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Research Article

Open paleoenvironment and dry climate in south India immediately before the Youngest Toba Tuff eruption (~75 ka) are suggested by *Vondrichnus* structures at the Jwalapuram locality, Jurreru valley

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Abstract

The Younger Toba Tuff (YTT) eruption is regarded as one of the largest of its time and possibly responsible for changing past climate and vegetation from C_3 to C_4 in the Indian subcontinent. A paleosol constituting a Toba pre-tephra horizon at the Jwalapuram locality, exhibits the preservation of biogenic structures identified as *Vondrichnus planoglobus* and *Vondrichnus obovatus*. This study investigated their paleoecological and paleoenvironmental significance. These structures are hard and compact, rounded to sub-rounded, spherical to sub-spherical bodies with empty chambers, surrounded by carbonate layers, and preserved in close proximity to termite pipes and nests and rhizolith structures. Their occurrence in the Jwalapuram area is significant, as the locality has been well documented as suitable for reconstruction of past climate and vegetation in light of the impact of the YTT eruption. Based on the present findings, we assume that the investigated locality would likely have an insect population and bush to scrub vegetation, indicating a dry environment immediately before the YTT eruption.

Keywords: Paleosol, *Vondrichnus*, Dry climate, YTT eruption, Quaternary

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Introduction

The Jwalapuram locality in the Jurreru valley, south India, has a preserved section of the Youngest Toba Tuff (YTT, 75 ka) ash of the Toba Caldera (Sumatra) and artifacts therein that act as significant source to reconstruct paleoclimate and human history (Petraglia et al., 2007; Jones, 2010; Haslam et al., 2012) (Fig. 1A and B). In this study, the locality is explored for *Vondrichnus* structures, important biogenic structures for climatic interpretation that are preserved in the paleosol horizon forming the lower part of the Quaternary succession as calcretized bodies of distinct morphologies and dimensions. The paleosols are considered to be marker horizons, because they preserve a variety of biogenic structures produced due to animal activities (Wright et al., 1988). As per Genise and Bown (1994), *Vondrichnus* structures possess systems of oblate chambers connected by a boxwork of simple burrows that branch or unbranch on the periphery of chambers. These structures are internally structureless, alveolar, or arranged in concentric layers. A group of one to three chambers is perceptible (Genise, 2016).

Based on 58 paleosol trace fossil assemblages, occurring from the Triassic to the Recent (Genise et al., 2000, 2013; Bostelmann et al., 2014; Roberts et al., 2016) redefined the continental ichnofacies model and hypothesized a new *Coprinisphaera* ichnofacies that consists of trace fossils produced primarily by bees, wasps, ants, termites, beetles, and other insects. Structures resembling *Vondrichnus* were recognized from paleosol horizons in the Eocene–Oligocene Jebel Qatrani Formation of Egypt by Bown and Genise (1993) and Genise and Bown (1994), who saw them as instrumental in reconstructing paleoenvironmental, paleoclimatological, and paleogeographic histories. Besides *Coprinisphaera*, other significant ichnofacies—*Termitichnus*, *Celliforma*, *Camborygma*, rhizolith, and vertebrate burrow ichnofacies—are also reported from paleosols (Smith et al., 1993; Genise et al., 2000; Melchor et al., 2012; Melchor, 2015; Cardonatto et al., 2016; Roberts et al., 2016, Ramos et al., 2021).The *Termitichnus* ichnofacies represent termite nest assemblages formed in a warm and humid climate (Smith et al., 1993; Genise et al., 2000; Roberts et al., 2016), and the *Celliforma* ichnofacies includes structures like *Celliforma*, *Rebuffoichnus*, and some beetle trace fossils (Genise et al., 2010). Genise et al. (2016) suggested that the *Camborygma* ichnofacies had traces of crayfish and earthworms that indicated wetlands and swamps. The rhizolith ichnofacies incorporates structures having diversified morphologies of plant roots, an indicator of subaerial exposure, whereas, the vertebrate burrow ichnofacies comprises tetrapods that are formed in well-drained calcified paleosols, indicating an arid to semiarid climate (Melchor et al., 2012; Melchor, 2015). Given the foregoing, it is evident that biogenic structures in paleosols are potentially valuable in reconstructing past climates. The present study includes: (1) the first report of *Vondrichnus* from the pre-YTT ash-bearing succession of the Jwalapuram area, along

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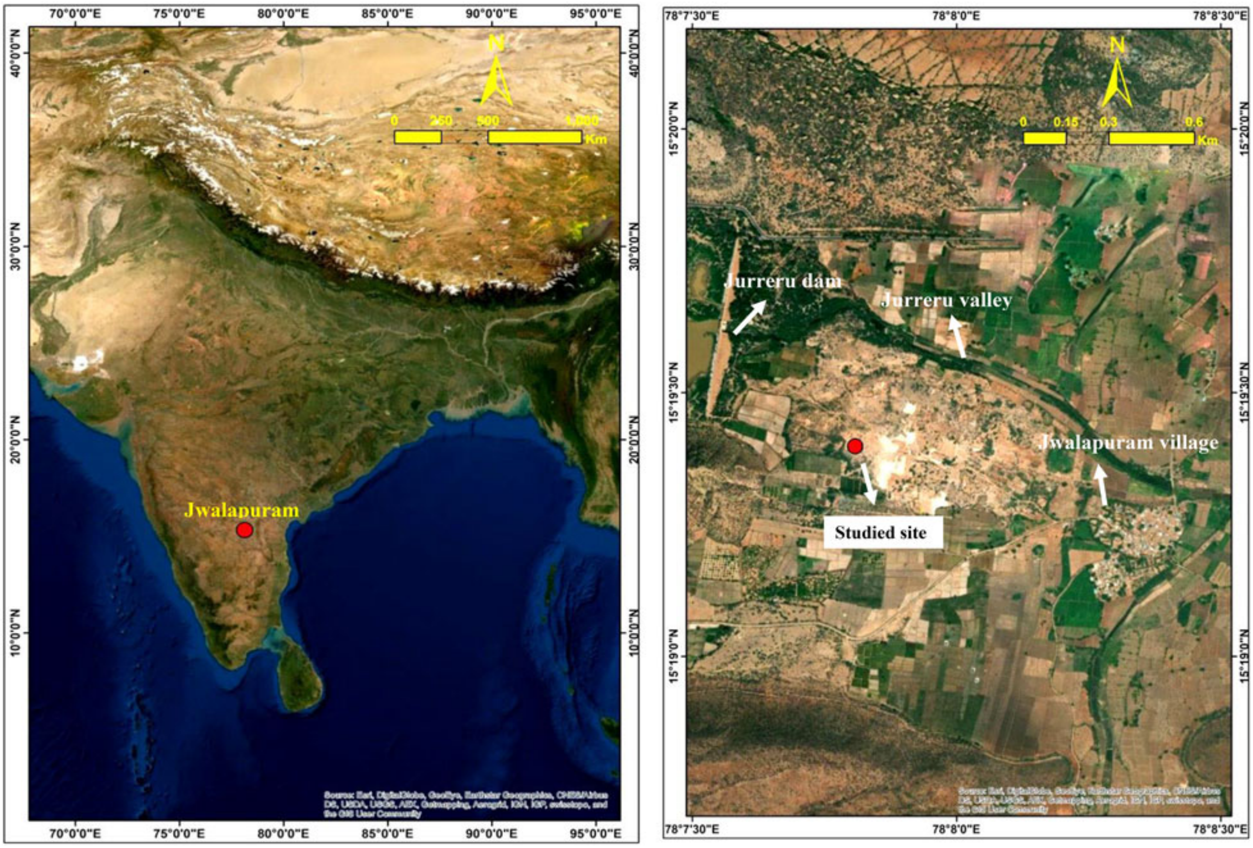

Figure 1. Maps showing (**A**) the location of the Jwalapuram locality in South India and (**B**) the studied site along with other landmarks.

with its morphological and preservational details; and (2) analysis of the lithologic architecture of the succession to infer paleoenvironmental conditions during the formation of these biogenic structures.

Materials and Methods

Fieldwork at the site included examination of an approximately 2-km-long and 3.5-km-wide area in order to locate an undisturbed and well-exposed site for the collection of samples and the description of host sediments. The selected site is characterized by its reddish to yellowish-brown color, massive size, and highly calcified nature that exhibits a rich assemblage of carbonate structures. These structures, previously unreported and a new paleoclimate proxy for India, were chosen to identify their genesis and significance for interpreting paleoecological and paleoenvironments in the region. About 215 samples of rounded to subrounded, spherical to subspherical carbonate structures were collected from the site. Profiling of the site for interpreting sediment types and the local geologic setting was also carried out. In addition, systematic photography of each specimen was undertaken in the field at the time of collection. After that, the samples were packed in zipper bags and sent to the sedimentology lab at the Department of Geology, Sant Gadge Baba (SGB) Amravati University, Maharashtra, India, where their morphological description and identification were carried out. Because these structures are being reported for the first time, this study followed Genise (2016), and the collected structures were classified into (1) *Vondrichnus*, (2) termite pipes and nests, and (3) rhizoliths. *Vondrichnus* structures were further subdivided into two types: (1) *Vondrichnus planoglobus* and (2) *Vondrichnus obovatus* following the classification of Genise (2016).

Geologic Setting

The geologic setting of the Jwalapuram locality (15°19′23.9″N, 78° 7′48.5″E), a part of the Jurreru valley (Fig. 1A and B), south India, is significant as having exposures of YTT ash-bearing Quaternary successions with evidence of an artifact industry of Paleolithic to Neolithic and Iron Age that are intermingled with the volcanic ash. The valley is drained by the Jurreru River, a major tributary of the Penner River that flows over the hard and compact terrain of sedimentary rocks of the Cuddapah Supergroup of Precambrian age. It is a conspicuous river valley located in the central part of Andhra Pradesh State, in which the river flow is easterly with steep sides and a relatively broad channel (Clarkson et al., 2012). The Jwalapuram locality, situated on the south bank of this valley, constitutes a part of Banaganpalle Taluk in the Kurnool District of Andhra Pradesh (Haslam et al., 2010).

The Quaternary sequence in the locality is represented by deposits of sandy-silty clay and volcanic ash beds. Haslam et al. (2012) and Mark et al. (2014) have distinguished three major lithounits at the locality in stratigraphic order as (1) paleosols constituting a 4-m-thick lower section represented by reddish to yellowish-brown, sandy-silty clay with abundant trace fossils and lithic artifacts; (2) a ~2- to 3-m-thick section of reworked volcanic ash with preservation of rhizoliths that are spread over a wide surface; and (3) a 1.5-m-thick yellowish-brown, laminated silty-clay mixed with volcanic ash.

Lithologic Framework

In accordance with previous reports (Haslam et al., 2012; Mark et al., 2014), the present paper has also identified three major lithounits at the site: (1) reddish to yellowish-brown sandy-silty clay, (2) volcanic ash, and (3) yellowish-brown sandy to silty clay (Fig. 2). The reddish to yellowish-brown sandy-silty clay lithounit, occupying the base of the succession, is about 4.5 m thick, bedded, and finely laminated. This unit contains abundant preserved fossils, termite passageways, and lithic artifacts (Jones, 2010; Haslam et al., 2012). Based on physical characteristics and rich preservation of organic sedimentary structures, this unit fits the criteria of a paleosol horizon of an aridisol nature. In particular, it lies above the section (stratum D) with pedogenic character, proposed by Blinkhorn et al. (2012). Haslam et al. (2012) dated this lithounit with optically stimulated luminescence and generated three ages in close proximity, 83±9, 87±7, and 85±6 ka. This unit is overlain by light gray, soft to semi-consolidated, reworked, and distal volcanic ash with a thickness of up to 2–3 m. This tephra unit has many horizontal laminations and faint cross beddings. It preserves abundant rhizoliths that normally stand in vertical orientations with some rarely parallel or inclined. This ash succession is comparable to stratum C of Blinkhorn et al. (2012). It is succeeded upward by yellowish-brown, thinly stratified, unconsolidated, loosely packed, and sandy-silty clay with a thickness of about 1.5 m, reaching the top of the succession. It is intermixed with the underlying ash and constitutes stratum B proposed by Blinkhorn et al. (2012).

Description of the Paleosols

The profile shows development of reddish to yellowish-brown sandy-silty clays from bottom to top, but its continuity is interrupted by the preservation of the distal tephra. The reddish to yellowish-brown (10YR 6/6) sandy-silty clay is characterized by preservation of various pedogenic features and biogenic structures that alternate with calcic horizons. This horizon is 5–18 cm thick. Furthermore, the pedogenic features also include sandy-silty clay coatings of iron-manganese mottles giving a reddish to yellowish-brown (10YR 6/6) color of the succession. The biogenic structures include *Vondrichnus*, termite pipes, and rhizoliths. Based on the high calcification, pedogenic features, and biogenic structures, this reddish to yellowish-brown sandy-silty clay succession qualifies as a paleosol facies, indicating existence of both insects and vegetation in the area (Retallack, 1988).

Systematic Ichnology

The investigated samples are stored at the Department of Geology, SGB Amravati University, Maharashtra State, India. Photographs of specimens included in this study were taken in the field because of their deep preservation in the host sediments and relatively large size. These specimens were recorded in close proximity to termite pipes and nests and rhizoliths, and sometimes in groups of two to three chambers. I applied the classification of Genise (2016) and divided the samples into two ichnospecies: (1) *Vondrichnus planoglobus* and (2) *Vondrichnus obovatus*. The structures of these ichnospecies are spherical to subspherical and sometimes oval-shaped oblate chambers that reveal simple to intricate networks of burrows. These chambers, additionally, may have branches, sometimes unbranching on

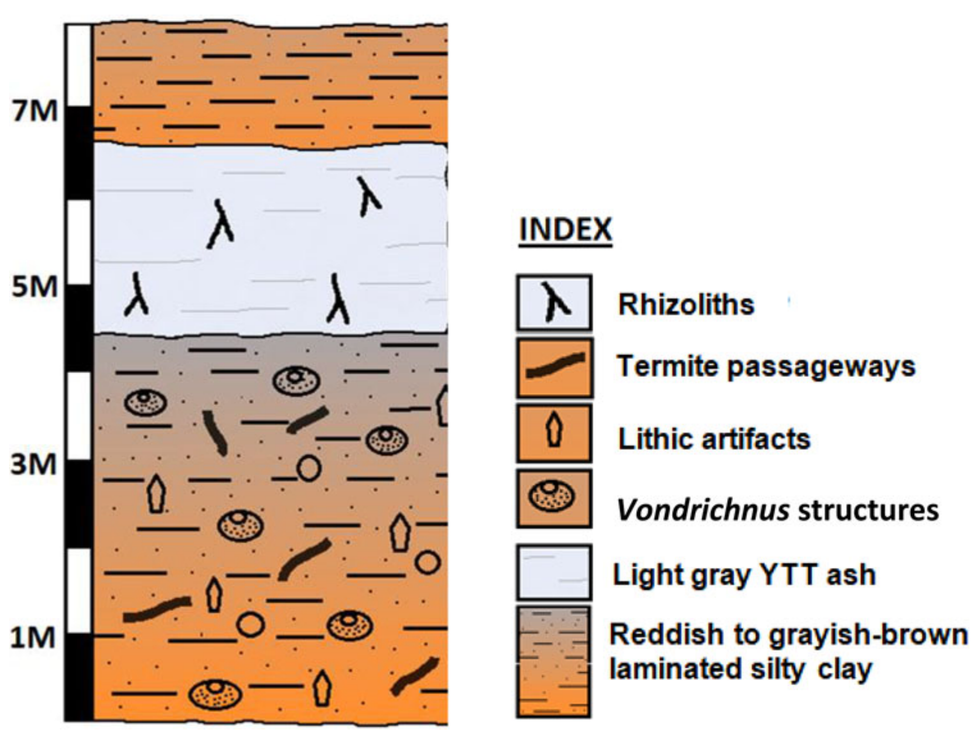

Figure 2. Schematic lithologic description of the investigated area demonstrating three major lithounits and confinement of *Vondrichnus* structures within the constraints of the paleosol horizon exposed at the bottom.

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their external surface. Internally, they may be structureless, alveolar, or arranged in concentric layers (Genise, 2016).

Vondrichnus planoglobus

Ichnofamily *Krausichnidae* Genise, 2004
Ichnogenus *Vondrichnus* Genise and Bown, 1994
Type and ichnospecies *Vondrichnus Planoglobus* Duringer et al., 2007

Diagnosis: As per Duringer et al. (2007), *Vondrichnus planoglobus* is a system that exhibits a single horizontal plane comprising chambers with flat floors and arched roofs. These chambers are attached at their bases to a rectilinear, long principal burrow up to 50 m long by shorter, straight auxiliary burrows emerging at right angles from the main one (Genise, 2016). Burrows found on these structures are suggested to be secondary, as they attach the principal long one to the chambers (Duringer et al., 2007).

About 40 specimens were investigated in both the field and laboratory for their morphological identifications and comparison with Genise et al. (2016) in order to infer the paleoclimate and paleoecology in the basin area. Of them, three have been identified as *Vondrichnus planoglobus*, and rest include *Vondrichnus obovatus* and termite structures. These specimens in the field were encountered in groups of two to three and sometimes as solitary structures associated with rhizoliths, *Vondrichnus obovatus*, and termite structures.

In contrast, *Vondrichnus planoglobus* are spherical to subspherical, rounded to subrounded, hard to compact in nature, calcretized and pear-shaped structures, with an 8–12 cm diameter and rough surface. There is a relatively large and deep cavity at the center of each specimen (Fig. 3B–D). Based on a comparison with Genise (2016), this cavity has been suggested to be a chamber. In addition, *Vondrichnus planoglobus* demonstrate horizontal to vertical, poor to good occurrence of burrows on the surface connecting with chambers. Sometimes, these burrows are pointed outward from the surface of the bodies (Fig. 3C and D).

Vondrichnus planoglobus, preserved in the paleosol deposits, demonstrate diverse morphologies and features along with various shapes and sizes. Groups of two to three structures, and, occasionally, solitary preservation are also perceptible. Rhizoliths,

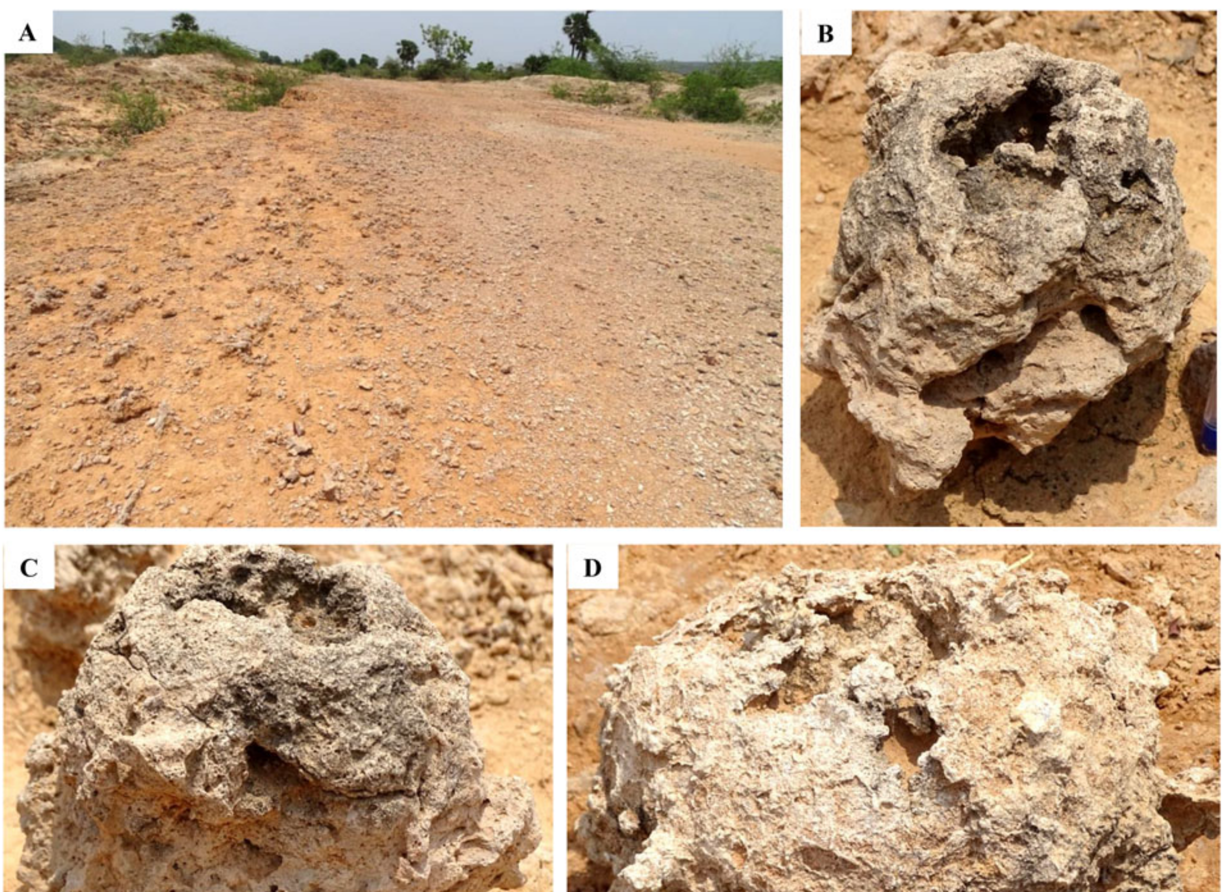

Figure 3. Field views revealing (**A**) typical succession of paleosol exhibiting preservation of *Vondrichnus* structures and (**B–D**) different shapes and sizes of *Vondrichnus planoglobus* structure with spherical to oval shapes and rough surfaces.

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Vondrichnus obovatus, and termite structures are associated in the field.

Vondrichnus obovatus

Ichnofamily*Krausichnidae* Genise, 2004
Ichnogenus *Vondrichnus* Genise and Bown, 1994
Type and ichnospecies *Vondrichnus obovatus* Genise and Bown, 1994

Diagnosis: Genise and Bown (1994) identified the characteristics of *Vondrichnus obovatus* and described them as underground excavated systems possessing fabricated chambers. These structures are principally oblate chambers and are found in dense swarms. *Vondrichnus obovatus* reveals simple, but dense masses of anatomizing branched or unbranched burrows emerging from one or more points on the peripheries of the chambers that connect them. Alveolar shapes are the main component of the sediment in the centers of the chambers and commonly have concentric bands. Chambers in the structures are made up of ~~aligning of~~ one to three parallel chambers to ~~against~~ one another (Genise and Bown, 1994).Forty-seven specimens were encountered in the field, of which seven were selected for morphological description. *Vondrichnus obovatus* is characterized by rounded to subrounded, occasionally hard to compact, calcretized, and silty to clayey bodies of 7–15 cm diameter and having rough surfaces. These structures have large chambers surrounded by a hard to compact irregular rim attached externally to the bodies. The rim is usually disturbed due to weathering. The structure frequently shows burrows and holes on the surface (Fig. 4A–C). Small, lobed-type structures with smooth surfaces are quite common on the fringe part of the body that points mostly toward the chamber, but outwardly in a few cases (Fig. 4D). In certain structures, the rim is connected externally in a rounded form, which may be well preserved or weathered (Fig. 4E and F).

Vondrichnus obovatus has a variety of various shapes, sizes, and morphologies, and their features are constrained mainly within the paleosol successions of relict soils and are lacking in the overlying ash unit, establishing a definite boundary for their vertical distribution. These structures are preserved mostly in groups of two to three bodies; however, solitary occurrences are also common. Their occurrences are likewise discernible in association with termites, rhizoliths, and *Vondrichnus planoglobus* structures in the column.

Description of Termite Structures

As mentioned in the preceding sections, termite structures containing nests and horizontal passages have been recorded close to *Vondrichnus* structures in diverse morphologies. They are spread throughout the paleosols exposed at the site. The termite structures are flat and ball-shaped with 5–12 cm diameters. These structures reveal smooth to rough surfaces and a hole on the top of the body having an elongated to oblate shape. In addition, they show small to large intricate galleries associated with the surfaces of the structures, while the passages are horizontal structures and occur as hollow pipes that are 3 cm to 1 m long and a few centimeters wide. These pipes are connected with the nest at one end, indicating that insects could move from one end to the other. Given the morphological characteristics of termite structures, the study infers that they were likely produced by fossil termitaria, which are reported from continental ecosystems (Hasiotis, 2003). Bown and Laza (1990) suggested that the Miocene termitarium *Syntermesichnus fontanae* is characterized by having chambers and intricate galleries. However, De (2005) reported similar termite structures from the Radhanpur area of the Banas River, India, and noted termite bodies are architecturally different from the *Syntermesichnus fontanae*, *Tacuruichnus*, and *Archeoentomichnus*, and probably represent a new ichnogenus calichnia.

Discussion

Genesis of Vondrichnus structures in the paleosols

Two types of *Vondrichnus* structures occurring within the paleosol succession and having various morphologies and sizes are investigated to understand their development in a specific time span, including the climatic conditions responsible for their formation. As per Ruhe (1956) and Mack (1992), the paleosols are widely regarded as the result of a number of climate-controlled proxies formed by physical, biological, and chemical interactions of various vegetation types and insect activities in the past.

The investigated structures are compacted, massive, and calcified, and each exhibits a large chamber at the center of the body and burrows. The observations regarding their diversity of dimensions, morphologies, patterns, and appended features, like lobes, suggest that they were likely formed by activities of termites that existed in an open paleoenvironment and with abundant grasses under a semiarid climate (Genise et al., 2016).They also indicate the existence of scrub to desert-type vegetation in the area (Cardonatto et al., 2016).

Reports of the structure of *Vondrichnus planoglobus* outside of India have also been documented in the past by Genise et al. (2016), who noted that *Vondrichnus planoglobus*, a system of chambers and straight secondary galleries at the base, demonstrate flat floors and arched roofs, 5–10 cm diameters, and 3–5 cm heights with alveolar, concentric, or no filling connected by a rectilinear main tunnel. Those authors further stated that the entire system of *Vondrichnus planoglobus* structures forms on a single horizontal plane most likely in an orthogonal or random manner. The formation of *Vondrichnus planoglobus* has been connected with the activities of termites, found principally in a grassy environment under a temperate climate (Duringer et al., 2000; Genise, et al., 2016; Ramos et al., 2021). Duringer et al. (2000) initially reported that the *Vondrichnus planoglobus* structures were dung beetle brood balls. However, Genise et al. (2016) corrected this and stated that *Vondrichnus planoglobus* are preserved in the paleosol succession and are large among all insect trace fossils, having good regularity of shape and structures that are likely formed by two probable insect species: *Microfavichnus alveolatus* and *Termitichnus schneideri*.

Significance of Vondrichnus structures in a paleoecological and paleoenvironment context

Because the *Vondrichnus* structures are being reported for the first time from south Asia, they can be seen as valuable proxies for defining paleoecological and paleoenvironmental conditions during their formation. Our interpretation suggests two different paleoenvironments. The first includes the paleosols, a pre-tephra succession of areno-argillaceous nature, containing a variety of biogenic remains in the form of calcium carbonate, as the *Vondrichnus* structures are in close proximity to rhizoliths. The second is silty clay containing the YTT ash. Owing to the strongly

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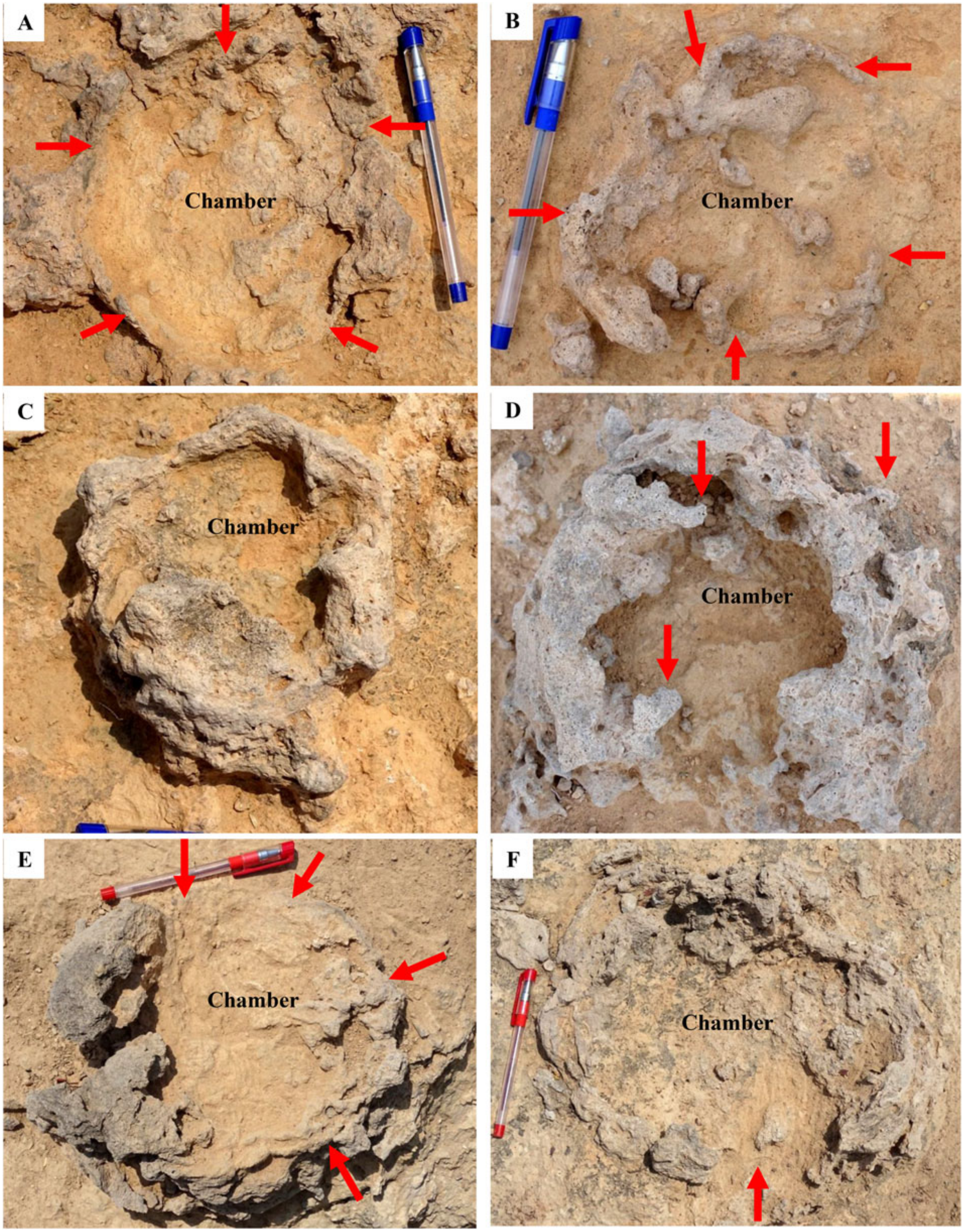

Figure 4. Field photographs demonstrating *Vondrichnus* obovatus structures with various shapes, sizes, and features as (**A and B**) the structures exhibiting chambers inside the irregular and disturbed rims (arrows), (**C**) the ant construction with well-developed rims around the chamber, (**D**) the structure with an irregular rim revealing lobed structures (arrows), and (**E and F**) the bodies with open-space chambers demonstrating a circular rim that is quite disrupted, probably due to weathering.

calcified nature and preservation of abundant biogenic and vegetational remains, it is possible that the paleosols would likely have developed in a waterlogged environment within the periphery of a closed forest area under dry periods. More specifically, the vegetation was likely bush to scrub type, in which insect activity occurred and its remains survived. Furthermore, The study suggests that this vegetation type ~~may have overgrown~~ grew across the area. As a result, our interpretation is concordant with the hypotheses that advocate either C_3 or mixed C_3/C_4 vegetation and dry climate was the prominent environment in India before the YTT eruption (Williams et al., 2009; Haslam et al., 2012). Williams et al. (2009) claimed that immediately before the YTT eruption, central India was overgrown by dense closed forest to woodland, indicating either mixing or alternate occurrences of the two vegetational environments. Haslam et al. (2012) carried out an isotopic study of soil carbonates collected below the YTT layers at the Jwalapuram locality and reported that the landscape of the Jurreru valley experienced change, with a higher proportion of C_4 grasses and a drier climate to increased C_3 woodland in the area. In addition, they also reported mixed C_3/C_4 vegetation at the Jwalapuram locality. However, our interpretation of a waterlogged environment for the development of paleosol atop stratum D is consistent with Blinkhorn et al. (2012), who argued a wetland environment in the Jurreru valley. The *Vondrichnus* structures identified as *Vondrichnus planoglobus* and *Vondrichnus obovatus* in various shapes, sizes, and orientations suggest that the landscape in the area was likely open wooded grassland and a closed lake environment that supported insect activity and a grassy environment under an arid to semiarid climate (Genise, 2016). Furthermore, their distinct shapes, sizes, and orientations in the host sediments suggest an inconsistent nature of the paleosol during development of these structures, indicating varied paleoenvironmental and climatic conditions under dry climates.

Rhizolith, an organo-sedimentary structure, is regarded as the product of plant roots (Retallack, 1988). The rhizoliths with various orientations in the studied area are preserved horizontally, vertically, and sometimes inclined, with sizes varying from 5 to 15 cm in close proximity to the *Vondrichnus* structures and distal YTT ash, an upper horizon of the paleosol. Given the significance of rhizoliths in interpreting vegetation, they indicate that the area was likely overgrown by shrub to scrub-type vegetation that was either mingled with the wooded grasslands or developed later under a dry climate. Our arguments are identical with those of Retallack (1988),who suggested that rhizoliths indicate existence of scrub vegetation, most probably grasses with occasional occurrence of tall vegetation. Overall, the study suggests that past climate as well as paleoenvironmental conditions fluctuated, most probably due to unstable local phenomena like temperature and precipitation. This fluctuation in paleoenvironmental conditions is reflected by existence of a wetland environment for the paleosol and a fluvial environment for the silty clay with the YTT ash. It has already been reported that the YTT ash was deposited in the investigated locality by fluvial processes (Jones, 2010).

The preservation of termite nests and horizontal passages have been noticed in close association with *Vondrichnus* structures and in the host paleosol of the latter, which suggests that the termite community existed and mingled with the *Vondrichnus* population at the site. In addition, it also indicates that termites would have reprocessed soil, which helped in developing dry deciduous forests to savannahs under a drier environment and tropical climates in the area. Moreover, it indicates that the insect community preferred to produce nests and passages in well-drained soils with a low water table and high environmental moisture. However, in due course, these nests were covered by soil, particularly during the period of waterlogging (Collins, 1969). The presence of waterlogging in the area is also supported by the formation of *Vondrichnus* structures. Furthermore, different nest morphologies suggest the existence of small to large termites, indicating a suitable environment for reproduction. Horizontal passages connecting with the nests have one end open and would likely provide communication to the other end and shelter inside the chambers, probably during harsh conditions. Our observations accord with Mathews (1977),who suggested that the termite population in Matto Grosso State, Brazil, survived and grew in dry deciduous forests. Genise (2016) also suggested the paleoenvironment of the termite population to be rain forests and tropical savannahs in the South American continent. Our interpretations accord with Genise (2016), who interpreted the formation of *Vondrichnus* structures by insect activity in the paleosol under the arid to semiarid climate in the region. Furthermore, similar interpretation can be extended to the Purna alluvial basin, central India, a YTT-bearing river basin of India, from which similar calcretized biological remains, interpreted as ant nests and archived from the paleosol horizons, have been recovered (Srivastava and Singh, 2019a, 2019b, 2020a; Singh and Srivastava, 2021). Through extension of these interpretations of climate conditions to other YTT-bearing river basins of India, it can be inferred that these basins were likely open paleoenvironments with varied grass environments under the dry climate immediately before the YTT eruption that continued after the cessation of the ash deposit.

Conclusions

The YTT-bearing succession at the Jwalapuram locality, south India, has been explored for the first time for the preservation of *Vondrichnus structures* with an emphasis on morphological description and paleoecological and paleoenvironmental interpretations. Three main conclusions can be drawn:

Vondrichnus structures are in close proximity to termite pipes and rhizoliths in various shapes, sizes, and orientations in the paleosol succession, identified as an aridisol. Based on the morphologies, they have been distinguished as two types:(1) *Vondrichnus planoglobus* and (2) *Vondrichnus obovatus*. *Vondrichnus* structures indicate the presence of insect activity in a grassy environment, whereas termite pipes and nests suggest dry waterlogging and drier environments, and rhizoliths reveal presence of tall vegetation under the arid to semiarid climate in the region.

Given the morphological construction of *Vondrichnus planoglobus*, it is suggested that they were likely produced by *Microfavichnus alveolatus* and *Termitichnus schneideri*, whereas *Vondrichnus obovatus* are the product of Macrotermitinae and *Termitichnus simplicidens*. These insect species favor an open paleoenvironment with bush to scrub-type vegetation, most probably grasses with occasional occurrence of tall plants under a humid to dry climate.

This study suggests that during the formation of these *Vondrichnus* structures, there were two different paleoenvironments. The first included paleosols of areno-argillaceous nature and the second comprised silty clay incorporating YTT ash. Based on the highly calcified nature and preservation of abundant biogenic and vegetational remains, it can be inferred that the paleosols developed in a wetland environment within the periphery of closed forest area under humid and dry periods, while silty clay indicates fluvial processes.

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