Effect of heat on crystal size distributions of quartz

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Here we report the effect of heat on crystal size distributions (CSDs) of quartz crystals in schists. CSD plots for the two samples from the Lunavada Group of Precambrian rocks of Gujarat, India were prepared. One sample is from close to the granite (Godhra granite) while the other lies far from it. The two show quite distinct 'CSD plots', the former a bell-shaped plot while the latter a near-linear plot. It is suggested that the bell shape is a manifestation of the strong annealing and Ostwald-ripening that the rock underwent owing to its proximity to the granite. The linearity of the CSD plot for the sample away from the granite indicates that it did not undergo any significant Ostwald-ripening.

THE crystal lattice of deformed crystals consists of several defects. These can be point defects (e.g. vacancies), line defects (e.g. dislocations) or planar defects (e.g. subgrain boundaries)[1]. Deformation of a crystal at relatively low temperatures and/or fast strain rates results in the increase in dislocation density and the formation of dislocation tangles or pile-ups[1–4]. This phenomenon is similar to that of cold-working in metals. The increased dislocation density causes the crystal to harden and thus more stress is required to further deform the crystal. This phenomenon is known as work-hardening[5,6]. A cold-worked crystal is characterized by a higher internal energy than the undeformed crystal and is thermodynamically less stable. With increasing temperature the cold-worked state tends to become increasingly unstable and eventually the crystal softens and reverts to a strain-free condition. The process by which this occurs is called annealing[5,6], which involves three distinct processes, viz. recovery, recrystallization and grain growth. It results in coarsening of the grain size with concomitant reduction in the total number of grains to achieve greater thermodynamic stability. In this paper we report the effect of heat and annealing on the crystal size of quartz in naturally deformed rocks.

Schist samples belonging to the Lunavada Group of Precambrian rocks of the Aravalli Supergroup, western India were collected for the present study. The Lunavada Group of rocks lie between latitudes N 22°45′ and N 23°45′ and longitudes E 73°15′ and E 74°30′ (Figure 1) and occupy an area of approximately 10,000 km^2, extending from southern Rajasthan into northeastern Gujarat[7–9]. The Group has been classified into six formations, viz. Kalinjara, Wagidora, Bhawanpura, Chandanwara, Bhukia and Kadana[7,8]. Of these, only the Kadana Formation falls within Gujarat[9] and consists of alternating layers of quartzites and schists. The quartzites form sinuous ridges around Lunavada, Sant-Rampur and Kadana[8–10]. Two episodes of deformation have been recorded and the metamorphism is dominantly up to greenschist facies. At the southern and southwestern limit of the Lunavada Group lies the Godhra granite. This granite has been dated to 955 my (ref. 11) and is considered to be a remobilized basement[12]. Near the contact of the granite and schists, the metamorphism is slightly higher, almost of the order of lower amphibolite facies[8]. To the south of Lunavada town the granite and associated quartz–feldspar pegmatites intrude the rocks of the Lunavada group. Thus, the area to the south of Lunavada has provided an ideal geological setting to study annealing and Ostwald-ripening of quartz crystals due to the heat supplied by the Godhra granite.

Microscopic examination of several thin sections revealed that samples of schists that lie close to the granite possess coarse crystals of quartz and muscovite, while those that lie at a greater distance from the granite possess smaller crystals of quartz and extremely fine micas. Two representative samples of schists – one close to the granite (marked 1 on Figure 1) and the other far from it (marked 2 on Figure 1) were selected. The two localities lie at a distance of 4 km and 22 km from the margin of the Godhra granite (see Figure 1). Our intention was to carry out a systematic statistical analysis of the information that can be derived from the microscope so that the variation in the crystal size of the two samples could be graphically represented and the effect of heat on crystal size be studied. For this purpose we used the crystal size distribution (CSD) theory described by Marsh[13].

The CSD theory was first formulated and adapted in chemical engineering literature by Randolph and Larson in 1971 and subsequently applied to earth sciences[13]. It has been used to understand the effect of heat on CSDs, to calculate nucleation and growth rates of crystals, the growth time of crystals in igneous and metamorphic rocks[13–15] and also to calculate the magma storage time[16]. The fundamental steps involved are as follows:

A 1 cm^2 area of thin section is selected. Measurements of the longest crystal dimension of all the grains of a particular mineral being studied (in this case quartz) are made for the selected area. This gives the frequency distribution of crystals (N_A) of various size (L) in the unit area. Using the formula $N_V = N_A^{1.5}$, the number of crystals of size L in unit volume, i.e. N_V is determined. N_V is the true grain size distribution. From these data the volume frequency histogram (N_V vs L) is prepared, which gives a good graphical representation of the distribution of crystals of different sizes. Subsequently, the population density (n) of the crystals of different sizes is calculated. Population density (n) is defined as

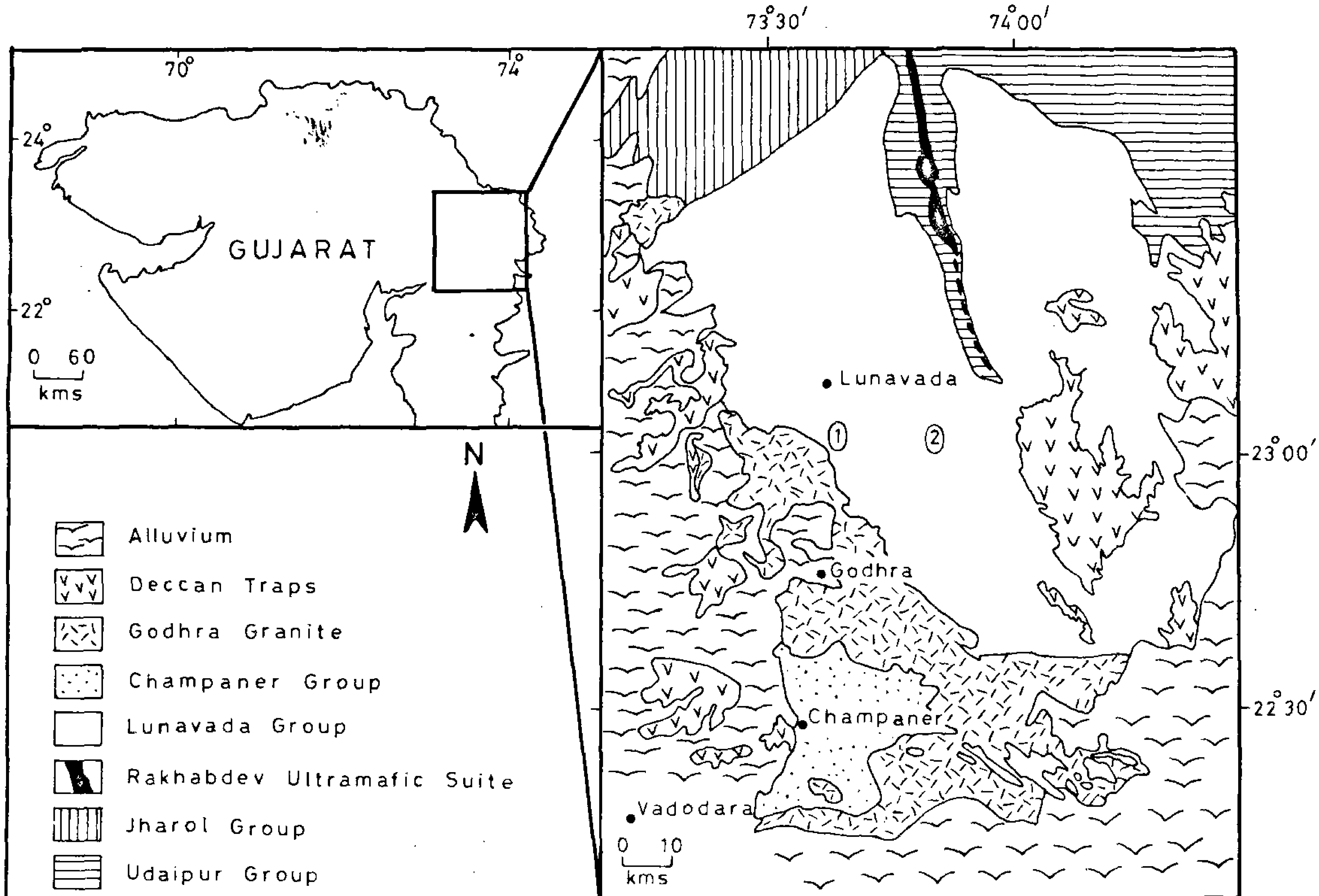

Figure 1. Lithostratigraphic map of the area around Lunavada[7]. (1) and (2) are the locations of the samples.

the number of crystals in a given size class per unit volume and is obtained by the formula: $n = \Delta N/\Delta L = dN/dL$, where N is the cumulative number of crystals per unit volume. The plot of $\ln(n)$ against L is referred to as the CSD plot and the shape of this plot is the manifestation of the effect of heat on the CSDs and gives a good graphical representation of the extent of annealing the rock underwent.

Using the above principles, CSDs of quartz grains were calculated in thin sections of the two schist samples. The schist closer to the granite was found to contain a total of 1225 grains in a unit area with a mean crystal size of 0.1851 mm. The sample away from the granite contains 5931 grains in a unit area with the mean crystal size of 0.05 mm. Using the formula described above the number of quartz crystals in unit volume (N_V) for different sizes were calculated, from which the population density (n) of crystals was obtained. Tables 1a and b show the data calculated for samples, closer and farther from the granite respectively. Figure 2 *a* and *b* show the volume frequency histograms (N_V vs L) for the samples, closer and farther from the granite respectively. The former shows that the quartz grains have crystallized over a wide range, with the maximum frequency being in the intermediate size range. On the other hand, the quartz grains in the sample away from the granite have crystallized in a limited size range and the maximum frequency is in the smaller size range. These histograms thus provide a good graphical representation of the effect of heat on the size of quartz crystals. However the 'CSD plot', $\ln(n)$ vs L is much more informative to understand this aspect.

Figures 3 *a* and *b* are the 'CSD plots' for the samples occurring close and far from the Godhra granite respectively. These two plots are observed to be conspicuously different. The former shows a bell shape while the latter is more or less linear. These different shapes of the CSD plots reflect the varied thermal histories of the two samples. Linear CSDs have been described for crystals in igneous rocks and hornfelses and have been interpreted to indicate continuous nucleation and growth of crystals[14,15]. On the other hand, the bell-shaped CSDs have been described for minerals like garnet and sphene in regionally metamorphosed rocks and are considered to indicate (i) an initial continuous nucleation and growth of crystals, and (ii) later loss of small crystals due to annealing[14,15]. Accordingly, we interpret that the bell-shaped 'CSD plot' (Figure 3 *a*) indicates strong annealing and 'Ostwald-ripening' – a term used to describe the increase in grain size which occurs upon annealing[13]. On the other hand, the greater linearity of the 'CSD plot' for the sample away from granite (Figure 3 *b*) suggests that there was no significant 'Ostwald-ripening'. It has been observed by us that (i) the sample closer to the granite has a total of 1225 quartz crystals in a unit area and mean quartz crystal size of 0.1851 mm. The sample away from the granite has 5931 quartz crystals in a unit area with a mean size of only 0.05 mm. (ii) The quartz crystals in the sample close to granite have crystallized over a wide size range of 0.025 mm to 0.675 mm with maximum crystals occurring in the intermediate sizes (Figure 2 *a*), while the quartz crystals in the sample away from the granite have crystallized in a limited size range of 0.025 mm to 0.175 mm, with maximum crystals occurring in the smallest sizes (Figure 2 *b*). (iii) The CSD plot ln(n) against L for the sample away from the granite is bell shaped while that for the other sample is linear.

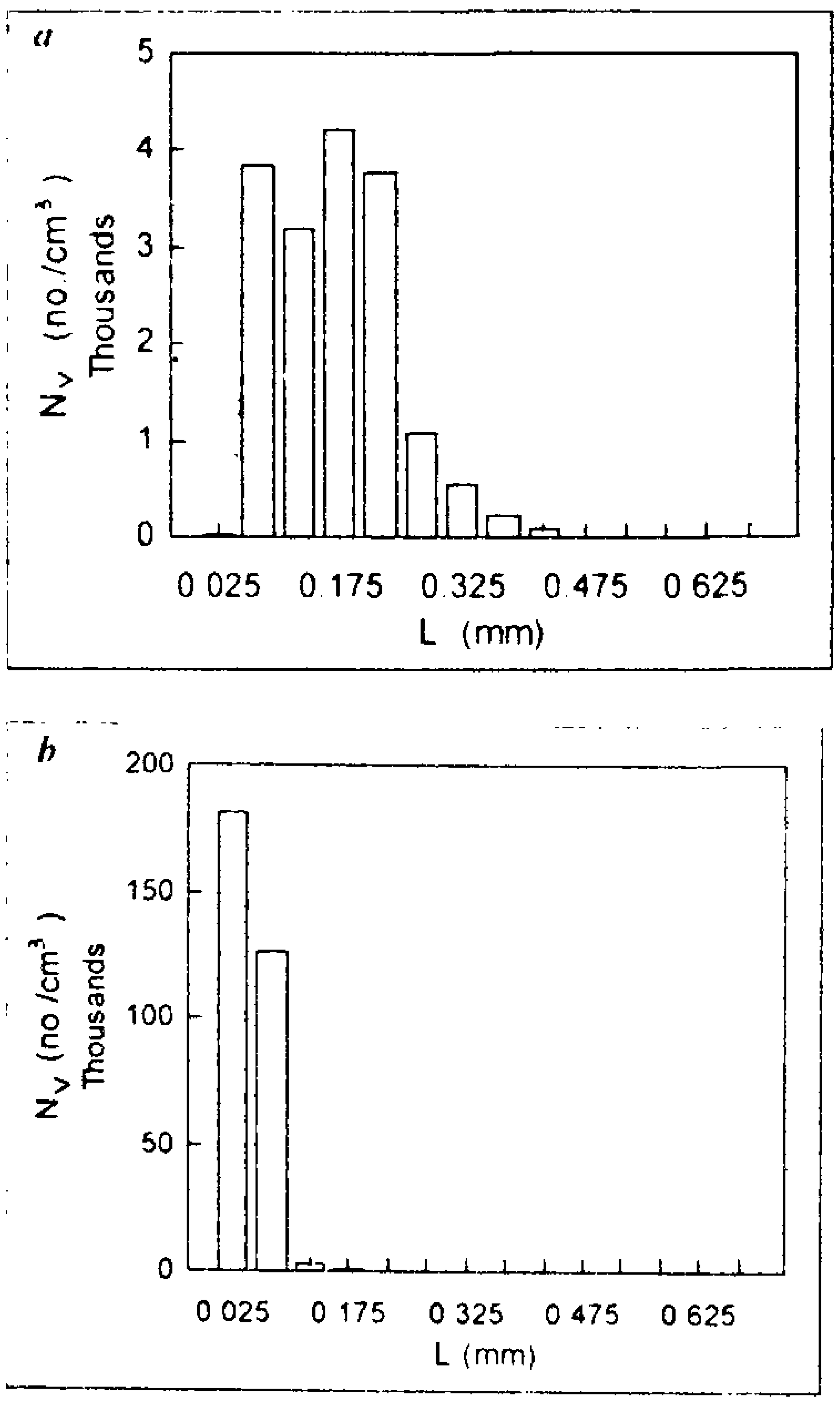

Figure 2. Volume frequency histograms, N_V vs L of quartz crystals for sample close to granite (*a*) and far from granite (*b*). L is the mid-point of each size class interval. Both graphs are plotted on the same scale along X-axis for comparison.

All the above observations lead to the conclusion that the sample in proximity to the Godhra granite has undergone strong Ostwald-ripening. The initial growth of quartz crystals in this sample was continuous. This is represented by the linearity of the right hand portion of the bell-shaped CSD plot which represents ln(n) at larger values of L (Figure 3 *a*). Subsequently, the smaller crystals were resorbed at the expense of the larger crystals due to annealing which was triggered by the heat supplied due to intrusion of the Godhra granite and resulted in a prolonged cooling at high temperatures. It is this later phenomenon which gives the bell shape to the CSD plot. Prior to the intrusion of the granite,

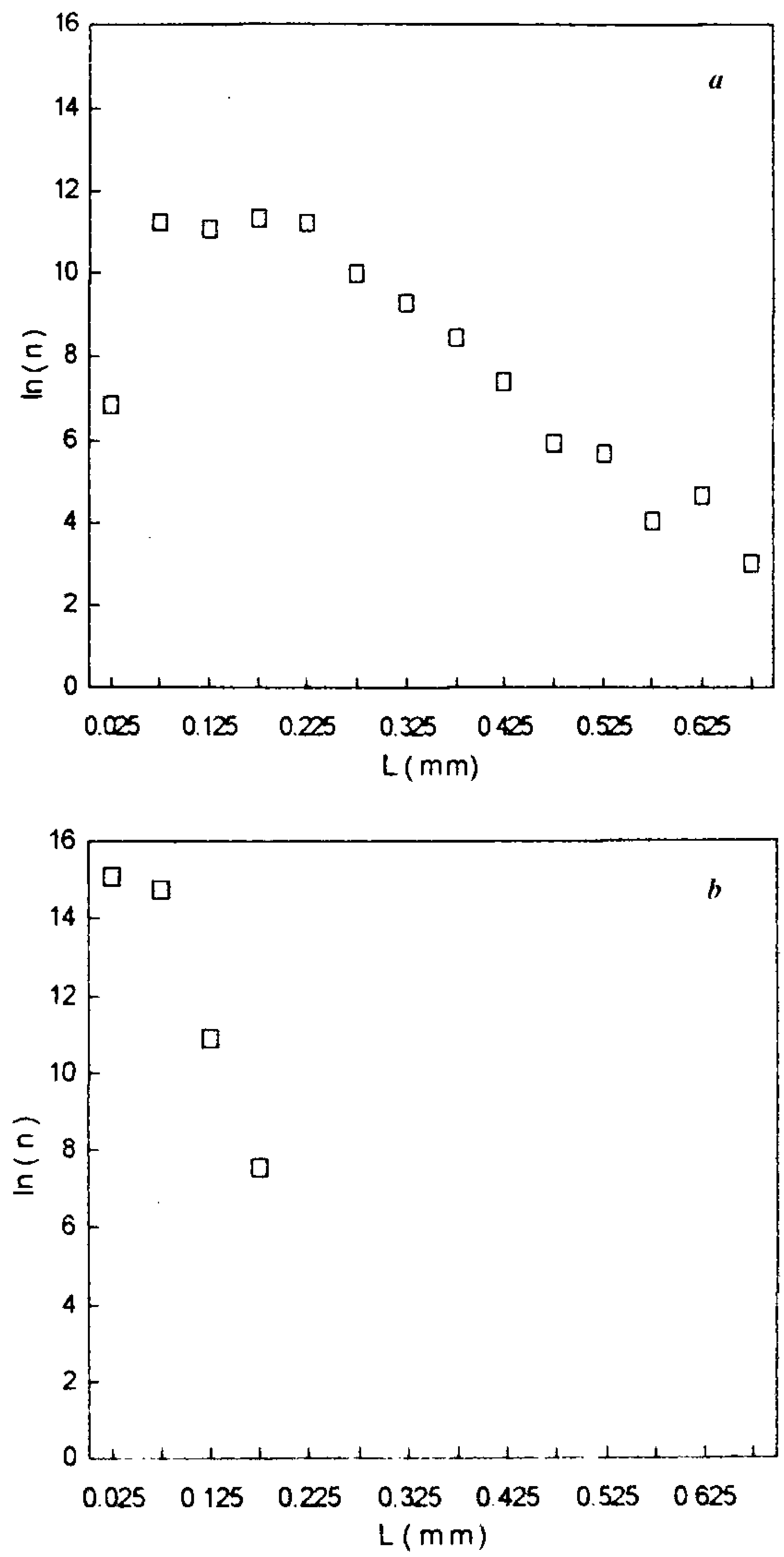

Figure 3. CSD plots, ln(n) vs L of quartz crystals for sample close to granite (*a*) and far from granite (*b*). L is the midpoint of each size class interval. Both graphs are plotted on the same scale for comparison.

Table 1a. Data of sample close to granite (marked 1 in Figure 1)

L (mm)	N_A (no./cm^2)	N_V (no./cm^3)	n (no./cm^4)	ln(n)
0.025	13	46.87	937.44	6.84
0.075	245	3834.85	76697.13	11.24
0.125	217	3196.60	63932.19	11.06
0.175	260	4192.37	83847.48	11.33
0.225	242	3764.63	75292.73	11.22
0.275	105	1075.92	21518.59	9.97
0.325	67	548.41	10968.37	9.30
0.375	38	234.24	4684.95	8.45
0.425	19	82.81	1656.38	7.41
0.475	7	18.52	370.40	5.91
0.525	6	14.69	293.93	5.68
0.575	2	2.82	56.56	4.03
0.625	3	5.19	103.92	4.64
0.675	1	1.00	20.00	2.99

Table 1b. Data of sample far from granite (marked 2 in Figure 1)

L (mm)	N_A (no./cm^2)	N_V (no./cm^3)	n (no./cm^4)	ln(n)
0.025	3200	181019.33	3620386.71	15.10
0.075	2515	126126.68	2522533.71	14.74
0.125	195	2723.02	54460.53	10.90
0.175	21	96.23	1924.68	7.56

the rock must have been in a cold-worked state with a high dislocation density. With the intrusion of the granite, the quartz crystals annealed and ripened because of the rise in temperature so as to achieve greater thermodynamic stability. During this process the quartz crystals grew in size and reduced in number. Contrary to this, the sample away from the granite shows a CSD plot for quartz crystals with greater linearity. This connotes that the growth of quartz crystal was continuous. This sample possesses a large number of small crystals of quartz, a low mean crystal size and a large number of total quartz crystals. According to us, all this is directly related to the absence of any significant post-deformational Ostwald-ripening due to the greater distance of this sample from the Godhra granite.

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Trace and REE signatures in the Maastrichtian Lameta Beds for the initiation of Deccan volcanism before KTB

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Assignment of Maastrichtian age[1–3] for the Lameta sediments locally underlying the Deccan basaltic flows in the eastern lobe of the Deccan volcanic province has been integrated with the radiometric and palaeomagnetic data of the Deccan Trap by recent workers[4,5] in evolving an extremely shorter duration model for the Deccan volcanism at KTB. However, the earlier mineralogical studies[6,7] and the current geochemical findings on the detrital clay assemblages of the Lametas are indicative of their derivation from Deccan basalt. The negative Ce anomalies recorded in the smectites of Lametas are supportive of their basaltic lineage, implying early eruptions of Deccan volcanism predate these Maastrichtian sediments. This finding is incongruent with the rapid eruptive duration model of < 1 Ma, at KTB[4,5] proposed for the Deccan volcanic episode.

ARGUMENTS in favour of an *internal cause*[4,8] for the mysterious mass extinction at KTB largely revolved around the coincidence of Deccan volcanism in central