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ORIGINAL ARTICLE

Styles and origin of post- and syn-depositional structures of metagreywacke-argillite strata (Goa Group), and formation of Bouma sequence, West Coast of India

Glancia Q. Fernandes[1] · **Sridhar D. Iyer**[2] · **Mahender Kotha**[3]

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Abstract

Study of the sedimentary structures helps to interpret the depositional process of siliciclastic sediments. Sedimentary structures are classified based on the morphology, formation process, sediment rheology, deformation mechanism and relative timing of sedimentation. In this study, the structures are categorized as Primary depositional, Diagenetic, Soft Sediment Deformation Structures (SSDS) and Deformational Structures. Laminations, dropstone, graded beddings, and cross-bedding are primary structures formed during sedimentation and among the diagenetic structures, liesegang rings were identified. The other structures such as convolute, flame and load, ball and pillow (pseudonodules), slump fold and syn-sedimentary fault are classified as SSDS and are reported for the first time. The dykes and shear zone are the intrusive and deformational structures, respectively. In our study, the regional geology and structural data suggest a deltaic environment with a turbiditic condition of deposition for the formation of the SSDS. In a deltaic environment the SSDS were formed due to rapid deposition of sediments by suspension, their disruption due to liquefaction, and movement of sediment in a water-logged state. The processes were controlled by slope of the basin, gravity controlled density currents and differential compaction. In this environment of high sediment supply, fluctuating water level, slope instability and sediment density there resulted an in situ deformations of the sediments and formation of the SSDS. We have correlated the typical Bouma sequence with the various structures including the SSDS that are associated with the metagreywacke-argillite strata in the study area. The strata with 4 units (A–D) reveal a typical Bouma sequence which was influenced the low-density turbidity currents. With time, the deep basin sediment depositional environment progressively changed to a shallow environment.

Keywords Metagreywacke · Argillite · Soft-sediment deformation structures · Turbidite · India

1 Introduction

Several sedimentary structures are reliable features and help to delineate the depositional history of sediments. Primary sedimentary structures form at the time of deposition or shortly after that and before the consolidation of the rock in which they are found (Pettijohn & Potter, 1964). These structures such as laminations, dropstone structures, graded bedding, cross-bedding, ripple marks, etc., are most useful for interpreting sediment particles' transportation and deposition at the water–sediment interface. Among the other important structures identified in the field are the Soft Sediment Deformation Structures (SSDS). SSDS are also called penecontemporaneous features, that form before lithification of the clastic sediments (Van Loon, 2009) and reflect deformational processes (Collinson, 2003; Mills, 1983; Van Loon, 2009). The SSDS are also indicators of the early

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✉ Glancia Q. Fernandes
queenieglancia@gmail.com

Sridhar D. Iyer
sdiyer2001@gmail.com

Mahender Kotha
mkotha@unigoa.ac.in

1 Present Address: Directorate of Mines and Geology, Panaji, Goa 403001, India

2 Formerly at CSIR-National Institute of Oceanography, Dona Paula, Goa 403004, India

3 School of Earth, Ocean and Atmospheric Sciences, Goa University, Taleigao, Goa 403206, India

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consolidation history of sediments (Allen, 1982) and are early diagenetic features that form due to liquefaction of the water-saturated unconsolidated sediments (Owen, 1987; Topal & Özkul, 2014). The SSDS are related to sedimentary and tectonic features and are controlled by the degree of compaction of sediments (Kundu et al., 2011; Mazumder et al., 2009).

Further, turbidite deposits typical of a Bouma sequence also exhibit SSDS (Valente et al., 2014). Soman (1993) noted the occurrence of SSDS in the Sanvordem Formation, Goa Group which is exposed along the Aguada-Chapora region of North Goa, India. He opined that turbidity currents that were responsible for the Bouma sequence were of low density. Besides this report, there are no details of the SSDS and associated features along the coast of Goa.

In the above background, this paper deals with a new finding of various depositional structures, including post- and syn-depositional, structures exhibited within the sediment substrate of the Sanvordem Formation, Goa Group, India comprising metagreywacke, argillite and conglomerate. We provide evidence for the presence of SSDS in the Sanvordem Formation to highlight the sedimentological conditions that prevailed in the depositional basin. In addition, we discuss the characteristics of rocks and the formation process of the sedimentary features such as the extent and lithological association of the structures that occur in the metagreywacke-argillite strata.

2 Geological setting

The Dharwar Craton is divided into Western Dharwar Craton (WDC) and Eastern Dharwar Craton (EDC) based on the crustal thickness and characteristics, distribution of greenstones, Basement Gneiss and younger granites (Jayananda et al., 2006, 2013; Sreehari & Toyoshima, 2020; Swami Nath & Ramakrishnan, 1981). Goa is situated towards the north-western part of the Western Dharwar Craton (WDC) and forms a part of the Shimoga-Goa supracrustal belt (Fernandes, 2018). The general trend of the Dharwar Craton is NW–SE, with sediments at the base that are superimposed by metamorphosed basic and acid volcanic rocks. These are overlain by greywacke, followed by pyroclasts and tuff associated with precipitates of chemogenic lime, iron, and manganese and superimposed by another suite of greywacke. This heterogeneous assemblage has suffered greenschist facies of metamorphism and as these are found in Goa, they have termed the Goa Group (Gokul et al., 1985).

The Goa Group of rocks belongs to the Dharwar Supergroup of Archaean-Proterozoic age (Gokul et al., 1985). Dessai (2011) classified the Goa Group into two lithostratigraphic sequences: Barcem Group and Ponda Group. The Barcem Group comprises the Barcem Formation while the Ponda Group comprises Sanvordem Formation, Bicholim Formation and Vageri Formation (Fernandes, 2018) (Table 1). Three cycles of folding were identified by Gokul et al. (1985). The first cycle of folding (F1) observed towards SW of Goa is developed with an E-W trend of fold axis. The second folding cycle (F2) was the most powerful, resulting in the rocks' NW–SE trend. The third cycle of folding (F3) had resulted in a major syncline in the north-eastern part of Goa. The nearly straight coastline of Goa is another confirmation of a major fault along the west coast of India and is associated with several small-scale faults in the study area (Gokul et al., 1985). Faults are exposed in the hinterland iron ore mines of Goa trend NE–SW and NW–SE. In general, the drainage pattern is dendritic and structurally controlled (Iyer & Wagle, 1987).

Apart from faulting shearing and tectonisation in an N-S direction are reported along the Western Ghat section at the Goa-Karnataka border. The NW–SE trending lineaments can be compared to the main folding episodes and the area is also intruded by dyke swarms that correlate with the regional Precambrian trend (NNW–SSE) and the other episode of folding (WNW–ESE).

The rocks of the Sanvordem Formation are unconformable to Barcem Formation and are exposed at various locations and the dominance of these outcrops varies from place to place (Fig. 1). Conglomerates are well exposed at Sanvordem, whereas metagreywacke and argillite are exposed along the coast of North Goa and in the hinterland of Tiswadi Taluka in various quarries (Fig. 1). The erosion of the rocks has resulted in the formation of placer minerals along the 105 km of Goa's coast (Gujar et al., 2021).

3 Methods

Firstly, the topographic and geologic maps were studied to identify areas of probable rock exposures. The use of Google maps gave valuable information during fieldwork to identify the exposures for a detailed study. During the fieldwork, the measurements of structural data such as the attitude of bedding planes, fold and shear zone were noted, also the geologic relationships were observed. Rock samples were collected for petrographic, microstructural study and whole-rock geochemistry, which are discussed in Fernandes et al. (2016) and Fernandes (2018). The study area is marked on the map (Fig. 1).

The outcrops in the study area were mainly identified as cliffs and headlands along the coast. Outcrops were also studied in the hinterland and several quarries. Samples of metagreywacke were collected throughout the study area to represent the rock types present. Sampling was done

Table 1 Stratigraphy of Goa Group after Gokul et al. (1985) and Dessai (2011)

After Gokul et al. (1985)			Dessai (2011)		
			Basic Intrusives		Metadolerite/Dolerite
			Canacona Granite	2395 ± 390 (?) Ma	
			Mafic–ultramafic layered complex		
		Metadolerite	Ponda Group (= Chitradurga Group)	Vagheri Formation	Metabasalt, Argillite and Metagreywacke
Basic Intrusives		Dolerite, Gabbro		Bicholim Formation	Banded ferruginous quartzite, Manganiferous chert, breccia with pink ferruginous phyllite, Limestone, Pink ferruginous phyllite Quartz-chlorite amphibolite-schist
Chandranath Granite Gneiss	2600 ± 100 Ma	Granodiorite		Sanvordem Formation	Metagreywacke, Argillite, Quartzite, tilloid
	Vagheri Formation	Metabasalt, Argillite and metagreywacke	Unconformity		
	Bicholim Formation	Banded ferruginous quartzite, Manganiferous chert, breccia with pink ferruginous phyllite Limestone, Pink ferruginous phyllite Quartz-chlorite-biotite-schist	Barcem Group (= Bababudan Group)	Barcem Formation	Matagabbro Peridotite, talc-chlorite schist, Quartzite, quartz-sericite schist, Red Phyllite, Quartz-porphyry massive, Schistose and Vesicular metabasalt
	Sanvordem Formation	Argillite, Quartzite, Tilloid	Unconformity		
	Barcem Formation	Metagabbro Peridotite, Talc-chlorite-schist, Quartzite, Quartz-sericite-schist, Phyllite Quartz-porphyry massive, Schistose and Vesicular basalt	Chandranath Granite Gneiss	2700–2900 Ma	Granodiorite
	Basement: not identified		Anmode Ghat Trondhjemite gneiss	3300–3400 Ma	Basement: Trondhjemite-Tonalite Granodiorite

especially across the contours (especially in the quarries) to observe the vertical variations in the metagreywacke (Fernandes et al., 2016).

4 Results and discussion

The metagreywacke of the study area has a strike of NE-SW and dips in SE direction with an average dip amount of 30°. The sedimentary processes involving the deposition of metagreywacke and interbedded argillite (originally shale) in the Goa Group play a significant role in influencing the chemical composition of metagreywacke (Fernandes, 2018; Hegde & Chavadi, 2009). Metagreywacke exposed along the coast of North Goa is about 1 to 6 m in thickness while in the hinterland quarries the maximum thickness is about 30 m. The reduced thickness of the coastal outcrops is perhaps either due to marine erosion or the decrease over time of the depth of the depositional basin. The metagreywacke of the study area is classified into five types, metagreywacke, quartzo-feldspathic metagreywacke, metagreywacke with biotite, metagreywacke cataclasite and argillite (Fernandes, 2018). At several places, the outcrops are capped by lateritic tablelands. The sedimentary features identified in the study area are grouped into primary depositional structures, diagenetic structures and SSDS and these are detailed in this study as follows.

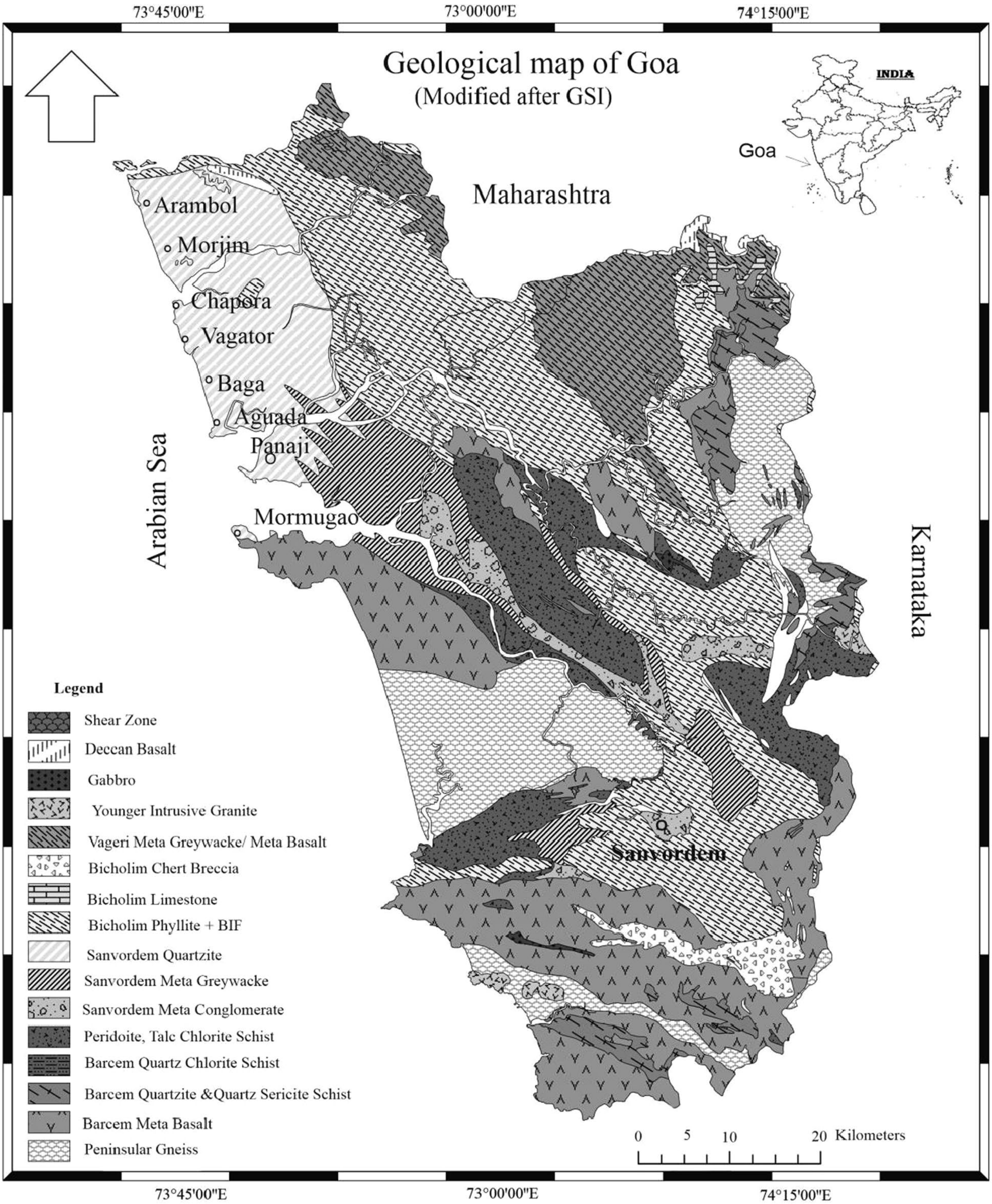


Fig. 1 Geological map of Goa (modified after Gokul et al. 1985)

4.1 Field occurrence and structural descriptions

4.1.1 Primary depositional structures

Primary depositional structures form contemporaneously during the deposition of the sediments. The primary structures comprise laminations, dropstone, graded bedding and cross-bedding.

Laminations are easily recognizable in the study area and are a few centimetres thick (Fig. 2a). The laminations suggest uniform and quiet aquatic conditions in a depositional basin wherein silt and clay-sized particles accumulate.

Dropstone structure exhibited by conglomerates, that occur at Sanvordem is comprised of quartzitic and granitic fragments that range in size from 10 to 15 cm and are cemented by sand to silt size material (Fig. 2b, c). The presence of conglomerate among the metagreywacke of the Sanvordem Formation might represent high-density flow proximal deposits (Soman, 1993).

The fragments of the dropstone have a broad and convex base at the bottom and are almost flat at the top. The laminations associated with it are present without any disturbance on top of the fragment. The laminations below the fragment are distorted, while they are discontinuous and broken in the fragment's mid-region. Dropstone structure in conglomerate perhaps formed due to the sinking of quartzitic and granitic pebbles into the underlying soft-sediment which may cause a local distortion and bending of the laminae beneath which there is the load protuberance (cf. Stow, 2010).

The medium to fine-grained metagreywacke with conglomerate at its base (Fig. 2d, e), suggests the role of turbidite gravity flow sediments deposited by the same flow mechanism as that of the metagreywacke (Feary, 1979; Soman, 1993Leggett, 2012). Some conglomerate exposures are interbedded with argillite. Intercalations of fine-grained clayey laminated argillite in the form of lentoid pockets were also noticed in the conglomerates (Fig. 2e).

Graded beddings with a gradation from fine to very fine-grained layers at millimetre-scale are identified under a microscope (Fig. 2f). Graded beddings form an intrabed structure with an upward fining sequence implying deceleration of sediment-laden current with the coarsest grains settling first representing normal sedimentation in the sedimentary basin and is formed both due to mass flow and distal turbidites or by low-density turbidity flows.

Cross beddings are noticed within a bed of arenaceous metagreywacke strata, with the foreset having an angular truncation with the topset and a tangential contact with the bottomset bounding surfaces of the beds indicating a trough – cross-bedding (Fig. 2g).

4.1.2 Diagenetic structures

Liesegang rings in metagreywacke have a characteristic concentric or ring-like appearance with the thickness of the band ranging between 2 and 5 mm, which are bounded by cracks and fissures. The rings are perpendicular to the bedding planes (Fig. 2h) and form when the fissures and cracks act as conduits for the solutions and rock porosity result in mass transport of ions. In the process, rhythmic precipitation or diffusion occurs with each joint compartment bounded by fissures behaving as an independent cell (Henisch, 1988; McBride, 2003). Liesegang (1913) suggested the diffusion of cells from inside to outside whereas Carl and Amstutz (1958) opined that the diffusion occurs from outside to inside. Since the bands are perpendicular to the bedding planes in the study area, these indicate that rhythmic precipitation or diffusion occurred parallel to the bedding planes. The absence of a nucleus suggests the inception of the rings to be from the rim and not from the centre.

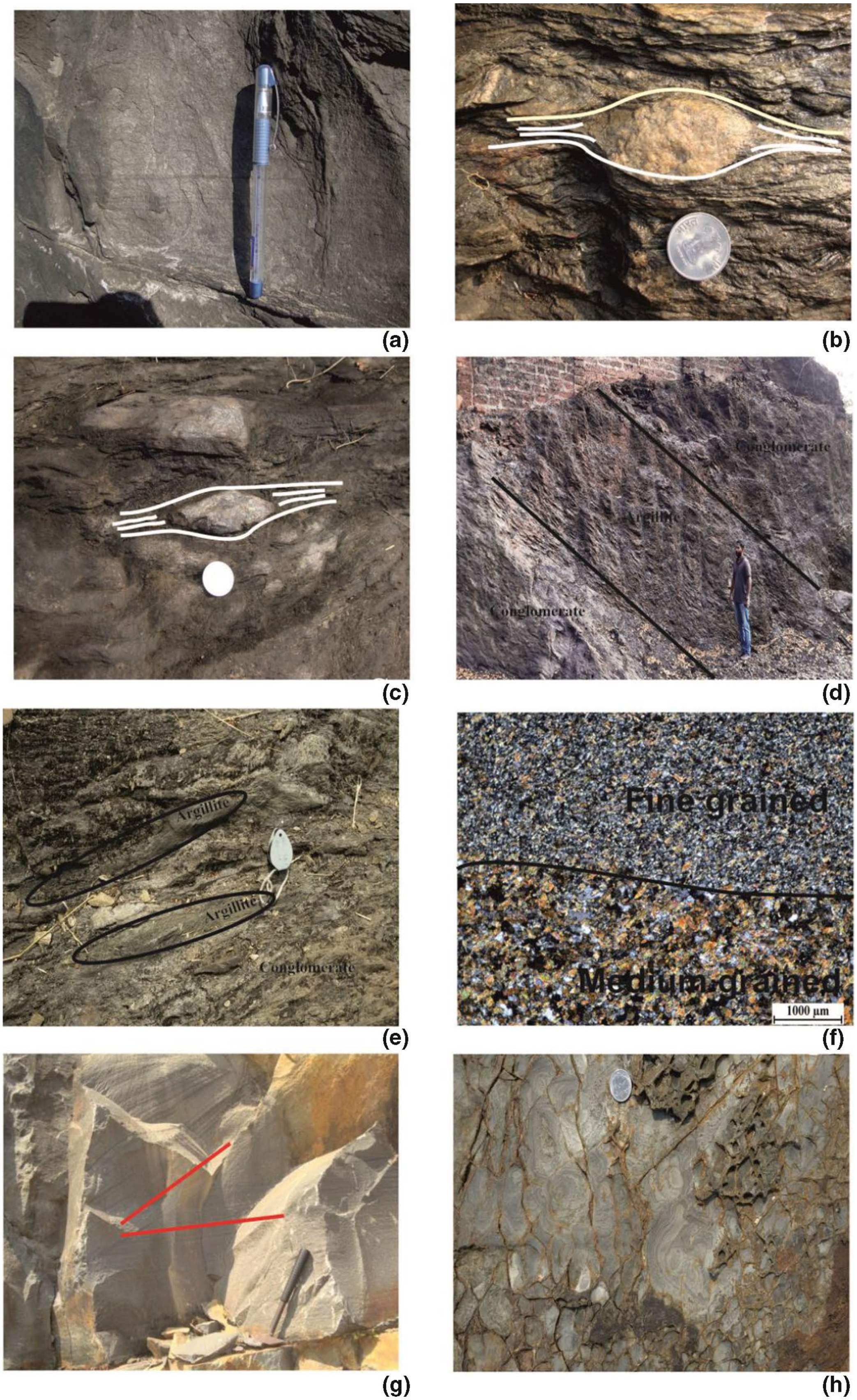
4.1.3 Soft sediment deformation structures (SSDS)

Overall, the metagreywacke of the study area is massive and laminated while at certain outcrops, such as at the cliffs of Aguada and headlands of Arambol (Fig. 1), various SSDS are preserved which possibly could be due to the deformation of the original laminations. The destruction of laminations leading to the formation of SSDS has been attributed to several reasons: rapid deposition of sediments by suspension, disruption of sediments due to liquefaction, and movement of sediment in a water-logged state (cf. Collinson & Thompson, 1982). We now detail the various SSDS that are observed in the Goa Group of rocks.

Convolute laminations occur in a 50-cm-thick layer and are sandwiched between undeformed sedimentary layers in the metagreywacke (Fig. 3a). The convolute laminations are associated with load and flame structures which occur as wavy undulations. Convolute laminations form due to penecontemporaneous dewatering during fluidization—liquefaction processes and expulsion of pore water which is probably set by the turbidity flow (cf. Kundu et al., 2011; Owen, 1996; Samaila et al., 2006). Convolute laminations are typical of turbidites and represent Bouma units (Fernandes, 2018; Selley, 2000) and these have been noted in the Goa Group (Soman, 1993) and are discussed later.

Flame and Load Structures that were noted are about 5 cm thick. The flame structure indicates a rise of the underlying finer-lighter sediments into the overlying coarse-denser sediments while the load structure shows coarse-denser sediment that has sunk into the underlying finer and lighter sediments (Fig. 3b).

Ball and pillow structures (pseudo-nodules) form bulbous features (Fig. 3c, d) and occur as isolated masses of


(a)
(b)
(c)
Conglomerate
Argillite
Conglomerate
(d)
Argillite
Argillite
Conglomerate
(e)
Fine grained
Medium grained
1000 µm
(f)
(g)
(h)

◂**Fig. 2** Field photographs of structures in metagreywacke. **a** Laminations in 'Metagreywacke with biotite' horizon identified by the presence of mica (biotite) flakes and clay minerals (Location: 15.6354° N, 73.7207° E). **b**, **c** Dropstone structure in matrix-supported conglomerate unit with pebbles of quartzite and granite. (White lines indicate the laminations) (Location: 15.2643° N, 73.1117° E). **d** Argillite interbedded between conglomerate (Location: 15.2647° N, 73.1116° E). **e** Conglomerate with intercalations of argillites in the form of lentoid pockets. **f** Photomicrograph of metagreywacke with graded bedding (under polarized light). **g** Metagreywacke with cross laminations (Location: 15.4864° N, 73.8815° E). **h** Liesegang rings with a characteristic concentric or ring-like appearance (Location: 15.4073°N, 73.7859° E)

fine-grained sedimentary nodules and are nearly circular to elliptical. These features form when the load structure separates from the overlying sediments as the load-bearing strength of liquefied sediment is lost (Fernandes, 2018; Kundu & Goswami, 2008).

Slump fold structures (Fig. 3e) occur in a single stratum of metagreywacke and are bounded by undisturbed sediments above and below. The folds were possibly formed when the sediment layers behaved as plastic or semi-consolidated media, and due to gravity, the sediments moved downslope (Kundu et al., 2011), either as the slope exceeded the angle of repose of the sediments (Mills, 1983) or under the influence of large-scale water movements (Siegenthaler et al., 1987) or along exceptionally low angle (< 1°) subaqueous slopes (Alsop & Marco, 2013).

Syn-sedimentary faults (Fig. 3f) are identified in metagreywacke with undeformed strata overlying and underlying them, wherein the hanging wall of the fault exhibits thickening or growth and represents syn-sedimentary faults. These faults and their association with undeformed strata are evident of brittle deformation when the sediments were partly consolidated (cf. Rossetti & Góes, 2000). Syn-sedimentary faults can also develop during the late stage of deformation due to a sudden increase in pore water pressure by applying stress (Pandey & Pandey, 2015).

4.1.4 Intrusive and deformational structures

Dykes: Besides the above described various structures in the study area, several dolerite dykes and numerous quartz veins were noted to intrude the country-rock of metagreywacke (Fig. 3g). The quartz veins were perhaps formed when silicic fluids were injected into the metagreywacke due to the emplacement of dolerite dykes.

Shear Zone: A shear zone was observed at Vagator and this indicates faulting, wherein the metagreywacke was seen to be sheared along the quartz veins. The ductile deformation resulted in a haphazard arrangement of quartz grains within the metagreywacke (Fig. 3h).

5 Discussion

The various features that occur in a sedimentary formation are dependent on sediment rheology, sediment texture, deformation mechanism and timing of deformation relative to sedimentation. We now discuss the formation and implication of the different structures noted in the Goa Group of rocks.

Water-saturated sediments often result in a variety of SSDS ranging from load, flame, pseudonodules, slump folds and syn-sedimentary faults (McDonald & Shilts, 1975; Brodzikowski et al., 1987; Chunga et al., 2007; Gruszka and Van Loon, 2007; Van Loon, 2009). The significant controls leading to the formation of deformation structures are rapid deposition, slope and gravity controlled density currents (Bowman et al., 2004) and also differential compaction (Mazumder et al., 2009). The metagreywacke in the study area is massive and laminated while at certain outcrops mainly at the cliffs of Aguada and headlands of Arambol, various SSDS are preserved. Ortner (2007) explained that the SSDS could form during sediment gravity flow and due to the rapid deposition of water and sediments. During this process, water gets trapped in the interstitial pores of sediments resulting in an unstable pore pressure. During the course of burial and compaction of the sediments, the interstitial water escapes leading to the formation of the various styles of SSDS.

Most of the SSDS such as flame, load and pseudonodules observed in the study area need density contrast within the sediment layers. The SSDS mostly results when liquidised or hydroplastic and more competent sediments are stressed during or shortly after deposition.

Kundu et al. (2011) listed five processes for the formation of flame structures: (i) fluvial current drag (Kuenen & Menard, 1952), (ii) action of pressure due to loading (Anketell et al., 1970), (iii) slope-controlled movement of sediment load (Brenchley & Newall, 1977; Fernandes, 2018), (iv) earthquake shock (Fernandes, 2018; Sukhija et al., 1999) and (v) differences in dynamic viscosity between sediment layers (Anketell et al., 1970) when the fine-grained sediments behave as diapiric intrusions (Mills, 1983). Because of the difference in the grain size, we attribute the formation of flame structures in the study area (Fig. 3b) as either to differences in dynamic viscosity between the sediment layers and overlying pressure of the sediment or slope-controlled movement of the deposited sediment.

Load structures (Fig. 3b,4) in the study area that co-occurs with the flame structures were perhaps formed as the denser sediments settled into lighter sediments coupled with a gravitational readjustment due to instability of the strata. When the substrate is liquidised, it loses its capacity

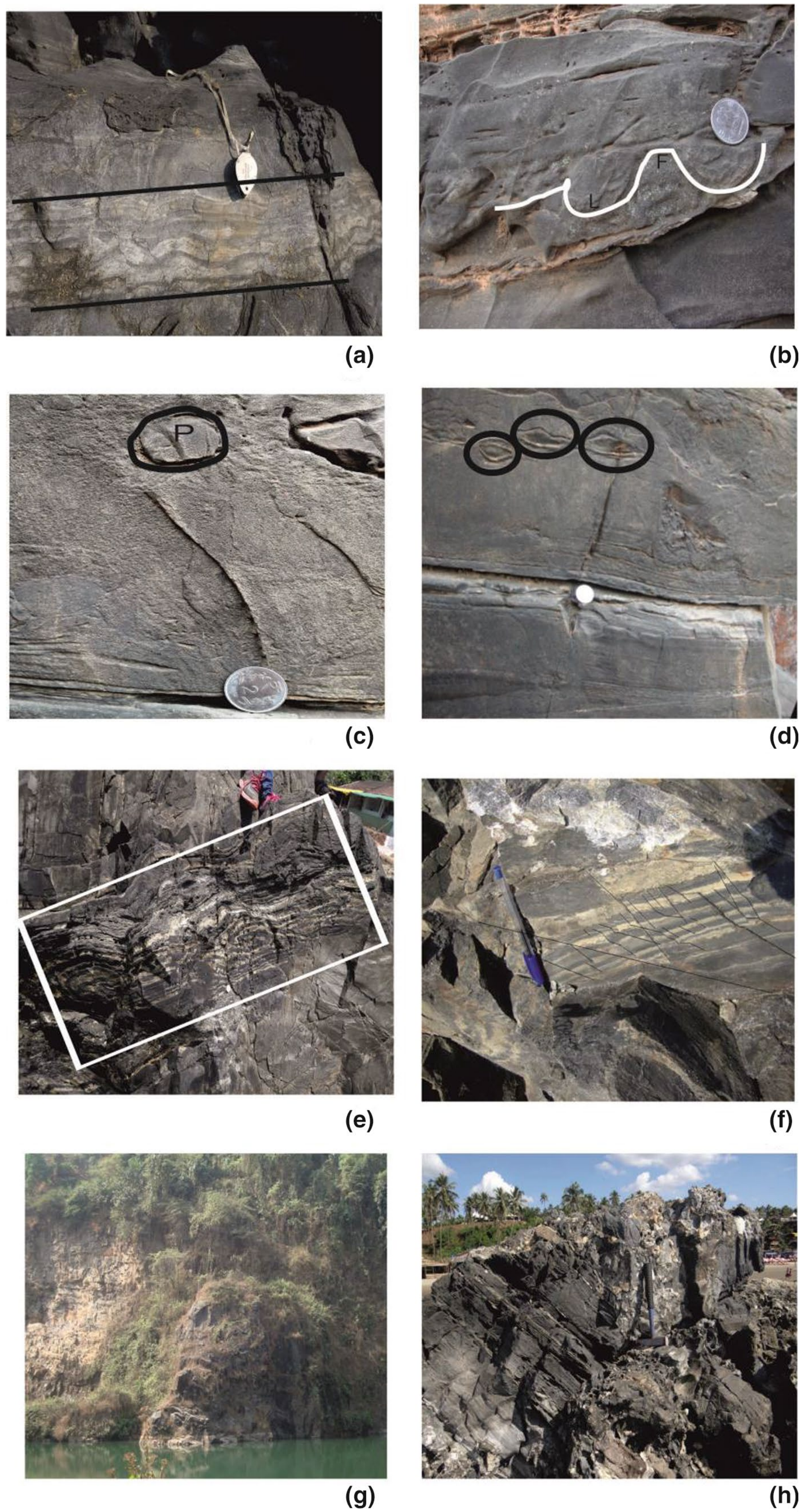


Fig. 3 Field photographs of metagreywacke. **a** Convolute lamination in metagreywacke sandwiched between undeformed layered sedimentary strata (Location: 15.6052° N, 73.7329° E). **b** Load (L) and Flame (F) structure occur as crenulations or wavy undulations having about 3–5 cm thickness (White lines indicate the laminations) (Location: 15.4966° N, 73.7646° E). **c**, **d** Pseudonodules (P) seen as circular to elliptical shape (marked—with a circle) (Location: 15.4966° N, 73.7646° E). **e** Slump folds (marked by white box) bounded by undisturbed sediments above and below, having a broad and U-shaped and with a near-vertical axial plane (Location: 15.6923° N, 73.6985° E). **f** Syn-sedimentary faults truncate against undeformed continuously layered strata above and below them (Black lines mark fault planes) (Location: 15.6923° N, 73.6984° E). **g** Dolerite dyke intruded into country rock of metagreywacke (Location: 15.4954° N, 73.8929° E). h) Shear zone of metagreywacke (Location: 15.6052° N, 73.7328° E)

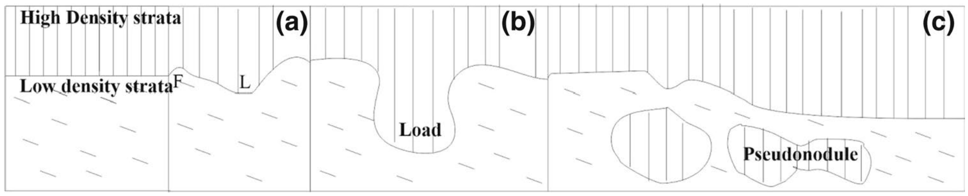


Fig. 4 Schematic illustration showing the development of pseudonodule from a load structure. Load and flame structures are formed (**a**), followed by prominent load structures (b), these load structures sink into the underlying strata (b) to form ball and pillow or pseudonodule. (F-Flame structure; L-Load structure)

to support sediments and hence there is a lateral redistribution of the sediment load associated with flame structures (Fernandes, 2018; Owen, 2003).

Ball and pillow structures (pseudonodules) result when the loaded cast or dense sediment sink into the underlying strata. The development of flame and load structure in the pseudo-nodule is schematically illustrated in Fig. 4.

5.1 Sedimentation history and depositional environments

A systematic study of the various structures in sedimentary rock yield significant details about the sedimentation history and the depositional environment that affected the sediment during and after their deposition (Fernandes et al., 2016a). The structures that develop in the sedimentary rocks act as clues to decipher the environment at the time of sediment deposition (Collinson & Thompson, 1982; Reading, 1978; Selley, 2000). Understanding the SSDS helps to delineate the environmental conditions which occurred between the various sediment depositional events because the SSDS are formed either by gravitational movements, density differences or by the movement of intergranular fluid (Fernandes, 2018; Potter et al., 1984; Valente et al., 2014).

The presence of argillaceous material within the conglomerate in the study area is indicative, either that the transporting media was less or inactive. It could also result when some areas of the depositional basin were isolated from the rapid downslope movement of coarser materials or if there was a local shallowing of the depositional basin (Fernandes, 2018).

The SSDS form during or just after deposition of sediments when these are in an unconsolidated or liquid or mush-like. The congenial sites where SSDS can develop can range from nearshore to the deep water basin subjected to turbidity currents (continental margins). The areas also include storm-dominated shallow marine regions, deltas and rivers. SSDS can also form because of seismic activity as this could result in liquefaction of the sediments (Ortner, 2007; Chunga et al., 2007; Kundu et al., 2011 Pisarska-Jamrozy & Weckwerth, 2013; Valente et al., 2014). The development of SSDS depends mainly on the rapidly changing hydrological conditions in the deltaic environment (Pisarska-Jamrozy and Weckwerth, 2013).

The SSDS are observed along a horizon of the Sanvordem Formation which is exposed along the coast of North Goa at Aguada and Arambol (Fig. 1). The SSDS are overlain and underlain by undisturbed sediments and hence may be unrelated to regional tectonics but demarcate a period of quiescence before and after the growth of the SSDS (Fernandes, 2018). The SSDS might have formed in a single instantaneous event such as a short natural trigger that disturbed the water-saturated semi-consolidated sediments, which are attested by the occurrence of the SSDS strata in a localized area, their limited lateral extent and less thickness. A similar phenomenon occurs in River Yamuna, in NW Sub-Himalaya India, wherein the SSDS are overlain by undeformed beds (Pandey & Pandey, 2015). Those authors suggested the variable geometry of the SSDS to have formed by local gravity-driven, viscous–brittle deformation in the sediment strata.

Ortner (2007) explained that SSDS could develop during sediment gravity flow and due to rapid deposition of water and sediments, aided by the interstitial water of the sediment, which causes an unstable pore pressure. During burial and compaction, the interstitial water escapes and as a consequence various SSDS are formed (Fernandes, 2018**)**. The SSDS mostly result when liquidised or hydroplastic and more competent sediments are stressed during or shortly after deposition. In the present study area, the SSDS could result from similar factors associated with the early stages of sediment consolidation in a deltaic environment. The association of SSDS in deltas is reported by Postma (1984), Porebski and Steel (2003), Owen and Moretti (2008), Koc Tasgın et al. (2011) and Perov and Bhattacharya (2011).

Most of the SSDS such as flame, load and pseudo-nodules observed (Fig. 3) need density contrast, within the sediment layers, for their formation (Fernandes, 2018) and this is possible in a deltaic setting. The load structures are commonly observed in the proximal and distal delta front deposits where coarse denser material overlie finer lighter materials. As such these are common in areas or strata with less muddy sediments (Ekwenye et al., 2020). Besides, the downslope mass transport over the delta could be responsible for slump fold formation (Pisarska-Jamrozy and Weckwerth, 2013).

The presence of syn-sedimentary faults in the study area could have possibly formed due to subsidence or due to slumps that moved downslope due to overloading and over-steepening of the subaqueous delta (Pisarska-Jamrozy and Weckwerth, 2013).

Turbidity current is a mixture of water and detritus flow comprising of mud, silt and sand, which remains in suspension by turbulence. Under the influence of gravity, there is a downward flow movement creating turbidity current and as the turbulence of current decays, sedimentation commences. The resulting facies represent deposition from turbidity currents (Bouma, 1962; Fernandes, 2018; Valente et al., 2014) and the various structures can be sequentially arranged to form regular units of a Bouma sequence that consists of texture and bedding subdivisions resulting due to changing hydraulic regimes (Fernandes, 2018; Potter et al., 1984). The various structures exhibited by the entire succession of metagreywacke of the Goa Group can be integrated to portray the internal structure of the Bouma sequence (cf. Soman, 1993) in which each surge of turbidite flow produced an individual graded sequence or a turbidite. The SSDS, typically the convolute laminations, are characteristics of turbidites and imply deformation of either massive or laminated or cross-laminated Bouma units. One of the factors that could favour the formation of the SSDS is the dewatering of sediment aided by shear stresses that develop because of turbidity flow of sediment (Collinson & Thompson, 1982; Valente et al., 2014).

Soman (1993) reported deformed horizons of argillites to be sandwiched between normal bedded deposits showing internal deformation. He also reported parallel laminations, current ripple lamination, convolute laminations and pelagic clay intervals corresponding to the Bouma sequences B, C, D, and E units. He also reported that the massive graded interval, i.e., A unit of Bouma is commonly lacking. Besides, slump folds, sandstone dykes and metagreywackes containing thin conglomerates were also reported.

5.2 Bouma sequence

We correlate the typical Bouma sequence with the various structures including the SSDS, associated with the metagreywacke-argillite strata in the study area. The strata are arranged regularly to represent a Bouma sequence with 4 units (A to D) while in an ideal Bouma sequence 5 units are present (A to E) (Fig. 5). Unit A is massive well graded, formed due to the rapid deposition of coarser to fine sediments during the initial surge of turbidity currents. Unit A is succeeded by the B unit that consists of laminated deposition of planar bedforms. This unit is overlain by a C unit that formed indicated convolutions and the various SSDS. Followed by this is a D unit with fine laminations that indicate settlement of sediments from suspension in a basin.

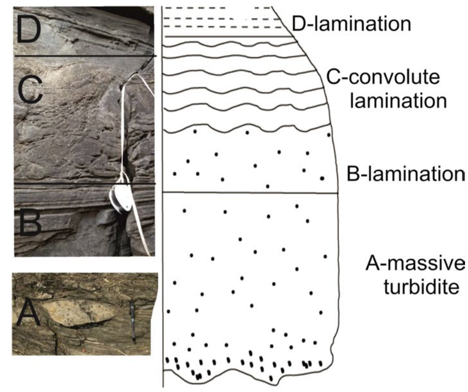


Fig. 5 Illustration of the Bouma units as identified in the present study (cf. Bouma, 1962; Middleton & Hampton, 1973; Walker, 1965)

The E unit of pelagic mud is not identified in the study area and was perhaps eroded. The SSDS strata could have possibly formed all along the coast of Goa, however faulting along the Chapora River and its vicinity may have led to the displacement of blocks towards the north and south and resulted in the presently observed restricted exposures of the SSDS at Aguada and Arambol regions (Fig. 1).

5.3 Dykes and shear zone

Two episodes of volcanism are suggested during which the dykes were emplaced along the Goa coast and indicate a thin continental crust along the coast (Fernandes, 2018; Iyer et al., 1990). The younger generation dykes are related to the post-Deccan Traps that occurred at the end of Deccan volcanism about 63 Ma corresponding to late Mesozoic tectonism, while the other dykes could be the older dykes of Precambrian age. This was also recently corroborated by Gadgil et al. (2019).

The shear zone could have possibly formed due to faulting which occurred contemporary to the major fault of the west coast of India during which time several fault planes developed in W to WSW direction (cf. Fernandes, 2018; Gokul et al., 1985; Iyer et al., 1990).

5.4 Model for the evolution of the depositional basin

The lithological similarity and stratigraphic disposition suggest that the metagreywacke-argillite strata (Goa Group) from the present study can be correlated with the Hiriyur Formation of Chitradurga Schist Belt in Karnataka. The greywacke in both the cases is massive to poorly graded, medium to coarse-grained compact greenish grey sandy rock which alternates with the argillite. Only A, B, and C units of typical turbidites are represented in Hiriyur Formation while at some places Unit D is eroded (Burhanuddin & Mohakul, 2020). In contrast, in the present study, units A, B, C, and D are observed and the topmost unit E is not observed in the exposed sections possibly due to erosion. The conglomerate unit can be interpreted to be a part of the proximal re-sedimented facies and the greywacke deposition in a quiet water condition below the wave base mainly by turbidity currents (cf. Walker and Pettijohn, 1971). Typically, the deltaic systems are commonly represented with SSDS due to slope instability, rapid sedimentation, storm waves, and/or overloading mainly in the proximal region with a rapid sediment accumulation (Bann & Fielding, 2004; Bhattacharya & Walker, 1992; Coleman, et al., 1983; Oliveira et al., 2011).

Based on the morphologies of the structures and the association of various types of sediment material, we draw the following inferences regarding the events of formation and evolution of the depositional basin depicted with the help of a schematic model (Fig. 6):

1. A surge of turbidite current at the continental margin of Goa leads to the deposition of sediments in a deltaic environment.
2. Coarser sediments deposit produced the conglomerates.
3. Subsequently, the deposition of coarse-grained/sand-rich to fine-grained/mud-rich sediments occurred.
4. The SSDS were formed due to the processes of liquefaction followed by the lithification of the water-saturated sediments.
5. Deposition of sediments further continued as the SSDS horizon is seen to be overlain by undeformed strata.
6. Dolerite dykes intruded in metagreywacke country rocks leading to the occurrence of cracks and fissures in metagreywacke and along these quartz veins are emplaced.
7. The region was locally deformed due to folding and faulting which caused a small localised but significant deformation.

The overall sedimentary sequence can be interpreted to be a resultant product of fault-controlled sedimentation in a high energy environment along with turbidity currents associated with a prograding deltaic environment.

6 Conclusion

The State of Goa (India) is situated in the North-western part of the Western Dharwar Craton. The Sanvordem Formation of Goa Group, best exposed along the North coast of Goa, constitutes a part of this craton and is dominated by clastics that formed as a result of settling of sediment load from turbidity current leading to deposition of coarse grains and formation of a conglomerate bed with extraneous pebbles at the base of the flow. The units grade upwards from a well-graded metagreywacke (A), through

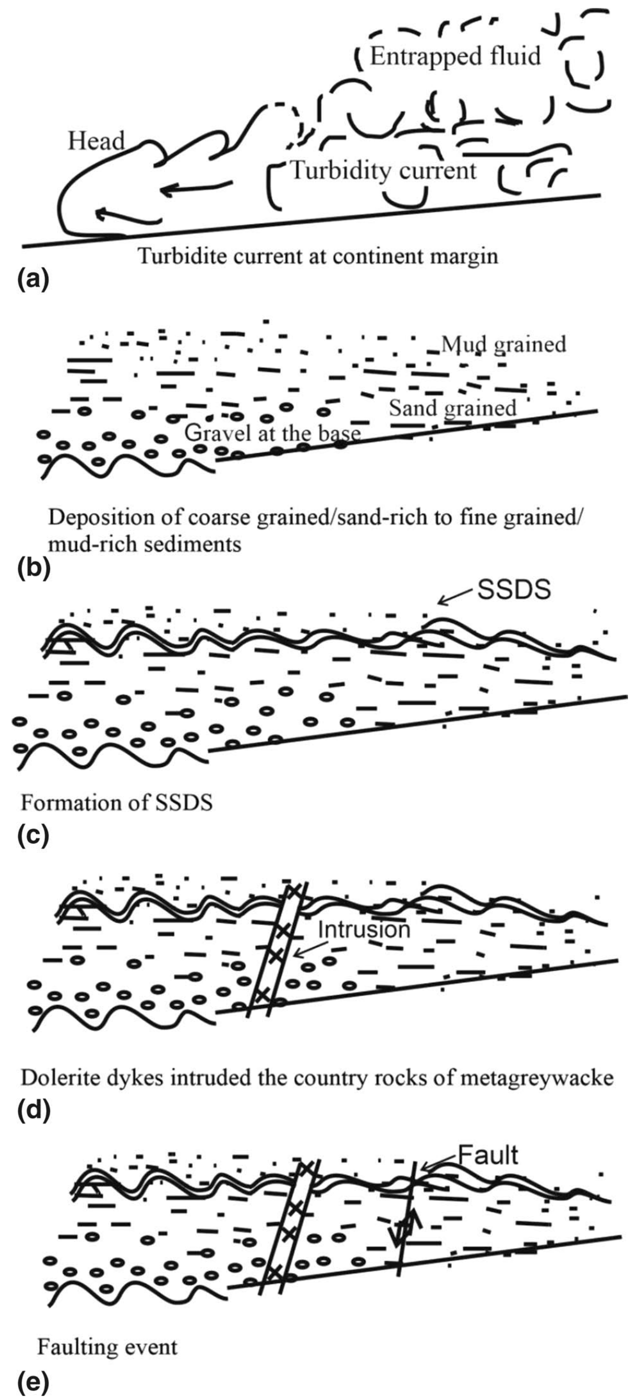


Fig. 6 Schematic model depicting the phases of basin development in the study area

a laminated (B), followed by a convolute laminated unit (C) which is again followed by a laminated unit (D). These units are identified in the field to resemble a substantial part of a typical Bouma sequence. The rapid deposition of saturated sediments led to the formation of the SSDS. The region was exposed to an episode of folding. Subsequently, there was an intrusion of dolerite dykes into the country rock, emplacement of several quartz veins and faulting in the region.

Several primary, diagenetic and deformational structures (including SSDS) have been delineated for the first time in the metagreywacke-argillite strata of the Goa Group. The deltaic setting with high sediment supply and with changing water level, slope instability and density differences in sediments resulted in an in situ deformations and formation of the SSDS. The regional geology and structural data also attest to a deltaic environment with a turbidite condition for the deposition of the sediments. During the process, the low-density turbidity currents gave rise to the Bouma sequence. Sediment deposition occurred in a deep basin which progressively changed to a shallow environment.

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Author contributions Dr. G. Fernandes carried out a large part of the fieldwork, analysed the data and initiated a manuscript write-up. Drs. Iyer and Kotha contributed to the discussion and editing of the paper.

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References

Allen, J. R. L. (1982). Developments in Sedimentology: S*edimentary Structures: Their Character and Physical Basis*. v. II (30), Elsevier, Amsterdam, 343–393.

Alsop, G. I., & Marco, S. (2013). Seismogenic slump folds formed by gravity-driven tectonics down a negligible subaqueous slope. *Tectonophysics, 605*, 48–69.

Anketell, J. M., Cegla, J., & Dzulynsky, S. (1970). On the deformational structures in systems with reversed density gradients. *Annales Societatis Geologorum Pololiae, 40*, 3–30.

Bann, K. L. and Fielding, C. R. (2004). An integrated ichnological and sedimentological comparison of non-deltaic shoreface and subaqueous delta deposits in Permian reservoir units of Australia. In: McIlroy, D. (Eds.). The application of ichnology to palaeoenvironmental and stratigraphic analysis. *Geological Society of London,* Special Publications 228, 273–310.

Bhattacharya, J.P. and Walker, R.G. (1992). Deltas. In: Walker, R.G., James, N.P. (Eds.), Facies Models: Response to Sea Level Change. *Geological Association of Canada*, St Johns, Newfoundland, 157–178.

Bouma, A. H. (1962). *Sedimentology of some flysch deposits*. Elsevier.

Bowman, D., Korjenkov, A., & Porat, N. (2004). Late-Pleistocene seismites from Lake Issyk-Kul, the Tien Shan range, Kyrghyzstan. *Sedimentary Geology, 163*(3–4), 211–228.

Brenchley, P. J., & Newall, G. (1977). The significance of contorted bedding in upper Ordovician sediments of the Oslo region, Norway. *Journal of Sedimentary Petrology, 44*, 819–833.

Brodzikowski, K., Gotowała, R., Hałuszczak, A., Krzyszkowski, D., & Van Loon, A. J. (1987). Soft sediment deformations from glaciodeltaic, glaciolacustrine and fluviolacustrine sediments in the Kleszczów Graben (central Poland). *In:* Jones, M. E., & Preston, R. M. F. (Eds.), Deformation of sediments and sedimentary rocks. *Geological Society Special Publication*, 29, 255–267.

Burhanuddin, M., & Mohakul, J. P. (2020). Litho-stratigraphic analysis of Dharwar Supergroup in Chitradurga Schist Belt, Karnataka: a re-appraisal. *Indian Journal of Geosciences, 74*, 447–462.

Carl, J. D., & Amstutz, G. C. (1958). Three-dimensional Liesegang rings by diffusion in a colloidal matrix and their significance for the interpretation of the geological phenomenon. *Geological Society of America Bulletin, 69*, 1467–1468.

Chunga, K., Livio, F., Michetti, A. M., & Serva, L. (2007). Synsedimentary deformation of Pleistocene glaciolacustrine deposits in the Albese con Cassano Area (Southern Alps, Northern Italy), and possible implications for paleoseismicity. *Sedimentary Geology, 196*, 59–80.

Coleman, J. M., Prior, D. B., & Lindsay, J. F. (1983). Deltaic influences on shelf edge instability processes. In: Stanly, D. J., Moore, G. T. (Eds.). The shelfbreak: critical interface on continental margins. Society of Economic Paleontologists and Mineralogists, Special Publication 33, 121–137

Collinson, J. D. (2003). Deformation of sediments. In G. V. Middleton (Ed.), *Encyclopedia of sediments and sedimentary rocks* (pp. 190–193). Kluwer Academic Publishers.

Collinson, J. D., & Thompson, D. B. (1982). *Sedimentary structures*. Allen and Unwin.

Dessai, A. G. (2011). The geology of goa: revisited. *Journal of the Geological Society of India, 78*, 233–242.

Ekwenye, O., Mode, A., Oha, I., & Onah, F. (2020). Soft-sediment deformation in the Campanian-Maastrichtian Deltaic deposits of the Afikpo Sub-basin, South-eastern Nigeria: Recognition of endogenic trigger. *Jordan Journal of Earth and Environment Sciences, 11*, 1–11.

Feary, D. A. (1979). Geology of the Urewera Greywacke in Waioeka Gorge, Raukumara Peninsula, New Zealand, *New Zealand. Journal of Geology, 22*, 693–708.

Fernandes, G. Q. (2018). Geology and characteristics of metagreywacke and associated rocks of Goa Group, India. Unpubl Thesis, Goa University, 195.

Fernandes, G. Q., Iyer, S. D., & Kotha, M. (2016). Origin and tectonic setting of Precambrian greywacke of Ribandar-Chimbel, Goa, India: Petrological and geochemical Evidences. *Acta Geologica Sinica-English, 90*, 2036–2048.

Gadgil, R., Viegas, A. and Iyer, S.D. 2019. Structure and emplacement of the coastal Deccan tholeiitic dyke swarm in Goa, on the western Indian rifted margin. *Bulletin of Volcanology,* 81, https://doi.org/10.1007/s00445-019-1297-6

Gokul, A. R., Srinivasan, M. D., Gopalkrishnan, K., & Viswanathan, L. S. (1985). Stratigraphy and structure of Goa. In: Seminar volume on Earth Resources for Goa's Development, Panaji, Goa.

Gruszka, B., & Van Loon, A. J. (Tom). (2007). Pleistocene glacio lacustrine breccias of seismic origin in an active graben (central Poland). In: Gruszka, B., Van Loon, A.J. (Tom), & Zieli´nski, T., (Eds.), Quaternary Geology—Bridging the gap between East and West. *Sedimentary Geology Special Issue*, 193, 93–104.

Gujar, A. R., Iyer, S. D., Udayaganesan, P., Ambre, N. V., Mislankar, P. G., & Dhinesh, S. (2021). Nature, characterization and resource potential of littoral placer deposits of Goa, central west coast of India. *Journal of Sedimentary Environments*. https://doi.org/10.1007/s43217-021-00064-5

Hegde, V. S., & Chavadi, V. C. (2009). Geochemistry of late Archaean metagreywackes from the Western Dharwar Craton, South India: Implications for provenance and nature of the Late Archaean crust. *Gondwana Research, 15*, 178–187.

Henisch, H. K. (1988). *Crystals in gels and liesegang rings* (p. 197). Cambridge University.

Iyer, S. D., Wagle, B. G., & D'Cruz, E. E. (1990). Dyke swarms along the Goa coast, India. *In:* Proceedings of the National Seminar on Recent Research in Growth of Western India. M.S. University of Baroda, Vadodara, Gujarat, India 14.

Iyer, S. D., & Wagle, B. G. (1987). Morphometric analyses of the river basins in Goa. *Geographical Review of India, 49*, 11–18.

Jayananda, M., Chardon, D., Peucat, J. J., & Capdevila, R. (2006). 2.61 Ga potassic granites and crustal reworking in the Western Dharwar Craton, Southern India: Tectonic, geochronologic and geochemical constraints. *Precambrian Research, 150*, 1–26.

Jayananda, M., Peucat, J. J., Chardon, D., Krishna Rao, B., et al. (2013). Neoarchean greenstone volcanism and continental growth, Dharwar Craton, Southern India: constraints from SIMS U-Pb zircon geochronology and Nd isotopes. *Precambrian Research, 227*, 55–76.

Koc Tasgın, C. K., Orhan, H., Turkmen, I., & Aksoy, E. (2011). Soft-sediment deformation structures in the late Miocene Selmo Formation around Adiyaman area, Southeastern Turkey. *Sedimentary Geology, 235*, 277–291.

Kuenen, P. H., & Menard, H. W. (1952). Turbidity currents, graded and non-graded deposits. *Journal of Sedimentary Petrology, 22*, 83–96.

Kundu, A., & Goswami, B. (2008). A note on seismic evidences during the sedimentation of panchet formation, Damodar Basin, Eastern India: Banspetali Nullah Revisited. *Journal of the Geological Society of India, 72*, 400–404.

Kundu, A., Goswami, B., Eriksson, P. G., & Chakraborty, A. (2011). Palaeo seismicity in relation to basin tectonics as revealed from soft-sediment deformation structures of the Lower Triassic Panchet formation, Raniganj basin (Damodar valley), eastern India. *Journal of Earth System Sciences, 120*, 167–181.

Leggett, J. K. (2012). Marine Clastic Sedimentology: Concepts and Case Studies. Springer Netherlands. Liesegang, R. E. (1913). Geologische Diffusionem. Steinkopf, Dresden 180.

Mazumder, R., Rodŕıguez-Lóopez, J.P., Arima, M., & Van Loon, A. J. (2009). Palaeo Proterozoic seismites (fine-grained facies of the Chaibasa Fm., E India) and their soft-sediment deformation structures. *In:* Reddy S, Mazumder, R., Evans, D., & Collins, A. (Eds), Palaeoproterozoic supercontinents and global evolution. Geological Society, London, Special Publications 323, 301–318.

McBride, E. F. (2003). Pseudo faults resulting from compartmentalized Liesegang bands: Update. *Sedimentology, 50*, 725–730.

McDonald, B., & Shilts, W. W. (1975). Interpretation of faults in glaciofluvial sediments. *In:* Jopling, A., & McDonald, B. (Eds.), Glaciofluvial and glaciolacustrine sedimentation. *Society of Economic Paleontologists and Mineralogists Special Publication*, Tulsa, Oklahoma, USA, 23, 123–131.

Middleton, G. V., & Hampton, M. A. (1973). Sediment gravity flows: mechanics of flow and deposition. In: Middleton, G. V., & Bouma, A. H. (Eds.), Turbidites and Deep-Water Sedimentation. Pacific Section of the Society of Economic, Paleontologists and Mineralogists, California. Short Course Lecture Notes, 38 p.

Mills, P. C. (1983). Genesis and diagnostic value of soft-sediment deformation structures—a review. *Sedimentary Geology, 35*, 83–104.

Oliveira, C. M. M., Hodgson, D. M., & Flint, S. S. (2011). Distribution of soft-sediment deformation structures in clinoform successions of the Permian Ecca Group, Karoo Basin, South Africa. *Sedimentary Geology, 235*, 314–330.

Ortner, H. (2007). Styles of soft-sediment deformation on top of a growing fold system in the Gosau Group at Muttek of Northern Calcareous Alps, Austria: Slumping versus tectonic deformation. *Sedimentary Geology, 196*, 99–118.

Owen, G. (1987). Deformation processes in unconsolidated sands. In: Jones ME, Preston RMF (Eds), Deformation of Sediments and Sedimentary Rocks. *Journal of the Geological Society of London*, 29, 11–24.

Owen, G. (2003). Load structures: gravity-driven sediment mobilization in the shallow subsurface. In: Van Rensbergen, P., Hillis R. R., & Maltman, A. J. (Eds), Subsurface Sediment Mobilization. *Geological Society of London*, *Special Publication, U.K,* 216, 22–34.

Owen, G. (1996). Experimental soft-sediment deformation: structures formed by the liquefaction of unconsolidated sands and some ancient examples. *Sedimentology, 43*, 279–293.

Owen, G., & Moretti, M. (2008). Determining the origin of soft-sediment deformation structures: a case study from Upper Carboniferous delta deposits in south-west Wales. *Terra Nova, 20*, 237–245.

Pandey, A. K., & Pandey, P. (2015). Soft sediment deformation structures in late Quaternary abandoned channel fill deposit of Yamuna River in NW Sub-Himalaya, India. *Current Science, 108*, 1717–1725.

Perov, G., & Bhattacharya, J. P. (2011). Pleistocene shelfmargin delta: Intradeltaic deformation and sediment bypass, northern Gulf of Mexico. *American Association of Petroleum Geologists, 95*, 1617–1641.

Pettijohn, F. J., & Potter, P. E. (1964). *Atlas and glossary of primary sedimentary structures* (p. 370). Springer-Verlag.

Pisarska-Jamroży, M., & Weckwerth, P. (2013). Soft-sediment deformation structures in a Pleistocene glaciolacustrine delta and their implications for the recognition of subenvironments in delta deposits. *Sedimentology, 60*, 637–665.

Porebski, S. J., & Steel, R. J. (2003). Shelf-margin deltas: their stratigraphic significance and relation to deepwater sands. *Earth-Science Reviews, 62*, 283–326.

Postma, G. (1984). Slumps and their deposits in fan delta front and slope. *Geology, 12*, 27–30.

Potter, P. E., Maynard, J. B., **&** Pryor, W. A. (1984). Overview. In: Sedimentology of Shale: Study guide and reference source. Springer-Verlag, 3–73.

Reading, H. G. (1978). *Sedimentary Environments and Facies* (p. 557). Blackwell Sci. Publ.

Rossetti, D. F., & Góes, A. M. (2000). Deciphering the sedimentological imprint of paleoseismic events: an example from the Aptian Codo Formation, northern Brazil. *Sedimentary Geology, 135*, 137–156.

Samaila, N. K., Abubakar, M. B., Dike, E. F. C., & Obaje, N. G. (2006). Description of soft-sediment deformation structures in the Cretaceous Bima sandstone from the Yola Arm, Upper Benue Trough, Northeastern Nigeria. *Journal of African Earth Sciences, 44*, 66–74.

Selley, R. C. (2000). Sedimentary structures. *Applied sedimentology* (pp. 130–180). Academic Press.

Siegenthaler, C., Finger, W., Kelts, K., & Wang, S. (1987). Earthquake and seiche deposits in Lake Lucerne, Switzerland. *Eclogae Geologicae Helvetica, 80*, 241–260.

Soman, G. R. (1993). Low density turbidity currents deposits from coastal parts of North Goa. Recent Researches in Sedimentology, 165–172.

Sreehari, L., & Toyoshima, T. (2020). Structural architecture and geological relationships in the southern part of Chitradurga Schist Belt, Dharwar craton, South India. *Journal of Mineralogical and Petrological Sciences*, J–STAGE Advance Publication, 1–16.

Stow, D. A. V. (2010). Principal characteristics of sedimentary rocks. *In: Sedimentary rocks in the field: A color guide. Academic Press, Elsevier*, 77.

Sukhija, B. S., Rao, M. N., Reddy, D. V., Nagabhushanam, P., Hussain, S., Chadha, R. K., & Gupta, H. K. (1999). Timing and return period of major palaeoseismic events in the Shillong Plateau, India. *Tectonophysics, 308*, 53–65.

Swami Nath, J., & Ramakrishnan, M. (1981). Early Precambrian supracrustals of southern Karnataka. *Geological Survey of India Memoir, India, 112*, 350.

Topal, S. G., & Özkul, M. (2014). Review article: Soft-Sediment Deformation Structures Interpreted as Seismites in the Kolankaya Formation, Denizli Basin (SW Turkey). *The Scientific World Journal,* 13.

Valente, A., Slaczka, A., & Cavuoto, G. (2014). Soft sediment deformation structures in seismically affected deep-sea Miocene turbidites (Cilento Basin, southern Italy). *Geologos, 20*, 67–78.

Van Loon, A. J. (2009). Soft-sediment deformation structures in siliciclastic sediments: an overview. *Geologos, 15*, 3–55.

Walker, R. G. (1965). The origin and significance of the internal sedimentary structures of turbidites. *Proceedings of the Yorkshire Geological Society,* 35, l-32.