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Depositional environment of Himmatnagar Sandstone (Lower/Middle Cretaceous): a perspective

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ABSTRACT

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Himmatnagar Sandstone (lower to middle Cretaceous) is exposed in between Sabarmati River in the west to Vantada in the east around Himmatnagar Town in north Gujarat, India. The sequence is divisible in two members: The lower member is 65 m thick, mostly massive, horizontally stratified to hummocky stratified with abundant plant and trace fossils in assorted shales and sandstones. The upper member is ~ 12 m thick, cross–stratified and medium to coarse grained–gritty to cobbly in nature. Six lithofacies have been identified in the sequence, viz. 1. grey wacke (GW), 2. silty–shale (SS), 3. cross–stratified sandstone (CS), 4. horizontally stratified sandstone (HSS), and 5. planar cross–stratified sandstone (PCS) in the lower member; and 6. gritty–cobbly cross–stratified sandstone (GCCS) in the upper member.

The lower member consists of plant fossils which are poor to moderately preserved and transported. The silty–shale lithofacies contains plant fossils (*Pagiophyllum, Brachyphyllum, Gleichenia, Araucarites*, circinate vernation of ferns, *Williamsonia* flower, twigs, petrified wood, conifer and its cone, etc.), body fossil (insect wing) and trace fossils (*Skolithos, Monocraterion, Psilonichnus, Thalassinoides, Chondrites, Planolites, Palaeophycus, Calycraterion, Circulichnus, Ophiomorpha, Phoebichnus*, etc.). In the cross–stratified sandstone lithofacies, body fossils (mainly fragmented bivalves, plant fossils (*Weichselia reticulata, Matonidium indicum, Ptilophyllum,* cycadean frond and fossil wood) and trace fossils (*Monocraterion, Chondrites, Calycraterion, Thalassinoides, Psilonichnus* and *Skolithos*) are recognized. On the other hand in horizontally stratified sandstone lithofacies plant fossils (*Sphenopteris, Pagiophyllum, Gleichenia, Elactocladus, Brachyphyllum,* ferns, petrified wood, etc.) and trace fossils (*Skolithos, Ophiomorpha, Psilonichnus, Monocraterion, Arenicolites, Diplocraterion*, *Thalassinoides, Teichichnus, Palaeophycus, Planolites*, etc.) are present. While, large crustacean and vertebrate burrows, *Skolithos, Thalassinoides, Ophiomorpha*, etc are found in planar cross–stratified sandstone lithofacies. The trace fossils belong to *Psilonichnus, Skolithos* and *Cruziana* ichnofacies as per Seilacher (1967). The member also contains wedge shape geometry of beds similar to tidal partings as well as ridge and runnel structures, low–angle to hummocky cross–stratification, herringbone structure and parting lineation. Here, north to northeast palaeo–current direction is indicated by cross–stratification in the member. All these features lead to the depositional environment, which seems to be foreshore–tidal flat to middle shoreface for the lower member of the sequence.

The upper member is composed of trough cross–stratified sandstones showing prominently southwest to south palaeo–current direction with angular to sub–rounded pebbles and cobbles of underlying rocks and fossil wood with lower erosional contact and channel structures at places. Based on above characteristics, depositional environment of upper member can be interpreted from estuarine to fluvial.

Key–words—Himmatnagar Sandstone Formation, Cretaceous, Trace fossils, Lithofacies, Ichnofacies, Sedimentary structures.

हिम्मतनगर बलुआपत्थरों (निम्न/मध्य चाकमय) का निक्षेपणीय पर्यावरण : परिदृश्य

निशीत वाई. भट्ट, पारस एम. सोलंकी, नीरू प्रकाश एवं नीलम दास

सारांश

हिम्मतनगर बलुआपत्थर (निम्न से मध्य चाकमय) उत्तर गुजरात, भारत में हिम्मतनगर कस्बे के चारों ओर पूरब में पश्चिम से वंतदा तक साबरमती नदी के बीच में अनावरित हुआ है। अनुक्रम दो घटकों में विभाज्य हैः निम्न घटक 65 मीटर मोटा है, अधिकांशतः स्थूल, प्रचुर पादप एवं मिश्रित शेलों व बलुआपत्थरों में अनुपथ जीवाश्मों सहित क्षैतिज रूप से स्तरित से ककुदी स्तरित। ऊपरी घटक ~ 12 मीटर मोटा है, तिर्यक स्तरित तथा प्रकृति में मध्यम से मोटा दानेदार–शितकणी से गोल। अनुक्रम में छः अश्म संलक्षणियाँ अभिनिर्धारित की गई हैं अर्थात 1 स्लेटी वेक (जी डब्ल्यु), 2 गाद–शेल (एस एस), 3 तिर्यक– स्तरित बलुआपत्थर (सी एस), 4 क्षैतिज रूप से स्तरित बलुआपत्थर (एच एस एस) एवं 5 निचले घटक में समतली तिर्यक स्तरित बलुआपत्थर (पी सी एस); और 6 ऊपरी घटक में शितकणी–गोल तिर्यक स्तरित बलुआपत्थर (जी सी सी एस)।

निचला घटक पादप जीवाश्मों से सन्निहित है जो अल्प से मध्यम परिरक्षित व वाहित हैं। गाद–शेल अश्मसंलक्षणी पादप जीवाश्मों (*पेजियोफायल्लम, ब्रचीफायल्लम, ग्लीचिनिया, एरौकेराइटिस,* पर्णागों के *सिर्सीनेट वर्नेशन, विलियमसोनिया* पुष्प टहनियाँ, अश्मीभूत काष्ठ, शंकुवृक्ष एवं इसके शंकु इत्यादि), काय जीवाश्म (कीट पंख) और अनुपथ जीवाश्म (*मोनोक्रेटेरिअन, प्सिलोनिकस, थलासीनॉइड्स, कॉन्ड्राइट्स, प्लनोलाइट्स, पैलियोफायकस, कैलीक्रेटेरिअन, सर्कुलीचनस, ऑफिओमॉर्फा, फोबिकनस* इत्यादि) सन्निहित है। तिर्यक–स्तरित बलुआपत्थर अश्मसंलक्षणियों में काय जीवाश्म (मुख्यतः खंडज द्विकपाटी), पादप जीवाश्म (*विसेल्लिया रेटिकुलेट, मातोनिडियम इंडिकम, प्टिलोफायल्लम,* साइकैडीय फ्रॉड व जीवाश्म काष्ठ) तथा अनुपथ जीवाश्म (*मोनोक्रेटेरिअन, कॉंड्राइटिस, कैलीक्रेटेरिअन, थलासीनॉइड्स, प्सिलोनीकनस* एवं *स्कोलीथस*) पहचाने गए हैं। दूसरी ओर क्षैतिज रूप से स्तरित बलुआपत्थर अश्मसंलक्षणी में पादप जीवाश्म (*स्फीनोप्टेरिस, पेजियोफायल्लम, ग्लीचिनिया, इलेटोक्लेडस, ब्रचीफायल्लम,* पर्णाग, अश्मीभूत काष्ठ इत्यादि) तथा अनुपथ जीवाश्म (*स्कोलीथॉस, ओफियोमॉर्फा, प्सिलोनिकनस, मोनोक्रेटेरिअन, अरेनी कॉलाइटिस, डिप्लोक्रेटेरिअन, थलासीनॉइड्स, टीचीकनस, पैलियोफायकस, प्लनोलाइटिस* इत्यादि) विद्यमान हैं। जबकि, समतली तिर्यक–स्तरित बलुआपत्थर अश्मसंलक्षणियों में विशाल क्रस्टेशियाई एवं कशेरूकी बिल, *स्कोलीथस, थलासीनॉइड्स, ऑफिओमॉर्फा* इत्यादि पाए गए हैं। सील्चर (1967) के मुताबिक अनुपथ जीवाश्म *प्सिलोनिकनस, स्कोलीथस* एवं *क्रुज़िएना* पदचिह्नसंलक्षणी के हैं। घटक में कटक व नदिका संरचनाओं के साथ–साथ ज्वारीय पृथकन से सदृश संस्तरों के फन्नी आकार ज्यामिति, अल्प–कोंण से ककुदी, तिर्यक स्तरण, हैरिंगबोन संरचना एवं पृथकन संरेखण सन्निहित हैं। यहाँ घटक में तिर्यक स्तरण द्वारा उत्तर से उत्तरपूर्व पुरा–धारा दिशा इंगित की गई है। ये समस्त लक्षाण निक्षेपणीय पर्यावरण की ओर अग्रसर होते हैं जो अनुक्रम के अधो घटक हेतु अग्रतट– ज्वारीय सपाट से मध्य तट मुख प्रतीत होता है।

मूलाधार शैलों के कोणीय से उप–पूर्णन गुटिकाओं व गोलाश्मिकाओं सहित तथा जगहों पर अधो अपरदन संपक्र व वाहिका संरचनाओं सहित जीवाश्म काष्ठ दक्षिण पश्चिम से दक्षिण पुरा–धारा दिशा प्रमुखता से दर्शाते हुए ऊपरी घटक अपकर्ष तिर्यक–स्तरित बलुआपत्थरों से सन्निहित है। उपर्युक्त अभिलक्षाणनों के आधार पर ऊपरी घटक का निक्षेपणीय पर्यावरण ज्वारनदमुखी से नदीय तक व्याख्यायित किया जा सकता है।

सूचक शब्द—हिम्मतनगर बलुआपत्थर शैलसमूह, चाकमय, अनुपथ जीवाश्म, अश्मसंलक्षणी, पदचिह्नसंलक्षणी, अवसादी संरचनाएं।

INTRODUCTION

THE Himmatnagar Town is situated at about 80 km NNE of Ahmedabad on banks of Hathmati River, a tributary of Sabarmati River. The latitudes and longitudes of Himmatnagar Town are 23º36'16" N and 72º57'39" E (Fig. 1). The Mesozoic rocks exposed in the study area range in age from Neocomian to Albian, i.e. early to middle Cretaceous and are overlain by the Deccan Traps. Alluvium of Quaternary age is exposed along low grounds while in river valleys and on gentle hill slopes the hard sedimentary rocks are exposed. The Himmatnagar Sandstone is name given to alternate sequence of conglomerates, sandstones and shales after Himmatnagar Town. The sandstones predominate as the rock type. Limited work has been carried out on this rock, which is classified in to a single unit–Himmatnagar Sandstone Formation. In the southeast part of the study area, the formation is overlain by Deccan Traps. Exposures of the formation cover an area of approximately 700 km^2 mainly in Sabarkantha District of Gujarat State.

Limited work has been carried out by various workers such as Middlemiss (1923), Sahni (1936), Murty (1967), Hardas (1981), Merh (1995), Gombos Jr. *et al.* (1995), Prakash *et al.* (in press), etc. on geology, stratigraphy, granulometry and plant fossils of Himmatnagar sandstones. Most of the workers have not commented on the depositional environment of the formation. Few workers have considered it as fluvial to deltaic in environment of deposition based on grain size analysis, plant fossils and frequent cross–stratification.

Present work is carried out to interpret the environment of deposition of the rocks on the basis of geology, lithology, stratigraphy, bed geometry, sedimentary structures, plant fossils and trace fossils.

GEOLOGICAL SETTINGS

The area under investigation forms part of Himmatnagar Tehsil of Sabarkantha District in north Gujarat which is covered by igneous, metamorphic and sedimentary rocks. The rocks are chiefly granites and gneissose granites of intrusive nature with minor dykes and veins of quartz, pegmatites, intermediate and basic igneous rocks of Precambrian age; quartzites, schists and phyllites of Aravalli and Delhi super–groups; shales, sandstones and conglomerates of Himmatnagar Sandstone Formation, Deccan Trap lava flows of Cretaceous–Tertiary age and soils and alluvium of mainly Holocene age. The rocks of Aravalli and Delhi super–groups are oldest which are highly folded, faulted and intruded by younger intrusive. Himmatnagar Sandstone Formation is mainly horizontal to sub–horizontal and exposed in form of flat topped hillocks on east of Himmatnagar and in stream and river sections on west of Himmatnagar Town below thin alluvium cover.

STRATIGRAPHY

Rocks of Himmatnagar Sandstone Formation of lower and middle Cretaceous age has been deliberated here for its environment of deposition (Fig. 2). The age ranges from Neocomian to Albian as to Middlemiss (1923).

HIMMATNAGAR SANDSTONE FORMATION

The rock formation includes various alternations of silty–shales, dominant sandstones and conglomerates patches. Fossil content (plant fossils) is also abundant in the lower part in sandstones and silty–shales which decreases or altogether absent in the upper gritty and conglomeratic rocks. Trace fossils are present in almost all the rocks of the sequence except few and abundant in the silty–shale–sandstone intercalations. Fossil wood is preserved in various rock types.

Based on field observations, the rocks of Himmatnagar Sandstone Formation are sub–divided in two members based on different parameters such as rock types, sedimentary structures, grain size variation, types of contacts, thickness

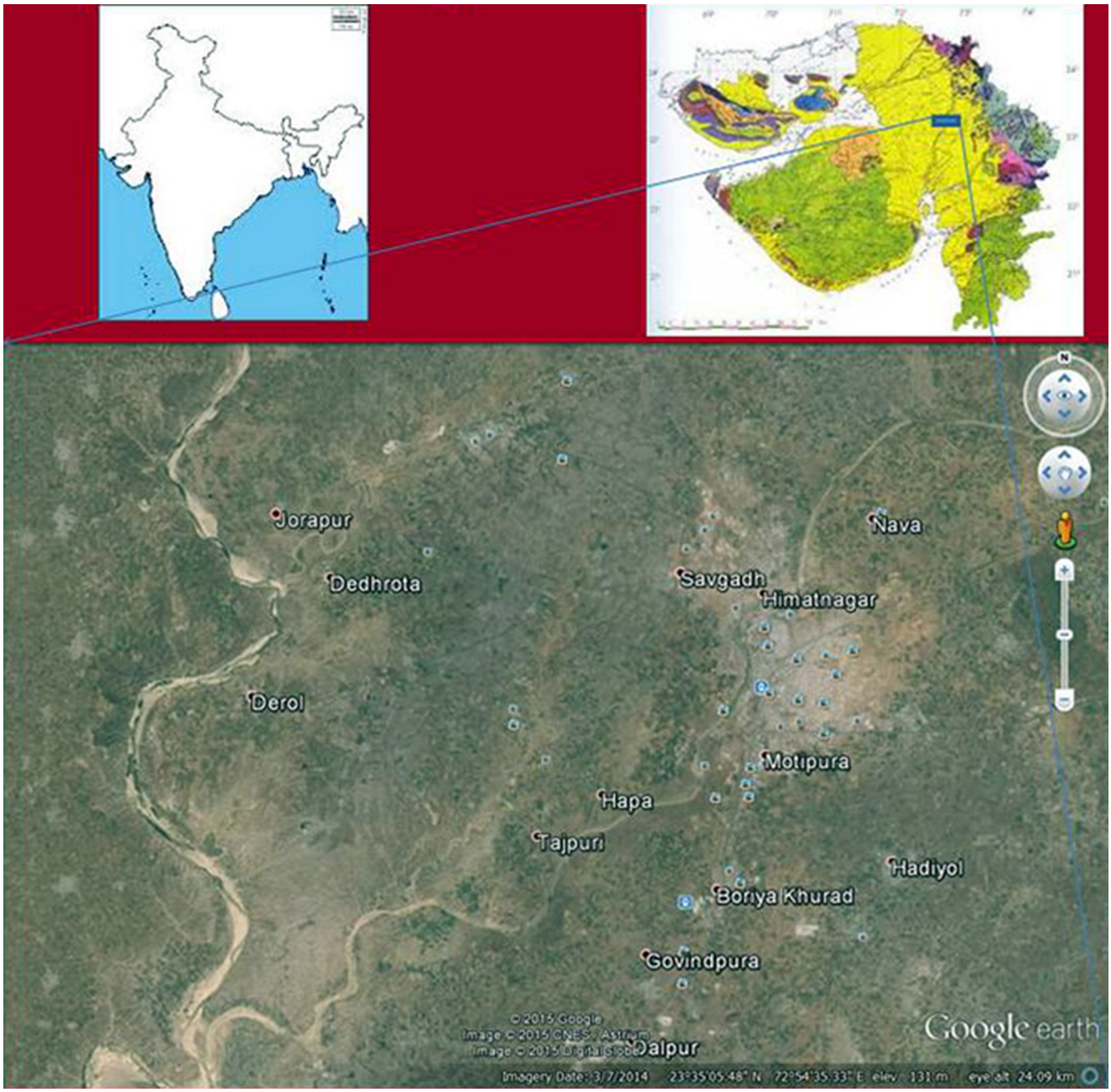

Fig. 1—Location map of the study area (based on Google Earth).

Table 1—Lithostratigraphic classification of Himmatnagar Sandstone Formation.

Formation	Member	Lithology		Thickness	Age
Himmatnagar Sandstone	Upper Member	Gritty–cobbly trough cross–stratified sandstone; coarser fragments are angular, sub–angular to sub–round.		~12 m	Mid–Cretaceous
	Lower Member	Horizontally stratified sandstone Planar cross–stratified sandstone Silty–shale Horizontally stratified sandstone Silty–shale Horizontally stratified sandstone Cross–stratified sandstone Silty–shale grey wacke	04 m 04 m 03 m 04 m 02 m 06 m 12 m 08 m 22 m	65 m	Early Cretaceous

of strata, vertical and lateral extension and presence of body (plant) and trace fossils.

Up till now, Himmatnagar Sandstone Formation is considered as fluvial to deltaic in environment of deposition based on plant fossils, grain size analysis and frequent cross–stratification. Here, we put forward the view of marginal marine to marine environment of deposition for the Lower member of the formation based on sedimentary structures, grain size variation, types of contacts, thickness of strata, vertical and lateral extension and presence of body (plant) and trace fossils. The depositional environment of Upper member is estuarine to fluvial on the basis of trough cross–stratification, channel structures at base, presence of large wood fossils, presence of angular to sub–rounded pebbles to cobbles in gritty sandstones and limited thickness without delta structure.

The members in the study area are described in Table 1.

Thickness of the beds is less towards north and northeast which increases in south and southwest. The formation seems to be continuous with the rocks of Bhuj Formation and Wadhwan groups of the same age, which later on detached due to the rifting along Cambay Basin.

Middlemiss (1923) has provided details of lithological characters of the Himmatnagar sandstones. Plant fossils are common in various horizons of Lower member of these rocks based on which lower Cretaceous age is assigned to the sequence. The Himmatnagar sandstones have yielded a small but interesting flora including *Weichselia* and *Matonidium*–two extinct genera of ferns of considerable stratigraphic value (Merh, 1995). The former is a very characteristic Wealden species. The latter is closely allied to European species. *Matonidium* reached to its apex in lower Cretaceous. Murty (1967) has reported occurrence of cycadean leaf such as *Dictyozamites*; while Sahni (1936) has published on the occurrence of Pteridophytes fern *Matonidium indicum* from the Himmatnagar Sandstone Formation. The Himmatnagar Sandstone Formation is thus considered younger than Dhrangadhra sandstones group; and of the same age as the Wadhwan Sandstone Group of Saurashtra, Songir Sandstone Formation of Vadodara, Bhuj Formation of Kachchh, Nimar Sandstone Formation of the Nimar Valley (M.P.) and the Barmer Sandstone Formation of west Rajasthan.

To the east and north of Himmatnagar, the formation is seen resting over a weathered granite–gneiss basement. To the west, disseminated exposures of the rocks are found along stream valleys up to Sabarmati River. The Himmatnagar sandstones are siliceous to ferruginous in nature with subrounded to rounded sand grains.

Rocks of the formation have been studied in detail at three different localities, viz. (1). In the hills of Berna and Vantada (240 m), respectively 5 km and 12 km east of the Himmatnagar Town. (2). around Himmatnagar Town on both the banks of Hathmati River and their tributaries where, it forms discrete outcrops spread over an area of about 200 km^2. (3). on the banks of Sabarmati River at Aglod and near Sapteshwar, on the western margin of the area investigated. At few exposures of second and third locality, unconformable junction between Lower and Upper members is clearly visible. Palaeosol (Pl. 3.7; 4.5, 15) is also present at the unconformity at Hathmati and Sabarmati River sections. The formation comprises an almost undisturbed–near horizontal sequence.

LOWER MEMBER

Rocks of the Lower member are well exposed in the Vantada (Wantra) hill, Hathmati and Sabarmati River sections. The thickness of the rocks is ~65 m. greywacke is the lowermost unit of this member on weathered granite–gneiss basement of the Precambrian age forming nonconformity.

Thickness of the greywacke is 22 m, which is exposed only at Vantada. The rock is highly friable and chiefly made up of angular, sub–angular to sub–rounded grains of quartz, felspar, hornblende and mica with >15% clay content in which framework grains float. Few pebbly bands are also present. It is followed by white silty–shale at Vantada hill. It is argillaceous rock with few silt and fine sand grains. The

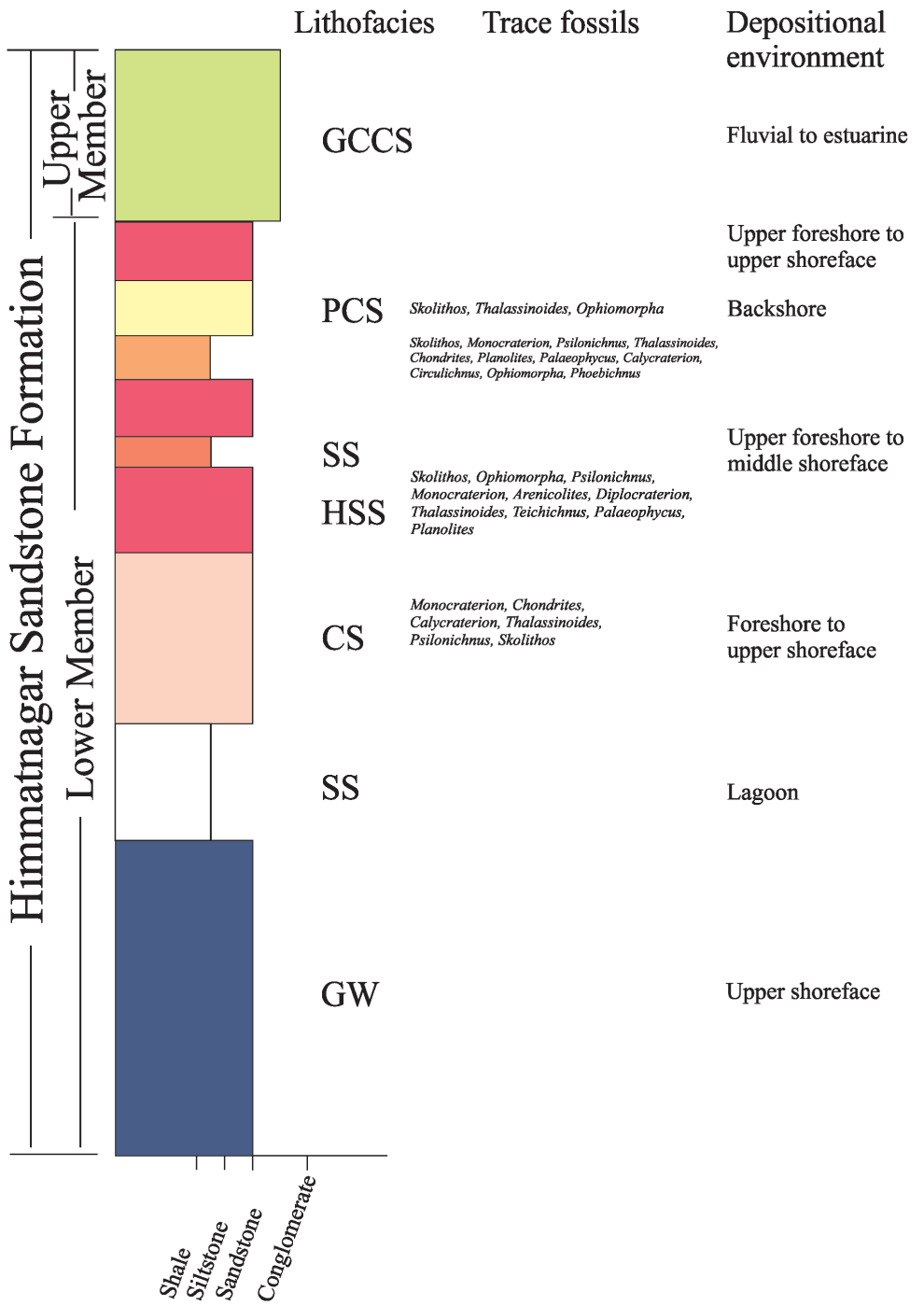

Fig. 2—Composite litholog showing stratigraphic divisions and lithofacies distribution along with trace fossils in various lithofacies and environment of deposition.

rock also contains much plant debris. It is wide lens shape covering east side of Vantada hill extended in north–south direction. Mottled burrows are also present at few places in the rock. The silty–shale is overlain by cross–stratified sandstones which occur only at Vantada hill. Burrows and ferruginous concretions are common in the sandstones. The rocks contain fragmented invertebrate shells in addition to plant fossils near the hill top. The rocks are medium to fine grained with rounded to sub–rounded grains. This sequence is conformably followed by rocks around Himmatnagar on banks of Hathmati River and at Aglod and Sapteshwar on banks of Sabarmati River, represented by alternations of horizontally stratified sandstones, silty–shale and planar cross–stratified sandstone (only at Sapteshwar) are present overlying cross–

stratified sandstone of Vantada hill. The horizontally stratified sandstones in Hathmati and Sabarmati River sections are ferruginous–pink to brown in colour. Framework grains are sub–rounded to rounded. The silty–shales in Hathmati and Sabarmati River sections are pinkish in colour and ferruginous in nature. The silty–shales consist most of the plant remains, which are without root portions and hence transported. The planar cross–stratified sandstone exposed near Sapteshwar on Sabarmati River section, is white to yellowish–white in colour, clay rich, friable in nature with fine, rounded grains.

This member shows development of various sedimentary structures such as wave ripple marks, stratification, lamination, hummocky stratification, planar cross–stratification, trough cross–stratification and herringbone structure. Inverse grading and mud drapes are also present in the horizontally stratified sandstone. The strata commonly show wedge shape geometry. Burrows are also common in horizontally stratified sandstones, silty–shale and planar cross–stratified sandstone. Intertidal ridge–runnel structures are observed with hummocky cross–stratification in cross–stratified sandstone.

Horizontally stratified sandstone is the top most rock of the Lower member in Hathmati and Sabarmati River sections. The rock also shows convolute bedding in Hathmati River section and number of sand/mud volcano structures in Sabarmati River section indicating seismic events. Neptunian dykes (Pl. 4.4), which are narrow at the base, with a height of 3–4 m, width of 20–30 cm and length of several meters and filled passively with yellow calcareous palaeosol (Pl. 4.4), are present in the Hathmati River section. The neptunian dykes may have been developed as a result of formation of fractures in the rocks due to seismic activity.

The rocks contain few body fossils (mainly fragmented bivalves); trace fossils (*Skolithos, Monocraterion, Thalassinoides, Teichichnus, Palaeophycus, Planolites, Psilonichnus, Chondrites, Phoebichnus*, etc.) and plant fossils (*Sphenopteris, Pagiophyllum, Gleichenia, Elactocladus, Brachyphyllum,* ferns, petrified wood, etc.). The Lower member also contains plant fossils, which have already been identified as *Matonidium indicum* and *Weichselia reticulata* (Sahni, 1936). The planar cross–stratified sandstone also contains large scale crustacean and vertebrate burrows.

All these characters of the rock sequences of the Lower member are indicative of marginal marine–backshore–foreshore to shoreface environment of deposition.

UPPER MEMBER

The rocks of Upper member are well exposed in Hathmati River at Himmatnagar and Sabarmati River at Agload and Sapteshwar. The maximum observed thickness of the Upper member is ~12 m. The thickness of this rock is varied at different places. The Upper member comprises of gritty to cobbly sandstone. The rock shows trough cross–stratification and occurs above Lower member forming large scale channel structures. In that way, contact between the two is erosional and unconformable. The sandstones are made up of sub–angular to sub–rounded gritty quartz and feldspar grains with angular to sub–rounded gravels to cobbles of quartz, granite, gneiss, quartzite and pegmatite mainly in the lower part. Few boulders are also visible. On many pebbles/cobbles white siliceous encrustation is present. The cement is siliceous makes the rock much hard and compact. Body fossils are absent but, burrows and fossil wood are present in this rock.

Above characters suggest that the rocks were deposited in fluvial to estuarine environment.

LITHOFACIES

According to Miall (1985), the word facies is used in a descriptive and an interpretive sense and described on an outcrop scale based on textures, sedimentary structures, fossils and lithologic association of sedimentary rock. According to him, descriptive facies include certain observable attributes of sedimentary rock bodies, which can be interpreted in terms of depositional processes. Each lithofacies represents an individual depositional event, which are characteristic of particular depositional environment. These are commonly cyclic and form the basis for defining sedimentation models (Miall, 1985). In the present study an individual lithofacies is considered to be a rock unit defined on the basis of its grain size with texture, physical and biological sedimentary structures and lithological characteristics. Sedimentary facies are bodies of sediment recognizably different from adjacent sediment deposited in a different but adjacent depositional environment. Sedimentary facies reflect depositional environment, each facies being a distinct kind of sediment for that area or environment. Generally, facies are distinguished by aspect of the rock or sediment being studied. Thus, facies based on petrological characters such as grain size, sedimentary structures and mineralogy is called lithofacies. In

PLATE 1 →

Scales: Bar scales: mentioned in the plate; Pen: 15 cm; Hammer: 30 cm; Diary: 22 cm; Chisel: 10 cm; Goggles: 14 cm; Human: ~175 cm; Rs.1 coin: 2.2 cm; Rs.2 coin: 2.6 cm.

Trace fossils (1), (2) and (3) *Calycraterion* in HSS lithofacies at Sapteshwar (1) and Aglod (with *Chondrites*, 2 and 3) respectively; (4) to (7) *Chondrites* in SS lithofacies at Hathmati (4 and 5 with *Skolithos*) and Vantada section (6) and in CS lithofacies at Vantada section (7); (8) *Circulichnus* in SS lithofacies at Hathmati section; (9) *Diplocraterion* in HSS lithofacies at Aglod; (10) *Monocraterion* in SS lithofacies at Hathmati section.

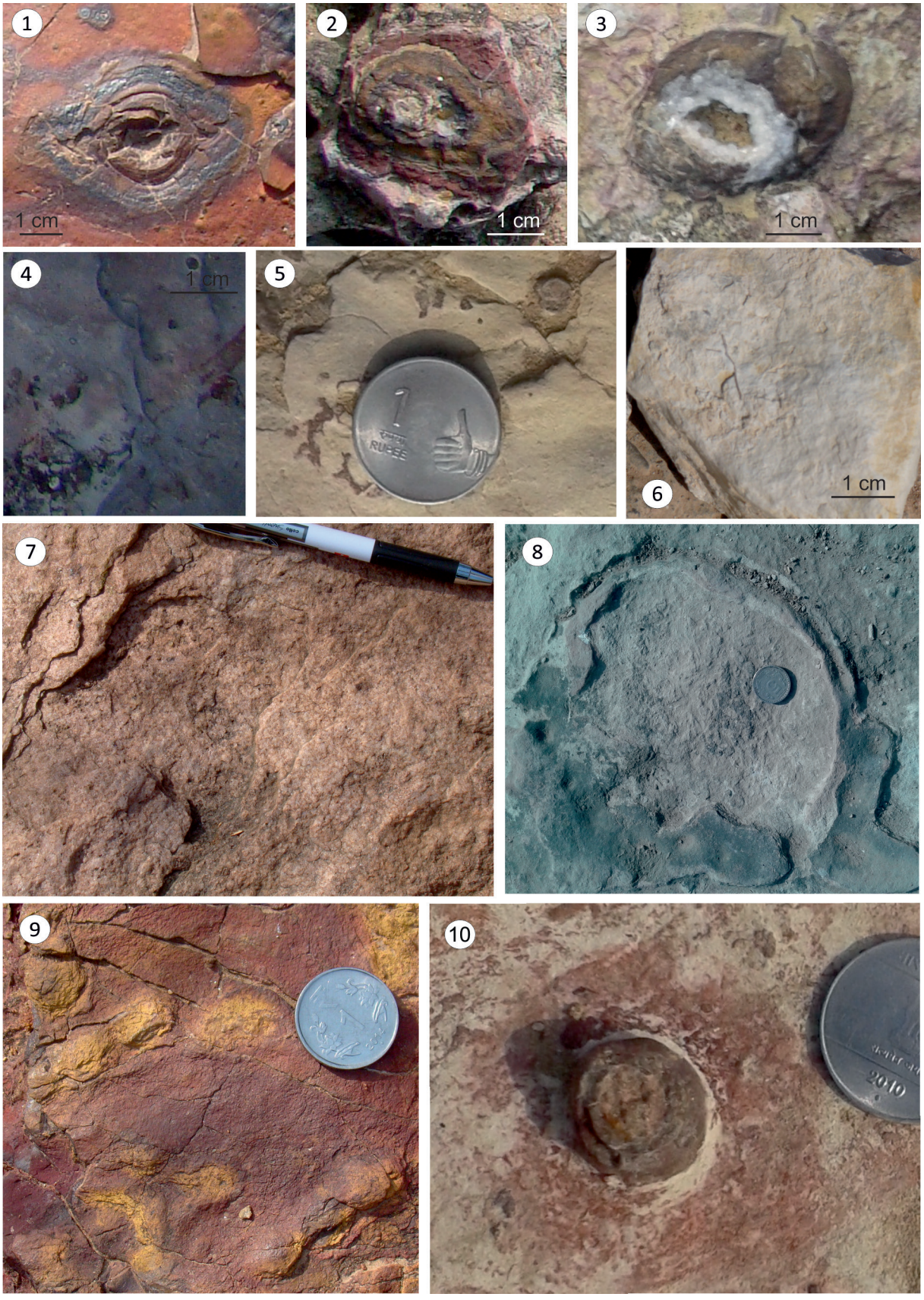

PLATE 1

order to gain detailed facies information, stratigraphic sections were measured at three localities.

The lower Cretaceous (Himmatnagar Sandstone Formation) sequences in the study area consist of six key lithofacies. This discrimination is based on area of occurrence, lithofacies geometry and stratigraphic position, distinctive lithologic features, including composition, grain size, bedding characteristics, lateral and vertical continuity, physical and biogenic sedimentary structure and pattern of vertical sequence.

Following lithofacies (Fig. 2) have been identified in the study area: (1). grey wacke (GW), (2). silty shale (SS), (3). cross–stratified sandstone (CS), (4). horizontally stratified sandstone (HSS), (5). planar cross–stratified sandstone (PCS) and (6). gritty–cobbly cross–stratified sandstone (GCCS).

GREY WACKE (GW) LITHOFACIES

Rock of grey wacke lithofacies is a variety of argillaceous sandstone that is highly indurated and poorly sorted. A good section of the lithofacies is exposed in the hillock located near Vantada Village about 12.5 km east of Himmatnagar Town. It occurs in Lower member of Himmatnagar Sandstone Formation in Vavdi, Vantada (Wantra) hill, Berna hill and adjacent flat toped hills in east of Himmatnagar at the base of the sequence. The lithofacies is 22 m thick at Vantada hill.

It is chiefly made up of angular, sub–angular to sub–round grain of quartz, feldspar, hornblende and mica with much clay content. Few pebbly bands are present. grey wacke is mostly grey, brown, black and greenish black dull coloured arenaceous rock. Few grains are gritty to pebbly. grey wacke is unfossiliferous. No body/trace/plant fossils occur in the lithofacies. Their component particles are usually not much rounded showing less transportation and mostly cement is argillaceous or clayey but the rocks have often been indurated by interstitial silica as cement. Some varieties include feldspathic grey wacke, which is rich in feldspar and lithic grey wacke, which is rich in tiny rock fragments.

The grains are fine to medium sand size with >15% matrix. Framework grains are of quartz, orthoclase, plagioclase, calcite, iron oxides and graphitic carbonaceous matters, together with fragments of granite, gneiss, various schists and quartzite. Few grains of biotite, chlorite, tourmaline, epidote, apatite, garnet, augite and pyrites are also present.

The grey wacke is resting over a weathered, uneven to undulating granite–gneiss forming nonconformity at the base. The exposure of the nonconformity is present around Vantada hill base on all the sides.

A 15 cm thick quartz–conglomerate is present ~2 m above the unconformable contact of the facies. Similar 10–15 cm thick conglomerate (Pl. 4.1) is exposed ~7.5 m above the base. Both are extra–basinal, oligomictic, para–conglomerates indicating some high energy event responsible for their deposition. The matrix of the conglomerate is mainly composed of white micritic mudstones and argillaceous to silty, red, ferruginous pebbly claystone. Clasts of conglomerate are matrix supported–float within the matrix. Para–conglomerates are commonly debris flow deposits. The continuous agitation of the sea floor in the upper shoreface environment results in sediments that are winnowed of the smallest grains, leaving only those grains heavy enough that the water cannot keep them suspended (Dean & Dalrymple, 1991). During fast rate of deposition or during calm conditions of receding tides in a daily cycle or during winter deposition of fine suspended sediment also take place with sand or coarser sediment.

Above characters suggest that the lithofacies has been deposited and preserved in a transgressed sea in the area on much older rocks in upper shoreface environment.

SILTY–SHALE (SS) LITHOFACIES

It occurs in Lower member of Himmatnagar Sandstone Formation in Vantada, Hathmati River near Himmatnagar and Sabarmati River near Sapteshwar. Colour of the rock is white (at Vantada) to pink (at Hathmati and Sabarmati River sections) and grain size is fine, made up of clay with silt and fine sand. The rock is thinly laminated shale with thin (0.5 to 1 cm thick) siltstone intercalations at places.

In Vantada section, the lithofacies is greyish white in colour showing 8 m thickness. It is lens shape and contains numerous fragmentary plant fossils without root portions. In Hathmati River section the facies is represented by pinkish silty–shale having 2–3 m thickness and repeated twice. Parting lineation is observed at one place. Here also, fragmentary plant fossils without root portions and various trace fossils are present. At Sabarmati River section near Sapteshwar, silty–shale lithofacies is 2 m thick and characters are identical to Hathmati River section. No repeatation of the lithofacies is found at Sapteshwar.

PLATE 2

Scales: Bar scales: mentioned in the plate; Pen: 15 cm; Hammer: 30 cm; Diary: 22 cm; Chisel: 10 cm; Goggles: 14 cm; Human: ~175 cm; Rs.1 coin: 2.2 cm; Rs.2 coin: 2.6 cm.

Trace fossils (1) *Arenicolites* and *Skolithos* in HSS lithofacies at Hathmati section; (2) *Planolites*; (3) *Ophiomorpha*; (4) Vertical *Ophiomorpha*; (2 to 4: in SS lithofacies at Hathmati section); (5) *Phoebichnus* in HSS lithofacies at Hathmati section; (6) *Palaeophycus*; (7) *Teichichnus*; (8) *Planolites* (6 to 8: in SS lithofacies at Hathmati section); (9) *Psilonichnus* in CS lithofacies at Vantada section; (10 and 11) *Psilonichnus* (with *Skolithos* in 10) in HSS lithofacies at Hathmati section; (12) *Skolithos* and (13) *Thalassinoides* in HSS lithofacies at Aglod section.

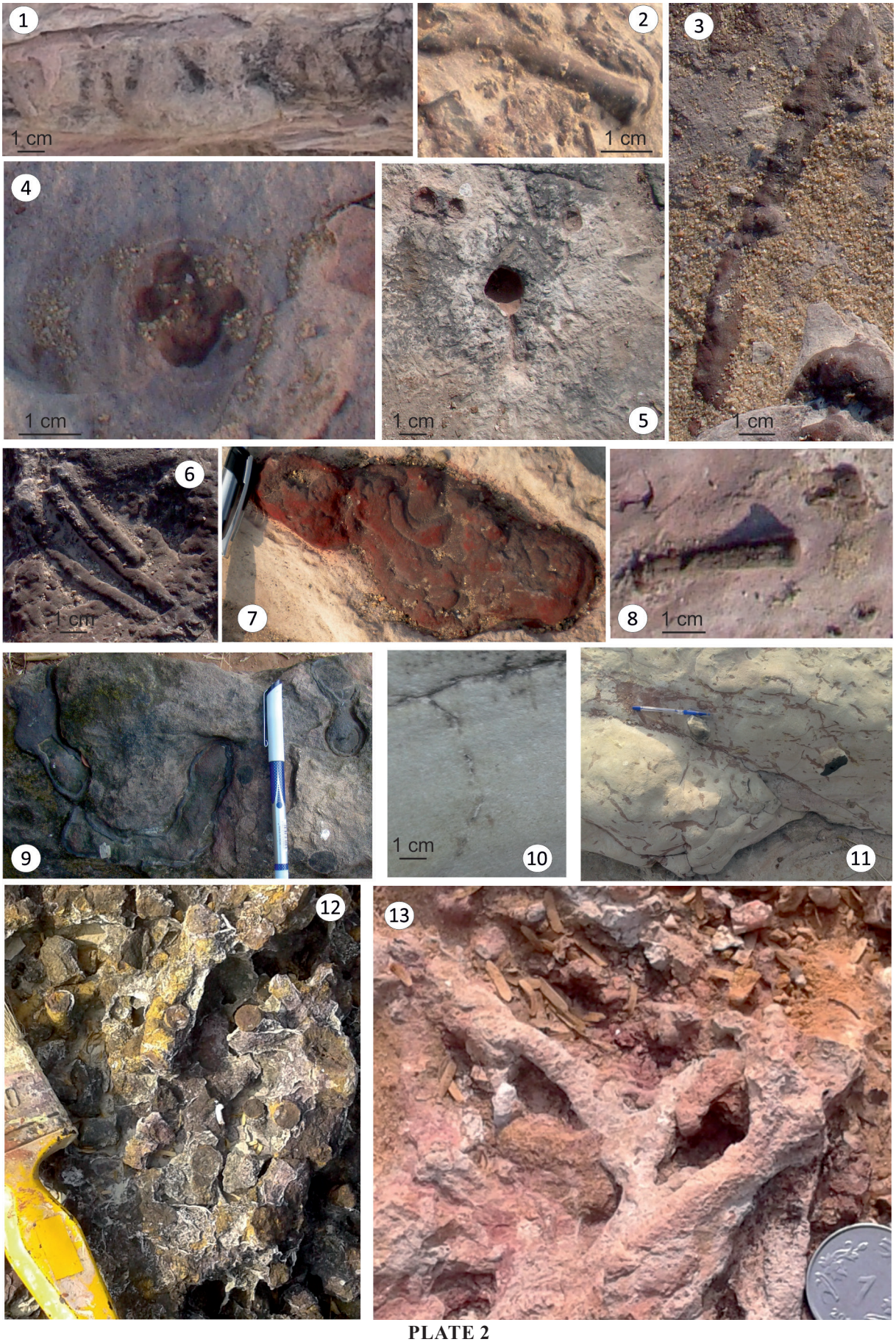

PLATE 2

Silt size particles are chiefly made up of angular to sub–angular quartz grains. Sediments are also showing horizontal lamination (Pl. 3.1) and hummocky stratification (Pl. 3.5, 7).

It contains many plant fossils (*Pagiophyllum, Brachyphyllum, Gleichenia, Araucarites, Circinate vernation* of ferns, *Williamsonia* flower, twigs, petrified wood, conifer and its cone, etc.), body fossil (insect wing; Pl. 4.7) and trace fossils (*Skolithos, Monocraterion, Psilonichnus, Thalassinoides, Chondrites, Planolites, Palaeophycus, Calycraterion, Circulichnus, Ophiomorpha, Phoebichnus*, etc.).

Based on above characters, it can be interpreted that at Vantada, the facies is deposited in marginal marine lagoon environment. While trace fossils and sedimentary structures indicate that the lithofacies at Hathmati and Sabarmati River sections must be deposited in tidal flat (foreshore) to middle shoreface environment.

CROSS–STRATIFIED SANDSTONE (CS) LITHOFACIES

It contains cross–stratified sandstone of Lower member and present in Vavdi, Vantada, Berna and adjacent hills on top part. This lithofacies consists of 30 cm to 1 m thick wedge shape cross–stratified tidal bundles. Total thickness of the lithofacies is ~12 m. Wedge shape geometry (Pl. 3.3), inverse grading, planar cross–stratification and wave ripples are common. Other structures include hummocky cross–stratification, tidal bundles, herringbone structure (Pl. 3.4), ridge–runnel structure, etc. Intertidal ridge–runnel structure (Pl. 3.2) is visible on Vantada hill top. Small scale ripple cross–lamination is visible along larger fore–set cross–stratified beds. The lithofacies is chiefly composed of fine to very fine sand and at few places it shows fine lamination.

The sandstone is grey (siliceous), purple to red (ferruginous) in colour; hard, compact and cherty in character and arenaceous varies from sand grained to gritty on top of the cross–stratified beds. In the lithofacies sub–angular to sub–rounded, moderate to poorly sorted, fine to medium grains of quartz, feldspar, muscovite flakes and opaque grains are recognized. The cement is mainly siliceous and at few place ferruginous. Over growth coating of very fine radiating quartz crystals is common on framework grains.

Herringbone structure in the lithofacies indicates tidal action of intertidal (foreshore) environment. Planar cross–stratification is typically developed by sheet flows. Wedge shape geometry of the rocks is characteristic of tidal bundles. Inverse grading is also typically developed only in foreshore environment. Wave ripple marks indicate high energy storm or tsunami event in marine to marginal marine environment above the wave base. Hummocky stratification is found in high energy condition of foreshore to upper shoreface environment due to deposition on swells and troughs. Ridge–runnel structure is a characteristic of foreshore environment. Much sorting is depicted by the grain size of the rocks.

Few body fossils (mainly fragmented bivalves; Pl. 4.2, 3), plant fossils (*Weichselia reticulata, Matonidium indicum, Ptilophyllum,* cycadean frond and fossil wood) and trace fossils (*Monocraterion, Chondrites, Calycraterion, Thalassinoides, Psilonichnus* and *Skolithos*) are recognized in the lithofacies.

All the above characteristics are indicating foreshore to upper shoreface environment of deposition for the lithofacies.

HORIZONTALLY STRATIFIED SANDSTONE (HSS) LITHOFACIES

Horizontally stratified sandstone lithofacies is present in Lower member at Hathmati River near Himmatnagar and Sabarmati River near Sapteshwar and Aglod. The cumulative thickness of HSS lithofacies at Sabarmati River section near Sapteshwar is ~14 m, where it repeats three times; while, same at Hathmati River section near Himmatnagar is ~10 m, where it repeats two times, and at Aglod it is ~8 m and occurs once only. It is characterized by horizontal stratification and lamination. Hummocky stratification, inverse grading and mud drapes (Pl. 3.6) are also common sedimentary structure found in the facies. Hummocky stratification (Pl. 3.7) is present on top at Hathmati section near Himmatnagar and at Sapteshwar on Sabarmati River. Parting lineation (Pl. 3.8) is also visible at Sapteshwar section.

The sandstones of the lithofacies are also ferruginous to cherty, pink, purple, red (ferruginous) and grey (siliceous) in colour, mostly fine grained to coarse gritty at few places. Grains are chiefly sub–rounded to well rounded.

The lithofacies also shows convolute bedding (Pl. 4.8–11) in Hathmati River section near Himmatnagar and

PLATE 3

Scales: Bar scales: mentioned in the plate; Pen: 15 cm; Hammer: 30 cm; Diary: 22 cm; Chisel: 10 cm; Goggles: 14 cm; Human: ~175 cm; Rs.1 coin: 2.2 cm; Rs.2 coin: 2.6 cm.

Sedimentary structures: (1) Lamination in SS lithofacies at Hathmati section; (2) Ridge–runnel structure in CS lithofacies at Vantada section; (3) Wedge shape geometry and wave ripples in vertical section in CS lithofacies at Vantada section; (4) Herringbone structure in CS lithofacies at Vantada section; (5) Hummocky stratification in SS and HSS lithofacies at Hathmati section; (6) Inverse grading, mud drapes and hummocky stratification in HSS lithofacies at Hathmati section; (7) Palaeosol at disconformity, channel structure and hummocky stratification in GCCS, SS and HSS lithofacies at Hathmati section; (8) Parting lineation in HSS lithofacies at Sapteshwar section; (9) Graded bedding and fine sandstone lens in GCCS lithofacies at Hathmati section.

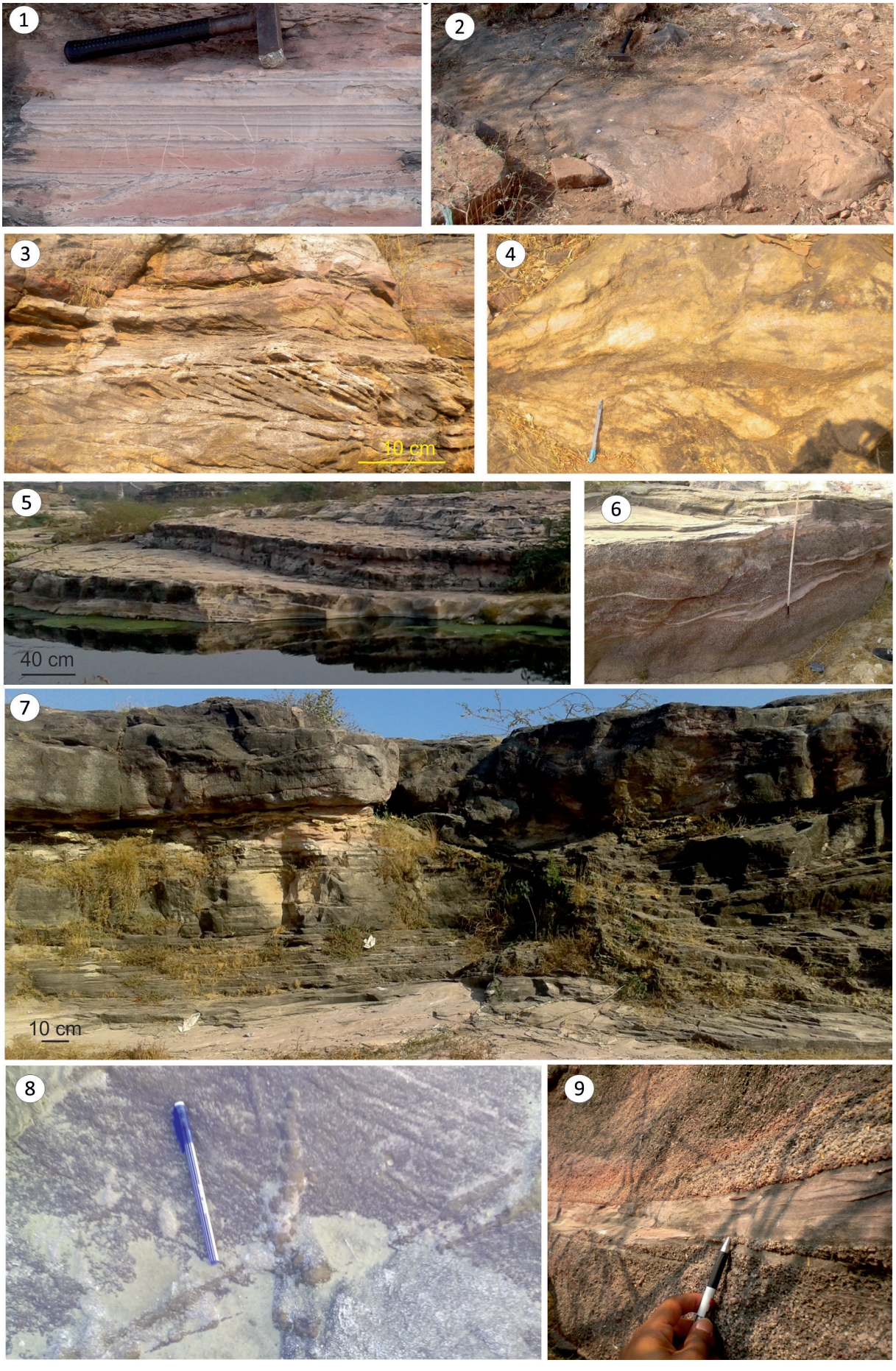

PLATE 3

Sabarmati River sections near Sapteshwar; and sand/mud volcanic structures in Sabarmati River sections near Aglod and Sapteshwar suggesting seismic activity at the time of deposition. At Sabarmati River section near Aglod, red, ferruginous, sandstone is present with dominance of trace fossils and plant fossils in the lithofacies. Entire section is covered by sand\mud volcanic structures. Diameter of volcanic craters is 1 to 3 m. Here, iron leaching is a common feature at the time of mud oozing which gives ferruginous nature to the rocks of the lithofacies. At places mud cracks, gas escape structures, heat front structure and bulbous heat swelling structures are present indicating sub–aerial exposure and hot nature of oozed material from the sedimentary volcano. The generation of sedimentary volcanoes indicates earthquake activities at the time of deposition. Sabarmati River section near Sapteshwar is similar to Aglod for HSS lithofacies, but size of mud volcanic plug is ~15 to 20 m in diameter suggesting intensity of seismic activity and nearness of epi–centre. Many small (up to 1 m diameter) parasitic cones (apophyses) are present around and adjacent to the larger structure.

The lithofacies contains silicified to ferruginised plant trunks and fossil woods. White, light, brittle matter (may be ash material of charred wood) filling voids is often noticed within the woody structure in the purple colour sandstone.

Plant fossils (*Weichselia reticulata, Matonidium indicum*, *Sphenopteris, Pagiophyllum, Gleichenia, Elactocladus, Brachyphyllum,* ferns, Cycadean frond, petrified wood, etc.) and trace fossils (*Skolithos, Ophiomorpha, Psilonichnus, Monocraterion, Arenicolites, Diplocraterion*, *Thalassinoides, Teichichnus, Palaeophycus, Planolites*, etc.) are commonly present in the lithofacies.

It is topmost lithofacies of Lower member, which occurs below unconformity with Upper member (represented by gritty–cobbly cross–stratified sandstone lithofacies).

Above characters (horizontal stratification/lamination, hummocky stratification, inverse grading and mud drapes and trace fossils) of the lithofacies are suggestive of environment of deposition, which must be upper foreshore to upper shoreface.

PLANAR CROSS–STRATIFIED SANDSTONE (PCS) LITHOFACIES

Planar cross–stratified sandstone (PCS) lithofacies (Pl. 4.6) is present at Sabarmati River section near Sapteshwar in Lower member of Himmatnagar Sandstone Formation. The rocks of the lithofacies are dirty white in colour, 4 m thick with large scale planar cross–stratified sandstone. The lithofacies is soft and friable in nature containing sub–rounded to well–rounded fine sand grains of mostly quartz. Cement is clayey.

Large size crustacean and vertebrate burrows range in 1 to 3 m in length and 20 to 30 cm in diameter are commonly present in the lithofacies with other trace fossils like *Skolithos, Thalassinoides, Ophiomorpha*, etc.

From the large scale planar cross–stratification, fine rounded quartz grains, friable nature and trace fossils, it can be interpreted that the lithofacies represents coastal aeolian (backshore) environment of deposition. The planar cross–stratified sandstone lithofacies seems to be deposited as a coastal dune ridge.

GRITTY–COBBLY CROSS–STRATIFIED SANDSTONE (GCCS) LITHOFACIES

The rocks of the lithofacies are cross–stratified, gritty to cobbly sandstone present at Hathmati River near Himmatnagar and Sabarmati River near Aglod and Sapteshwar in the Upper member and are absent at Vavdi, Vantada and Berna sections. Contact between GCCS lithofacies of Upper member with underlying HSS lithofacies of Lower member is always unconformable in channel structure (Pl. 3.7; 4.15). A thin to 30 cm thick yellow calcareous palaeosol (Pl. 3.7; 4.5, 15) is found present on the unconformity. Thickness of gritty–cobbly cross–stratified sandstone lithofacies varies from 3 to 12 m. The rudaceous fragments in the rocks are sub–angular to angular to sub–round in shape and average diameter of the elongated and oblong pebbles varies from 2 cm to 7 cm; boulders having dimensions ~25 cm x 18 cm are also present in the lithofacies. The rock depicts channel structure, trough cross–stratification and graded bedding (Pl. 3.9) at most of the exposures of the lithofacies and show southward palaeocurrent direction. Wood logs and irregular burrows are frequently present.

PLATE 4

Scales: Bar scales: mentioned in the plate; Pen: 15 cm; Hammer: 30 cm; Diary: 22 cm; Chisel: 10 cm; Goggles: 14 cm; Human: ~175 cm; Rs.1 coin: 2.2 cm; Rs.2 coin: 2.6 cm.

Lithofacies and typical structures: (1) Pebble layer indicating high energy in GW lithofacies at Vantada section; (2) Fragmented bivalves and plant fossils in CS lithofacies at Vantada section; (3) Bivalve casts in CS lithofacies at Vantada section; (4) Neptunian dyke in SS and HSS lithofacies at Hathmati section; (5) Repeated sequence of HSS and SS lithofacies with palaeosol and disconformity on top at Hathmati section; (6) PCS lithofacies at Sapteshwar section; (7) Insect wing in SS lithofacies at Hathmati section; (8, 9 and 10) Convolute bedding (with flame structure in 9) in HSS lithofacies at Hathmati section; (11) Convolute bedding in HSS lithofacies at Sapteshwar section; (12) Parasitic sand volcanic cone in HSS lithofacies at Sapteshwar section; (13 and 14) Sand volcanic cone in HSS lithofacies at Aglod and Sapteshwar sections; (15) GCCS lithofacies above palaeosol and disconformity in wide channel structure within HSS lithofacies at Hathmati section; (16) GCCS lithofacies with angular to sub–angular cobbles at base at Aglod section.

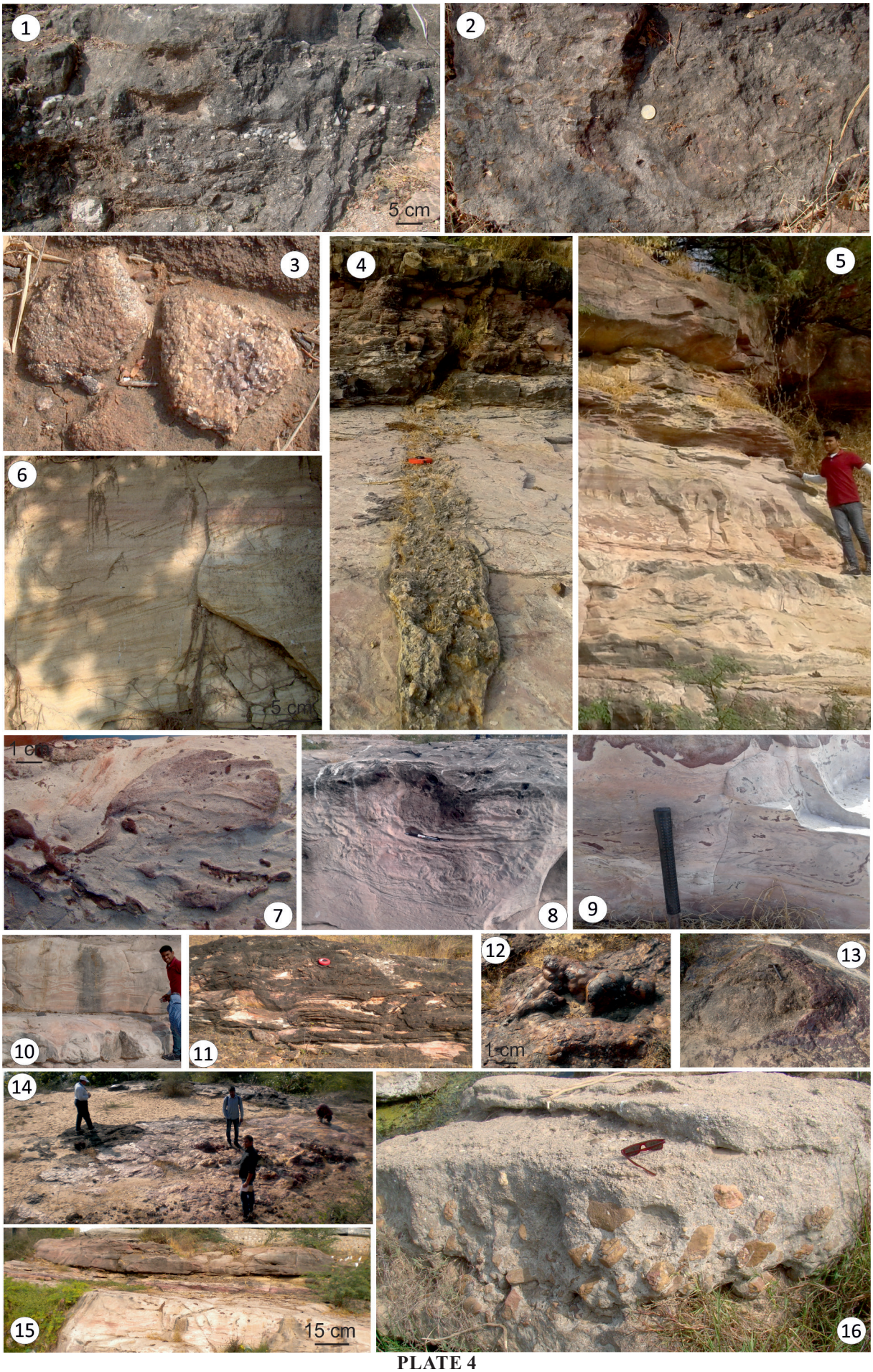

PLATE 4

At Aglod, GCCS lithofacies overlies on HSS lithofacies above mud/sand volcanic structure (Pl. 4.12–14). The rocks of the lithofacies are hard, coarse grain and made up of rounded to sub–angular quartz fragment and at base it contains boulder to cobble size (Pl. 4.16) mud/sand volcano fragments of HSS lithofacies within gritty–gravelly sandstone matrix. Near Sapteshwar, GCCS lithofacies contains coarse fragments of quartz and quartzite with few feldspar, granite, graphic granite, pegmatite, gneiss, rhyolite, rarely phyllite and petrified wood fragments varying in size from 2 to 10 cm within a medium to coarse grain sand matrix and occur nearer to the base.

Above characteristics are suggestive of fluvial to estuarine environment of deposition for the GCCS lithofacies over a gap of time after deposition of highest beds of Lower member. The limited thickness of the beds of the lithofacies may be due to its environment of deposition along with elevation of the area and regression of the sea.

ICHNOFACIES

Most of the trace fossils of the study area listed above belongs to the rocks of Lower member of Himmatnagar sandstones formation. It consists of variety of rocks of which mainly cross–stratified sandstone, silty–shale, horizontally stratified sandstone and planar cross–stratified sandstone have bioturbation. Trace fossil assemblages occur in a particular marine environment constituting ichnofacies, which includes specific associations of trace fossils. Trace fossils, being the preserved record of behaviour and associated functional morphology, generally reflect adaptations of organisms to specific ecologic conditions (Seilacher, 1967). Thus, particular assemblages of trace fossils tend to be characteristic of given environmental regimes (Frey and Pemberton, 1985). Based on trace fossil assemblages three ichnofacies are identified and described as follows in the Lower member of Himmatnagar Sandstone Formation. Table 2 shows the trace fossil distribution in the Lower member and in various ichno–and litho–facies of study area with brief morphology and probable trace producer.

PSILONICHNUS ICHNOFACIES

It comprises of the trace fossil *Psilonichnus* preserved in the CS, SS and HSS lithofacies and *Phoebichnus* in SS lithofacies. This ichnofacies is characterized by vertical small shafts, some with bulbous basal cells, to larger, irregularly J–, Y–, or U–shaped dwelling burrows. According to Frey and Pemberton (1987) amphibious crabs of the Family Ocypodidae typically excavate irregularly J–, Y–, or U–shaped dwelling burrows on sandy backshore to uppermost foreshore. As per the lithological and trace fossil characters the environment of deposition is foreshore.

SKOLITHOS ICHNOFACIES

Skolithos, *Monocraterion*, *Calycraterion, Arenicolites* and *Diplocraterion* traces constitute the *Skolithos* ichnofacies. It is preserved in CS, SS, HSS and PCS lithofacies, usually characterized by vertical, cylindrical or U–shaped dwelling burrows, but few horizontal structures may be present. In this ichnofacies rapid sedimentation and frequent transportation is common indicating relatively high wave and current energy conditions along with clean, well sorted, loose or shifting substrate. Substrates serve mainly as an anchoring medium for the organisms, most of which construct deeply penetrating, more or less permanent domiciles and because of shifting sediments, the dwelling burrows tend to have thick, reinforced wall linings (Frey and Pemberton, 1985). The latter may consist of thick layers of mucus, agglutinated sand, or chitinous materials. Abundance of *Skolithos, Diplocraterion* and *Psilonichnus* along with sedimentary characteristics (such as stratification and low–angle cross–stratification) may be attributed to a relatively moderate to high wave and current energy conditions and shifting substrate (Tiwari et al., 2013). According to Pemberton and MacEachern (1995) animals are chiefly suspension feeders or passive (tubicolous) carnivores. Here the ichnofacies indicating the foreshore to upper shoreface environment of deposition.

CRUZIANA ICHNOFACIES

It consists of number of trace fossils like *Thalassinoides*, *Teichichnus*, *Palaeophycus*, *Planolites*, *Chondrites* etc. They are preserved in the SS, CS, HSS and PCS lithofacies. The ichnofacies is usually characterized by well sorted silts and sands to interbedded muddy and clean sands and moderate to intense bioturbation. According to Fursich (1974), Frey and Howard (1985) this ichnofacies is observed in the storm–influenced ramp and also represents classical gradation from *Skolithos* to *Cruziana* in many different types of substrates as indicated either by change in hydrodynamic conditions, depositional dip or bathymetry in the basin. According to Pemberton et al (2001), because of lowered energy and less abrupt shifts in temperature and salinity levels, the burrows present tend to be developed horizontally rather than vertically. Animals may include mobile carnivores as well as various mixtures of suspension and deposit feeders. Diversity and abundance of traces is generally high. Here *Cruziana* ichnofacies is characterized by the abundance and variety of horizontal structures, which suggests low energy conditions of deposition on an unconsolidated substrate in upper to middle shoreface environment.

DISCUSSION

Generally, marine sediments are found preserved in a stratigraphic sequence. Preservation of terrestrial sediments

Table 2—Trace fossils in different ichno–and litho–facies with morphology and probable trace producer in the Lower member.

Trace Fossil	Brief Morphology	Trace Producer	Position of Trace Fossil
Psilonichnus Ichnofacies			
Phoebichnus (Pl. 2.5).	Vertical shaft with horizontal tunnels showing dwelling and feeding structures.	Unknown.	Lower member. In SS lithofacies.
Psilonichnus (Pl. 2.9–11).	I, J and Y shape dwelling burrows.	Crustacean.	Lower member. In SS, CSS and HSS lithofacies.
Skolithos Ichnofacies			
Arenicolites (Pl. 2.1).	Vertical endogenic U tube without spreite–a dwelling burrow.	Polychaete, annelid, crustacean.	Lower member. In HSS lithofacies.
Calycraterion (Pl. 1.1, 2–3).	Vertical burrow with funnel shape rings at the opening–a dwelling burrow.	Unknown.	Lower member. In SS and CSS lithofacies.
Diplocraterion (Pl. 1.9).	Vertical endogenic U tube with spreite and funnel or mound on either end–a dwelling burrow.	Crustacean, polychaete, annelid, worm.	Lower member. In HSS lithofacies.
Monocraterion (Pl. 1.10).	Vertical endogenic burrow with funnel shape opening–a dwelling burrow.	Worm.	Lower member. In SS, CSS and HSS lithofacies.
Ophiomorpha (Pl. 2.3, 4).	Horizontal or vertical endogenic burrow with pellet lining–a dwelling burrow.	Callianassid major.	Lower member. In SS, HSS and PCS lithofacies.
Skolithos (Pl. 1.5; 2.1, 10, 12).	Vertical endogenic tube with lining–a dwelling burrow.	Worm.	Lower member. In SS, CSS, HSS and PCS lithofacies.
Cruziana Ichnofacies			
Chondrites (Pl. 1.4–7).	Dichotomuosly branched burrows of the same diameter, which resemble the roots of a plant–a feeding trace.	Nematode (roundworm), polychaete, sipunculid, annelid.	Lower member. In SS and CSS lithofacies.
Circulichnus (Pl. 1.8).	Horizontal circular intergenic structures with varying diameters–a grazing trace.	Worm.	Lower member. In SS lithofacies.
Palaeophycus (Pl. 2.6).	Horizontal to inclined lined burrows with filling identical to host sediment–intergenic dwelling structure.	Worm, crustacean, polychaete.	Lower member. In SS and HSS lithofacies.
Planolites (Pl. 2.2, 8).	Horizontal to inclined unlined intergenic burrows with filling different than the host sediment–a grazing structure.	Worm, annelid, polychaete.	Lower member. In SS and HSS lithofacies.
Teichichnus (Pl. 2.7).	Horizontal to inclined burrow showing shifting produced by the stacking of thin sometimes sinuous ‘tongues’ of sediment, atop one another–a fodinichnia.	Polychaete.	Lower member. In HSS lithofacies.
Thalassinoides (Pl. 2.13).	Horizontal polygons to Y shape cylindrical endogenic burrows with vertical shafts–a feeding burrow.	Crustacean.	Lower member. In SS, CSS, HSS and PCS lithofacies.

is uncommon except under exceptional cases, where the sedimentation and subsidence takes place simultaneously. Otherwise terrestrial deposits are thin and found in pockets. The marginal marine and marine Environment can be interpreted based on sedimentary structures, geometry or boundary of the beds, presence of marine fossils/trace fossils and occurrence of calcareous sediments in the sequence.

In the area under investigation, grey wacke (GW) lithofacies occurs at the base above nonconformity. The lithological characters indicate fast rate of sedimentation with occasional high energy events as suggested by rudaceous sediments. In the lithofacies, no sedimentary structures or fossils are found preserved to show its deltaic, estuarine, fluvial or marine environment of deposition. But, based on wider extension of the lithofacies on base of hills in the east of Himmatnagar, more or less uniform thickness on nonconformity and absence of sedimentary structures, it may have been deposited in upper shoreface environment of a transgressive sea.

It is followed by silty–shale (SS) lithofacies in form of a lens only in Vantada hill section. Abundant plant fossils are present in this exposure of the lithofacies, which are without any root portions and transported in nature. The preservation is also very poor and hence identification is difficult in majority of the cases. Few trace fossils–mainly *Chondrites* is present in the lithofacies. The lithofacies is dull white in colour and massive, without any sedimentary structure. All these characters suggest the environment of deposition, which could be a lagoon in marginal marine condition.

It is followed by cross–stratified sandstone (CS) lithofacies in the hills east of Himmatnagar. The cross–stratification of the lithofacies mainly shows palaeocurrent direction towards north and north–east. The cross–stratified units also show wedge shape geometry which is common in the tidal bundles. Locally, herringbone structure is also present. Further, wave ripple marks are present on the top of many beds indicating stormy–high energy event at the time of deposition. Many top parts of the lithofacies show ridge and runnel structures which commonly occur in foreshore regions of tide dominated coast. At few places fragmented invertebrate fossils and plant fossils are also present in the lithofacies. Most important is the occurrence of typical marginal marine to marine trace fossils such as *Monocraterion, Chondrites, Calycraterion, Thalassinoides, Psilonichnus* and *Skolithos*. All these evidences lead to the development of mainly foreshore environment at the time of deposition of CS lithofacies with locally upper foreshore conditions.

The above sequence of CS lithofacies is followed by repetitions of horizontally stratified sandstone (HSS) lithofacies and silty–shale (SS) lithofacies. Both the lithofacies are pink to pale brown in colour, display extensive horizontal extension with horizontal stratification and lamination and commonly showing hummocky stratification in plan and vertical sections. Both the lithofacies are found at Hathmati River of Himmatnagar and at Aglod and Sapteshwar on Sabarmati River. The silty–shale contains plant fossils without roots and typical marginal marine to marine trace fossils like *Skolithos, Monocraterion, Psilonichnus, Thalassinoides, Chondrites, Planolites, Palaeophycus, Calycraterion, Circulichnus, Ophiomorpha, Phoebichnus*, etc. Kotake (2003) considered that *Phoebichnus* producers, which produced the stellate structure as a dump for fecal matter whereas the vertical shaft is thought to be a dwelling structure in marine environment. On the other end horizontally stratified sandstone contains mud drapes and inverse gradation along with characteristic marginal marine to marine trace fossils such as *Skolithos, Ophiomorpha, Psilonichnus, Monocraterion, Thalassinoides, Teichichnus, Palaeophycus, Planolites*, etc. The lithofacies also shows convolute bedding at Himmatnagar section of Hathmati River and Sapteshwar section of Sabarmati River, while sand volcano structures (Pl. 3.12-14) are present at Aglod and Sapteshwar sections of Sabarmati River indicating intense seismic activity at the time of deposition of the rocks.

The HSS lithofacies is followed by planar cross–stratified sandstone (PCS) lithofacies only at Sapteshwar on Sabarmati River. The lithofacies is dull white in colour with fine arenaceous grains and planar cross–stratification. It is lensoid in nature. The lithofacies contains larger crustacean and vertebrate burrows with *Skolithos, Thalassinoides, Ophiomorpha*, etc. These characters are suggestive of a coastal aeolian environment of deposition. At Sapteshwar, the lithofacies is overlain by HSS lithofacies indicating repetition of backshore, marginal marine to marine conditions and fluctuations in sea level.

Howard (1972), McCarthy (1979), Gaillard and Racheboeuf (2006), Bjerstedt and Erickson (1989), Bjerstedt (1987), Droser (1991), Kamola (1984), and Curran and White (1991) have described trace fossils as criteria for recognising shorelines–shoreface–foreshore and identical environment with sedimentary structures and lateral and vertical variation in the sedimentary sequence.

On the top, except at Vantada section, gritty–cobbly cross–stratified sandstone (GCCS) lithofacies occurs at Hathmati River section of Himmatnagar as well as at Aglod and Sapteshwar sections on Sabarmati River. At Himmatnagar, the GCCS lithofacies lies above SS lithofacies, while at Aglod and Sapteshwar it is present above HSS lithofacies disconformably. A thin (~30 cm) palaeosol layer is also present on the disconformity (Pl. 3.7; 4.5, 15) at Hathmati section. The rocks of the lithofacies also show graded bedding, wide channel structures, trough cross–stratification and gritty to cobbly base of the sequence. These characteristics are indicative of a fluvial to estuarine environment of deposition.

From the above discussion it can be interpreted that the sediments were laid down in two cycles, a Lower Cretaceous transgressive cycle and a Mid–Cretaceous regressive cycle. The lower cycle also includes short phases of transgressive–

regressive sub–cycles. The transgression of sea must have occurred from south and south–west towards north and northeast.

From the occurrence of plant fossils and absence of any marine body fossils, the depositional environment of Himmatnagar Sandstone Formation was interpreted as fluvial in the past. But except few scattered reports of plant fossils, no detail work or publication is available on the Himmatnagar Sandstone Formation. At the same time, at no place sedentary plant fossils/ root portions have been noted. Plant fossils are transported, ill preserved and fragmentary in nature. These facts indicate a different story. It has been observed that lower member of Himmatnagar sandstones formation, made up of hard, siliceous to ferruginous sandstones, is extended over vast areas. At places, presence of typical sedimentary structures, trace fossils, overall geometry of the rocks, few fragmentary body fossils and findings of foraminifers in fruit fossils by GSI geologist (personal communication–Dr. Z.G. Ghevariya, Director (Retd.), GSI) indicate that at least Lower member of Himmatnagar Sandstone Formation is marine to marginal marine in its origin.

CONCLUSIONS

The following general conclusions can be interpreted based on the investigations in the study area:

1. Himmatnagar Sandstone Formation is divisible in two parts: Lower member and Upper member.
2. Six lithofacies have been identified in the formation, viz. grey wacke (GW) lithofacies, silty–shale (SS) lithofacies, cross–stratified sandstone (CS) lithofacies, horizontally stratified sandstone (HSS) lithofacies, planar cross–stratified sandstone (PCS) lithofacies in Lower member and gritty–cobbly cross–stratified sandstone (GCCS) lithofacies in Upper member.
3. Trace fossils and plant fossils are common in the Lower member of Himmatnagar Sandstone Formation. Trace fossils belong to Seilacherian *Psilonichnus, Skolithos* and *Cruziana* ichnofacies in Lower member. While, Upper member contains few irregular 'I' and 'J' shape burrows and fossil wood.
4. Based on geometry of the beds, sedimentary structures, trace fossils and absence of root of plants, backshore, upper foreshore to middle shoreface depositional environment can be interpreted for the Lower member of Himmatnagar Sandstone Formation.
5. Unconformable lower contact with Lower member, channel structures, south to southwest trough cross–stratification, angular to sub–rounded gravels, pebbles and cobbles, petrified wood logs, wide occurrence and limited thickness suggest estuarine to fluvial environment of deposition for the Upper member of Himmatnagar Sandstone Formation.

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