Pseudo-surface velocities (densities) and pseudo-depth densities (velocities) along selected profiles in the Dharwar craton, India

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Pseudo-surface velocities were obtained from the density studies conducted along the Jadcharla–Panaji subtransect that cuts across the northern part of the Dharwar craton, via an empirical velocity–density relationship. Velocities in the range of 3.62–4.43 km/s, 3.51–5.24 km/s and 3.68–9.73 km/s were computed for the three major constituents of the Dharwar craton–granites, peninsular gneisses and schists, respectively. Further, a pseudo-depth density graph was also obtained from the established depth–velocity functions along the Kavali–Udipi DSS profile and also in the Dharwar craton. The Kolmogorov–Smirnov statistical test was applied to these two data sets – to the pseudo-velocities along the Jadcharla–Panaji subtransect and the psuedo-densities along the Kavali-Udipi profile – to determine whether any difference existed in the lateral and/or vertical variation, between the eastern and western blocks of the Dharwar craton. Results from both the tests indicated that the samples belonged to different population distributions, implying a surface as well as depth variation between the eastern and western blocks of the craton, thus reinforcing their separate nature.

THE Dharwar craton, distinguished by a complex course of geological evolution from the Archaean through to the Proterozoic, represents one of the most significant shields of the Precambrian. The three major geologic constituents[1] of the area in broadly decreasing order of age are, the peninsular gneisses (> 2900 Ma), schist belts (2600–2900 Ma for the western schist belts and 2500–2880 Ma for the eastern belts), and younger granites (~ 2500 Ma). While granites and gneisses cover large parts of Karnataka and the Indian peninsula[2], the distinctive schist belts and surrounding granitoids are believed to represent accreting arcs and intra-arc basins formed as a result of successive collision of micro-continents[3,4].

However, the stratigraphic sequence of the Dharwar craton is hardly conclusive. The schist belts as well as the gneiss complex do not exhibit a uniform chronological relationship[5–7]. Further, while on the basis of the observed parallelism of the granite and greenstone belts, Newton[8] and Jayananda *et al.*[9] suggested a common evolutionary mechanism for the two Naha *et al.*[10] opine that the different deformational episodes have affected all the Archaean cover sequences, giving an apparent overall unity in structural style.

There are differing opinions on the geology and nomenclature of the two constituent units – the eastern and western blocks – of the Dharwar craton. Radhakrishna[11] opines that though the western block can be called a craton, the eastern block is an early Archaean mobile belt. On the other hand, Rajamani[12] discusses the separate and different geological evolution of the western and eastern Dharwar cratons. In spite of these differences, it is established that the western block of the Dharwar craton (broadly the region to the west of the Closepet granite body or to the west of the Chitradurga schist belt) is characterized by mature sediment-dominant greenstone belts with subordinate volcanics and intermediate-pressure metamorphism. The eastern block (lying to the east of the Closepet granite), in sharp contrast, is characterized by volcanics-dominated greenstone belts and low-pressure metamorphism[1]. Furthermore, given the general lack of consensus on the nature of variation between the eastern and western blocks of the Dharwar craton, the Jadcharla–Raichur–Panaji subtransect (Figure 1) that traverses the northern part of the craton is specially suitable for studying the variation (if any) between the constituent units. This transect traverses all major formations of the craton – the predominant peninsular gneisses, the geologically and economically important Gadag, Tawergiri, Sindhanur, Kushtagi, Raichur and Makthal schist belts, as well as the polyphase Closepet granite, which is a linear body that traverses the Dharwar craton north to south, roughly parallel to the greenstone belts.

It is known that for most deep-structural studies, velocity information is indispensable. Further, the velocity–density relationship[13], appropriately established empirically for a given region permits calculation of pseudo densities, provided the velocities are known, and vice versa. This paper (1) uses an assumed velocity–density relationship to compute (a) pseudo-velocities from measured densities and (b) pseudo-densities from observed velocities[14] and (2) statistically analyses (a) the surface variation between the constituent blocks of the Dharwar craton along the Jadcharla–Panaji subtransect from the pseudo-velocities for each of the major rock formations of the craton, and (b) the depth variation between the constituent blocks of the Dharwar craton from computed pseudo-depth densities along the Kavali–Udipi DSS profile[14].

Bulk densities of a total of 860 samples from all geological formations (Closepet granite – 250 samples, peninsular gneiss – 260 samples and schist – 216 samples) along the entire length of the 600 km Jadcharla–Panaji transect were measured in the laboratory for

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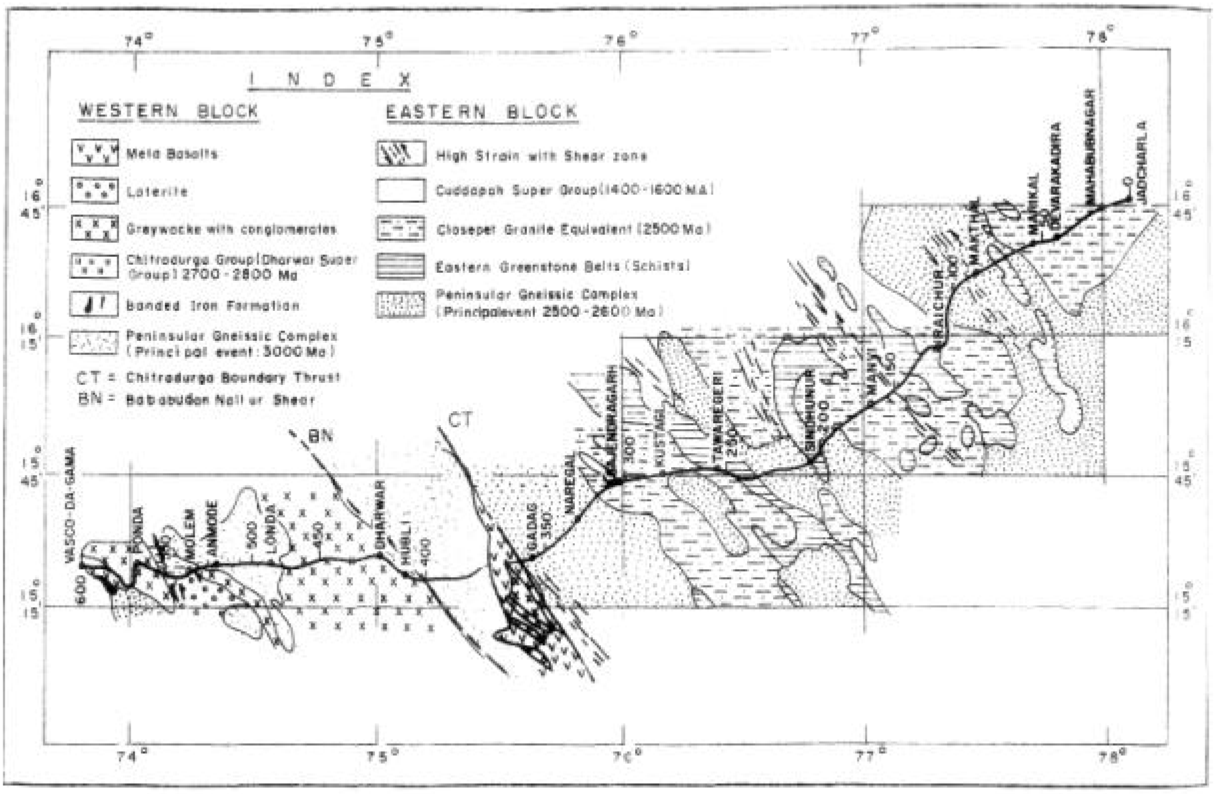

Figure 1. Geology map along the Jadcharla–Panaji subtransect.

petro-physical analysis using a direct reading densitometer[15] fabricated in the Department of Geophysics, Osmania University, Hyderabad[16].

From Figure 2, which gives the density profile along the transect and the corresponding geological section, we can qualitatively examine the correlation between the two. Thus, the measured and average density values for younger granites, peninsular gneisses and schists (Figure 2 and Table 1) vary over a wide range. The eastern block schist belts (Raichur and Makhtal schists) show a mean density ranging from 2.80 to 2.85 g/cc, and the Sindhanur, Tawergiri, Gadag and Dharwar schists in the western block show a higher mean density varying over a wider range from 2.85 to 3.14 g/cc. These results agree fairly well with those reported earlier[17–19].

Velocity information is the most common tool for deep-structure evaluation of a region. It is also useful in another different but related way: in its relationship with rock density. Zhuravlev[13], basing his inferences on large experimental data over a wide variety of geological units, arrived at an empirical relationship between the density (σ) and velocity (v):

$$\sigma = 1.891157 + 0.17349\, v, \qquad (1)$$

where σ and v are in g/cc and km/s, respectively.

Using eq. (1) above, the ranges of pseudo-surface velocities for various formations along the transect were inferred from the corresponding densities. Thus, for the western Dharwars, these velocities were found to range from 3.74 to 4.2 km/s and, 4.2 to 4.72 km/s for younger granites and peninsular gneisses, respectively and from 5.12 to 5.93 km/s for Dharwar schists and Dharwar schist equivalents, and from 5.12 to 7.08 km/s for Gadag schists (Table 1). The corresponding picture for the eastern Dharwars is 3.86–4.03 km/s and 4.09–4.49 km/s for younger granites and peninsular gneisses, respectively and 5.93–8.83 km/s, 6.28–8.47 km/s, 4.78–6.28 km/s and 4.2 – 7.31 km/s for the Tawegiri, Sindhanur, Raichur and Makthal schists, respectively.

While the authors are alive to the argument regarding the area-specific nature of eq. (1) above, the pseudo-surface velocities obtained (average of 5.05 km/s and 4.74 km/s for the western and eastern Dharwars, respectively) were found to generally agree with those obtained by Reddy *et al.*[14], who established upper crust P-wave velocities of 6.0 km/s at the surface, increasing to 6.2 km/s at a depth of 22–24 km in the central part of the western Dharwar, and 5.9 km/s at the surface in the central part of the eastern Dharwar craton to 6.2 km/s at a depth of 5–8 km (Table 2). The error percentages for average surface velocities as obtained by Reddy *et al.*[14] and the present study were found to be 16.05% and

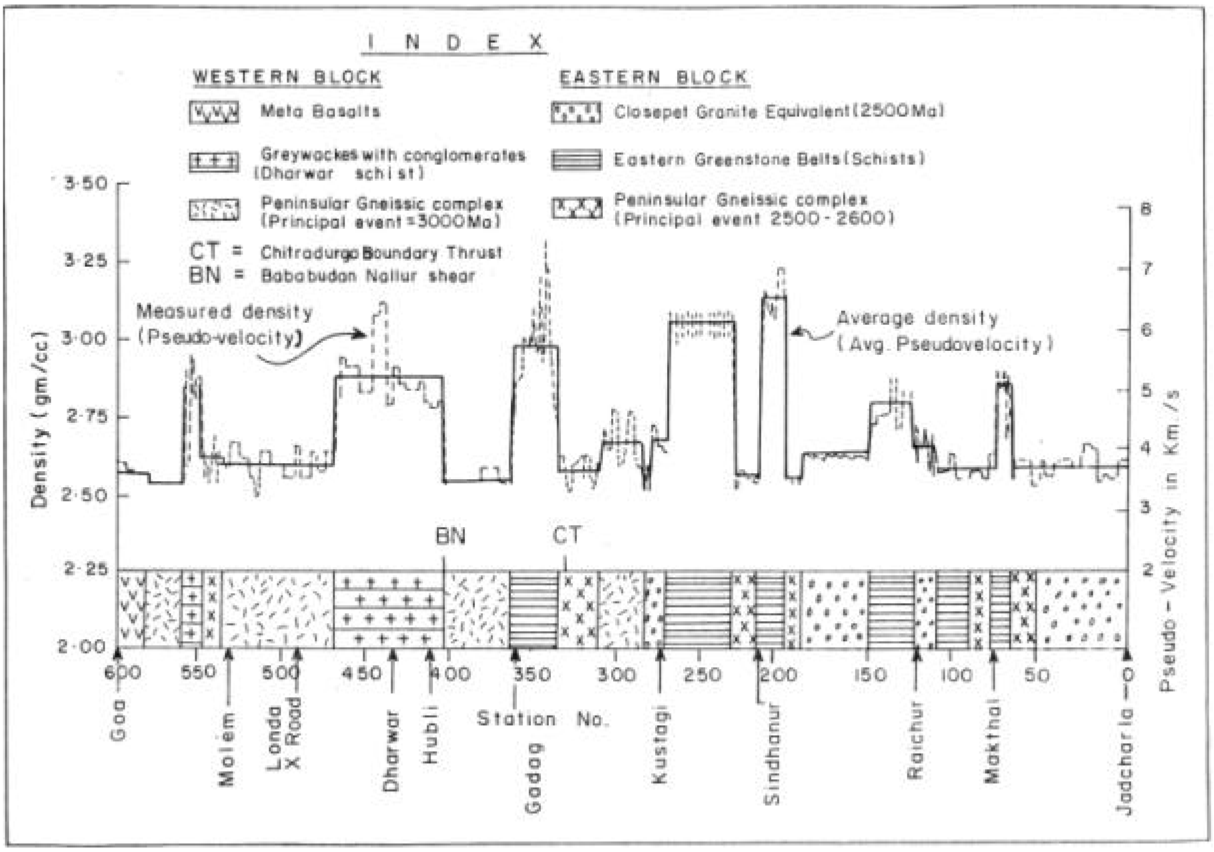

Figure 2. Density/pseudo-velocity profile along with the corresponding geological section along the Jadcharla–Panaji subtransect.

Table 1. Densities (pseudo-velocities) for different rock formations in the western and eastern Dharwar cratons

Rock type	No. of samples	Modal density (g/cc)	Standard deviation (g/cc)	Range of observed densities (g/cc)	Computed modal velocity (km/s)	Range of computed velocities (km/s)
Densities and pseudo-velocities in the western Dharwar craton						
Younger granites	55	2.58	0.06	2.54–2.62	3.97	3.74–4.20
Peninsular gneiss	63	2.67	0.07	2.62–2.71	4.49	4.20–4.72
Dharwar schists equivalent	10	2.85	0.14	2.78–2.92	5.53	5.12–5.93
Dharwar schists	68	2.85	0.09	2.78–3.12	5.53	5.12–5.93
Gadag schists	44	2.98	0.22	2.87–3.07	6.28	5.12–7.08
Densities and pseudo-velocities in the eastern Dharwar craton						
Younger granite	195	2.57	0.01	2.56–2.59	3.91	3.86–4.03
Peninsular gneiss	197	2.64	0.2	2.60–2.67	4.32	4.09–4.49
Kustagi schists	39	3.06	0.15	2.92–3.34	6.74	5.93–8.35
Sindhanur schists	41	3.14	0.31	2.98–3.36	7.20	6.28–8.47
Raichur schists	58	2.80	0.08	2.72–2.98	5.24	4.78–6.28
Makthal schists	50	2.85	0.09	2.62–3.16	5.53	4.20–7.31

19.59% for the western and eastern Dharwars, respectively. The difference in computed velocities can be attributed in part to the basic method employed as well as primary data obtained – seismic velocities in the former as opposed to density-derived velocities in the latter, and in particular, to the essentially discrete though

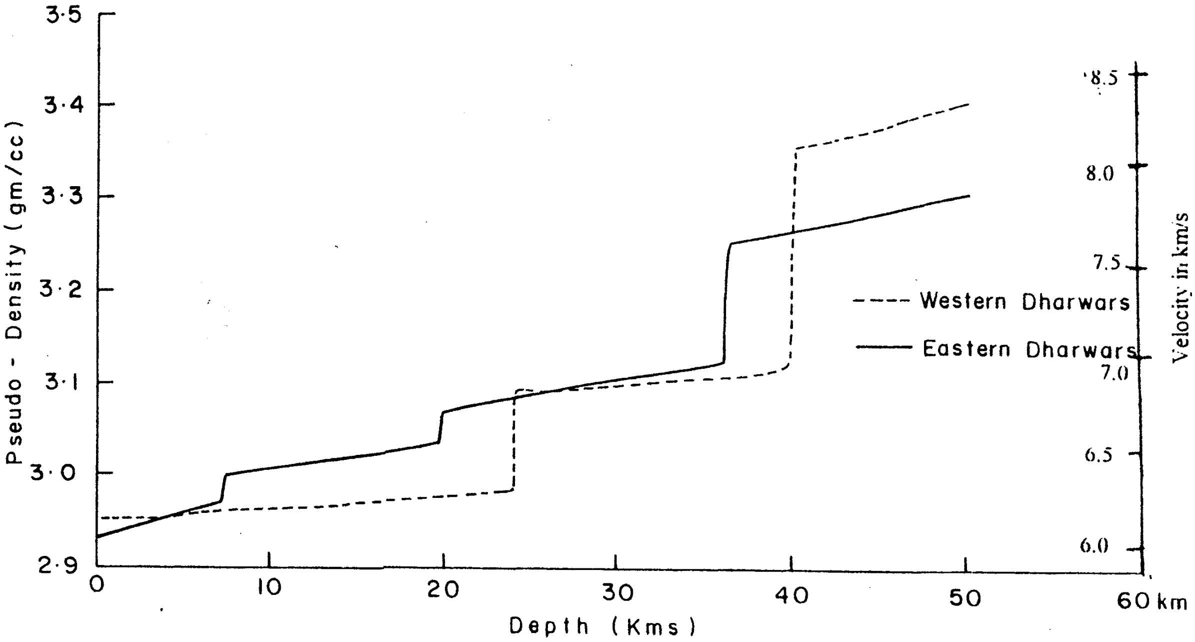

Figure 3. Pseudo-density (computed velocity) vs depth plot for the eastern and western Dharwars along the western and middle parts of the Kavali–Udipi DSS profile (after Reddy *et al.*[14]).

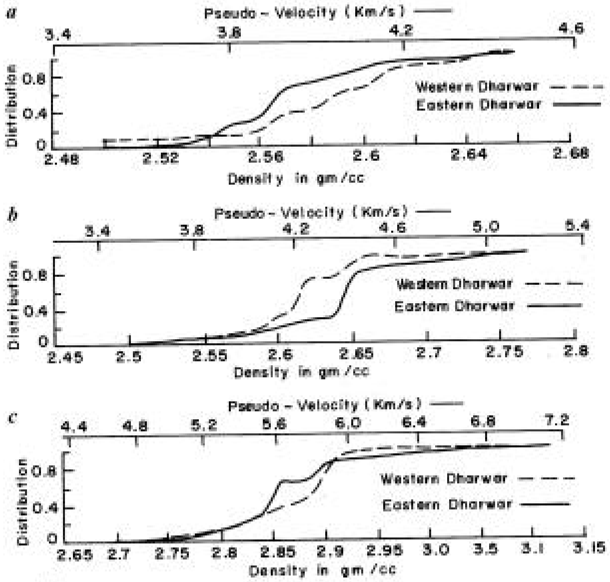

Figure 4. Kolmogorov–Smirnov test distributions for pseudo-surface velocities (or densities) of rock samples in the eastern and western Dharwars (***a***) for younger granites, (***b***) for peninsular genisses and (***c***) for schists along the Jadcharla–Panaji subtransect.

random sampling in the present study as against the assumed continuous sampling in the former. Encouraged by the near agreement and extendibility of eq. (1) to the area under study, the corresponding pseudo-depth density data (Figure 3) were generated from the depth–velocity function of Reddy *et al.*[14]. Thus, the pseudo-depth density picture for the western Dharwar craton shows an upper crustal layer with a density increase from 2.93 to 2.96 g/cc at a depth of 22–24 km, and a lower crustal layer with a density increase from 3.07 to 3.10 g/cc above the Moho, which appears to occur at an average depth of 40 km and a density of 3.34 g/cc below it. Correspondingly, in the eastern Dharwar craton, an upper crustal layer with density increasing from 2.91 g/cc at surface to 2.96 g/cc at a depth of 5–8 km and a lower crustal layer with a density of 3.05–3.10 g/cc at a depth of 20–37 km is seen. The Moho in this case occurs at a depth of 37 km, with a density of 3.24 g/cc below it.

The Kolmogorov–Smirnov test is sensitive to differences in random population distributions. To determine the nature and extent of variation between the two blocks of the craton, this test was performed on two different sets of independent samples from the eastern and western Dharwars, to compare the populations. The first comprised the pseudo-surface velocities (as obtained from densities measured by the authors along the Jadcharla–Panaji subtransect) shown in Figure 4, and the second, velocity-derived depth-densities (pseudo-depth densities) along the western and middle parts of the Kavali–Udipi DSS profile[14], shown in Figure 5.

Thus, if we let $W_n(x)$ and $E_m(x)$ represent the unknown population distribution functions with respective sample sizes m and n from the eastern and western Dharwars, respectively, for the surface densities and velocity-derived depth densities, then the test statistic $D_{n,m}$ in each case is defined[20,21] as:

$$D_{n,m} = \mathrm{Sup}_x |W_n(x) - E_m(x)|, \qquad (2)$$

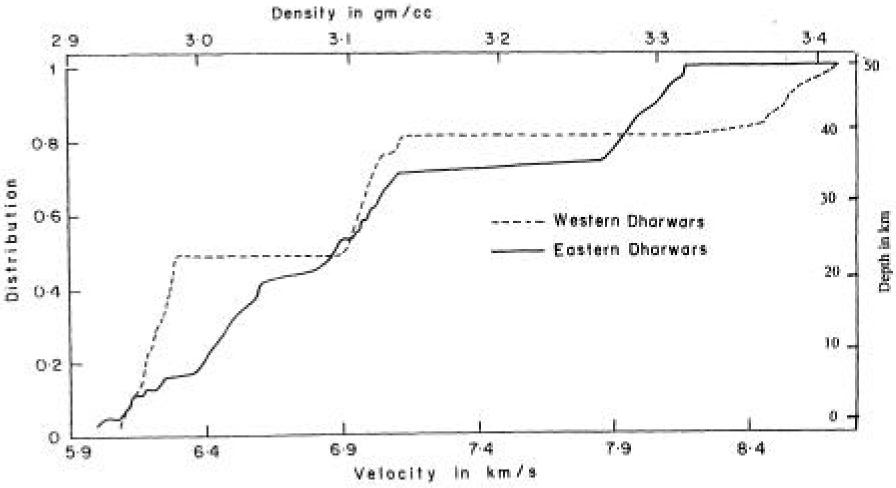

Figure 5. Kolmogorov–Smirnov test distributions for pseudo-depth densities (depth–velocities in the eastern and western Dharwars).

Table 2. Comparison between obtained average surface velocities/pseudo-velocities (from density studies along the Jadcharla–Panaji subtransect) and seismics (along the Kavali–Udipi profile, after Reddy *et al.*[14])

Average velocities/pseudo-surface velocities in the Dharwar craton (km/s)			
	Jadcharla–Panaji subtransect	Kavali–Udipi profile (after Reddy *et al.*[14])	Error (%)
Eastern Dharwars	4.74	6.0	16.05
Western Dharwars	5.05	5.9	19.59

where $D_{n,m}$ is the greatest vertical distance between the two empirical distribution functions and

$$W_n(x) = (\text{Number of observed } W_n\text{'s} \le x)/n, \tag{3}$$

and

$$E_m(x) = (\text{Number of observed } E_m\text{'s} \le x)/m. \tag{4}$$

The value of $D_{n,m}$ can also be determined graphically from the corresponding distribution graphs. For larger sample sets, the following equation can be used to determine $w_{0.95}$:

$$w_{0.95} = 1.36\,[(m+n)/mn]^{1/2}. \tag{5}$$

Then, depending upon whether the table values for $w_{0.95}$ are greater than or less than the calculated values of the test statistic, the samples belong to the same or different populations, respectively.

For the two-sided test with n and m equal to 63 and 197, 55 and 195 and 78 and 138, for pseodo-surface velocities (or surface densities) for the three rock units (peninsular gneiss, younger granites and schist), from the western and eastern Dharwars, respectively for the transect as a whole, the computed $w_{0.95}$ values were 0.19, 0.21 and 0.19, respectively while the corresponding observed $D_{n,m}$ in each of these cases was 0.44, 0.28 and 0.26, respectively.

A similar procedure was followed to determine the variation between the pseudo-depth densities (or depth–velocities, which were obtained by digitizing the pseudo-depth plot along the Kavali-Udipi profile[14] shown in Figure 3). Thus, for the two-sided test with n and m equal to 37 and 38 in this case for the western and eastern Dharwars, respectively the table $w_{0.95}$ value and the corresponding observed test statistic were 0.31 and 0.33, respectively indicating different source populations. As the observed test statistic for all cases is greater than the corresponding $w_{0.95}$ values, the samples belong to different populations in all cases. This could be the result of either the correctness of the one corresponding to a craton while the other to a mobile belt[11], or that the two blocks of the Dharwar craton evolved separately.

From measured bulk densities of 820 rock samples – mainly younger granites, peninsular gneisses and schists – from the eastern and western Dharwars along the Jadcharla–Panaji subtransect and an analytical density–velocity relationship, pseudo-surface velocities were computed. These computed velocities broadly agree with the reported results for the region and were studied statistically using the Kolmogorov–Smirnov statistical test to determine whether or not they represented the same population; they were found to belong to different populations. Further, from the depth–velocity function established along the Kavali–Udipi

DSS profile earlier by Reddy *et al.*[14], the corresponding pseudo-depth density graph was derived. In keeping with the expected geology of the region, similar patterns of variation between members of the constituent blocks of the Dharwar craton, both at the surface (along the Jadcharla–Panaji subtransect) as well as with depth (along the Kavali–Udipi profile) were observed.

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How long will triggered earthquakes at Koyna, India continue?

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Continued occurrence of triggered earthquakes in the vicinity of the artificial water reservoir at Koyna, India over the past 39 years is comprehended in terms of Kaiser effect (water level exceeding the previous maxima), rate of loading and duration of retention of high water levels. It is inferred that the increase in heterogeneity of the media due to mechanical changes caused by the impoundment of the reservoirs may not permit occurrence of another M 6.3 earthquake. However, smaller ($M \sim 5$) earthquakes will continue for another 3 to 4 decades.

KOYNA, located near the west coast of India is known to be the most significant site of artificial water reservoir-triggered seismicity[1–5], which started soon after the initiation of filling of the lake in 1961 (ref. 6). Over the past 39 years, the site has experienced globally the largest reservoir-triggered earthquake of M 6.3 on 10 December 1967 (ref. 7), seventeen earthquakes of $M \geq 5$, over 150 earthquakes of $M \geq 4$ and several thousand smaller events. Impoundment of another reservoir, Warna, some 30 km south of Koyna, started in 1985 and it was filled to a depth of 60 m in 1993. Earthquakes exceeding M 5 occurred during 1967–68, 1973, 1980, 1993–94 and 2000. Gupta *et al.*[8,9] showed the correspondence between the earthquake occurrence and factors like rate of increase in water level in the reservoir, maximum level reached and the duration for which higher levels are retained. It has also been pointed out that a rate of loading of 12 m/week is a necessary, but not a sufficient condition for $M \geq 5$ events to occur in the Koyna region[10]. It is hypothesized that the region between Koyna and Warna and capable of generating an earthquake of M 6.8, was stressed close to critical when Koyna Dam was impounded. As demonstrated amply by study of b values in earthquake magnitude–frequency relation, foreshock–aftershock patterns and ratio of the largest aftershock to the mainshock magnitude in earthquake sequences observed at Koyna, the heterogeneity of the media has increased. With the occurrence of one earthquake of M 6.3, 17 earthquakes of $M \geq 5$ and other smaller earthquakes, about one-half of the stored energy for an M 6.8 earthquake has been released. The remaining stored strain energy is likely to be released through smaller earthquakes during the next 3 to 4 decades. Occurrence of $M \sim 5$ earthquakes will be governed by Kai-

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