of *P. nubifer* have distinctly diverged, genetically, and probably female heterogamety has been established in them. Following the results of some earlier studies and our present data, it seems clear that the replacement of one sex-determining mechanism (XX-XY) by another (ZZ-ZW) has rather frequently preceded speciation in Chironomidae as it has occurred in Simuliidae.

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Geothermal and seismic evidence for the fluids in the crust beneath Koyna, India

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The presence of fluids in the crust beneath Koyna region has been examined, by computing the isochoric thermal pressure, pore fluid pressure and pore fluid factor at the pressure-temperature beneath the area. A reduction of 0.2 km/s in compressional wave velocity in the depth range from 6 to 11.5 km beneath Koyna region as revealed by DSS studies is not an unequivocal constraint about the existence of fluids in the shallow crystalline crust. Therefore, these data along with the geothermal seismicity of the region and other relevant data have been considered and isochoric thermal pressure (19 to 21 bar/°C) and pore fluid factor (0.78 to 0.83) were analysed to evaluate the possible presence of fluids. These results indicate the existence of sialic low velocity layer enriched in fluids beneath Koyna area.

THE understanding of the role of the fluids in the earth's crust on various physical properties, attracted much attention in recent years[1–6]. The basic question, 'whether the fluids present in the crust or in what form' has been addressed by many workers in geosciences. A minor quantity of fluids influences all types of physical properties measurable by geophysical means, like elasticity, electrical conductivity, thermal, mechanical and rheological properties of rocks[7–12]. Koyna (73°45'E, 17°33'N) which lies in the western margin of the Deccan Trap (Figure 1) is one such region where a variety of studies have been carried out since the 1967 major earthquake of magnitude 6.8, to understand the seismicity, earthquake parameters and tectonothermal nature of the region[13–19]. However, little work has been reported about the occurrence of fluids in the shallow crust beneath this region.

Presence of fluids has been reported in the crust up to 20 km (refs 3, 20, 21). Fluid-filled layers are thought to be responsible for low seismic velocities in low porous rocks[7]. The existence of fluids tends to reduce the rock strength substantially, which in turn decreases the ability to sustain any deviatoric stress. The rocks can be deformed plastically at moderate pressure and temperature conditions[22]. The roles of fluids and their pressure are also significant in understanding the earthquake failure process[6,23]. The presence of fluids beneath Koyna may be of particular interest to explain the seismicity of the region which is hypothesized to be reservoir induced[13] and also due to tectonic strain[24].

In this context, we has carried out analyses of deep seismic sounding (DSS) velocity structure, heat flow, geochemical data of thermal waters of nearby areas, seismicity of the region. The isochoric thermal pressure, pore fluid pressure and pore fluid factors were computed. These results are discussed in the light of possible existence of fluids in shallow crust beneath Koyna region and their tectonic implications.

Deep Seismic Sounding (DSS) studies were carried out along two profiles, each about 200 km long in and around Koyna region (Figure 1)[16,17]. Krishna *et al.*[25] further refined the velocity model after digitizing the analog records and delineated a low velocity zone (LVZ) between 6 and 11.5 km depth. The amplitude modeling using these digitized records indicated the reduction of *P* wave velocity (V_p) by 0.2 km/s at this depth range which was further confirmed in their later studies[26,27].

Koyna earthquake of December 1967 has been studied and the focal depth estimated to be 4.5 km (refs 13, 24). An analysis of the earthquakes of magnitudes up to

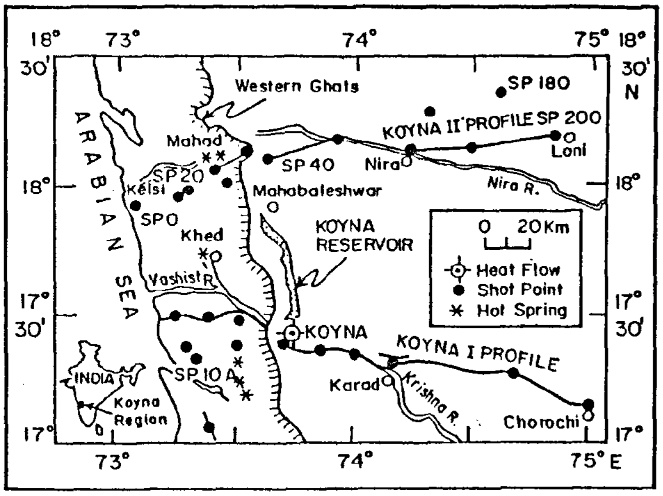

Figure 1. Location map showing heat flow, hot springs and deep seismic sounding profiles in Koyna region.

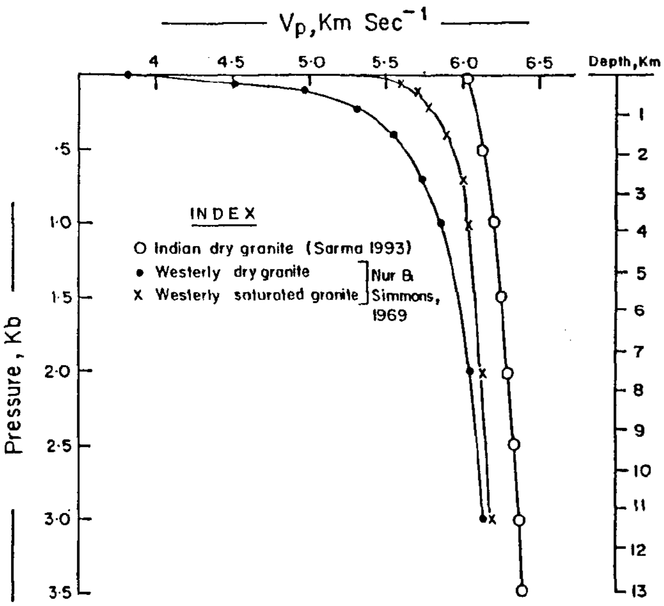

Figure 2. Variation of compressional wave velocity with pressure for Indian and Westerly granites.

Mb 5 for the period of August 1993–December 1995, recorded by a close network of 19 seismic stations deployed by Maharastra Engineering Research Institute and National Geophysical Research Institute reveal that majority of these earthquakes lie within 6 km depth range and very few up to 12 km depth[28]. Hypocentral parameters were estimated using HYPO71PC and the velocity model constrained by model of DSS profile-II[16,17]. The estimates of epicentral location was within 1 km and the depth estimation was less than 2 km for a majority of the earthquakes which was checked by wave form analysis[29].

Laboratory results of V_p with pressure on dry granites (ρ = 2.65 g/cc) of Southern Indian Shield[30] and of Westerly granites (ρ = 2.465 g/cc) under dry and saturated conditions[31] up to 3.5 kb are plotted in Figure 2. The results show a positive velocity gradient 0.04 to 0.07 km/s/kb in the pressure range 1.5 to 3.5 kb which corresponds to the depth range of 5 to 13 km. The chemical analysis and oxygen and hydrogen isotopic studies of hot spring waters of Konkan coast near the Koyna region indicate that the thermal waters are predominantly of meteoric origin. This meteoric water interacts with the rocks/minerals present in the reservoir at subsurface temperature resulting in a cation exchange between the minerals and the water and controlled by temperature–mineral–water equilibria. The reservoir temperatures of these geothermal systems at Khed, Unhavere, Aravalli, Rajawadi are found to vary from 95 to 135°C with the uncertainty of 5°C (refs 32, 33).

Geothermal gradients, thermal pressure, pore fluid pressure and pore fluid factor have been computed using heat flow data and properties of water system at pressure and temperature beneath Koyna region. Geothermal gradients have been estimated by using the surface heat flow data and calculating the temperatures profile by considering an exponential 1D model[34] for the heat producing elements and using the following equations

$$Q = Q_r + A_0 D, \qquad (1)$$

$$T_z = T_0 + Q_r Z/K + A_0 D^2 (1-\exp(-Z/D))/K, \qquad (2)$$

where T_0, Q_r, K, A_0 and D are the mean ambient temperature, reduced heat flow, thermal conductivity of crustal rocks, heat generation in the surface rocks and characteristic thickness of top radioactive layer. Koyna region is found to be associated with the low surface heat flow of the order of 41 mW m^{-2} (ref. 15) (Figure 1) for the region, being a part of Southern Indian Shield, the values of geothermal parameters, i.e. K, Q_r, D were taken as 2.7 W m^{-1} K^{-1}, 23 m W m^{-2} and 11.5 km respectively as reported by Gupta *et al.*[35]. The computed temperature vs depth profile up to 12 km is shown in Figure 3.

Pore fluid pressure affects deformation processes, seismic velocities and seismicity of the region[36]. For H_2O system and considering constant volume condition, the pore fluid pressure has been computed as a function of depth for the Koyna crust using the following eq. (3)

$$dp/dz = \alpha_f/\beta_f \, dT/dz, \qquad (3)$$

where α_f/β_f is the isochoric thermal pressure, dT/dz is the geothermal gradient. Thermal pressure, as defined by the expansivity to compressibility ratio has been computed with the equation of state for the H_2O system[37]. The variation in pore fluid pressure is varying as

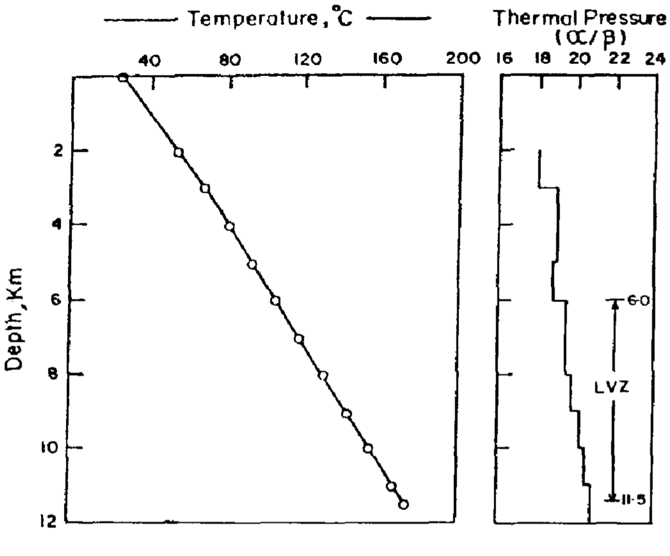

Figure 3. Temperature-depth profile and isochoric coefficient of thermal pressure for the H_2O system beneath Koyna area.

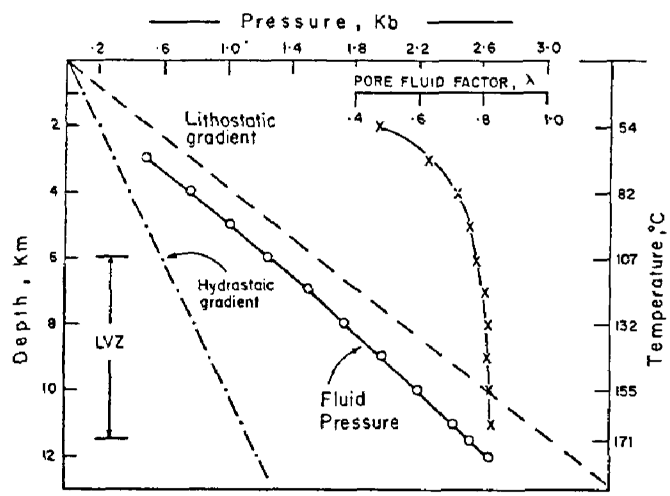

Figure 4. Computed pore fluid pressure, pore fluid factor, hydrostatic and lithostatic pressure beneath Koyna area.

a function of the thermal pressure of the fluid. The variation of the thermal pressure of the fluid, with depth beneath Koyna crust up to 12 km is shown in Figure 3. The average thermal pressure at the depth range from 6 to 11.5 km varies from 19.4 to 20.9 bar/°C. The variations in pore fluid pressure can be quite large and expressed in terms of pore fluid factor (defined as the ratio between pore fluid pressure and lithostatic pressure). In dry rocks it is zero and in water saturated sediments it reaches a value of 0.9 (ref. 36). For the crust beneath Koyna, the pore fluid factor is 0.47 up to 2 km and it is in between 0.78 to 0.83 up to 11.5 km depth. The variation of hydrostatic pressure, pore fluid pressure, lithostatic pressure and pore fluid factor with depth are shown in Figure 4.

It has been mentioned earlier in this paper that a reduction of 0.2 km/s in V_p in the depth range from 6 to 11.5 km in the upper crust beneath Koyna has been reported by DSS studies[26]. High crustal temperatures[38], granitic intrusion into the surrounding basement[39], α/β transition of quartz[40], and presence of fluids[31–41] have been postulated as possible causes for such reduction in V_p in shallow crust in other regions.

Laboratory studies on temperature dependence on ultrasonic velocity of rocks show that compressional wave velocity of crustal and upper mantle rocks with temperature varies from -4.1×10^{-4} to -8.1×10^{-4} km/s/°C (refs 40, 42). This relation yields that a decrease in V_p of 0.1 km/s corresponds to an increase in temperature of about 160°C. It means that the observed reduction of 0.2 km/s in V_p in the Koyna crust requires the temperature increase by about 320°C in the LVZ. Such high crustal temperatures at this depth would cause anomalously high geothermal gradient of the order of 40–70°C/km and surface heat flow of the order of 100–200 mW m^{-2}. But the Koyna region is associated with low temperature gradient, 20°C/km observed in 310 m bore-hole and low surface heat flow 41 mWm^{-2} (ref. 15). Secondly, low geothermal gradient and low crustal temperatures (Figure 3) also negate the possibility of α/β transition of quartz for the observed reduction in V_p as this transition takes place at about 573°C (ref. 43) at one atmospheric pressure. This transition temperature increases with the depth (pressure).

As mentioned above, the analyses of hot spring waters (Figure 1) of nearby areas[32] around Koyna and oxygen and hydrogen isotopic studies on thermal waters (Kumar, pers. commun.) indicate that the geothermal systems whose temperatures range between 95 and 135°C are dominated by meteoric water. Overall chemistry of thermal waters rule out the magmatic source (granitic intrusion) of heat for this geothermal activity[33]. The reservoir temperatures of geothermal systems near Koyna area are nearly equal to geotherms estimated from heat flow data at 6 km (Figure 3). This suggests that part of the meteoric waters reaches the surface after circulating to depths of nearly 6 km or deeper and discharges as hot springs having temperatures from 35 to 70°C after heat losses while ascending to the surface. These indicate that the reduction in V_p at shallow crustal level beneath Koyna is not due to high temperature magmatic intrusion, but probably caused by the presence of fluids at 6 to 11.5 km range. Similar case has been reported by Cermak[44] for the Bohemian massif in Czechaslovakia in the Maldanubicum region, which is associated with an average low heat flow around 50 mW m^{-2} and is characterized by a low velocity zone in the upper crust. *P*-wave data alone cannot provide an unequivocal constraint to the presence of fluids at shallow crustal level. We have further considered the laboratory data on seismic properties of dry and saturated granitic rocks, pore fluid pressure, pore fluid factor and seismicity of the region to support the possible occurrence of fluids in the shallow crust beneath Koyna.

Laboratory measurements of V_p on dry samples of Indian granites (ρ = 2.65 g/cc) in the pressure range of 1.5–3.5 kilo bar shows an increase of V_p at the rate of 0.073 km/s/kb (ref. 30) and for the Westerly granites (ρ = 2.646 g/cc), it increases at the rate of 0.04 km/s/kb (ref. 31) in the same pressure range (Figure 2). Temperature derivative of V_p of dry Westerly granites varies from -2.69×10^{-4} to -3.9×10^{-4} km/s/°C (refs 45, 46). In dry crystalline (granitic) crust the effective pressure will be nearly equal to the lithostatic pressure. Using these data, it is expected that V_p would increase from 0.033 to 0.089 km/s in the depth range from 6 to 11.5 km beneath Koyna region. Such an inference is not compatible with the results of DSS studies in Koyna region[26] which indicated the reduction of V_p by 0.2 km/s. However, in saturated granites under unconfined condition, compressional wave velocity increases with pressure as shown in Figure 2 (ref. 31), but under confined condition, the pore fluid pressure plays an important role to reduce the effective pressure, thereby reduction in V_p. Near the surface, fluid pressure is controlled by hydrostatic pressure and lithostatic pressure is considerably greater than the fluid pressure owing to the higher density of the rocks. At higher depths, the closure of pores and the resultant decrease in permeability causes the fluid pressure gradient to increase drastically, so that the fluid pressure becomes equal to the lithostatic pressure. In this situation, the compressional wave velocity in confined rock formation will be about 10% lower than the unconfined velocity[31]. Excess pore fluid pressure may even produce as much as 16% reduction of V_p in saturated rocks[38].

According to Knapp and Knight[47], for thermal gradients less than 10°C/km, pore fluid pressure, within constant volume condition would remain less than the confining pressure (lithostatic pressure) and for larger geothermal gradients, the pore fluid pressure increases to values much higher than the confining stress. It is to be mentioned here that the variation in fluid pressure is a function of thermal pressure of the fluids and its upper limit depends on pore strength and failure process of the rocks. For Koyna region, our estimated geothermal gradient is found to be 12°C/km and the thermal pressure is calculated to be about 20°C/kb. So the pore fluid pressure increases and becomes very close to lithostatic pressure in the depth range from 6 to 11.5 km (Figure 4). As already mentioned, the variation in pore fluid pressure can be expressed in terms of pore fluid factor, which varies from 0.0 to 0.9 for dry to saturated rocks[36]. Figure 4 shows the hydrostatic pressure, lithostatic pressure, pore fluid pressure and pore fluid factor as a function of depth for Koyna crust. At depth below 2 km, the value of the fluid pressure begins to depart from the hydrostatic pressure and at a depth beyond 6 km, the pore fluid pressure is very close to lithostatic pressure (0.83). So the observed reduction in V_p by 3% in the depth range from 6 to 11.5 km depth beneath Koyna region[26] could be attributed to the presence of fluids. As stated earlier, when fluid pressure becomes equal to lithostatic pressure, the value of V_p is around 10% less in confined condition than that of unconfined condition in crystalline rocks[31]. Similar situation has been observed in a number of wells in the US Gulf coast where the fluid pressure reaches the value of the lithostatic pressure at a depth of 5.5 km determined from well bottom hole fluid pressure measurements[48].

The focal depth of the 1967 event of the Koyna was estimated to be 4.5 km (ref. 24) and the recent analysis of the subsequent earthquakes in Koyna region revealed that 60% of seismic activity is confined to the focal depth less than 6 km (ref. 19). The reason for the reported focal depths for the earthquakes, could be the fluid-filled granitic rocks below 6 km (LVZ) which allow lesser accumulation of stress developed due to deformation or fault displacement, as minor quantity of fluids in granitic rocks is sufficient to cause a substantial reduction in rock strength[49]. Tectonically, such saturated rocks behave like soft layers which are unable to sustain high deviatoric stresses and frequency of earthquakes is reduced[8,38]. These stresses are most likely transmitted through the uppermost brittle part of the crust above the fluid saturated zone causing the mechanical failure[6].

Our present studies on the geothermal data analysis, seismicity and seismic velocity structure along with the computed values of thermal pressure, pore fluid pressure, and pore fluid factor reveal the possible occurrence of fluid in the crust beneath Koyna, in the depth range of 6–11.5 km, where a reduction in V_p has been observed.

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Nonchaotic earthquake occurrence near Oroville reservoir, California

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Existence of deterministic chaos has been examined for earthquakes near Oroville reservoir, California through strange attractor dimension and Lyapunov exponent based on the data of earthquake occurrences during the years 1975–1994. It is found that the earthquake occurrence in this region is random. This result is contrary to that reported for earthquakes near Koyna, Aswan and Nurek reservoirs where evidence for deterministic chaos was found.

APPLICATION of deterministic chaos to earthquakes has attracted the attention of geoscientists throughout the world. Earthquake data recorded through local networks around Koyna (India), Aswan (Egypt) and Nurek (Tadjikistan) reservoirs have been used to determine the strange attractor dimensions which were found as 4.4, 3.8 and 7.2 respectively[1]. We want to examine the existence of deterministic chaos near Oroville reservoir (USA) due to two reasons. While Beck[2], who examined the stresses due to reservoir loading, remained inconclusive about the effect, Lahr *et al.*[3] surmised the seismicity increase during 1975 as reservoir-induced. However, Rajendran and Gupta[4] based on statistical criteria concluded that the seismicity in this region may not be included in the category of reservoir-induced seismicity. The objective of this paper is to examine the applicability of deterministic chaos near Oroville reservoir using the data from 1975 to 1994 based on the two different approaches as discussed in the next section.