help of proxy climate indicator along with very long instrumental record, that the 20th century was the warmest in six hundred years and the three warmest years of 1990s are hotter than any other period since the middle ages.

Global warming has been discerned from studies on temperature fluctuations, which have revealed an increase of a few tenths of degrees at some places during the course of last 50 years or so. An attempt was made to see whether global warming was making anomalously hot spells more frequent and intense. Figure 5 shows the mean anomaly of average maximum temperatures of these 28 stations in different years. There is no systematic slow increase of mean anomaly as per global warming signal. The pronounced heating in April 1999 cannot therefore be linked with global warming and is attributable to local anomalous circulation setting over India and its neighbourhood. According to a recent WMO Bulletin, 1999 as a whole has been in the series of anomalously hot years. This study indicates that only April 1999 and no other April in 1990s has been so hot. It shows an anomaly on the scale of a month. Again it is to be noted that April in 1892 was relatively hotter than 1999 over north-west and central India.

April 1999 turns out to be the most anomalous April of the 20th century in the north-west and central India, in which the hot spell had the highest extent and also the largest anomaly from the normal. It has a close match with 1892 in which north-west India experienced most pronounced unprecedented heat wave conditions, which have not been surpassed even in 1999. April 1999 has also been quite dry in which settled weather conditions have prevailed in association with prevalence of anomalous anti-cyclonic flow over India and its neighbourhood. There is no evidence that can indicate that global warming signal seems to be associated with increased intensity and frequency of hot spells over north-west and central India. This study reveals the hottest spell in April 1999 as an anomaly on the scale of a month.

ACKNOWLEDGEMENTS. We thank the Director General of Meteorology, India Meteorological Department for his encouragement. We also thank the National Data Centre, O/o Additional Director General of Meteorology (Research), India Meteorological Department, Pune for the supply of required data.

Received 3 July 2000; revised accepted 22 December 2000

A tectonic model of the Narmada region

H. C. Tewari*, A. S. N. Murty, Prakash Kumar and A. R. Sridhar
National Geophysical Research Institute, Hyderabad 500 007, India

Analysis of the reinterpreted results of the seismic refraction and wide-angle reflection data across Narmada–Son Lineament (NSL) indicates that the upper crustal features to the east and west of the Barwani–Sukta fault are different. To the west of this fault a graben exists under the Deccan volcanics, while to the east of it a north-south horst feature between the Narmada north and south faults divides the region in three distinct zones—north, middle and south. This feature is accompanied by upwarp in the mid-crustal as well as the Moho levels, suggesting deep-seated tectonics. The horst correlates with the gravity low axis of central India and large thickness of high density mafic material is present in the upper crust on both sides of it. The present-day crustal structure of the Narmada region appears to have developed in three major phases of the tectonic activity during the Archean–Proterozoic, Jurassic–Cretaceous and late Cretaceous.

TECTONICS of the central Indian region is greatly influenced by the east-west trending Narmada–Son Lineament (NSL), a conspicuous linear tectonic feature extending eastwards for about 1300 km from the west coast of India.

*For correspondence. (e-mail: ramaharish@hotmail.com)
This lineament has been considered as an ancient rift or an active fault zone and is a zone of crustal upwarping through which lava intruded. NSL is also a zone of moderate seismicity. The epicentres of a number of shocks were found to align nearly parallel to the NSL. The faults bounding the Narmada zone are believed to have played a significant role in deposition of the Vindhyan sediments (Meso–Neooproterozoic) on the northern side and Gondwana (Perm–Carboniferous) sediments on the southern side of the Narmada zone. The boundary faults limiting this zone have been identified to the east of 76°E, as Narmada north and Narmada south faults. A large number of experiments have been carried out to study the evolution of the region and to understand the tectonic processes that might have taken place in the region since geological times. To delineate the crustal features of this region, seismic refraction and wide-angle reflection data in analogue form were acquired along five Deep Seismic Sounding (DSS) profiles cutting the NSL zone in the N–S direction (Figure 1). Their purpose was to delineate the Deccan Trap thickness, subtrappean sediments, if any, and to configure the basement and deep crust, including the Moho boundary.

Results based upon the interpretation of analogue DSS data of all the five profiles were published in various research journals and summarized by Kaila and Krishna. Later the data were digitized with a sampling interval of 4 ms and assembled into trace normalized record sections for various shot points along each profile. The normalized record sections plotted in reduced time scale, have the advantage of representing the data in a compact form that helps in identifying various phases and to view the entire wave field at a glance, and are useful to carry out amplitude analysis by using the forward modelling techniques. The analysis of reinterpreted first arrival refraction phase for seismic profiles I–IV (Figure 1) and the crustal reflection phases, including the crust–mantle boundary for profile I were carried out through forward modelling, using the software package SEIS 81 (ref. 6) based on 2-D ray tracing technique.

In this paper, we analyse the reinterpreted results of the seismic data and present our inferences to understand the tectonics of the region.

Reinterpretation of the entire seismic data recorded across NSL zone in central India has been taken up to update the 2-D crustal seismic velocity models, utilizing the digitized analogue record sections. The seismic refraction and wide-angle reflection data along Hirapur–Mandla (profile I) have been reinterpreted in combination with 2-D gravity modelling. Prakash Kumar et al. have ana-

---

**Figure 1.** Geological map of central India showing the recorded seismic profiles (Fault boundaries after Acharya et al. 20).
lysed and reinterpreted the first arrival refraction data along Kajurakalan-Pulgaon (profile II) and Ujjain-Mahan (profile III) seismic profiles. Srihari and Tewari* while reinterpreting the seismic refraction data along the Thuda-Sindar profile (profile IV), reported the existence of a sedimentary graben in the western part of the Narmada zone. They also concluded that the Barwani-Sukta fault divides the Narmada zone into two parts. However, to understand the seismic structure of the Narmada region as a whole, it is necessary to integrate the above results with other data sets, particularly the gravity data.

Results of these analysis show that while the structural model up to the basement along profiles I, II and III is more or less similar, the model of profile IV (west of Barwani-Sukta fault) is different. Along profiles I, II and III the upper crust can be divided into three structural elements, viz. (a) north of Narmada zone, (b) Narmada zone (between Narmada north and south faults), and (c) south of Narmada zone. It is worthwhile to describe the seismic results along these parts and profile IV in brief.

Considering the upper crustal model and north of Narmada zone, Murty et al.? show that along profile I, the upper Vindhyan directly overlie the Archaean basement (velocity 5.9 km s\(^{-1}\)) between Hirapur and Narsinghpur. Between Narsinghpur and Katangi, the Vindhyan basin consists of the upper and lower Vindhyan. In this part, the velocity representing the Archaean basement has not been recorded in the first arrivals and apparently a velocity of 6.5 km s\(^{-1}\) directly underlies the lower Vindhyan. Here the Archaean velocity probably remained hidden. Since the same has been recorded in the northern part of the Vindhyan basin and also because the Archaean is exposed in the Narmada zone, it is conjectured that a small thickness of Archaean exists below the lower Vindhyan. Along profiles II and III, except in the extreme north of profile II where a Vindhyan velocity is indicated, a two-layer case is seen, wherein the Deccan Traps directly overlie the Archaean basement. A high velocity layer (6.5 km s\(^{-1}\)) is present along all the three profiles. This layer is at a depth of 5–9 km in this region.

Considering the Narmada zone, between Narmada north and south faults, the basement is at a depth of 200–300 m only. The seismic data show a high-velocity interface (6.5–6.7 km s\(^{-1}\)) at less than 2 km depth on profiles I and III and at a depth of about 5 km on profile II.

To the south of the Narmada zone, the Deccan Traps directly overlie the basement along all the three profiles. However in some parts of profiles II and III, the Gondwana sediments may be present under the traps. The upper crustal high-velocity layer exists at a depth of 8 to 9 km.

Profile IV shows an upper crustal structure that is different from those along the profiles I, II and III. Here a subtrappocean low-velocity basin exists between the Barwani-Sukta and Tapti faults and the maximum depth to the basement is about 5 km (ref. 8). The upper crustal high-velocity layer seen in the first three profiles is not visible here.

The revised seismic model (deep crustal model) along profile I (Figure 2a) indicates that the crust basically consists of two layers with seismic velocities of 6.35–6.4 and 6.8 km s\(^{-1}\) at approximately 17 and 22 km depth, respectively. However, the upper crust consists of an additional anomalous layer with a velocity of 6.5–6.7 km s\(^{-1}\). In the density model, this layer has been modelled as a high-density mafic intrusive body, as the velocity of 6.5–6.7 km s\(^{-1}\) does not conform to the velocities in the upper crust, where the seismic velocities normally do not exceed 6.4 km s\(^{-1}\). Within the Narmada zone, the top of this body is at about 2 km depth and its thickness is also of the same order. To the north of the Narmada zone, its top is between 5 and 8 km depth. Here this layer continues up to 16–17 km depth. To the south of the Narmada zone also, the top of this mafic body is at about 8 km and it continues to a depth of 16–17 km. The Narmada zone thus appears as a horst block with the north and south boundary faults bounding it. The layer of 6.35–6.40 km s\(^{-1}\) velocity also shows up-dip from both the sides towards the Narmada zone, thus indicating the deep nature of the two Narmada faults. The lower crust (6.8 km s\(^{-1}\)) is about 20 km thick. The bottom of the lower crust (Moho boundary) is continuously mapped, with a depth variation between 41 and 44 km and shows an upwarp in the

Figure 2. Two-dimensional crustal seismic velocity model (a) and two-dimensional gravity model (b) along Hirapur–Mandla seismic profile.
Narmada zone. The crust on either side of the Narmada zone is thicker compared to that in the Narmada zone.

2-D gravity modelling (Figure 2 b) based on the above seismic results is able to explain the gravity anomalies along profile I. The density values (in g cm\(^{-2}\)) considered for the model are upper Vindhyan, 2.40; lower Vindhyan, 2.50; Alluvium, 1.8; Deccan Trap, 2.85; Archean basement and upper crust, 2.70; lower crust, 2.90 and upper mantle, 3.3. A density of 2.86 g cm\(^{-2}\) is attributed to the high-velocity upper crust on the southern side of Narmada south fault and 2.82 g cm\(^{-3}\) on the northern side of it. The crustal structure along profiles II and III is more or less similar to that along profile I, except that a high velocity of 7.1–7.2 km s\(^{-1}\) is seen just above the Moho towards south of the Narmada zone. Along profile IV also this velocity is observed.

The 2-D crustal seismic velocity model along profile I, in combination with the gravity model (Figure 2) and results along profiles II–IV (refs 7 and 8) form the basis on which a few speculations about the tectonics of the region can be made. The faults delineated along profile I divide the upper crust in such a way that a horst–grabens structure is evident. The contour map (Figure 3) depicting the top of the upper crustal high-velocity layer\(^{9}\) shows that the Narmada horst exists in large parts of this region. The upwelling in the Narmada zone indicates that both the Narmada faults have deeper origins, involving deep-seated tectonics.

Sridhar and Tewari\(^{8}\) inferred that the Narmada zone is divided into two parts separated by more or less NE-SW trending Barwani–Sukta fault, which is different from the Narmada south fault. To the east of it, the Narmada zone is a basement uplift, while to its west, it is a sedimentary graben below the Deccan Traps. Based on the possibility of sediment occurrence under the Deccan Traps on the southern parts of profiles III and II and also from the results of geo-electric survey in the nearby regions\(^{11}\), it is suggested that the sedimentary basin extends to south-east and the Barwani–Sukta fault represents its northern limit.

According to Mishra\(^{11}\), the mid-continenal gravity high in central India is similar to mid-continental gravity high of USA, which is caused by basaltic intrusions of high density. The gravity high between Jabalpur and Mandla has been explained due to the presence of a magmatic body at different depths, by several workers\(^{10,32–34}\). Our results, based on seismic interpretation and its gravity interpretation (Figure 2) place this body at 8 km depth with a thickness of about 9 km.

What, however, appears to be important is not the gravity high, but the gravity low axis (Figure 4). This axis appears to correspond to the zone of Narmada uplift, where the depth and thickness of the mafic intrusion is the lowest and divides the region in two distinct parts, north and south of the Narmada zone. Since the effect of upwelling is seen even at the Moho level it appears to be related to deep-seated tectonics. Such a belief is shared by several workers. Agarwal et al.\(^{13}\) believe that the Moho upwarpment found under the Aravalis, the Satpuras and the NSL is related to vertical mass transfer from upper mantle into the crust, during the late Archean to Palaeo proliferous period. Ghosh\(^{16}\) too observed a domal upwarp along this lineament. Based on the satellite magnetic data (MAGSAT), Mishra\(^{11}\) suggests a thick crust to the south of the NSL encompassing the entire region of the Tapti basin and the Gondwana rift valleys, suggesting basic rocks and feels that the presence of linear and extensive basic intrusives in the crust is due to some deep-seated phenomenon such as asthenospheric upwelling related to a mantle plume or hot spot trace. In his opinion, this activity appears to have been transmitted in time from central India to the east coast, providing the necessary thermo-mechanical framework for the separation of India from the Gondwanaland along the east coast, during the late Jurassic or the early Cretaceous. Venkat Rao et al.\(^{17}\) indicate a rise in Moho level followed by rifting/replacement of the shallow crust by emplacement of mantle-derived rocks at shallow crustal levels. Shrivaji and Agarwal\(^{18}\) consider the Moho configuration along this zone as highly disturbed due to intense crustal movements and suggest that the southern and northern Narmada faults might have acted as fissure zones through which molten magma has erupted and emplaced on either side of the Narmada zone. Singh and Meissner\(^{19}\), while analysing the upper crustal configuration of the Narmada–Tapti region from gravity studies, suggested that the Deccan flood basalt eruption was associated with a huge magmatic intrusion (migmatite underplating) at the base of the crust.

Earlier workers have interpreted the gravity high to the north of NSL as due to underlying intrusives/volcanics which form a part of Bijawah Formation\(^{14}\). The Bijawahs are composed of volcanic material that could have solidified within the upper crustal layer before emerging fully onto the surface. However, our interpretation suggests

---

*Figure 3. Contour map of the high-velocity layer (6.5–6.7 km s\(^{-1}\)) in the upper crust in central India.*

---

876 CURRENT SCIENCE, VOL. 80, NO. 7, 10 APRIL 2001
the presence of a high velocity/high density body similar to that in the southern part below the Archaean basement. Due to lower density of the Vindhyan sediments (2.50 g cm\(^{-3}\)) compared to the basement (2.70 g cm\(^{-3}\)), the gravity high in the Vindhyan region is not as prominent as the southern gravity high.

Acharya et al.\(^{20}\) are of the view that no major reactivation of north fault has taken place in the post-Vindhyan period. This view, combined with the fact that smaller thickness of the intrusive body is seen between the Narmada faults compared to those beyond the Narmada faults (Figure 2 a) and the upper crustal uplift indicate that the intrusive activities on the two sides of Narmada zone are independent. This further suggests that the two Narmada faults may have been active at different geological times. Jain et al.\(^{4}\) reported that the initiation of the Narmada north fault must have been at a period not later than the late Archeans. According to them, the reactivation of the Narmada north fault is indicated by trachytic intrusives and related lamprophyres and syenite plutons along the fault around 1600–1800 m.y. It can, therefore, be conjectured that major magmatic activity to the north of Narmada zone accrued during the Proterozoic. During this activity, very little or no magmatic deposition took place in the Narmada zone. The magmatic activity along the south fault might have taken place during or after the breakup of Gondwanaland. This allowed the deposition of magma in the upper crust. Whether the north fault was also active at that time is not clear, as there is no geological evidence for its activation at that time. What is, however, true is that the south fault is still active as is evidenced by occasional seismic activity along this fault. The Narmada uplift is obviously older than the activity along the south fault, as indicated by smaller thickness of the intrusive layer here.

A cartoon of the present-day crustal and lithospheric structure of the Narmada region based on the above discussion is shown in Figure 5. On the basis of this figure it appears that the present-day structure of the region has developed in at least three major tectonic phases I–III.

During phase I in the Archaean-Proterozoic, the north Narmada fault was active. During this activity high-
density intrusive material was deposited in the upper crust to the north of the Narmada. Upper crustal deposition did not take place to the south of Narmada.

During phase II, activity along the south fault started during the Jurassic–Cretaceous period. The mafic intrusion in the upper crust caused due to this activity was limited to the region south of Narmada and east of Barwani–Sukta fault.

Phase III coincided with the passage of India over the reunion plume during late Cretaceous. The plume head at that time was situated to the south of Narmada region. Due to tectonic disturbances close to the west coast, material from the plume head got emplaced at the base of the crust and extended to east to a large distance. This caused underplating in large parts of the crust. Subsequent erosion from the plume led to the Deccan Trap activity and its deposition. Around the same time some eruption might also have taken place from the upper crustal mafic body to the south of Narmada zone.

The reinterpreted results of the seismic data across NSl, lead to the following conclusions. (1) The Barwani–Sukta fault divides the Narmada zone into two parts. While the SW part is a graben, the NE part is a basement uplift. (2) The upper crust east of the Barwani–Sukta fault shows a horst feature between the Narmada north and south faults, indicating that the Narmada zone is a ridge between two pockets of mafic intrusion of different ages. (3) Upwarp of the Moho and intra crustal layers in the Narmada zone suggest that the two faults involve deep-seated tectonics. (4) On the basis of present-day crustal structure, at least three major phases of tectonic activity during the Archaean–Proterozoic, Jurassic–Cretaceous and late Cretaceous can be identified in the Narmada region.

7. Acknowledgements. We thank the Director, NGRI for permission to publish this work. Our thanks are due to Department of Science and Technology for funding the project for reinterpretation of the seismic data across Narmada region. We also thank Sri M. Shankarayya and Sri B. S. Rana for drafting the figures.

Received 16 September 2000; revised accepted 4 December 2000

Photoregulation of adventitious and axillary shoot proliferation in menthol mint, Mentha arvensis


1 Central Institute of Medicinal and Aromatic Plants, P.O. CIMAP, Lucknow 226 015, India
2 National Botanical Research Institute, Rana Pratap Marg, Lucknow 226 001, India
3 School of Biotechnology, Devi Ahilya Vishwavidyalaya, Indore 452 001, India

A direct and indirect methodology for efficient shoot proliferation and regeneration from various explants of Mentha arvensis has been developed by studying the interactive effect of plant growth regulator and light colour. Nodal explants cultured on Murashige and Skoog’s (MS) medium supplemented with 10 μM thidiazuron and incubated under red light, proliferated an average of 50 shoots after 30 days, whereas internodal explants cultured in modified MS medium supplemented with 40 μM 6-benzylaminopurine and 0.5 μM α-naphthaleneacetic acid and exposed to red light, regenerated an average of 200 shoots after 60 days. Among the six cultivars tested, internodal explants of cv. Gomti regenerated about 90 shoots after 20 days of culture. Under the above conditions, leaf explants were observed to regenerate an average of 60 shoots after 60 days of culture, which was preceded by callus development. The protocol standardized for high efficiency shoot proliferation and regeneration in M. arvensis from nodal, internodal and leaf explants is suitable for micropropagation, genetic transformation and for obtaining somaclonal variants in this essential oil-yielding crop plant.

Mentha ARVENSI, a member of Lamiaceae, is a source of several single monoterpenes, including menthol and their mixtures that are extensively used in flavour, fragrance,