THE CRUSTAL STRUCTURE AND CTBT MONITORING OF INDIA: NEW INSIGHTS FROM DEEP SEISMIC PROFILING

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ABSTRACT

The nation of India has been collecting seismic data for nearly three decades. However, because it has historically been difficult for Western scientists to access this valuable resource or identify individuals responsible for program development, this information has not readily been made available. In the past year (2000), a collaborative effort began between the National Geophysical Research Institute (NGRI) in Hyderabad, India and the US Geological Survey (USGS) in Menlo Park, CA. Since NGRI is a leading organization for geophysics in India, the scope of this collaborative effort will strengthen our knowledge of crustal structure of India. On a continent-wide scale, it was observed that crustal thickness values range from 35 to 40 km in most of India, with the Himalayas being the biggest exception (thickness about 80 km). We have summarized the internal velocity structure of the crust with crustal columns from throughout India. Crustal structure correlates with geological province, and generally thins at the margins, as a result of the transition from continental to oceanic crust. In addition, we have recently reprocessed newly obtained seismic reflection images and interpreted these results with geological and other geophysical constraints. The deep seismic reflection data was acquired using a recording geometry of 100 m shot/detector spacing, utilizing two DFS-V recording units under master-slave mode. Reprocessing was done using ProMax software at the US Geological Survey in Menlo Park, California. Seismic images across the Central Indian Suture Zone reveal a reflection band from 4 to 19 s (twt) that shallows to the SE. A strong reflection band, at 14 s (twt) (~ 44 km) in the northeast, is interpreted as the Moho. The Moho is not identified continuously along the profile, but is observed as a strong reflector again just before the Central Indian Suture Zone. The divergent reflection fabric across the profile is interpreted as the signature of a collision process between two protocontinents in which buckling of the upper and middle crustal layers took place. Inter-wedging associated with shallow ramp anticlines further support the collision theory. These data, both from seismic reflection and refraction profiling, provide a wealth of information needed for the purposes of seismic monitoring of India.

Key Words: crustal structure, India, seismic reflection, Deep Seismic Sounding

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OBJECTIVE

High quality regional models of crustal structure are necessary for accurate seismic locations required by the monitoring of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). This paper presents an overview of the crustal structure of India, as well as a newly-interpreted seismic reflection profile through the Central Indian Suture Zone.

RESEARCH ACCOMPLISHED

1 Introduction

The seismic structure of the crust and upper mantle provides critical information regarding lithospheric composition and evolution. There are large variations in fundamental properties, such as crustal thickness, crustal and upper mantle velocity structure, and the depth to the lithospheric / asthenospheric boundary in different tectonic domains. These properties can be interpreted in terms of geological processes that have formed and modified the lithosphere.

India is a geologically complex continent that includes both ancient shields and young mountains (Fig. 1). Seismic reflection and refraction studies have been conducted in different geological and tectonic environments in India. These include: rifts, collisional boundaries, shield and platform areas, and exposed lower crustal granulites. These studies, together with complimentary investigations elsewhere, have provided sufficient insight to understand the geological processes and tectonic features responsible for the evolution of the crust. For a clear view of the subsurface structures in different geological settings, coincident deep seismic reflection and refraction studies provide the most reliable measurements of the structure and physical properties of the crust. This in turn can be useful in monitoring of the Comprehensive Nuclear-Test-Ban-Treaty, as India has recently demonstrated its nuclear capabilities.

2.1 Main Features of the Crustal Structure of Central India

Crustal seismic studies in India were started during 1972. Twenty Deep Seismic Sounding (DSS) profiles have been conducted totaling 6,000 km (Fig. 2). Long range refraction and wide-angle reflection techniques with a dense geophone spacing of 80-200 m and shot point interval of 10-40 km were used in acquiring this data. Kaila and Krishna (1992), Mahadevan (1994) and Reddy et al (1999) provide reviews of Indian continental crustal structure. Estimates of crustal thickness fall into the range of 35-40 km throughout most of the continent, with the biggest exception being the Himalayas that are known to have thicknesses up to 80 km (Mahadevan, 1994). Even here, large lateral variations are suggested, and the thickness of the Himalayas may differ from east to west.

Representative velocity models from the Indian shield are presented in Figure 3. Crustal structure is used to differentiate various portions of the Indian shield. The crust is thicker along the middle of the east coast than along the west coast. Thinning of the crust is probably due to its transition from continental to oceanic at the eastern and south-eastern flanks of the Mahanadi and Bengal basins, respectively. The sharp rise in the Moho from west to east clearly points to the presence of a significantly thinned crust in the eastern and southeastern parts of the Bengal basin. The Cambay basin on the west coast is characterized by an up warp of Moho during the late Cretaceous period, probably representing a transitional type crust as a major source of Deccan trap flows.

The Narmada-Son lineament is the most conspicuous linear geological feature in the Indian Shield after the Himalayas, and has played a significant role in the formation of the crust (Fig. 4). This ancient lineament cuts across central India in a NNE-SSW direction and has been periodically reactivated since the Precambrian. Results from five DSS profiles show a modest variation in crustal thickness from 38-43 km across the lineament. A high velocity of 6.9 km/s at a shallow depth of ~10 km and a 7.3 km/s high velocity layer above the Moho are indicative of magmatic underplating in the region. Recent deep seismic reflection studies (e.g. Reddy et al, 1995) indicate that a continent-continent collision occurred during the Proterozoic Eon and formed a suture between the Dharwar and Bundelkhand cratons. The collisional process is thought to be responsible for the presence of a high velocity layer at shallow depth. The region has repeatedly undergone reactivation since the Proterozoic and presently has a low level of seismic activity. It is also associated with high heat flow.

In general terms, a low average crustal velocity (6.0-6.3 km/s) is indicative of a dominantly felsic composition and a higher average velocity (6.5-6.8 km/s) indicates a more mafic composition. The average crustal velocity for most of the Indian subcontinent, except the basins, is equal to the global average of 6.45 km/s (Christensen and Mooney, 1995; Mooney et al, 1998). This suggests a typical platform / shield crust with a bulk composition equivalent to a diorite.

Crustal reflection studies across the Paleo/Mesoproterozoic Aravalli Delhi Fold Belts in the northwestern Indian shield have revealed crustal scale thrust faults extending down to the Moho and beyond (Fig. 4). A thick high-velocity (7.3 km/s) lower crust is observed in this region (Tewari et al, 1997). Similar crustal velocity structures are also observed in the Trans-Hudson orogeny (Lucas et al, 1993) of the North American continent. This part of the Indian shield has witnessed two collisional episodes during the end of the Paleo and Mesoproterozoic period, viz. 1800 Ma and 1100 Ma.

Recent investigations of continental and oceanic structure around India show significant variations in the upper mantle structure, with the former being characterized by low Q or low velocity layers and the latter by their absence. In addition, P- and S- wave velocities higher than average global models have led to the inference of lower temperature gradients in the mantle under these areas (Mahadevan, 1994). Models of the upper mantle show a continuous linear increase in P-wave velocity with depth from 8.24 km/s at 55 km followed by a gradient of 0.18 km/s/100 km to a depth of 220 km. The gradient then falls to 0.08 km/s/100 km, arriving at a velocity of 8.62 km/s at 310 km depth (Mahadevan, 1994).

2.2 Presentation of newly processed data from the Central Indian Suture

Seismic reflection data provide the highest resolution image of the internal structure of the crust (Mooney and Meissner, 1992) and provides an estimate of the scattering and attenuation properties of the crust needed for calibrating high-frequency seismic wave propagation. Imaging of the Central Indian Suture (CIS) (Fig. 4), a mega-shear zone, by coincident deep seismic reflection and refraction data shows that there is a distinctly different reflectivity character to the northwest compared with the southeast of the CIS (Fig. 5). Reflections northwest of the CIS are predominently short, and the reflectivity is, in general, only of moderate strength. Toward the CIS, the crust is dominated by long reflections, resembling chevron folds. These folds are similar to cross-sections of structural duplexes, and are usually seen in a compressional environment. Southeast of the CIS, the reflections are longer compared to those in the northwest. The shallow detachments seem to be linked to mid-crustal dipping reflectors that are regarded as ramps.

Time sections show the presence of a strong reflector, commencing at a depth of about 7-8 sec (two way travel time, twt) in the northwest, shallowing up to a depth of 4 sec (twt) near the middle of the profile. This reflector is disrupted close to the CIS by what appears to be reverse-dipping reflectors. Southeast of the CIS, especially from around 6 s to 8 s, one can see a criss-crossing reflection fabric. These two reflectivity characteristics in turn suggest that when the collision occurred (between the Bundelkhand and Deccan proto-continents) buckling of the upper and middle crustal layers of the proto-continents took place, resulting in the western block’s lower crustal column subducting below the Deccan proto-continents. Thus, the collision process was of such severe magnitude that the impact was seen in both crustal blocks. The presence of the distinct opposite dipping reflectors, with the CIS zone acting as the divider, also suggests a collisional environment.

The inter-wedging of seismic reflections that are found to be associated with shallow ramp anticlines further supports the collision theory. The available refraction control indicates the presence of a refraction Moho at an average depth of 43 km. This agrees with the reflection Moho that is associated with the deepest set of reflections (at an average depth of 44 km), but is not as distinct as one normally expects. In spite of this, the reflection signatures show that the thrusting and subduction signatures are present at Moho level, with probable thrusting of the Deccan proto-continent over that of the Bundelkhand proto-continent. The dipping reflections across the deep crust and the upper mantle, especially the southeastward dipping branches of deep reflectors, may be regarded as the remnants of former crustal slabs now largely metamorphosed. The presence of a lower crustal, low-velocity zone (which has been inferred from refraction data) further supports the collision theory, as it is evident that the collision resulted in the development of a weak, highly-sheared zone below the midcrustal column.

CONCLUSIONS AND RECOMMENDATIONS

A vast geophysical database can be compiled from extensive seismic profiling which has been carried out in India. Much of this data is slowly becoming available in digital format, and thus can be re-evaluated in terms of the seismic velocity structure and attenuation of the crust and upper mantle. This new data will improve our knowledge of this region of the world, which has recently demonstrated its ability to produce and detonate nuclear weapons. The improved knowledge of the seismic structure, in turn, will enable significantly improved determinations of seismic source parameters as needed by the Comprehensive Nuclear-Test-Ban Treaty. It is, therefore, imperative that cooperation with American agencies and scientists in India be allowed to continue. Such a reasonable exchange of data will foster new research and cooperative efforts which may lead to more stability in the region.

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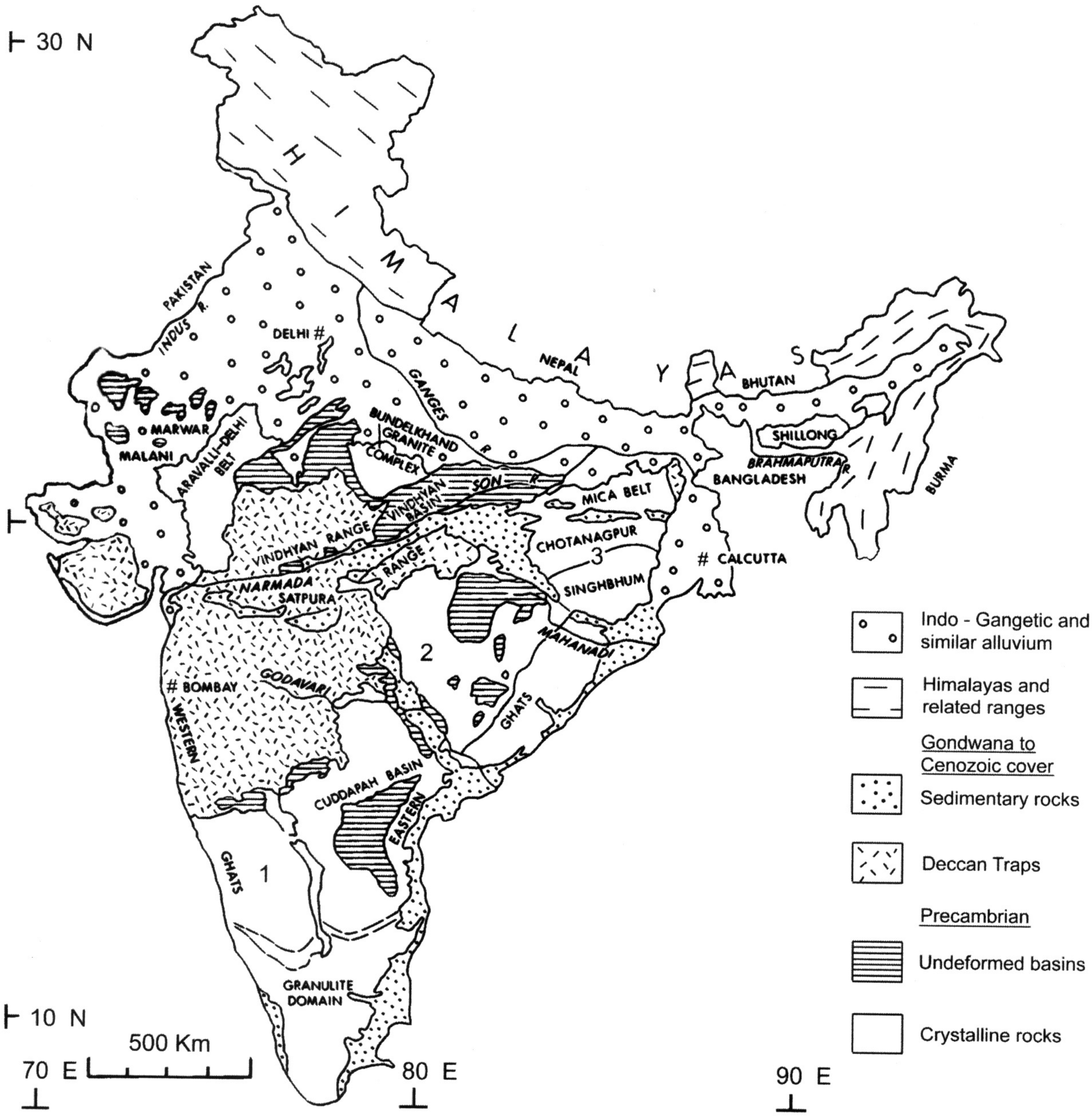

Figure 1. Geological map of India (after Goodwin, 1996)

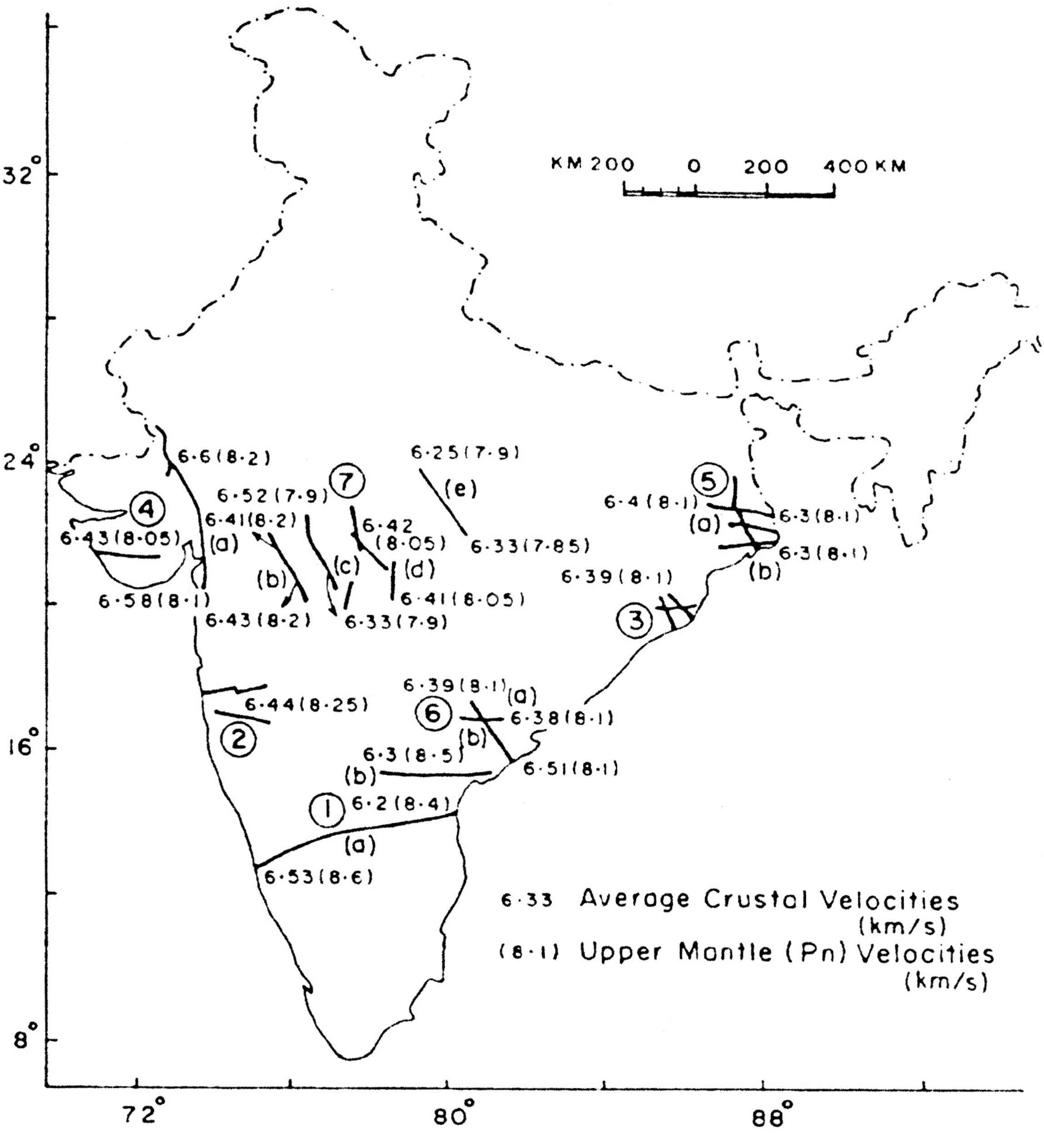

Figure 2. Locations of Deep Seismic Sounding profiles. Circled numbers correspond to seismic velocity depth columns shown in Figure 3.

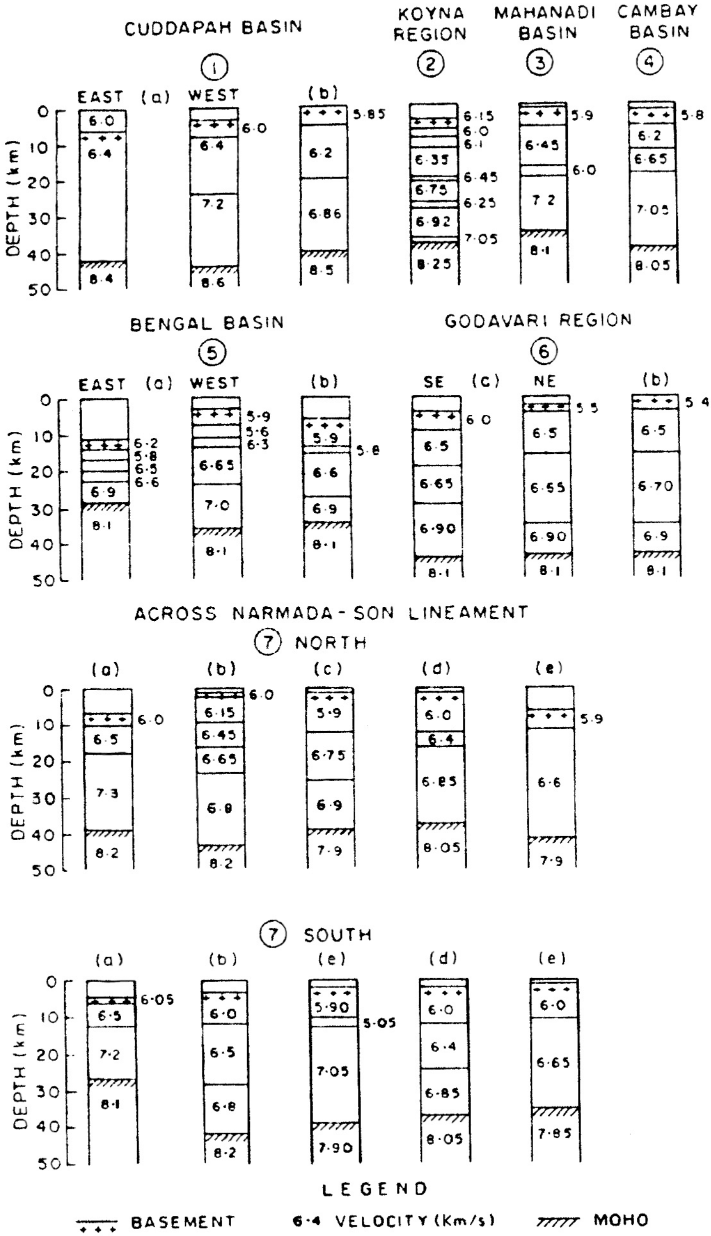

Figure 3. Seismic velocity-depth columns of various regions in the Indian Shield (average crustal and upper mantle velocities along the different DSS profiles shown in Figure 2).

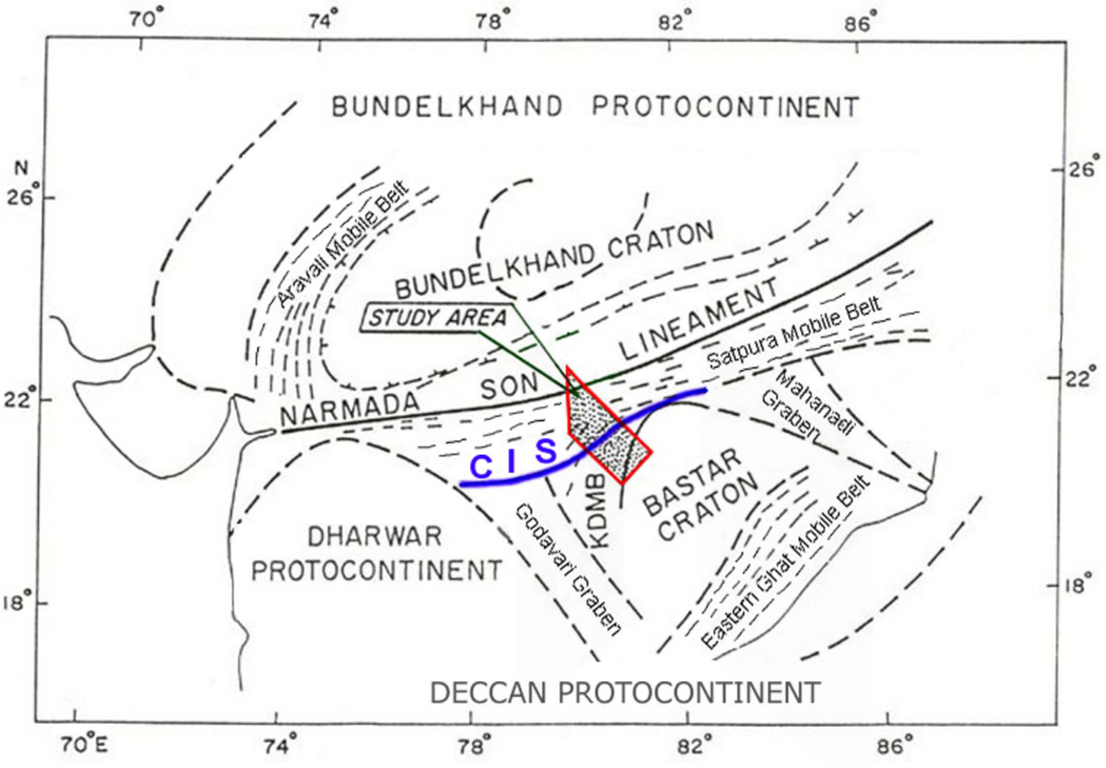

Figure 4. Location map of seismic profile crossing the Central Indian Suture Zone.

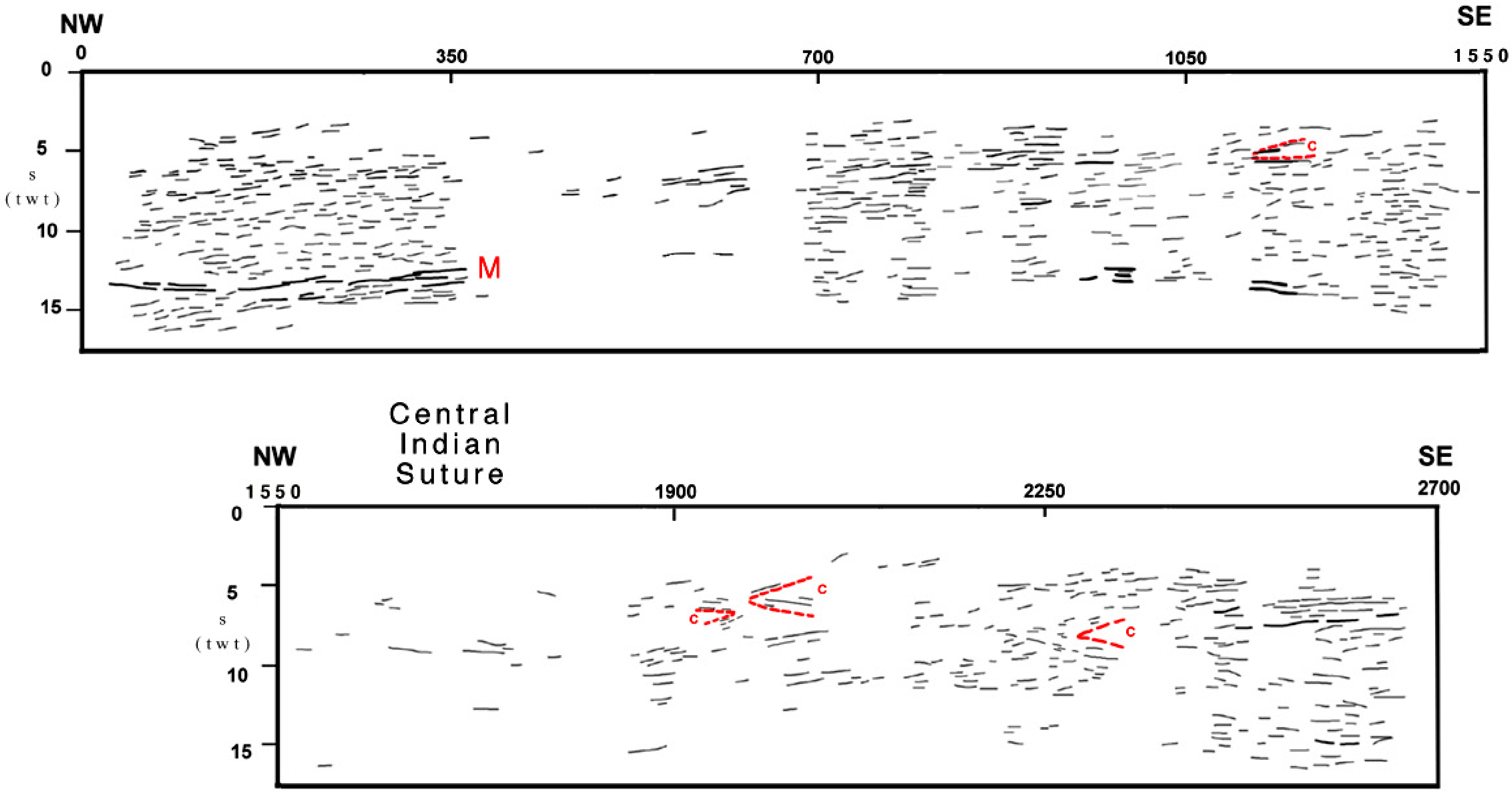

Figure 5. Interpreted profile across the Central Indian Suture Zone. M = Moho, c = inter-wedging (crocodiles). Data were collected and processed by the National Geophysical Research Institute (NGRI), Hyderabad, India (c.f. Reddy et al, 1999)