CHAPTER 6
ICHNOLOGY

6.1 INTRODUCTION

Trace fossils are autochthonous in nature and intimately related to the depositional environment; they are significant in interpreting the various geological and biological processes. They have been recorded since the Neoproterozoic Era, and their abundance and diversity have increased throughout the Phanerozoic Eon. The Mesozoic Era witnessed the Gondwanaland break up and inundation of the sea on the continent during the Jurassic-Cretaceous Period. The encroachment of the sea on the Indian continent resulted in the deposition of thick marine sedimentary rocks, including the Narmada Basin. The global sea-level rise during the Cenomanian- Turonian time invited a variety of fauna evidenced by diverse trace fossils in the Lower Narmada Valley. The Western Lower Narmada Valley is characterized by various rock types, including fine and coarse clastics, nonclastics, and mixed siliciclastic-carbonate sediments, bioturbated to varying degrees. Trace fossils are mainly reported from moderately bioturbated Vajepur Formation, intensely bioturbated Bilthana Formation, Nodular Limestone, and Narmada sandstone Member of Uchad Formation. The Bagh Group rocks in the WLNV possess diverse trace fossils and variability in its sedimentary record. There have been several advancements in the study of trace fossils taxonomy; several old ichnogenera and species are merged, renamed, replaced, or invalidated. In the present study, the Cretaceous trace fossil record of the Indian Tethyan basins is discussed, emphasizing their taxonomic status. The study aims to revive the status of the earlier reported and the newly proposed ichnogenera and ichnospecies from the Cretaceous Period of India and understand the depositional conditions in Cretaceous basins based on the trace fossil record. To derive the information on the depositional environment of the Cretaceous basins in India, the data is synthesized, re-evaluated, and corrections are made to the old invalid names. Also, the present status of the ichnogeneric and ichnospecies name and their potential synonyms is reviewed.

To date, most of the ichnological studies of the Bagh Group rocks were carried out in the eastern part of the Lower Narmada Valley- ELNV (Chiplonkar and Badve, 1969, 1970, 1972;

Chiplonkar and Ghare, 1975a and b; Singh and Dayal, 1979; Ghare and Badve, 1980, Singh, 1982; Badve, 1987, Sanganwar and Kundal, 1997; Kundal and Sanganwar, 1998b, 2000; Nayak, 2000) and very few studies in the western part of the Lower Narmada Valley- WLNV (Verma, 1970; Chiplonkar and Badve, 1972; Badve and Ghare, 1980; Patel et al., 2017 and Shitole et al., 2019). However, studies reporting trace fossils from the WLNV and interpreting them from a paleoecological point of view are scarce. Based on occurrence, preservation style, ethology, trophic type, and distribution of the trace fossils, ichnoassemblages and ichnofacies have been identified. Quality exposures and abundant well-preserved trace fossils in the study area make ichnology an ideal tool for studying paleodepth, oxygen, salinity, food supply, and organisms flourishing in the transgressive Cretaceous Palaeo-Tethys Sea.

6.2 TRACE FOSSILS DESCRIPTION

Treatise of InvertertebratePaleontology was the first compilation of valid invertebrate trace fossils done by Häntzschel (1975). Knaust (2012) updated the original version of the treatise and proposed a nomenclature key based on the hierarchy of diagnostic features (ichnotaxobases like orientation, presence or absence of branching, shape, and presence or absence of lining). Buatois et al. (2017) categorized the 523 ichnogenera into seventy-nine architectural designs based on morphological characters. The concept of ichnodisparity is similar ichnotaxonomy since both involve morphological studies and ethological interpretation. However, the concept differs from ichnodiversity since it merges the minor behavioral variants within a single morphological plan, whereas it may lead to a high ichnodiversity interpretation. Ichnodisparity identifies the number of architectural design categories, whereas ichnodiversity measures the number of ichnogenera. The application of ichnodiversity lies in analyzing environmental stress (viz., low ichnodiversity suggests a more stressful environment), stability in facies interpretation, reconstructing evolution history, and evaluating species richness in different depositional settings geological times (Buatois and Mángano, 2013). Taphonomy has a huge impact on the ichnodiversity viz. the low diversity can be interpreted in terms of stressed environmental conditions, or it can reflect stable conditions giving rise to deep-tier climax communities and thus has a taphonomic origin, i.e., produced due to intense bioturbation of deep tier organisms and does not reflect environment stability (Buatois and Mángano, 2013). This suggests low ichnodiversity cannot always be attributed to stressful environmental conditions. Buatois and Mángano (2013) suggest that ichnodiversity is essential in the information provided for the otherwise unfossiliferous rocks. Still, their comparison with the actual diversity of organisms is equivocal because ichnodiversity is the outcome of organism-substrate interaction and is unrelated to the factors which control species or body fossil diversity, i.e., contrasting substrate conditions can produce different biogenic structures. A single organism shows variable behavior; therefore, several ichnogenera can result from the same producer.

The previous literature is the primary backbone and forms a strong foundation for any research investigation. Trace fossils are the fossil record of biological activity; although more common than body fossils, they are not so readily discernible in the field. In the present study, historical record of the Cretaceous ichnology in the Narmada Basin is compiled (Table 6.3) to ensure that they do not escape records of their occurrence and can be used in a purposeful manner. The study describes the present status of the ichnogeneric and species names, and a broader interpretation is derived regarding the Cretaceous depositional environment in the basins of the Indian subcontinent based on the occurrences of trace fossils. The history of invertebrate ichnology in India has been divided into three periods: 1800-1960 involving a report of trace fossils; 1960-2000 report, erection of new ichnotaxa and palaeoecological interpretations and 2000 to present involving new ethological interpretations, demonstration of trace fossils, and combining sedimentological and ichnological studies for demonstrating the sea-level changes and the evolutionary change in trace fossils. Studies on invertebrate ichnology as a separate field started in 1800, but it was not until 1960 that it began to bloom worldwide (Cadée and Goldring, 2007). However, ichnological studies in India gained popularity in early 1970. 1970-80 was a period of development in ichnological studies in India when many occurrences of ichnotaxa were reported, and the concept of ichnofacies was used enormously, which strengthened the paleontological and sedimentological interpretations (Figure 8.3). The period 1969-2000 in India witnessed intense ichnological research, during which many new ichnogenera and species were reported and preserved in the museums. The ichnological studies in India were initially started by Chiplonkar, Badve, and Ghare and later by Borkar, Patel, Kundal, Sanganwar, etc. Their studies substantially contributed to the development of ichnological studies in India during the early 1970 and culminated in many significant contributions, which is the foundation for the present investigation. Recently Knaust (2012) and Buatois et al. (2017) have made important contributions to the trace fossils systematics part by compiling the valid and invalid names of the ichnogenera and species and providing details and lists of the synonyms.

Chiplonkar and Badve (1969, 1970) reported two new genera, *Arthropodichnus*, *Diplopodomorpha* and twelve new species *Arthropodichnus indicus*, *Diplopodomorpha cretacea, Dreginozoum orientale, Nereites malwaensis, Oniscoidichnus communis, O. ampla, O. elegans, O* *robustus, Permichnium bosei, Taphrhelminthopsis subauricularis, Asterosoma spatulata* and *Phycodes gregarious* from the Bagh Group rocks LNV. *Arthropodichnus* (Chiplonkar and Badve, 1970) was also reported by Ghare and Badve (1980) from the Bagh Group, WLNV; Viglietti et al. (2020) from the Karoo Group, South Africa; Shibata and Varricchio (2020) from the Cretaceous of Two Medicine Formation, USA, and the Ordovician Welsh basin by Nicholls (2019) and was validated by Häntzschel (1975). However, *Arthropodichnus* was also proposed by Gevers et al. (1971) for paired parallel track impression; later, Gevers realized the name was already used for another ichnogenus and changed it to *Beaconichnus* in 1973. Bradshaw (1981) redescribed Gevers specimens and synonymized the ichnospecies with *Diplichnites gouldi*. The ichnogenus was recently considered nomina dubia by Buatois et al. (2017), lacking adequate description and unclear diagnostic characteristics. Ichnogenus *Permichnium* (Guthörl, 1934) is invalidated and regarded as a junior synonym of *Lithograptus* by Minter and Braddy (2009). Chiplonkar and Badve, (1970) erected new ichnospecies *Dreginozoum orientale*. The ichnogenus *Dreginozoum* (Marck, 1894), although reported by several authors (Cuerda et al., 1990; Nielsen et al., 2015) has been considered as ichnogenera with unclear taxonomic status by Knaust (2012) and is not much in usage. The ichnospecies *Fucusopsis cf. angulatus* (Vassoevich, 1932) was reported by Chiplonkar and Badve (1969, 1970) and by Saha et al. (2010) from the Narmada basin. The ichnogenus *Fucusopsis* and its three ichnospecies (*F. angulata, F. annulate,* and *F. striata*) were included in *Halopa* as its junior synonym by Uchman (1998). However, it was added to the list of valid ichnogenera but with an unclear taxonomic status by Knaust (2012). *Diplopodomorpha* was introduced as an ichnogenus with type species *D. cretacea* by Chiplonkar and Badve (1970). The ichnogenus was validated by Knaust (2012) but was considered nomina dubia by Buatois et al. (2017). The new ichnospecies *Nereites malwaensis, O. communis, O. ampla, O. robustus,* and *Asterosoma spatulata* erected by Chiplonkar and Badve (1970) are not found in usage but are also not invalidated. *O. elegans* is reported only from the Tertiary rocks of Bengal Basin by Bera (1996). Uchman (1995) included the ichnotaxa *Taphrhelminthopsis* and ichnospecies (*T. auricularis, T. plana, T. convolute, T. auricularis, T. vagans, T. sacco,* and *T. recta*) in *Scolicia strozzi* (Savi and Meneghini, 1850). However, the status of *Taphrhelminthopsis subauricularis* (Chiplonkar and Badve, 1970) was not made clear, but the revision of ichnogenus should be synonymized with *Scolicia*. The ichnospecies *Phycodes gregarious* (Chiplonkar and Badve, 1970) was regarded to be nomen dubium by Han and Pickerill (1994) because of its small size and was considered to be similar to *P. circinatus*.

Later in 1970, Chiplonkar and Badve erected one new ichnogenus *Discotomaculum* and two new ichnospecies *Discotomaculum variabilis, Protovirgularia mongraensis* from the Bagh Group rocks WLNV. The new ichnogenera *Discotomaculum* (Chiplonkar and Badve, 1972), although not much in usage, was considered to be a valid ichnogenus by Gutiérrez-Marco et al. (1984) and was also reported by Fraunfelter (1987) from the Cambrian Davis Formation of Missouri. *Protovirgularia mongraensis* was later considered a junior synonym of *P. dichotoma* (Han and Pickerill, 1994).

Verma (1970) reported one new ichnogenus *Baghichnus* and three new ichnospecies- *Baghichnusbosei, Laevicyclus mongraensis,* and *Pholeus robustus,* from the Bagh Group rocks exposed in the Ambadongar area, WLNV. Knaust (2012) considered *Baghichnus* to be nomen dubium and added it to the list of invalid ichnogenera. *Pholeus robustus* was removed from the ichnogenus *Pholeus* by Knaust (2002) in lack of oblique burrow and a small vertical burrow. *Laevicyclus mongraensis* is a valid ichnospecies reported from the Jurassic rocks of Kachchh basin (Desai et al., 2008; Joseph et al., 2020); Jurassic rocks of Jaisalmer basin (Desai and Saklani, 2014); Cretaceous rocks of Narmada basin (Chiplonkar and Badve, 1970; Sanganwar and Kundal, 1997; Kundal and Sanganwar, 1998); Cretaceous-Eocene of Julian basin (Tunis and Uchman, 1996); Tertiary rocks of Cambay basin (Mude, 2012a and b) and Surma Group (Tiwari et al., 2011). However, Alpert and Moore (1975) suggested its resemblance with *Dolopichnus*.

Chiplonkar and Tapaswi (1972) described new ichnospecies *Scalarituba indica* from the Cretaceous rocks of the Cauvery Basin. Uchman (1995) suggested that ichnogenus *Scalarituba* should be regarded as a junior synonym of *Nereites*. Later Mángano et al. (2002) suggested that the species *Scalaritubaindica* be removed from the *Nereites* Group and included in *Taenidium*.

Chiplonkar and Ghare (1975a) erected nine new ichnospecies, an ichnogenus from the Cretaceous Bagh Group rocks and a new ichnospecies from the Lameta Group rocks. Of the newly proposed ichnospecies, *Cosmorhaphe filiformis, Cylindricum curvosus, Eoclathrus subramanyami, Hirmeria khandluensis, Pelecypodichnus chikliensis, Phycodes mongraensis, Paleodictyon mongraensis,* and *Rhizocorallium mongraensis* are not in usage but also not invalidated. However, the ichnospecies *Rhizocorallium mongraensis* was reported by Kundal and Sanganwar from the Nimar Sandstone Formation of Bagh Group rocks, ELNV. The authors erected new ichnogenus *Arthrotelsonichnus namadicus*; the genus was recently considered nomen dubia by Buatois et al. (2017) based on lack of adequate description and unclear diagnostic characteristics. The ichnogenus *Pennatulites* reported by the authors was synonymized with *Protovirgularia* by Seilacher and Seilcher (1994). The newly erected ichnospecies *Spongeliomorpha reticulata* was invalidated by

Melchor et al. (2009) owing to its erection based on a single specimen, cylindrical structure, and lack of network. The authors proposed new ichnospecies *Granularia obliqua*; however, the ichnogenus *Granularia* was synonymized with *Ophiomorpha* (Pemberton and Frey, 1982) and invalidated by Uchman (1995, 1998).

Chiplonkar and Ghare (1975b) reported *Keckia annulata* and *Paleodictyon isp.* from the Bagh Group rocks, ELNV. The ichnospecies were also reported by Ghare and Badve (1980) and Nayak (2000) from the Bagh Group rocks. The status of specimens later described as *Keckia* is highly debated and not clear (see Uchman, 1998 and references therein; Knaust, 2012). The ichnogenus is considered nomen dubium (D'Alessandro and Bromley, 1987), and its usage is not recommended (Buatois et al., 2017). Uchman (1998) included *Keckia annulata* in *Protovirgularia;* thus, the status of *Keckia annulata* reported by Chiplonkar and Ghare (1975b) stands revised to *Protovirgularia*.

Singh and Dayal (1979) erected new ichnogenera *Striatolites* and ichnospecies *Striatolites bariaensis* from the Bagh Group rocks exposed between Avalda and Zeerabad villages, ELNV. The ichnogenus lacked usage and was regarded as a junior synonym of *Halopoa* (Buatois et al., 2017).

Badve and Ghare (1980) reported two new ichnogenera from the Bagh Group rocks exposed in Deva River, South of Narmada, Maharashtra, namely *Annetuba* and *Notocubichnia*. The authors also erected four new ichnospecies- *Annetuba chapdiensis, Imponoglyphus kevadiensis, Monomorphichnus crefacea,* and *Notocubichnia minuta*. The newly introduced ichnogenera *Annetuba* with typespecies *A. chapdiensis* (Badve and Ghare, 1980) was also reported by Kundal and Sanganwar (1998) from the Bagh Group rocks and was later considered to be the junior synonym of *Arenituba* verso (Knaust, 2015). The new ichnogenera *Notocubichnia* and ichnospecies *N. minuta* (Badve and Ghare, 1980) and ichnospecies *Imponoglyphus kevadiensis* (Badve and Ghare, 1980) are not in usage but are also not invalidated. The ichnospecies *I. kevadiensis* is reported from the Jurassic rocks of Jaisalmer Basin by Parihar et al. (2017) and Desai and Saklani (2014). However, Uchman (1998) suggested that *Imponoglyphus* is a preservational variant of Taenidium.

Ghare and Badve (1980) reported *Pennatulites* (de Stefani, 1885) from the Cretaceous Bagh Group rocks. *Pennatulites* has been regarded a junior synonym of *Protovirgularia* by Seilacher and Seilacher, 1994; Uchman (1998) and Buatois et al. (2017). However, Knaust (2012) added it to the list of valid ichnogenera.

The ichnogenus *Aulichnites* reported by Krishna (1987) from the Cretaceous of Kachchh basin and by Kundal and Sanganwar (2000) from the Cretaceous Bagh Group of Narmada basin are invalidated by Knaust (2012). The ichnotaxa is highly debated (Mángano and Rindsberg, 2003 and references therein) and was reported abundantly by several authors; later, it was found that the holotype of *Aulichnites* was a poorly preserved specimen of *Psammichnites* (Hakes, 1977; D'Alessandro and Bromley, 1987; Mángano and Rindsber, 2003). However, it is still used in the lack of ichnogeneric name for smooth, bilobate, tape-like, epirelief traces (Mikuláš et al., 2017).

Badve (1987) described two new species, *Palaeophycus annulatus,* and *Granularia velamensis,* from the Bagh Group rocks, Barwah area, ELNV. Badve also reported *Brookvalichnus obliquus* (Webby, 1970); the ichnogenus is not used but is considered a valid ichnogenus (Knaust, 2012). However, it has not been regarded as a trace fossil by Buatois et al. (2017). *Palaeophycus annulatus* (Badve, 1987) was considered to be a junior synonym of *Palaeophycus anulatus* (McCann and Pickerill, 1988) by Fillion and Pickerill (1990). McCann (1993) suggested using the name *Palaeophycus serratus,* considering the dilemma associated with the name *P. anulatus*. Later Buckman (1995) regarded *P. anulatus* as a homonym of *P. annulatus* and synonym of *P. serratus* and considered *P. serratus* nomen dubium. *P. annulatus* was also considered to be nomen dubium and invalidated by Buckman (1995) based on incomplete description and illustration and lack of sectioned material and suggested it should be referred informally. Buckman argued that the annulations seen on Badve's figure might be a taphonomic feature due to compaction or weathering; the annulation could be swelling as seen in the specimens of *Planolites tubularis*, or it could be the compartmentalized fill seen in *Taenidium* or *Eione*. Moreover, Buckman erected a new genus *P. crenulatus*, an annulated specimen differing from *P. annulatus* and *P. anulatus* based on the width of annuli and well-defined lining. The ichnogenus still stands valid and is widely used to describe the irregular annulated *Palaeophycus* specimens and is also used to describe similar specimens occurring in the study area. The Cretaceous occurrences of the ichnospecies in India are from the Narmada basin (Kundal and Sanganwar, 1998; Sanganwar and Kundal, 1997). The ichnogenus *Granularia* was synonymized with *Ophiomorpha* and invalidated by Uchman (1995, 1998). The ichnospecies *Granularia velamensis* described by Badve (1987) lacks resolution hence cannot be convincingly regarded as a synonym of *Ophiomorpha. Keckia annulata* reported by Chiplonkar and Ghare (1975), as discussed earlier, is revised to *Protovirgularia* (Uchman, 1998).

Sanganwar and Kundal (1997) identified new ichnospecies *Arthropodichnus chiplonkari, Rhizocorallium yelamensis* and reported *Uvaites catanus* (Badve and Ghare, 1978) from the Nimar

Sandstone Formation of Bagh Group, ELNV. The ichnogenus *Arthropodichnus* was recently invalidated by Buatois et al. (2017) in lack of adequate description and unclear diagnostic characteristics. The ichnospecies *Arthropodichnus chiplonkari* (Sanganwar and Kundal, 1997) is a poorly preserved specimen and can be tentatively assigned to *Protovirgularia*. The new ichnospecies *Rhizocorallium yelamensis* (Sanganwar and Kundal, 1997) reported from the Bagh Group rocks was recently synonymized with *Rhizocorallium commune* (Schmid, 1876) by Knaust (2013). The ichnogenus and ichnospecies *Uvaites catanus* erected by Badve and Ghare (1978) and reported by Sanganwar and Kundal (1997) is barely used but is also not invalidated.

Kundal and Sanganwar (1998) identified new ichnospecies *Palaeophycus intermediatus* from the Nimar Sandstone of Bagh Group rocks, ELNV. *Annetuba chapdiensis* (Badve and Ghare, 1980) was regarded to be the junior synonym of *Arenituba verso* (Knaust, 2015). The ichnospecies *Granularia yelamensis* (Badve, 1987) was reported by Kundal and Sanganwar (1998) from the Bagh Group rocks. However, the ichnogenus *Granularia* was synonymized with *Ophiomorpha*. Kundal and Sanganwar (1998) reported *Imponoglyphus kevadienesis* (Badve and Ghare, 1980), *Keckia annulata* (Glocker, 1841), and *Laevicyclus mongraensis* (Verma, 1970); their status of is already discussed above. *Palaeophycus intermediatus* (Kundal and Sanganwar, 1998) is not much in usage but also not invalidated.

Tewari et al. (1998) reported *Teredolites clavatus* and *Teredolites longissimus* from the Cauvery basin. However, the type species of *Teredolites* (*T. clavatus*) was regarded to be *Gastrochaenolites clavatus* (Leymerie, 1842) by Donovan and Ewin (2018) and *Teredolites longissimus* (Kelly and Bromley, 1984) is reclassified as the type ichnospecies of *Apectoichnus* (Donovan, 2018).

Kundal and Sanganwar (2000) reported *Corophioides luniformis* from the Bagh Group rocks. The ichnogenus *Corophioides* (Smith, 1893) has been regarded as a synonym of *Diplocraterion* (Torell, 1870) by Fürsich (1974) and is considered to be invalid by Knaust (2012). The new ichnospecies *Cylindrichnus karondiaensis* (Kundal and Sanganwar, 2000) from the Bagh Group rocks exposed in the Manawar area of ELNV is not in usage but also not invalidated. The status of *Granularia* and *Keckia annulata* is already discussed. *Rhizocorallium mongraensis* (Chiplonkar and Ghare, 1975), reported by Kundal and Sanganwar (2000), was recently synonymized with *Rhizocorallium commune* by Knaust (2013). The status of ichnogenus *Aulichnites* is specified above and is invalidated by Knaust (2012) but is still in usage.

Trace fossil		Orientation	Branching	Shape	Fill	Ichnogenus
I	**Burrows**	Subhorizontal	Unbranched	Cylindrical, ridge-like	Passive	*Palaeophycus*
					Active	*Planolites*
					Active/ Passive	*Ptychoplasma*
					Active	*Taenidium*
		Subvertical	Unbranched	Cylindrical	Passive	*Skolithos*
				Plug- shaped	Passive	*Bergaueria*
						Conichnus
						Conostichus
						Lockeia
				U- and bow-shaped	Passive	*?Arenicolites*
		Complex	-	Boxwork	Passive	*Thalassinoides*
II	**Trails**	Number of Lateral Elements	Unary	Straight or curved		*Archaeonassa*
					-	*Helminthoidichnites*
				Winding with loops	-	*Gordia*
			Binary	Straight or curved		*Didymaulichnus*
III	**Trackways**	-	Biserial	Bract-like-	-	*Oniscoidichnus*
IV	**Bioerosional**	-	Unbranched	Clavate	-	*Apectoichnus*

Table 6.1 Morphological classification of the trace fossils based on the hierarchy of ichnotaxobase (Knaust, 2012).

Nayak (2000) erected four new ichnospecies *Arenicolites phataensis, Monocraterion variabilis, Thalassinoides badvei,* and *Scalarituba kanwaraensis* from the Nimar Sandstone of Bagh Group exposed in the Jhabua area, ELNV. The ichnogenus *Scalarituba* (Weller, 1899) is also reported by Chiplonkar and Tapaswi, 1972 from the Cauvery basin and by Bhatt and Patel (2017) from the Kachchh basin. The ichnogenus is synonymized with *Nereites* by Uchman (1995). The ichnospecies *Arenicolites phataensis* (Nayak, 2000) is not in usage and based on the examination of the specimen, Kulkarni et al. (2008) regarded its ichnogeneric identification to be doubtful. *Keckiaannulata* (Glocker, 1841) was reported by Nayak (2000) from the Bagh Group rocks; its status is already discussed in the preceding paragraphs. The new ichnospecies *Monocraterion variabilis* and *Thalassinoides badvei* erected by Nayak (2000) are not in usage but also not invalidated.

Saha et al. (2010) reported several trace fossils from the Maastrichtian Lameta Group of the Narmada Basin. The ichnogenus *Calycraterion* (Karaszewski, 1971) is regarded as a junior synonym of *Laevicyclus* (Quenstedt, 1879) by Knaust (2012, 2015) and the ichnogenus *Stipsellus* (Howell, 1957) was put in synonym with *Skolithos* by Alpert (1974). However, several authors later reported it, and it is still in usage.

After the first compilation of trace fossils by Häntzschel (1975), several new ichnogenera were erected, synonymized, and invalidated. Therefore, in the present study, trace fossils are classified based on Buatois et al. (2017) and Knaust (2012), an updated treatise of trace fossils and would serve as a base for systematics. For trace fossil description, the preservational and ethological classification schemes proposed by Seilacher (1953, 1964) and Martinsson (1970) are adopted, and the nomenclature is done as per ICZN guidelines. Each trace fossil is further described, interpreted for the probable trace maker, and noted for its occurrence in the lithology (Table 6.1). Thus, trace fossils in the present study are described following five major approaches, i.e., descriptive, preservational, behavioral, organism, and taxonomic.

6.2.1 BURROWS

Orientation: Subhorizontal

Branching: Unbranched

Shape: Cylindrical, Ridge-like

Fill: Passive

Burrow Wall: Lined

Ichnogenus: *Palaeophycus* HALL, 1847

Diagnosis: Branched or unbranched, smooth or ornamented, lined, essentially cylindrical, predominantly horizontal burrows of variable diameter; infillings typically structureless, of the same lithology as host (Pemberton and Frey, 1982).

Ichnospecies: *Palaeophycus tubularis*, HALL, 1847

(Plate 6.1 a-b)

Diagnosis: Smooth, unornamented burrows of variable diameter, thinly but distinctly lined (Pemberton and Frey, 1982).

Description: Horizontal, epichnial, parallel to bedding, straight to gently curved, distinctly lined, smooth-walled, unbranched, cylindrical trace fossil, burrow fill same as host sediments. The maximum observed length in the Men River valley specimens is 7.59 cm, and its diameter is 1.12 cm. In contrast, the Gulvani specimen is about 25.46 cm long and has a diameter of 4.2 cm.

Interpretation: Thin wall of *Palaeophycus tubularis* distinguishes it from *Palaeophycus heberti.* It differs from similar-looking *Planolites* and other ichnospecies of *Palaeophycus* by prominent lining and fills identical to the host rock. It is distinguished from *P. striatus* by lack of parallel striations, *P. heberti* by its thinner wall, *P. sulcatus,* which has anastomosing striations, and *P. alternatus,* which possesses alternate striations (Pemberton and Frey, 1982). *Palaeophycus* is reported from the foreshore and lower shoreface-offshore environments and is more common in nearshore settings (Pemberton et al., 2001; Buatois and Mángano, 2011). Pemberton and Frey (1982) interpreted *Paleophycus* to be passively filled open burrows constructed for domicile purposes based on the identical fill of the host and type specimen and the "apparently hollow" observation of Hall (1847). *Paleophycus* is facies crossing form constructed by predaceous or suspension feeders (Pemberton and Frey, 1982) or by insects and arthropods in continental settings (Buatois and Mángano, 1993).

Occurrence: *Palaeophycus* occurs at bed junction as epichnia in the sandy allochemic limestone facies of Bilthana Formation and calcareous rippled sandstone of Vajpeur Formation, Men River valley.

Orientation: Subhorizontal

Branching: Unbranched

Shape: Cylindrical, ridge-like

Fill: Active

Burrow wall: Unlined

Ichnogenus: *Planolites* NICHOLSON, 1873

Diagnosis: Unlined, rarely branched, straight to tortuous, smooth to irregularly walled or annulated burrows, circular to elliptical in cross-section of variable dimensions and configurations; infillings essentially structureless, differing in lithology from the host (Pemberton and Frey, 1982).

Ichnospecies: *Planolites annularis* WALCOTT 1890
(Plate 6.1 c)

Diagnosis: Distinctly annulated, subcylindrical burrows.

Description: Horizontal, unbranched, slightly curved, unlined, elliptical in cross-section, transversely annulated, maximum length and diameter of the burrow is 4.81 cm and 0.63 cm, respectively. Burrow is parallel to the bedding and tapers at one end.

Interpretation: The lack of lining differentiates it from *Palaeophycus annulatus*. The specimen shows faint, transverse, irregularly spaced annulations, differentiating it from the other ichnospecies of *Planolites*. The annulation in *P. annularis* is interpreted to represent the peristaltic movement of the organism such that the prominence and spacing of rings are related to ease and efficiency of feeding (Pemberton and Frey, 1982).

Occurrence: It occurs at bed junction as epichnia in the calcareous sandstone facies of Vajepur Formation, Uchad village.

Ichnospecies: *Planolites beverleyensis* BILLINGS, 1862
(Plate 6.1 d)

Diagnosis: Relatively large, smooth, straight to gently curve or undulate cylindrical burrows (Pemberton and Frey, 1982).

Description: Burrows are cylindrical, elliptical in cross-section, unlined, unbranched to rarely branched, isolated or crowded and cross each other at some places, straight to gently curved, burrows horizontal to the bedding plane, show much variation in shape and diameter, length of burrow varies from 17 to 18 cm, and width ranges from 0.6 to 1.6 cm.

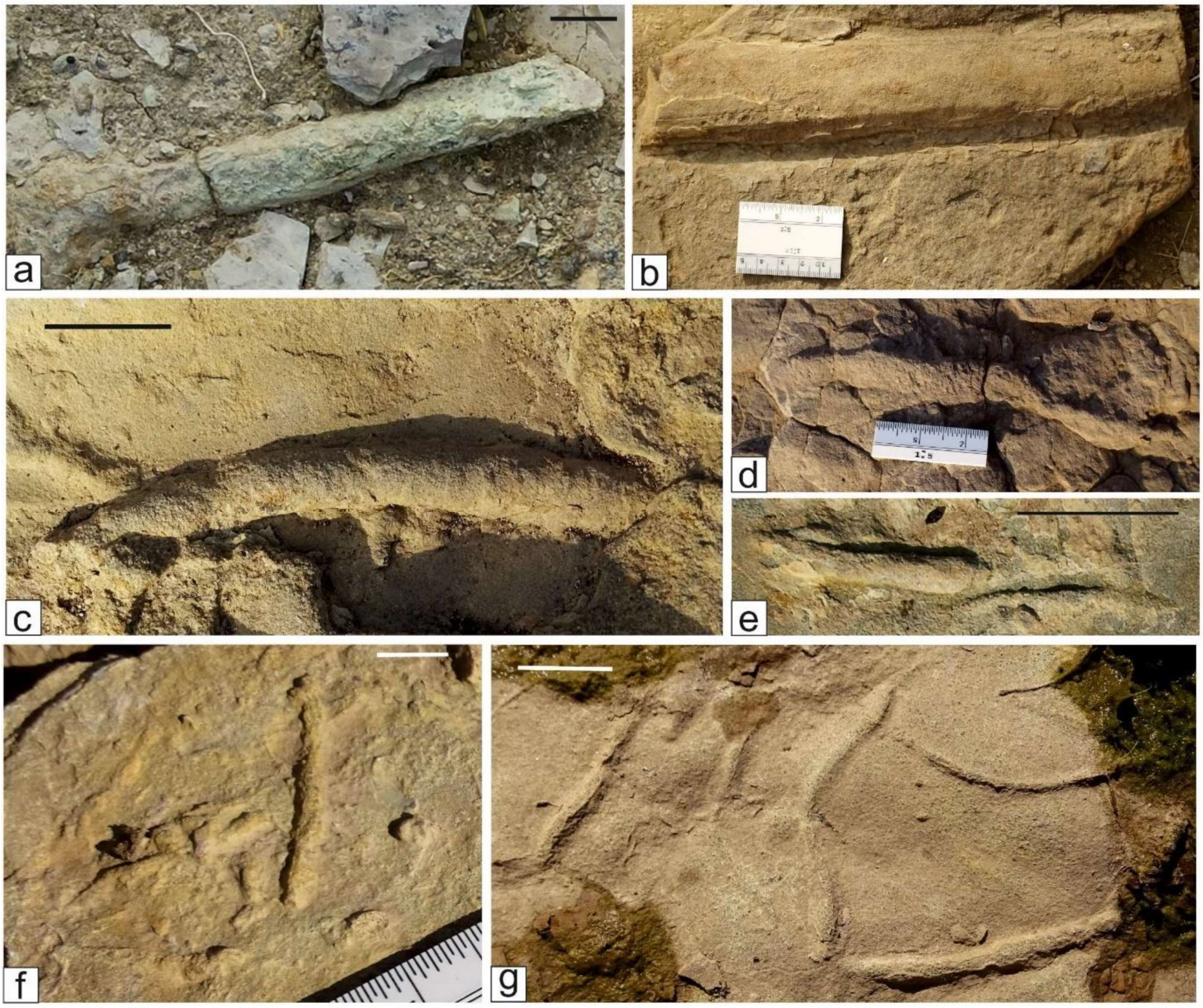

Plate 6.1 Passively filled horizontal burrows and simple actively filled (massive) horizontal to oblique structures. a. *Paleophycus tubularis* horizontal, lined burrow, sandy allochemic limestone facies, Bilthana Formation (Scale bar = 1 cm). b. *Paleophycus tubularis* horizontal, lined burrow, calcareous sandstone facies, Vajepur Formation, Gulvani village. c. *Planolites annularis* horizontal, lined burrow with annulations, sandy allochemic limestone facies, Bilthana Formation, Uchad village (Scale bar = 1 cm). d. *Planolites beverlyensis* in the calcareous sandstone facies, Vajepur Formation, Devaliya village. *Planolites montanus* in e. Calcareous sandstone facies of Vajepur Formation, Uchad section (Scale bar = 1 cm). f. Sandy allochemic limestone facies of Bilthana Formation, Bhekhadiya (Scale bar =1 cm) and g. Sandstone-siltstone-shale facies, Bilthana Formation, Bhekhadiya village (Scale bar = 1 cm).

Interpretation: The absence of burrow lining results in the collapse of the burrow wall, suggests the semi-permanent nature of the burrows (Bromley, 1996). *Planolites* have a long stratigraphic range from Proterozoic to Recent (Häntzchel, 1962), also found in a wide range of facies. *Planolites beverleyens is* differs from *Palaeophycus* and other ichnospecies of *Planolites* by its long, straight, slightly curved, and unlined nature (Pemberton and Frey, 1982). The burrow is interpreted as a trace of an active backfilling mobile deposit feeding worms (Nicholson, 1873; Pemberton and Frey, 1982) or arthropods in a terrestrial environment (Buatois and Mángano, 1993). The present specimens show a smooth burrow surface and lack of any collapse structures favoring the active backfill, whereas *Palaeophycus* has irregular walls and shows collapse structures (Frey and Chowns, 1972). The diameter exceeding 0.5 cm and gently curved nature differentiate it from *Planolites montanus.*

Occurrence: This ichnospecies occurs at bed junction as epichnia in the calcareous sandstone facies of Vajepur Formation, Devaliya village.

Ichnospecies: *Planolites montanus* RICHTER, 1937

(Plate 6.1 e-g)

Diagnosis: Relatively small, curved to contorted burrows (Pemberton and Frey, 1982).

Description: Cylindrical, circular to elliptical in cross-section, gently curved, parallel to bedding and preserved as epichnial ridges. The burrow population shows variable dimensions; diameters range from 0.22 to 0.38 cm, and length varies from 1.23 to 3.29 cm.

Interpretation: The small, curved nature of *P. montanus* with diameters less than 0.5 cm differentiates it from the large, gently curved burrows of *P. beverleyensis* characterized by diameters between 0.8-0.1 cm (Pemberton and Frey, 1982). It is made by deposit-feeding worms (Pemberton and Frey, 1982).

Occurrence: It occurred at bed junction and preserved as epichnia in the sandy allochemic limestone facies of Bilthana Formation, Uchad section, calcareous sandstone facies, Vajepur Formation, Bhekhadiya village, and sandstone-siltstone-shale facies, Bilthana Formation, Bhekhadiya village.

Orientation: Subhorizontal

Branching: Unbranched

Shape: Cylindrical, Ridge-Like

Fill: Active/Passive

Burrow wall: Lined/Unlined

Ichnogenus: *Ptychoplasma* FENTON AND FENTON, 1937a

Diagnosis: In hypichnial aspect, nearly smooth, undulating, continuous to discontinuous subhorizontal ridges that display a characteristically amygdaloid, carinate or blocky cross-section, little or no chevron sculpture, and commonly a straight, winding, irregularly meandering, or looping course (Uchman et al., 2011).

Ichnospecies: *Ptychoplasma vagans* KSIĄŻKIEWICZ, 1977

(Plate 6.2 a)

Diagnosis: In hypichnial view, an irregularly meandering or looping, discontinuous ridge containing a series of elongate mounds, carinate in cross-section, amygdaloid in outline, and pointed at both ends. The mounds are at least two and half times and commonly three or more times longer than their width. They are rarely preserved as relevant epichnial depressions (Uchman et al., 2011).

Description: Stright row of hypichnial mounds which does not overlap and are welded to the surface. The ridges are 0.9 cm long and 0.33 cm wide. The mounds are symmetrical, tear-shaped, and tapering at one end. The serial arrangement of the mounds resembles the ichnospecies *Lockeia serialis* proposed by Seilacher and Seilacher (1994) but which is now considered to be *nomen dubium* (Schlirf et al., 2001) due to lack of holotype. *L. serialis* is regarded to be *Ptychoplasma* which is further categorized into different species based on their continuity (Uchman et al., 2011). The present specimen occurs as discontinuous series of mounds. Thus, it differs from *P. excelsum,* a relatively continuous trace, and *P. conica,* a less welded form consisting of conical mounds (Uchman et al., 2011).

Interpretation: The present specimen resembles *Lockeia vagans;* however, Uchman et al. (2011) restricted *Lockeia* as a resting trace of the bivalve, isolated in nature. *Tuberculichnus vagans,* which is a locomotion trace similar to the present specimen, is considered to be *Ptychoplasma vagans* (Uchman et al., 2011). *Ptychoplasma* is common in shallow marine sandstones and is interpreted to be produced by wedge-foot bivalves (Uchman et al., 2011). The ichnospecies is also reported from the Jurassic rocks of the Jaisalmer basin by Paranjape et al. (2013).

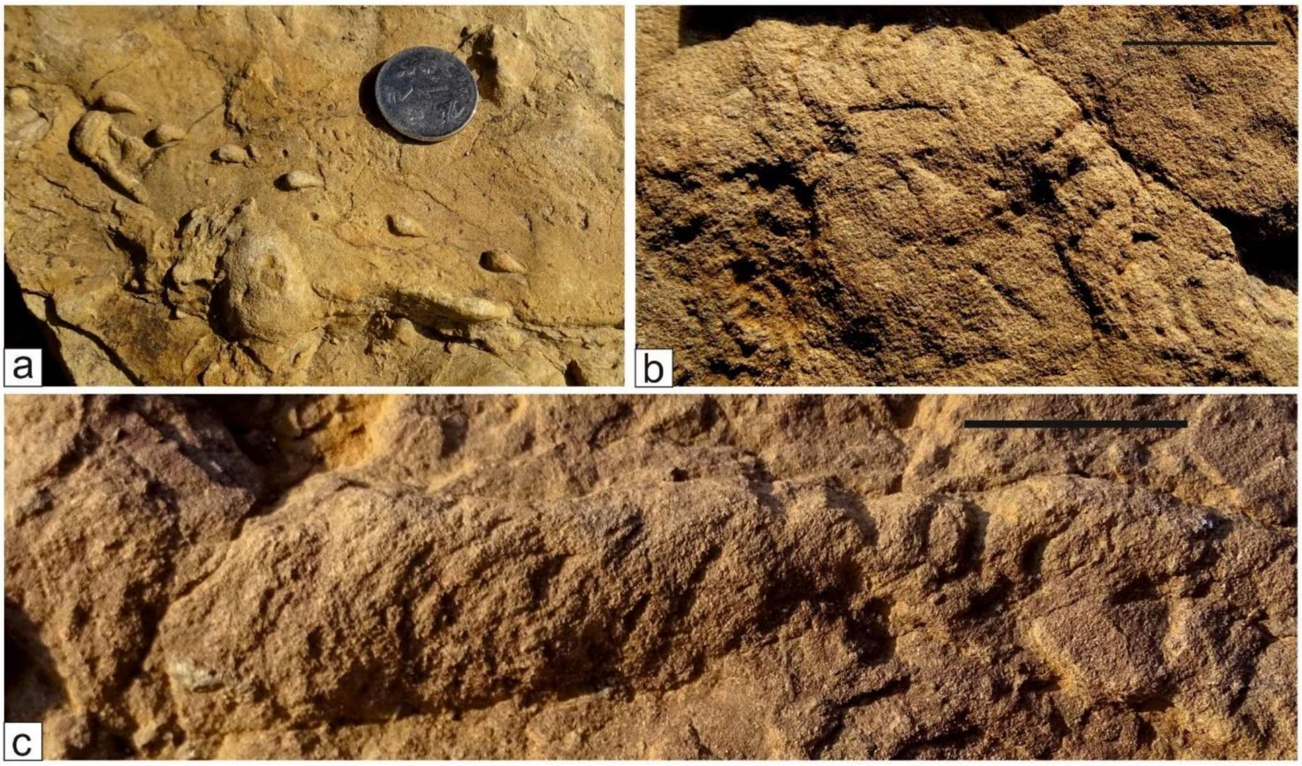

Plate 6.2 Cylindrical ridge-like active and/ or passively filled burrows. a. *Ptychoplasma vagans* hypichnion, stout, almond-shaped structures in sandstone-siltstone-shale facies, Vajepur Formation, Mogra village (coin diameter = 2.193 cm). b. *Taenidium serpentinum* serpentiform burrow with arcuate menisci in calcareous sandstone facies, Vajepur Formation, Devaliya village (Scale bar = 2 cm). c. *Taenidium barretti* unlined, unbranched, segmented cylindrical burrow in calcareous sandstone facies, Vajepur Formation, Devaliya village (Scale bar = 2 cm).

Occurrence: It occurs as hypichnia in the sandstone-siltstone-shale facies of Vajepur Formation, Mogra village.

Orientation: Subhorizontal

Branching: Unbranched

Shape: Cylindrical, ridge-like

Fill: Active

Burrow wall: Unlined

Ichnogenus: *Taenidium* HEER 1877

Diagnosis: Variably oriented, unlined or very thinly lined, unbranched, straight or sinuous cylindrical burrows consisting of segmented fill articulated by meniscus-shaped partings (D'Alessandro and Bromley, 1987) lack true branching, but secondary branching may occur (Keighley and Pickerill, 1994).

Ichnospecies: *Taenidium barretti* BRADSHAW, 1981

(Plate 6.2c)

Diagnosis: Straight to variably meandering, unbranched, unwalled, meniscate backfilled burrow. Menisci are commonly hemispherical or deeply arcuate, tightly packed or stacked, lacking compartmentalized backfill (Keighley and Pickerill, 1994).

Description: Horizontal, straight to curved, unbranched, unwalled, cylindrical meniscate burrow with irrregular boundary and preserved as endichnia. Menisci are diffuse, deeply arcuate, forming non-compartmentalized heterogeneous backfill. The width of the burrow range from 0.85 to 2.0 cm, and the length is about 9.2 cm. The burrow fill is homogeneous and similar to the host rock lacking fine-grained sediments and are less long and sinuous.

Interpretation: *Taenidium* differs from *Scoyenia* by lack of wall striations. D'Alessandro and Bromley (1987) originally recognized three ichnospecies, *T. serpentinum, T. cameronensis,* and *T. satanassi*. Forms initially considered to *Beaconites barretti* were later assigned to *Taenidiumbarretti* due to their unlined and unwalled nature (Keighley and Pickerill,1994). *Taenidium barretti* differs from other ichnospecies because of its uncompartmentalized nature and lack of distinct lining. The lack of well-spaced menisci, longer intermeniscate segments, and alternating meniscate of two sediment types distinguishes it from *T. serpentinum, T. cameronensis* and *T. satanassi* respectively. The meniscate fill is interpreted to be produced by ingestion and excretion of worm-like deposit-feeding organisms and compacting the sediment behind the body (Fürsich, 1974; see Díez-Canseco et al., 2016 and references therein) or by transport around the body during movement of the organism (Heinberg, 1974; Bromley and Asgaard, 1975) and with few ingestion evidence (Bradshaw, 1981) or by a combination of physical and ingestion process (Bromley and Asgaard, 1975; Pemberton and Frey, 1984). However, the fill resembling the host rock is non-ingested (D'Alessandro and Bromley, 1987), as observed in the present case. Keileigh and Pickerill (1994) suggested an external backfill process for the thinly and densely packed sediments. The trace maker of *Taenidium* is variable interpreted till date viz. burrows of less than 3 cm are assigned to variable trace makers, whereas burrows more than 3 cm wide are interpreted to be made by arthropods (Rolfe, 1980; Bradshaw, 1981; Pearson and Gooday, 2019)

Occurrence: It occurs as endichnia in the calcareous sandstone facies of Vajepur Formation, Devaliya village.

Ichnospecies: *Taenidium serpentinum* HEER 1877

(Plate 6.2b)

Diagnosis: Serpentiform *Taenidium* having sharp boundary and well-spaced, arcuate menisci; distance between the menisci is equal to or less than the burrow width. External moulds may show slight annulations related to the menisci or wrinkling. Secondary branching and intersections occur (D'Alessandro and Bromley, 1987).

Description: Curved, unbranched burrows parallel to the bedding, preserved in positive epichnia with fill similar to the host rock. Menisci are arcuate, regular in shape and spacing; distances between the menisci are much less than the burrow's width. The burrow is 7.0 cm long, and its width is almost constant, about 1.07 cm to 1.1 cm.

Interpretation: The present specimen differs from other species of *Taenidium* in having a homogeneous fill and well-spaced, moderately curved menisci. The determination of trace maker of *Taenidium* has remained problematic; however, it is related with the insects/larvae in the terrestrial environment, worm-like organisms (Fürsich, 1974; see Díez-Canseco et al., 2016 and references therein) and arthropods (Rolfe, 1980; Bradshaw, 1981; Pearson and Gooday, 2019).

Occurrence: It occurs as hypichnia in the calcareous sandstone facies of Vajepur Formation, Devaliya village.

Orientation: Subvertical

Branching: Unbranched

Shape: Cylindrical

Fill: Passive

Burrow wall: Lined

Ichnogenus: *Skolithos* HALDEMAN, 1840

Diagnosis: Unbranched, vertical or steeply inclined, cylindrical or subcylindrical, lined or unlined burrows, with or without funnel shaped top. Wall distinct or indistinct, smooth to rough, possibly annulated; fill massive; burrow diameter may vary slightly along its length (Schlirf, 2000).

Ichnospecies: *Skolithos linearis*, HALDEMAN, 1840

(Plate 6.3 a-b)

Diagnosis: Cylindrical to subcylindrical, perfectly straight and vertical to slightly curved or inclined burrows. Burrow wall distinct to indistinct may be annulated (Schlirf, 2000).

Description: Vertical, unbranched, cylindrical, isolated burrow, circular in cross-section; tubes straight to slightly inclined, unbranched, and unlined; oriented perpendicular to the bedding plane with a structureless fill identical to the host sediments. Burrow tubes lack funnel shape aperture, and tubes protrude on the surface (Plate 6.3b). The burrow wall is distinct and lacks ornamentation (Plate 6.3a). The Men River Valley specimen has a burrow length of 5.0 cm and a diameter of 1.24 cm. In contrast, the Navagam specimens are crowded on the surface (Plate 6.3b) and have a burrow tube diameter of 1.3 cm.

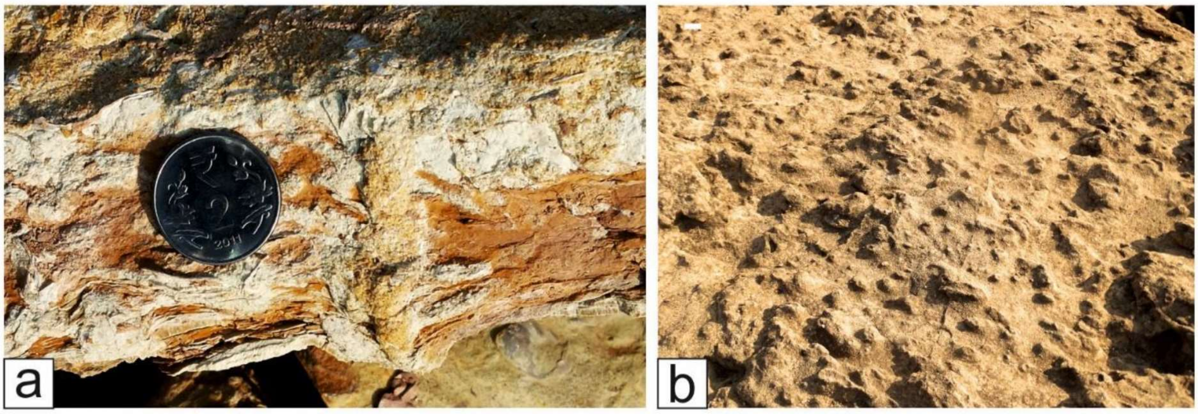

Plate 6.3 Vertical burrows of *Skolithos linearis.* a. Cylindrical, straight, unbranched burrows in fossiliferous limestone facies, Bilthana Formation, Bhekhadiya village(coin diameter = 2.7 cm)b. Top view of thickly-lined burrows in calcareous sandstone facies, Narmada Sandstone Member, Uchad Formation, Navagam village (Scale bar = 2 cm).

Interpretation: Ichnogenus *Skolithos* is characterized by a simple, cylindrical, circular aperture at the top of the bedding surface compared with funnel-shaped *Monocraterion*. Pemberton and Frey

(1984) suggested that *Skolithos* represent the dwelling burrows of suspension-feeding polychaete or phoroid in a marine environment (Alpert, 1974, Fürsich, 1974) or by insects and spiders in continental settings (Schlirf and Uchman, 2005 and references therein). *Skolithos* is typical of shallow marine high-energy settings and has a broad geographical and geological occurrence (Fillion and Pickerill, 1990).

Occurrence: It is preserved as full-relief in the wackestone of Bilthana Formation in Sultanpura and Bilthana village and the calcareous sandstone facies, Narmada Sandstone Member, Navagam village.

Orientation: Subvertical
Branching: Unbranched
Shape: Plug-shaped
Fill: Passive
Burrow wall: Unlined
Ichnogenus: *Bergaueria* PRANTL, 1945

Diagnosis: Cylindrical to hemispherical, vertical burrows with rounded base, lack ornamentation, circular to elliptical in cross-section, structureless fill, with or without central depression and radial ridges (Prantl, 1945).

Ichnospecies: *Bergaueria hemispherica* CRIMES, LEGG, MARCOS AND ARBOLEYA, 1977
(Plate 6.4 a-i)

Diagnosis: Bergauerians lack a shallow central depression (Crimes et al., 1977).

Description: Usually unornamented, vertical to inclined (35º–90º), cylindrical burrow with rounded base, preserved as hypichnia on the sole of sandy allochemic limestone facies (Plate 6.4b-i). The burrow fill is essentially structureless, and some specimens display faint, thin, equally spaced ring-like structures (Plate 6.4 c-d). The dimensions of 44 specimens have been measured (Table 6.2). The diameter (D) of the burrow ranges from 1.5 to 2.9 cm, and its height (H) varies from 0.5 to 4.0 cm. The measured specimen displayed variable D/H ratios; 29 specimens show D/H = 0.7–1.5, 11 specimens have D/H = 1.5–2 and, for 3 specimens, D/H exceeds 2.0 (Table 6.2).

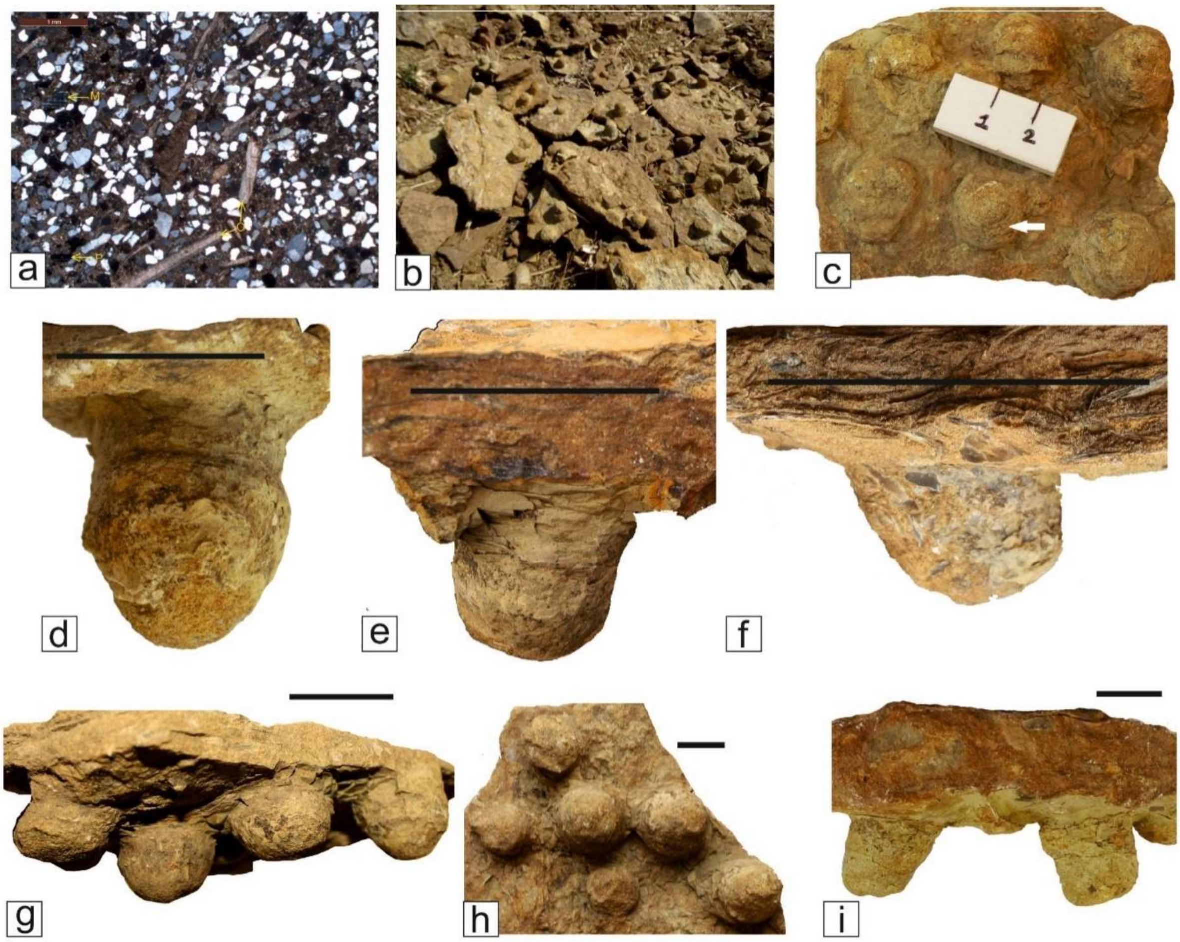

Plate 6.4 Photographs of burrow fill material and *Bergaueria hemispherica*. a. Photomicrograph of the burrow in 2.5× showing allochemic sandstone composition with microcline (M), plagioclase feldspar (F), and oyster shell fragments (O). b. Field photograph of inverted blocks of sandy allochemic limestone facies showing densely packed *B. hemispherica* burrows c. Close-up view of *B. hemispherica*. Note the overall size variation and the circular impressions (arrow) of circumferential muscles on the lower part of the burrow. Morphological variation of *B. hemispherica* showing d. Vertical burrow with subconical base and e. Slightly inclined burrow with rounded base showing contracted and relaxed state of muscles respectively. f. Inclined burrow showing infill of oyster shell fragments. g. Normal and h. Inverted view of vertical to sub-vertical burrows of different sizes, indicating different age groups of sea anemones; i. Normal view showing inclined burrows. Scale bar represents1.5 cm.

Interpretation: Based on morphological features such as thin wall lining and lack of ornamentation, the present specimens are identified as *B. hemispherica* (Crimes et al., 1977). The burrow occurs as hypichnia on the sole of oyster bearing sandy allochemic limestone facies within shale and is filled with allochemic sandstone and small bivalves shell fragments (Plate 6.4 a, f). The general shape is

Specimen No.	Diameter (D) cm	Height (H) cm	(D/H) Ratio
GEPBE01	2.32	2.3	1.01
GEPBE02	2.16	2	1.08
GEPBE03	1.68	0.9	1.87
GEPBE04	2.92	2.0	1.46
GEPBE05	2.35	2.4	0.98
GEPBE06	2.38	1.6	1.49
GEPBE07	1.78	0.9	1.98
GEPBE08	2.35	2.7	0.87
GEPBE09	1.9	1.7	1.10
GEPBE10	1.97	1.0	1.97
GEPBE11	2.32	2.1	1.10
GEPBE12	2.13	1.8	1.18
GEPBE13	1.93	1.3	1.48
GEPBE14	2.3	2.1	1.09
GEPBE15	2.1	1.1	1.90
GEPBE16	2.13	2.5	0.85
GEPBE17	2.03	1.0	2.03
GEPBE18	1.74	1.3	1.34
GEPBE19	2.25	1.4	1.61
GEPBE20	1.9	1.2	1.58
GEPBE21	2.57	1.3	1.98
GEPBE22	1.93	1.5	1.29
GEPBE23	2.13	2.7	0.79
GEPBE24	2.25	2.3	0.98
GEPBE25	1.87	1.0	1.87
GEPBE26	2.3	2.1	1.09
GEPBE27	1.78	1.5	1.19
GEPBE28	2.22	1.8	1.23
GEPBE29	1.84	1.0	1.84
GEPBE30	1.81	1.8	1.01
GEPBE31	2.06	2.0	1.03
GEPBE32	2.4	4.0	0.60
GEPBE33	2.54	3.2	0.79
GEPBE34	1.93	2.0	0.97
GEPBE35	1.81	2.3	0.79
GEPBE36	2.16	3.0	0.72
GEPBE37	1.9	2.5	0.76
GEPBE38	2.13	2.8	0.76
GEPBE39	1.49	0.5	2.98
GEPBE40	1.97	2.1	0.94
GEPBE41	1.62	1.0	1.62
GEPBE42	2.22	1.0	2.22
GEPBE43	2.16	1.7	1.27
GEPBE44	2.1	1.1	1.90

Table 6.2 Morphometry of the 44 specimens of *B. hemispherica*. Note: Height is highly variable as compared to diameter.

cylindrical to hemispherical, which resembles the ichnospecies *B. hemispherica* (Crimes et al., 1977). The holotype specimen described by Alpert (1973) shows a diameter of 5.5 and a depth of 1.4 cm, while the three specimens of *B. hemispherica* described by Hofmann et al. (1994) from the Cambrian of Arctic Canada are 2.5–5.0 cm wide and 1.0–2.7 cm long. The Late Cretaceous Bagh Group specimens show considerable variation in height, which causes variation in D/H compared to the type specimen. Pemberton et al. (1988) have noticed an overlap in diameter and height of plug-shaped burrows, but they evidenced consistency in the diameter/height (D/H) ratio; the considered *Bergaueria* has a diameter about twice the height. The numerical data (Table 6.2) of the 44 measured specimens of *B. hemispherica* reveals three specimens having diameters twice the height. In contrast, most specimens have diameters either less than or equal to the height. The specimens show significant variations in D/H but offer a high degree of similarity in morphological features, which have priority to consider as *B. hemispherica* (Crimes et al., 1977). The ichnogenus was also reported from the upper part of the Nimar Formation in ELNV by Singh (1982).

Occurrence: *B. hemispherica* is observed in the sandy allochemic limestone facies (oyster limestone) of the Bilthana Formation, Karvi village.

Orientation: Subvertical

Branching: Unbranched

Shape: Plug-shaped

Fill: Passive

Burrow wall: Lined/Unlined

Ichnogenus: *Conichnus* MYANNIL, 1966

Diagnosis: Conical, amphora-like, or acuminated subcylindrical structures oriented perpendicular to bedding plane; base may be rounded or exhibit a distinct, papilla-like protuberance. Fillings may reveal patterned internal structures such as chevron laminae but not radial medusoid symmetry.

Ichnospecies: *Conichnus conicus* MYANNIL, 1966

(Plate 6.5 a-c)

Diagnosis: Indistinctly to thinly lined conichians tapering to a smooth, rounded, but distinctly basal apex.

Description: Short conical, filled burrows with unornamented vertical shaft, circular in a transverse section, gently tapering and terminating in a smooth, rounded base. The height of the specimen is 42 mm, and the diameter of 27 mm; the diameter/height ratio is 0.64. (Plate 6.5 a and b); and 55mm height and diameter of 45 mm with diameter/height ratio is 0.81 (Plate 6.5 c). Burrow fill is carbonate mud (Plate 6.5 a-b) and siltstone (Plate 6.5 c). The lining is very thin but marks a distinct boundary between the cone fillings and the adjacent rock. Basal part smooth and rounded, without apical protuberance.

Interpretation: Specimens of *Conichnus* have been interpreted as the dwelling burrow of an anemone-like organism (Frey and Howard, 1981). The nested internal laminae in *Conichnus* burrows suggest that the trace maker kept pace with sedimentation by periodically moving upward in an aggrading substrate (Curran and Frey, 1977). The burrow in sandstone-siltstone-shale facies and sandy allochemic limestone facies is different from the overlying nonclastic sediments suggesting passive filling in low-energy shallow marine environments (Patel et al., 2018).

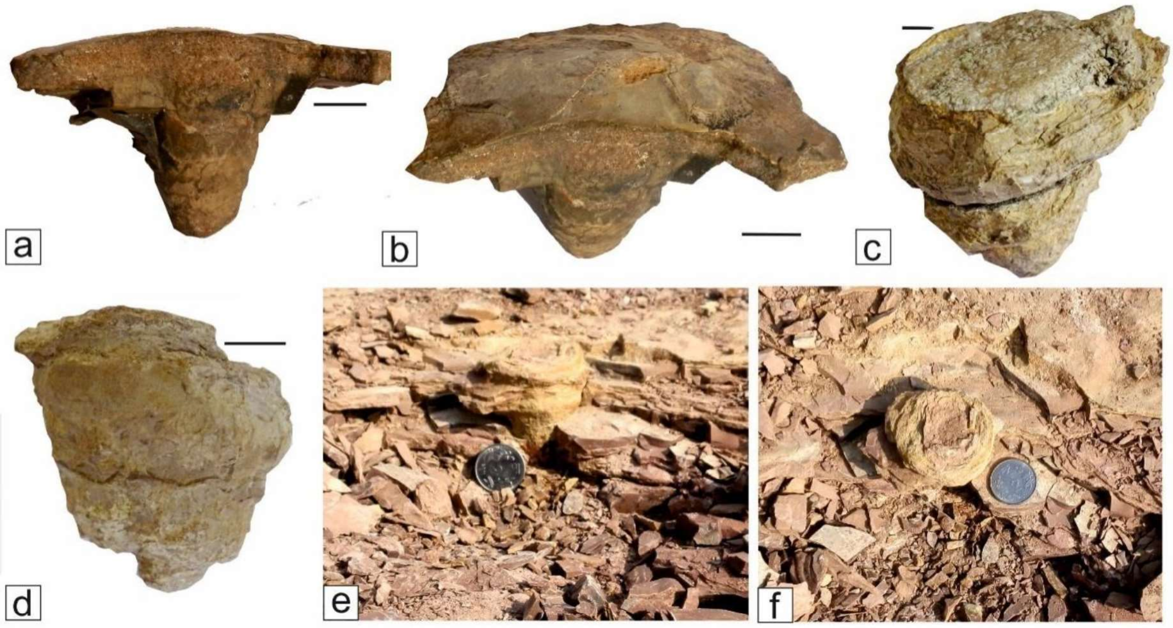

Plate 6.5 Photographs of plug-shaped burrows *Conichnus* and *Conostichus.* a. and b. Vertical view of *Conichnus conicus* displaying conical shape and passive filled burrow materials undiscerning the opening; c. Vertical view of *C. conicus* in rippled sandstone-siltstone-shale facies. d. Vertical view of *Conostichus broadheadi* with a prominent narrow apical protuberance in rippled sandstone-siltstone-shale facies. e. and f. Field photograph of *Conostichus stouti* in sandy allochemic limestone-shale facies. Scale bar represents 1 cm, and the coin’s diameter is 2.7 cm.

Occurrence: It is preserved as hypichnia with burrow fill different from host sediments. It occurs in sandstone-siltstone-shale facies of Vajepur Formation, Bhekhadiya village, and sandy allochemic limestone facies of Bilthana Formation, Uchad village.

Orientation: Subvertical

Branching: Unbranched

Shape: Plug-shaped

Fill: Passive

Burrow wall: Unlined

Ichnogenus: *Conostichus* LESQUEREUX, 1876

Diagnosis: Conical to sub-conical, vertical burrows, most of which display a duodecimal symmetry on the apex sides. Most walls are fluted by transverse constrictions and longitudinal ridges, and furrows. Well-developed apical disc and central sub-cylindrical core may not be present. Burrow fills may be structureless or composed of concentric conical or subconical laminae.

Ichnospecies: *Conostichus broadheadi* LESQUEREUX, 1880

(Plate 6.5 d)

Diagnosis: Strongly conical conostichians having well-developed longitudinal fluting; the apical disc is narrow and short and does not display prominent septation.

Description: Burrow appears as a short cone and possesses weakly developed longitudinal furrows and apical disc. It consists of a distinct knob-like structure at the apex. The diameter of the burrow is 38 mm, and the length is 40 mm. Diameter/height ratio is 0.95. The apical disc is small and narrow and does not display any septation. Burrow fill sediments are different from the host sediments. According to Pemberton et al. (1988), *Conostichus broadheadi* is the most distinctive ichnospecies of *Conostichus* and is strongly conical in shape. *Conostichus broadheadi* of the Late Cretaceous of Bagh Group comprises of small apical disc distinguishing it from the other plug-shaped ichnospecies like *Conostichus typicus,* which is characterized by extremely broad and flat apical disc (Harrington, and Moore, 1955).

Interpretation: *Conostichus broadheadi* occur in the rippled sandstone-siltstone-shale facies and is characterized by an inclined burrow opening with a small apical disc that lies below the inclined surface rather than the center. The weakly developed apical disc of *C. broadheadi* indicates that the animal dug the soft clastic fine-grained sediments at a shallow depth to stabilize using its smaller appendages. Later on, it periodically pushed the appendages by swirling action till the animal fully stabilized itself (Pfefferkorn, 1971). However, the position of the apical disc indicates that the animal holdfast the sediments which prevented uproot against the currents. The trace maker was a suspension feeder which burrowed in fine-grained clastic sediments and vacated it during the deposition of mixed carbonate-siliciclastic sediments in a shallow marine environment.

Occurrence: It occurs as hypichnia in sandstone-siltstone-shale facies of Vajepur Formation, Bhekhadiya village.

Ichnospecies: *Conostichus stouti* BRANSON, 1961

(Plate 6.6 a-b)

Diagnosis: Conical to sub-conical conostichians having well-developed transverse constrictions and short longitudinal furrows near the apex; the small apical disc is planar to slightly hemispherical and displays very weak septation.

Description: Conical-shaped structure having circular to slightly oblong cross-section at the burrow entrance while later part subconical. The structures reflect the anteroventral features of the trace producer and clearly show the different parts of the organism like capitulum, scapus, and physa. The burrow fills show thick concentric laminae (Plate 6.5 e-f, 6.6a-b, d, f) at the entrance (capitulum part) but the latter part shows faintly developed longitudinal striations (Plate 6.6 c and e) exteriorly throughout the structures (scapus and physa parts). Prominent transverse constrictions are lacking in the conical part. Two specimens of *C. stouti* are recovered from the Bhekhadiya village. The height of specimen 1 (Plate 6.5 e-f, 6.6 a-c) is 92 mm, and it shows concentric structures from the top to up to 25 mm; diameter varies from 52 to 60 mm (diameter/height ratio- 0.65), and decreases downward from 40 mm to 26 mm and again increases at the bulbous structure (physa part); apical bulbous structure attached with the core of the apex with a flat inclined surface-displayed variable diameter ranging from 28 mm to 15 mm. Specimen 2 (Plate 6.6 d-f) shows variable dimension (height-60 mm, diameter-25 mm, diameter/height ratio-0.41) with faintly developed striations on apical side. The infill material of the burrows is lime mud or siltstone, which is different than the host i.e., fine clastic sediments.

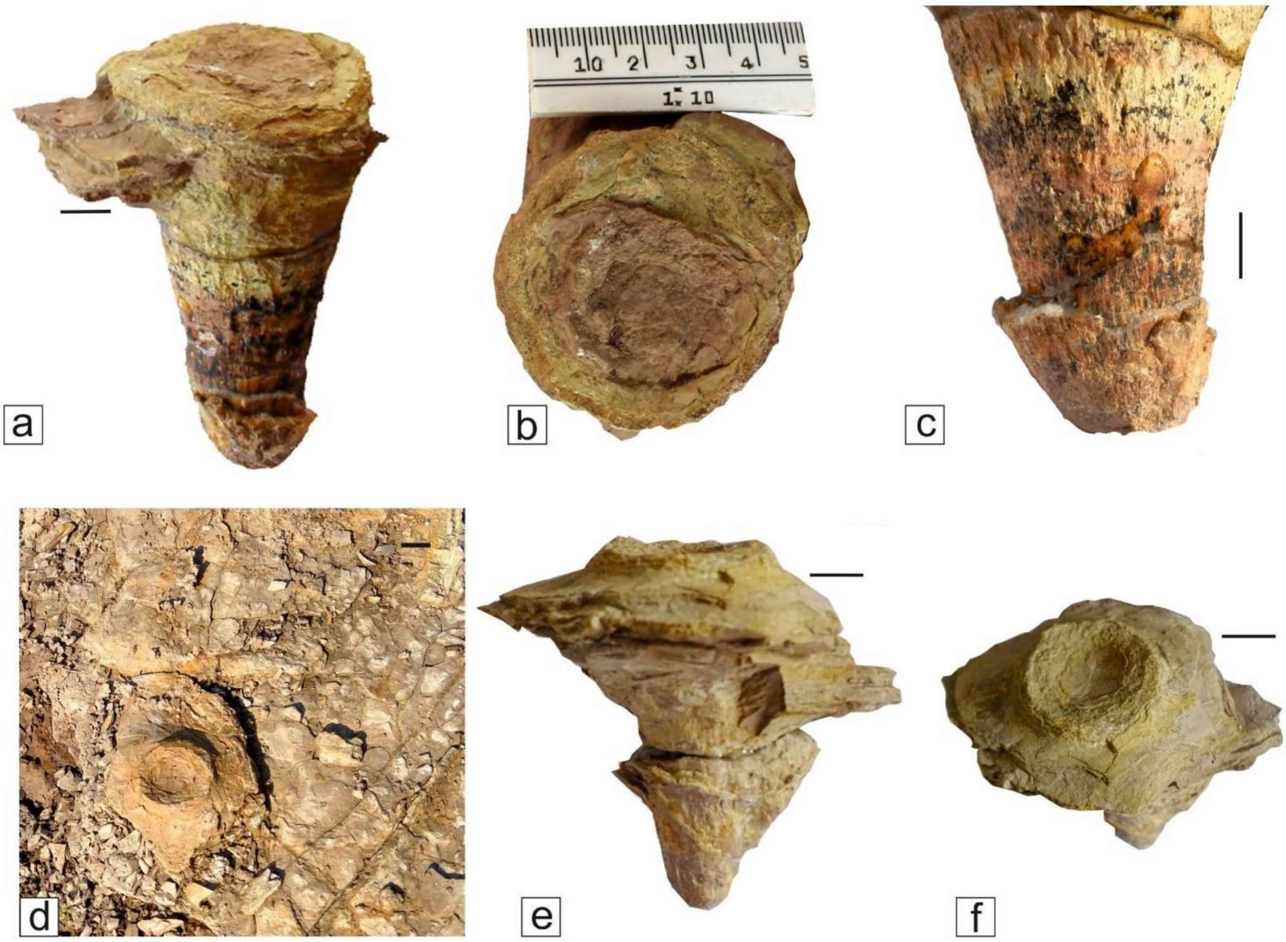

Plate 6.6 Photographs of plug-shaped burrow *Conostichus.* a. Vertical view of *Conostichus stouti* displaying concentric laminae at the top. b. The top view of *C. stouti* shows concentric filling with the argillaceous sediments. c. Close-up view of *C. stouti* displaying longitudinal striations and bulbous apex. d. Field photograph of *C. stouti* in sandstone-siltstone-shale facies. e. Vertical view of *C. stouti* displaying faintly developed longitudinal striae at the lower end of the burrow. f. Top view of *C. stouti.* Scale bar = 1 cm.

Interpretation: Pemberton et al. (1988) examined numerous specimens of *Conostichus,* indicating its overall geometry, and recognized five ichnospecies. The Bagh specimen shows the diameter generally one-half to three-quarters the height, which differentiates it from the ichnospecies *C. ornatus* and *C. broadheadi* having a diameter equal to the height and double the height, respectively. Accordingly, the presence of a subconical burrow form also differentiates it from the strongly conical burrow form *C. broadheadi* and subcylindrical burrow form *C. wycherlyi*; and the small narrow apical disc having weak septation differentiates it from *C. ornatus* and *C. typicus*. The sea anemones might have required a muddy substrate favoring its consistency, found in alternating lithologies i.e., intercalated sandstone-siltstone-shale/sandy allochemic limestone facies. The column of *Conostichus* specimens constitutes a subcylindrical core, and the physa is represented by the bulbous base, which accounts for several behavioral aspects of the burrowing anemones. The animal body parts, capitulum, scapus, and physa are reflected in the burrow structure.

Occurrence: It is preserved as hypichnia in the sandstone-siltstone-shale facies of Vajepur Formation and the sandy allochemic limestone facies of Bilthana Formation, Bhekhadiya village.

Orientation: Subvertical

Branching: Unbranched

Shape: Plug-shaped

Fill: Passive

Burrow wall: Unlined

Ichnogenus: *Lockeia* JAMES, 1879

Diagnosis: Bilaterally symmetrical traces; lower end with sharp median ridge; outline of hypichnion almond- or heart-shaped, tall vertical spreite may be present (Schlirf, 2000).

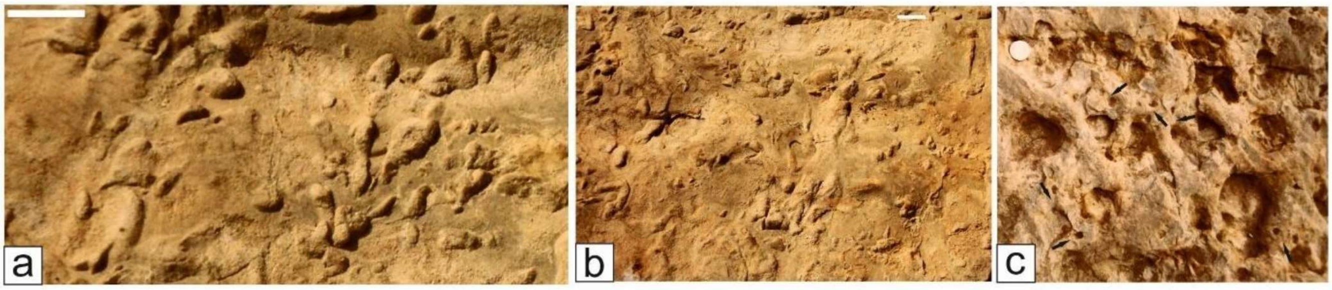

Plate 6.7 Subvertical unbranched burrows (coin diameter = 2.7 cm and Scale bar = 2 cm). a. *Lockeia cuncator* and b. *Lockeia siliquaria*, hypichnion, stout, almond-shaped structures in calcareous sandstone facies, Vajepur Formation, Uchad village. c. *Arenicolites* isp. paired openings of the burrow (marked with black arrows), mudstone facies, Nodular Limestone, Uchad village.

Ichnospecies: *Lockeia cunctator* SCHLIRF AND UCHMAN 2001

(Plate 6.7 a)

Diagnosis: Horizontal to oblique club-shaped or dumb-bell to almond-shaped probes more or less arranged in a row. Clubs diverge laterally, bilaterally, or semi-radially from the main axis of the row, all inclined in the same direction with respect to the row.

Description: Epichnial, horizontal to oblique dumb-bell shaped and almond-shaped probes, arranged in a row. The length and width of probes are irregular; length varies from 1.02 to 2.27 cm, and width ranges from 0.35 to 0.89 cm. Clubs diverge laterally from the central axis.

Interpretation: The lack of medial line and distorted shape of appendages separates it from the ichnogenus *Protovirgularia*. It is observed on the same slab on which *L. siliquaria* occurs, suggesting the ethological variability of the trace maker. According to Schlirf et al. (2001), *L. cunctator* indicates both locomotion and probing; the producer paused to probe the sediments and then moved forward. The almond-shaped forms are assigned to *Lockeia,* produced by the wedge-foot of resting bivalves, and the chevron-shaped forms to *Protovirgularia*, produced by the cleft-foot during locomotion (Uchman et al., 2011). Cabrere et al. (2019) marked that transitional irregular bilobate-shaped structures are difficult to be allocated to any anatomical part or behavioral activity of the bivalves. The enlargement of dumbells observed in the present specimen is interpreted to be due to the expansion of the foot during anchoring (Schlirf et al., 2001). It is also reported from the Jurassic rocks of the Jaisalmer Basin by Paranjape et al. (2013).

Occurrence: It occurs as epichnia in the calcareous sandstone facies of Vajepur Formation, Uchad village.

Ichnospecies: *Lockeia siliquaria* JAMES 1879

(Plate 6.7 b)

Diagnosis: Thin elongated to stout, bilaterally symmetrical, generally high relief almond-shaped to seed-like shaped, smooth hypichnial ridges, with strongly arcuate to almost obtuse terminations; occasionally showing vertical spreite(Schlirf et al., 2001).

Description: Small, stout, elongate mounds with smooth surface, tapered tip at both the ends, the outline of some mounds is not very distinct, semi-rounded nature at one of its ends; mounds are crowded, at few places they are slightly overlapping. The length varies from 0.81 to 2.67 cm; width ranges from 0.5 to 1.27 cm, and height is 0.38 cm.

Interpretation: *Lockeia* is the resting traces of the small burrowing pelecypods, possibly semi sessile forms (Osgood, 1970; Häntzschel, 1975). Stout shapes of mounds earlier regarded as *Lockeia amygdaloides* (Seilacher, 1953) are also observed on slabs on which narrower forms occur (Plate

6.7b). However, *L. amygdaloides* was considered a junior synonym of *L. siliquaria* (Seilacher and Selacher, 1994; Schlirf et al., 2001) based on the occurrence of all morphological shapes on the same slab. The almond to elongate shape structure of *Lockeia* differentiates it from the chevroned *Protovirgularia.* Isolated *Lockeia* structures are interpreted to be cubichnion produced by wedge-foot bivalves (Seilacher and Seilacher, 1994). The expansion of the bivalve foot in the protraction phase is observed to produce almond to oval-shaped structures peculiar to the ichnogenus *Lockiea* (Seilacher and Seilacher, 1994; Cabrera et al., 2019). According to Ekdale and Bromley (2001), *L. siliquaria* indicates the size and shape of the organism‘s shell, whereas *Protovirgularia* indicates the size and shape of the animal‘s foot. *Lockeia* is reported from fluvial to deep marine deposits (Kim, 1994). The ichnospecies *L. siliquaria* is also reported from the Jurassic rocks of the Kachchh and Jaisalmer basins (Joseph et al., 2012; Paranjape et al., 2013).

Occurrence: It occurs as epichnia in the calcareous sandstone facies of Vajepur Formation, Uchad village.

Orientation: Subvertical
Branching: Unbranched
Shape: U- and bow-shaped
Fill: Passive
Burrow wall: Lined/Unlined
Ichnogenus: *Arenicolites* SALTER, 1857

Diagnosis: Vertical U-shaped tubes without spreite (Fürsich, 1974) and two apertures above (Rindsberg and Kopaska-Merkel, 2003).

Ichnospecies:*?Arnecolites* isp.
(Plate 6.7 c)

Description: Endichnial, vertical to slightly inclined paired burrows of U-shaped with circular cross-section and paired opening, perpendicular to bedding, burrow fill is identical to the host sediment. Burrow diameter is about 1.21 cm, and burrow arms are approximately 0.96 cm apart.

Interpretation: Based on paired circular opening on the surface, it has been provisionally assigned to the ichnogenus *Arenicolites*; however, paired vertical U-shaped tubes could not be located to establish the diagnostic U-shaped form of the burrow. It differs from *Diplocraterion* in absence of spreiten (Fürsich, 1974). It is interpreted as dwelling structures of suspension-feeding organisms like polychaete worms, amphipod crustaceans, and insects (Häntzschel, 1975; Chamberlain, 1977; Fillion and Pickerill, 1990; Rindsberg and Kopaska-Merkel, 2005). *Arenicolites* is considered to be an opportunistic suspension feeder (Bromley, 1990) typical of a shallow marine environment (Crimes, 1977). *Arenicolites* is considered to be a facies-crossing form reported from marine and fresh-water environments and occur as suspension-feeding or surface deposit-feeding form active during increased and reduced sedimentation rate, respectively (Crimes, 1977; Bromley and Asgaard, 1979; Uchman, 1995).

Occurrence: This ichnospecies occurs as negative epichnia in the mudstone facies of Nodular Limestone, Uchad village.

Orientation: Complex
Branching: Branched
Shape: Boxwork
Fill: Passive
Burrow wall: Lined/Unlined
Ichnogenus: *Thalassinoides* EHRENBERG, 1994

Diagnosis: Three-dimensional burrow systems consist predominantly of smooth-walled, essentially cylindrical components of variable diameter; branches Y- to T-shaped enlarged at bifurcation points (Howard and Frey, 1984).

Ichnospecies: *Thalassinoides horizontalis* MYROW, 1995
(Plate 6.8 a-b)

Diagnosis: Branching framework of smooth-walled, unlined burrows. It has an entirely bedding-parallel orientation, absence of vertically oriented offshoots from polygonal frameworks, and the diameter of both inner and outer burrow walls is consistent within specimens, including a notable lack of constrictions or swellings at both junctions and inter-junction segments (Myrow, 1995; Blisett and Pickerill, 2004).

Description: Smooth walled, unlined, three-dimensional, Y-shaped junctions with sharp branching, parallel to the bedding, more or less uniform burrow diameter. Burrow consists of thin cylindrical straight arms that bifurcate at an angle of 80^0-130^0, with no swelling at bifurcation points. The structure length is 10-12 cm, and the diameter varies from 0.6-1.0 cm.

Interpretation: The burrows of *Thalassinoides horizontalis* are made by small crustaceans or soft-bodied organisms in firmground sediments, and the burrow diameter is less than 1.0 cm. Burrow oriented parallel to the bedding, consistent diameter and lack of swelling at Y-T junction, vertical or inclined offshoots, and scratches differentiate it from the other ichnospecies (Myrow, 1995).

Occurrence: It occurs as endichnia in the sandy allochemic limestone facies of Bilthana Formation, Gulvani village, and the calcareous sandstone facies of Vajepur Formation, Uchad and Vajepur villages.

Ichnospecies: *Thalassinoides paradoxicus* KENNEDY 1967

(Plate 6.8 c-d)

Diagnosis: Irregularly branched, subcylindrical to cylindrical burrows oriented variably with respect to bedding; T-shaped intersections more common than Y-shaped, and diameter of offshoots may differ from the parent trunk (Howard and Frey, 1984).

Description: Three dimensional branched complex boxwork burrow, irregularly branched, oriented at various angles with respect to the bedding plane. Bifurcation is common within short distances, forming complex boxwork patterns. Dimension of the burrow is highly variable in different burrow populations; it ranges from 2.5 to 3 cm at the point of bifurcation, and diameters of offshoots range from 1.0 cm to 2.7 cm. The small blunt proterburence indicates an abandoned tunnel (Plate 6.8 c).

Interpretation: The specimen differs from the other ichnospecies by its short blind tunnels. The highly variable and irregularly branched system of *T. paradoxicus* distinguishes it from *T. suevicus* (Fürsich, 1974), a horizontal form consisting of enlarged Y-shaped bifurcations, and from *T. ornatus,* which is a large form with tunnels. *T. paradoxicus* is characterized by more T-shaped bifurcations than Y-shaped and less swelling at the junctions than *T. suevicus* (Rodríguez-Tovar et al., 2017). *T. horizontalis* is a strictly horizontally oriented burrow with a uniform diameter. The maze work indicates vigorous exploitation of deposit feeders (Giannetti et al., 2007). The narrowing in the

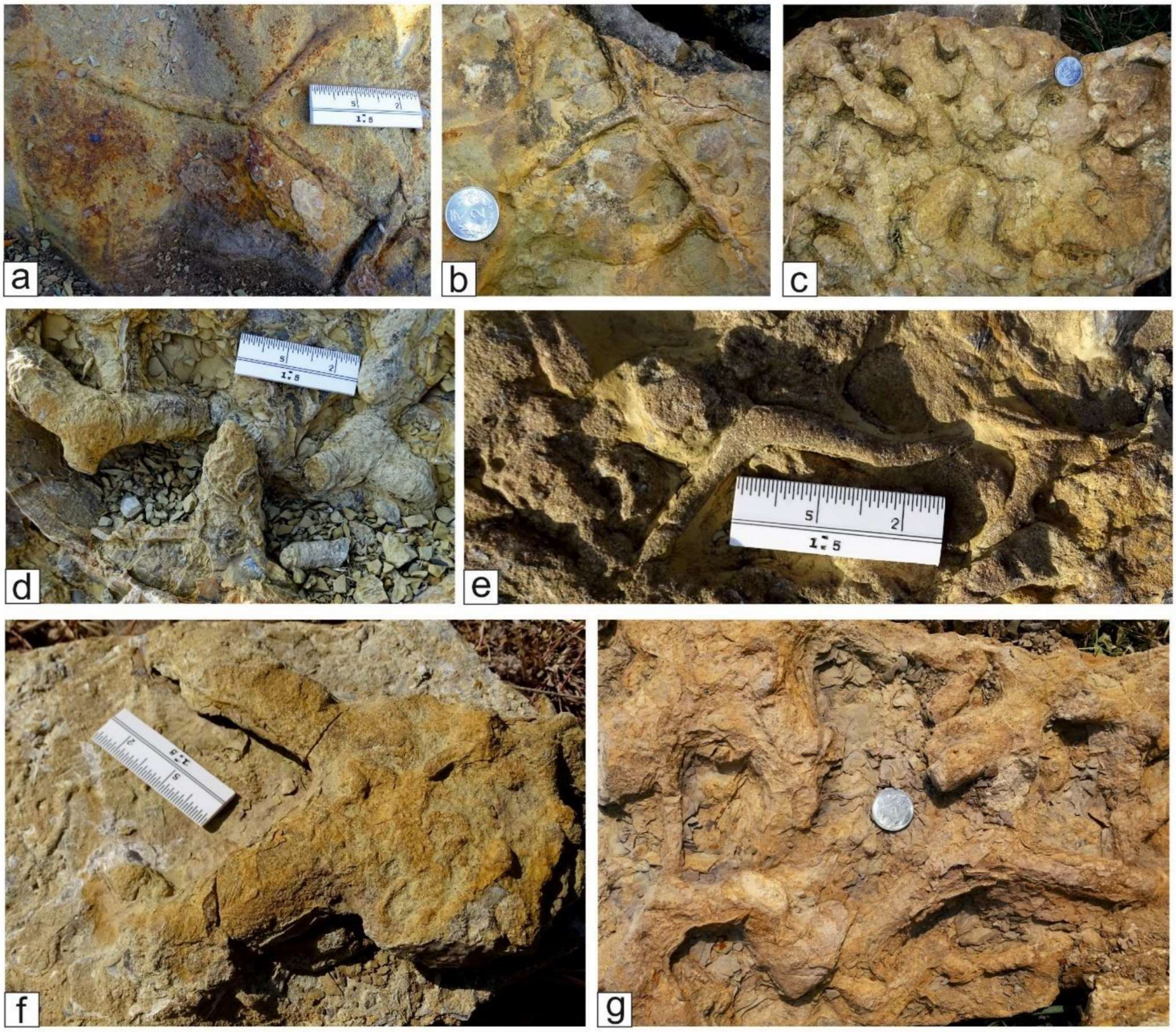

Plate 6.8 Maze and boxwork burrows of *Thalassinoides*. a. *T. horozontalis*, horizontal, straight, Y-shaped burrow, calcareous sandstone facies, Vajepur Formation, Uchad village. b. T-shaped sharp branching, calcareous sandstone facies, Vajepur Formation, Uchad village. c. *T. paradoxicus* displaying complex boxwork, irregular burrows, sandy allochemic limestone facies, Bilthana Formation, Uchad village. d. A close-up of *T. paradoxicus* displaying medium-sized tunnels and branches terminates at a short distance. e. *T. suevicus* displaying horizontal, curved tunnels and irregular branching in sandy allochemic limestone facies, Bilthana Formation, Uchad village. f. *T. suevicus* displaying swelling at bifurcation points in sandy allochemic limestone facies, Bilthana Formation, Bhekhadiya. g. *Thalassinoides* isp. displaying three-dimensional, curved tunnels, sandy allochemic limestone facies, Bilthana Formation, Bhekhadiya. Length of scale = 5 cm and Coin diameter = 2.7 cm.

cross-section of the burrows restricts the efficient water flow. Consequently, the organism depends strongly on the seafloor sediments for nutrition purposes (Giannetti et al., 2007), as observed in *T. paradoxicus* (Plate 6.8d). The presence of vertical and irregular branching in *T. paradoxicus* indicates the burrow required a firm, semi-consolidated substrate to avoid collapse of the burrow (Myrrow, 1995). It is interpreted to be a passively filled, fodinichnion burrow produced by crustaceans (Frey et al., 1984) or other types of arthropods (Ekdale, 1992). It is reported from Nimar sandstone Formation from the Bagh Group of ELNV by Sanganwar and Kundal (1997) and Kundal and Sanganwar (1998).

Occurrence: It occurs as endichnia in fossiliferous limestone facies of Bilthana Formation, Uchad, and Karvi villages and in the Nodular Limestone, Uchad village.

Ichnospecies: *Thalassinoides suevicus* REITH, 1932

(Plate 6.8 e-f)

Diagnosis: Predominantly horizontal, more or less regularly branched, essentially cylindrical burrow system; dichotomous bifurcations are more common than T-shaped branches (Howard and Frey, 1984).

Description: Full relief, horizontal cylindrical burrow system parallel to the bedding, burrow system consists of curved and straight tunnels. Y-shaped branching is more common than T-shaped bifurcations. The photographs of two specimens show varying dimensions; one structure is characterized by a circular knob (Plate 6.8f) whereby burrow arms radiate from approximately six directions, and the diameter is 3.0 cm. The other specimen (Plate 6.8e) is characterized by a gently curved arm with a variable diameter (1.0 to 1.6 cm). Burrow fill is passive, different from the host sediments.

Interpretation: *Thalassinoides suevicus* and *Thalassinoides horizontalis* are regularly branched, horizontal forms. However, the large burrow diameter and enlarged Y-shaped bifurcation separate *T. suevicus* from the *T. horizontalis, T. paradoxicus, T. saxonicus,* and *T. ornatus*. The *Thalassinoides* occur at the middle position in the tier; however, the ichnospecies *Thalassinoides suevicus,* when occurs in sand deposits, indicates a shallow tier (Bromley, 1996) and is abundant in the silicified Chalk deposits of Cretaceous (Bromley and Ekdale, 1984). The absence of vertical components in *Thalassinoides suevicus* suggests the trace maker was a surface deposit feeder which depended mainly on the organism on the seafloor (Giannetti et al., 2007). *Thalassinoide*s is produced by crustaceans, mainly decapods (Frey et al., 1984). The enlargement of burrow walls at junctions and other places is interpreted to be due to the turning around of the shrimps or crustaceans unable to move bi-directionally (Frey et al., 1984; Ehrenberg, 1994).

Occurrence: It occurs in the sandy allochemic limestone facies of Bilthana Formation, Bhekhadiya and, Uchad villages.

Ichnospecies: *Thalassinoides* isp.

(Plate 6.8 g)

Description: Endichnial, full relief, horizontal to slightly oblique Y-shaped burrow system, diameter about 2.0 cm. It consists of short, regularly branched, curved arms. Preservation does not warrant classification at the ichnospecies level.

Interpretation: Due to its curved nature of branching and absence of visible vertical components, this specimen is kept open as *Thalassinoides* isp. According to Frey et al. (1984), *Thalassinoides* is a facies crossing form produced by crustaceans and indicates the shallow marine environment mainly reported from the Paleozoic and Mesozoic; however, occurrence in deep water in Tertiary are also reported (El-Sabbagh et al., 2017 and references therein).

Occurrence: *Thalassinoides* isp. occurs as endichnia in the sandy allochemic limestone facies, Bilthana Formation, Bhekhadiya village, and in fossiliferous limestone of Bilthana Formation, Uchad village.

6.2.2 TRAILS

Orientation: Horizontal

Lateral Elements: Unary

Shape: Straight or Curved

Fill: ---

Burrow wall: ----

Ichnogenus: *Archaeonassa* FENTON AND FENTON, 1937a

Diagnosis: Trails consist of regularly convex furrows bounded by low, narrow, subangular ridges. The furrows are smooth only in those trails, modified by water action. Others are crossed by rounded to subangular wrinkles, which are convex in the anterior direction. Burrows are round, oval, or irregularly elongate, deeper at one end than at the other; they generally terminate indistinct trails. They are distinct from round, abrupt pits and low mounds, which seem to be the work of annelids (Fenton and Fenton, 1937a).

Ichnospecies: *Archaeonassa* cf. *fossulsata* FENTON AND FENTON, 1937a

(Plate 6.9 a)

Diagnosis: Same as for ichnogenus

Description: Medium, horizontal, curved, epichnial trails lacking orientation. It has low relief, flattened, and broad central area but poorly preserved transverse ornamentation. The margins of the burrows are slightly elevated. The length of the trail is around 44.0 cm and is 2.0 - 2.5 cm wide.

Interpretation: The present specimen resembles *Archaeonassa fossulsata* but has poorly preserved faint transverse ridges in the central area and lacks transverse or oblique ornamentation on the ridges. It differs from bilobate *Gyrochorte* in lack of obliquely aligned plaited lobes, and the lack of back-filled nature differentiates it from *Scolicia* group trace fossils viz. *Psammichnites, Palaeobullia*. It shows variation in width and has a broad central region and hence resembles *Archaeonassa* type A species of Schatz et al. (2013) produced by gastropods. The trace maker of *Archaeonassa* is highly debated. Initially, it was interpreted as a grazing trail made by gastropods, echinoderms, or trilobites (Fenton and Fenton, 1937a; Buckman, 1994; Stanley and Feldmann, 1998; Häntzschel, 1975. Yochelson and Fedonkin (1997) proposed arthropods to be trace makers. Later Jensen (2003) suggested a molluscan origin for the trace.

Occurrence: It occurs as negative epichnia in the muddy micrite of Bilthana Formation, Uchad village.

Ichnospecies: *Archaeonassa* isp.

(Plate 6.9 b-d)

Description: It is crowded, long, horizontal, narrow, straight to gently curved epichnial grooves, V-shaped in cross-section, crossovers are common and abrupt termination in many trails. Prominent leeves characterize it on either side of the trail all along the length. It spread on top of the ripple calcareous sandstone where attained maximum length is 300 cm (Plate 6.9b) and width of 0.6-1.54 cm.

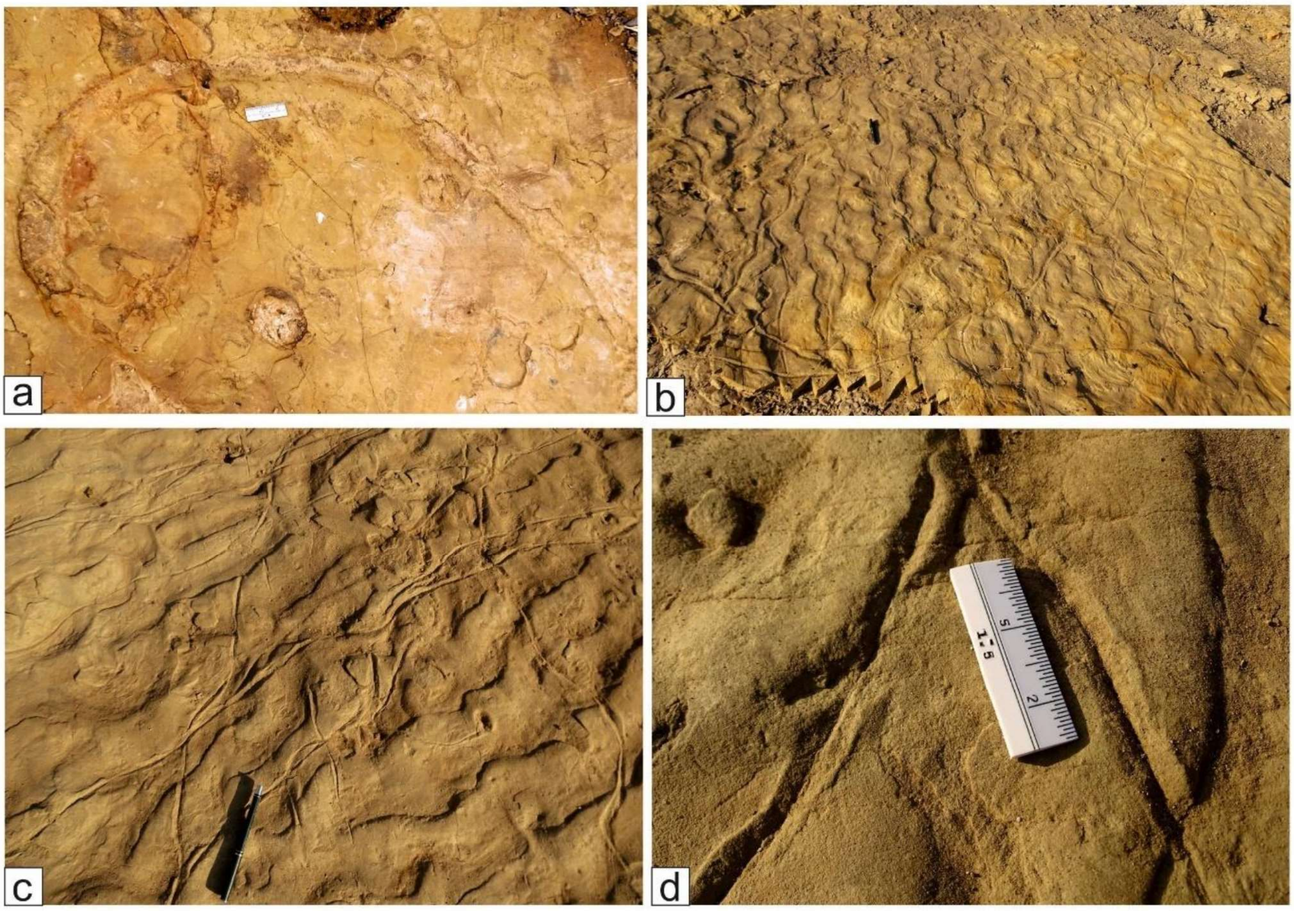

Plate 6.9. Photographs of *Archaeonassa* trails. a. *A. fossulata* with curved faint transverse ridges, muddy micrite, Bilthana Formation, Uchad village. b. *A.*isp., long narrow meandering trails on sinuous crested, rippled calcareous sandstone facies, Vajepur Formation, Devaliya village (length of pen = 15 cm). c. Trails showing cross-covers (length of pen = 15 cm) and d. Close-up of *Archaeonassa* isp.

Interpretation: Morphological characteristics described herein allow the ascribing the trail to *Archaeonassa fossulata,* but due to the lack of convex parallel ridges on both sides, it is placed under open ichnospecies level. It is synonymous with the *Archaeonassa* type C specimen of Schatz et al. (2013) and differs from type A and type B specimens due to deep narrow central depression. It differs from other horizontal trails like *Gordia,* which consists of characteristic loop nature, ribbon-like and lacks meandering; *Circulichnus,* which is knotted, cylindrical, winding ring; *Cochlichnus,* which is a thin epichnial meandering groove or hypichnial meandering ridges; *Helminthoidichnites* which is slightly winding, irregular ribbon-like and consist of occasional loops; *Helminthopsis* which is loosely meandering lacking loops but is hypichnial. *Archaeonassa* has been reported on the modern seafloor of Maktak, Coronation, and North Pangnirtung Fjords (Schatz et al., 2013) and interpreted to be produced by gastropods living in intertidal environments (Häntzschel, 1975; Buckman, 1994).

Occurrence: It is preserved as negative epichnia on the rippled calcareous sandstone facies of Vajepur Formation, Devaliya village.

Orientation: Horizontal
Lateral Elements: Unary
Shape: Straight or Curved
Fill: ---
Burrow wall: ----
Ichnogenus: *Helminthoidichnites* FITCH, 1850.

Diagnosis: Horizontal, small, thin, unbranched, simple, straight or curved, irregularly meandering or winding trails or burrows with occasional loops that commonly overlap among specimens but lack self overcrossing (Schlirf et al., 2001).

Ichnospecies: *Helminthoidichnites tenuis* FITCH, 1850
(Plate 6.10 a-b)

Diagnosis: Same as for the ichnogenus

Description: Horizontal, slender, unbranched, straight to slightly curved trail. Fill resembling the host rock. Diameter ranges from 0.3- 0.56 cm; maximum observed length is 40 cm. Diameters are constant within the individual trail. Trail cross-over each other (Plate 6.10 a-b).

Interpretation: It differs from similar-looking *Helminthopsis* and *Gordia* in lacking meanders and loops, respectively and possessing straight to slightly curved paths (Hofmann, 1990; Hofmann and Patel, 1989). It can be differentiated from *Helminthoidichnites multilaqueatus,* which is curved to multithreaded densely packed trails or burrows. The present specimen lacks the zigzag burrow shape and projections/offshoots of *Treptichnus bifurcus*. The burrows are a grazing trail produced by arthropods, nematomorphs, or insect larvae (Buatois et al., 1997; Schlirf et al., 2001; Uchman et al., 2009). However, an arthropod as a trace maker can be excluded if the specimen lacks two sets of densely packed oblique striations (Martín and Netto, 2018). Based on the transitions observed from *Gordia*to *Helminthoidichnites*, Gaigalas and Uchman (2004) suggested the same tracemaker.

Occurrence: It occurs as epichnia on the planar cross-stratified sandstone facies of Vajepur Formation, Kara River, Vajepur village.

Orientation: Horizontal

Lateral Elements: Unary

Shape: Winding with loops

Fill: ---

Burrow wall: ----

Ichnogenus: *Gordia* EMMONS, 1844.

Diagnosis: Smooth, cylindrical or subcylindrical, non-branching, winding, and irregularly curving burrows, commonly self-overcrossing.

Ichnospecies: *Gordia marina* EMMONS, 1844

(Plate 6.10 a)

Diagnosis: *Gordia,* in which level crossing is fully developed and meanders are unguided (Miller, 1989; Fillion and Pickerill, 1990; Uchman, 1998).

Description: Irregularly winding, horizontal, thin, unbranched burrows of uniform meander with cross-overs resulting in loops. Fill resembles the host rock. Preserved length of the burrow is about 25 cm, and the diameter ranges from 0.3 to 0.4 cm.

Interpretation: The presence of cross-overs differentiates it from *Helminthopsis* and *Helminthoidichnites*. The lack of median and transverse internal structures differentiates it from the meandering *Psammichnites*. The present specimen differs from *Gordia meandria,* which has a broader diameter and subtriangular shape in cross-section, and from *Gordia molassica,* which occurs as a discontinuous string. The ichnogenus is interpreted variably and assigned to be pascichnion, repichnion, or fodinichnion produced by worms, insect larvae, or gastropods (Gaigalas and Uchman, 2004; Wang et al., 2009 and references therein). *Gordia* is a facies crossing form reported from non-marine and marine settings (Pickerill et al., 1984; McIlroy, 1998; Gaigalas and Uchman, 2004).

Occurrence: It occurs as epichnia on the planar cross-stratified sandstone facies of Vajepur Formation, Vajepur village.

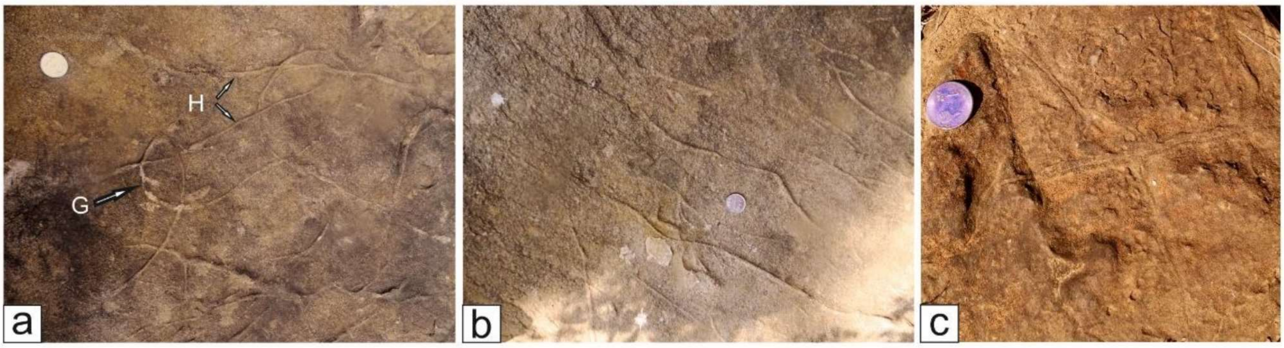

Plate 6.10 Photographs of winding and straight trails (coin Diameter = 2.193 cm). a. *Gordia* (G) and *Helminthoidichnites* (H) occurring as epichnia on the quartz arenite, Songir Formation, Vajepur section. b. *Helminthoidichnites* on the same bed. C. *Didymaulichnus* cf. *lyelli* longitudinally bisected trails in calcareous sandstone facies, Vajepur Formation, Mathsar village.

Orientation: Horizontal
Lateral Elements: Binary
Shape: Straight or Curved
Fill: ---
Burrow wall: ----
Ichnogenus: *Didymaulichnus* YOUNG, 1972

Diagnosis: Smooth, furrow-like horizontal trails or burrows, bisected longitudinally by a narrow median groove if preserved in hypichnia (Fillion and Pickerill, 1990).

Ichnospecies:*Didymaulichnus* cf. *lyelli* ROUAULT, 1850
(Plate 6.10 c)

Diagnosis: Same as for ichnogenus.

Description: Horizontal, simple, smooth, straight to slightly curved, bilobate trails, 0.83- 0.27 mm wide, parallel to bedding, lobes are flat separated by a distinct furrow. Trails are narrow and overlap; the maximum observed length is 17-18 cm.

Interpretation: *Didymaulichnus* differs from bilobed *Gyrochorte* in lack of transverse meniscii on the lobes. The lack of rounded ridges (sharply defined lateral margins, Yochelson and Fedonkin, 1997) and width of central furrow more than the ridges differentiate it from *Archaeonassa,* and the absence of scratches distinguishes it from *Cruziana.* The trace producer of the *Didymaulichnus* is variably interpreted as mollusks (Glaessner, 1969; Häntzschel, 1975; Vossler et al., 1989) arthropods, specifically trilobites (Crimes and Herdman, 1970; Bradshaw, 1981) or worms (Zonneveld et al., 2012). Based on the morphological characteristics, gastropods as probable trace makers are suggested. *D. lyelli* differs from *D. alternatus* and *D. tirasensis* characterized by alternating deepening and shallowing segments, and *D. miettensis* and *D. rouaulti* in lack of lateral bevels or grooves. The absence of pits distinguishes it from *D. nankervisi.* The ichnogenus is reported from the offshore and marginal marine (tidal flat, deltaic and lagoonal) environments (see Ding et al., 2020 and references therein). It has also been reported from the Middle-Late Jurassic deposits of the Kachchh Basin, Western India (Darngawn et al., 2018; Joseph et al., 2020).

Occurrence: Occurs as epichnia on the calcareous sandstone facies, Vajepur Formation, Mathsar village.

6.2.3 TRACKWAYS

Orientation: Horizontal
Lateral Elements: Biserial - One Track
Shape: Bract-like
Fill: ---
Burrow wall: ----

Ichnogenus: *Oniscoidichnus* BRADY, 1949

Diagnosis: Track with low, sinuous median ridge and forward-pointing bract-like footprints on each side at 1mm interval; width of track about 1cm.

Ichnospecies: *Oniscoidichnus communis* CHIPLONKAR AND BADVE, 1970
(Plate 6.11 a-c)

Diagnosis: Trails have a depressed central axis with a small central ridge, fine longitudinal striations along the entire length of the trail, the variable shape of footmarks such as lobes, arcuate to sickle-shaped, seen on both the sides.

Plate 6.11 Trackways in sandstone-siltstone-shale facies (Scale bar = 1.0 cm and coin diameter = 2.7 cm). *Oniscoidichnus communis* track with tear-shaped appendages and median ridge occurs as a. Gently curved, Vajepur Formation, Mogra village. b. Appears strongly curved with prominent median ridge, Vajepur Formation, Bhekhadiya village. c. Zig-zag trail with poorly preserved median ridge, Vajepur Formation, Bhekhadiya village.

Description: Track with low sinuous to strongly curved median ridges and forward pointing footprints on each side. Length is variable in different specimens, it is about 12 cm, and the width is 1.2 cm (Plate 6.11a) whereas, in other specimens, the length ranges 12- 24 cm and width from 1.0-2.6 cm (Plate 6.11c); medial line present. Lateral elements of drop like or elongated that converge on the trace axis. According to Chiplonkar and Badve (1970), *O. communis* differs from *O. filiciformis* (Brady, 1949) based on close footmarks. The present specimen differs from the similar-looking *Cruziana, Nereites,* and *Psammichnites,* lacking scratch markings in the chevrons, wide median furrow, and median dorsal structure, respectively.

Interpretation: Brady (1949) interpreted *Oniscoidichnus* as an isopod trackway because of its resemblance to modern isopod *oniscus*. *Oniscoidichnus* can indicate the habituation of invertebrates in opportune terrestrial environments (Buatois et al., 1998). *Oniscoidichnus* indicates locomotion and shallow feeding. The small footprints and sharp turns are suggestive of a small-bodied organism.

Occurrence: All the traces are preserved as epichnia on the sandstone-siltstone-shale facies of Vajepur Formation, Mogra, and Bhekhadiya villages.

6.2.4 BIOEROSIONAL

Orientation: Complex

Branching: Unbranched

Shape: Clavate

Fill: ---

Burrow wall: Unlined

Ichnogenus: *Apectoichnus* DONOVAN 2018

Diagnosis: Elongate borings, commonly circular in section, smooth-sided, straight or sinuous to contorted and intertwined, with or without a calcareous lining. The boring may change direction and cause a constriction of the tube, but tubes are common of more or less constant diameter. May be solitary or gregarious (Donovan, 2018).

Ichnospecies: *Apectoichnus longissimus* KELLY AND BROMLEY 1984

(Plate 6.12 a-b)

Diagnosis: Same as for ichnogenus

Description: Full relief, preserved as clusters, tightly-spaced, strongly elongated straight to curved borings, some short borings of irregular shape also seen. Ellipsoidal, flattened and/or distorted cross-section. The length and width of boring are highly variable and range from 6 to 14 cm and 1.0 to 2.0 cm, respectively. Borings are parallel to subparallel to the bed surface and have fill identical to the host rock. Few borings have sharp boundaries with oxidized rims and tapering at one or both ends or with rounded termination.

Interpretation: *Teredolites* initially included two ichnospecies, *T. clavatus,* and *T. longissimus.* Donovan (2018) suggested the two ichnospecies do not share any common form but are included in the same ichnogenus considering their similar substrate (wood). Donovan (2018) also suggested that if the importance of substrate is to be denied, the two ichnospecies can be separated at the ichnogeneric level, and *T. longissimus* is considered to be the type ichnospecies of *Apectoichnus*.

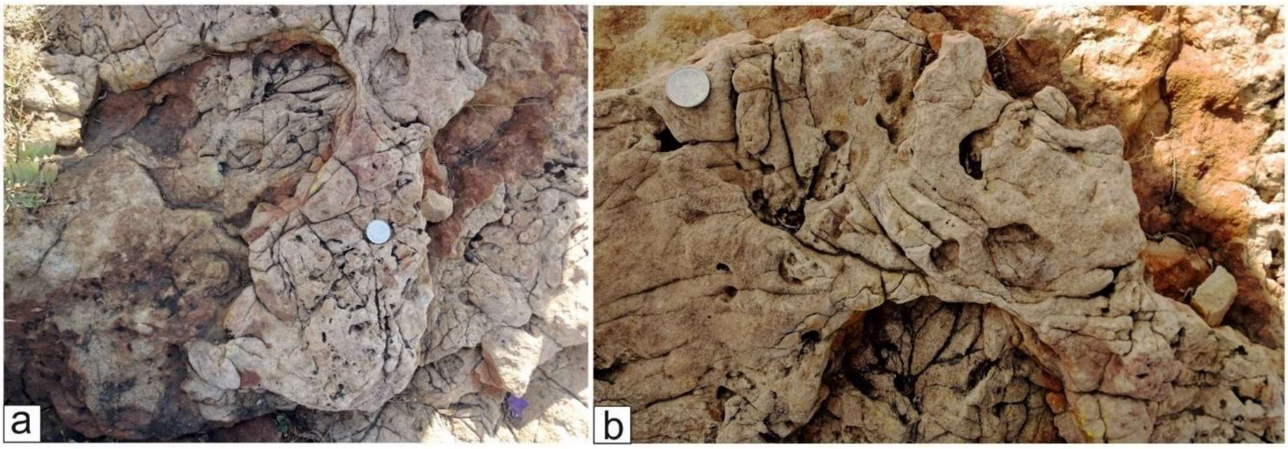

Plate 6.12 Bioerosional structure, *Apectoichnus longissimus*.a. shows variable shapes of borings in quartz arenite facies, Songir Formation, Songir section. b. Close-up of *A. longissimus* showing cylindrical to ellipsoidal boring.

Later Donovan and Evin (2018) transferred *T. clavatus* to *Gastrochaenolites* Leymerie (1842). *A. longissimus* can be differentiated from *Gastrochaenolites clavatus* (formerly *Teredolites clavatus*) based on the slender nature of borings (L:W ratio >5) as described by Kelly and Bromley (1984). Recently, Mayoral et al. (2020) identified the occurrence of *T. clavatus* in amber and contested one more host substrate. The lack of scratch marks differentiates some tongue-shaped Bagh specimens from *Glossifungites*. The ichnospecies *A. longissimus* is associated with *Teredinidae* bivalves (Savrda and King, 1993; Gingras et al., 2004; Kříž and Mikuláš, 2006) which are efficient filter feeders but are obligate wood-eaters (Shipway et al., 2019). However, its occurrence in the lithic substrate suggests its capability to ingest sandy substrate into which it bores. A similar exception to the occurrence of *Teredinidae* bivalves in the xylic substrate with shipworms efficiently boring the carbonate lithic substrate is demonstrated by Shipway et al. (2019). *Apectoichnus* and *Teredolites* are reported from marine and brackish settings (see Mayoral et al., 2020 and references therein). Shipway et al. (2019) reported *Teredinidae* bivalves in freshwater fluvial environments. Based on the variable axes of *Gastrochaenolites* or *Apectoichnus* Shipway et al. (2019) concluded phobotactic behavior of the trace maker and competition for limited space; are equally applicable to the Bagh specimens.

Occurrence: It occurs in the quartz arenite facies of Songir Formation, Chametha-Chosalpura villages.

6.3 UNDETERMINED BRANCHED MEANDERING BURROWS

Description: Horizontal to subhorizontal, branched meandering burrows. The irregularly spaced loops show sharp turns at places. Closely-spaced second-order loops branch from the first-order. It has a main shaft that curves outward and laterally branches (Plate 6.13) in the distal part with lined walls (Plate 6.13b, g), branches recurved, overall shows a dendritic pattern (Plate 6.13b), burrow walls lined, annulated at places (Plate 6.13g), burrows are filled with host sediments. The length of the burrows is highly variable, 10-15 cm long and width of 0.5 to 1.5 cm. Definite terminations not recognized.

Interpretation: The uneven spacing and branched nature of the structures in the present specimen differentiates it from *Helminthoida,* which is a tightly spaced, non-branching structure. The present specimen differs from other meandering ichnogenera like *Olenichnus* in having burrow-fill similar to the enclosing host rock and from the ichnospecies of the *Scolicia* group (*Taphrhelminthopsis, Taphrhelminthoida, Scolicia*) in lack of bilobate ridge and a medial groove. The structure displays a second-order branching loop with sharp turns from the center or the first-order loop (Plate 6.13 f-e). It thus differs from grapholgyptid ichnotaxa (*Cosmorhaphe, Helminthorhaphe, Lorenzia, Paleodictyon, Spirohaphe, Arabesca, Urohelminthoida*). The specimen resembles *Protopaleodictyon* but lacks net structure and appendix branching from the apex. It is separated from *Vagorichnus* due to the lack of ridge-like knob in the structure, while the lack of central furrow distinguishes it from *Nereites*. It can be easily distinguished from winding *Helminthopsis, Helminthoida,* and *Cochlichnus* burrow by its branched nature, from *Megagrapton* and *Multina* due to lack of net/polygon like structure, and *Paleomeandron* due to lack of rectilinear secondary meanders. The meniscate structure seen at a few places (Plate 6.13g) resembles the burrows of *T. serpentinum.* Similar traces were reported by Badve and Ghare (1980) from the Bagh Group rocks exposed south of the Narmada River. Badve and Ghare (1980) erected new ichnogenus and species *Annetuba chapdiensis* for the curving burrows with slightly raised margins. Half of the burrow is preserved as negative epichnia and half as endichnia; the burrows lack vertical shaft and tunnel filling with cross annulations, differentiating it from *Keckia* and *Micatuba*. Badve and Ghare (1980) erected new ichnospecies *Imponoglyphus kevadiensis* for the curved beaded chains observed on the same horizon but adjacent

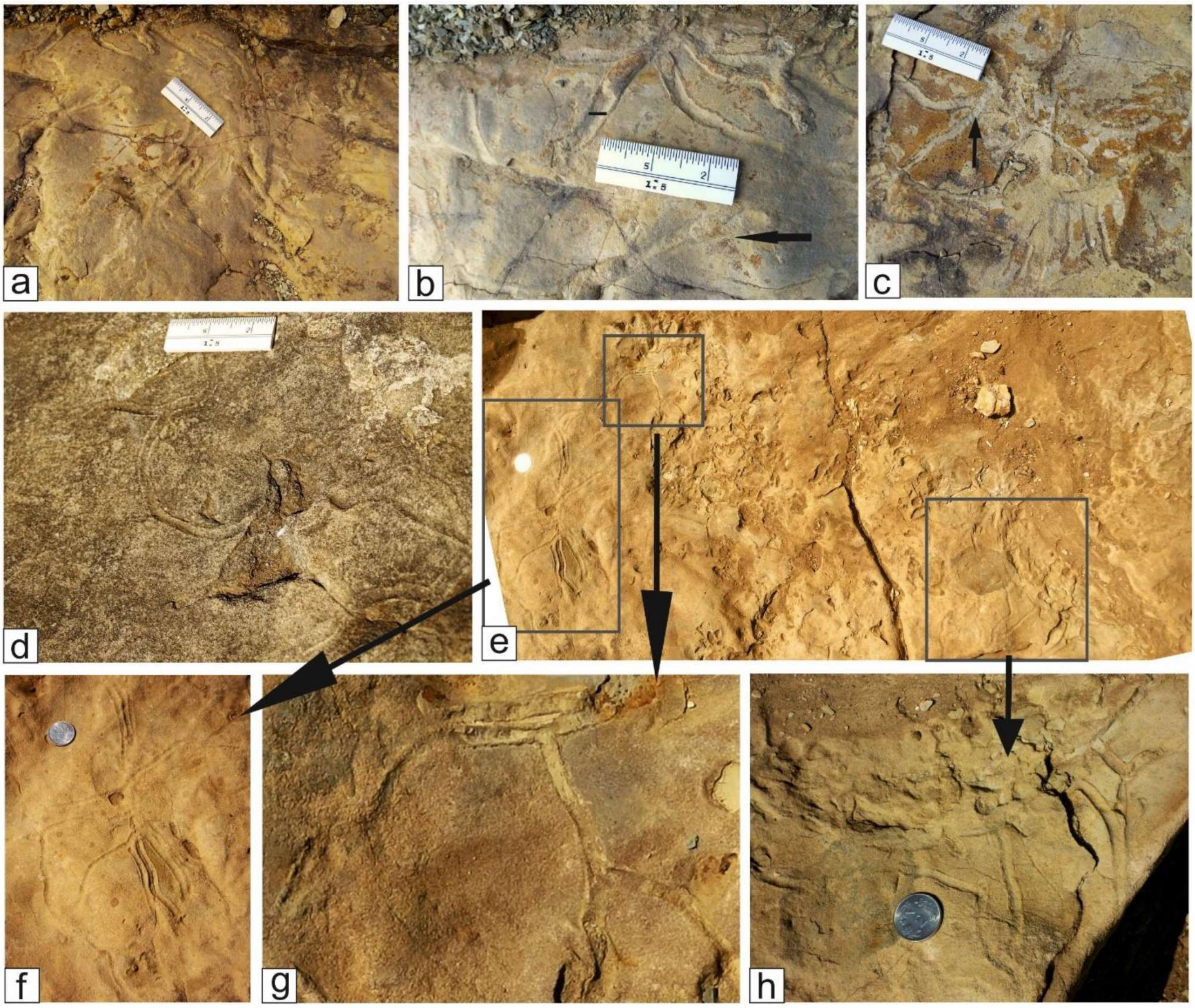

Plate 6.13 Undetermined branched meandering burrows on calcareous sandstone facies, Vajpeur Formation, Men River valley. a. The curved burrows, and b. Enlarged view of a. showing distal branching, lined tubes, half of which are eroded, and meniscate fill in subhorizontal burrow (marked by arrow). c. Sinuous branched burrows showing beaded chains seen in the eroded part of the lined burrow. d. Winding burrows forming irregular networks, false branching is seen here due to overcrossing at the same depths. e. Bioturbated surface characterized by various types of structures. f. Multiple and overlapped burrows, gently curved or forming loops with sharp u-shaped turns. g. Branching and meniscate fill of the lined burrow preserved as negative epichnia. h. Irregularly branched burrows preserved as positive epichnia.

section. However, the ichnospecies (*A. chapdiensis* and *I. kevadiensis*) are observed as parts of the same trace (Plate 6.13c) from the same stratigraphic horizon exposed in the Men River Valley. Based on the presence of a curved central shaft branching outward laterally in the distal part (Plate 6.13a-b) of burrows, lining, and meniscate structure, they can be tentatively assigned to *Hartsellea* *sursumramosa*. However, Knaust (2015) considered the ichnogenus *Annetuba* and *Hartsellea* to be junior subjective synonyms of *Arenituba verso*. The lack of radial nature in the *Annetuba* specimens of Badve and Ghare (1980) and in the present study differentiates it from *Arenituba*.

Occurrence: It occurs as epichnia on the calcareous sandstone facies of Vajepur Formation, Uchad village.

6.4. PSEUDO FOSSILS

In the lack of significant palaeoenvironmental fossils, it is common to explore it more intensely; thus, it is crucial to eliminate the possibilities of chemical and physical origin before assigning the structure a biogenic origin (Goldring et al., 2005). The sedimentary markings, particularly with a regular pattern, are often confused with trace fossils (Knaust and Hauschke, 2004). The illusion of biogenic origin becomes more common if the physical/chemical structure coexists with an actual biogenic structure. The weathered surface of rippled micritic sandstone belonging to the Vajepur Formation in the Devaliya village shows a structure resembling the spreiten of *Zoophycos villae;* moreover, it is cross-cut by grazing gastropod trails of *Archaeonassa* (Plate 6.14b). The superficial lobate shape of the spreiten-like structure winded by *Archaeonassa* trails is seen at most places, imitating the lobes of *Zoophycos*. The filaments appear to originate from a common point in a lobe-shape pattern and diverge up to the marginal tube-like appearing *Archaeonassa* trials (Plate 6.14c). However, *Archaeonassa* trails when cross-cutting the structure showing uneven margins, which further rule out the existence of the marginal tube (Plate 6.14b). The occurrence of *Zoophycos* on the rippled calcareous sandstone contradicts its origin in slope and deep basins during the early and late Cretaceous (Olivero, 2003; Buatois and Mángano, 2011). The mound structure from which trails of *Archaeonassa* originate coincides with the apex of the physical structure, superficially resembling the mound-shaped central shaft of *Zoophycos villae*; besides, the structure shows primary lamination of sandstone on its weathered surface, resembling the J-shaped curved furrowed radiating laminae of *Zoophycos villae*. The J-shaped curved laminae of the physical structure are described as rib and furrow pattern by Collinson and Thompson (1989), observed in ancient medium-fine grained sandstones, a horizontal expression of trough cross-bedding. The lack of branching, apex, and marginal tube and the presence of uneven margins of the filaments differentiate it from the biogenic origin of the structure.

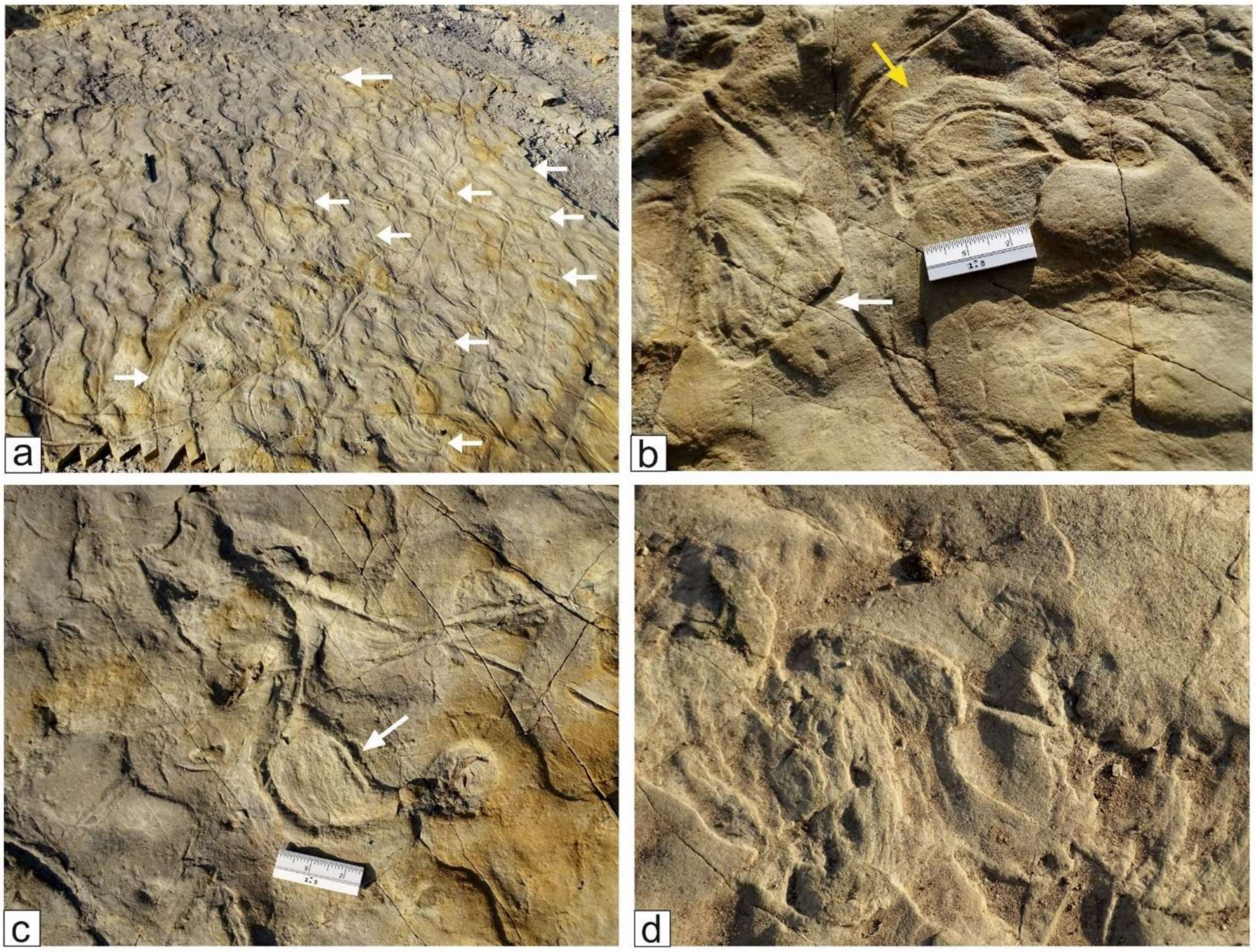

Plate 6.14 Examples of pseudofossil from the Vajepur Formation, Devaliya sectiona. Pseudofossils (marked with arrows) occurring along with long meandering trails of *Archaeonassa* on the sinuous rippled calcareous sandstone facies (length of pen = 15cm). b. The superficial lobate structure of the spreiten-like structure is cross-cut by *Archaeonassa* trails (marked by white arrow). c. *Archaeonassa* trails wind the superficial lobate outline of the spreiten-like structure. d. False biogenic laminae.

6.5 PALEOECOLOGICAL ANALYSIS

The study reports seventeen trace fossils from the Cretaceous sequence of the Bagh Group of the WLNV. To interpret the paleoecological parameters, the author made an attempt to analyze the trace fossils in terms of the ethology, ichnoassemblage, and ichnofacies discussed below.

6.5.1 ETHOLOGY

Trace fossils are the behavioral activities of the soft-bodied organisms produced due to the interaction with substrate and are preserved as tracks, trails, burrows, borings, etc. They are mainly reported from moderately bioturbated Vajepur Formation, Songir Formation, intensely bioturbated

Bilthana Formation, Nodular Limestone, and Narmada sandstone Member of Uchad Formation and preserved as epichnia, endichnia, and hypichnia.

Total seventeen ichnogenera are reported from the Cretaceous sequence of the WLNV, including, *Apectoichnus, Archaeonassa*, *?Arenicolites*, *Bergaueria, Conichnus, Conostichus, Didymaulichnus, Gordia, Helminthoidichnites, Lockeia, Oniscoidichnus, Paleophycus, Planolites, Ptychoplasma, Skolithos, Taenidium* and *Thalassinoides*. The overall density and diversity of the trace fossils are moderate; the maximum ichnogenera are reported from the Vajepur Formation. These trace fossils are further analyzed in terms of behavioral categories (Seilacher, 1953), representing five ethological categories viz. cubichnia (resting), repichnia (crawling/locomotion), pascichnia (grazing), fodinichnia (feeding), and domichnia (dwelling). The ethological categories include resting/dwelling traces like *Conichnus, Conostichus, Bergaueria,* and *Lockeia;* locomotion traces like *Didymaulichnus, Oniscoidichnus, Archaeonassa, Ptychoplasma*; grazing traces like *Gordia*, *Helminthoidichnites*, and *Planolites;* feeding traces such as *Taenidium*; dwelling traces like *Apectoichnus, ?Arenicolites*, *Paleophycus* and *Skolithos;* and dwelling-feeding combined activity, *Thalassinoides*. These ethological categories reflect the high density and diversity observed in the resting, crawling, and dwelling structures, moderate grazing, and least in the feeding structures.

Trace fossils are attributed to presumed polychaetes (?*Arenicolites*, *Gordia, Helminthoidichnites, Paleophycus, Planolites, Skolithos*) are common, as are burrows of mollusks (*Apectoichnus*, *Archaeonassa, Didymaulichnus*, *Lockeia, Ptychoplasma*) and arthropods (*Oniscoidichnus, Taenidium, Thalassinoides*) and sea anemones (*Bergaueria*, *Conichnus*, *Conostichus*).

Ichnotaxa	Frequency				Stratino-my			Ethology					Lithofacies								Trophic			Probable Trace maker	Stratigraphic range
	Very rare (1 specimen)	Rare (2-5 specimens)	Common (6-20 specimens)	Abundant (>20 specimens)	Epirelief	Fullrelief	Hyporelief	Cubichnion	Repichnion	Domichnion	Fodichnion	Pascichnion	Fine-grained sandstone-Siltstone	Calcareous sandstone	Planar cross-stratified sandstone	Sandy allochemic limestone	Bedded Quartz arenite	Mudstone	Micritic Sandstone	Fossiliferous limestone	Suspension feeding	Deposit feeding	Predation		
Apectoichnus				x		x				x							x					x		Bivalves	Early Cretaceous-Miocene
Archaeonassa			x		x				x			x	x	x								x		Mainly Gastropods and possibly arthropods and echinoderms in marine env. Annelids or mollusks in non-marine env.	Cambrian-Recent
?Arenicolites				x		x				x								x			x	x		Polychaetes or crustaceans	Cambrian-Recent
Bergaueria				x			x	x		x						x					x			Actinarian or ceriantharian coelenterates	Precambrian-Miocene
Conichnus		x					x	x		x			x			x					x			Actinarian (sea anemones)	Cambrian-Tertiary
Conostichus		x					x	x		x			x			x					x			Actinarian (sea anemones)	Ordovician-Cretcaeous
Didymaulichnus	x				x				x				x								x	x		Gastropods, bivalves or arthropods	Precambrian-Cretaceous
Gordia	x				x				x		x	x			x							x		Worms, insect larvae or gastropods	Precambrian-Recent
Helminthoidichnites	x				x							x			x							x		Arthropods, nematomorphs or insect larvae	Precambrian to Pleistocene
Lockeia			x		x			x						x								x		Bivalves	Ediacaran-Eocene and Late Cambrian-Pleistocene
Oniscoidichnus		x			x				x					x									x	Isopod	Paleozoic-Recent
Paleophycus			x		x					x			x	x		x					x	x	x	Polychaetes	Ediacaran-Recent
Planolites		x			x							x	x	x		x						x		Worms or arthropods in terrestrial env.	Precambrian-Recent
Ptychoplasma	x						x		x				x											Wedge-foot bivalves	Ordovician-Recent
Skolithos				x		x				x									x	x	x		x	Annelids or phoronids in marine env. or by insects and spiders in terrestrial env.	Precambrian-Recent
Taenidium		x				x					x	x		x								x		Arthropods (terrestrial myriapods), insects, annelids (earthworms) or variety of organisms	Cambrian-Recent
Thalassinoides				x		x					x			x		x		x		x	x	x		Infaunal crustaceans or other kind of arthropods	Cambrian-Recent

Table 6.3 Trace fossils abundance, preservation, behavior, trophic type, trace makers are shown in the various facies of the Bagh Group and their stratigraphic range.

6.5.2 ICHNOASSEMBLAGE

Trace fossils are grouped based on occurrence on particular lithofacies, which are exposed at different localities. The name of the ichnoassemblage is assigned based on the dominance of the trace fossils; nine ichnoassemblages have been identified, viz. *Apectoichnus*, *Archaeonassa, Bergaueria, Conichnus-Conostichus, Helminthoidichnites-Gordia, Lockeia-Planolites, Skolithos, Taenidium,* and *Thalassinoides* (Fig. 6.5).

1.	*Archaeonassa*	10.	*Palaeophycus*
2.	*Bergaueria*	11.	*Thalassinoides horizontalis*
3.	*Taenidium*	12.	*Lockeia*
4.	*Planolites*	13.	*Didymaulichnus*
5.	?*Arenicolites*	14.	*Ptychoplasma*
6.	*Conostichus*	15.	Indeterminate trace fossils
7.	*Conichnus*	16.	*Oniscoidichnus*
8.	*Skolithos*	17.	*Helminthoidichnites*
9.	*Thalassinoides paradoxicus* and *T. suevicus, T. isp*	18.	*Gordia*

Legend representing the trace fossils marked in ichnoassemblages diagram.

6.5.2.1 *Apectoichnus* assemblage

The ichnoassemblage consists of monospecific suites of *Apectoichnus longissimus* observed in the coarse-grained siliceous sandstones of the Songir Formation. Monodominant structure preserved as full relief in the quartz arenite facies suggests its capability to ingest sandy substrate into which it bores. This structure is probably produced by Teredinidae bivalves (Savrda and King, 1993; Gingras et al., 2004; Kříž and Mikuláš, 2006, Shipway et al., 2019) which is reported from a wide range of environments. *Apectoichnus* structure is considered as phobotactic behavior of the trace maker and is reported from the marine, brackish and fluvial environments (Shipway et al., 2019).

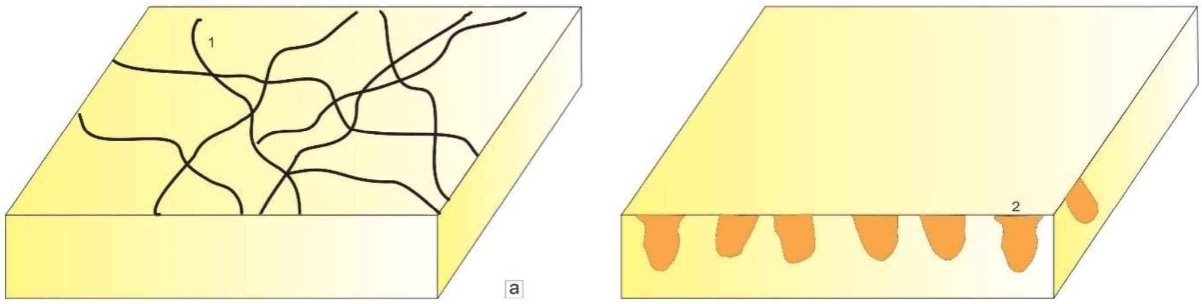

Figure 6.1 Diagrammatic representation of a). *Archaeonassa* and b). *Bergaueria* assemblages.

6.5.2.2 *Archaeonassa* assemblage

The assemblage is characterized by deposit-feeding organisms' high density, monospecific, simple crawling/grazing trails (Fig. 6.1a). It occurs as epirelief in the calcareous sandstone facies of Vajepur Formation at Devaliya and on the sandstone-siltstone-shale facies of Bilthana Formation at the Uchad section. It is preserved on the bedding plane of rippled sandstones. The ichnogenus *Archaeonassa* is a grazing structure produced by gastropods (Häntzschel, 1975) and has a wide geological range and is reported from Cambrian to the present (Fenton and Fenton, 1937; Buckman, 1994). According to Hofmann et al. (2012), the monospecific ichnoassemblage of *Archaeonassa fossulata* is representative of a break in sedimentation and low energy conditions in a stressed environment. *Archaeonassa* trails in rocks containing laminae and ripple marks are considered to be produced by gastropods in tidal environments and are typical of intertidal zones (Fenton and Fenton, 1937; Buckman, 1994). They are also considered to be superficial grazing structures produced by detritus feeders (Hofmann et al., 2012). According to Buckman (1994), *Archaeonassa* occurring on thinly-bedded, wave-rippled, muddy sandstones interbedded with shales is deposited in intertidal flat environment with fluctuating salinity. The lack of flat central region and presence of leeve on either side as observed in *Archaeonassa* isp. suggests epifaunal plowing and organism movement through the sediments directly beneath the sediment-water interface pushing sediment on either side (Jensen, 2003; Hofmann et al., 2012). The flat zone between the levees suggests mollusk-like animals be the producer (Jensen, 2003), also observed in the present specimens of *Archaeonassa fossulata*. The massive colonization of deposit feeders in this assemblage indicates reduced sediment supply in a probably tidal flat environment with fluctuating salinity.

6.5.2.3 *Bergaueria* assemblage

The assemblage consists of monospecific suites of *Bergaueria hemispherica* (Fig. 6.1b). The ichnoassemblage is a sea anemone-dominated suite consisting of high ichnodensity burrows preserved at the base of oyster-limestone beds (sandy allochemic limestone facies). *Bergaueria* reflects the filter feeders' (sea anemones) combined resting and/or dwelling behavior. The high density of burrows and its occurrence in the limestone-shale intercalated sequence suggests a stressed environment with varying energy levels (Shitole et al., 2019). The occurrence of *Bergaueria* indicates a slightly agitative and clean environment which supported the sea anemone to be stranded on the fine-grained partially dewatered sediments.

6.5.2.4 *Conichnus- Conostichus* assemblage

Thisichnoassemblage comprises an ethologically diverse group of trace fossils, including the *Conichnus, Conostichus, Oniscoidichnus, Paleophycus, Planolites, Thalassinoides,* and indeterminate trace fossils (Fig. 6.2a). It is dominated by vertical dwelling/resting burrows with a moderate occurrence of locomotory and feeding traces. It is developed in the sandy allochemic limestone facies intercalated with shale and the sandstone-siltstone-shale facies of Bilthana and Vajepur formations, respectively. The trace makers are mainly sea anemones, gastropods, crustaceans, polyphyletic vermiform, and arthropods.

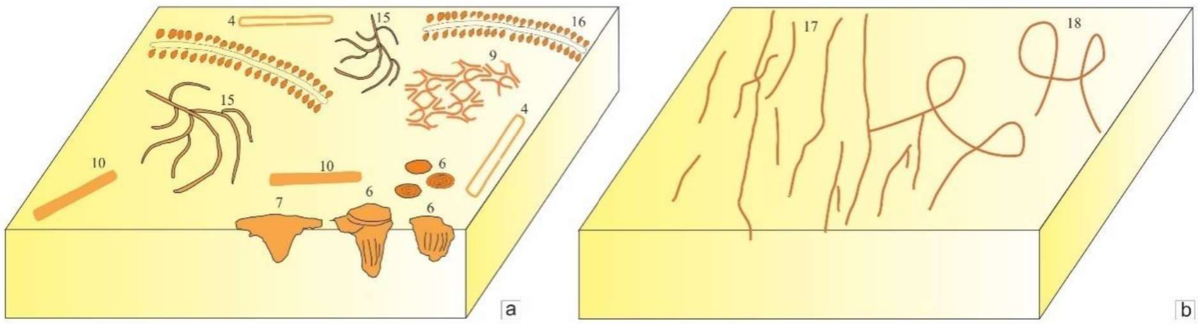

Figure 6.2 Diagrammatic representation of a).*Conichnus- Conostichus* and b). *Helminthoidichnites-Gordia* assemblage.

6.5.2.5 Helminthoidichnites-Gordia assemblage

The assemblage is characterized by simple grazing trails *Helminthoidichnites tenius,* and *Gordia marina* (Fig. 6.2b) represents variations within individual community i.e., a common producer. *Gordia* occurs in the same bed bearing *Helminthoidichnites,* on the top of thickly-bedded, medium-grained planar cross-stratified sandstones. This assemblage shows low ichnodensity, and ichnodiversity and co-occurrences of *Gordia* and *Helminthoidichnites* are reported by Gaigalas and Uchman (2004) and Uchman et al. (2009). It suggests locomotion in search of nutrients in the substrate and represents a short-term colonization window in low energy deposits between high energy conditions characterized by cross-stratified sandstones in a probably tidal flat environment. *Helminthoidichnites* and *Gordia* are mat grazers, grazing the organic matter on mats preserved below a thin veneer of sediments (Seilacher, 1990; Buatois and Mángano, 2012). According to Buatois et al. (2020), the trace fossil *Helminthoidichnites* is a facies-crossing form reported from various depositional environments but is more common in fluvial settings.

6.5.2.6 *Lockeia-Planolites* assemblage

The ichnoassemblage comprises a behaviorally diverse group of trace fossils, viz. *Didymaulichnus*, *Lockeia*, *Oniscoidichnus*, *Palaeophycus,* *Planolites,* *Ptychoplasma,* *Thalassinoides,* and undetermined trace fossils (Fig. 6.3a). It is mainly characterized by locomotion traces of bivalves preserved in the calcareous sandstone facies or sandstone-siltstone-shale facies occurring in the upper part of the Vajepur Formation. The presence of abundant *Lockeia* specimens in the Vajepur Formation suggests the substrate was rich in nutrients. Their close occurrence on the same bed suggests a behavioral variation of the bivalves, and the preservational variant aspect arising out of the different depositional environment and sediment consistency can be ruled out. The grazing trails of *Planolites beverlyensis* are commonly associated with *Lockeia* and occur in calcareous sandstone facies of Vajepur Formation, suggesting communalism. Moreover, the crawling trail *Didymaulichnus lyelli* and dwelling structure *Paleophycus tubularis* of suspension feeder (Hofmann et al., 2012) in calcareous sandstone bed suggest soft unconsolidated substrate of foreshore/shoreface environment.

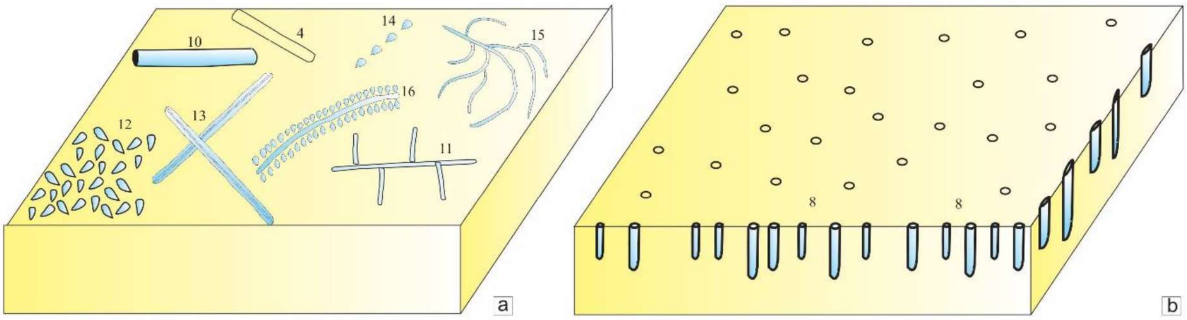

Figure 6.3 Diagrammatic representation of a). *Lockeia-Planolites* and b). *Skolithos* assemblage.

6.5.2.7 *Skolithos* assemblage

The ichnoassemblage is characterized by the monodominant occurrence of *Skolithos* (Fig. 6.3b) in the calcareous sandstone facies of the Narmada Sandstone Member of the

Uchad Formation. It is also associated with *Thalassinoides* in the fossiliferous limestone facies of the Bilthana Formation. It consists of vertical dwelling burrows of suspension feeders and indicates unconsolidated, shifting substrate and high wave and current energy conditions (Pemberton et al., 2001). The suspension-feeding as a dominant trophic type suggests moderate turbidity and thus the availability of food and oxygen in the water column.

6.5.2.8 *Taenidium* assemblage

*Taenidium*is an active back-filled meniscate structure and occurs with *Planolites* (Fig. 6.4a) in the middle part of the Vajepur Formation, which consists of cross-bedded, coarse-grained, calcareous sandstone facies. It is dominated by the deposit-feeding activity of various organisms (Díez-Canseco et al., 2016). Its co-occurrence with *Planolites* indicates the presence of nutrient-rich substrate, exploited for feeding purposes. The present study's horizontal forms of *Taenidium* suggest a stiffer, compacted substrate that offered resistance to burrowing in contrast to the vertical forms generated in less-compacted sediments (Díez-Canseco et al., 2016).

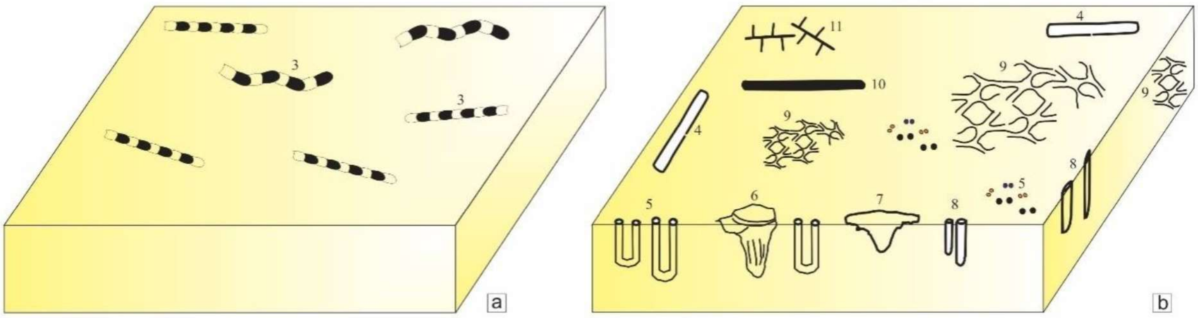

Figure 6.4 Diagrammatic representation of a). *Taenidium* and b). *Thalassinoides* assemblages.

6.5.2.9 *Thalassinoides* Ichnoassemblage

This ichnoassemblage occurs at three different level and occur either monodominant or associated with some less abundant forms. It predominantly occurs in the fossiliferous limestone facies of the Bilthana Formation and consists of various *Thalassinoides* species, including *T. paradoxides, T. suevicus,* and *Thalassinoides* isp. while it occurs with *Planolites* and *Palaeophycus* (Fig. 6.4b) in the calcareous sandstone of Vajepur Formation and with ?*Arenicolites* in mudstone facies of Nodular Limestone. This ichnoassemblage is extensively developed in the intercalated sequence of oyster limestone (fossiliferous limestone facies)-shale facies. The burrows were made in a cohesive muddy substrate and were passively filled with the overlying sediments. The recurring pattern of occurrence of *Thalassinoides* burrows in the oyster beds (fossiliferous limestone facies) is in accordance with their deposition in contrasting energy conditions, suggesting the trace maker's opportunistic behavior. The monodominant occurrence of *Thalassinoides* burrows as hyporelief in the oyster beds intercalated with the shale facies was caused due to the rapid passive fill of the burrow with the overlying sediments either due to the burial of the whole burrow causing death and decay of the organism in it (Tsujita, 2003), or due to the vacation of burrow because of exhumation of the cohesive sediments by the high energy event.

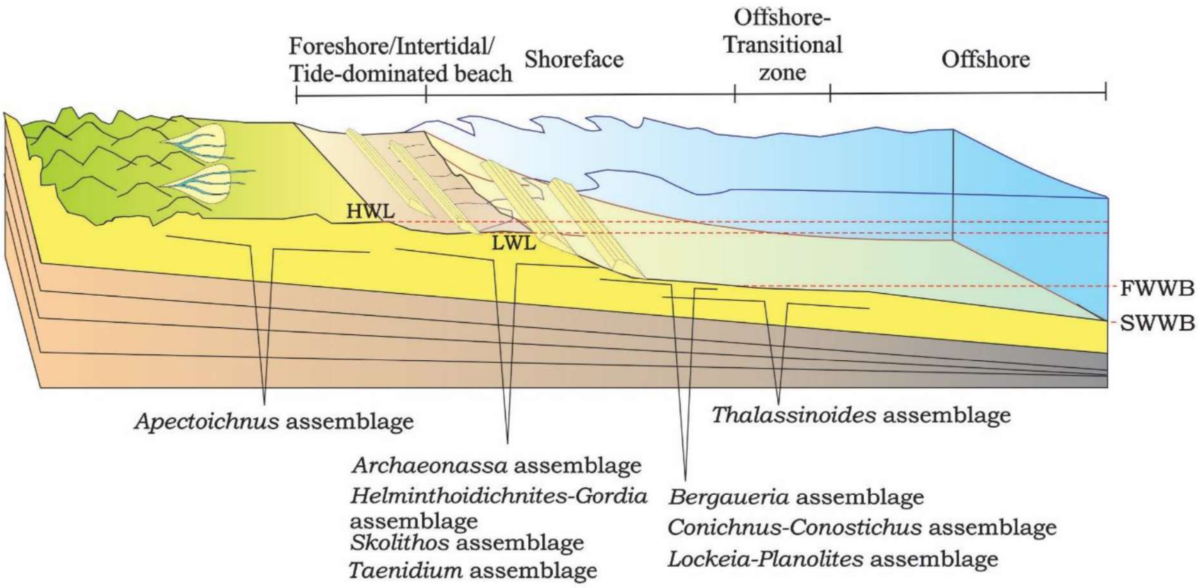

Figure 6.5 Schematic 3-dimensional diagram representing ichnoassemblages in the shallow marine depositional environment of the Western Lower Narmada Valley.

6.5.3 ICHNOFACIES

Ichnofacies constitute biogenic structures made by organisms in response to changes in energy conditions, deposition rates, food resource types, substrate consistency, water salinity, oxygenation, subaerial exposure, substrate moisture, and temperature (MacEachern et al. 2007). This ichnofacies concept, when linked with ichnological and sedimentological data, can help in deciphering depositional environment and paleoecological conditions. In the study area, trace fossils are most common in the Bilthana and Vajepur formations and are rare in the Songir, Nodular Limestone, and Uchad formations. The ichnoassemblages analyzed further represents *Skolithos, Cruziana,* and *Glossifungites* ichnofacies.

6.5.3.1 *Skolithos* Ichnofacies

This ichnofacies is composed of monospecific, crowded *Skolithos* burrows with thickly lined tubes observed in the calcareous sandstone facies of Narmada Sandstone Member (Plate 6.3b). The typical occurrence of *Skolithos* can be attributed to a short-term colonization window reflecting a change in energy conditions and water depth affected by bedform topography and sedimentation rate (Buatois and Mángano, 2011; Santos et al., 2017). The occurrence of vertical burrows (*Skolithos*) of suspension-feeders observed in the Narmada Sandstone Member suggests high-energy conditions at the time of colonization. The *Skolithos* Ichnofacies in the study area represent a sudden change in the environmental conditions from low energy offshore deposits of the Nodular Limestone to the high energy middle shoreface deposits of the cross-bedded Narmada Sandstone Member. Mángano and Buatois (2004) have also observed the *Skolithos* Ichnofacies that consist of opportunistic organisms, represented by their monodominant occurrence in shallow subtidal to intertidal deposits, as well as Knaust and Bromley (2012), have noticed that the middle shoreface environment is dominated by abundant suspension-feeding traces belonging to the *Skolithos* Ichnofacies. The presence of *Skolithos* Ichnofacies in the calcareous sandstone of the Narmada Sandstone Member suggests that opportunistic organism like tube-dwelling suspension-feeding polychaetes colonized in the marine habitats after a major environmental change like bottom substrate consistency followed by well-oxygenated bottom water conditions and abundant food supply (McCall and Tevesz, 1983; Vossler and Pemberton, 1988; Dam, 1990).

6.5.3.2 *Cruziana* Ichnofacies

This ichnofacies is associated with poorly sorted, unconsolidated marine substrates, indicating deposition in the subtidal environment between the fair-weather base and storm wave base in wave-dominated lower shoreface to distal fringes of the lower offshore region (MacEachern and Pemberton, 1992; MacEachern et al., 1992; MacEachern et al., 1999a; Pemberton et al., 2001). *Cruziana* Ichnofacies is observed in the sandstone-siltstone-shale, planar cross-stratified sandstone, and calcareous sandstone facies, with characteristics genera like *Archaeonassa*, *Didymaulichnus, Gordia, Helminthoidichnites, Lockeia, Oniscoidichnus, Palaeophycus, Planolites, Ptychoplasma, Taenidium,* and *Thalassinoides.* The ichnofacies include a wide range of behavioral traces, including feeding, dwelling, resting, dwelling, grazing, and locomotion. The *Cruziana* Ichnofacies consists of both suspension and deposit feeders and has a mixed association of horizontal, vertical, and inclined burrows (Miller III, 2011) due to the suspended and deposited components of food supplies in moderate energy settings. However, the dominance of horizontal feeding burrows of deposit feeders observed in the Bagh Group sediments suggests low to moderate-energy conditions. Moreover, the ichnofacies is characterized by diversified ethologies, indicating an overall stable environment with low to moderate sedimentation rates (Buatois and Mángano, 2011). The traces of deposit-feeding in different beds of the upper part of the Vajepur Formation consisting of the fair-weather suite are dominated by *Lockeia*, *Oniscoidichnus*, *Planolites*, *Paleophycus*, *Thalassinoides,* and horizontal undetermined traces. The high density and diversity of deposit-feeding traces suggest abundant nutrients and oxygenation in the sediments (Han and Pickerill, 1995). The presence of *Lockeia*and *Ptychoplasma* in the sandstone-siltstone-shale facies of Vajepur Formation suggests a compact, unconsolidated substrate which favored emplacement and preservation of burrows (Paranjape et al., 2013).

6.5.3.3 Glossifungites Ichnofacies

This is a substrate-controlled ichnofacies and typically developed at the omission surface and characterized by typical burrows. The burrows in firmground substrate need no reinforcement to stabilize the wall (Ghibaudo et al., 1996; MacEachern and Burton, 2000) and hence should be discussed in the context of *Glossifungites* Ichnofacies (Ekdale et al., 1984). *Thalassinoides* is one of the most common elements of the *Glossifungites* Ichnofacies, which are abundant in the post-Paleozoic rocks (Myrow, 1995; Pemberton et al., 2004). In the Bagh Group sequence, characteristic elements of the *Glossifungites* Ichnofacies, *Thalassinoides* burrows in the Bilthana Formation and the Nodular Limestone and plug-shaped *Conichnus*, *Conostichus,* and *Bergaueria* in the Bilthana and Vajepur formations are observed. These burrows are found in high density in the fossiliferous limestone facies of oyster beds, indicating opportunistic colonization.

Thalassinoides is considered a semi-permanent dwelling system that may have remained open for a long period during which the organisms circulated water through it, and

at omission surfaces, the burrows are filled passively with the contrasting post-omission sediments to a greater depth (Bromley, 1975). Their occurrence beneath the omission surface is interpreted as the existence of an open system at that depth beneath the seafloor (Bromley and Ekdale, 1984). The presence of burrows in the shale facies of the Bilthana Formation and the mudstone facies of Nodular Limestone indicate water circulation in the tunnels.
The dominance of vertical plug-shaped burrows like *Conichnus*, *Conostichus,* and *Bergaueria* of suspension-feeding sea anemones were observed in shale facies of the upper part of Vajepur and Bilthana formations (Patel et al., 2018; Shitole et al., 2019). The organisms made burrowed in the compact cohesive mud and left the burrow in intact form, evidenced by sediments filled with the overlying bed and were preserved at the bed-junction of the oyster bed and shale. The dominance of vertical plug-shaped burrows of suspension feeders observed in the present study suggests fluctuating energy conditions and an ample supply of nutrients carried by the bottom currents on the seafloor.

The ichnofacies is characterized by low diversity and high density branched, unbranched, sharp-walled, unlined, and passively filled, dwelling burrows of suspension feeders. The ichnofacies indicate a stable and cohesive substrate, mainly dewatered muds reflected by the unlined, sharp-walled, passively filled burrows (MacEachern et al., 1992). The passive fill of the burrows indicates the substrate stability as the burrows remained open and were filled by the transgressive sediments of the fossiliferous limestone and calcareous sandstone facies of the Vajepur and Bilthana formations.

6.6 DISCUSSION

The Bagh Group succession of the WLNV provides a glimpse of the Cretaceous ichnofauna of the invertebrate organisms in response to the fluctuating sea level, oxygen conditions, and changing sedimentation rates. This study highlights the animal-substrate interactions and other palaeoecological parameters that governed during the deposition. The trace fossils are observed throughout the sequence, and most of the trace fossils are reported from the sandy allochemic limestone facies, fossiliferous limestone facies, sandstone-siltstone-shale facies, and calcareous sandstone facies, whereas the quartz arenite facies, planar cross-stratified sandstone facies, and mudstone facies are bioturbated to a lesser degree. Most of them occur at the bed-junction of sandstone-shale or limestone-shale due to high preservation potential. These trace fossils show ethological diversity and are represented as cubichnia (*Bergaueria, Conichnus, Conostichus, Lockeia*), pascichnia (*Archaeonassa, Gordia, Helminthoidichnites*), domichnia (*Apectoichnus, ?Arenicolites, Paleophycus, Skolithos*), repichnia (*Didymaulichnus, Oniscoidichnus, Ptychoplasma*) and fodinichnia (*Planolites, Taenidium, Thalassinoides*). These ichnofossils can be grouped into nine ichnoassemblages that recur in time and space and represent *Skolithos, Cruziana,* and *Glossifungites* ichnofacies.

Monospecific occurrences of *Archaeonassa*, *Apectoichnus*, and *Bergaueria* are observed at different stratigraphic levels. The *Conichnus*-*Conostichus* and *Lockeia*-*Planolites* ichnoassemblage host a moderately diverse trace fossil association consisting of three to four ichnogenera. Generally, high intensity of bioturbation is reported from the shallow and marginal marine environments; however, the rocks in the study area are moderately bioturbated except for the Bilthana Formation, which consists of abundant *Thalassinoides* burrows of endobenthic decapod crustaceans.

The trace fossils like *Thalassinoides, Bergaueria, Conichnus, Conostichus,* and *?Arenicolites* preserved at the sandstone-shale or limestone-shale bed junction suggest a change in the hydrodynamic and substrate conditions. The *Skolithos* Ichnofacies occurs in the Narmada Sandstone Member and consists of monodominant occurrence of the *Skolithos* genus. Sedimentary structures such as planar, trough, and herringbone cross-stratification amalgamated with the *Skolithos* Ichnofacies observed in the sandstone unit of the Narmada Sandstone Member above the Nodular Limestone suggest deposition took place above the FWWB. The *Cruziana* and *Glossifungites* ichnofacies observed in the fossiliferous limestone, sandy allochemic limestone facies, and mudstone facies of Vajepur and Bilthana formations suggest deposition in lower shoreface to the offshore environment. Also, the large diameter of *Thalassinoides* burrows observed in the Nodular Limestone is consistent with low-moderate energy conditions, well-oxygenated, nutrient-rich waters of the shallow marine environment. The Nodular Limestone, Bilthana Formation, and Vajepur Formation were deposited in low to moderate energy conditions with intermittent high energy events in the intertidal to the subtidal environment.

The presence of cross-stratification in the middle-lower part of the Vajepur Formation and low degree of bioturbation suggest high energy conditions and rapid sedimentation rate with a short colonization window. Bioturbation is observed to increase towards the top of

Vajepur Formation and Bilthana Formation, suggesting a low sedimentation rate and a longer colonization window. The firmgrounds also support the low sedimentation rate. The presence of oyster shells in the oyster beds of the Bilthana Formation limited the burrowing activity; however, at the contact with the underlying shale bed, it increased the preservation potential by infilling the burrows. The transition from storm accumulations of oyster shells in Bilthana Formation to mudstones of Nodular Limestone suggests decreasing intensity of high energy storm events, reduction in wave/current strength, and increased bathymetry. The shells and early cementation at shallow depths that formed the firmgrounds did not favor the burrowing of organisms in the oyster-beds.

Bergaueria and *Thalassinoides* are abundant (>20 ichnotaxa) on discrete horizons suggesting opportunistic colonization and occurring related to the omission surfaces. This Bilthana Formation allowed the opportunistic suspension-feeding organisms to flourish during long periods of quiescence (Shitole et al., 2019). The sudden increase in ichnodiversity and ichnodenisty is observed towards the top of the Vajepur Formation suggests a low-energy, detritus nutrient-rich, shoreface environment. The ichnological analysis has provided valuable information on the distribution of the trace fossils and their paleoecological controls in the shallow marine environment during the Cretaceous sedimentation in the Narmada Basin.