

THREE-DIMENSIONAL RECONSTRUCTION OF “PHYCOSIPHONIFORM” BURROWS: IMPLICATIONS FOR IDENTIFICATION OF TRACE FOSSILS IN CORE

Malgorzata Bednarz and Duncan McIlroy

ABSTRACT

Phycosiphon-like trace fossils are some of the most common and important ichnofabric forming trace fossils in marine facies. This study was conducted to reconstruct the three-dimensional (3D) morphology of a *Phycosiphon*-like trace fossil from Cretaceous turbidites in Mexico in order to test the validity of criteria used to recognize such fossils in vertical cross sections similar to those seen in cores through hydrocarbon reservoir intervals. The geometry of the trace fossil was computer-modeled using a series of consecutive images obtained by serial grinding. The recognition of *Phycosiphon* in cross section is usually based on comparison with hypothetical cross sections of bedding-parallel specimens. The authors critically reassess *Phycosiphon*-like burrows in the light of existing conceptual and deterministic models, for comparison with three-dimensional reconstruction of *Phycosiphon*-like trace fossils from the Cretaceous Rosario Formation of Baja California, Mexico.

Observed morphological differences between our material and typical *Phycosiphon* suggest that the characteristic “frogspawn” ichnofabric that is usually attributed to *Phycosiphon* (*sensu stricto*) can be produced by other similar taxa. Our palaeobiological model for the formation of the studied *Phycosiphon*-like trace fossil is fundamentally different to that proposed for *Phycosiphon*, but produces remarkably similar vertical cross sections. We consider that identification of *Phycosiphon incertum* in core is not possible without detailed 3D examination of burrow geometry. We propose the term “phycosiphoniform” for this group of ichnofabric-forming trace fossils.

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KEY WORDS: burrows; ichnofabric; ichnofossil; three-dimensional; 3D; morphology; *Phycosiphon*; reconstruction; trace fossils; core; halo; cross sections

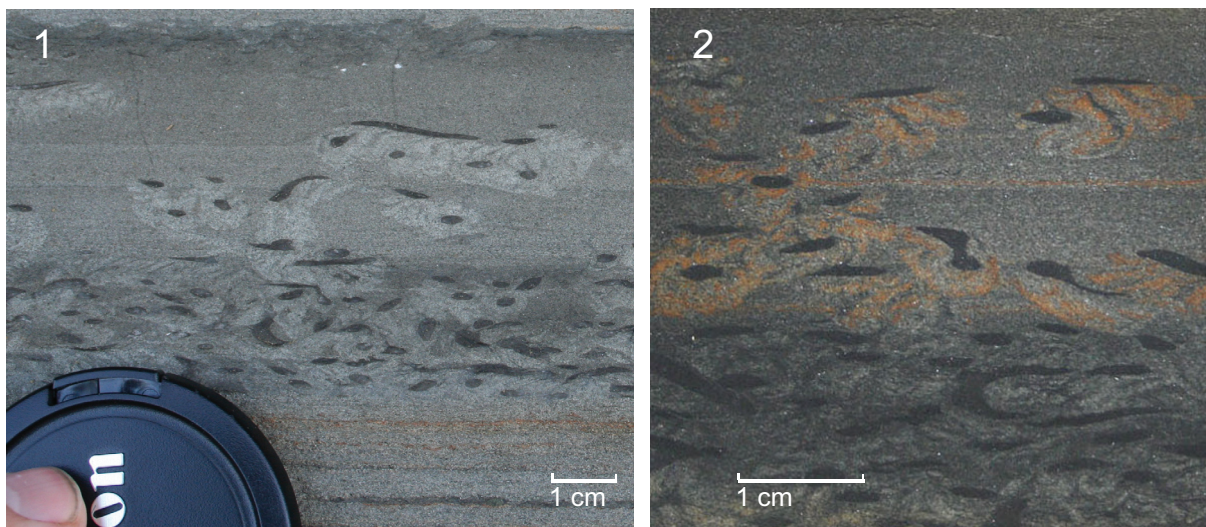


FIGURE 1. Siltstone from Cretaceous Rosario Formation, Mexico, containing *Phycosiphoniform* burrows with “frogspawn texture” in vertical section. **1.1.** Outcrop photograph; **1.2.** Photograph of cut and ground surface of the sample examined during three-dimensional reconstruction of burrows. The halo is accentuated by diagenetic pyrite precipitation. Note that the burrow halo is predominantly located below the black mudstone core.

INTRODUCTION

Phycosiphon-like trace fossils are perhaps the most common group of trace fossils identified in vertically slabbed cores of mud-rich sedimentary rocks in petroleum fields worldwide (e.g., Bockelie 1991; Goldring et al. 1991; Wetzel and Bromley 1994; Bromley 1996; Pemberton and Gingras 2005). We herein use the term “phycosiphoniform” to encompass all burrows that, when seen in cross-sectional view, have a *Phycosiphon*-like central core of clay-grade material surrounded by a bioturbated zone of clay-poor silt or very fine-grained sand that is inferred to have been produced during deposit feeding. The ichnofabric generated is commonly termed frogspawn texture (Figure 1). Phycosiphoniform trace fossils are found in a range of marine depositional environments from marginal- to deep-marine settings in rocks ranging in age from the Palaeozoic to the recent (e.g., Goldring et al. 1991; Fu 1991; Wetzel and Bromley 1994; McIlroy 2004b). The trace maker(s) of phycosiphoniform burrows are unknown small, probably vermiform, deposit feeding organisms, which are common in clay-rich siltstones (Kern 1978; Wetzel and Bromley 1994; Bromley 1996).

While phycosiphoniform burrows are common in the rock record, there is little consistency in the literature regarding the ichnogenic assignment of such burrows. A number of taxa with Phycosiphoniform cross section have been recognized from the core including: *Phycosiphon incertum* (Wetzel and

Bromley 1994; McIlroy 2004b, 2007); *Helminthopsis* (Dafoe and Pemberton 2007; forms lacking a halo); *Helminthoidichnites* isp. (MacEachern et al. 2007); *Anconichnus* (Kern 1978; latterly synonymized with *Phycosiphon* by Wetzel and Bromley 1994); *Nereites* isp. (Wetzel 2002); *Cosmorhaphis* isp. (e.g., MacEachern et al. 2007). Most Palaeozoic occurrences of burrows in vertical cross section with a mudstone core and silty halo have been assigned to *Nereites*.

Since the behaviour of all of these phycosiphoniform trace fossils is conventionally interpreted to be systematic, selective deposit feeding, precise ichnogenic identification is perhaps not necessary for palaeoenvironmental analysis. In ichnofacies studies, which rely partly upon assessment of ichnogenic diversity, a full appreciation of ichnodiversity can be integral (MacEachern et al. 2007; McIlroy 2008), and thus in need of careful consideration. The three-dimensional geometry and full range of potential vertical cross sections of most phycosiphoniform taxa are imperfectly known. This work focuses on reviewing existing data on the most commonly recognised phycosiphoniform burrow *Phycosiphon incertum* Fisher-Ooster 1858 for comparison with our three-dimensional reconstruction of well-preserved phycosiphoniform burrows from the late Cretaceous of Mexico.

The phycosiphoniform trace fossil reconstructed herein was studied from a hand specimen containing many phycosiphoniform trace fossils

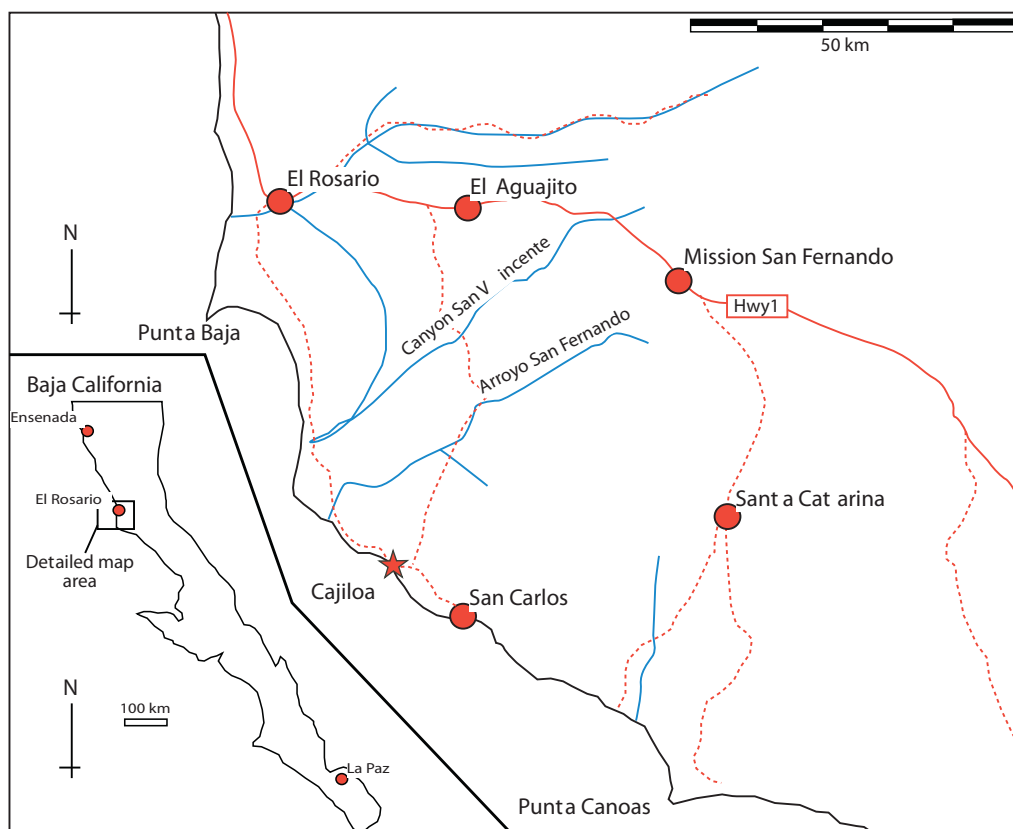


FIGURE 2. Locality map showing the field locality (Pelican Point near Cajilloa marked with a star) relative to the town of Rosario in Baja California (Mexico). Redrafted with permission of Ben Kneller, University of Aberdeen unpublished field guide.

from a succession of well-exposed slide blocks in a slope channel complex from coastal exposures of the Upper Cretaceous Rosario Formation in the coastal outcrop at Pelican Point near Cajilloa, close to the town of El Rosario, Mexico (Figure 2). The ichnofabric is distinctive in containing anomalously large, slightly atypical, phycosiphoniform burrows. The host-sediment is a laminated turbidite siltstone. The burrow cores were subject to differential compaction relative to the host sediment, with the plane of flattening being parallel to bedding (Figure 1).

PHYCOSIPHONIFORM BURROWS IN MARINE ICHNOFABRICS

Phycosiphoniform trace fossils are an important component of most post-Palaeozoic shallow marine ichnological assemblages, particularly those with a mixture of clay and silt grade material (Goldring et al. 1991; Fu 1991). The recognition of *Phycosiphon incertum* has been greatly encouraged by publication of a series of representative hypothetical cross sections based on bedding-par-

allel specimens (Bromley 1996). We consider it likely that all phycosiphoniform burrows result from deposit feeding by organisms that selectively ingest clay grade material in order to process microbial biomass, dissolved organic matter (DOM), bio-films on sediment grains and the associated meiofaunal/interstitial biomass. The clay grade material ingested is concentrated into a faecal strand, surrounded by a zone of biologically processed sediment (silt to very fine-grained sand) that has been cleaned of clay-grade material. Published occurrences of *Phycosiphon* are commonly taken to include older literature mentioning the trace fossil *Anconichnus horizontalis*, which was described exclusively from vertical and horizontal cross sections in slabbed material (Kern 1978). The synonymization of *A. horizontalis* with *Phycosiphon incertum* (Wetzels and Bromley 1994), based on revision of the type material of *A. horizontalis*, and emendation of the original diagnosis of *P. incertum* to include non-bedding-parallel specimens, has been widely adopted. As a result,

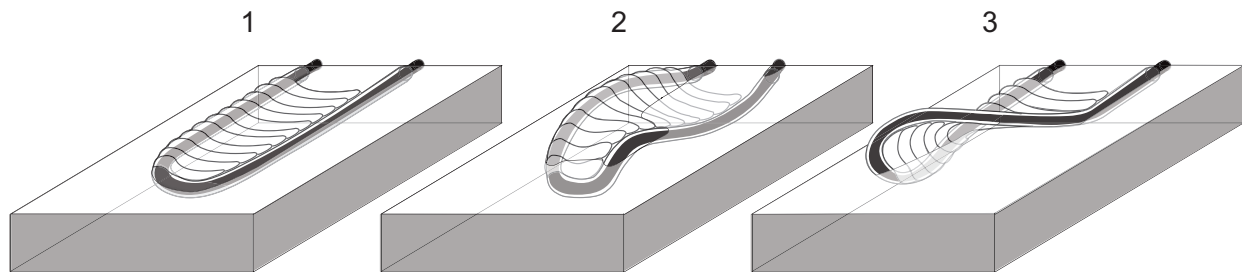


FIGURE 3. Conceptual model showing the non-planar orientation of a single *Phycosiphon* burrow lobe with the mantle and spreite shown as being transparent to facilitate viewing of the central mudstone strand. **3.1.** Lobe parallel to the bedding plane; **3.2-3.3.** Possible variations of twisted *Phycosiphon* burrow lobes. This model is an expanded version of the bedding plane conceptual model (Bromley 1996), but incorporating the possible twisting allowed by the emended diagnosis of Wetzel and Bromley (1994).

Anconichnus is seldom referred to in modern literature.

In most cases, phycosiphoniform burrows are found as part of diverse ichnofabrics developed in shallow marine depositional environments (Goldring et al. 1991; Bockelie 1991; MacEachern et al. 2007). In ichnotaxonomically diverse shallow marine ichnofabrics, *Phycosiphon incertum* is generally a late-stage component of the ichnofabric, cross-cutting and reworking earlier burrow fills (e.g., Goldring et al. 1991; McIlroy 2007). Modern *Phycosiphon incertum* are common in deep marine settings (Wetzel 2008), though the trace maker is not as yet identified. Where phycosiphoniform burrows are found in mono-taxic assemblages, the depositional environment is typically inferred to have been stressed. Examples of stressful depositional environments with mono-taxic assemblages of phycosiphoniform trace fossils include tide dominated deltaic deposits, in association with fluid mud deposits (McIlroy 2004b), and dysoxic mudstones (Bromley and Ekdale 1984, 1986; Ekdale and Mason 1988; Savrda 2001).

INTERPRETED THREE-DIMENSIONAL MORPHOLOGY OF *PHYCOSIPHON INCERTUM*

The trace fossil *Phycosiphon* was first described by Fisher-Ooster (1858) from Gurnigel Flysch strata of Maastrichtian age (van Stuijvenberg 1979) in the western part of Switzerland (see Wetzel and Bromley 1994). Study of topotype material facilitated the proposition of an emended diagnosis as follows: “*Extensive small-scale spreite trace fossils comprising repeated narrow, U-shaped lobes enclosing a spreite in millimetre to centimetre scale, branching regularly or irregularly from an axial spreite of similar width. Lobes are protrusive, mainly parallel to bedding/seafloor.*”

However, the plane enclosing their width may lie horizontally, obliquely or even vertically to bedding/seafloor.” (Wetzel and Bromley 1994, p. 1400).

In emending the diagnosis, the authors allowed for a strong vertical component to the fecal string, which is not evident in the type material. A vertical or oblique looped fecal string is present in other similar material collected from modern depositional settings (Wetzel and Wijayananda 1990; Wetzel and Bromley 1994). The diagnostic spreite have not, however, been fully documented from such material. The re-description of the type material by Wetzel and Bromley (1994) included review of *Anconichnus* Kern 1978, recognizing the latter as junior synonym of their emended *Phycosiphon* (i.e., *Anconichnus* is interpreted to be a morphotype of *Phycosiphon* with oblique to vertically oriented spreiten-bearing limbs). Supplementary block diagram models for *Phycosiphon* are needed to encompass cross sections of non-bedding-parallel burrows (Figure 3).

The Mud-Filled “Marginal Burrow”

The most visually striking part of *Phycosiphon*, and all phycosiphoniform burrows in cross section, is the marginal burrow, which is generally filled with dark clay-grade material, is usually less than 1mm in diameter and is surrounded by a silty halo. The marginal burrow has not been demonstrated to self-cross (Bromley 1996). The marginal burrow of any given lobe of *Phycosiphon sensu lato* may be in any orientation relative to bedding (Kern 1978; Wetzel and Wijayananda 1990; Wetzel and Bromley 1994; Bromley 1996; Figure 3). Detailed three-dimensional imaging of the marginal burrow of a *Phycosiphoniform* burrow has been undertaken recently (Naruse and Nifuku 2008), demonstrating that the sub-horizontal to oblique limbs may lie above one another. Neither a

siltstone halo nor spreiten were reconstructed, perhaps because of a lack of lithological contrast. These burrows have been assigned to *Phycosiphon incertum* (Naruse and Nifuku 2008), though we consider that the lack of a full complement of ichnotaxobases precludes confident ichnotaxonomic assignment of this material.

Existing models for the orientation of lobes in *Phycosiphon incertum* (Wetzel and Bromley 1994) suggest that: 1) oblique lobes are most common in sandstone; 2) the same taxon in laminated siltstones and mudstones produces bedding-parallel lobes [comparable to the type material]; and 3) that lobes in homogeneous silty mudstones are commonly randomly oriented.

The marginal tube of *Phycosiphon* is looped, and defines the outer margin of spreiten-bearing regions that are discussed in detail below. A series of these curved probes are developed on one margin of the trace fossil in bedding-parallel material (Figure 4). The tube, which is surrounded by very thin “mantle” of coarser grained sediment (from which the original clay-grade material has been removed by the activity of the trace maker), is generally considered to be composed of fecal material selectively collected by deposit feeding activity in the central spreiten-bearing region.

Spreiten and Hhalos in *Phycosiphon*

Spreiten are positioned inside of the marginal tube and are considered to consist of zones of sediment that have been processed during feeding. The outer curves of the spreite are orientated in the direction of progressive feeding (e.g., Wetzel 1983; Wetzel and Bromley 1994; Bromley 1996; Seilacher 2007; Figure 4 including animation). It is anticipated that individual spreite would be meniscate if vertically sectioned through the axis of a lobe. Such a cross section has never been figured, perhaps due to either a lack of lithological contrast between spreite or the small size of most *Phycosiphon*.

In some cases the mud-filled tube and mantle are not associated with a spreiten bearing loop. This phenomenon was attributed to locomotory behaviour by the trace-making organism in its search for a new region of rich organic detritus (Wetzel and Bromley 1994). It is implied that when an organic-rich area is found by the trace maker, that the full spreiten-forming behaviour would resume.

The preservation of spreiten and mantle is highly dependent upon sufficient grain size contrast in the bioturbated sediment. If there is no vari-

ability in grain size in the host sediment there is little potential for spreiten formation. It has also been considered that spreiten are best preserved at sand-mud interfaces (Fu 1991). The clay-rich marginal tube is commonly the most prominent feature seen in field material. Some degree of mantle and spreiten preservation is generally seen in cross-section.

The marginal tube is generally filled with dark coloured clay-grade material and is surrounded by a thin, pale mantle of coarser grains, lithologically similar to the spreiten (Wetzel and Bromley 1994). The combination of pale mantle and spreiten material around the dark mudstone core gives rise to the colloquial term “frogspawn texture” (Bromley 1996; Figure 1).

PALAEOBIOLOGY OF THE *PHYCOSIPHON* TRACE-MAKER

Style of Feeding

The *Phycosiphon*-making organism was sensitive to grain size variability of the host sediment, and is not found in sediments coarser than fine-grained sandstone (Ekdale and Lewis 1991, in reference to *Anconichnus*). The trace maker is considered to selectively ingest the clay-grade material from the sediment, leaving clean, coarser grained spreite or halos, and depositing behind it a continuous clay-rich fecal string. This is perhaps analogous to the selective deposit feeding behaviour of *Euzonus mucromata*, which is known to produce *Macaronichnus*-like burrows (cf. Gingras et al. 2002a, b). The depth to which *Phycosiphon* is thought to bioturbate is up to 15 cm below the sediment-water interface in a wide range of bathymetric conditions from shallow marine to bathyal and perhaps even abyssal depths (Wetzel and Bromley 1994).

The presence of a meniscate backfill in the marginal tube strongly supports its origin as a fecal string (Ekdale and Lewis 1991 in reference to *Anconichnus* [= *Phycosiphon*]). The trace maker was probably a vermiform organism that produced a series of closely spaced feeding probes lateral to the marginal tube (in the centre of what is eventually a feeding loop Figure 4.1). Each probing, feeding activity leaves a tubular zone of manipulated sediment that is cleaned of clay-grade material (upon which the trace maker feeds). Successive probes are made until the organism has produced a marginal tube the length of its body (Figure 4.2). The trace maker is then inferred to burrow along the outer margin of the earlier probes, to produce

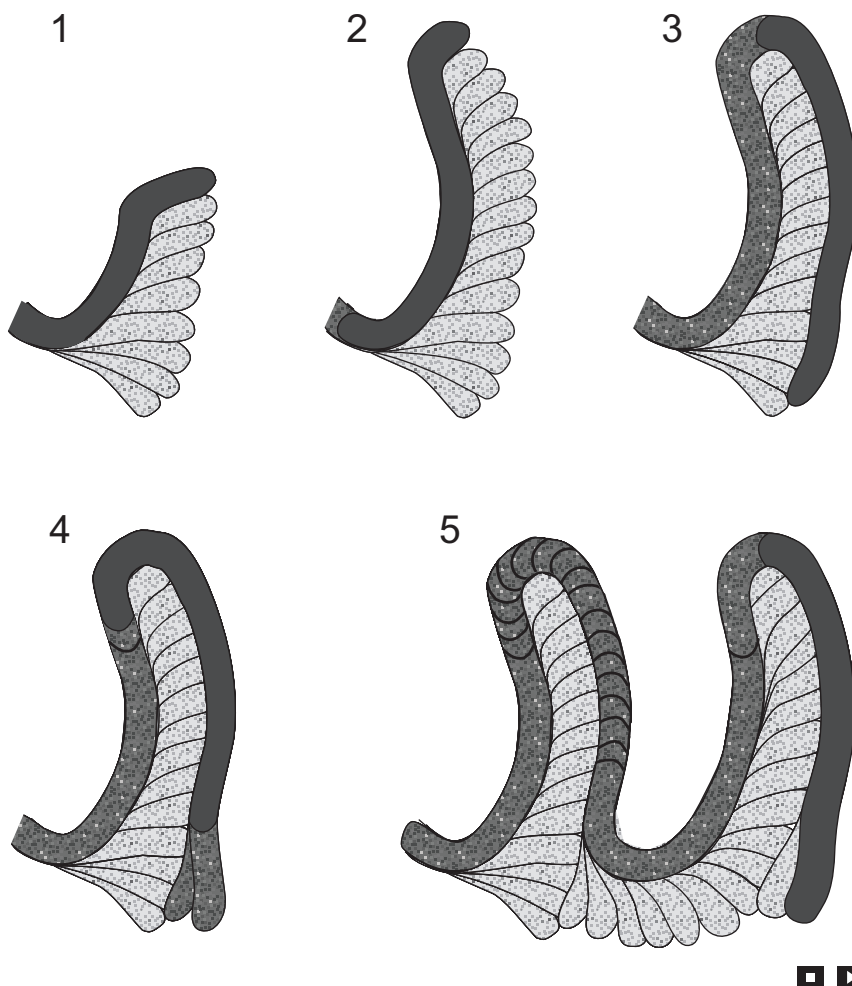


FIGURE 4. Reconstruction showing how multiple phases of foraging by an unknown vermiform organism creates *Phycosiphoniform* looped burrows composed of marginal tube and spreiten (Based upon Wetzel and Bromley 1994; Bromley 1996; Seilacher 2007). Different shades of grey represent distribution of silt-sized (light grey) and clay-sized (dark grey) material. **4.1.** Foraging organism creates feeding probes lateral to the marginal tube. **4.2.** Successive probes are made until the organism has produced a marginal tube the length of its body. **4.3.** Outer margin of the loop is produced by the organism moving along previously produced probes. **4.4.** Second loop is started after the organism body is straight one again. **4.5.** Animation in EXE (for Windows) and APP (for Mackintosh) file format presenting multiple phases of *Phycosiphoniform* trace fossil formation.

the outer margin of a loop (Figure 4.3). When the body of the trace maker is once again straight, either lateral probes are produced at the start of a second loop (Figure 4.4) or the organism abandons the region and moves in search of a new food-rich region (based upon Wetzel and Bromley 1994; Bromley 1996; Seilacher 2007). When considered together these multiple phases of burrowing can be seen to leave behind a *Phycosiphoniform* trace fossil (Figure 4.5 - animation).

INTERPRETATION OF THREE-DIMENSIONAL MORPHOLOGY FROM CROSS SECTIONS OF PHYCOSIPHONIFORM BURROWS

Bridging the gap from the two-dimensional cross sections commonly seen in core and slabbed material to a three-dimensional interpretation of morphology is a significant challenge for applied ichnologists (McIlroy 2004a, 2008; Bromley and Pedersen 2008). The starting point for this process has to be reliable three-dimensional reconstructions of known taxa; preferably type material. To address the issue of identifying phycosiphoniform burrows from cross-sectional views, we will review

and update the model for *Phycosiphon incertum* for comparison with our phycosiphoniform material from Mexico.

Interpreting “Frogspawn Texture” as *Phycosiphon*-Generated Ichnofabrics

Phycosiphon is a morphologically complex trace fossil in three dimensions; consequently it has a diverse range of expressions in vertical cross section. These vertical cross sections can closely resemble other phycosiphoniform burrows (e.g., *Helminthoidichnites* cf. Chamberlain 1978; *Nereites* cf. Wetzel 2002). The characteristic frogspawn fabric (Bromley 1996) is produced by cross sections of the marginal tube (“embryo”) and the spreite or mantle (“jelly”). A number of vertical cross sections of bedding parallel *Phycosiphon* have been figured by Bromley (1996), and are supplemented by our digitally dissected deterministic model (Figure 5.1-5.3). Since the emendation of the ichnogeneric diagnosis for *Phycosiphon* (Wetzel and Bromley 1994) includes the possibility of non-bedding parallel lobes, we have created a 3D digital model of *Phycosiphon* inclined 17° from the vertical and created virtual vertical cross sections from it (Figure 5.4). The resultant cross-sections include the comma-shaped cross sections so common in outcrop material but not explained by pre-existing hypothetical models (Bromley 1996). The vertically stacked, bent paired marginal tubes not linked to a cross section by Bromley (1996) can also be explained by our model (Figure 5.5).

Comparison of our three-dimensional model, and cross sections obtained from it (Figures 3 and 5), with published cross sections of *Phycosiphon* (Goldring et al. 1991; Wetzel and Bromley 1994; Bromley 1996; Naruse and Nifuku 2008) allows us to confidently state that the model of Bromley (1996) has the potential to produce the full range of *Phycosiphon* cross sections seen in vertical sections from core. It is thus entirely possible that the *Phycosiphon* trace maker deposit fed in vertical, oblique or bedding parallel orientations as well as the horizontal orientation seen in the type material. Not encompassed by our three-dimensional model, are twisted lobes, though it is inferred that those would produce broadly similar vertical cross sections to those in Figures 5.4-5.5.

METHODS

Creation of three-dimensional conceptual models of trace fossils differs greatly from the process of direct reconstruction of the three-dimensional morphology of fossil material based on serial

grinding and tomography. This paper aims to produce a three-dimensional deterministic model of some phycosiphoniform burrows from turbiditic siltstone of Cretaceous Rosario Formation and compare them to the *Phycosiphon* model of Bromley (1996). The approach used involves the use of serial grinding and computed tomography as outlined below.

Serial Grinding

Three-dimensional geometry of the studied burrows was systematically exposed through serial grinding of the hand specimen. This approach has been successfully employed for three-dimensional imaging of body fossils (e.g., Baker 1978; Hammer 1999; Sutton et al. 2001), ichnofabric (Wetzel and Uchman 1998, 2001) and trace fossils (Naruse and Nifuku 2008). Serial grinding allowed us to obtain a sequence of regularly spaced images of the resultant vertical cross sections. The photographic dataset thus created is the basis for subsequent computer-based three-dimensional reconstructions.

To aid in creating parallel regularly spaced cross sections, the irregularly shaped sample of turbiditic siltstone was placed in a tight fitting box and set in plaster of Paris. When the plaster was set, and regular 0.5 mm increments inscribed on the outer surface of the rectangular block, it was then ready to be serially ground. The regular outline of the block was essential to create reference points, for alignment of the photographic images to be used in digital analysis. The 0.5 mm spacing of images was chosen to capture a sufficiently large number of data-points to allow gridding of surfaces and reconstruction of the burrows. A total of 60 images were acquired through a 29.5 mm thick slab of the sample. The consecutive series of photographs were taken from parallel surfaces with a digital camera, which was stationed an identical distance above the sample surface, under the same lighting and zoom conditions for every surface. The camera was attached to a photographic stand with height controlling screw feed.

Ichnofabrics have not generally been studied using a serial grinding approach. In contrast to body fossil material, trace fossil fabrics are commonly complex, tortuous, and without sharply defined limits (both morphologically and mineralogically). A particular problem is that burrows may branch and inter-penetrate, making closely spaced slicing essential, and poses particular challenges in image processing (discussed below). The size of the block studied is larger than has typically been

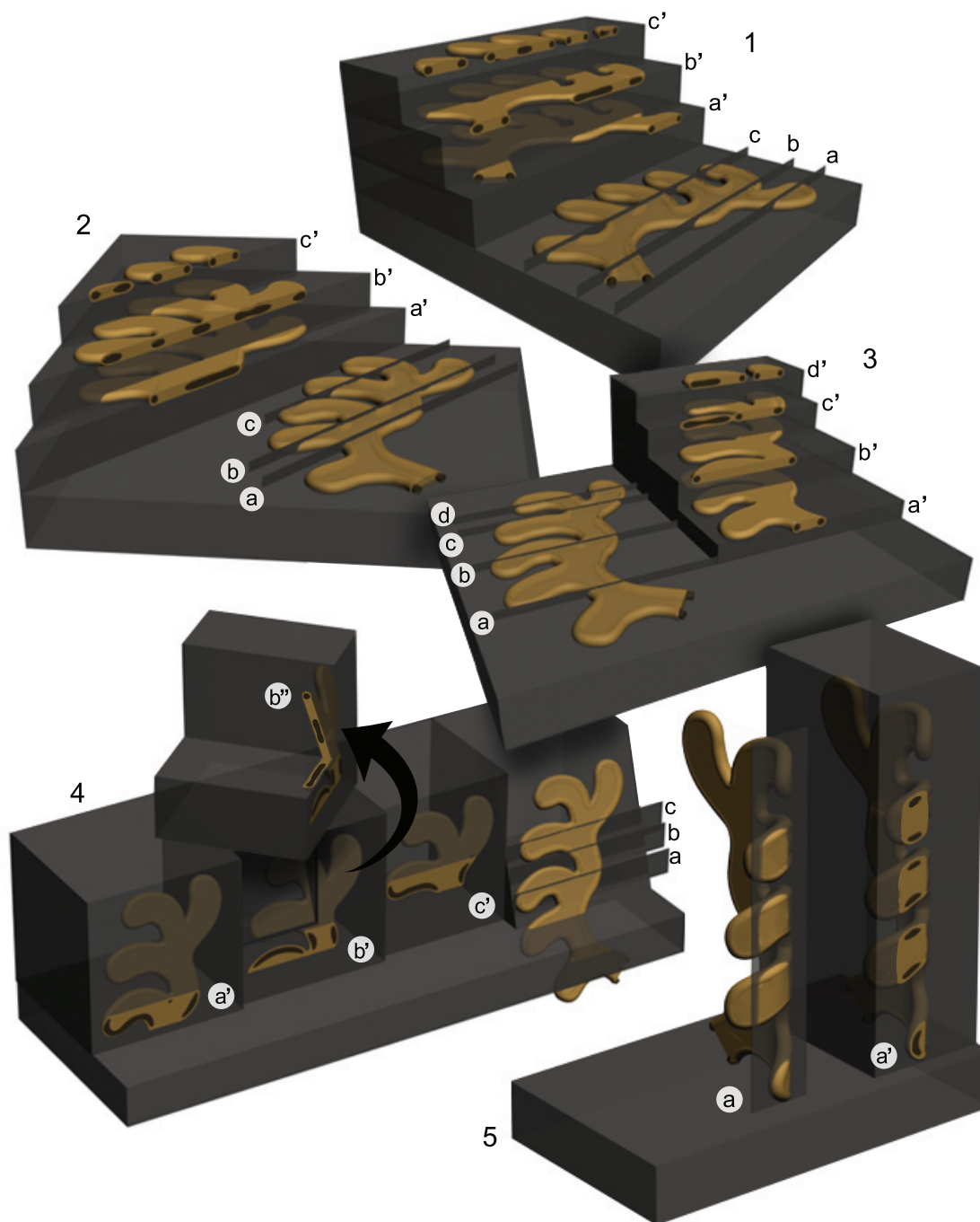


FIGURE 5. Idealized 3D conceptual model showing the antler-like morphology of *Phycosiphon* structure cut to show the expected vertical cross sections. Each of the boxes 5.1-5.5 show the 3D form of *Phycosiphon* in different orientations along with the location of labelled cut sections, which are alphabetically linked to the vertical cross sections, which are analogous to the common sections seen in petroleum cores. **5.1-5.3.** Burrow loop parallel to bedding plane and intersected with perpendicular planes to show cross sectional views. **5.4.** Burrow inclined 17° from the vertical and cut by vertical planes to show cross-sectional views. **5.5.** Burrow vertical to bedding plane, with bent lobes, cut in the vertical plane to show cross-sectional views.

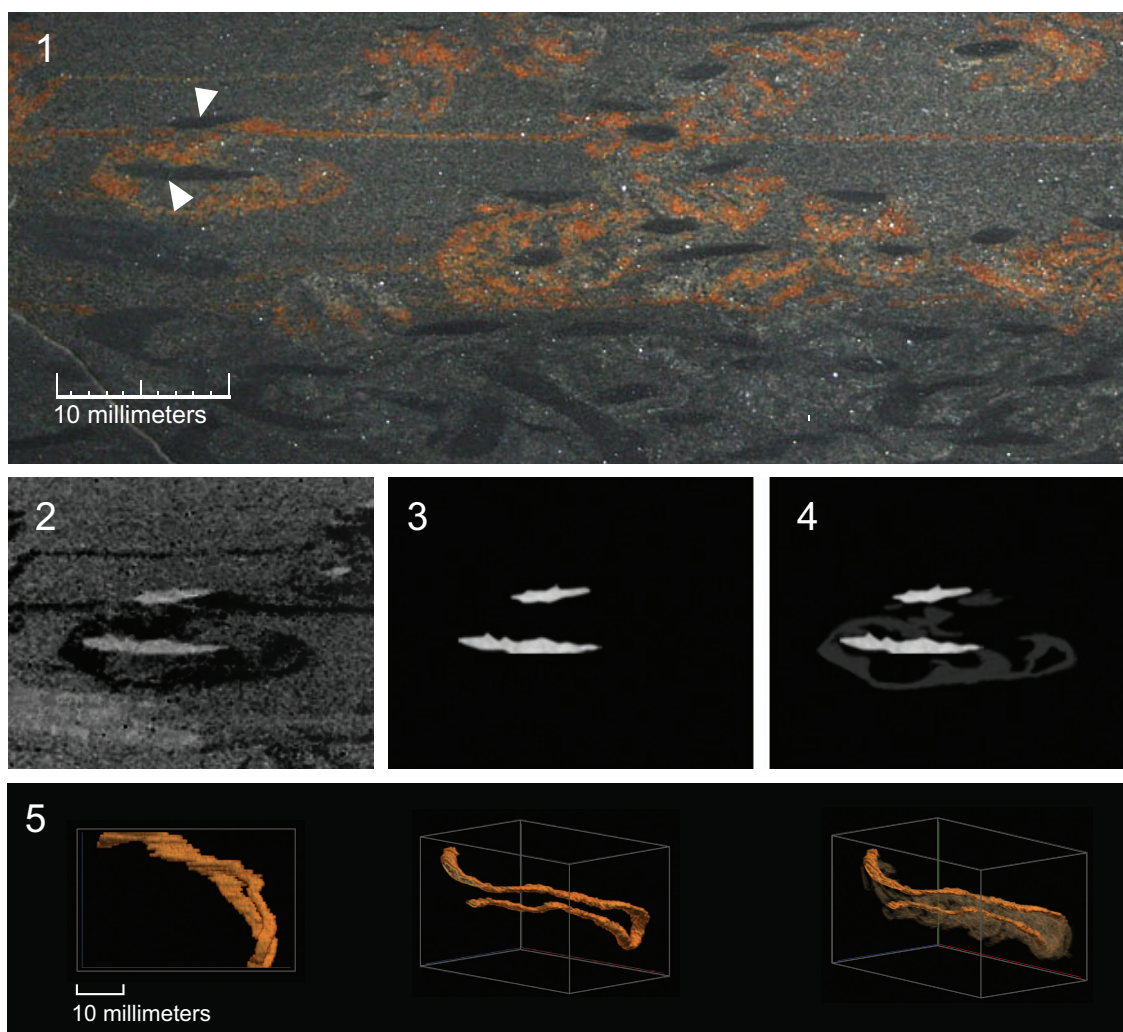


FIGURE 6. Image processing stages during three-dimensional reconstruction of phycosiphoniform from Rosario Formation. **6.1.** Investigated material from Rosario Formation containing phycosiphoniform forms. Each photograph obtained during serial grinding (set of 60 sequential images) was aligned and cropped. The continuous burrow cores were selected manually as the object of study (indicated by white arrows). **6.2.** To improve contrast, images were converted to gray scale. **6.3.** Distinct burrow cores were manually selected using layer masks in Photoshop and hiding all other burrow cores in the investigated area of the original images. Selected cores were tracked on all processed images. Images were then cropped to size that encompassed isolated burrow cores on all processed images. **6.4.** For additional reconstruction of burrow with its surrounding halos, areas of the halos were manually marked on all sequential images uncovering it from the masked layer. **6.5.** Three-dimensional visualisation of phycosiphoniform obtained through volume rendering of sequential images imported to VolView software.

studied by palaeontologists, but did not pose any particular methodological problems.

Image Processing

The set of sequential slice images acquired through the serial grinding technique was processed to select the regions to be studied. The phycosiphoniform burrows studied include a dark mud core and a halo of coarser sediment, which in the present material is accentuated through the

presence of pyrite (Figure 1.1, 6.1). To obtain adequate contrast, the images were made into gray scales (Figure 6.2). All images were put into a single Photoshop document in consecutive order. Discrete burrow cores were chosen as the objects for tracing the location of the chosen burrow. The burrow core was tracked through each consecutive image and manually selected using layer masking to hide all other burrow cores and halo that might confuse the reconstruction of the chosen burrow

(Figure 6.3). A masking layer was used to allow retention of the original, gray scaled images, including location of adjacent burrows, should it become subsequently desirable to study adjacent burrows (Figure 6.4). The layered Photoshop document was then cropped to the smallest size that encompassed the isolated burrow core. Each layer, representing the equidistant ground surfaces, was saved as a JPEG image in the same directory with a numeric name that indicates its position in the sequence. This set of image-processed two-dimensional binary images was used for the subsequent three-dimensional reconstruction.

Three-Dimensional Rendering

The set of the binary images was imported to the commercial edition of VolView 2.0 software. Consecutive, gray scaled intersections of burrow core were converted by the software to the volume shape that represents the three-dimensional geometry of the examined phycosiphoniform burrow. Artificial colors were attributed to the reconstructed burrow and to the halo in order to aid illustration (Figures 6.5, 7, 8 and 9). Three-dimensional reconstruction of the phycosiphoniform burrow from examined rock was additionally saved as a movie file that shows the burrow rotating around the axis that is perpendicular to the bedding plane (see attached animation files, Figure 7.7 and 9.4).

Three-Dimensional Morphology of the Rosario Formation Phycosiphoniform Burrows

By choosing a sparsely bioturbated portion of the ichnofabric, it was possible to identify a single isolated burrow. The burrow consists of a single loop shaped clay-filled tube that is identifiable in the series of ground vertical cross sections. This isolated burrow was subjected to detailed three-dimensional reconstruction of both the mud-filled burrow core (Figure 7.1-7.5) and the burrow halo (Figure 7.6-7.7). The volume of rock subjected to three-dimensional reconstruction, and containing the fossil burrow was 40.9 mm in length (X axis), 21.9 mm in height (Y axis) and 29.5 mm thick (Z axis) (Figures 7-9). The two limbs mud-filled burrow core that describe the shape of the lobe are parallel to each other in vertical section and vary in diameter between 3 and 4 mm. Slight thickening in tube width is noted in the distal portion of the loop that cannot be attributed to compaction. Thickening of this part of the tube was described as one of the diagnostic characteristics of *Phycosiphon* (Wetzel and Bromley, 1994). The paired limbs of the examined form are not in the same horizontal plane, and

the terminal portion of the loop is at a steep angle to the limbs.

Nature of the Halo in the Rosario Phycosiphoniform Burrows

Our 3D reconstruction of Phycosiphoniform burrows from the Rosario Formation, Baja California, Mexico, demonstrates that the reworked silt-rich, clay-poor material that forms the halo around the clay-filled burrow core is dominantly present below the level of the clay-filled burrow (Figure 9). This feature is also prevalent in most natural vertical cross sections studied in the field (Figure 1.1). The halo is demonstrably meniscate, as determined from cross-sectional views, but especially through three-dimensional reconstruction (Figure 9). It is also noted that the burrow halos of adjacent burrow limbs are closely juxtaposed with little if any undisturbed host sediment between them (Figure 9). The halo around phycosiphoniform burrow cores has been described from other occurrences (Wetzel and Wijayananda 1990; Ekdale and Lewis 1991), but has not previously been reconstructed in three dimensions.

A similar halo associated with a phycosiphoniform burrow (attributed to *Anconichnus*) was interpreted as an early diagenetic oxidation halo (Ekdale and Lewis 1991). This feature was subsequently reinterpreted as being due to bioturbation, specifically the formation of spreiten in accord with newer conceptual models (Wetzel and Bromley 1994; Bromley 1996). Three-dimensional reconstruction of the Rosario Formation phycosiphoniform fossil, with its associated coarser-grained structure, demonstrates that the coarser-grained material is indeed asymmetric and lies below the level of each of the two lobe arms (Figure 9). This asymmetry is also visible from vertical surfaces prepared in the laboratory and in natural outcrop (Figure 1). The burrow halo is characteristically pyrite rich (Figure 1.2). Pyritization is interpreted to have been caused by sulphate-reducing bacteria during early diagenesis. The marked color contrast between the pyritized halo and clay-rich burrow cores relative to the surrounding rock matrix allowed us to distinguish the three components of the fabric for the purpose of image analysis.

The presence of the coarser-grained (silt-sized) material, not only between lobe arms, but also external to the marginal tube (Figure 9) precludes the presence of spreite and allows rejection of the possibility that the phycosiphoniform trace fossil reconstructed herein is *Phycosiphon*. In the accepted conceptual model of Bromley (1996; Fig-

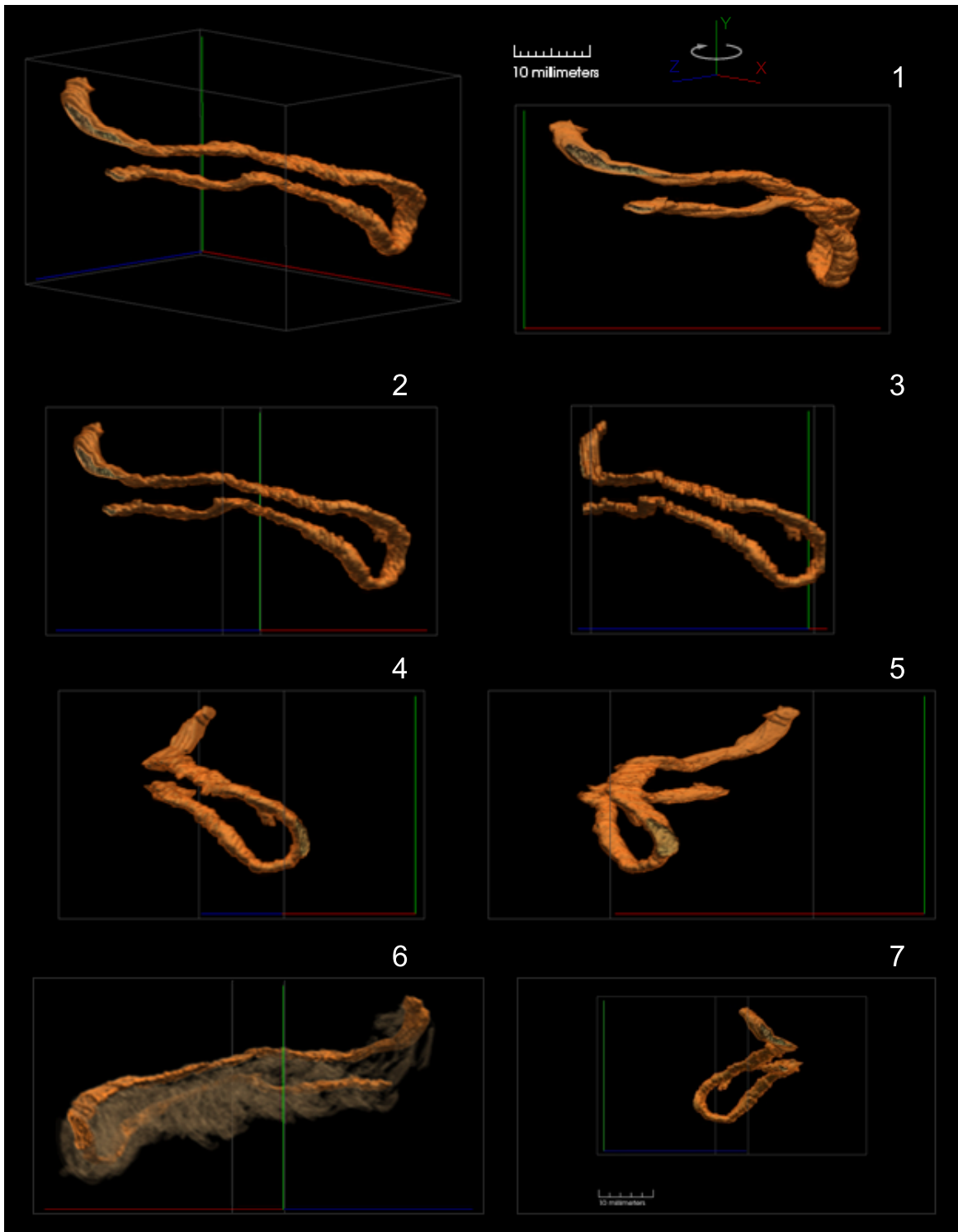


FIGURE 7. Three-dimensional reconstruction of phycosiphoniform from Rosario Formation, Mexico. **7.1-7.5.** Burrow core without the halo. **7.6.** Burrow core with surrounding halo. **7.7.** Quicktime format video file of rendered reconstruction of the phycosiphoniform burrow core.

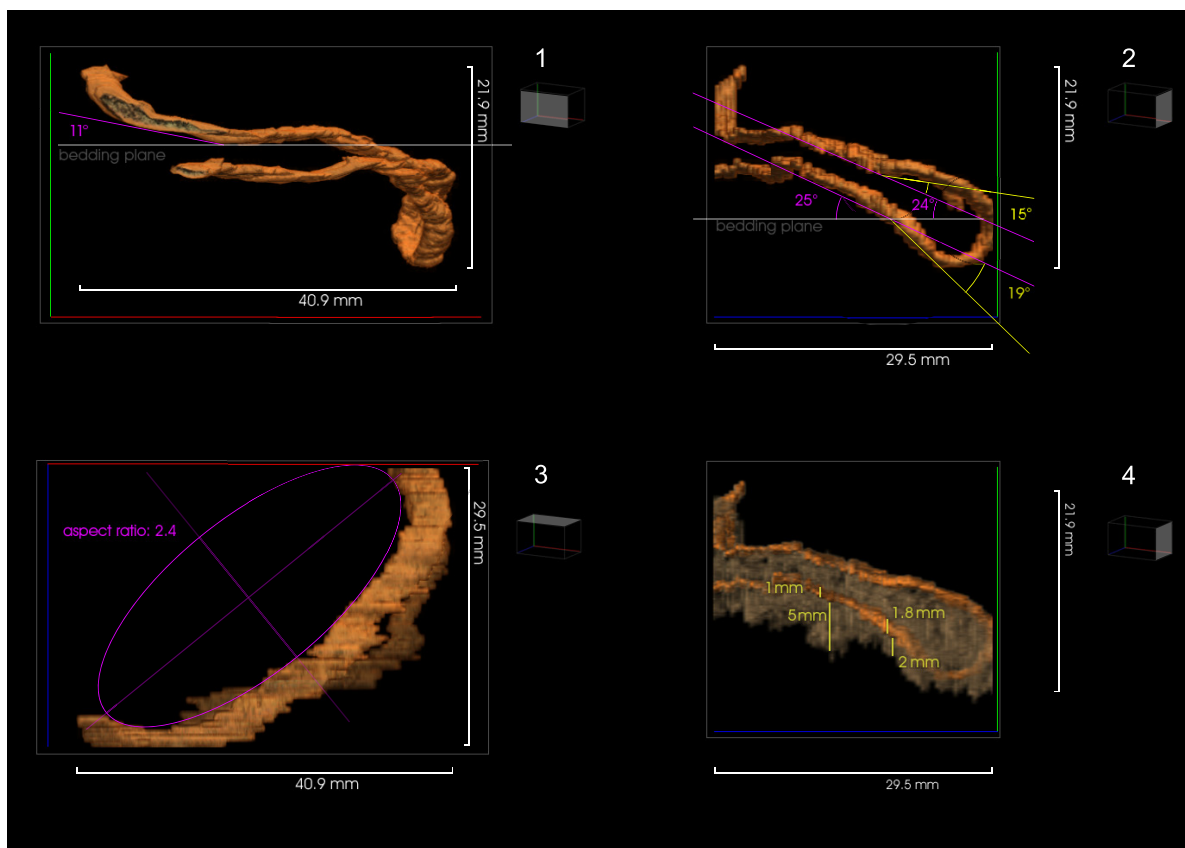


FIGURE 8. Three-dimensional reconstruction of the lobe of the phycosiphoniform burrow from Rosario Formation, Mexico. **8.1.** The longer arm of the lobe descends gently downward for about 30% of the lobe length and is inclined in about 11° to the bedding plane. Then in about next 30% of lobe length both arms continue more or less parallel to the stratification in order to incline in 24 -25° downward to the sediment. **8.2.** In about last 15% of lobe length the arms incline for further 15-19% each in opposite directions (upward and downward) and then direct back to create the apex of the lobe (so in the last part of formed loop the arms are the most distant from each other before they connect in the apex). **8.3.** Whole lobe bent in the horizontal direction along a half-ellipse of with an aspect ratio of 2.4. **8.4.** The halo can be several times thicker than the burrow core.

ures 3-5), spreiten are predicted only between arms of a single lobe and between marginal burrows. The behavioural model proposed for *Phycosiphon* (Bromley 1996) precludes the possibility of formation of the halo/spreiten below the level of a marginal tube that borders the *Phycosiphon* structure. Spreiten are demonstrably not present in our material from Rosario Formation. Instead, the phycosiphoniform cross sections are inferred to have been formed by bulk sediment processing at the anterior of the burrow during continuous burrowing rather than successive probing as is proposed for *Phycosiphon* s.s.

CONCLUSION

Mud-rich siltstones from Rosario Formation are characterized by dense monospecific assem-

blages of phycosiphoniform burrows and are analogous to many shale-gas reservoir facies. Local concentrations of burrowing may reflect patches of labile organic matter. The phycosiphoniform burrow-makers are thought to be selective deposit feeders that ingested clay-grade material and left a clean mud-poor feeding halo of processed sediment.

Our image analysis of two-dimensional slices allows reconstructing the three-dimensional geometry of the *Phycosiphoniform* trace fossil. The reconstructed burrow is unlike *Phycosiphon* (*sensu lato*), but produces very similar “frogspawn texture” ichnofabrics. The cross sections of our burrow system are distinguished from those of *Phycosiphon* s.l. in that the halo is generally present only beneath the level of clay-rich burrow cores.

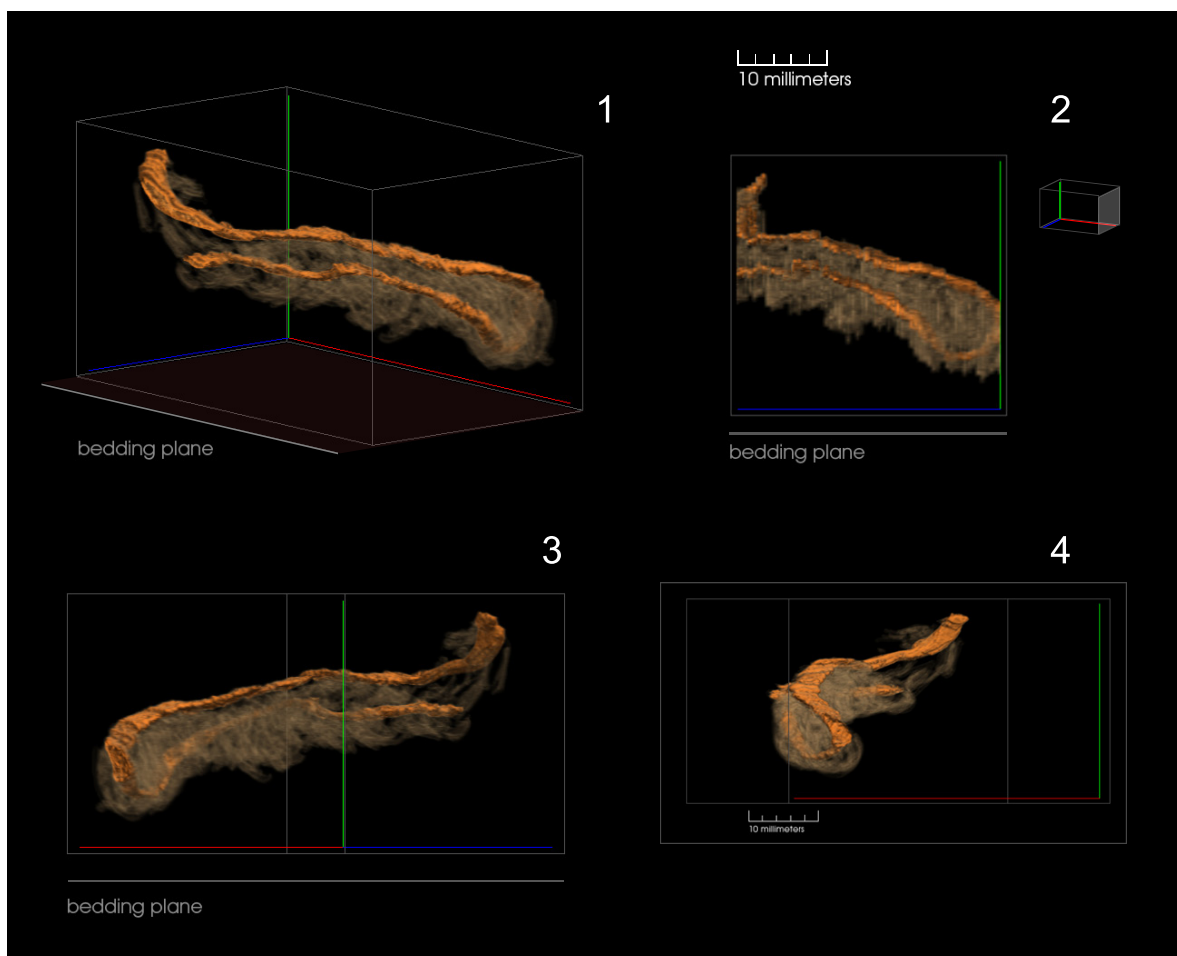


FIGURE 9. Reconstructed phycosiphoniform burrow with associated halo from Rosario Formation, Baja California, Mexico. Coarser grained material of the halo propagates downward from the line of each lobe arm (in direction to bedding plane) and fills the space between the lobe arms. **9.1-9.3.** Different views of reconstructed burrow with surrounding halo in relation to the bedding plane. **9.4.** Quicktime format video file of rendered reconstruction of burrow with the associated halo.

The examined phycosiphoniform burrow geometry presents the following characteristics that allow differentiation from *Phycosiphon incertum*: 1) Arms of the single lobe are parallel in the vertical plane (Figure 8.1-8.2), and the lobe is seen to bend into a half ellipse when viewed in the plane of the lobe (Figure 8.3); 2) In side view, the lobe arms extend parallel to bedding and are steeply bent downward at the termination of the loop (Figure 8.1); 3) in axial view, the lobe is steeply inclined relative to the bedding plane (Figure 8.2); 4) The halo of the burrow is present only below the level of the burrow core and completely fills the space between the lobe arms (Figures 1 and 9); 5) The halo can be several times thicker than the burrow core (Figure 8.4); and 6) No spreiten have been observed.

Our palaeobiological model for the formation of the studied *Phycosiphoniform* trace fossil is fundamentally different to that proposed for *Phycosiphon*, but produces remarkably similar vertical cross sections. We consider that identification of *Phycosiphon incertum* in core is not possible without detailed three-dimensional examination of burrow geometry. We propose the term “phycosiphoniform” to describe this group of ichnofabric-forming trace fossils. We consider that, at present, our material should be left in open nomenclature pending thorough three-dimensional analysis of the type material of other phycosiphoniform burrows including *Anconichus horizontalis*. We note that there are many possible burrow geometries that can produce phycosiphoniform cross sections, but that much work needs to be done before

many taxa can be convincingly recognized in vertical cross section.

ACKNOWLEDGEMENTS

Preliminary discussion with A. Wetzel and R. Bromley are acknowledged with thanks. M. Sutton kindly provided initial guidance in the art of serial grinding and tomographic reconstruction. Material from Cajilloa, Baja California, was collected with B. Kneller, whose help and logistical support are much appreciated. Support for this research came from an NSERC grant to DMc, the SLOPES consortium and the award of Canada Research Chair to DMc. We would like to recognize the contribution of Dr. Wetzel and an anonymous reviewer, which helped us to clarify our arguments.

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