Seismic and magnetotelluric studies over a crustal scale fault zone for imaging a metallogenic province of Aravalli–Delhi Fold Belt region

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Seismic reflectivity signatures across the Proterozoic Aravalli–Delhi Fold Belt of the NW Indian shield suggest a tectonic history of continental collisions. The associated deep-seated faults indicate thick skinned tectonics in their evolution. A crustal scale thrust fault (Jahazpur thrust) originates from the top of reflection Moho at the boundary of the Sandmata and Mangalwar Complex and surfaces near Jahazpur. The presence of zinc–lead mineralization at Agucha, Sawar and Jahazpur in the thrust zone region suggests a close relationship between crustal scale tectonics and mineralization of the region. The gross geoelectrical section derived by digitizing magnetotelluric data along a part of the seismic profile correlates well with seismic reflectivity characteristics. The geophysical signatures suggest that the crustal scale fault zones might have acted as conduits for transportation of the ore fluids. Such a process was responsible for the high reflectivity and high conductivity, thus making the structures excellent targets for delineation by seismic and magnetotelluric methods.

DEEP seismic reflection profiling is being used world over to image the crust and upper mantle for better understanding of the geological and tectonic processes. Such a study has been carried out in India for the first time along a 400 km long Nagaur–Kunjer profile during 1991–1993 as a major component of multidisciplinary effort under the Deep Continental Studies Programme (Figure 1) to unravel the Precambrian tectonic history of the NW Indian shield. The profile traverses across the Neoproterozoic Marwar Basin (MB), Paleo/Mesoproterozoic Delhi Fold Belt (DFB), the middle Archaean Bhilwara Gneissic Complex (BGC), the late Archaean Hindoli Group (HG) and the Meso/Neoproterozoic Vindhyan Basin.

The NW Indian shield is a complex mosaic of different lithological units of varying magmatic, metamorphic and evolutionary histories of different periods. Most of the boundaries of the crustal blocks are demarcated by deep-seated ductile shear zones[1,2] that originate at great depths and propagate upwards with hundreds of kilometers of areal extension. The present paper synthesizes seismic images with other geophysical signatures to focus the relationship between crustal scale fault zones, mineralization and tectonics of the region.

The Bhilwara Gneissic Complex with 3.3 Ga age[3] rocks represents the oldest cratonic nucleus of the NW Indian shield and forms the basement to all the Proterozoic cover sequences. The Aravalli and Delhi sediments were deposited successively over this Archaean basement. It includes the Sandmata Complex (SC) and Mangalwar Complex (MC). The SC constitutes the high-grade granulites emplaced along the tectonic boundary. The MC consists predominantly of tonolitic gneisses with several enclaves of amphibolites and metasediments representing an older granite–greenstone belt. The HG with a thick pile of metavolcanic and metasedimentary sequences constitutes a younger granite–greenstone belt with green schist to lower amphibolite facies metamorphism. The Jahazpur Group is treated as equivalent to Aravallis[1]. The MB consists of flat, undeformed clay evaporite sequences mostly lying over Malani igneous suite (750 Ma) and Erinpura granites (850 Ma) as their basement. The DFB consists of highly folded and deformed rocks exhibiting polyphase metamorphism. The Vindhyan basin is undeformed and unmetamorphosed.

The Aravalli–Delhi fold belts have evolved through several volcano-sedimentary cyclic sequences each separated by an unconfirmity. Sychanthavong and Desai[4] believed that the BGC–Aravalli as a protocontinent in the east and a Precambrian oceanic plate with a mid-ocean ridge towards west. The eastward subduction of the oceanic plate has resulted in the evolution of DFB. According to Sinha Roy[5], the NW Indian shield has evolved through plate tectonic processes involving rifting, generation of oceanic crust and subduction resulting in the development of the Proterozoic Aravalli Delhi Fold Belt (ADFB). Such a tectonic scenario clearly indicates the need for examining the paleoprocess of base metal mineralization in the region with the help of geophysical, geochemical and geochronological tools.

Base metal mineralization is essentially through four main process, viz. hydrothermal processes, syntectonic volcanism, synsedimentary volcanism and strata bound deposition. Of these, the hydrothermal circulation and syntectonic volcanism generally account for most of the mineralization and are complementary to each other[6–10]. The general concept involves convective geothermal systems at greater depths and ore fluids rising to the surface from subducting plate boundaries or through tectonic wedges/shear zones. When these rising hot ore fluids pass through the cold dry host rocks, the water is absorbed/expelled leaving rich sulfide deposits along the weak shear zones. Large metallogenic provinces, world over are associated with crustal scale tectonic features.

The NW Indian shield presents us with ideal geological conditions for base metal mineralization, such as existence of meta-volcanic sequences, polyphase metamorphism and tectono-magmatic activity[1] over a protracted

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*For correspondence. (e-mail: postmast@csngri.ren.nic.in) period from Archaean to Neogene[11]. Notwithstanding the differences in lithostratigraphic classification among various workers, four major tectono-magmatic events are recognizable in the ADFB with their closing geochronological ages as 3.2, 2.0, 1.6 and 0.7 Ga corresponding to the BGC, Aravalli, Delhi and post-Delhi orogenic cycles[2,3,12] respectively. Such an activity over the geological time scale leaves ample scope for reactivation of the faults which helps in the enrichment of the ore deposits under favourable hydrothermal regime as evidenced by the re-equilibrated younger Moho fabric under the Jahazpur thrust.

Seismic, magnetotelluric and gravity signatures of the crustal scale fault have been studied to establish the linkage between crustal scale fault zones and metallogeny.

The preliminary results of the Nagaur–Kunjer profile were reported by Reddy *et al.*[13] and Tewari *et al.*[14]. The reprocessed seismic sections along this profile show that the upper crust in most parts of the profile is nonreflective. However, the lower crust exhibits different reflectivity patterns in various geological/tectonic units. The seismic section (Figure 2) shows a crustal scale NW dipping thrust fault (Jahazpur thrust) originating at an approximate depth of 40 km at the Moho boundary and traversing a distance of over 80 km and surfacing near Jahazpur. It is associated with the oppositely dipping E-reflection band at the middle and lower crustal levels. A subhorizontal reflection fabric corresponding to younger Moho is also observed at 13–14.5 s two-way travel time (TWT). A line drawing of the prominent reflections in the seismic section along with the Bouguer gravity anomaly is presented in Figure 3. The probable migration path of the ore fluids to the surface and their relation to the crustal features are also depicted.

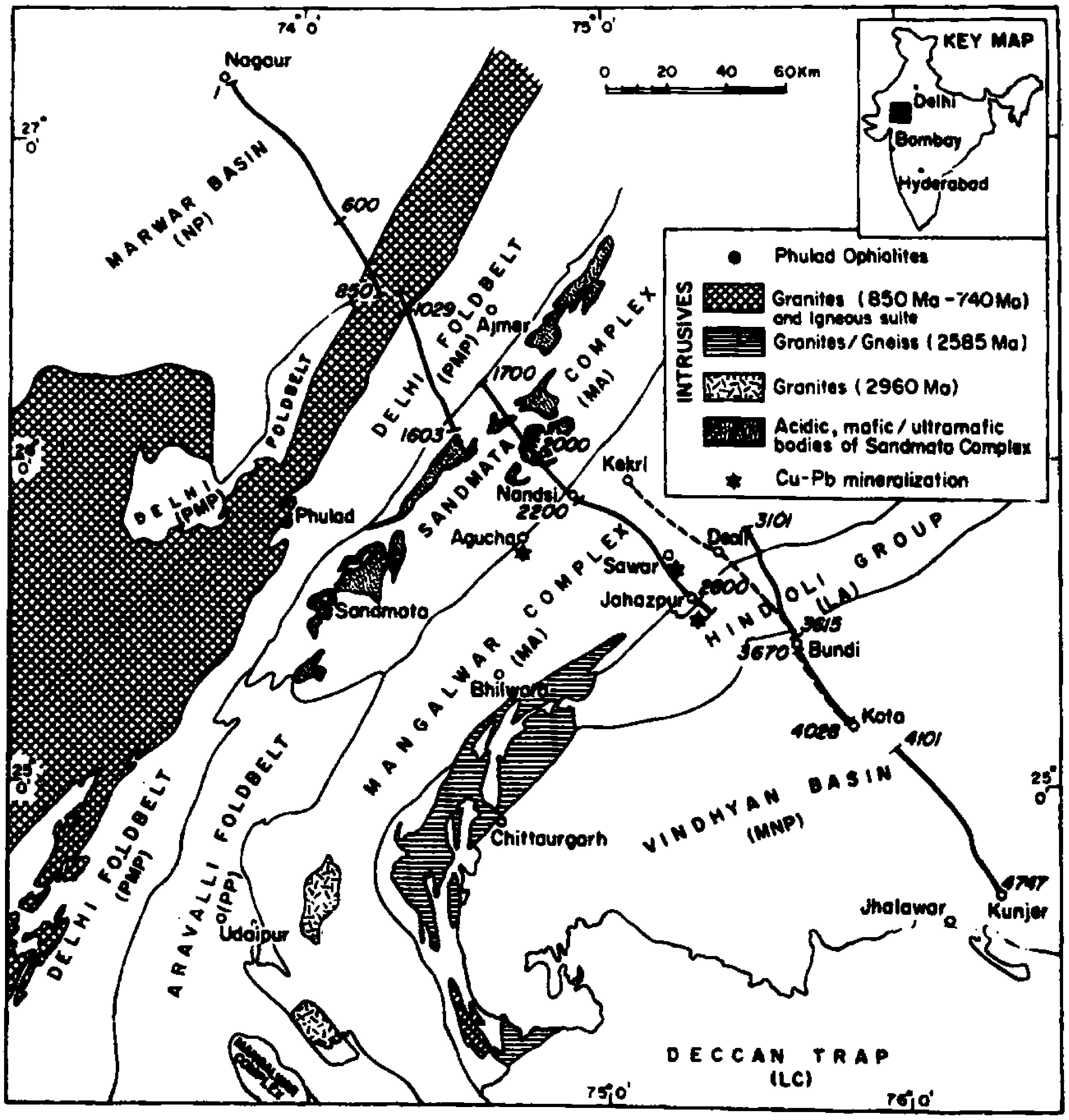

Figure 1. Location of the Nagaur–Kunjer deep reflection profile plotted over the main tectonic units of the NW Indian shield (simplified and redrawn after Gupta *et al.*) along with copper–lead–zinc mineralized zones. The dashed line from Kekri–Kota indicates the magnetotelluric sounding profile. The figures along the profile represent shot point numbers. LC – Late Cretaceous, NP – Neoproterozoic, MNP – Meso/Neoproterozoic, PMP – Palaeo/Mesoproterozoic, PP – Palaeo-proterozoic, LA – Late Archaean, MA – Middle Archaean.

The magnetotelluric (MT) data along Kekri–Kota[15,16] over a part of Nagaur–Kunjer profile are digitized. A true to scale section is presented in Figure 4. The salient feature of the geoelectrical section is a 10 km thick NW dipping 50 ohm.m. conductor extending from a depth of 3 km near Jahazpur to a depth of 25 km near Kekri. This feature could not be delineated beyond 25 km due to non-availability of data at frequencies below 0.01 Hz.

The Jahazpur thrust is a 25 km wide band of parallel dipping reflections and has a great significance in the tectonic evolution of the region as it juxtaposes different lithotectonic units of varying ages and metamorphic grades, viz. the high grade Mangalwar Complex of the mid Archaean age and the low grade Hindoli Group of the late Archaean age. The reflectivity characteristics on either side of the thrust are different with a highly reflective Moho on one side and its absence on the other. This suggests that the crustal blocks on either side are different. The dimensions and deep-seated nature of the thrust fault indicate that the thick skinned tectonics are involved in its evolution. The westward movement of the eastern crustal block, its underthrusting and collision with the

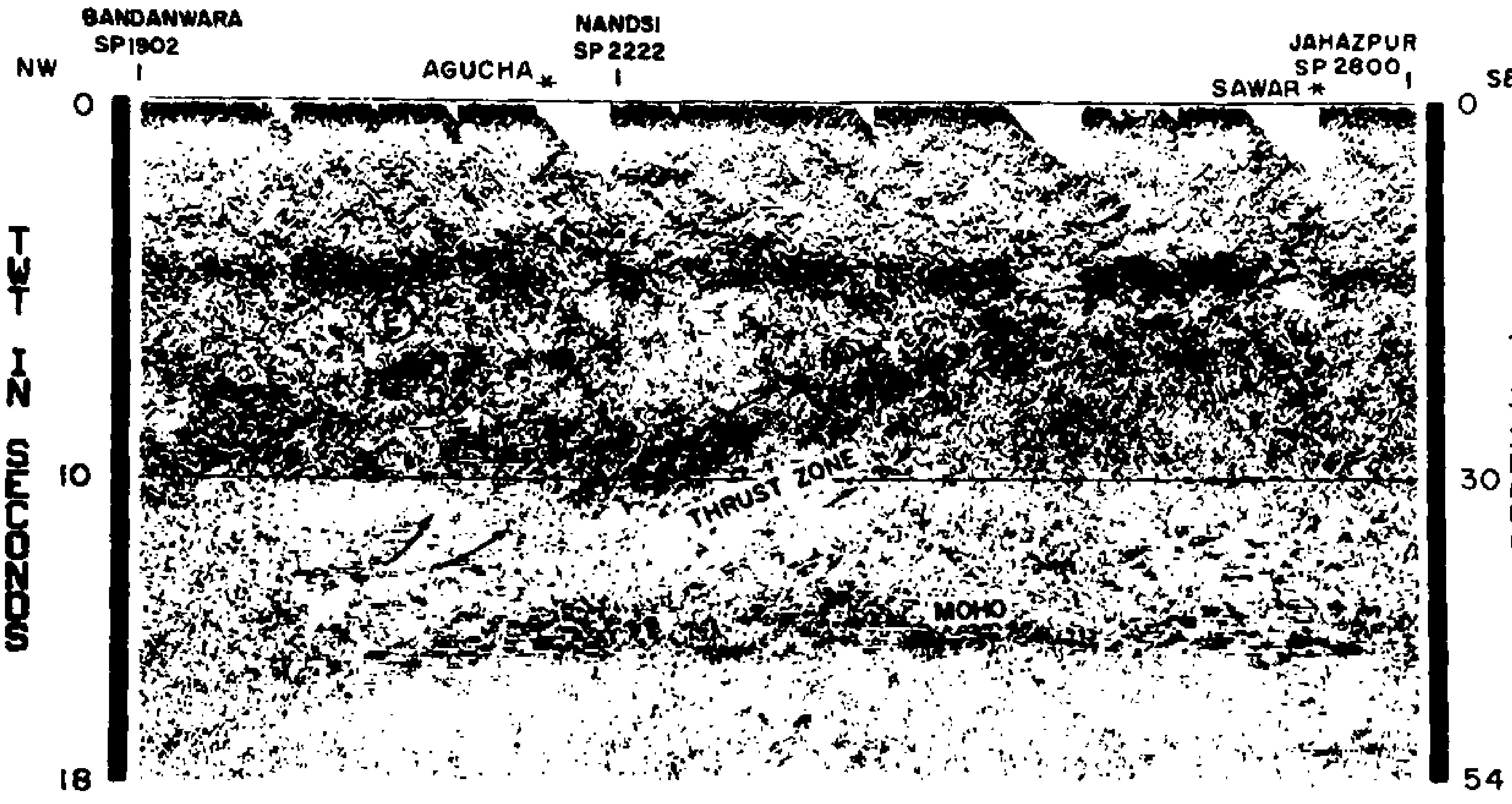

Figure 2. Crustal seismic reflection section of a portion of the profile from Bandanwara to Jahazpur depicting the crustal scale thrust zone (F).

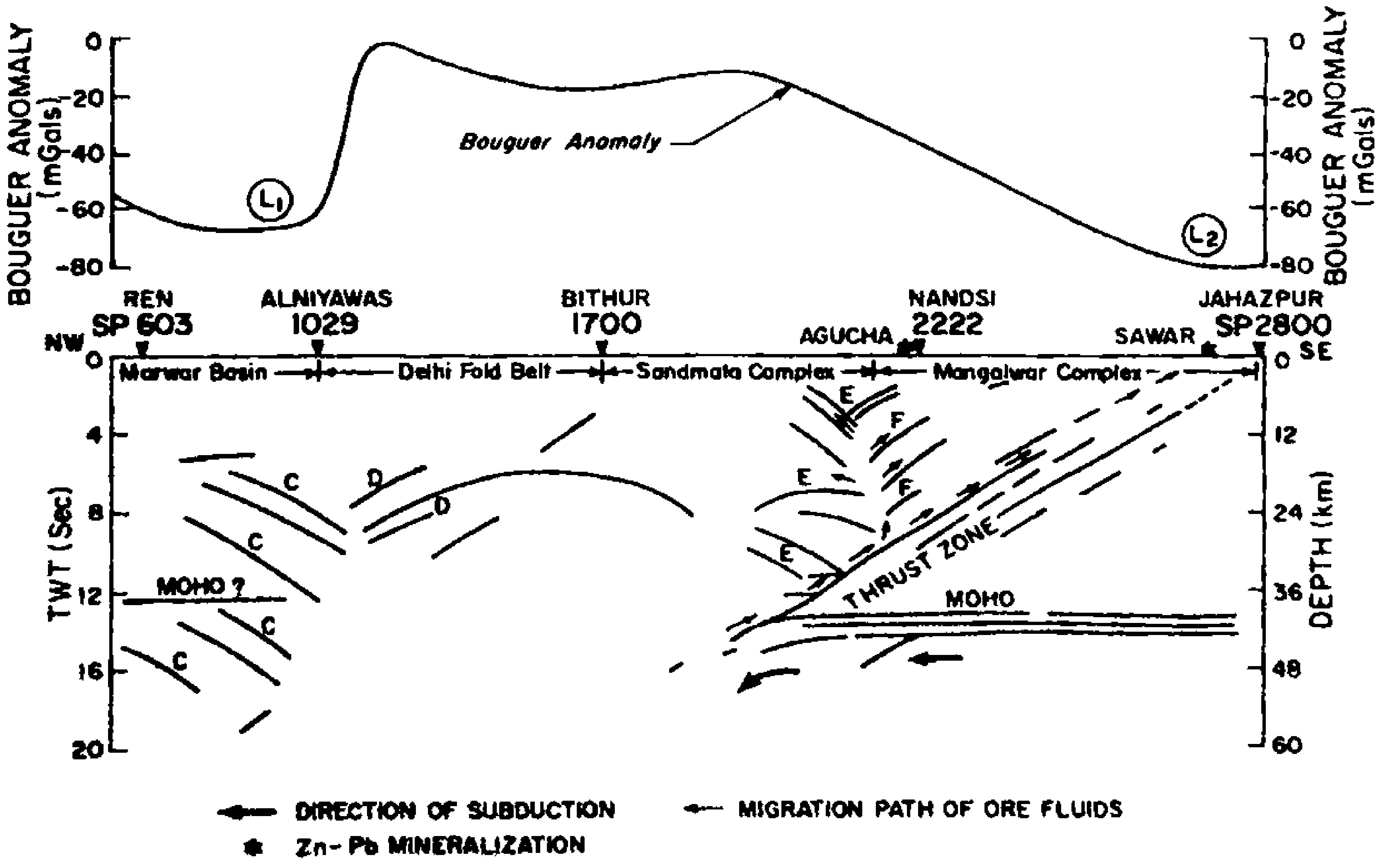

Figure 3. A line drawing of prominent reflections of the seismic section with Bouguer gravity anomaly. The arrows indicate possible migration path of the ore fluids. C–D and E–F reflection patterns correspond to Delhi and Aravalli orogenies respectively. The two way travel time is converted to approximate depth by using an average velocity of 6 km/s for the crust. The scales on Figures 2 and 3 are different.

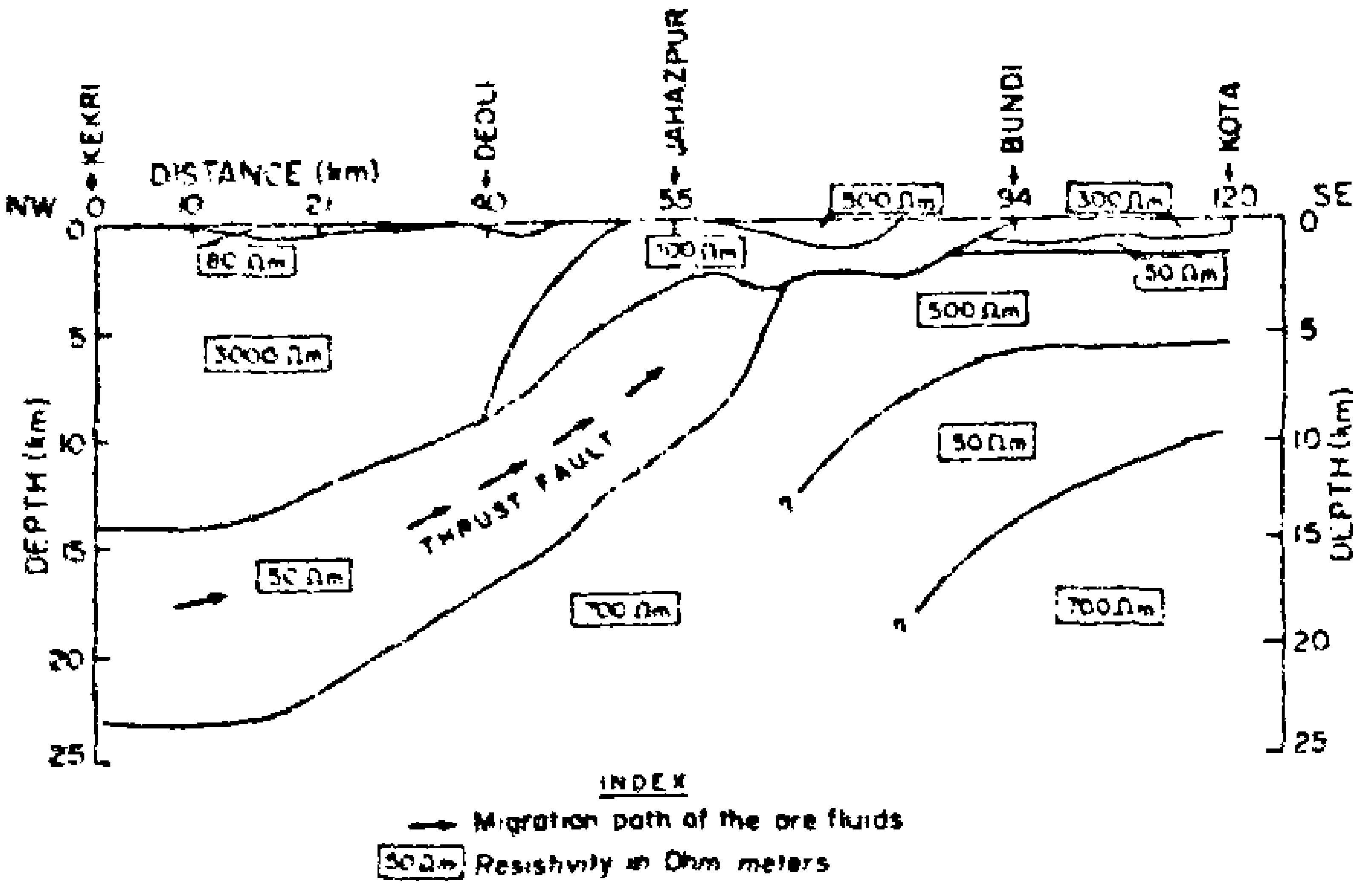

Figure 4. Geoelectrical section along the Kekri–Kota part of the Nagaur–Kunjer deep reflection profile. (Modified and redrawn after Gokaran *et al.*).

western crustal block during the Mesoproterozoic times resulted in the development of the thrust fault. The updoming of reflections (E-reflections, Figure 3) constituting a divergent reflection fabric corresponds to the collision-related process[17]. This is in general agreement with the plate tectonic model of Sinha Roy[5]. Continuous underthrusting of the crustal block during the evolution of the Aravalli Fold belt, was adequate to produce high temperatures for generating partial melts. The convective hydrothermal regime developed due to the partial melts and the metamorphic events led to sulphide enrichment of the ore fluids. These ore fluids might have migrated up along the thrust fault resulting in the formation of mineralized zones. It is suggested that the Sawar and Jahazpur zinc–lead deposits are associated with the surface expression of the Jahazpur thrust (Figure 3). Sinha Roy[5] feels that Wilson cycles were operative during the Proterozoic period in the region corresponding to the Aravalli and Delhi orogeny and the Jahazpur belt is folded in the Mesoproterozioc. Such a model could have provided ample scope for the operation of a convective hydrothermal process through fault zones and in turn to the mineralization. Fyfe *et al.*[18] are of similar opinion that crustal scale thrusts act as conduits for the rising ore fluids. It is widely believed that sulphide mineralization is generally confined to large shear zones which juxtapose different tectono-stratigraphic units. Beaudoin *et al.*[19] identified the ore fluid migration path by a careful study of the paleo-hydrological regime. In the present study the seismic image and the MT section (Figures 3 and 4) are used to depict the probable migration path of the ore fluids.

The partial melts associated with the deeper parts of the thrust might have risen vertically as in the case of a subduction zone volcanism. The Rampur–Agucha zinc–lead mineralized zone at the boundary of SC–MC is situated in such a place and may represent the mineralization at the volcanic arc. It is supported by the geochemistry of sulphide ores that also indicates their volcanic origin[20]. Greenstone belts are regarded as remnants of a Precambrian volcanic arc system[21]. The MC is identified as a greenstone belt by Sinha Roy[5] and others. In the present context, the greenstone belt might have evolved due to the collision process in the region. The geochemical data[22] also suggest that the greenstone sequence has evolved by a collision mechanism. The mineralization at the volcanic arc system is one of the ways of deposition. It is interesting to note that many other metallogenic provinces of the region are located further south of Agucha along the same linear belt between SC and MC. It is beyond the scope of the present paper to provide a complete tectonic framework of the region.

The seismic image when interpreted in conjunction with the geoelectrical section provides more meaningful interpretation and helps in better understanding of the tectonic history of the region in general and mineralization in particular. The NW dipping 50 ohm.m. conductor is the geoelectrical expression of the seismically imaged crustal scale thrust fault as it matches very well in most of its attributes, viz. location, dip and attitude (Figure 4). The high electrical conductivity of the above conductor might be due to the presence of sulphur that has its surface expression at Sawar and Jahazpur of this region with the occurrence of base metal sulphide mineralized zones. This suggests that high conductivity could be due to the passage of sulphur-bearing ore fluids through the Jahazpur thrust. We opine that the litho-unit resting over the mid crustal conductor is a remnant (less altered) tectonic wedge. The lower resistivities of 80 and 100 ohm.m. resting over high resistivity (3000 ohm.m) rocks (Figure 4) can be better explained as paleosignatures of fluid migration.

A Bouguer gravity high of 80 mGals is observed over DFB and SC flanked by lows (L_1 and L_2) on either side all along the strike of ADFB to a distance of 700 km. These two gravity lows coincide with the Jahazpur thrust on one side and the C–D reflection band on the other end at the MB–DFB boundary. Both these locations are associated with base metal deposits (Figure 3). Reddy and Ramakrishna[23] with their gravity and magnetic studies across the known base metal belts have correlated them with gravity lineaments. Regional gravity, magnetic and satellite imagery studies reveal that the metallogenic provinces follow the major lineaments and tectonic trends[24,25], further supporting that the deep-seated faults extending to the mantle might have played a major role in the magmatic history and metallogeny of the region. In fact, it has been established that a number of mineral provinces in the world (Sweden, Scotland and Ireland) owe their metallogeny to geofractures and related magmatic activity[26–28].

The locations of the above mineralized zones associated with the Jahazpur thrust and the reflection fabric with its geoelectrical signature suggest that they may be genetically related to the Aravalli orogeny. The passage of large volumes of fluids through the Jahazpur thrust might have created good acoustic impedance contrast within the fault zone. Such a fault zone structure can generate moderate to high reflectivity due to the constructive interference among various events[29]. The subhorizontal reflections at 12–14.5 s near the Jahazpur thrust correspond to Moho. This reflection Moho fabric is identified as an younger event[17] and is due to the post-collisional deformation processes which provides enough scope for subsequent tectonic activity to reactivate the existing faults and enrich the ore deposits.

Similar deep-seated faults are delineated near the boundary of the Marwar basin and the Delhi Fold belt (Figure 3). The oppositely dipping (C–D) reflections corresponding to the Delhi orogeny are also well documented in the present study. This deep-seated structure is an ideal environment for the transportation of ore fluids to the surface. The Khetri, Saladipura copper mineralization in the north and Ambaji, Deri, Basantgarh deposits in the south of the study area are located along the MB–DFB tectonic boundary. The presence of mafic and ultramafic rocks and various granites in the region near the tectonic boundary of MB–DFB suggests the transportation of deep-seated material to the surface. These mineralized zones may be related to the Delhi orogeny.

In conclusion, the present study suggests that the crustal scale seismic images along with the other geophysical signatures can help in understanding large-scale mineralization of a region. An integrated approach of using the seismic image for constraining the geometry and the conductivity structure from MT studies for identifying the lithological units can enhance our understanding of the metallogeny of a region. The crustal scale fault zones developed due to the collision tectonics involved in the Jahazpur region of the NW Indian shield might have acted as conduits for transportation of ore fluids to the surface, resulting in the mineralization of the region.

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