CHAPTER – 7

MICROSCOPIC EVIDENCE OF LATE QUATERNARY SURFACE FAULTING

The present study area, the Katrol Hill Fault (KHF), located in the southern mainland Kachchh, shows excellent exposures of deformed Quaternary sediments due to Late Quaternary surface faulting events. One of the two sites that show deformation in Quaternary deposits is found along the Khari river cliff section (Figure 5.3), located exactly on the fault plane of KHF and displays three surface rupturing events during Late Quaternary (Patidar et al., 2007; 2008; Kundu et al., 2010; Maurya et al., 2017a). The other site, which records deformation in Late Quaternary deposits is located to the south of Bhujodi area (Figure 5.6). As recent events of faulting are recorded by deformation in Late Quaternary deposits within the KHF zone (Patidar et al., 2008; Kundu et al., 2010), it is pertinent to consider the extent to which the exhumed fault rocks record the seismogenic processes. However, along the trace of KHF between the two aforementioned sites, there are no field evidences of neotectonic deformation recorded due to the scattered and sporadic nature of Quaternary deposits, their high erodibility, and the effects of urbanization. The propagation of KHF in to the Quaternary sediments has already been demonstrated by the GPR survey results (Chapter – 6) carried out at locations such as Bharasar, Tapkeshwari, Bhujodi and Ler areas. Thus, these sites provide the evidence of surface faulting. The GPR results are supplemented by microscopic analyses such as petrography and SEM of Late Quaternary deposits exposed along the KHF in order to establish the continuity of surficial deformation by observing the microscopic signatures of tectonic deformation. The fluvial and aeolian microtextures have already been described in detail in Chapter – 4. In this chapter, different microtextures related to tectonic deformation observed on quartz grains are described. These are then correlated and compared with the microtextures reported from various fault related regions of the world. A better understanding is attained about surface faulting related microfeatures found along the KHF.

Thin-sections of the samples from sites S3 to S8 marked in Figure 4.2a are prepared, to observe the grain-to-grain relationship, nature of grain boundaries, grain orientation and recrystallisation in the petrologic (optical) microscope. In order to investigate the possible origin of the quartz grain surface microtextures in soft and semi-consolidated Quaternary sediments, the quartz grains separated from the samples of all the 15 sites i.e., S1 to S9 and S1* to S6* marked in Figure 4.2a, are subjected to analysis under the SEM. The sample preparation method for analysis in SEM is described in detail in Chapter – 3.

PETROGRAPHIC STUDIES OF SAMPLES FROM KHF ZONE

The term 'miliolite' for the rock has been derived from the common foraminifera of Genus *Miliolina* present in the rock in large amount (Biswas, 1971). He suggested that the miliolite rock mainly consists of three components i.e., allochemical grains, detrital grains and authigenic carbonate cement. The allochemical grains consists of mainly peloids, foraminifera, echinoid grains, coralline algae fragments and molluscan shell fragments. The detrital grains are mostly quartz and rock fragments derived from the country rocks. The cement is mainly meniscus and calcitic rim cement of low magnesian micro-sparite and sparite. The rock is highly porous and exhibits primary inter-granular porosity in thin sections. The allochemical contents indicate its derivation from the shallow marine source (Biswas, 1971). The study of Talati and Bhatt (2018a) demonstrates the petrographic studies carried out for the Quaternary miliolitic deposits located at Gangeshwar area and the Gunawari river channel cliffs, away from the fault zone, towards the south of KHF. They reported the occurrence of fibrous form of calcite (Lublinite) from the miliolite samples and correlated it with earthquake activities in the region.

The petrography of Quaternary miliolite deposits lying very close or exactly on the fault plane (sites S3 to S8, marked in Figure 4.2a) has been carried out to appreciate the microscopic or grain-scale effects of neotectonic activity.

Fluvial miliolite deposits

For the thin-section studies, the samples collected from the sites S3, S4, S6 and S8 (marked in Figure 4.2a) belonging to fluvially deposited miliolite deposits were analysed under a petrological microscope. Irregularly serrated grain boundaries due to microcracking along with recrystallization can be distinctly observed in the thin-section of fluvially reworked miliolite (Figure 7.1a, b). The reworked miliolite samples show slight orientation of constituent mineral grains (Figure 7.1c). The thin-section also shows recrystallization indicated by the presence of radial extinction, as observed in a few allochems (Figure 7.1d). Occurrences of well-developed microfibers of calcite on the periphery of recrystallized constituent grains can also be observed (Figure 7.1e). Very few quartz grains show polycrystalline nature along with undulose extinction (Figure 7.1f).

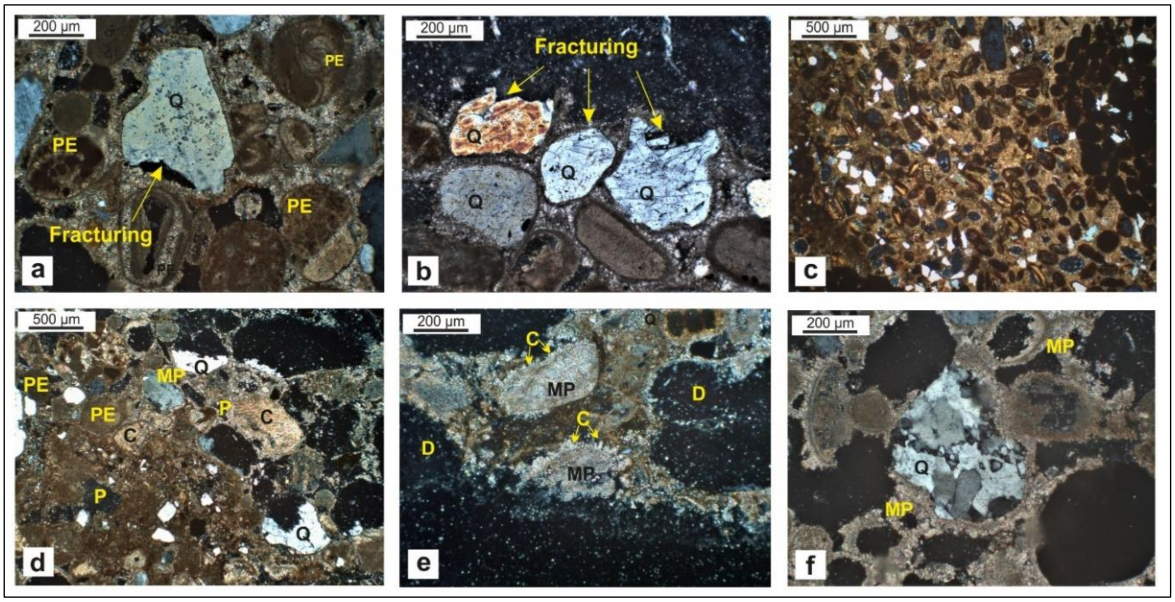

Figure 7.1 Thin-section photomicrographs of fluvially reworked miliolite deposits sampled from the KHF zone. **a.** and **b.** Microcracking along grain boundaries of detrital quartz grains. **c.** Slight orientation of constituent mineral grains and bioclasts. **d.** Recrystallization in the form of radial extinction observed in allochem grains. **e.** Micro-sparitization of calcitic cement with development of calcitic micro-fibres along the grain boundaries. **f.** Polycrystalline quartz grain showing undulose extinction. (D-Dissolution, MP-Micro-sparite, O- Orthoclase, P-Porosity, PE-Peloid, Q-Quartz).

Additionally, the thin sections of the samples belonging to the sites S2 and S8 (marked in Figure 4.2a) showing fluvial origin of miliolite located along the KHF trace from Deshalpar to Bharasar and from Ler to Wavdi respectively, did not exhibit the above-mentioned features such as irregularly serrated grain boundaries, orientation of constituent mineral grains, development of calcitic microfibres and polycrystallinity of quartz grains. The observations from thin sections and their interpretation are performed in Chapter – 4 (Figure 4.6a to c). Their thin section properties show a marked difference between the observed microfeatures, which are conversely, most evident in the samples collected from the sites S3, S4, S6 and S8 as shown in Figure 7.1.

Aeolian miliolite deposits

The sites S5 and S7 (marked in Figure 4.2a) correspond to aeolian origin of miliolites. The thin-section were prepared from these two locations to be observed under a petrological microscope. In the thin-section of aeolian miliolite collected from steeply dipping miliolite outcrop located south of Bhujodi (site S7) and prepared perpendicular to the fault plane, the microfractures are clearly visible in the angular to sub-angular detrital quartz grains (Figure 7.2a) and also in the peloidal bioclasts (Figure 7.2b). The constituent mineral grains are well sorted, angular to sub-angular, and show slight orientation in the thin-section prepared parallel to the fault plane (Figure 7.2c). Most of the quartz grains and peloid bioclasts show some amount of recrystallization along the grain boundaries with development of calcitic microfibers (Figure 7.2d). Moreover, the thin-section (Figure 7.2e) exhibits recrystallization and microcracking of the detrital quartz grains. The point contact among the grains indicates weak compaction after deposition. Polycrystalline quartz grains are observed (Figure 7.2f), which show undulose extinction.

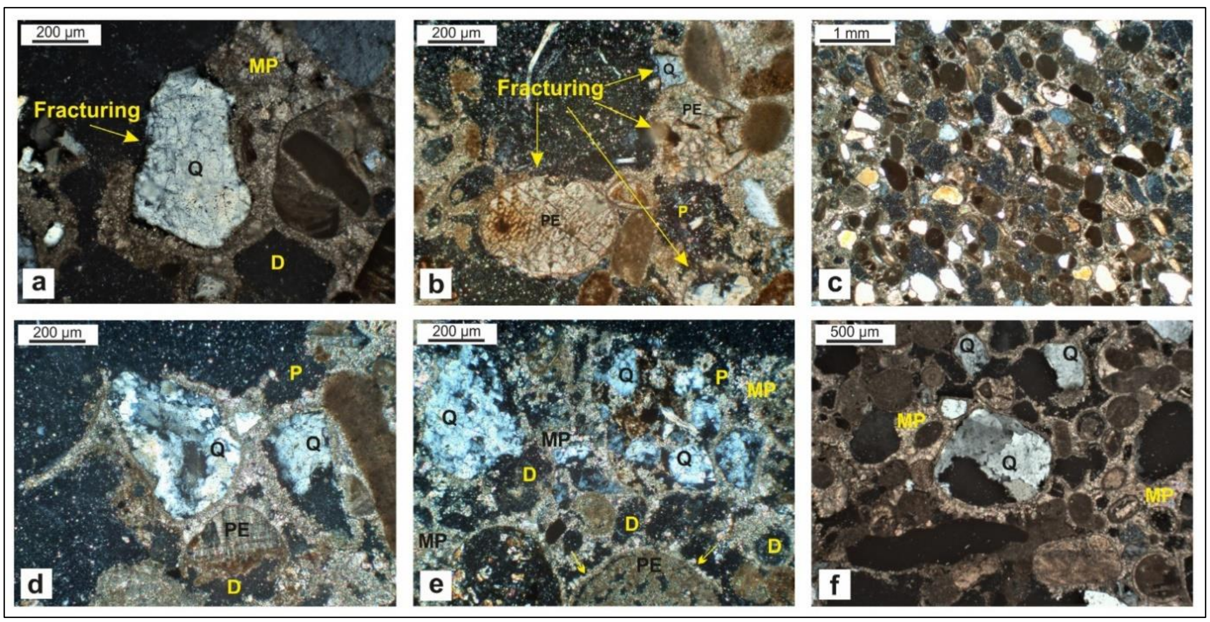

Figure 7.2 Thin-section photomicrographs of aeolian miliolite deposits sampled from the KHF zone. **a.** Fault perpendicular thin-section showing microfractures in the angular to sub-angular detrital quartz grains. **b.** Microfracturing of peloid bioclast and detrital grains. **c.** Fault parallel thin-section showing well sorted, angular to sub-angular and slight orientation of the constituent mineral grains. **d.** Recrystallization and microcracking of the detrital quartz grains. **e.** Recrystallization along the grain boundaries of quartz grains and peloid bioclasts. Note the calcitic microfibers developed on the peloid grain boundaries. **f.** Polycrystalline quartz grain showing undulose extinction. (D-Dissolution, MP-Micro-sparite, O- Orthoclase, P-Porosity, PE-Peloid, Q-Quartz).

The occurrence of polycrystallinity and undulose extinction in quartz grains from the samples of both aeolian and fluvially reworked miliolites is rare and is not noticed among all the quartz grains. It is only observed in some grains, which are >300-350μm.

However, the observations from the thin section studies of the sample taken from the site S1 located along the fault trace from Deshalpar to Bharasar (marked in Figure 4.2a), as mentioned in Chapter – 4, Figure 4.6d to f, showed absence of microcraking of grains, grain boundaries and bioclasts, lacked the orientation of the constituent grains and no evidence of calcitic microfibres and polycrystallinity is observed. The lack of these microfeatures differentiates these samples from those observed in the thin sections of the samples from site S5 and S7 as shown in Figure 7.2.

SCANNING ELECTRON MICROSCOPY (SEM) OF SAMPLES FROM KHF ZONE

Quartz grains were separated from the samples collected from all units (*I* to *IV*) of the Khari river section (Figure 5.3), which have undergone deformation during the Late Quaternary. Additionally, fourteen other sites were sampled, 8 along and 6 away from the KHF. Among all the samples collected during the field studies, samples from the site south of Bhujodi – S7 (Figure 5.6), which shows steeply dipping, almost vertical miliolite beds deposited in the foot-hill region, Shiv Paras – S5 (Figure 5.7) and two more – S1, S3* belonged to miliolite deposits of aeolian origin, present towards the north of the KHF scarp as obstacle dunes. The remaining belonged to fluvially-reworked origin of miliolite deposits. The size of the individual quartz grains from aeolian miliolite deposits ranges from 100-500 μm and the shape is mostly sub-rounded to sub-angular and elongated. The grains of fluvially reworked deposits were mostly angular to sub-angular with the individual grain size ranging between 300-500 μm and occasionally 1.00 mm. The grain size distribution does not appear to affect the frequency of microtextures on the grain surfaces in the fault zone. Discussed next are the microtextures observed from the SEM analysis of the two different types of samples.

SEM of quartz grains of fluvial miliolites along KHF zone

Majority of quartz grains obtained from the fluvial deposits along or very near to the fault zone (site S3 to S8, marked in Figure 4.2a) showed a variety of microtextures such as irregular breakage patterns in the form of large and small conchoidal fractures, straight and arcuate steps, v-shaped percussion marks, breakage blocks and fractured cleavage plates as observed in Figure 4.7. The solution action on the quartz grains was observed in the form of chemical etching, silica precipitation and dissolution features (Figures 4.7 and 4.8). As the sites were reworked by fluvial agencies, they display a range of microtextures characteristic of fluvial transport (Krinsley and Doornkamp, 1973; Manker and Ponder, 1978; Mahaney, 2002; Vos et al. 2014). The features related to fluvial transport observed in the present study are elaborated in Chapter – 4, Figures 4.7 and 4.8. Described in the upcoming section are the microtextures attributed to tectonic deformational processes, which took place along the KHF zone after the deposition of miliolite sediments during Late Quaternary time.

Excessive breakage

In addition to the above discussed microtextures belonging to the fluvial origin of miliolite deposits, the samples collected from near the fault zone also show microtextures belonging to tectonic deformation of the rocks that have undergone faulting. Excessively fractured nature of the grains with the development of surface cracks (marked by arrows in Figure 7.3) can be observed in the microphotographs. A highly abraded surface with the development of a prominent crack along the grain boundary (Figure 7.3a) may facilitate the breakage of the grain if it is further disturbed by any phenomenon. A subsidiary fracture is also seen to be developed in the lower portion of the grain. Another grain surface (Figure 7.3b) shows highly abraded surface with an exfoliated sheet on the surface and meandering ridge pattern developed over most of the surface. Exfoliation mostly develops when there is a sudden release in the confining pressure (Mahaney et al., 2004). This grain also shows a crack on the surface. Similarly, other grains (Figure 7.3c, d) also show prominent surface cracks developed on abraded grain surface. The larger cracks on the grain surface are accompanied by minor or accessory fractures. There is no particular trend of cracks observed on the grains. It can be said that the cracks originated due to mechanical wear of the grain, which later got widened or acted upon by solution activity. The fractured part of the grain surface (Figure 7.3e) comprises of small and large, sub-parallel conchoidal fractures, affected by solution action and silica precipitation. A sub-angular grain (Figure 7.3f) shows numerous cracks on the surface with deeply engrossed straight and curved grooves on the fresh fracture surface exposed on the right side of the grain. A triangluar faceted grain comprising of fresh fractured surface can be seen in one of the grains (Figure 7.3g), alongwith sub-parallel and small conchoidal fractures on each facet of the grain. Another grain surface (Figure 7.3h) exposes the fresh fractured surface with large conchoidal fractures and breakage blocks.

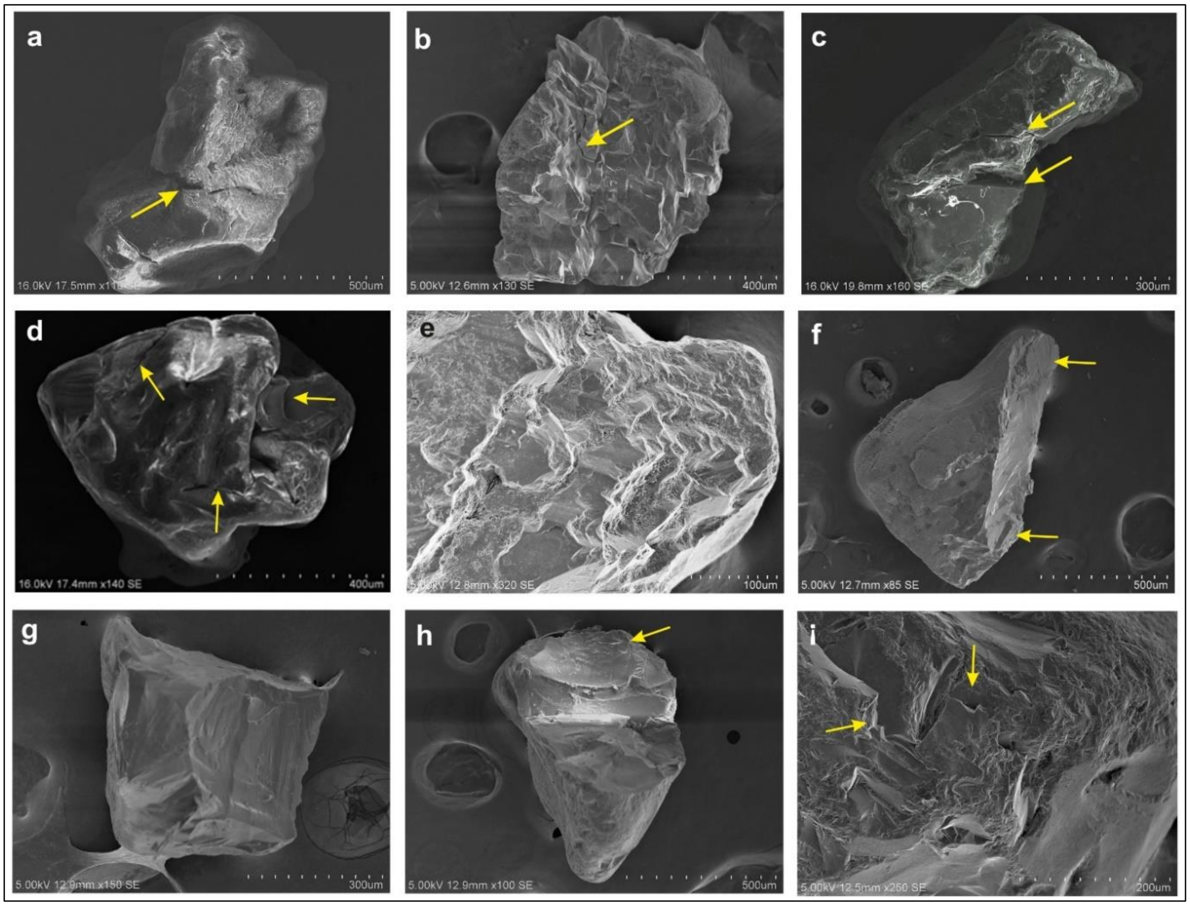

Figure 7.3 SEM photomicrographs of representative quartz grains of fluvial miliolite samples from the KHF zone showing excessively fractured nature. **a**. Highly abraded surface with a prominent crack along grain boundary. **b**. Abraded surface with exfoliated sheet and meandering ridge pattern. **c**. Prominent surface cracks developed on an abraded grain surface. **d**. Cracks and fractures on smoothed grain surface due to solution activity. **e**. Fractured grain surface with small and large, sub-parallel conchoidal fractures smoothened by solution action and silica precipitation. **f**. Sub-angular grain with numerous cracks on the surface with deeply engrossed straight and curved grooves on the fresh fracture surface. **g**. Triangular faceted grain with fresh fractured smooth surface. **h.** Fresh fractured smooth surface of the grain. **i**. Chemically etched and highly abraded grain surface, deeply engraved grooves and upturned plates.

Here, the lower portion of the grain is affected by chemical etching and silica precipitation. Highly abraded grain surface (Figure 7.3i) due to chemical etching and deeply engraved grooves and upturned plates can also be seen. Here, the phenomenon of sheet rupturing has given rise to the ruptured sheets and exfoliation along with the upturned plates.

The breakage patterns in all the grains are randomly distributed all over the grains' surfaces, and are rarely seen to be oriented in any particular direction. All different kinds of breakage patterns are a result of mechanical wear and chemical alterations that the grain has undergone during its fluvial transport (Mahaney, 2002; Vos et al., 2014). They are produced by a powerful impact or pressure on the grain surface. As the pressure wave propagates through the crystal lattice, it generates the ribbed appearance of the fractures (Margolis and Krinsley, 1974). Mahaney and Sjoberg (1993) reported that fractured edges and upturned plates may result from the pressure exerted by the neotectonic processes.

Striations and exfoliation

Prominent striations on the quartz grain surfaces are shown in Figure 7.4 (marked by arrows).

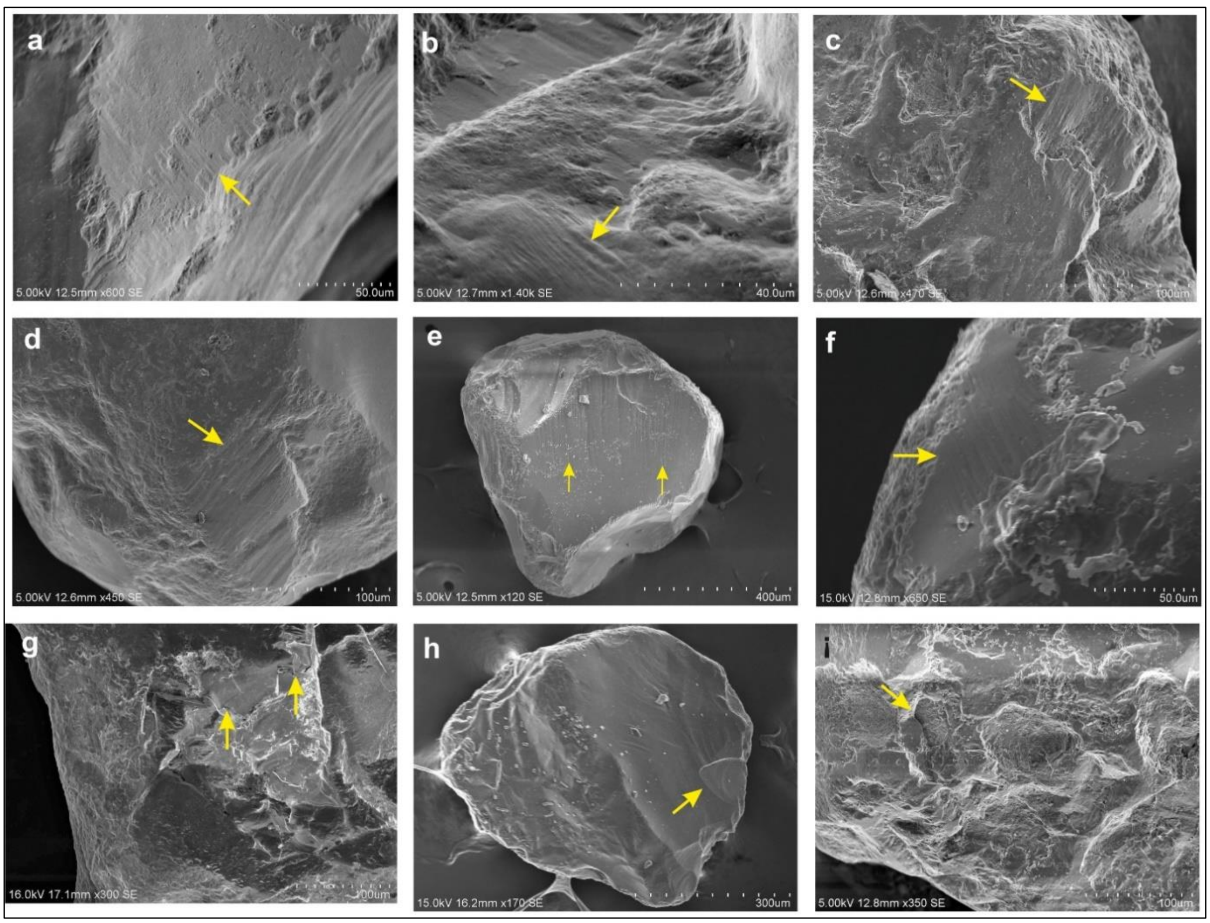

Figure 7.4 SEM photomicrographs of representative quartz grains of fluvial miliolite samples from the KHF zone showing prominent striations (a to f) and exfoliation (g to i) features marked by arrows. Note that striations do not fully cover the grain surfaces (a to f) in all the grains except in (e). Exfoliation on the grain surfaces (g to i) is seen in patches. Also note the fractured nature of the grains and grain boundaries.

These striations are not overlapped by any other feature present on the surface. The striations can be seen on parts of the grain (Figure 7.4a to d) and they don't fully cover the whole surface of the grain. These grains (Figure 7.4a to d) also appear to be highly abraded and fractured and consisting of upturned plates. Another grain (Figure 7.4e) is observed to show striation marks, which cover most of the grain surface, alongwith the presence of small conchoidal fractures, breakage blocks and curved grooves along the grain edges. Striations can be noticed on part of a grain surface with silica precipitation and abraded grain edges (Figure 7.4f). Mahaney (2002) used the word "groove" for lightly embedded striations and stated that occassional straight and linear grooves could have a tectonic origin and can occassionally be regarded as byproducts of neotectonic release and movement within fault planes. Some grain surfaces in (Figure 7.4g, h and i) show exfoliation features in which some part is chipped off from the grain surface. They also show weathered surfaces and conchoidal fractures.

Adhering particles

The common feature, which can be noticed among all the grains and grain surfaces (Figure 7.5) is the presence of adhering particles. Various other features such as curved grooves, irregular depressions, upturned plates and highly fractures grain edges can be noticed. The abraded surface of the grain with extensively abraided edges can be seen (Figure 7.5a), while abraded edges with upturned plates and smoothened left portion of the grain due to solution action can be noticed as well (Figure 7.5b). Another grain surface (Figure 7.5c) is characterized by numerous parallel fracture pattern with edge abrasion. Some grain surfaces (Figure 7.5d, e and f) appear to be rough and weathered, and shows breakage in the form of elongated depressions and deeply inscribed grooves. A few grains (Figure 7.5g, h and i) are characterized by small and large conchoidal fractures and breakage blocks exposing fresh fractured surfaces.

Rolled quartz grains

The photomicrographs (Figure 7.6a to f) consist of rolled quartz grains. Rolled quartz grain with chemically altered surface, irregular depressions and v-shaped percussion marks, later modified by chemical etching (Figure 7.6a) can be noticed. Figure 7.6b shows a highly abraded, rolled quartz grain with crescentic gouges and irregular depressions, distributed unevenly on the surface.

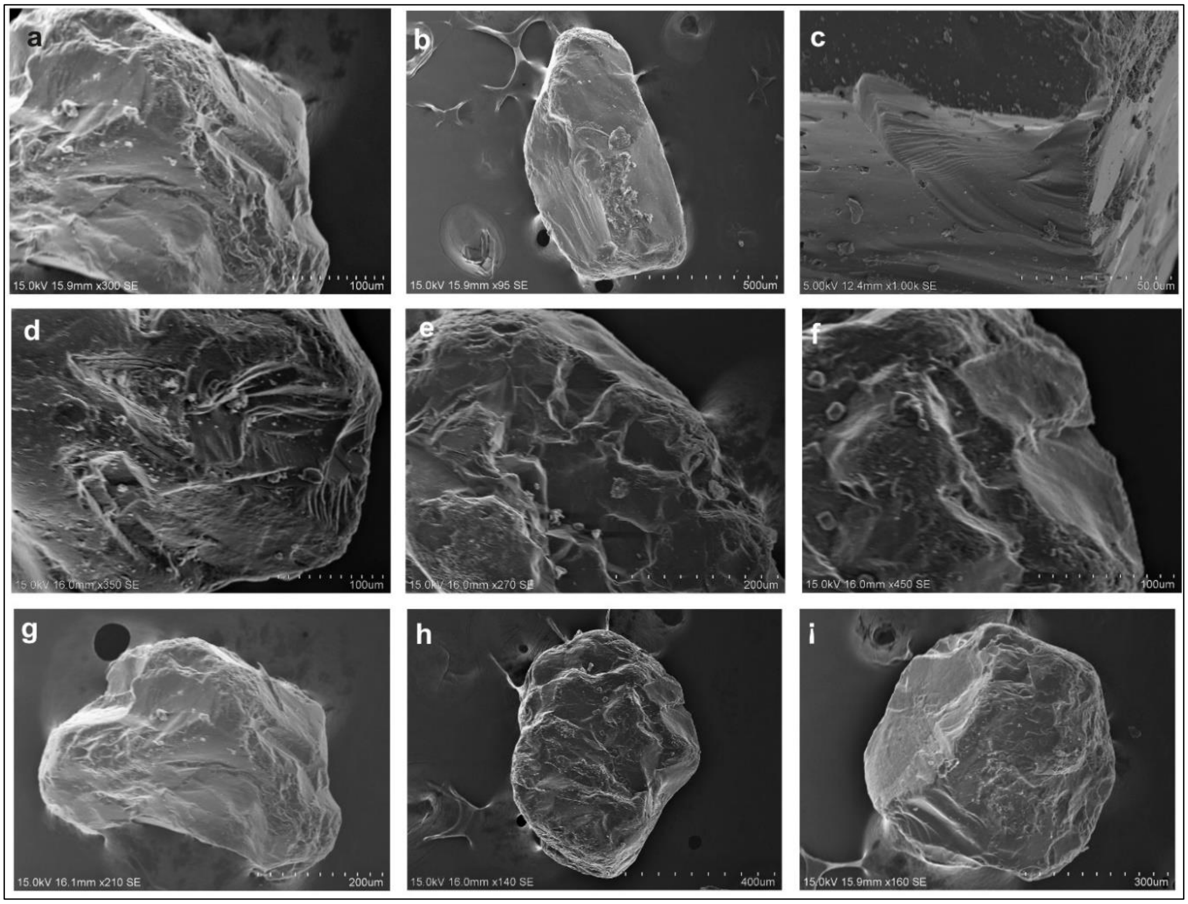

Figure 7.5 SEM photomicrographs of representative quartz grains of fluvial miliolite samples from the KHF zone showing the presence of adhering particles on the grain surfaces. Note the excessively fractured nature of the grains and broken grain boundaries.

A partly rounded and rolled quartz grain with new growth of quartz (Figure 7.6c), which has also been rounded to some extent by solution action can be seen. Rolled quartz grain with a damaged lower left side (Figure 7.6d), and a damaged right edge (Figure 7.6e) can be seen. Another partly rounded and rolled quartz grain (Figure 7.6f) shows patches of chemical alterations spread over its surface. Very faint striations can also be noticed on the surface of another grain (Figure 7.6f). A few of these grains (Figure 7.6a, b and c) also exhibit upturned plates. Such rolled and crystallographically realigned quartz grains are common in massive large-scale faults such as the San Andreas (Mahaney, 2002). The evidences of rare euhedral quartz grains (Figure 7.6g, h and i) are also obtained from the samples of fluvial miliolites along the KHF zone. Similar evidences of rare euhedral and rolled quartz grains were also recovered from the samples in close proximity to the Boconó Fault (Mahaney et al., 2004).

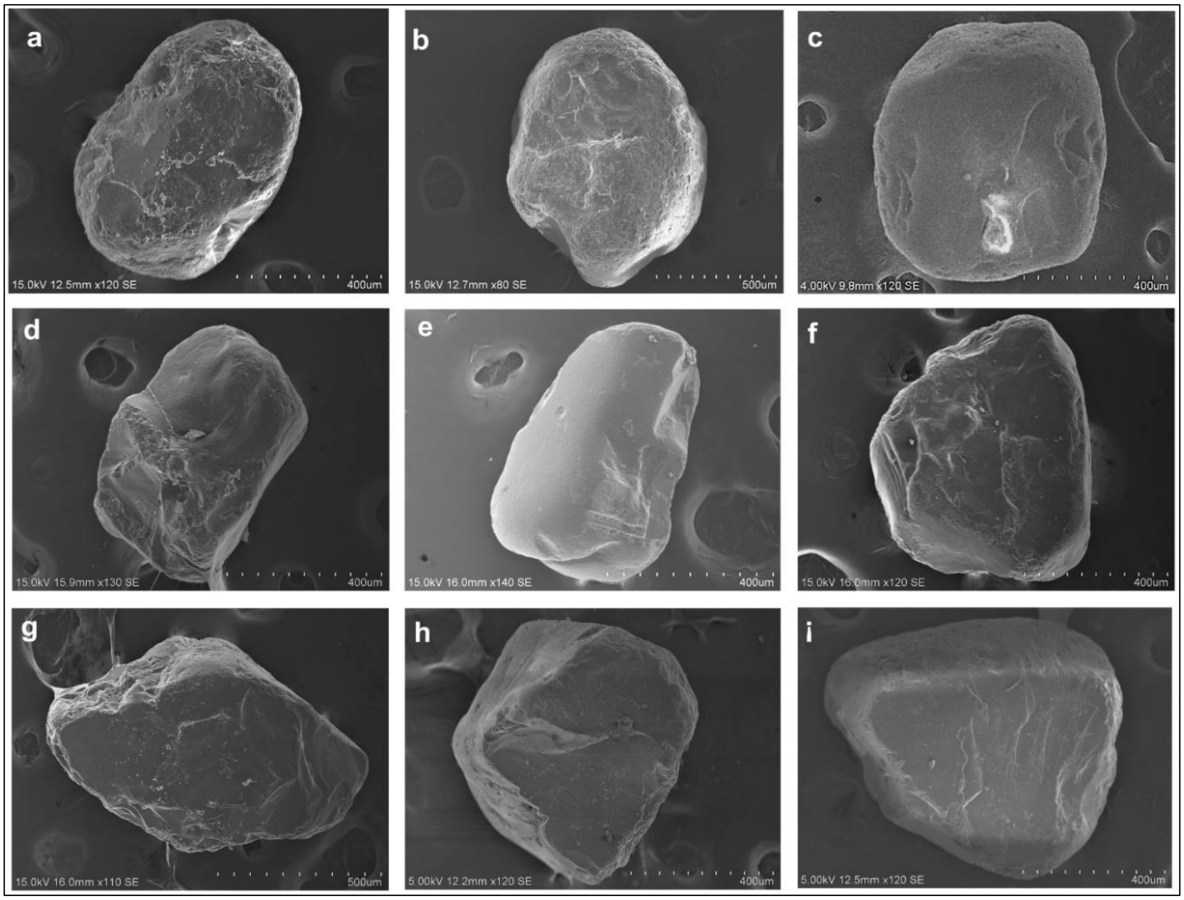

Figure 7.6 SEM photomicrographs of representative quartz grains of fluvial miliolite samples from the KHF zone consisting of rolled quartz grains (a to f) and euhedral crystal (g to i). Note the presence of abraded surface of the grains. Faint striations on the surface can be seen in (f).

SEM of quartz grains of aeolian miliolites along KHF zone

The quartz grains of aeolian origin separated from the samples collected from the sites S5 and S7 (marked in Figure 4.2a) along the KHF zone, displayed a lesser range of features as compared to the fluvially reworked quartz grains, However, they did display well defined conchoidal fractures, irregular depressions, elongated straight and curved grooves, quartz cleavage planes, upturned plates, silica precipitation and solution features, straight and arcuate fractures, also in step like and radial pattern typical in aeolian deposits as stated by Krinsley and Doornkamp (1973), are explained in Figure 4.9 in Chapter – 4. Discussed next are the microtextures observed in the aeolian miliolite quartz grain samples due to the effect of surface faulting along the KHF.

Excessive breakage

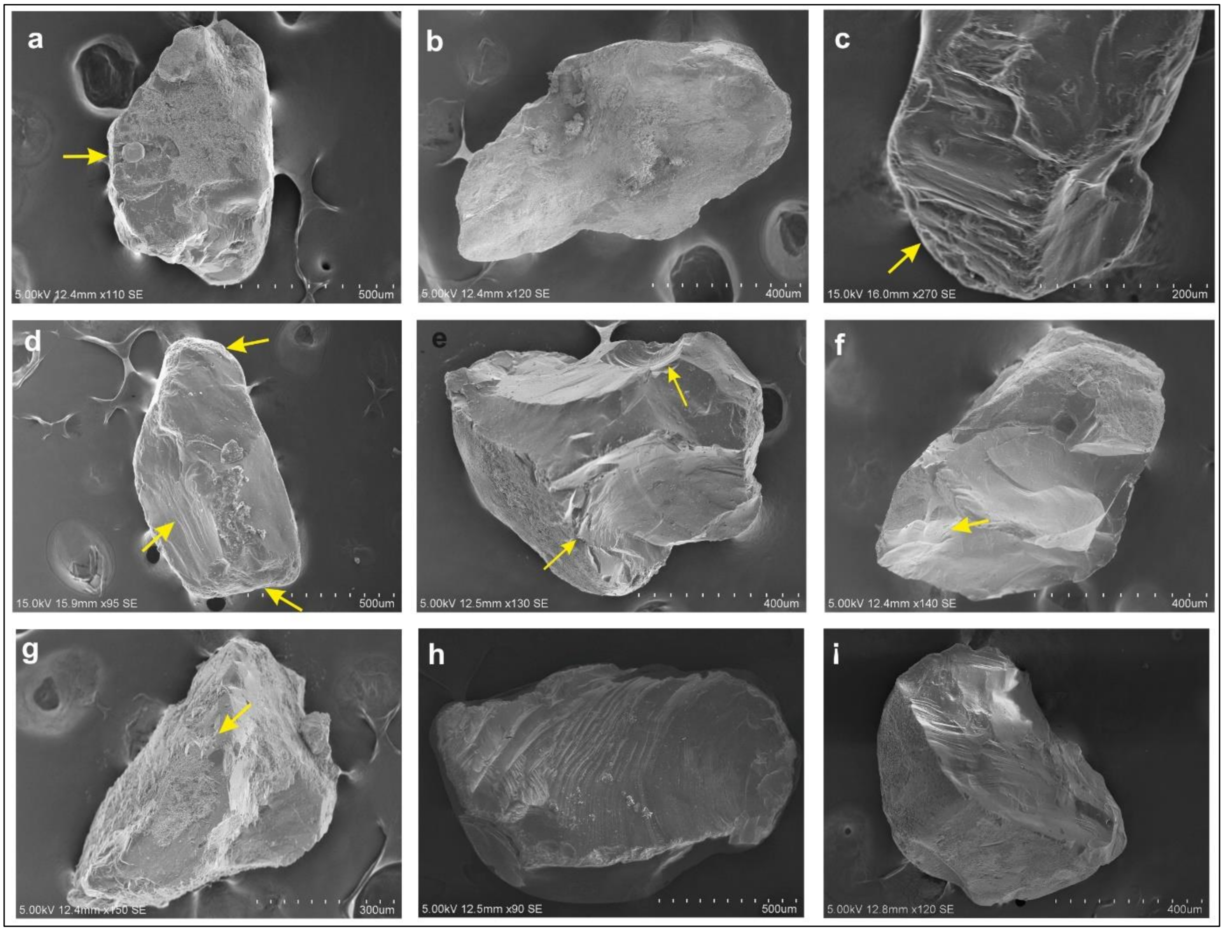

Figure 7.7 SEM photomicrographs of representative quartz grains of aeolian miliolite samples from the KHF zone showing fractured nature (marked by arrows) of the grains. **a.** Excessive silica precipitation with abrasion fatigue. **b.** Silica precipitation covers the microtextures present on whole of the surface. **c.** Smoothed quartz cleavage plates and elongate depressions resulting due to fracturing. **d.** Upturned plates are present on the upper and lower edges of the elongated quartz grain and shows smoothed left boundary due to solution action. **e.** Fresh fractured and abraded quartz surface with deeply engrossed conchoidal fractures surrounded by upturned plates in lower left portion and silica precipitation over the abraded surface of the grain. **f.** Fresh fractured quartz grain depicting radial fractures and sharp edges. **g.** Elongated grain with sub-angular edges and v-shaped fractures on the top of the grain with irregular depressions and upturned plates on the grain edges. **h.** Small arcuate step like fractures grade into straight steps of relatively larger size. **i.** Chemically etched grain boundary with parallel to sub-parallel fractures on the fresh fractured grain surface. Note the fractured surfaces and excessive silica precipitation on the grain surfaces.

The aeolian quartz grains (Figure 7.7a, b) show excessive silica precipitation indicating diagenesis of Quaternary deposits. Also, abrasion fatigue (Figure 7.7a) is expressed on quartz grains as a reactive surface layer containing cracks and dislocations to which small grains can attach (Mahaney, 2002). The surface of grain (Figure 7.7b) is fully covered by silica, which masks the microtextures present on the surface. In Figure 7.7c, d the exposed quartz cleavage plates and elongate depressions have undergone smoothening due to solution action. Upturned plates (Figure 7.7d) are also present on the upper and lower edges of the elongated quartz grain. A fresh fractured and abraded quartz surface with deeply engrossed conchoidal fractures surrounded by upturned plates in lower left portion and silica precipitation over the abraded surface of the grain (Figure 7.7e) can be seen. The photomicrograph (Figure 7.7f) shows fresh fractured quartz grain depicting radial fractures and sharp edges. Figure 7.7g shows elongate quartz grain with rounded edges and v-shaped fractures on the top of the grain with irregular depressions and upturned plates on the edges of the grain. Fractures in the form of small arcuate steps are seen (Figure 7.7h), which grade into straight steps of relatively larger size. Parallel to sub-parallel fractures are present on the fresh fractured grain surface (Figure 7.7i) and the grain boundary appears to be chemically etched.

Although there is no apparent cleavage visible for a quartz grain in thin sections, an unusual cleavage/weak plane is evidenced in many of these grains when examined through SEM. Krinsley and Smalley (1973) suggested that when particle size of a quartz grain is reduced below a certain threshold, the cleavage mechanism becomes functional. The tendency to cleave is suppressed in large quartz crystals.

<u>Striations and exfoliation</u>

As the sample of aeolian miliolite was collected from the steeply dipping miliolite outcrop (Figure 5.6), it also showed microtextures typical of deformation in tectonically active environments. Some quartz grains (Figure 7.8a, b) show distinct striation marks on the surface and in a few, the striations were overlapped by silica precipitation (Figure 7.8b). Another grain (Figure 7.8c) shows exfoliated sheet on the surface, which exposes the underlying cleavage plates. Abraded edges with adhering particles and exposed cleavage plates (Figure 7.8d) can also be seen. One of the grains (Figure 7.8e) shows bulbous edge of quartz grain and rough surface with silica precipitation, upturned plates and adhering particles. Also observed are some rare euhedral quartz grains with rounded and weathered edges (Figure 7.8f, g).

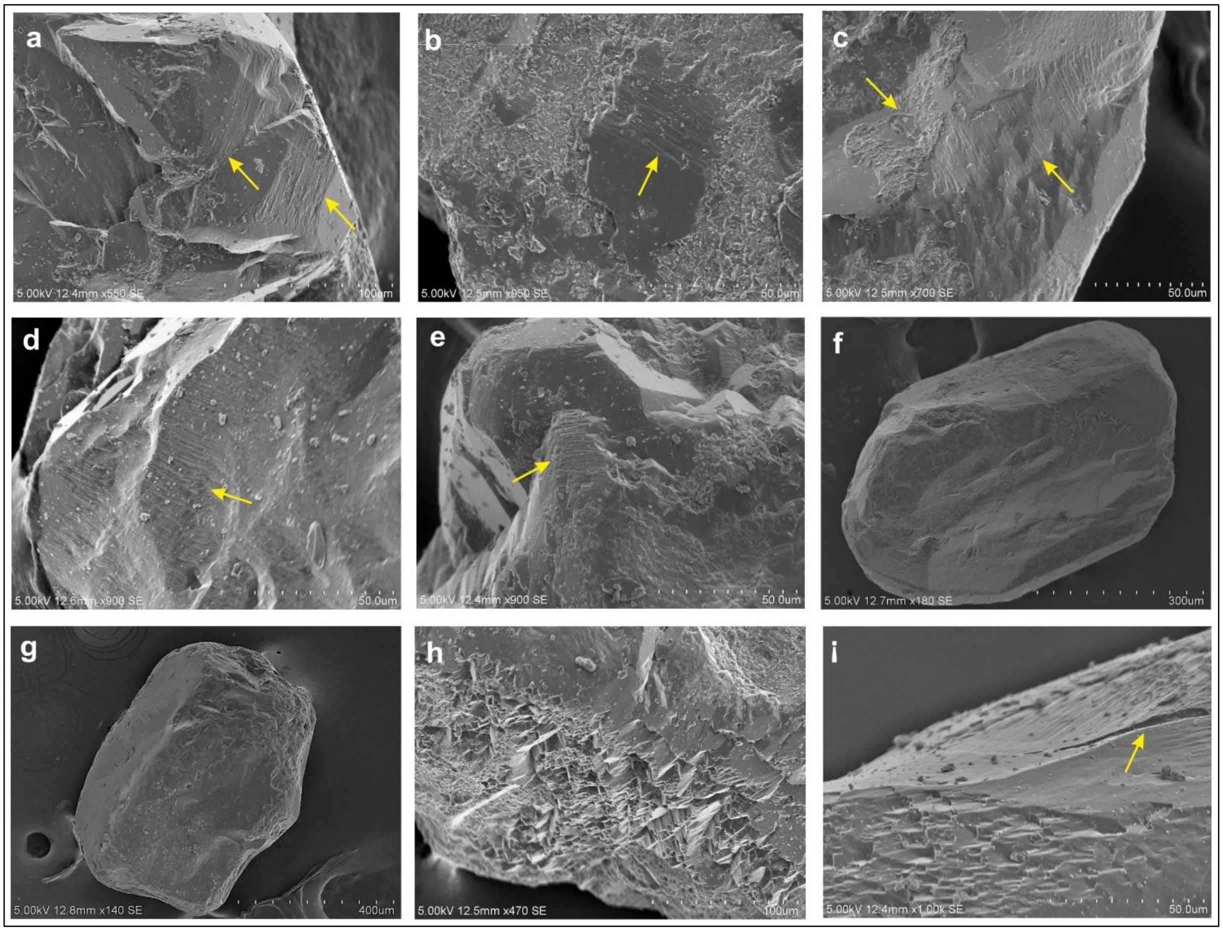

Figure 7.8 SEM photomicrographs of representative quartz grains of aeolian miliolite samples from the KHF zone showing striated, excessively broken and exfoliated grain surfaces. **a.** The grain shows distinct striation marks on the surface. **b.** Striation marks are seen overlapped by silica precipitation. **c.** Exfoliated sheet on the surface, which exposes the underlying cleavage plates. **d.** Abraded edges with exposed cleavage plates. **e.** Quartz grain with bulbous edges and rough surface with silica precipitation and upturned plates. **f.** Euhedral quartz grain with traces of silica precipitation. **g.** Euhedral quartz grain with rounded and weathered edges. **h.** Excessively broken grain surface (sawtooth fractures) and highly fractured cleavage plates. **i.** Highly eroded grain surface showing exfoliation. Note the presence of silt sized adhering particles on the grain surfaces.

The microphotograph (Figure 7.8h) show excessively broken grain surfaces and highly fractured cleavage plates. It shows fractures along grain boundary in a well-developed sawtooth shaped pattern. Such feature indicates the start of corrosion from an already fractured grain surface or a breakage surface, which had originated as a straight fracture (Kanaori, 1985). A highly eroded quartz grain showing exfoliation can be observed (Figure 7.8i). Other than striations, the surfaces of the grains are observed to be intensively abraded, fractured and containing upturned plates.

Fractured cleavage plates and silica precipitation

Excessively broken (features marked by arrows) aeolian quartz grains as observed in Figure 7.9a and b show the presence of distinct v-shaped fractures and presence of fractured cleavage plates (Figure 7.9c). The ability to observe the fractured nature of cleavage plates points towards excessively broken nature of the grains. Figure 7.9d shows that the grain surface is highly affected by solution action, which has given rise to deeply engrossed numerous small and large pits and weathered surface. Exfoliated surface can be observed in Figure 7.9e along with parallel fractures and weathered surface. In Figure 7.9f, silica precipitation in the form of silica pellicle can be observed on a rough surface.

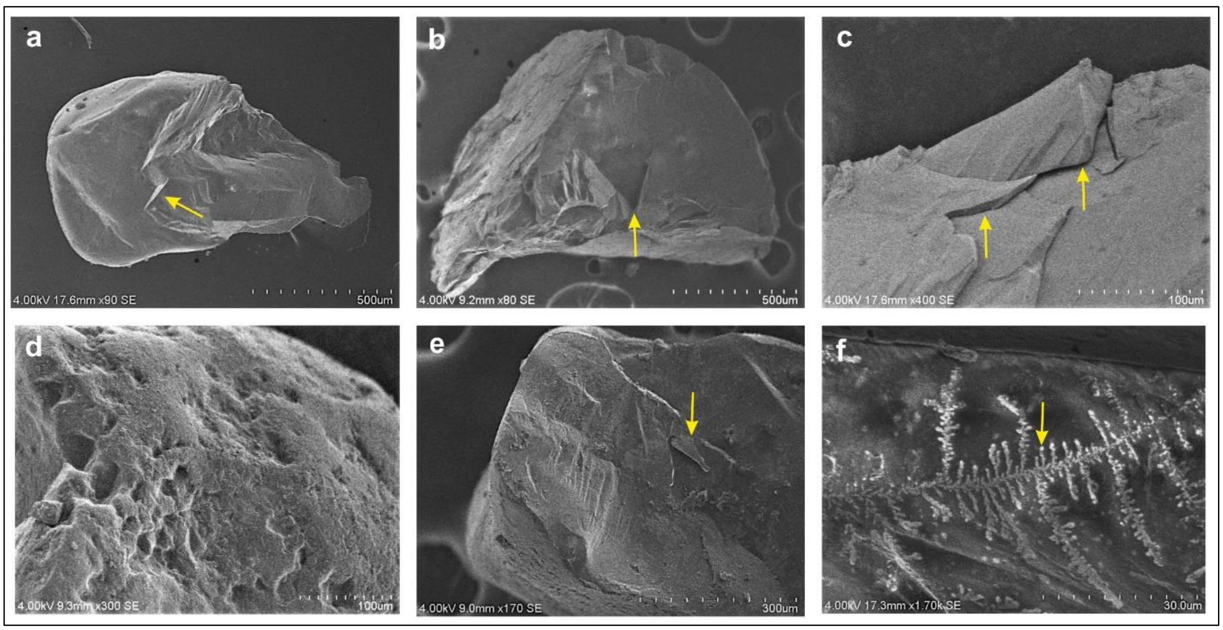

Figure 7.9 SEM photomicrographs of representative quartz grains of aeolian miliolite samples from the KHF zone. **a.** and **b.** Large breakage block exposing fresh fractured surface and typical v-shaped fracture. **c.** Excessively broken quartz cleavage plates. **d.** Deeply engrossed small and large depressions or solution pits developed due to solution action on a weathered surface. **e.** Fractured surface displaying parallel fractures and exfoliation surface. **f.** Weathered surface showing silica precipitation and development of silica pellicle.

The striation marks are observed in many representative grains from samples of both fluvial and aeolian origin located along the KHF zone. This may essentially be an attribute of fault environment (Mahaney, 2002). In Figures 7.4 and 7.8, faint striations can be seen over the quartz surfaces. The striations look similar to the those of the fault gouge sample derived from Atotsugawa fault (Kanaori, 1983). The other common features grains of fluvial and aeolian deposits are the presence of adhering silt size particles, exfoliation and being rolled. Such adhering particles may suggest deformation and faulting of the soft sediments (Mahaney et al., 2004). In the present case and these are assumed to arise from release during grain fracture at the time of faulting.

SEM of quartz grains located away from KHF zone

For comparison purposes samples were also collected from different sites of Quaternary deposits that were located away from the fault. The six sampling sites selected (S1* to S6*, location marked in Figure 4.2a) were mostly the dried stream channels located towards the SW of Samatra, south-west of Bharasar road, south of Khari river section, north of Tapkeshwari road, east of Gangeshwar road and east of Khatrod scarp (Figure 7.10). Samples from these sites mainly consist of fluvially reworked miliolite deposits as they were collected from the river cliff sections, except for S3* site. The quartz grains show abraded surface in some parts of the grain surface with irregular breakage pattern, small and large conchoidal fractures and irregular depressions (Figure 7.10). Some grains display a pitted appearance (solution pits) due to solution activity with moderate to low relief (Figure 7.10a, b). Sub-conchoidal fractures can also be observed (Figure 7.10b). The edges of one of the grains displays abrasion with small conchoidal fractures and relatively smooth surface and limited silica precipitation in small pits (Figure 7.10c). Numerous upturned plates can be seen in the upper portion of another grain surface with small depressions (Figure 7.10d), while the lower portion of the grain appears to be comparatively less weathered. Excessive silica precipitation masks the microtextures present on the surface on some grains, but curved grooves can be seen covered by the silica (Figure 7.10e). One of the grains (Figure 7.10f) shows small and large conchoidal fractures and grooves with limited silica precipitation, while another (Figure 7.10g) shows the presence of solution pits throughout the abraded surface. A grain with sharp lower edge and abraded upper portion of the surface with limited silica precipitation can also be seen (Figure 7.10h). And another grain shows weathered surface with small fractures along the cleavage plates (Figure 7.10i). The samples of the quartz grains collected from the sites away from the fault zone showed only the characteristics typical of their transporting agency, which is fluvial for all the three sites, as the samples were collected from stream sections. The SEM microphotographs also support their fluvial origin. In addition to the above microtextures, the grains did not show any evidence of striation or exfoliation or excessive breakage. The quartz cleavage plates were also not seen in the above samples, which indicate that the grains are comparatively intact and have not been acted upon by anything but a fluvial agency.

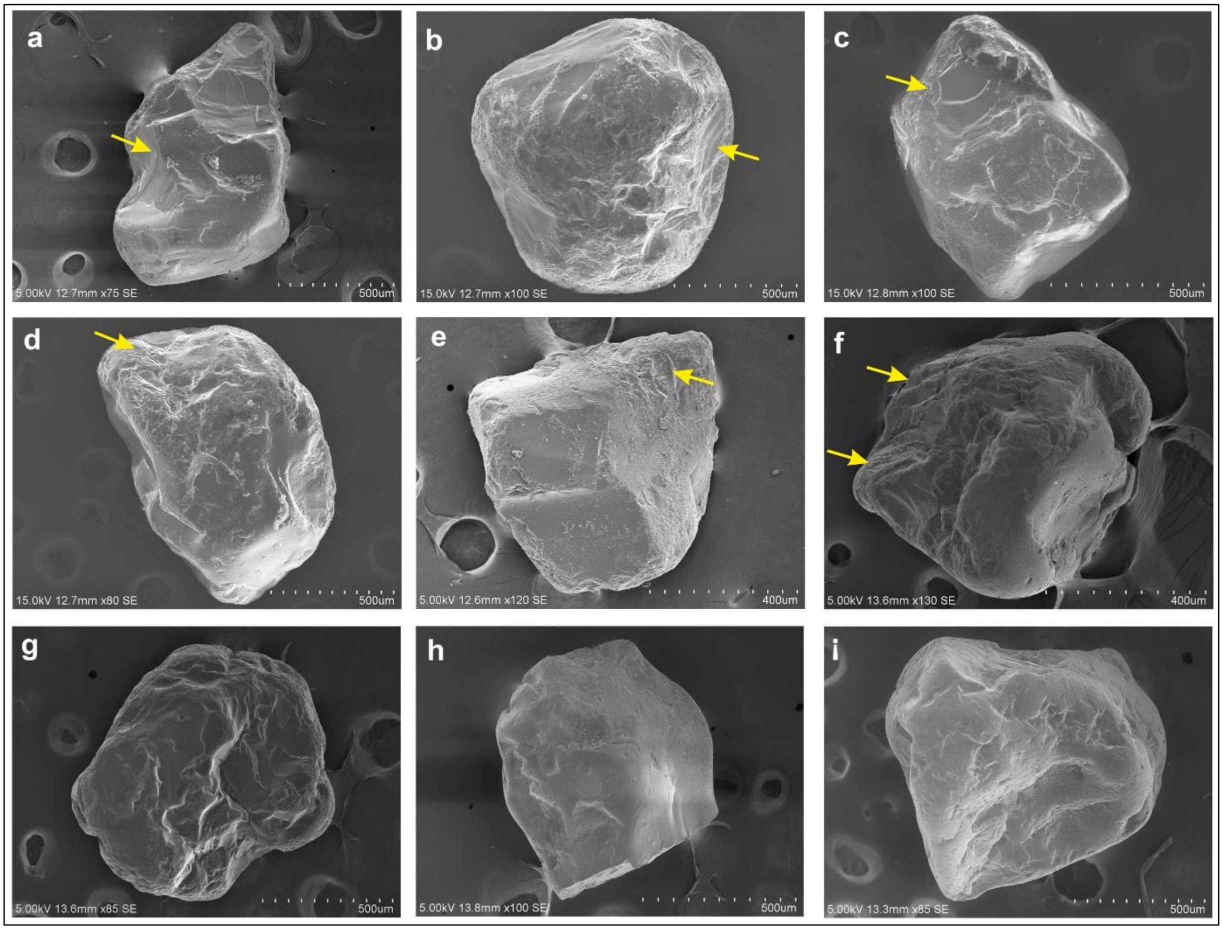

Figure 7.10 SEM photomicrographs of representative quartz grains of fluvial miliolite samples away from the KHF zone. **a.** Breakage in the form of conchoidal fractures. **b.** Sub-conchoidal fractures and solution activity giving rise to pitted appearance on the surface. **c.** Abraded grain edges with small conchoidal fractures with relatively smooth surface and limited silica precipitation in small pits created due to solution action. **d.** Numerous upturned plates in the upper portion of the grain surface with small depressions and less weathered lower portion. **e.** Curved grooves are seen covered by silica precipitation towards the upper right portion of the grain. **f.** Small and large conchoidal fractures and grooves with limited silica precipitation. **g.** Solution pits observed throughout the abraded grain surface. **h.** Abraded upper portion of the grain surface with sharp lower edge and limited silica precipitation. **i.** Weathered grain surface with small curved fractures. Note the absence of excessive breakage and striated surfaces.

The sites located along the fault trace from Deshalpar to Bharasar (S1, S2 location marked in Figure 4.2a) and from Ler to Wavdi (S8, location marked in Figure 4.2a) displayed evidence of faulting in the Mesozoic rocks (Figure 5.1); while the Quaternary miliolite deposits appeared to be undeformed, unaffected by Quaternary faulting events. The SEM observations of quartz grains from these Quaternary deposits show surface abrasion features due to variable amounts of solution action (Figure 7.11a to d) and the presence of upturned plates.

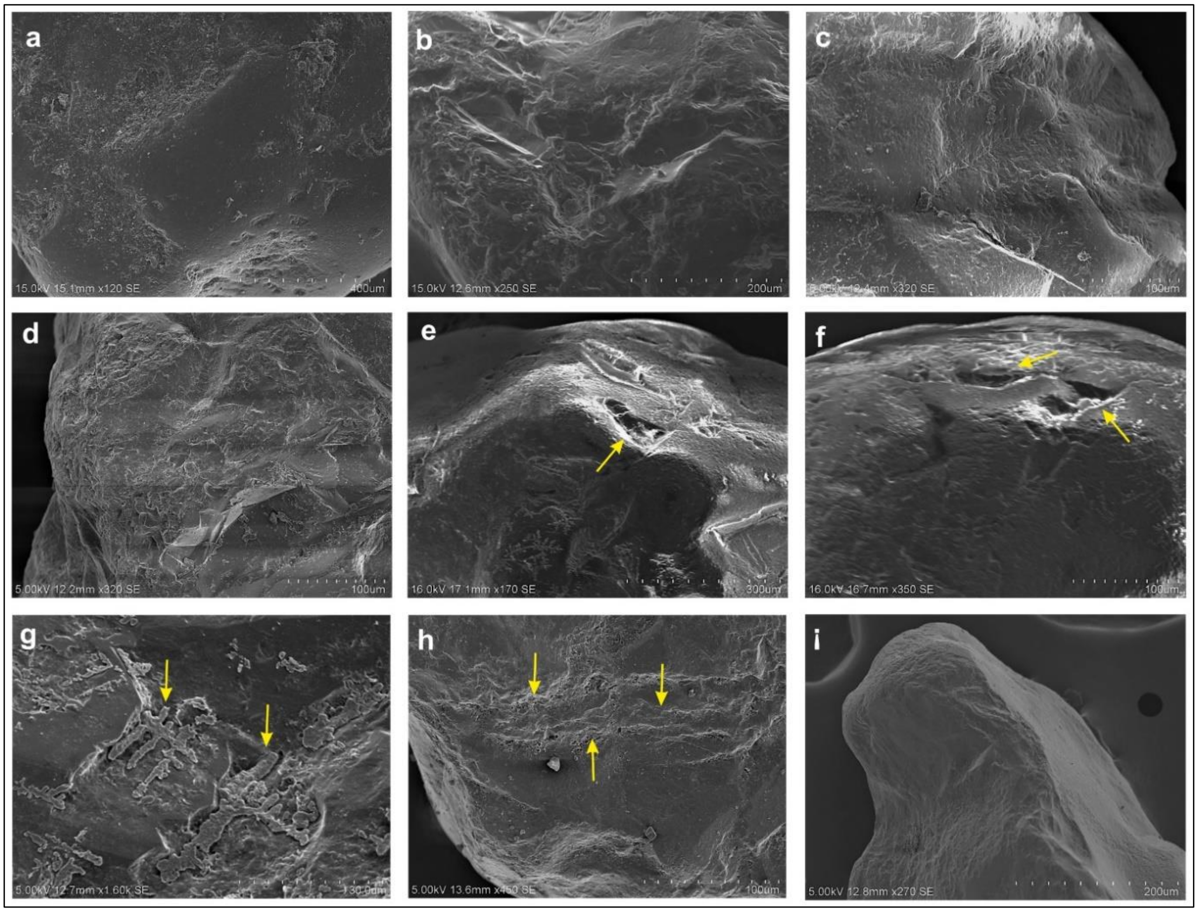

Figure 7.11 SEM photomicrographs of representative quartz grains of fluvial miliolite samples along the segment of KHF from Deshalpar to Bharasar and from Ler to Wavdi. Grain surfaces in (a to d) show abrasion features like chemical etching due to variable amounts of solution action and the presence of upturned plates. **e.** and **f.** show relatively larger solution pits on chemically etched surface. **g.** Silica precipitation in the depressions formed on the grain surface due to breakage or solution action. **h.** Set of parallel fractures modified and smoothened by solution action. **i.** Weathered and abraded edges of the grain.

The grain surfaces have been affected by chemical etching showing a highly altered surface due to solution action (Figure 7.11a to d). The development of relatively larger solution pits can be observed (Figure 7.11e, f) on chemically etched surface. Figure 7.11g shows silica precipitation feature in the depressions formed on the grain surface due to breakage or solution action. The pre-existing set of parallel fractures are seen to be modified and smoothened by solution action (Figure 7.11h). Edge of another grain is seen to be abraded (Figure 7.11i). There is no evidence of excessive breakage giving a sub-rounded to sub-angular outline to the grains. Although lying along the fault plane, the quartz grains of the above samples also did not show any evidence of striation, exfoliation and excessive breakage, and are comparable to the samples located away from the fault zone (Figure 7.10). It can be inferred that the Quaternary miliolite deposits deposited in the segment of the KHF trace from Deshalpar to Bharasar and from Ler to Wavdi, marked in Figure 4.2a are undisturbed by the process of surface faulting.

Sample-wise details regarding the observation and interpretation pertaining to field studies, optical microscopy and scanning electron microscopic (SEM) analyses are outlined below in Table 7.1.

Table 7.1 Summary of observations and interpretation from field studies, optical microscopy and scanning electron microscopic (SEM) analyses of samples collected along and away from the KHF. Location of samples is shown in Figure 4.2a.

Observations - Field and Microscopic studies (thin sections and SEM)		**Interpretation**
Site S1		
Field characteristics	Homogenous grain size, absence of cross bedded units, semi-consolidated, moderately sorted, occur as obstacle dune deposits, thickness unknown	Deposited as aeolian miliolite
Optical characteristics	Depositional features- consists of allochemical grains, poorly to moderately sorted detrital grains and authigenic carbonate cement, grains are <0.25mm size, point contact relation between the grains Tectonic features- absent	Depositional features suggest aeolian origin of miliolite
SEM characteristics	Depositional features- bulbous edges, upturned plates, deeply engrossed curved grooves, v-shaped percussion marks, radial fractures, irregular depressions on the surface, no sign of fracturing among the grains Tectonic features- absent	Depositional features indicate aeolian origin of miliolite Absence of tectonic features attributed to location away from surface faulting
Site S2		
Field characteristics	Well-developed horizontal stratification, heterogenous grain size, semi to unconsolidated, poorly sorted,	Deposited as fluvially reworked miliolite

	presence of coarse lithic sand, pebble-cobble sized clasts of Mesozoic rocks, occur in valley depression, thickness ~2-3m	
Optical characteristics	Depositional features- consists of allochemical grains, poorly sorted detrital grains and authigenic carbonate cement, grains are <0.25mm size, undergone weak diagenesis Tectonic features- absent	Depositional features suggest fluvial origin of miliolite
SEM characteristics	Depositional features- pitted and grooved appearance of the surface, conchoidal fractures, rounded to sub-rounded grain, presence of solution pits or depressions, less fractured surfaces Tectonic features- absent	Depositional features indicate fluvial origin of miliolite Absence of tectonic features attributed to location away from surface faulting
Site S3		
Field characteristics	Heterogenous grain size, unstratified, semi to unconsolidated, moderately sorted, occur in valley depression, thickness ~5-6m	Deposited as fluvially reworked miliolite
Optical characteristics	Depositional features- consists of allochemical grains, detrital grains and authigenic carbonate cement, grains are <0.25mm size, dissolution of allochems forms secondary porosity Tectonic features- fracturing of detrital quartz grains and allochems	Depositional features suggest fluvial origin of miliolite Tectonic features show the effect of faulting
SEM characteristics	Depositional features- radial fracturing pattern, unevenly broken edges, Si precipitation over rough surfaces, smooth fractures on some edges probably indicating a split grain, randomly oriented and deep V-shaped percussion marks, triangular shaped depressions, chemically altered and etched surface with crescentic gouges, conchoidal fractures Tectonic features- highly fractured and cratered surface, prominent striations on the grain surface, highly abraded surface with exfoliated sheets, the occasional occurrence of rolled quartz grain.	Depositional features indicate fluvial origin of miliolite Tectonic features manifest the effect of faulting
Site S4 (Khari river section)		
Field characteristics	Heterogenous grain size, unstratified, semi- to unconsolidated, poorly sorted, presence of coarse lithic sand, pebble-cobble sized clasts of Mesozoic rocks, a layer of rotated clasts observed along the	Deposited as fluvially reworked miliolite

	fault, occur in valley depression, thickness ~8m	
Optical characteristics	Depositional features- consist of allochemical grains, detrital grains and authigenic carbonate cement, grains are <0.25mm size, dissolution of allochems forms secondary porosity Tectonic features- recrystallisation of calcitic cement, fracturing of detrital quartz grains and allochems	Depositional features indicate fluvial origin of miliolite Tectonic features attributed to effect of faulting
SEM characteristics	Depositional features- breakage and cracks on the surface, step-like fractures sometimes parallel, irregular pits and depressions on the grain surface, solution pits, crescentic gouges, elongated linear and curved shallow depressions cleavage plates Diagenetic feature- uniform Si covering over pitted and grooved surface Tectonic features- highly abraded and fractured surface, consisting of upturned plates, striations on parts of the grain, occasional occurrence of rolled quartz grains	Depositional features indicate fluvial origin of miliolite Tectonic features result due to the effect of faulting
Site S5 (Shiv Paras)		
Field characteristics	Unimodal grain size, medium to fine-grained, moderately to well-sorted fine sand grains, occur as obstacle dune deposits, absence of cross bedded units or structure, thickness ~1 – 2m	Deposited as aeolian miliolite
Optical characteristics	Depositional features- consist of allochemical grains, detrital grains and authigenic carbonate cement, grains are <0.25mm size, dissolution of allochems forms secondary porosity Tectonic features- recrystallisation of calcitic cement, fracturing of detrital quartz grains and allochems	Depositional features indicate aeolian origin of miliolite Tectonic features result due to the effect of faulting
SEM characteristics	Depositional features- sub-rounded grain, bulbous and abraded edges, conchoidal and v-shaped fractures, linear parallel to sub-parallel fractures, irregular depressions, elongated straight and curved grooves, irregularly broken surfaces, upturned plates, Diagenetic feature- silica precipitation Tectonic features- shallow sawtooth fractures, intensively fractured surface, rolled quartz grains abrasion fatigue, highly fractured cleavage plates, striation marks, adhering fine silty particles to the surface, exfoliated sheet	Depositional features indicate aeolian origin of miliolite Tectonic features result due to the effect of faulting

Site S6		
Field characteristics	Well-developed horizontal stratification, heterogenous grain size, semi consolidated, poorly sorted, presence of coarse lithic sand, pebble-cobble sized clasts of Mesozoic rocks, occur in valley depression, thickness ~1-2m	Deposited as fluvially reworked miliolite
Optical characteristics	Depositional features- Consist of allochemical grains, detrital grains and authigenic carbonate cement, grains are $\leq$0.2mm size, sub-rounded, inter-granular dissolution of allochems forms secondary porosity, Tectonic features- micro-sparite formation suggests recrystallization of calcitic cement, development of calcitic microfibers	Depositional features indicate fluvial origin of miliolite Tectonic features formed due to the effect of faulting
SEM characteristics	Depositional features- Numerous cracks on the surface, angular to sub-angular grain, arcuate and straight steps, conchoidal fractures, abraded edges with a relatively smooth surface and minor radial fractures, deeply engrossed curved grooves Tectonic features- striations on parts of the grain surface, lattice distortion, the occasional occurrence of rolled quartz grain	Depositional features indicate fluvial origin of miliolite Tectonic features result due to the effect of faulting
Site S7 (South of Bhujodi)		
Field characteristics	Unimodal grain size, medium to fine-grained, moderately to well-sorted carbonate sand, occur as obstacle dune deposits, display cross bedding structure, thickness ~2m	Deposited as aeolian miliolite
Optical characteristics	Depositional features- consist of allochemical grains, detrital grains and authigenic carbonate cement, well sorted, grain-size of about 0.2 - 1.0mm and <1mm size bioclasts, dissolution of bioclasts leads to the development of secondary porosity, allochems and detrital grains shows point contact relation due to minimal compaction Tectonic features- detrital quartz grain shows fracturing, recrystallization and serrated grain boundaries, the weak orientation of constituent grains	Depositional features indicate aeolian origin of miliolite Tectonic features result due to the effect of faulting
SEM characteristics	Depositional features- sub-rounded grain, conchoidal and v-shaped fractures, linear parallel to sub-parallel fractures, irregular depressions, elongated straight and curved grooves, straight and arcuate fractures, also in step like pattern, irregularly broken surfaces, upturned	Depositional features indicate aeolian origin of miliolite

	plates, bulbous and abraded edges Diagenetic feature- excessive silica precipitation Tectonic features- shallow sawtooth fractures, intensively abraded and fractured surface abrasion fatigue, highly fractured cleavage plates, striation marks, adhering fine silty particles to the surface, chemically etched surface, exfoliated sheet	Tectonic features result due to the effect of faulting
Site S8		
Field characteristics	Heterogenous grain size, well developed horizontal stratification, semi consolidated, poorly sorted, presence of coarse lithic sand, pebble-cobble sized clasts of Mesozoic rocks, occur in valley depression, thickness ~7-8m.	Deposited as fluvially reworked miliolite
Optical characteristics	Depositional features- consist of allochemical grains, detrital grains and authigenic carbonate cement, grains are $\leq$0.25mm size, sub-rounded to sub-angular, development of secondary porosity due to dissolution of allochems Tectonic features- shows recrystallization by forming microsparite	Depositional features indicate fluvial origin of miliolite Tectonic features attributed to effect of faulting
SEM characteristics	Depositional features- conchoidal fractures, Si globules precipitated over most of the surface, scattered upturned plates, curved grooves along the grain edges Diagenetic feature- silica precipitation Tectonic features- highly abraded surface, striation marks cover most part of the grain surfaces, breakage blocks, sawtooth shaped fracture pattern, exfoliation surfaces	Depositional features indicate fluvial origin of miliolite Tectonic features result due to the effect of faulting
Site S9		
Field characteristics	Heterogenous grain size, poorly developed stratification, semi consolidated, poorly sorted, occur along first order dried stream channel, thickness ~4-5m	Deposited as fluvially reworked miliolite
Optical characteristics	Depositional features- consists of allochemical grains, poorly sorted detrital grains and authigenic carbonate cement, grains are <0.25mm size, point contact relation between the grains Tectonic features- absent	Depositional features suggest fluvial origin of miliolite
SEM characteristics	Depositional features- sub-rounded grains, smoothened surface due to solution action, edge	Depositional features indicate fluvial origin of

	abrasion, v-shaped percussion marks, curved grooves, no signs of breakage in the grains Tectonic features- absent	miliolite Absence of tectonic features attributed to location away from surface faulting
Site S1*		
Field characteristics	Heterogenous grain size, poorly developed horizontal stratification, semi consolidated, poorly sorted, presence of cobble sized clasts, occur in cliff of a small channel, thickness ~3-4m	Deposited as fluvially reworked miliolite
SEM characteristics	Depositional features- sub-rounded grain, small conchoidal fractures, straight and curved grooves, solution pits, very less breakage of grains Diagenetic feature- silica precipitation Tectonic features- absent	Depositional features observed through SEM indicate fluvial origin of miliolites Absence of tectonic features attributed to location away from fault line
Site S2*		
Field characteristics	Heterogenous grain size, unstratified, semi to unconsolidated, moderately sorted, occur in valley depression, thickness ~2-3m	Deposited as fluvially reworked miliolite
SEM characteristics	Depositional features- pitted and grooved appearance of the surface, conchoidal fractures, rounded to sub-rounded grain, less fractured surfaces Diagenetic feature- limited silica precipitation Tectonic features- absent	Depositional features observed through SEM indicate fluvial origin of miliolite Absence of tectonic features attributed to location away from fault line
Site S3*		
Field characteristics	Homogenous grain size, fine to medium grained, moderately to well sorted, semi consolidated, occur on the southern slope of the north facing scarp, thickness-undefined	Deposited as aeolian miliolite
SEM characteristics	Depositional features- rounded to sub-rounded grains, smoothened surface due to solution action, edge abrasion, V-shaped percussion marks, no signs of breakage in the grains Tectonic features- absent	Depositional features observed through SEM indicate aeolian origin of miliolite Absence of tectonic features attributed to location away from fault line
Site S4*		

Field characteristics	Well-developed horizontal stratification, heterogenous grain size, semi consolidated, poorly sorted, presence of coarse lithic sand, pebble-cobble sized clasts of Mesozoic rocks, occur along cliff of a small stream, thickness ~0.5m	Deposited as fluvially reworked miliolite
SEM characteristics	Depositional features- chemically etched surface, crescentic gouges, v-shaped percussion marks, conchoidal fractures, solution pits on the surface, comparatively intact grains with very less breakage Tectonic features- absent	Depositional features observed through SEM indicate fluvial origin of miliolites Absence of tectonic features attributed to location away from fault line
Site S5*		
Field characteristics	Heterogenous grain size, poorly developed horizontal stratification, semi to unconsolidated, moderately sorted, occur in valley depression, thickness ~7m	Deposited as fluvially reworked miliolite
SEM characteristics	Depositional features- Si globules precipitated over most of the surface, deeply engrossed curved grooves, v-shaped percussion marks, irregular depressions on the surface, no evidence of fracturing of grains Tectonic features- absent	Depositional features observed through SEM indicate fluvial origin of miliolite Absence of tectonic features attributed to location away from fault line
Site S6*		
Field characteristics	Heterogenous grain size, unstratified and unconsolidated deposits, moderately sorted, presence of cobble sized clasts, occur in small first order dried stream channel	Deposited as fluvially reworked miliolite
SEM characteristics	Depositional features- conchoidal fractures, chemically etched surface, crescentic gouges, smooth surface, rounded outline parallel fractures visible on small part of the grain surface Diagenetic feature- silica precipitation on abraded and rough surface Tectonic features- absent	Depositional features observed through SEM indicate fluvial origin of miliolite Absence of tectonic features attributed to location away from fault line