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# Microtextures on detrital quartz grains of upper Maastrichtian-Danian rocks of the Cauvery Basin, Southeastern India: implications for provenance and depositional environments

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**ABSTRACT: Quartz grains from the Kallamedu (late Maastrichtian) and lower Niniyur (Danian) Formations, Cauvery Basin, Southeast India were examined under a scanning electron microscope, and twenty three distinct microtextures were observed. These microtextures have been grouped into three modes of origin, viz. mechanical (thirteen features), mechanical and/or chemical (five features) and chemical (five features) origins. Quartz grains from the Kallamedu and lower Niniyur Formations show conchoidal fractures, straight steps and arcuate steps which are the characteristic microtextures of quartz grains derived from crystalline source rocks. Quartz grains from the upper Kallamedu and lower Niniyur Formations show angular to subangular outline, whereas those from the lower Kallamedu Formation show subangular to rounded outline. The dominance of angular to subangular grains and the presence of straight and arcuate steps suggest that these clastic sediments were undergone short transportation and rapid deposition. The presence of rounded grains in the lower part of the Kallamedu Formation suggests that significant amounts of quartz grains are of recycled origin. Vs, straight scratches and curved scratches, the characteristic features of marine environment, are common on the quartz grains from the lower Niniyur Formation, which is consistent with the previous interpretation. However, quartz grains from the lower Kallamedu Formation exhibit very low frequency of these features, whereas they are moderately present in the upper Kallamedu Formation, suggestive of a change in depositional conditions with time. The lower Kallamedu Formation exhibits planar and trough cross-beddings, which suggests the fluvial depositional environment. The unfossiliferous upper Kallamedu Formation contains appreciable amount of illite and mixed-layer (illite/smectite) clay minerals, which suggests that the saline conditions prevailed during its deposition. Microtextures on the quartz grains coupled with dominant clay mineral types suggest the deltaic depositional environments for the upper Kallamedu Formation.**

**Key words:** microtextures, late Maastrichtian-Danian, provenance, depositional environments, Cauvery Basin, India

## 1. INTRODUCTION

The study of microtextures on quartz grains (>200 μm) with scanning electron microscopy (SEM) techniques has developed into a major method for interpreting sedimentary environments and transport mechanisms (Krinsley and Funnel, 1965; Margolis and Krinsley, 1974; Krinsley and McCoy, 1977; Bull, 1981; Krinsley and Marshall, 1987; Helland and Diffendal, 1993; Mahaney, 1995; Mahaney et al., 1996; Madhavaraju et al., 2004a; Armstrong-Altrin et al., 2005). The microtextures on quartz grains provide evidence of both mechanical and chemical processes acting on the grains during transportation and after depositon (Krinsley and Funnell, 1965; Doornkamp and Krinsley, 1971; Bull, 1981; Carter, 1984; Mahaney et al., 1996; Moral-Cardona et al., 1996, 1997; Mahaney, 1998; Newsome and Ladd, 1999). The typical microtextures for differentiating mechanical and chemical origin and their environmental implications were discussed by many authors (Krinsley and Doornkamp, 1973; Whalley and Krinsley, 1974; Krinsley et al., 1976; Rahman and Ahmed, 1996; Newsome and Ladd, 1999). Thus, the microtextural study on quartz grains can assist in the identification of provenance, processes of transport and diagenetic changes of the sediments. Microtextures of mechanical origin are formed by frequent impacts and abrasions on the quartz grains during transportation in various dynamic environments. Likewise, chemical origin refers to the microtextures formed by various types of etching and overgrowth.

Quartz grains from aeolian environment show well rounded and dull, with low relief and display several "upturned plates" on their surfaces (Abu-Zeid et al., 2001), whereas quartz grains from marine environment generally exhibit partially rounded, frequently polished, with several protrusions and smooth edges (Krinsley and Trusty, 1985; Moral-Cardona et al., 1997). Based on the various types of microtextures observed on the quartz grains, it is possible to identify particular depositional environments such as aeolian, marine, and glacial.

The Cauvery Basin is situated adjacent to the Deccan Traps in Southeast India (Fig. 1), but the depositional environments across the Cretaceous-Paleocene boundary in the Cauvery Basin are poorly known. We report here the results

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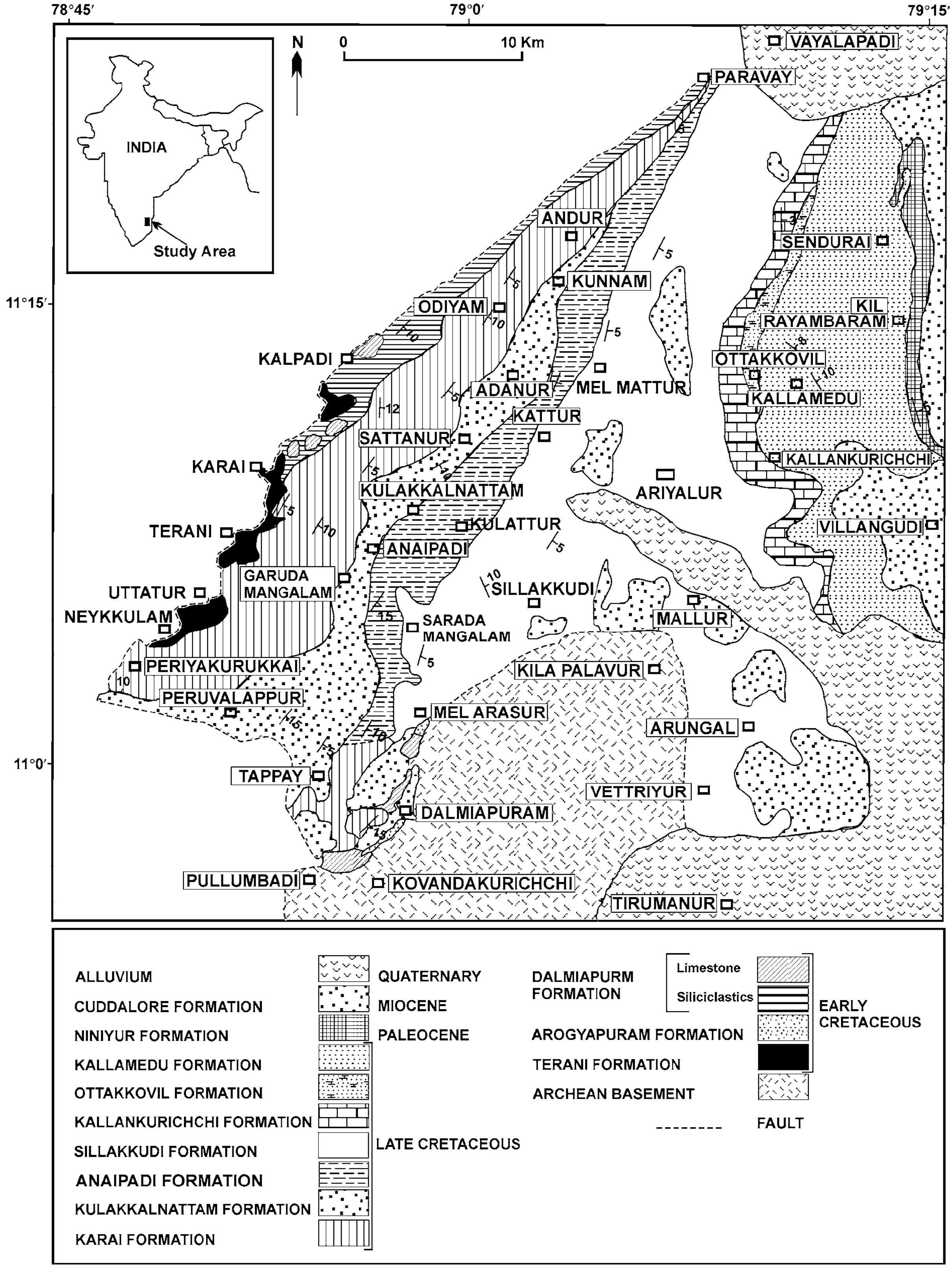


**Fig. 1.** Geological map of the Ariyalur area of the Cauvery Basin (modified after Sundaram et al., 2001).

of the study on the provenance and depositional environments of a sedimentary succession of late Maastrichian-Danian age by studying microtextural characters on quartz grains. A number of works have been carried out on the paleontology and sedimentology of the Cauvery Basin, however there exist few systematic studies on the provenance and depositional environments. The purposes of this study are to describe the microtextural characteristics of quartz grains from the Kallamedu (late Maastrichtian) and lower Niniyur (Danian) Formations, to unravel the provenance, and to discuss the changes in depositional environments through time.

## 2. GEOLOGY AND STRATIGRAPHY

The Cauvery Basin is considered as a rift basin which was developed as a result of Mesozoic extension during the break up of Gondwanaland (Prabhakar and Zutshi, 1993; Rangaraju et al., 1993). The Cauvery Basin contains thick accumulation of sediments (around 6 km) which were deposited on Archean basement (Rangaraju et al., 1993). The sedimentary rocks of Cretaceous age are well exposed in five isolated areas (Pondicherry, Vridhachalam, Ariyalur, Tanjore and Sivaganga) of the Cauvery Basin (Banerji, 1972). Among these areas, clastic and carbonate rocks of Cretaceous-Paleocene age are well developed in the Ariyalur area (Fig. 1). Many studies have been carried out on these sedimentary rocks, including stratigraphy, paleontology, clay mineralogy, geochemistry and tectonic evolution (Sastry et al., 1972; Nair, 1974; Ramanathan, 1979; Sundaram and Rao, 1986; Ramasamy and Banerji, 1991; Govindan et al., 1996; Madhavaraju, 1996; Madhavaraju and Ramasamy, 1999; Sundaram et al., 2001; Madhavaraju et al., 2002, 2004b).

Blanford (1862) divided Cretaceous sedimentary rocks into three distinct groups based on the lithological characters, i.e., the Uttatur, Trichinopoly and Ariyalur Groups. The Ariyalur Group is more widely exposed than the other two. Sastry et al. (1972) subdivided the Ariyalur Group into four formations, namely the Sillakkudi, Kallankurichchi, Ottakkovil and Kallamedu Formations with decreasing age (Fig. 2). Later, Sundaram and Rao (1986) studied the Cretaceous-Paleocene rocks and gave the detailed lithostratigraphic classification. They proposed the separate formation status to Paleocene rocks, the Niniyur Formation.

No detailed and systematic approach has been made to study the depositional conditions during the terminal Cretaceous and early Paleocene time (across the K/T boundary) in the Cauvery Basin. The Kallamedu Formation, the uppermost upper Maastrichtian sedimentary rocks, is the youngest stratum of the Ariyalur Group, and is generally interpreted to have been deposited in the fluvial environment. It mainly consists of sandstone, siltstone, silty shale and shale. It is generally unfossiliferous except for abundant dinosaurs bones which are yielded in some sandstone-siltstone rocks (Lydekker, 1879; Matley, 1929; Yadagiri and Ayyasami, 1987; Madhavaraju, 1996).

The Niniyur Formation (Early Paleocene) overlies the Kallamedu Formation conformably (Sundaram and Rao, 1986; Sundaram et al., 2001) and comprises calcareous sandstone, sandy claystones and limestone. Fossils of the Niniyur Formation are indicative of Early Paleocene in age (Leveille, 1889, Sastry et al., 1965, Mallikarjuna, 1996).

In the Ariyalur area three sections reveal good outcrop exposure (Kallamedu, Niniyur and Ellaikadambur sections; Fig. 3). The Kallamedu section comprises the lower Kal-

| Group | Formation | Lithology | Thickness (m) | Age |
|---|---|---|---|---|
| | Niniyur | Calcareous sandstone, fossiliferous limestone and claystone | 50-100 | Danian |
| ARIYALUR | Kallamedu | Unfossiliferous fine- to coarse-grained sandstone interbedded with siltstone, claystone, shale and marl | 60-100 | Maastrichtian |
| | Ottakkovil | Fossiliferous calcareous sandstone interbedded with claystone | 0-60 | |
| | Kallankurichchi | Fossiliferous calcareous conglomeratic sandstone, fossiliferous calcareous sandstone interbedded with claystone, sandy fossiliferous limestone, fossiliferous limestone and marl | 10-40 | |
| | Sillakkudi | Unfossiliferous to fossiliferous calcareous sandstone, interbedded with claystone and thin band of sandy limestone | 300-500 | Campanian |
| Trichinopoly | | | | Late Turonian to Santonian |

**Fig. 2.** Lithostratigraphy of the Ariyalur Group, Cauvery Basin (modified after Sastry et al., 1972).

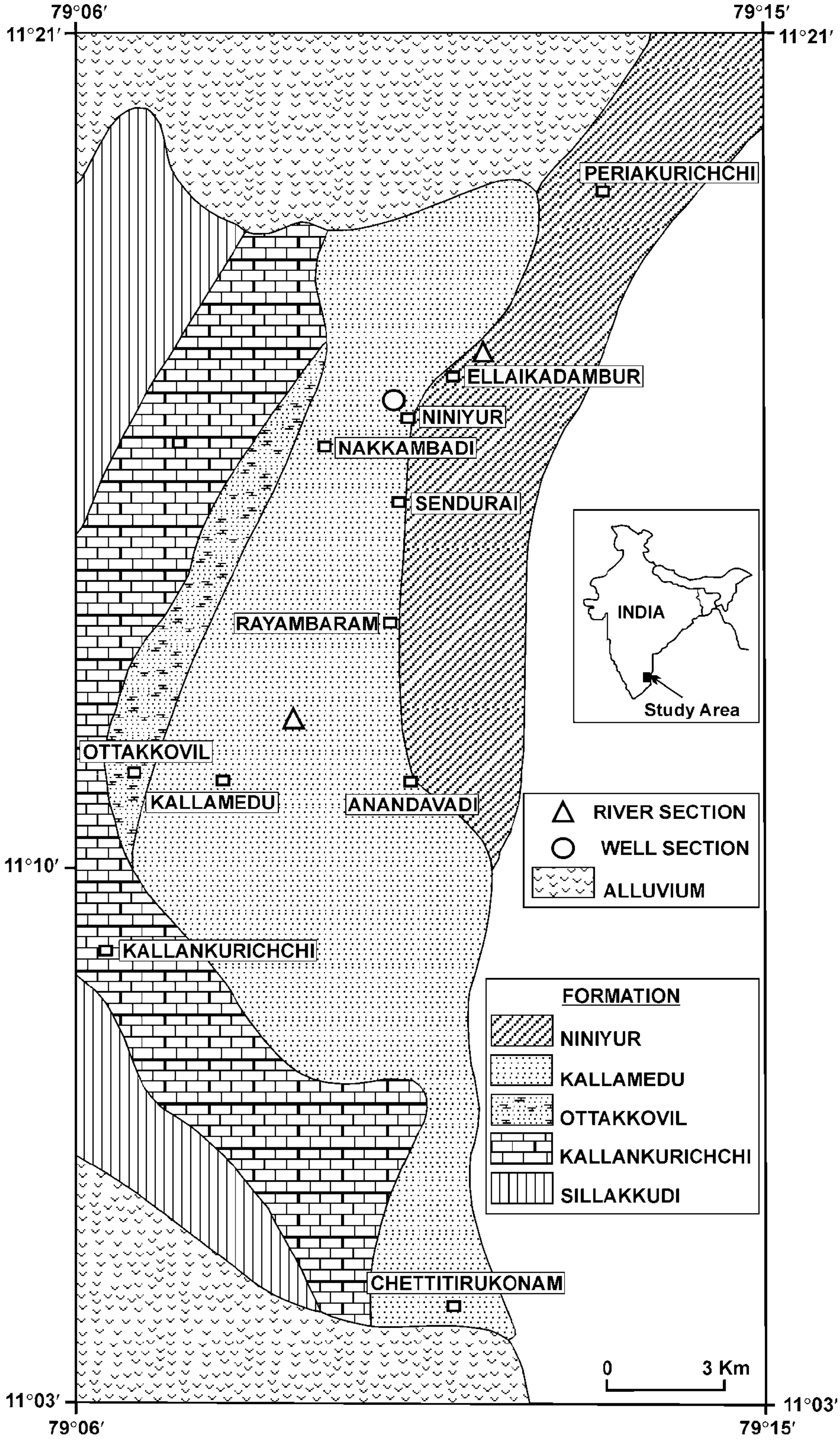


**Fig. 3.** Geological map showing sample locations.

lamedu Formation and exhibits a sandstone and siltstone succession. The sandstones are poorly consolidated, medium to coarse grained, and poorly sorted, and show various colors from light grey to white. They exhibit well-developed cross stratification and yield fragments of dinosaurian remains.

Five beds are identified at the Niniyur section, representing about 2 m thick nonfossiliferous upper Kallamedu Formation, and comprise various lithologies such as, from the base up, calcareous sandstone, thin band of limestone, silty shale, greenish shale and yellowish shale. The sandstone bed is about 1.4 m thick and varies in color from light grey to light brown, fine to medium grained, and contains clay pockets. The limestone bed is nodular and is 10 cm thick. The green silty shale (10 cm) contains fine-grained quartz silts. The succeeding bed of compact greenish shale is 15 cm thick and is overlain by a thin (2 cm) layer of yellowish shale.

The Ellaikadambur section (3.1 m thick) represents the lower Niniyur Formation, and is composed of clastic and carbonate rocks. Lithologies are: lower calcareous sandstone nodular limestone, middle calcareous sandstone, clay bed, upper calcareous sandstone and fossiliferous limestone. The sandstones are fossiliferous, light brown, fine to medium grained, and contain significant amount of argillaceous materials.

Based on the lithological variations and fossil evidence the boundary between the Cretaceous and Paleocene (K/T boundary) has been set between the Niniyur and Ellaikadambur sections (Madhavaraju et al., 2002).

## 3. METHODOLOGY

Fourteen samples were collected from the three sections of the Kallamedu (upper Maastrichtian) and Niniyur Formations (Danian) (Fig. 3). Sedimentary rocks of these formations were collected from stream sections (Kallamedu and Ellaikadambur) and well section (Niniyur). Approximately 20 g of each sample were treated with dilute hydrochloric acid to remove calcium carbonate, and washed with distilled water. Subsequently, the obtained residue materials were reacted with $H_2O_2$ solution to remove organic matter. Some quartz grains exhibit iron coatings and these coatings were removed by boiling the samples using stannous chloride solution. Then, the sediments were washed several times with distilled water. The treated samples were sieved to separate the sand size fractions. Quartz grains between 200 and 400 μm sizes were selected, as they generally bear most of the pre- and post- depositional features in any given environment (Krinsley and McCoy, 1977). Quartz grains were hand-picked under a binocular microscope, mounted on scanning electron microscope (SEM) stubs, sputter-coated with gold, and examined using a JEOL scanning electron microscope. Twenty quartz grains were selected from each sample for the present study, which is considered as sufficient to represent the variability present in a single sample and also to interpret the depositional environments (Krinsley and Doornkamp, 1973; Baker, 1976). Nine samples from the Kallamedu and five samples from the lower Niniyur Formations were selected for a microtextural study. The environmental implications of different types of quartz grain microtextures have been established by Higgs (1979) using published data by various authors (Krinsley and Donahue, 1968; Krinsley and Margolis, 1971; Margolis and Kennet, 1971, Krinsley and Doornkamp, 1973; Le Ribault, 1975). Bull et al. (1987) and Mahaney et al. (1996) have also discussed different types of microtexture.

## 4. MICROTEXTURE

Microtextures on quartz grains (Table 1) are considered as indicators of mechanical and chemical processes prevailing in various sedimentary environments. In the present study, twenty three types of microtextures (Figs. 4-6) have been identified and are summarized in Table 2. These microtextures were divided into various groups according to their origin. Thirteen microtextures are of mechanical origin, five microtextures of mechanical and/or chemical origin and five microtextures of chemical origin. Among five microtextures of chemical origin one feature is of dissolutional origin, whereas four features are characteristic of precipitational origin. The important characters of each microtexture are discussed below in detail.

Quartz grains from the Kallamedu and lower Niniyur Formations show various sizes of pits (Fig. 4A, B). These irregular pits are generally divided into three types, viz. small, medium and large, and these pits have widespread environmental distribution (Higgs, 1979). Small and medium pits are common in all stratigraphic levels. Large pits are common in the upper Kallamedu Formation, whereas these pits are sparsely distributed on the quartz grains from the lower Kallamedu and lower Niniyur Formations. Conchoidal fractures are most common and frequently observed on quartz grains. These features are categorized as small, medium and large based on the size of the fracture. Small to large conchoidal fractures (Fig. 4C-F) are most common on quartz grains from the upper Kallamedu and lower Niniyur Formations, whereas quartz grains from the lower Kallamedu Formation show small to medium conchoidal fractures. Straight and arcuate steps (Fig. 4G) are closely associated with conchoidal fractures. The frequency of straight steps is more in the lower Niniyur Formation, whereas it is less in the lower and upper Kallamedu Formations. Arcuate steps are common on quartz grains from all stratigraphic levels. Straight scratches (Fig. 4H) are moderately present in the upper Kallamedu and lower Niniyur Formations, whereas they are sparsely distributed on the quartz grains from the lower Kallamedu Formation. Curved scratches (Fig. 4H) are sparse on quartz grains from the lower Kallamedu Formation, whereas they are more common on quartz grains from the upper Kallamedu and lower Niniyur Formations. The length of scratches varies from 5 to 100 microns.

Most of the quartz grains from the upper Kallamedu and lower Niniyur Formations exhibit angular to subangular outlines (Fig. 5A), whereas subangular to rounded outlines (Fig. 5B) are common on quartz grains from the lower Kallamedu Formation. Rounded outline of the quartz grains is

**Table 1.** Microtextures as observed in clastic rocks of the Kallamedu and lower Niniyur Formations

| Sample No. | Microtextures |
|---|---|
| *lower Niniyur Formation* | |
| KTA1 | Small pits, medium pits, large pits, small conchoidal fractures, medium conchoidal fractures, large conchoidal fractures, curved scratches, straight steps, arcuate steps, adhering particles, fractured plate, deep depression, Vs, subangular outline and high relief |
| KTA2 | Small pits, medium pits, small conchoidal fractures, medium conchoidal fractures, large conchoidal fractures, straight scratches, curved scratches, arcuate steps, adhering particles, Vs, subrounded outline, high relief, silica flowers and silica pellicle |
| KTA3 | Small pits, large pits, small conchoidal fractures, medium conchoidal fractures, large conchoidal fractures, straight scratches, curved scratches, adhering particles, fractured plate, Vs, oriented etch pits, subangular outline, high relief and silica globules |
| KTA5 | Small pits, medium pits, medium conchoidal fractures, large conchoidal fractures, curved scratches, arcuate steps, adhering particles, Vs, subangular outline and high relief |
| KTA7 | Small pits, medium pits, small conchoidal fractures, medium conchoidal fractures, straight scratches, curved scratches, adhering particles, Vs, subangular outline and high relief |
| *upper Kallamedu Formation* | |
| KT1 | Small pits, large pits, small conchoidal fractures, medium conchoidal fractures, curved scratches, adhering particles, rounded outline and medium relief |
| KT3 | Small pits, medium pits, large pits, small conchoidal fractures, medium conchoidal fractures, large conchoidal fractures, straight scratches, curved scratches, Vs, straight steps, adhering particles, rounded outline and medium relief |
| KT6 | Small pits, medium pits, large pits, small conchoidal fractures, medium conchoidal fractures, large conchoidal fractures, straight scratches, curved scratches, Vs, upturned plates, adhering particles, subangular outline, high relief and silica globules |
| KT9 | Small pits, medium pits, large pits, small conchoidal fractures, medium conchoidal fractures, large conchoidal fractures, straight scratches, curved scratches, arcuate steps, upturned plates, adhering particles, Vs, subangular outline, high relief and silica overgrowth |
| KT12 | Small pits, medium pits, large pits, small conchoidal fractures, medium conchoidal fractures, curved scratches, adhering particles, rounded outline and high relief |
| *lower Kallamedu Formation* | |
| F26 | Small pits, medium pits, small conchoidal fractures, straight scratches, curved scratches, adhering particles, rounded outline and medium relief |
| F27 | Medium pits, small conchoidal fractures, adhering particles, arcuate steps, curved scratches, rounded outline and low relief |
| F29 | Small pits, medium pits, large pits, small conchoidal fractures, medium conchoidal fractures, curved scratches, subangular outline and high relief |
| F30 | Small pits, medium pits, medium conchoidal fractures, large conchoidal fractures, straight steps, arcuate steps, adhering particles, subangular outline and high relief |

related to the grain modification in eolian environments (Krinsley and Smalley, 1973) or under beach energy (Gravenor, 1985).

Quartz grains from the lower Niniyur Formation show V-shaped patterns (Fig. 5C, D), whereas the frequency of this feature is moderate in the upper Kallamedu Formation but low in the lower Kallamedu Formation.

Fracture plates/planes (Fig. 5E, F) are found on the quartz grains from the lower Niniyur Formation. The intensity of fracturing is more in the lower part of the Ellaikadambur section whereas the intensity of these fractures is gradually reducing towards the top of the sequence.

Quartz grains from the Kallamedu and lower Niniyur Formations show various types of relief, i.e., low, medium and high (Figs. 5G–6A). Most of the quartz grains from the Kallamedu Formation show medium to high relief, whereas some grains exhibit low relief. High relief is common on quartz grains from the lower Niniyur Formation, while some grains reveal low and medium relief. The relief of these grains has been identified mainly based on the extent of alteration of surface of the grain by either single or various types of microtextures. Adhering particles (Fig. 6B) are distributed on the quartz grains from the Kallamedu and lower Niniyur Formations.

The lower Niniyur Formation only exhibits oriented etch pits (Fig. 6C, D). These pits resulted from chemical action (dissolution) on quartz grains, which perhaps formed in the marine environment (Higgs, 1979). This feature is rare in the intertidal environment, whereas the frequency of this feature increases towards offshore (Nordstrom and Marg-

**Table 2.** Microtextures on quartz grains of the Kallamedu and lower Niniyur Formations

| Features | lower Kallamedu Formation | upper Kallamedu Formation | Lower Niniyur Formation |
|---|---|---|---|
| *Mechanical origin* | | | |
| Small pits | C | C | C |
| Medium pits | P | P | P |
| Large pits | S | P | S |
| Small conchoidal fractures | C | C | A |
| Medium conchoidal fractures | C | P | P |
| Large conchoidal fractures | S | P | P |
| Straight steps | S | S | P |
| Arcuate steps | P | C | C |
| Straight scratches | S | P | P |
| Curved scratches | S | C | A |
| Subangular outline | P | C | A |
| Rounded outline | C | S | S |
| V's | S | P | A |
| *Mechanical/Chemical origin* | | | |
| Fractured plates/planes | - | - | S |
| Low relief | S | S | S |
| Medium relief | C | C | S |
| High relief | C | C | A |
| Adhering particles | P | C | C |
| *Chemical origin* | | | |
| Oriented etch pits | - | - | P |
| Silica globules | - | S | S |
| Silica flowers | - | - | S |
| Silica pellicle | - | - | S |
| Crystalline overgrowth | - | S | - |

A=Abundant (>75%); C=Common (50–75%); P=Present (25–50%); S=Sparse (5–25%)

olis, 1972). This feature more or less resembles isosceles triangle in outline and generally occurs in sets at regular individuals, measuring up to 1 mm in diameter (Krinsley and Doornkamp, 1973).

Quartz grains from the upper Kallamedu Formation exhibit two types of chemical (precipitational) features, i.e., silica globules and crystalline overgrowth, whereas those of the lower Niniyur Formation show three types of chemical (precipitational) features, viz. silica globules, silica flowers and silica pellicle. Silica globules show smooth silica veneers, whereas silica pellicles exhibit plate/sheet like structures with a rough appearance. Silica globules (Fig. 6E) are observed on the quartz grains from the upper Kallamedu and lower Niniyur Formations, showing smooth appearance as if silica overprinting has taken place. This feature generally forms on immovable grains in contact with solutions, which are supersaturated with silica.

Silica flowers and silica pellicle (Fig. 6F, G) are only sparsely distributed on the quartz grains from the lower Niniyur Formation. The growth of silica globules may result in silica flower. These flowers form in groups on protected parts of the grain surfaces, where stagnated pore fluids having supersaturated silica are available (LeRibault, 1975). Coalescence of silica globules will lead to the formation of silica pellicle (LeRibault, 1975). This pellicle may grow on certain part or entire surface of the grain depending upon the availability of fluids, which are supersaturated with respect to silica. In some cases, the precipitated silica plate/sheet (silica pellicle) may mask the earlier-formed microtextures partly or entirely, and this feature appears to be formed during the final stage.

Quartz grains from the upper Kallamedu Formation show minor crystalline overgrowths (Fig. 6H), which exhibit small crystal faces. The difference between the development of silica pellicle and crystalline overgrowth is as follows. The silica pellicle mainly results from the rapid precipitation of amorphous silica, whereas the development of crystalline overgrowth requires more residence time of silica solution. The crystalline overgrowth is found in some quartz grains, which exhibits smaller crystal faces. These overgrowths are much smaller in size than those forming in the subsurface diagenetic environment. Generally, quartz overgrowths formed during the diagenesis exhibit well-developed crystal faces. So, it sug-

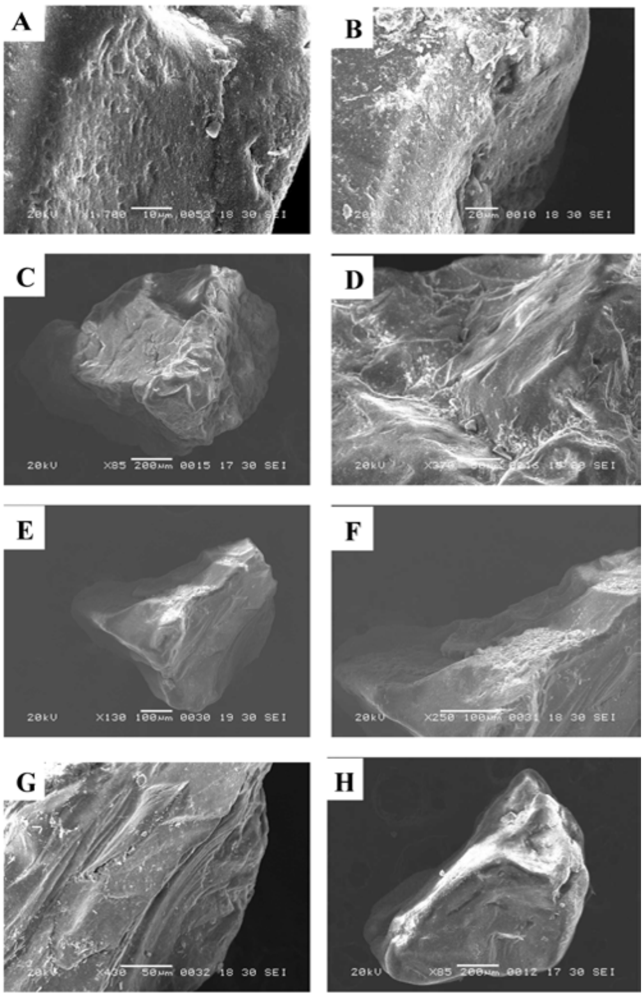


**Fig. 4.** (**A**) Quartz grain from the lower Niniyur Formation showing small and medium pits. (**B**) Quartz grain from the lower Kallamedu Formation showing close up view of large pits. (**C**) Subangular quartz grain shows small and medium conchoidal fractures (upper Kallamedu Formation). (**D**) Quartz grains from the upper Kallamedu Formation showing close up view of small and medium conchoidal fractures. (**E**) Large conchoidal fracture on the quartz grain from the lower Niniyur Formation. (**F**) Close up view of large conchoidal fracture in E. (**G**) Straight steps and arcuate steps seen on the quartz grain of the lower Niniyur Formation. (**H**) Subangular quartz grain from the upper Kallamedu Formation exhibits straight and curved scratches.

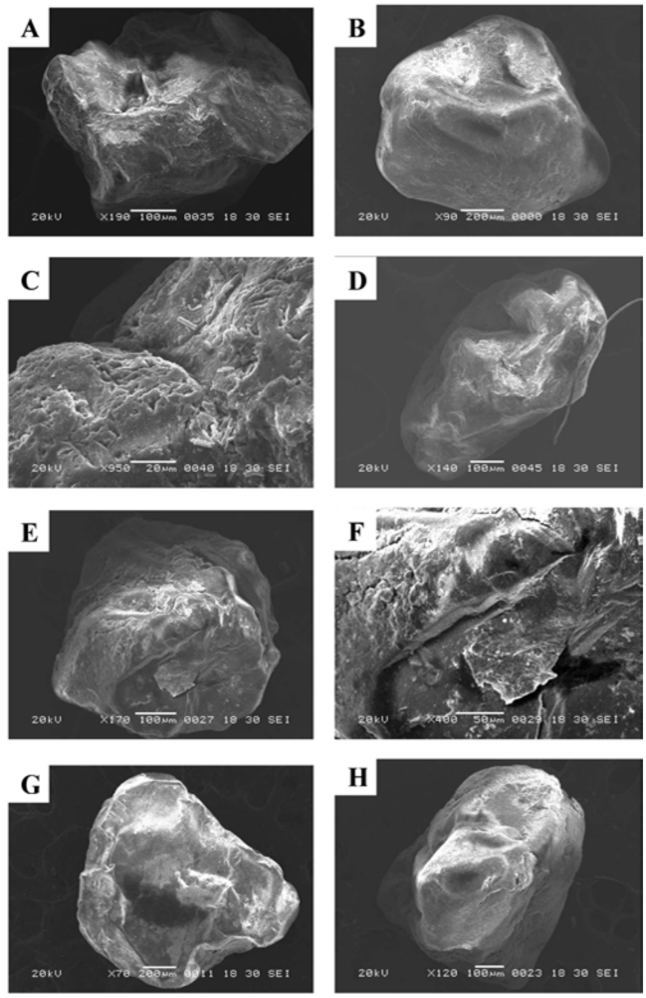


**Fig. 5.** (**A**) Quartz grain from the lower Niniyur Formation showing subangular outline. (**B**) Quartz grain from the lower Kallamedu Formation showing rounded outline. (**C**) Small Vs on the quartz grain from the lower Niniyur Formation. (**D**) Quartz grain from the lower Niniyur Formation showing some large Vs. (**E**) Quartz grain showing fracture plate and deep depression (lower Niniyur Formation). (**F**) Quartz grain from the lower Niniyur Formation showing close up view of fracture plate. (**G**) Subangular quartz grain from the lower Kallamedu Formation showing low relief. (**H**) Quartz grain from the upper Kallamedu Formation exhibits medium relief.

gests that this type of smaller overgrowths likely have formed during pedogenic process.

## 5. PROVENANCE AND DEPOSITIONAL ENVIRONMENT

Quartz grains from the Kallamedu and lower Niniyur Formations show various types of microtextures. Conchoidal fractures are common on the quartz grains from the studied Kallamedu and lower Niniyur Formations, and are closely associated with straight steps and arcuate steps, indicating that many quartz grains were derived from the crystalline source rocks (Krinsley and Margolis, 1969, Krinsley and Smith, 1981). The quartz grains from the upper Kallamedu and lower Niniyur Formations show angular to subangular outline, whereas the lower Kallamedu Formation show subangular to rounded outline. The dominance of angular to subangular grains and the presence of straight steps and arcuate steps reveal that quartz grains in the upper Kallamedu and lower Niniyur Formations were undergone short transportation and rapid deposition. On the contrary, the presence of rounded grains in the lower Kallamedu Formation

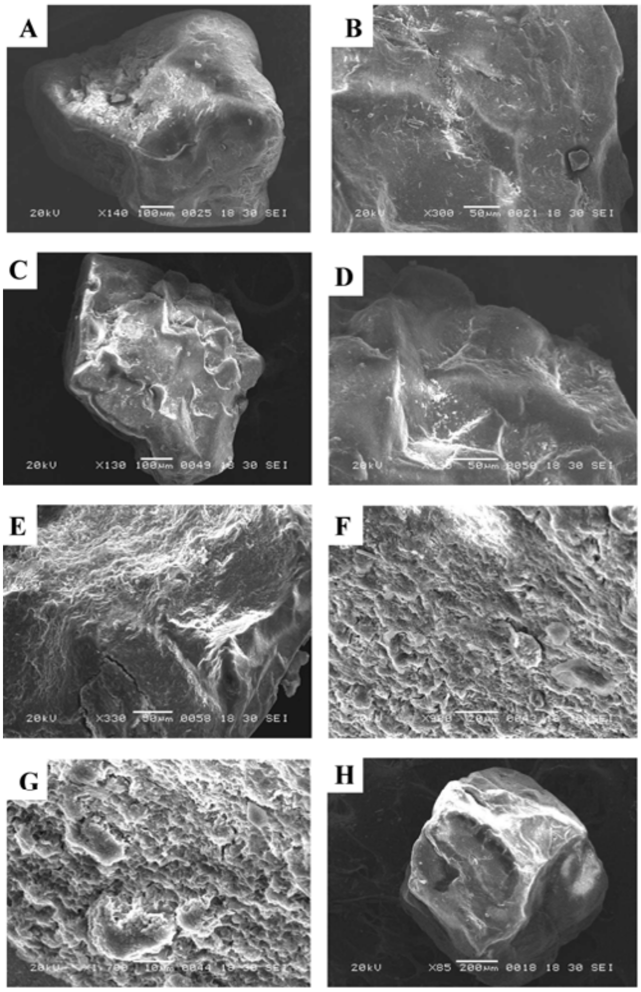


**Fig. 6.** (**A**) Quartz grain showing high relief (lower Niniyur Formation). (**B**) Subangular quartz grain showing adhering particles (upper Kallamedu Formation). (**C**) Quartz grain from the lower Niniyur Formation showing oriented etch pits. (**D**) Close up view of oriented etch pits in upper right of C. (**E**) Quartz grain of the upper Kallamedu Formation showing silica globules. (**F**) Silica flower seen on the surface of the quartz grain (lower Niniyur Formation). (**G**) Quartz grains from the lower Niniyur Formation showing close-up view of silica pellicle. (**H**) Quartz grain showing crystalline overgrowth (upper Kallamedu Formation).

suggests the recycling nature of the sediments. If the clastic sediments of both the Kallamedu and lower Niniyur Formations were subjected to long transportation, the quartz grains from these formations would not exhibit different types of microtextures.

The microtextures such as Vs, straight scratches and curved scratches with varying sizes and shapes are also common on many grains, especially in the lower Niniyur Formation. Vs, straight scratches and curved scratches are seen on quartz grains from marine, fluvial (high energy) and deltaic (seaward) environments. In general, V-shaped patterns are characteristic of littoral environment (Krinsley and Takahashi, 1962; Krinsley et al. 1964). V-shaped patterns result from both mechanical and chemical processes. The Vs resulted from mechanical processes show randomly oriented patterns and are characterised by irregular side and unevenly depressed central portion. On the other hand, oriented V-shaped patterns showing relatively flat inner surface with regular outer edges are probably resulted from chemical etching. In general, Vs are triangular in shape with maximum diameter of 5 microns and their density ranges from 1 to 6 individuals per square micron (Krinsley and Donahue, 1968; Krinsley and Margolis, 1971; Krinsley and Doornkamp, 1973).

V-shaped feature of mechanical origin is caused by gouging when one grain strikes another. It is thought that each V feature having similar orientation might have been caused by one collision between two grains. Thus, one set of Vs may have resulted from projection of one grain striking another grain with linear motion, whereas second collision may cause another set of Vs with different orientation (Krinsley and Donahue, 1968). In the present study, most of the samples studied reveal different orientations of V-shaped patterns, which are characteristic features of mechanical origin. V-shaped patterns of mechanical origin are generally found in subaqueous environment having high-energy conditions. Apart from this, Vs are generally associated with straight and curved scratches, which also supports the mechanical origin for their formation considering that Vs, straight scratches and curved scratches result due to sharp edges on one quartz grain striking another in subaqueous media.

Having defined Vs being of mechanical origin, the density of Vs are mainly related to the energy conditions in the marine environments. Hence, the presence of abundant Vs per square micron on the quartz grains of the lower Niniyur Formation suggests that these features were developed in the marine environment with high energy condition. On the contrary, V-shaped indentations are sparse on quartz grains from the lower Kallamedu Formation, whereas they show moderate abundance in the upper Kallamedu Formation. This upward change in the density of V-shaped indentations suggests the changes in depositional conditions with time.

The lower Kallamedu Formation contains dinosaur bone fragments and exhibits planar cross-bedding and trough cross-bedding, which suggests the fluvial environment for the lower Kallamedu Formation deposition. The microtextural analysis of quartz grains is consistent with this interpretation. The unfossiliferous sandstones of the upper Kallamedu Formation contains appreciable amount of illite and mixed-layer (illite/smectite) clay mineral types (Madhavaraju et al., 2002), which suggests that the saline conditions prevailed during the deposition of these sediments. Microtextures on the quartz grains and dominant clay minerals suggest that these sediments were deposited in the deltaic environment. The clastic rocks of the lower Niniyur Formation contain

**Table 3.** Depositional history based on common microtextures

| Age | Litho-units | Common microtexture | Shape of the quartz grains | Transport dynamics | Provenance characters | Depositional environment |
|---|---|---|---|---|---|---|
| Early Paleocene | Lower Niniyur Formation | Small to medium pits, small to large conchoidal fractures, straight and arcuate steps, straight and curved scratches, Vs, high relief and oriented etch pits | Angular to subangular | Short transportation and rapid deposition in high energy condition | Crystalline source | Marginal marine environment (subtidal) |
| Late Maastrichtian | Upper Kallamedu Formation | Small to large pits, small to large conchoidal fractures, arcuate steps, straight and curved scratches, moderate content of Vs and medium to high relief | Angular to subangular | Short transportation and rapid deposition | Crystalline source | Deltaic environment |
| | Lower Kallamedu Formation | Small to medium pits, small to medium conchoidal fractures, arcuate steps, curved scratches and medium to high relief | Subangular to rounded | Short transportation and rapid deposition in low to medium energy condition and recycling | Crystalline source | Fluvial environment |

fossils such as algae, bryozoa and molluscs (Leveille, 1889; Sastry et al., 1965; Mallikarjuna, 1996), indicative of the shallow marine environment. Apart from this, the quartz grains from the lower Niniyur Formation also show oriented etch pits, which is a characteristic feature of marine environment. It is also supported by the sequence stratigraphic study on mixed clastic and carbonate rocks of the lower Niniyur Formation (Madhavaraju et al., 2006) containing two sequence boundaries and various types of systems tracts (TST, MFS and HST) comprising meter-scale shallowing-upward parasequences of the subtidal cycles.

In summary, the microtextural and field studies reveal that the lower part of the Kallamedu Formation (early late Maastrichtian) was deposited in the fluvial environment, whereas the sedimentary rocks of the upper part of the Kallamedu Formation (latest late Maastrichtian) were deposited in the deltaic environment and this condition continued until the terminal Cretaceous period. Later, the marine transgression took place by which the sedimentary rocks of the Niniyur Formation were deposited in shallow marine environments. The distinct microtextures, grain shape, transport dynamic, provenance and depositional environments are summarized in Table 3.

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