking by the current system operating at the depositional site. Accumulation of large quantities of eolian sands along either inland lakes or marine embayments and reworking of most of such sands into marine shoreline and fluvial-deltaic deposits is a well known phenomenon (Pettijohn et al., 1972, p. 508, 513). It is probable that these processes were more common on bare Proterozoic surfaces.

Discussion on the textural inversions of the Pakhal sandstones

The explanation of the high degree of roundness of the Pakhal sandstones and the mixing of eolian and aqueous sands in common areas of deposition, has significant bearing on the interpretation of textural inversions in sandstones. Textural inversions in sandstones are generally considered to be the results of mixing of sands from either different sources or different environments (Pettijohn, 1957; Folk, 1964). The types of textural inversions in the Pakhal sands may be summarised as follows:

I, Rounded grains in clayey matrix
II, Abnormal size/roundness relations
III, Bimodal roundness in same size grade
IV, Well-sorted bimodal sediments

Of these, types I and III are attributed to mixing of sediments from two different environments (Folk, 1964, p. 104), and types II and IV are attributed to derivation from multiple sources (Pettijohn, 1957; Folk, 1964). Type IV has also been considered a result of the processes operating on deflationary desert flats.

The present study suggests that even though the type IV inversion may be a product of deflationary desert flats, the other types were neither the result of derivation from multiple sources nor the result of mixing of sands from different environments. The textural inversions in the studied sands are interpreted to be caused by mixing of sands transported by two different agencies, eolian and aqueous, even though derived from the same source and deposited in similar environments.

CONCLUSIONS

Textural and mineralogical studies of the Pakhal sandstones bring out the following points:

(1) First-cycle Pakhal sands were rounded by abrasion during eolian transport and were deposited in nearshore, marine environments together with water-transported, angular sediments.

(2) The textural inversion in the Pakhal sandstones are the results of the mixing of sands transported by eolian and fluvial processes.

(3) An arid, desert-like climate prevailed during Middle Proterozoic time in the areas adjoining the basin of the Pakhal sands. Wind was the most important sediment-transporting agency and effectively rounded the sand particles.

(4) This study suggests that highly rounded, mature sands can form in large volume directly from crystalline rocks in a single cycle of sedimentation.

(5) Eolian processes are most effective in rounding sand particles.

(6) Eolian processes were probably more effective in Proterozoic time than at present, and many of the rounded-grained, mature sands of that time owe their formation to eolian activities.

(7) Characteristic features of eolian deposits, e.g., primary structures, may be eliminated by eventual deposition in aqueous environments, though textural analysis aided by mineralogical studies can bring out the pre-depositional eolian history.

(8) Highly rounded, fresh grains of feldspar in any sandstone may be considered a good indicator of eolian activity.

(9) Besides the differences of sources and environment, contrasting mechanisms of transport may cause textural inversions in sandstones.

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