J. Earth Syst. Sci. (2019) 128:139
https://doi.org/10.1007/s12040-019-1131-8

The geological site characterisation of the Mandla region, Eastern Deccan Volcanic Province, Central India

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MS received 19 April 2018; revised 18 July 2018; accepted 19 October 2018; published online 15 May 2019

Detailed geological studies were carried out on the basaltic sequences along the Jabalpur–Niwas, Jabalpur–Chutka and Jabalpur–Mandla traverses covering an area of about 12 km×15 km to characterise various basaltic lava flows and their behaviour on seismotectonics and geodynamic setting of their formation in the Mandla region of the Eastern Deccan Volcanic Province (EDVP). The studies involve an analysis of the satellite images for the identification of lineaments/faults and field geological studies consisting of geological controls such as ground check, thickness of fractures and orientation along the acknowledged lineaments/faults. The results of the present research comprising 65 lineaments/faults mainly belonging to two geometric groups, minor and major dominantly in the NW–SE and the NE–SW and altered strata varying lithology (weathered to compact basalts) are recognised in the study area. Based on their extent, 57 lineaments have been classified as minor (<100 km) trends in three different orientations, i.e., NNE–SSW, ESE–WNW and ENE–WSW, whereas 8 lineaments were classified as intermediate (300–100 km) trends in NNE–SSW. No major (>300 km) lineaments are noticed in the study region. The field geological investigations have facilitated the recognition of 10 flows with different characteristic features and a variety of volcanic structures such as columnar, vesicular, amygdaloidal, inflated pahoehoe lava flows and red bole interflow horizons have been documented. Basement rocks of these Deccan basalt lavas are represented by Tirodi Biotite gneisses, quartzite, quartz–mica schists and crystalline limestone in the SE part of the study area of the Mandla region. The present study will help evaluate the localised site characterisation for urban planning and setting up major civil structures.

Keywords. The Mandla region; geological studies; lineaments; satellite images; the Eastern Deccan Volcanic Province.

1. Introduction

The Deccan Volcanic Province (DVP) is one of the largest igneous provinces (LIP) in the world which has been studied since many decades for its stratigraphy, structure, geochemistry, petrogenesis, geochronology and duration of the volcanism (Mukherjee *et al.* 2017). It is most extensive, with an area of >500,000 km^2 covering the states of Gujarat, Maharashtra, Madhya Pradesh, Andhra Pradesh, Karnataka and Goa, Daman and Diu. The Deccan basalt near the coast is 1500 m which decreases to 400 m in the central region (Alexander 1979, 1981; Kaila *et al.* 1979, 1981a, b). The variation in thickness is controlled by (i) the pre-Deccan topography, (ii) the N–S trending fault system, which is more prominent in the Western Ghat sections and (iii) the differences in the depth to Moho.

More than 48 flows were recognised, which erupted in a very short time (West 1981; Raja Rao *et al.* 1999; Mishra *et al.* 2017). The Deccan Continental Flood Basalt Province (DCFBP) is related to the reunion hotspot and eruptions of this voluminous lava took place within a short period of 0.5–2 Ma (Naqvi 2005), close to the cretaceous-tertiary boundary (Hooper 1999). The DCFBP has been studied at several locations and its structure, thickness, ages, composition and nature of intertrappean beds have been analysed using geological, geophysical and geochemical techniques. Out of the $\sim$5,00,000 km^2, the area comprising the Western Ghats, including the Mahabaleshwar hills have provided enormous information (Cox 1980; Cox and Hawkesworth 1984). Deep seismic sounding (DSS) data indicated that the volcanic pile is about 100 m in the northeast and gradually increases up to 1000 m in the west (Kaila 1988).

The Eastern Deccan Volcanic Province (EDVP) is an elongated outlier that extends up to 344 km E–W and 156 km N–S, covering an area of 29,351 km^2 around the Jabalpur, Mandla, Dindori, Amarkantak and Seoni areas (Kashyap *et al.* 2010). The Mandla Lobe forms a 900 m thick lava pile. The geological and tectonic framework of any continental region can be considered as a reflection of its time-bound integrated geodynamic evolution. Hence deciphering and understanding their physical, thermo-tectonic and compositional nature especially in areas which have a thick overburden becomes a major challenge. It is generally believed that shields are seismically stable but earthquakes in Jabalpur, Latur, Bhuj and Koyna and other earthquakes in the stable continental crust have indicated some subcrustal movement below the stable shields also (Gupta 1994; Gupta *et al.* 1995). Out of the several earthquakes, the Jabalpur earthquake of 1997 occurred at a depth of 35 km. Jabalpur is situated within the Central Indian Suture Zone (CISZ) and is characterised by a high surface heat flow of 70–100 W/m^2 (Ravi 1988; Mahadevan 1994).

In view of the above-mentioned intraplate seismicity, detailed geological field studies using satellite images were carried out in the relatively less studied Mandla region of the Eastern Deccan Continental Flood Basalt Province (EDCFPB). It is also believed that the basement below the thick cover of the continental flood basalt is highly resistive, but not uniform and appears to be intersected by faults (Harinarayana *et al.* 2004). The Western Ghat section in the Western Deccan Volcanic Province (WDVP) is regarded as one of the well-studied lava sections of the DVP in terms of structure, composition and dynamics (Kaila *et al.* 1987; Subbarao and Hooper 1988; Ramesh *et al.* 1993; Tiwari and Mishra 1999; Tiwari *et al.* 2001; Naqvi 2005; Ramakrishnan and Vaidhyanadhan 2008). But, the Mandla region has not been analysed using satellite images for the identification of lineaments/faults and field geological studies, consisting of geological controls such as ground check, thickness of joints/fractures and orientation along the acknowledged lineaments/faults. With an emphasis, geological field studies were adopted on the Jabalpur–Seoni (JS), Jabalpur–Mandla (JM) and Jabalpur–Niwas (JN) traverses (figure 2) and the results are discussed in the present paper.

2. Location of the study area

The study area is Mandla, located in the Seoni and Jabalpur districts of eastern Madhya Pradesh and also forms a part of the EDVP wherein the well-known Mandla region is situated in the northeastern part of the DVP (figure 1). The study region is located within the coordinates 22°30′N–23°15′N and 79°45′E–80°30′E. The detailed field geological studies carried out along

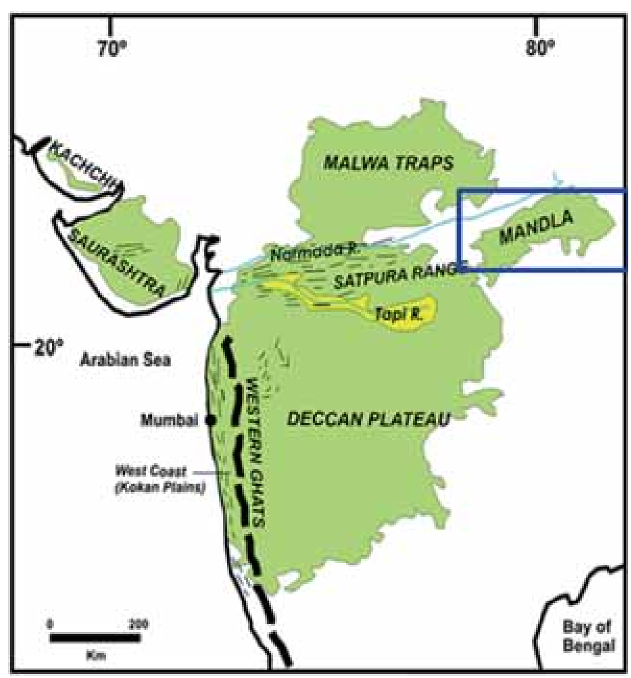

Figure 1. Location map of the Mandla region, EDVP (after the Geological Survey of India portal).

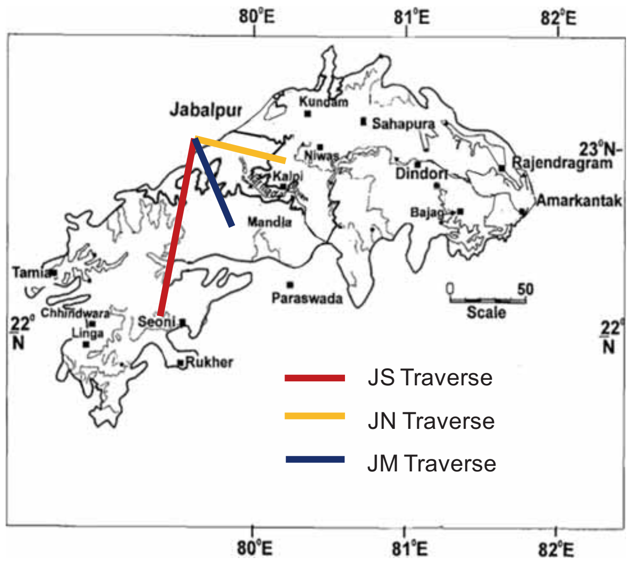

Figure 2. Geological studies along the Jabalpur–Seoni (JS), Jabalpur–Niwas (JN) and Jabalpur–Mandla (JM) traverses (base map after Pattanayak and Shrivastava 2002).

Jabalpur–Seoni (JS), Jabalpur–Mandla (JM) and Jabalpur–Niwas (JN) (figure 2).

3. Geological setting and lithology of the Mandla lobe

The study area lies mainly within the Mandla outlier in the EDVP. EDVP is an elongated outlier that extends 344 km E–W and 156 km N–S, covering an area of 29,351 km^2 around the Jabalpur, Mandla, Dindori, Amarkantak and Seoni areas (Kashyap *et al.* 2010). The Mandla lobe forms a 900-m thick lava pile. The landscape is covered by flat-topped plateaus and ridges with small mesas, mounds and buttes. The study of this outlier is significant because of its occurrence within the Narmada–Tapti rift system (Hooper 1990). Physiographically, this study region forms part of the Satpura hill range of Central India. The physiographic features include plateaus in the northern part formed by basalt and east–west trending hills in the southern part. The Narmada river and its tributaries drain the northern and north-western part of the study region. Geologically, the area forms the southern fringe of the Son–Narmada–Tapti (SONATA) lineament zone, the ENE–WSW trending major tectonic zone within the Central Indian Shield, with evidences of tectonic activity from the Palaeoproterozoic era to recent times. ENE–WSW trending Central Indian Tectonic Zone (CITZ) is located in the southern part. The study region is dominantly occupied by the Deccan traps (table 1 and figure 3). More than 95% of the area is covered by these rock types which unconformably overlie the Precambrian granite gneiss. Deccan trap flows are seen to occur at different elevations in the area probably because of the uneven nature of the basement and the uneven thickness of the individual lava flow (Keszthelyi *et al.* 1999). The Quaternary sediments lie unconformably over the eroded surface of the Deccan trap lava flows. Field geological investigations were carried out and are described in table 2.

Table 1. *Lithology and geological formations of the study area.*

Lithology	Formation	Age
Alluvium		Quaternary (2.6 Ma)
Non-porphyritic basaltic lava flows	Linga formation of Amarkantak group	Cretaceous to paleogene (145–28 Ma)
Highly porphyritic basaltic lava flows	Piperdehi formation of Amarkantak group	Cretaceous to paleogene (145–28 Ma)
Compound basaltic lava flows	Dhuma formation of Amarkantak group	Cretaceous to paleogene (145–28 Ma)
Simple to compound basaltic lava flows	Mandla formation of Amarkantak group	Cretaceous to paleogene (145–28 Ma)
Sandy limestone and arkosic sandstone, calcareous and conglomeratic sandstone and clay at places	Lameta group	Cretaceous (145–70 Ma)
Marble, tremolitic dolomite with intercalations of phyllite and slate	Bichua formation of Sausar group	Meso Proterozoic (1600–1200 Ma)
Grey and pink granite gneiss, gneiss and migmatite with enclaves of meta-sediments, Biotite gneiss and schist, para-amphibolite	Tirodi Gneissic complex	Archaean to Paleoproterozoic (3800–1800 Ma)

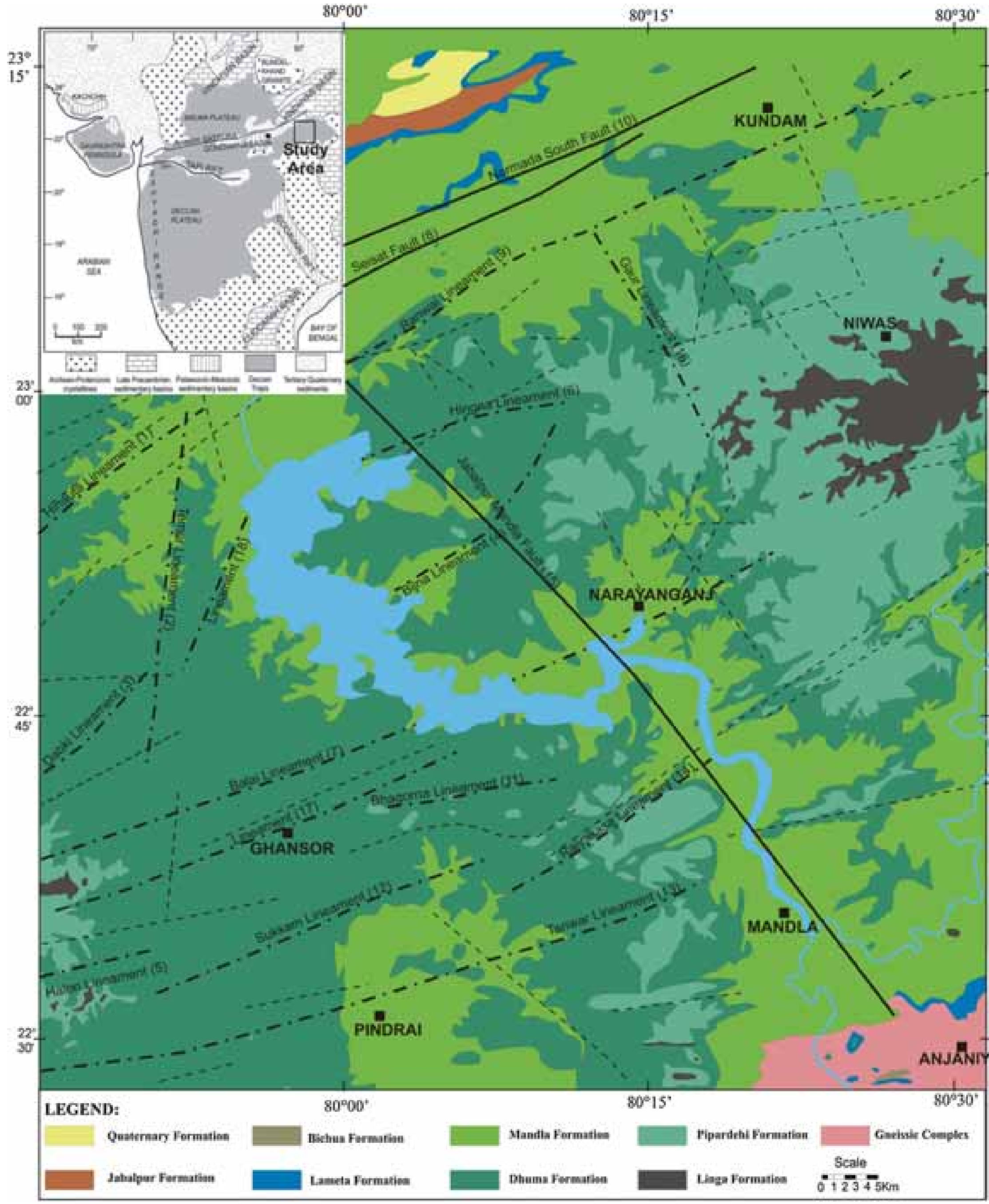

Figure 3. Geological map of the study area, the Mandla region, Madhya Pradesh, the EDVP (source: Digital rights management Mandla, Jabalpur and Seoni districts in Madhya Pradesh).

3.1 *Deccan basalts and basement rocks of the Mandla outlier*

In this section, the field geological and volcanological features of different basalts exposed along the JN, JM and JS traverses in the Mandla region of EDVP are described. The landscape of the study region is represented by flat-topped plateaus (figure 4a). The basement rocks are represented by gneisses showing their well-banded nature with abundant pegmatite intrusions in the study region (figure 4b). The basalt flows in the study area are nearly flat in nature and also exhibit sub-horizontal to gently dipping flows (figure 4b). At many places, these basalt flows show their nearly sub-horizontal flow banding and compact flows show fractures (figure 4c). The extensive development of joints in basalt is columnar noticed at Khirhani village, where sub-vertical columnar joints and thick curvilinear/splaying joints are well developed

Table 2. *Field geological studies in the study area, Mandla region.*

Sl. no.	Location/village	Latitude	Longitude	Geological observation and lithology	Fracture/joint pattern	Traverse
1.	Piparia	N22°56′40.2″	E79°48′46.6″	Dark grey, fine to medium grained, porphyritic basalt	Fractures varying from 0.20 cm to 1 m. About 165 sets of joints and fractures are observed in N35°E, N41°E, N38°E, N32°E, N31°E orientation	JS
2.	Khamariyatula & Riba	N22°56′58.3″	E79°51′47.6″	Dark grey, fine to medium grained, porphyritic basalt	About 200 sets of joints and fractures are recorded. N15°E, N10°E, N8°E, N12°E, N11°E, N−S	JS
3.	Katori	N22°47′50.1″	E79°50′01.7″	Dark grey, fine to medium grained, hard, massive moderately porphyritic basalt		JS
4.	Sikhora	N22°47′51.8″	E79°51′11.4″	Grey, fine grained, hard and massive, sparsely to moderately porphyritic basalt		JS
5.	Pararahotola & Basanpani	N22°53′51.3″	E79°50′51.4″	Dark grey, fine to medium grained, moderately porphyritic basalt		JS
6.	Patri	N22°42′49.1″	E79°50′38.8″	Dark grey, fine to medium grained, hard, compact, massive porphyritic basalt in nature		JS
7.	Batwani	N22°37′01.3″‘	E79°47′10.4″	Grey, fine grained, compact basalts		JS
8.	Chauki	N22°42′47.8″	E79°46′58.3″	Dark grey, fine to medium grained, hard, compact, massive porphyritic basalt in nature	About 160 sets of joints and fractures are recorded. Fractures are oriented in N25°E, N29°E, N30°E, N22°E, N18°E	JS
9.	Maniksura	N22°52′37.6″	E80°04′52.5″	Grey, fine grained, compact basalts	About 50 sets of joints and fractures are recorded and the orientations are in N55°E, N60°E, N50°E, N52°E, N54°E	JM
10.	Gwari	N22°33′08.6″	E79°45′32.8″	Dark Grey, fine to medium grained, compact basalts	About 190 sets of joints and fractures are recorded and the orientations are in N75°E, N70°E, N80°E, N72°E, N64°E	JS
11.	Mohgaon	N22°34′08.7″	E79°49′24.2″	Grey, fine grained, compact basalts and porphyritic		JS
12.	Newari	N22°56′40.2″	E80°01′12.5″	Grey, fine grained, compact basalts	About 110 sets of joints and fractures are recorded and the orientations are in N70°E, N71°E, N72°E, N72°E, N64°E	JN
13.	Salaiya	N22°58′35.4″	E80°09′41.9″	Grey, fine grained, compact basalts, non-porphyritic to porphyritic		JN
14.	Budra	N22°58′19.0″	E80°04′05.2″	Grey, fine grained, compact basalts, non-porphyritic to porphyritic		JN
15.	Malara	N22°50′04.3″	E80°15′12.3″	Grey, fine grained, compact basalts	About 175 sets of joints and fractures are recorded and the orientations are N45°E, N41°E, N38°E, N32°E, N31°E	JM

Table 2. *(Continued.)*

Sl. no.	Location/village	Latitude	Longitude	Geological observation and lithology	Fracture/joint pattern	Traverse
16.	Pipariya and Khamhariya	N22°46′46.3″	E80°10′21.4″	Grey, fine grained, compact basalts		JM
17.	Purwa	N23°06′38.2″	E80°06′52.8″	Dark grey, fine to medium grained and porphyritic basalt		JN
18.	Khirhani	N23°04′12.6″	E79°56′45.5″	Dark, fine to medium grained, porphyritic basalts	About 100 sets of joints and fractures are recorded and the orientations are in N47°E, N41°E, N42°E, N43°E, N50°E direction	JN
19.	Jogi dhana	N23°02′06.1″	E79°53′14.1″	Dark, fine grained, porphyritic basalts		JS
20.	Between Devri and Dhanpuri	N23°05′38.0″	E80°08′08.8″	Grey, fine grained, compact basalts	About 70 sets of joints and fractures are recorded and the orientations are in N50°E, N43°E, N46°E, N40°E, N44°E direction	JN
21.	Bilgara	N23°07′22.5″	E80°10′06.7″	Dark, fine to medium grained, porphyritic basalts		JN
22.	Narmada river	N23°04′48.2″	E79°56′57.3″	Dark, fine to medium grained, porphyritic basalts	About 200 sets of joints and fractures are recorded and the orientations are in N58°E, N60°E, N54°E, N56°E, N57°E	JS
23.	Nakotia	N23°04′22.2″	E79°51′02.6″	Greenish grey, fine grained, hard and foliated baslats		JS
24.	Jhiri	N23°03′49.2″	E79°49′32.6″	Dark, fine grained, porphyritic basalts		JS
25.	Jamunia	N23°07′36.9″	E80°03′46.8″	Dark grey, fine to medium grained porphyritic basalts		JN
26.	Bairagi	N23°09′39.0″	E80°05′43.5″	Dark grey, fine to medium grained porphyritic basalts		JN
27.	Kedarpur	N22°42′21.0″	E80°08′49.8″	Dark grey, fine to medium grained, hard, compact, massive porphyritic basalts	About 100 sets of joints and fractures are recorded and the orientations are in N85°E, N80°E, N70°E, N72°E, N64°E	JM
28.	Burhaina	N22°42′19.5″	E80°06′48.5″	Dark, massive to slightly porphyritic plagioclase bearing basaltic flows		JM
29.	Mundapar	N22°37′56.0″	E80°03′11.4″	Dark grey, fine grained, hard, compact, massive, non-porphyritic basalts	About 150 sets of joints and fractures are recorded and the orientations are in N65°E, N71°E, N68°E, N66°E, N64°E	JM
30.	Pindrai	N22°32′53.3″	E80°02′37.4″	Black to greyish black, fine grained, porphyritic, hard compact basalts	About 165 sets of joints and fractures are recorded and the orientations are in N65°E, N71°E, N68°E, N66°E, N64°E	JM

31.	Barbaspur	N22°33′53.8″	E80°07′41.5″	Greyish black, fine grained, porphyritic, hard and compact basalts		JM
32.	Katiya	N22°37′54.7″	E80°09′06.9″	Dark grey, fine grained, hard, compact, massive, non porphyritic to slightly porphyritic basalts	About 140 sets of joints and fractures are recorded and orientations are observed in N35°E, N41°E, N38°E, N32°E, N31°E	JM
33.	Bijaypur	N22°54′26.2″	E80°06′26.6″	Dark grey, fine to medium grained hard and compact basalts, highly porphyritic basalt	About 150 sets of joints and fractures are recorded and the orientations are in N30°W, N28°W, N32°W, N26°W, N29°W	JM
34.	Birampur	N22°56′19.0″	E80°05′11.5″	Grey, fine grained, compact basalts		JM
35.		N23°06′22.2″	E79°53′12.4″	Dark, fine to medium grained, porphyritic basalts		JM
36.	Devgaon	N22°49′46.5″	E80°10′30.8″	Grey, fine to medium grained, highly porphyritic, compact basalts		JM
37.	Between Takbeli and Paharikhera	N23°05′58.5″	E80°12′45.9″	Dark grey, medium grained, porphyritic basalts	About 160 sets of joints and fractures are recorded and the orientations are in N25°W, N23°W, N28°W	JN
38.	Devri	N22°36′59.3″	E79°49′12.9″	Grey, medium grained, compact basalts	About 185 sets of joints and fractures are recorded and orientations are observed in N35°E, N40°E, N38°E, N32°E	JS
39.	Darot kalan	N22°37′25.3″	E79°50′33.8″	Grey, fine grained, compact basalts		JS
40.	Saliwara	N22°53′50.2″	E79°54′02.4″	Dark grey, fine to medium grained and porphyritic basalt	About 150 sets of joints and fractures are recorded and orientations are observed. Fractures are oriented in N23°E, N20°E, N25°E, N22°E	JS
41.	Manegaon	N22°47′45.7″	E80°09′19.2″	Dark grey, fine to medium grained, hard, compact, highly porphyritic basalts	Ropy, pipe vesicles at some places observed	JS
42.	Chutka	N22°47′41.0″	E80°06′02.3″	Dark grey, fine to medium grained, hard, compact, highly porphyritic basalts	Plagioclase phenocrysts observed. flows in N60°W and N–S direction	JM
43.	Chutka–Tatighat road	N22°46′24.9″	E80°05′41.5″	Dark, massive to slightly porphyritic plagioclase bearing basaltic flows	Semi crystalline quartz is observed. Vesicular basalts are noticed. The river bank exhibits natural slope without any faulting	JM
44.	Sitiyatola	N22°45′00.4″	E80°05′37.0″	Dark grey, fine to medium grained, hard, compact, massive, moderately porphyritic basalts	About 110 sets of joints and fractures are recorded and the orientations are in N28°W, N33°W, N38°W	JM
45.	Nainipur	N22°21′53.3″	E80°06′21.3″	Granitic gneisses	Weathered gneisses, sheared zone, foliations dipping south, granitic gneisses are intruded by pegmatites	JM

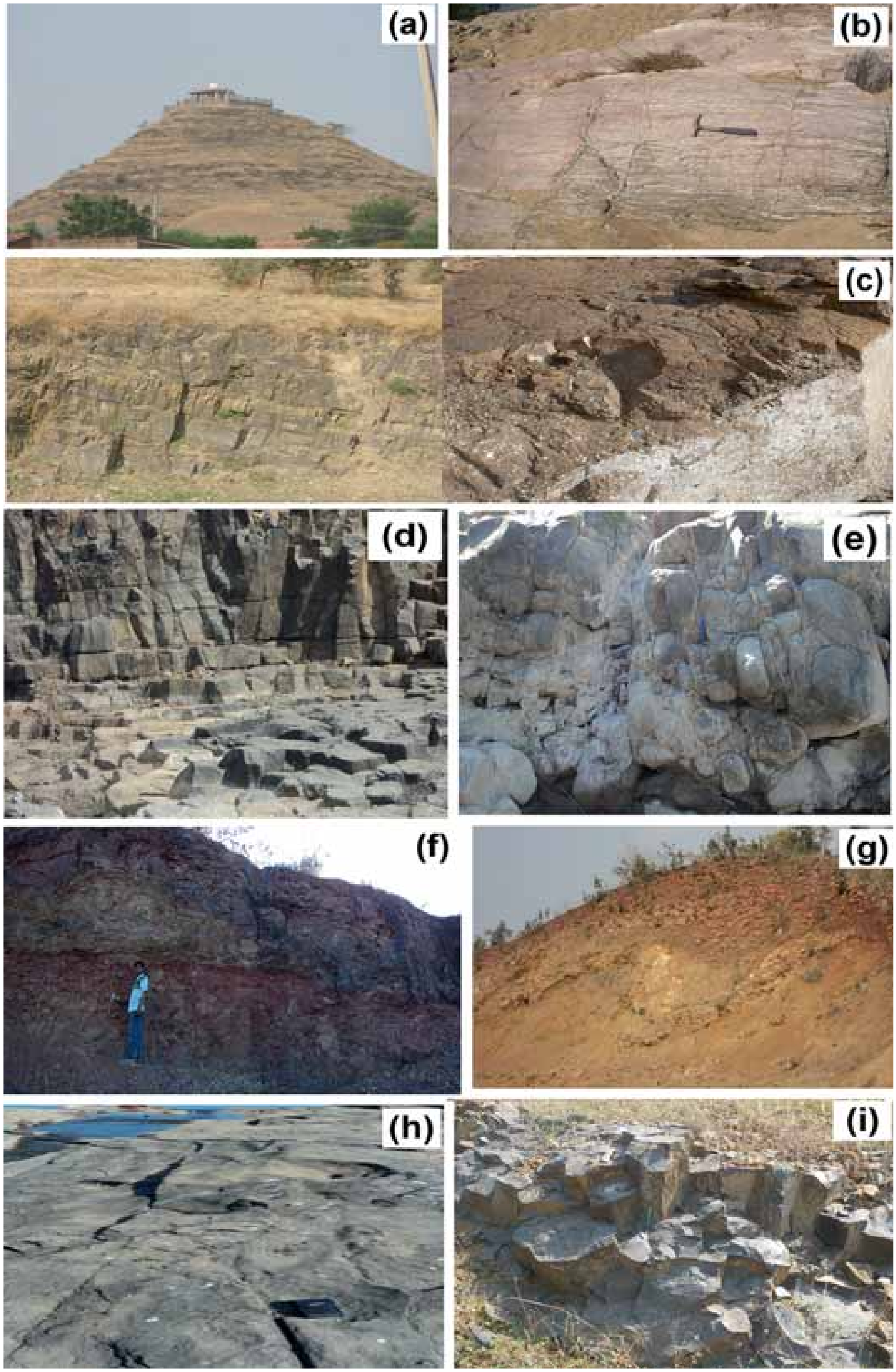

Figure 4. (**a**) Flat topped plateaus and ridges which exhibit small mesas, buttes and mounds in the study region; (**b**) the basement gneisses showing their well-banded nature with abundant pegmatite intrusions; (**c**) basalt flows showing a sub-horizontal flow banding and compact flows showing fractures; (**d**) dark, fine- to medium-grained, porphyritic basalts with horizontal, vertical joints and extensive columnar structures; (**e**) dark grey, fine- to medium-grained compact basalts showing spheroidal weathering; (**f**) well-preserved red bole horizons; (**g**) dyke intrusions with lower flows; the contour pattern has a NE–SW trend; (**h**) grey, fine-grained, compact basalts with major fractures observed along the lineament; and (**i**) fresh and less altered basalts from outcrops.

in the Khirhani hill (figure 4d). Eruption environment and the petrographic textural variations within the columnar structures have been reported from other flood basalt provinces (Philpotts and Dickson 2002).

In addition, the sub-horizontal basalt flows are also characterised by well-preserved spheroidal weathering especially at Mohgaon village (figure 4e). The occurrence of small-scale inflated pahoehoe lava flows, spiracles and lava lobes in the Mandla lobe of the EDVP and their physical characteristics of Mandla lavas indicate lower effusive rates, linked with the low magnitude of eruption, possibly related to its long-distance migration from a common source located in the western Deccan Province as reported by Kashyap *et al.* (2010). At some places, the basalt lava flow sequences are separated by a general red coloured interflow stratum widely known as 'bole bed' or 'red bole' (∼200 m stretch) in Mundapar village (figure 4f). These red boles serve as the marker beds between two basaltic flows. These boles are made up of friable earth clay occurring in a range of colours varying between brown, green, purple and grey, and there are no evidences of organic matter and biogenic remains (Ghosh *et al.* 2006). Their origin was defined by the weathering of the underlying basalt or volcanic ashes/pyroclasts in the time interval for the next pulse of eruption (Wilkins *et al.* 1994). In addition, thin basaltic dykes intrude into the basalt flows at some places in the study area (figure 4g). In the present study, excellent vertical exposure allowed us to collect fresh samples from identifiable flow units in the field. Grey, fine-grained compact basalts with major fractures and vesicular, amygdaloidal, columnar-jointed basalts are noticed near Dhanpuri and Devri villages (figure 4h). Proper care was taken to collect unaltered samples at various locations along the JN, JM and JS traverses. The location of each sample was recorded employing topographic maps and GPS. Most of the sampling in the present study was carried out along road cuttings and exposed quarries. Both phyric and aphyric basalts are characterised in the study areas of the Mandla region (figure 4a–h).

Basement rocks to these Deccan basalt lavas are represented by Tirodi biotite gneisses, quartzite, quartz–mica schists and crystalline limestones in the south-eastern parts, whereas in the remaining parts were covered by Deccan traps with sporadic lameta, intertrappean beds, laterite cappings and Mesoproterozoic to recent alluvium. The Tirodi biotite gneisses are well banded (figure 4b) and towards the south of Seoni where cliffs of gneisses and other schistose metamorphics dominated. Numerous representative fresh rock samples of the basement gneisses and basalts were identified from the available quarry sections and outcrops (figure 4b–i).

4. Study of lineaments

Lineaments are defined as straight linear elements visible at the Earth's surface and which are the representation of some geological or geomorphological phenomena. Bedrock faults and joints, linear sand dunes, and drumlins are such examples. Some lineament types are arranged typically as parallel or near-parallel sets rather than just as isolated forms (Clark and Wilson 1994). Linear surface features may include valleys, ridges, boundaries of elevated areas, rivers, coastlines, boundary lines of rock formations and fracture zones (Hobbs 1904; Bakliwal *et al.* 1983; Bakliwal and Ramasamy 1983a, b). Linear features on the Earth's surface have been a theme of study for geologists for many years (Hobbs 1904, 1912). From the beginning, geologists realised that linear features are the result of zones of weakness or structural displacement in the crust.

A lineament is a linear feature in a landscape which is an expression of an underlying geological structure such as a fault. Typically, a lineament will comprise a fault-aligned valley, a series of fold-aligned hills, a straight coastline or indeed a combination of these features. Fracture zones, shear zones and igneous intrusions such as dykes can also manifest as lineaments. The identification of lineaments is conditioned by the outcrop situation of the study area like the presence of dense vegetation, alluvial deposits and recent volcanic ashes. Human landscape transformation may prevent the identification of lineaments. They may be an expression of a fault or other line weakness.

The continuous subsurface fracture planes that extend over large distances and intersect the land surface produce linear traces (lineaments). The surface features making up a lineament may be geomorphological, i.e., caused by relief or tone, such as caused by contrast differences. Straight stream valleys and aligned segments of a valley are typical geomorphological expressions of lineaments. A tonal lineament may be a straight boundary between areas of contrasting tones. Differences in vegetation, moisture content, and soil or rock composition account for the most tonal contrast (O'Leary *et al.* 1976). In general, linear features are formed by edges, which are marked by subtle brightness differences in the image and may be difficult to recognise. The old age of many geological lineaments means that younger sediments commonly cover them. When reactivation of these structures occurs, these results in arrays of brittle structures are exposed on the surface topography. Similarly, the surface expression of a deep-seated lineament may be manifested as a broad zone of discrete lineaments (Richards 2000). In order to map structurally significant lineaments (Misra *et al.* 2014; Babar *et al.* 2017; Kaplay *et al.* 2017a, b), it is necessary first, by careful and critical analysis of the image, to identify and screen features not caused by faulting (Sabins 1997; Dasgupta and Mukherjee 2017, submitted). Lineament identification via remote sensing data is achieved by using two principal techniques. First, lineament data can be visually enhanced using image enhancement techniques (image ration, image fusion, directional edge-detection filters) and a lineament vector map can be produced using manual digitising techniques (Ray *et al.* 1980; Arlegui and Soriano 1998; Suzen and Toprak 1998). Second, a lineament map may be produced using computer software and algorithms (Burdick and Speirer 1980; Karnieli *et al.* 1996; Baumgartner *et al.* 1999; Hung *et al.* 2002; Hung and Batelaan 2003; Kim *et al.* 2004).

Lineaments are often apparent in geological or topographic maps and can appear obvious on aerial or satellite photographs. One common application of lineaments interpreted from satellite images is to reveal dominant azimuth sets whose orientations give an idea of the regional fracture pattern of an area (Heman 1961; Koike *et al.* 1998; Casas *et al.* 2000; McElfresh *et al.* 2002). A linear feature in general can show up in an aerial photo or space image as a discontinuity that is either darker (lighter in the image) in the middle and lighter (darker in the images) on both sides to verify the geological meaning of more certain lineaments. This study tested the multi-coverage geological interpretation of satellite imagery in an area of differentiated geological structures and morphologies (Pawel and Wojciech 1999). With the above background information in mind, the study area in the Mandla region was identified for the lineament analysis using satellite images.

For the delineation of structural lineaments of the study region, a linear imaging self-scanning sensor IV (LISS-IV) satellite image was used (figure 5). The satellite image was processed and analysed using ENVI software and a total of 65 prominent lineaments were identified and a seismotectonic map (figure 6) of the study area was generated. The length and trend of lineaments recognised are represented in table 3. ENVI software allows to display, process and enhance, viz., define settings and options, perform contrast adjustments, modify image geometry, perform spatial enhancements, spectral analysis, training sets, classification (supervised and unsupervised) and post-processing of raw data stored in several file formats and output raster data for various applications. There are eight characteristic image elements that aid image interpretation. They are tone/colour, texture, pattern, shape, size, shadows, site and association.

4.1 *Tone/colour*

Tone/colour is the fundamental property of an image directly related to the reflectance of light from terrain features. It refers to relative shades of grey on B/W images or colours on false colour composite images. Tonal variation is generally the most readily observable reflection of some variations in the scene. The image is varied in tone; distinct and extensive regions, both dark and light, can be seen. Marked variations of this order connote major lithological units/assemblages observable at the surface in the region. Four broad tonal units can be recognised: red (vegetation), blue to black (water bodies), dark green (schists/Deccan traps) and light green speckled with dark green and/or white (younger granites/biotite granite/pink and grey granites/peninsular gneisses/migmatites).

4.2 *Texture of remote sensing image analysis*

The texture of an image refers to the frequency of tonal changes and tonal arrangement (Lillesand *et al.* 2004) in the image and its analysis is used for the preliminary classification of terrain (Haralick 1979; Jensen 1986). The texture of remote sensing image analysis is produced by an aggregate of unit features, which may be too small to be clearly discerned individually on the image and is a product of their individual shape, size, pattern, shadow and tone.

4.3 *Spatial arrangement/pattern*

The spatial arrangement of the objects in a scene forms the pattern. The repetition of certain general forms or relationships is characteristic of many

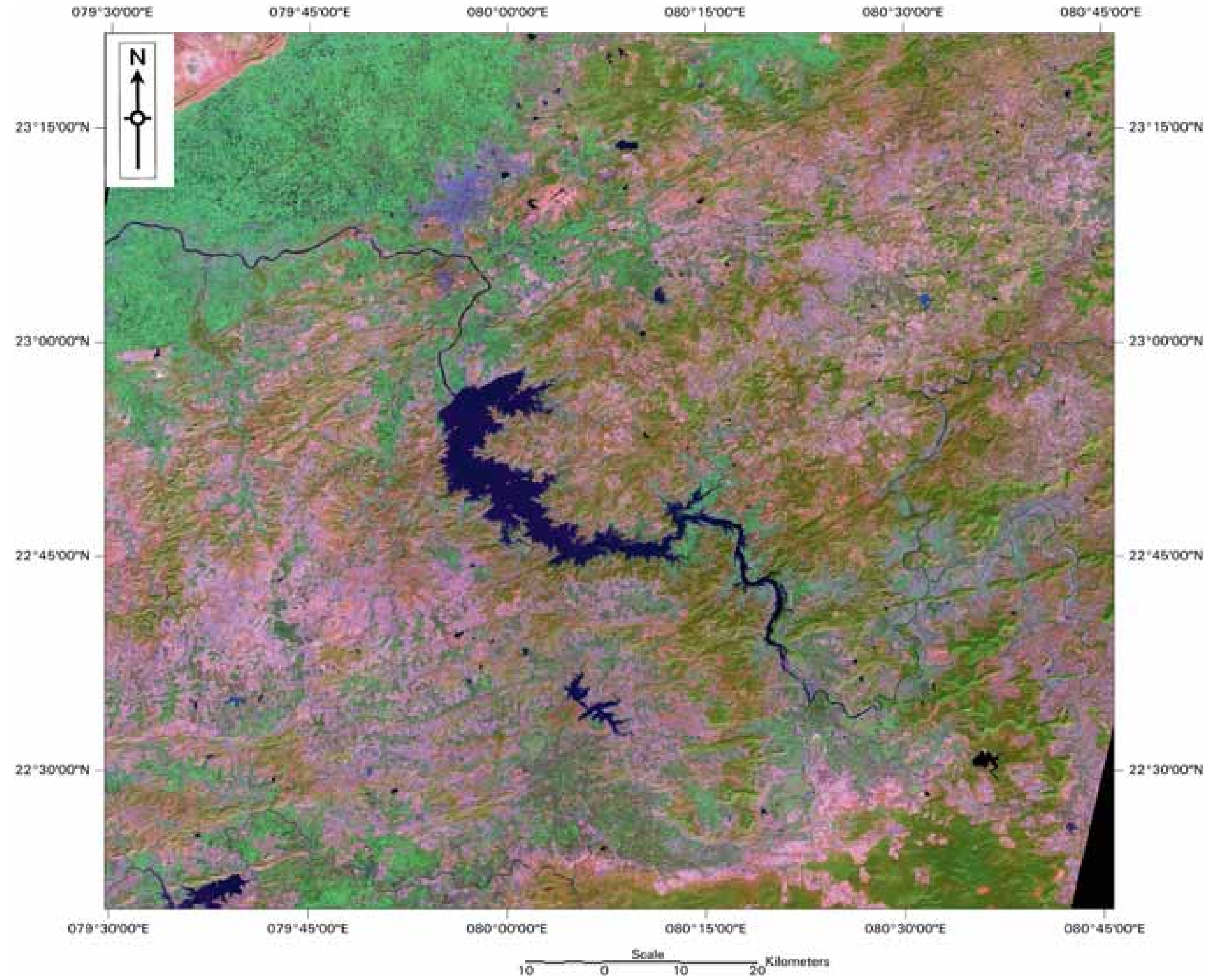

Figure 5. Satellite image (LISS-IV) of the study area.

objects, both natural and man-made and gives objects a pattern which aids the image interpreter in recognising them (Jensen 1986). The dendritic pattern of a river is possible which can contribute to form the shape of a vegetation area. Roads radiating from various villages and towns result in a distinct pattern for identification.

4.4 *Shape, size, shadows, site and association*

In addition to the above, other recognition elements like shape, size, shadows, site and association were also used in image interpretation. While shape and size elements were used to recognise geomorphic features such as the drainage, shadows were used for topographic analysis. Lastly, the location (site) of objects in relation (association) to other features is very useful for identification. For example, alluvial deposits are associated with major drainage features (narrow white regions along the river) and settlements with road junctions, etc.

5. Historical seismicity along the lineaments in the study region

The following are the active lineaments identified based on the available literature and field geological and geophysical studies within the study areas.

5.1 *Narmada south fault (L1a and L1b)*

The activation of the Narmada south fault caused the devastating Jabalpur earthquake (6.0 M) on 22 May 1997. The raised/dissected Quaternary alluvial pile along the southern fringe of the Narmada valley indicates its neotectonics. The ENE–WSW trending Narmada–Son Lineament (NSL)

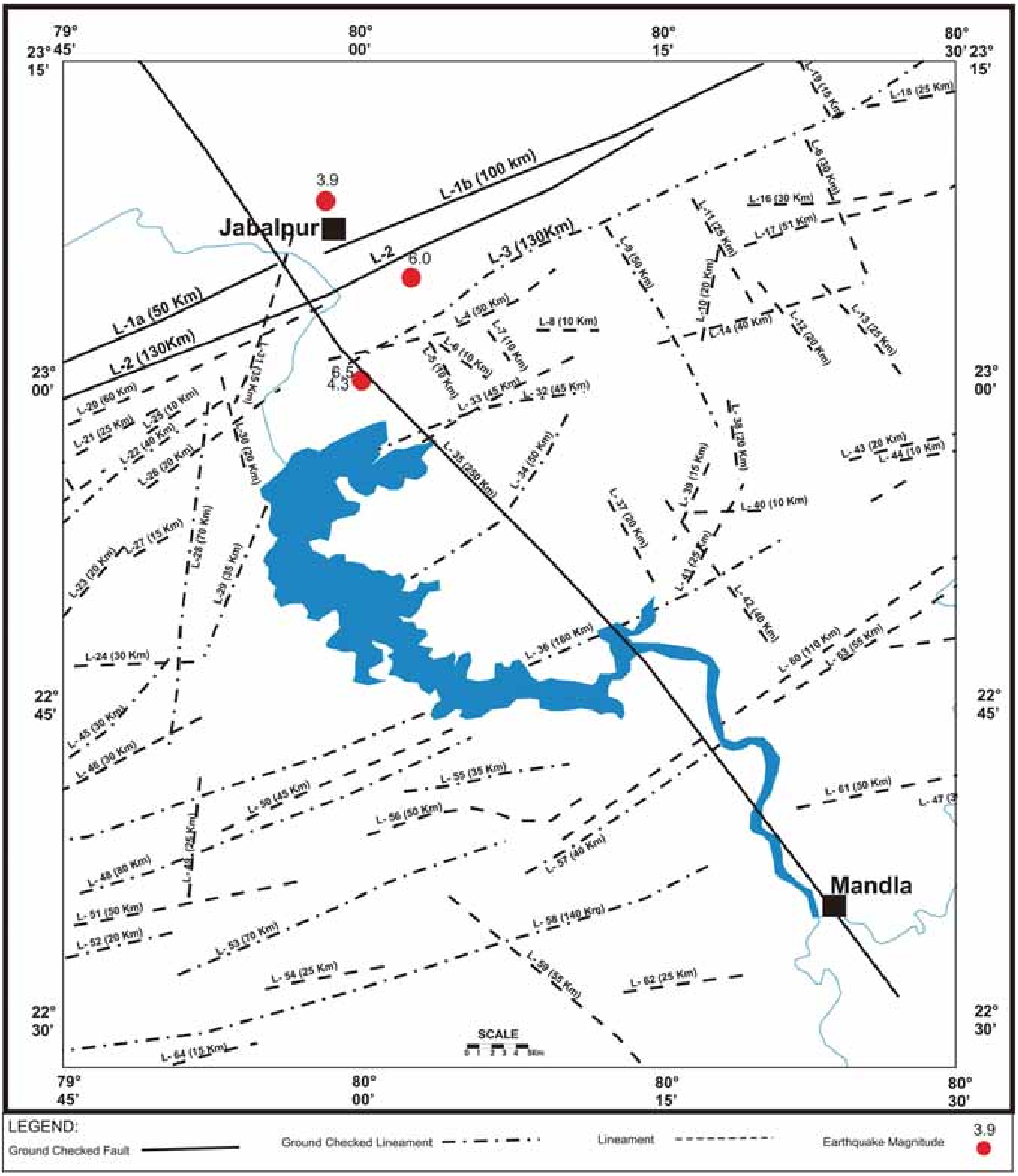

Figure 6. Seismotectonic map of the study area.

in Central India is a spectacular lineament zone about 1600 km long and 150–200 km wide, which is traceable across the Indian Peninsula between latitudes 21.5°N and 24°N and longitudes 70°E and 88°E and may further extend in either direction (Ravishankar 1991). The lineament has a Precambrian ancestry and may possibly be limited to the development of the Vindhyan basin to its north and the Gondwana basin to its south (West 1962). It has been considered as an ancient rift or active fault zone and is a zone of crustal upwarping through which lava intruded (Auden 1949).

Table 3. *The length and orientation of lineaments recognized in the study area.*

Lineament no.	Length (km)	Orientation	Reference	Lineament no.	Length (km)	Orientation	Reference	Lineament no.	Length (km)	Orientation	Reference
1a	50	66°	SEISAT 2000	22	40	50°	LISS-IV image	44	10	78°	LISS-IV image
1b	100	66°	SEISAT 2000	23	20	43°	LISS-IV image	45	30	43°	LISS-IV image
2	130	66°	SEISAT 2000	24	30	88°	LISS-IV image	46	30	51°	LISS-IV image
3	130	65°	LISS-IV image	25	10	51°	LISS-IV image	47	160	71°	SEISAT 2000
4	50	64°	LISS-IV image	26	20	50°	LISS-IV image	48	80	69°	LISS-IV image
5	10	327°	LISS-IV image	27	15	59°	LISS-IV image	49	25	4°	LISS-IV image
6	10	305°	LISS-IV image	28	70	5°	LISS-IV image	50	45	64°	LISS-IV image
7	10	326°	LISS-IV image	29	35	23°	LISS-IV image	51	50	80°	LISS-IV image
8	10	92°	LISS-IV image	30	20	346°	LISS-IV image	52	20	77°	LISS-IV image
9	50	330°	LISS-IV image	31	35	16°	LISS-IV image	53	70	67°	LISS-IV image
10	20	8°	LISS-IV image	32	45	81°	LISS-IV image	54	25	79°	LISS-IV image
11	25	329°	LISS-IV image	33	35	58°	LISS-IV image	55	35	81°	LISS-IV image
12	20	338°	LISS-IV image	34	50	45°	LISS-IV image	56	50	76°	LISS-IV image
13	25	316°	LISS-IV image	35	250	316°	LISS-IV image	57	40	54°	LISS-IV image
14	40	71°	LISS-IV image	36	160	62°	LISS-IV image	58	140	69°	LISS-IV image
15	30	333°	LISS-IV image	37	20	333°	LISS-IV image	59	55	310°	LISS-IV image
16	30	87°	LISS-IV image	38	20	351°	LISS-IV image	60	110	53°	LISS-IV image
17	50	71°	LISS-IV image	39	15	20°	LISS-IV image	61	50	76°	LISS-IV image
18	25	79°	LISS-IV image	40	10	90°	LISS-IV image	62	25	81°	LISS-IV image
19	15	325°	LISS-IV image	41	25	26°	LISS-IV image	63	55	54°	LISS-IV image
20	60	65°	LISS-IV image	42	40	328°	LISS-IV image	64	15	77°	LISS-IV image
21	25	55°	LISS-IV image	43	20	76°	LISS-IV image				

5.2 *ENE–WSW SEISAT fault (L2)*

The ENE–WSW trending fault is one of the sympathetic faults of the Narmada fault system. It is developed on the southern part of the Jabalpur area. Major seismic events (>5 M) were noticed along this fault during the last two decades indicating its neotectonic activity (Dasgupta *et al.* 2000). The associated seismic events along this fault confirmed that it is a neotectonically active fault.

5.3 *Jabalpur–Mandla fault (L35)*

This fault is located between Jabalpur and Mandla cities. About 80 km length of NW–SE trending Jabalpur–Mandla fault cuts across the Narmada south fault near the Jabalpur area. From the United States Geological Survey (USGS) earthquake catalogue, it is observed that two major earthquake events with M4.3 in 1903 and M6.5 in 1846 were associated with this fault (Dasgupta *et al.* 2000). A few hot springs located to the north of Mandla indicate the surface expression of this fault. Seismicity associated with this fault has remained indeterminate. However, as per the Seismotectonic Atlas (SEISAT) 2000 map, it is found in the range of 5.0–5.9 M during 1901–1963 along this fault confirming its active nature (Dasgupta *et al.* 2000).

6. Conclusions

The following are the salient results obtained from the geological and lineament studies in the study area.

- The field geological studies reveal massive columnar joints in the Khirhani area, fine-grained aphyric flows with dark coloured boulder formed near Kuduvan village, fine-grained dolerite dyke near Mandla, red bole horizon at the Mundapar area, vesicular and amygdaloidal basalt with zeolite, quartz, etc. at Pindari village which may represent different flows in the Mandla region of EDVP.
- Sixty-five prominent lineaments have been identified on the basis of satellite imageries and integrated field geological studies along the Jabalpur–Niwas (JN), Jabalpur–Seoni (JS) and Jabalpur–Mandla (JM) traverses.
- Fifty-seven lineaments have been classified as minor (<100 km), eight lineaments as intermediate (300–100 km) and no major (>300 km) lineaments are acknowledged.
- Seismicity along three lineaments (Narmada South fault, ENE–WSW SEISAT fault and the Jabalpur–Mandla fault) ranging from 3.9 to 6.5 M are accredited.

Acknowledgements

The authors would like to express their sincere thanks to Dr V M Tiwari, director, CSIR–NGRI, for his permission to submit this paper. The authors wish to thank Dr H V S Satyanarayana, project leader, Dr R K Tiwari, chief scientist (retd.) and Dr T Seshunarayana, chief scientist (retd.) for the encouragement and support during this research work. The authors also wish to thank the entire Engineering Geophysics group members of CSIR–NGRI for their help during field geological studies.

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