

Evidence of Archaean crustal shortening from deformed pillow lavas: An example from Sandur greenstone belt, Dharwar craton

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There is a continuous debate about the autochthonous or allochthonous model of the evolution of the greenstone belts. We report here evidence which suggests that the Sandur greenstone belt of Dharwar craton is an allochthonous remnant of accreted oceanic volcanism. Pillow structures of the western margin of the Sandur Schist Belt have been compressed in NE–SW and stretched in N 40°–45°W direction. The length/width (L/W) ratio (X'/Y') of these elongated pillows varies from 3 to 30, transforming them to pencil shape with well developed schistosity. Poisson's ratio of the elongated pillows at uniaxial stress of 1.5 kb is 1:24, whereas that of undeformed pillows 1:10 or 1:14. Such compression has not been witnessed in the eastern part of the belt. Generally, pillows in Sandur and other greenstone belts in an undeformed state show length/width ratio varying between 1 and 2. The comparison of the L/W ratio of the elongated and normal pillows and their Poisson's ratios from the western and eastern parts show that 7 to 8 times shortening has taken place along the western margin of the belt. This shortening along the belt is interpreted due to horizontal compression, consequent of convergent margin movement and rock mass transport, implying their allochthonous character.

It has been frequently suggested that a modified form of plate tectonics (smaller plates) operated during the Archaean and, greenstone belts are allochthonous remnants of accreted oceanic crust, plateaus and/or island arcs^{1–3}. Most of the supporting evidences of this aspect are mainly based on the geothermal inferences, structural patterns and geochemical data from Canadian and South African greenstone belts. However, for the greenstone belts of Karnataka, India, the continental rift model was advocated^{4,5}, although oceanic crust-based origin of these belts has been demonstrated^{6–9}. Recently¹⁰ it is suggested that the Dharwar greenstones were deposited in marginal or back arc volcano–sedimentary basins. These authors¹⁰ believe that the rocks in eastern Karnataka, including Sandur belt, formed as intra-arc basins above the evolving Dharwar batholith. Here we report evidence of horizontal compression, shearing and thrusting of volcanic rocks of oceanic origin and infer the consequent crustal shortening for the Sandur greenstone belt of Dharwar craton (Figure 1).

Sandur schist belt situated in the eastern margin of the Karnataka nucleus mainly consists of different types of metavolcanics and metasediments. The volcanic rocks are essentially tholeiitic basalts along with intermediate and acid volcanic rocks. These volcanics show well-developed pillow structures which on extensive deformation are elongated and stretched. The study of their stretching will provide a clue to the mechanism (process) of their deformation.

The pillow structures of the Deogiri and Donimalai formations at the western margin of the belt, south of Hospet, and south-west of Sandur (150 m thick across the strike) are stretched (Figure 2), whereas pillows of both the formations from the eastern part of the belt have normal length/width ratio (X'/Y') ranging from 1 to 2. More than 1200 pillows were measured at six places in the belt for their length, width, convexity and dip/inclination of the flow layers (Figure 1). Z' is exposed rarely and wherever exposed it is always less than X' and more than Y' ($X' > Y' > Z'$). The data are presented in the histograms depicting the variation in the L/W at each locality (Figure 3). All along the western margin of the belt, the pillows are compressed in NE–SW and stretched in N 40°–45° W direction. About 80% of the pillows have been stretched to give the length/width ratio ranging between 3 and 30, and 81% of the pillows have length/width ratio between 3 and 12 (Figure 3a). The width (Y') of these pillows varies from 0.5" to 20", with 88% of the pillows having a width (Y') between 1" and 10" only. On the other hand, the length (X') of these stretched pillows varies from less than 10" to 190" (Figure 3a). However, 72% of the pillows have length (X') more than 30" i.e. between 30", and 190". Most of them are stretched to such an extreme extent that they have a 'pencil shape' (Figure 2a) appearance in a vertical or semivertical exposure where Z' is available. Some of the pillows have width between 4" and 6" and length between 40" and 60" with pointed ends. Large-scale variation in the overall size of the pillows even in stretched form is illustrated in Figure 2b. Due to compression and metamorphism the recrystallization of original mineralogy into amphiboles and sodic plagioclase with development of well-defined axial plane schistosity has taken place (Figure 2a). This schistosity is observed in individual pillows too. Although the texture and mineralogy show recrystallization, the deformed boundaries (rims) of the pillows are preserved with the general destruction of the convexity (Figure 2) and the flow layers have become almost vertical. A fracture system (cleavage) parallel to the compression direction has developed in most of the pillows. This indicates that the post-consolidation directional stress has been very effective on these pillows and other associated rocks (Figure 2a) and continued to be active for a fairly long time. All along the belt the first generation axial plane cleavage (D_1 deformation) dips towards

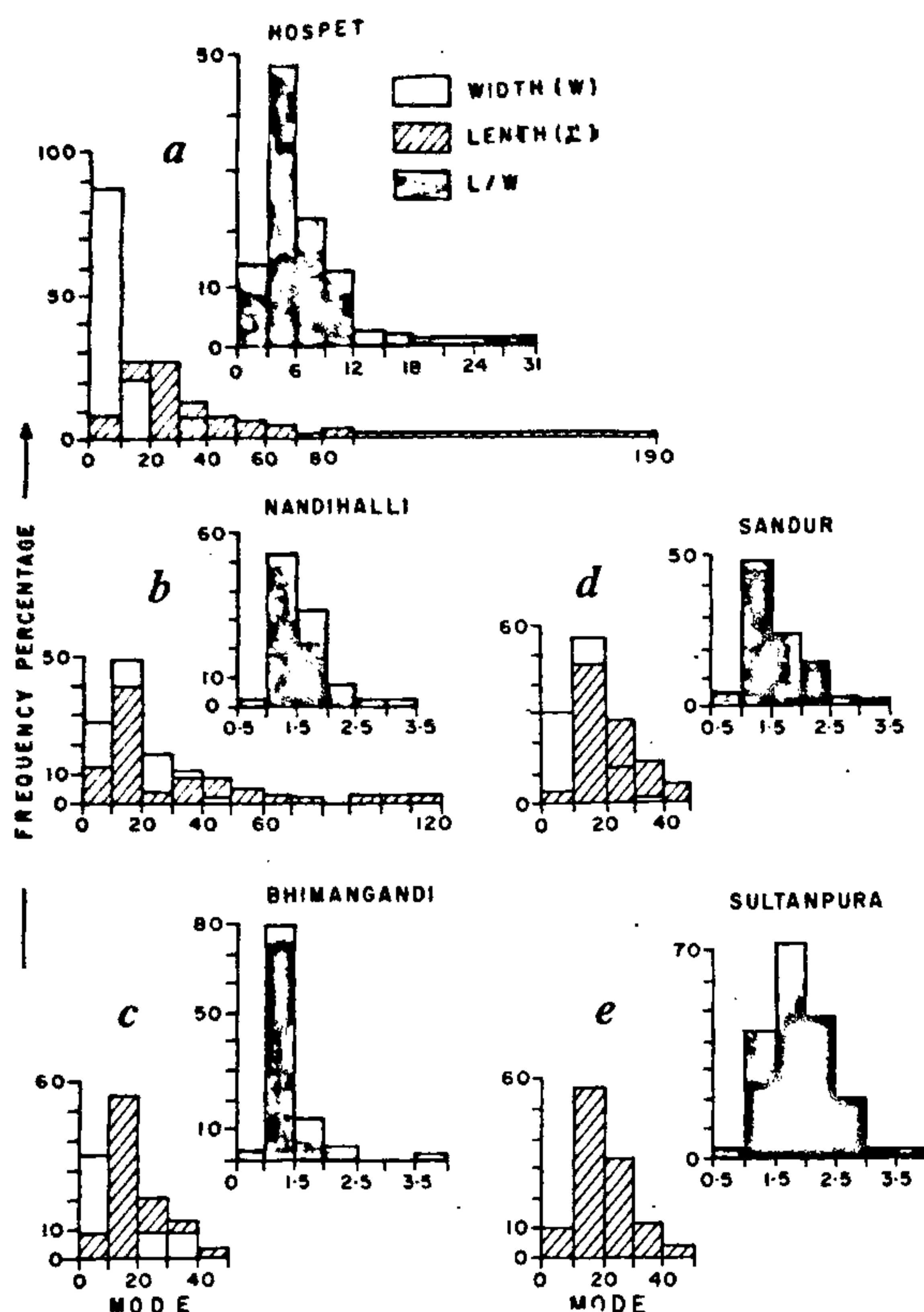


Figure 3a-e. Histograms showing the length, breadth and the length/breadth ratio of the pillows in different places in the Sandur schist belt.

north-east, indicating the compression direction (Figure 1). The pillows exposed in most of the eastern part of the belt do not exhibit this compression and stretching. Their length/width ratio generally remains between 1 and 2. Determination of length/width in the centre of the belt Nandihalli, south of Sandur (Figure 1, spot B) shows that 85.41% of the pillows have length/width ratio between 1 and 2, with 40% having length between 10" and 20" and 48% between 10" and 120" (Figure 3b). There are giant pillows in this region which have length and width measuring up to 120" and 80", respectively. The relict mineralogy and igneous texture are found in many sections. In most of the sections, relict augite is found rimmed by amphibole. Plagioclase boundaries are not clear as the reaction between plagioclase and other minerals has not been completed. Chlorite, amphibole and epidote are found along these boundaries with fibrous development of actinolite being quite common.

Along the eastern part near Bhimangandi (Figure 1, spot C), 80% of the pillows have their length varying between 10 and 40", and 84% pillows have their width varying between 5 and 20" (Figure 3c). Consequently,

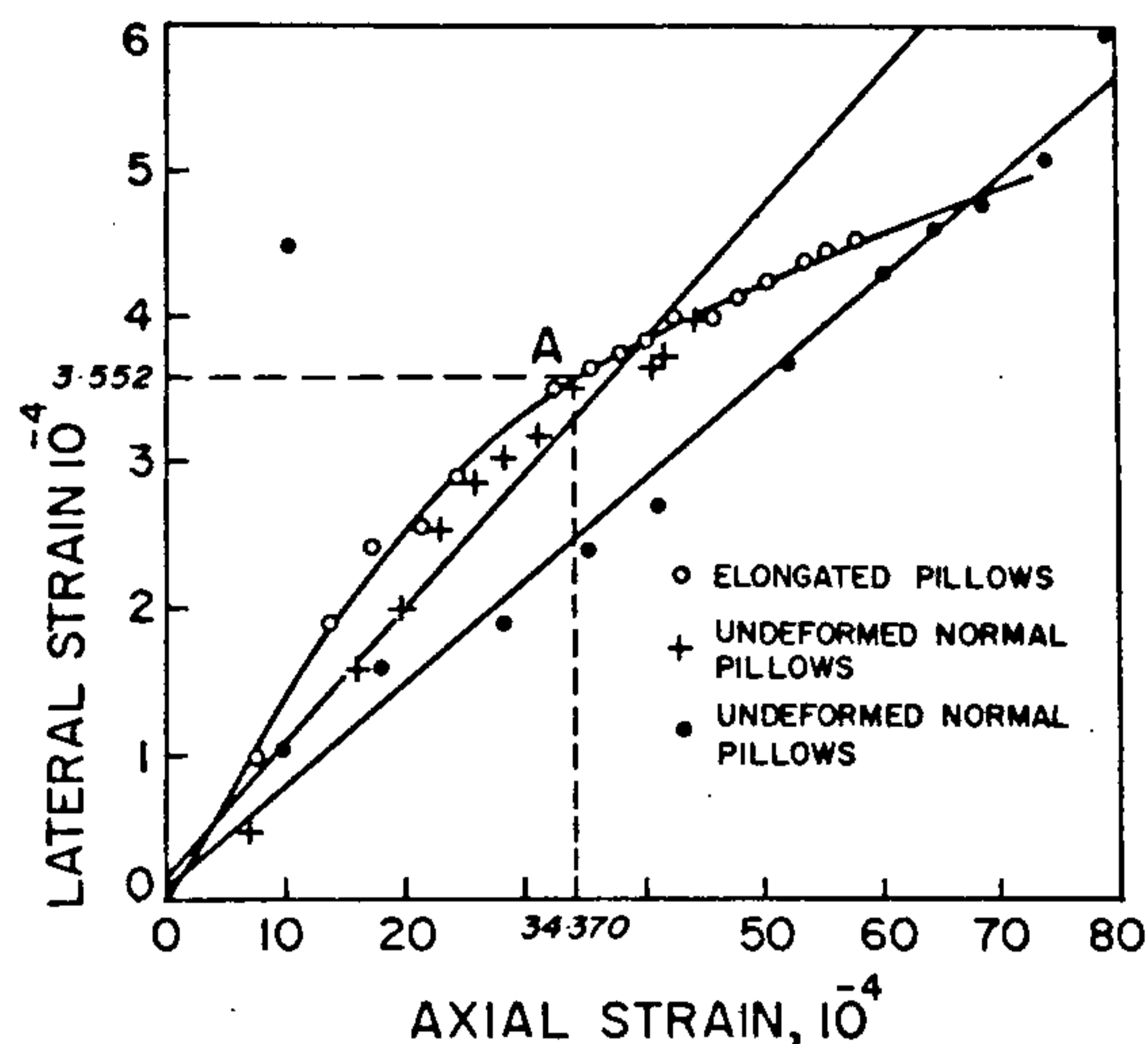


Figure 4. Poisson's ratio showing axial strain and lateral strain at 1.5 kb. It can be seen that up to 3.55 and 34.37 lateral and axial strain, the ratio maintains between 1:10 and 1:14, i.e. the range of the plastic deformation for these rocks. From point A onward, post-consolidation deformation is indicated, resulting in the elongation of the pillows.

92% of the pillows have length/width between 1 and 2. Similarly, west of Sandur (Figure 1, spot D) in the eastern volcanic block 83.61% of the pillows have a length varying between 10 and 40", and 93.44% of the pillows have width between 5 and 30" (Figure 3d). Therefore, 90.53% of the pillows have length/width ratio between 1 and 3 and 57% of them have this ratio between 1 and 2. Seldom anywhere in the eastern part of the belt does the length/width ratio of the pillows cross 3.5 or 4. Further east, after crossing the Eastern volcanic block (EVB) in Sultanpura block (Figure 1, spot E) there is considerable variation in the length and width of the pillows (Figure 3e). Here 48% of the pillows have length varying between 10 and 20" with a maximum length of 60". Width of these pillows ranges up to 40" with 56% of them ranging between 10 and 20". Most of these pillows show convexity towards east and 90% of them have length/width ratio between 1 and 3 (Figure 3e). This shows that in the entire belt, the maximum deformation, elongation and compression have occurred along the western part of the belt. The average reduction in the width of the pillows is around 7 to 8 times and the increase in the length also appears to be of the same order. This shows that at least 7 to 8 times crustal shortening in the NE-SW direction has taken place along the western margin. Similar elongated pillows have been noticed in the Nondweni greenstone belt, southern Kaapval Craton, South Africa, where a shortening factor of 100 has been suggested¹¹. Such zones of elongation and stretching are zones of high strain parallel to strike direction and represent thrusting.

Elastic properties of the elongated and normal pillows under uniaxial stress of 1.5 kb have been studied to understand the mechanical behaviour of lateral strain to axial strain (Figure 4). In undeformed pillows, the slope between lateral and axial strain remained nearly uniform, while in the elongated pillows the slope is distinctly different. The strain measurements indicate that the elongated pillows are brittle in their behaviour and the strain ratio is approximately 1:24, otherwise this ratio in case of undeformed pillows is 1:10 or 1:14. This change in the strain ratio appears to have been caused by the post-consolidation deformation during shearing and thrusting (Figure 4). Brittle deformation and development of fracture system almost at 90° to the schistosity is observed in most of the pillows.

Pillows are exposed in almost all late Archaean greenstone belts of Karnataka and other parts of the world¹² and the length/width measurements at other places such as Gadag and Ingaldhal in Chitradurga schist belt have confirmed that the length/width ratio of the normal undeformed pillows generally remains between 1 and 2. This increase in the length/width ratio along with change in the dip of the flows from 0 to 90°, almost vertical F_1 fold axis and the 20°–80° NE dip of the first generation axial plane schistosity are unequivocal evidence of horizontal compression and large-scale movement of the rock mass. Recently the 35 km thickness of the Sandur belt has been attributed to the thrust thickening¹⁰.

Under the P–T conditions of regional metamorphism (confining pressure), elongation of pillows would not have taken place, as in the case of other parts of the belt (Spot B to E, Figure 1). This suggests that in addition to confining pressure the lavas of the western margin were subjected to a directional stress, which continued to produce post-consolidation brittle deformation. This may mean that the lavas of western margin were part of a subducting slab and compression continued till the closing of the proto-ocean. Therefore, it is argued that the western margin of the Sandur belt has been overridden by its eastern part. Furthermore, geometry and the wavelength (2–10 m) of the D_1 fold closures at the northern and southern termination of the belt¹³ substantiate the inference that horizontal compression and crustal shortening have been a very significant and frequent aspect of tectonic evolution of this greenstone belt.

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Palaeotectonic implication of Lamayuru lake (Ladakh)

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The age of ancient Lamayuru lake in Ladakh, Trans-Himalaya, has been speculative due to non-availability of proper date at the base of its sediment profile. A date of 35,000 ± 600 yr B. P. was reported by earlier workers in the upper part of lower sedimentary profile but precise timing of the development of lacustrine conditions is all important to know the origin of the lake and the question whether it was formed by normal geomorphic processes of slope derived debris damming or tectonically induced slope instability leading to river impoundment. The present study shows that the lake developed around 45,000 years ago, which coincides with a regional tectonic event in the Trans-Himalaya. The geomorphic processes were but adjunct to the intrinsic process of earth shaking during this episode of tectonic activity in the region. Timing of initiation and closure of lacustrine sedimentation in the Himalayan river valleys could offer an important clue for determining the recurrence interval of major earthquakes in the Himalaya. This calls for extensive work both in space and time.

THE late Quaternary remnant lacustrine deposits lying at an altitude of 3600 m in Lamayuru, Ladakh (Figure 1), comprise mudstone, siltstone and sandy shale facies