The late Atokan (Moscovian, Pennsylvanian) chaetetid accumulations of Sierra Agua Verde, Sonora (NW Mexico): composition, facies and palaeoenvironmental signals

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Abstract: The La Joya Formation of the Sierra Agua Verde, Sonora (NW Mexico) is late Atokan in age, equivalent to the early late Moscovian (Podolskian) and fusulinid biozone A3. In this alternance of cherty limestones and thin shaly beds, fusulinellid or anchicodiacean ('phylloid algae') wackestones–packstones and crinoidal rudstones–grainstones are the predominant microfacies, but chaetetid boundstones are conspicuous. These chaetetid occurrences of the Sierra Agua Verde are compared with the accumulations of Arizona, Texas, Kansas and Nevada (USA), and the Cantabric Cordillera (Spain). In Sonora, the environments with chaetetids were quiet, and located below wave base. Shallower facies with staffellids and *Komia* generally top the chaetetids. Because of the associated micritic deposits, the chaetetids have inhabited probably a soft or firm substrate. As a result of the disphotic–aphotic reconstructed environments, the possible symbionts of the chaetetids are more probably heterotrophic bacteria than autotrophic algae. The most comparable ecological conditions exist in the Atokan Marble Falls Formation of central Texas (USA). Chaetetids are not mentioned in the southern suspect terranes of Mexico, but were possibly present because these regions were located along the probable migration way to Peru, the southernmost area where Pennsylvanian chaetetids are known.

As noted by many authors, chaetetids were one of the rare reef-mound builders during the Middle Pennsylvanian. They were responsible for unique framestones during this period, whereas other bioconstructions consist of algal bindstones or bafflestones with *Donezella*, beresellaceans, archaeolithophyllaceans and anchicodiaceans, i.e. 'phylloid algae' (e.g. Roux 1985; Mamet *et al.* 1987; Minwegen 2001; Della Porta *et al.* 2003; Mamet & Villa 2004). Occurrences of chaetetids are generally well described in the literature, and the aim of this paper is preferentially to describe a newly investigated outcrop in Sonora and some of its biosedimentological characteristics (see also Buitrón-Sánchez *et al.* 2007).

Geological setting

In the state of Sonora, in the NW corner of Mexico, the deposits of the Pennsylvanian subsystem are generally poorly described. They are listed in some general handbooks and stratigraphic compilations (López-Ramos 1985; Peiffer-Rangin 1987; Sánchez-Zavala *et al.* 1999; Vachard *et al.* 2000*b*). First, the Horquilla Formation, defined in the southern USA, has been studied the northern part of Sonora in the Cerros de Tule, and in the Sierra de Palomas in the adjacent state of Chihuahua (Wilson *et al.* 1969; Téllez-Girón 1979; González-León 1986). In central Sonora, the Pennsylvanian is well exposed in the Sierra Agua Verde, an hill located 120 km NE of Hermosillo City, the capital of Sonora (Fig. 1). This hill is formed by a series (2900 m thick) of platform rocks from Cambrian to Permian in age. In its southern flank (29°10′/29°22′N and 109°45′/109°58′W) the Pennsylvanian is referred as to the La Joya Formation (Ochoa-Granillo & Sosa-León 1993). It is composed of a series (*c.* 100 m thick) of micritic–bioclastic limestone, extensively silicified with

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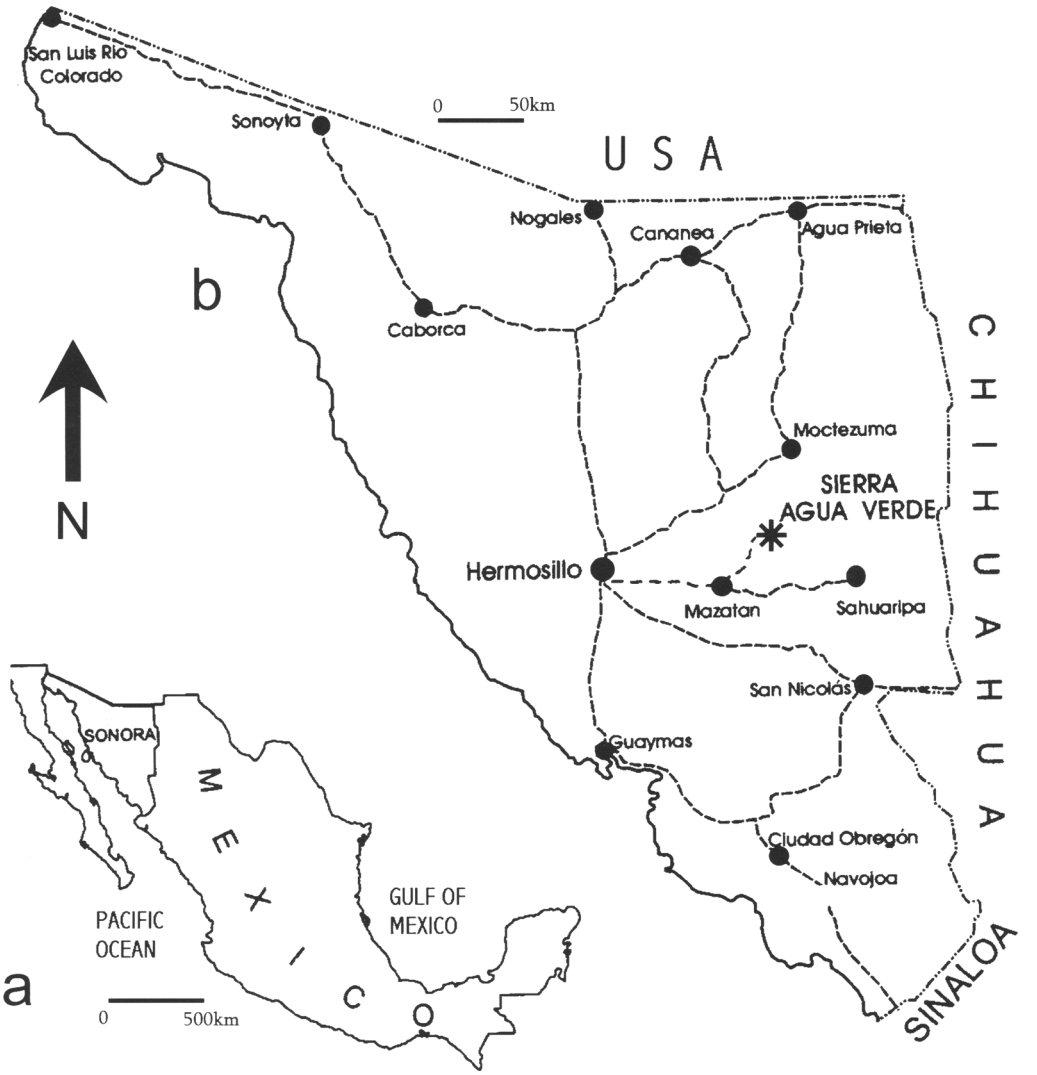

Fig. 1. Maps indicating the locations of (**a**) Sonora State in Mexico and (**b**) Sierra Agua Verde in Sonora.

nodular cherts and interstratified with siltstone (Fig. 2). The fossiliferous facies are generally decimetre-thick beds of cherty pale grey limestone. They contain mainly calcareous algae, fusulinids, chaetetids, gastropods, brachiopods, crinoids and conodonts (Stewart *et al.* 1997, 1999; Buitrón-Sánchez *et al.* 2004; Mendoza-Madera *et al.* 2004).

Biostratigraphy

In the United States, the subsystem Pennsylvanian is divided into five stages and 16 zones of fusulinids (Wilde 1990): Morrowan (biozones M 1–2); Atokan (A 1–4), Desmoinesian (DS 1–5); Missourian (MC 1–4) and Virgilian (VC 1–3). The equivalent international subdivisions (Heckel 2004) are the early–middle Bashkirian for the Morrowan; the late Bashkirian–early Moscovian for the Atokan; the late Moscovian for the Desmoinesian; the Kasimovian for the Missourian; and the Gzhelian for the Virgilian.

In the Sierra Agua Verde, several beds ('Fusulinids' levels of Fig. 2) permit the datation of the series thanks to their relatively diversified assemblages of carbonate microfossils. The

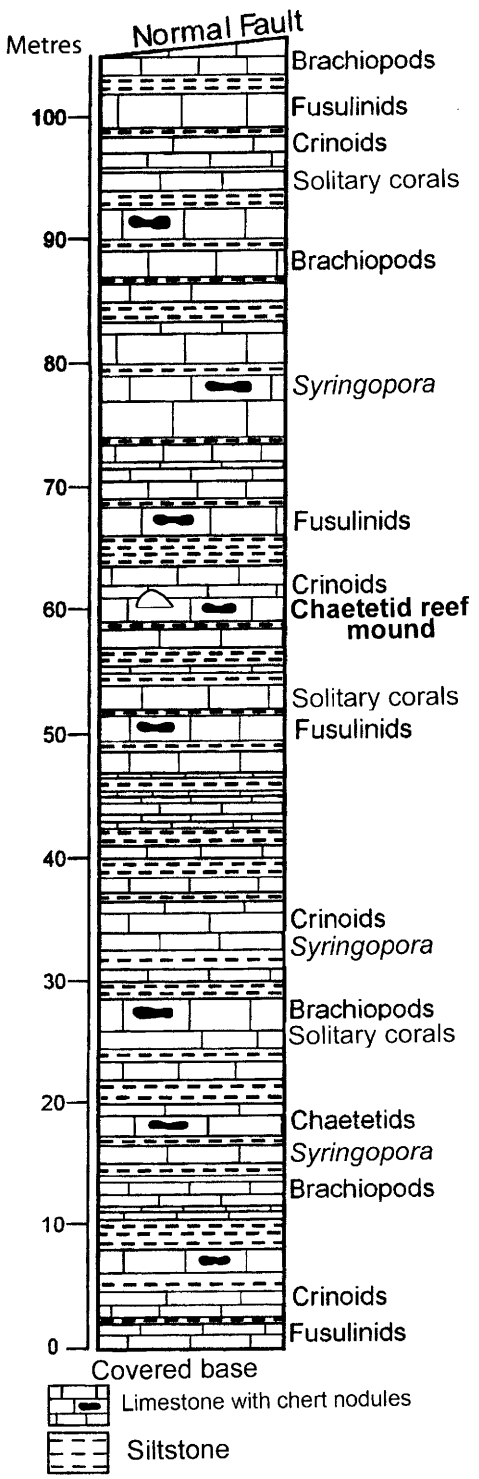

Fig. 2. Lithostratigraphic column of the Pennsylvanian La Joya Formation in Sierra Agua Verde, Sonora, Mexico.

problematic calcareous algae are represented by sporadic *Eugonophyllum* sp., *Zidella* (?) sp., *Kamaena* (?) sp. and *Komia eganensis*. Taxa of associated smaller foraminifers are *Pachysphaerina pachysphaerica*, *Eotuberitina reitlingerae*, *Insolentitheca horrida*, *Endothyra* ex gr. *bowmani*, *Globivalvulina bulloides*, *Climacammina* ex gr. *moelleri*, *Deckerella* sp., *Calcivertella* sp, *Baryshnikovia* sp. and *Syzrania* sp. The following fusulinids have been identified: *Mediocris breviscula*, *Eostaffella grozdilovae*, *Millerella* sp., *Pseudostaffella* sp., *Staffella powwowensis*, *Eoschubertella texana*, *Fusulinella thompsoni*, *F. llanoensis*, *F.* aff. *llanoensis* and *Nipperella* (?) sp. indet. This fusulinid assemblage indicates a late Atokan age (biozone A3: Wilde 1990). Similar species of fusulinids are known in the Upper Marble Falls Limestone of central Texas (Groves 1991), which also contains 'impressive chaetetid colonies' (West 1992, p. 165).

The first results of our analyses of biostratigraphy (C. Gómez-Espinosa, B. Buitrón-Sánchez and D. Vachard) and sequence stratigraphy (E. Almazán-Vázquez and D. Vachard) suggest that the 100 m of the La Joya Formation are entirely late Atokan in age, and were accumulated in the form of a transgressive systems tract (TST). This TST is probably coeval with the upper part of the TST of the Podolskian stage identified in the Ukrainian Donets Basin (Izart *et al.* 1996, text-fig. 9; sequences SM9 and/or SM10).

The dominant lithologies of the Atokan TST of the Sierra Agua Verde are: (a) fusulinellid, especially *Fusulinella llanoensis*, wackestone, packstone and floatstone; (b) crinoidal rudstone; (c) *Chaetetes* bafflestone; and (d) *Eugonophyllum* bindstone, alternating with shales.

The chaetetid organisms

Chaetetids are coralline (i.e. hypercalcified) demosponges (see discussion in Connolly *et al.* 1989, table 1), with unusual pseudomorphs of spicules (e.g. Cremer 1995). They are possibly capable of heterotrophic symbiosis (West 1994; Stanton *et al.* 1997), not necessarily attached to a hard substrate (Stanton *et al.* 1997), and essentially present during the Early and Middle Pennsylvanian (Morrowan, Atokan and Desmoinesian stages), but not exclusively a guide for this period (West 1992; Flügel 2004). The palaeocological and taphonomical elements of description of the chaetetids are clearly summarized in Connolly *et al.* (1989), Stanton *et al.* (1994) and Minwegen (2001); and the vocabulary for the description of the skeletons can be borrowed from Cremer (1995) and Stanton *et al.* (1997). According to West (1992, 1994), the seven

Fig. 3. Field photograph in Sierra Agua Verde, Mexico, showing some silicified chaetetids in life position, numerous cherts and the thickness of the associated limestone beds. The scale bar is 20 cm.

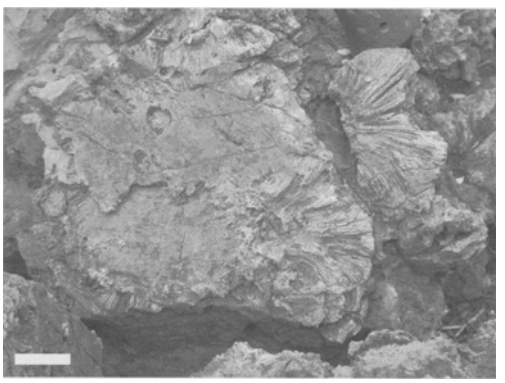

Fig. 4. Silicified *Chaetetes* showing the clinogonal growth of the tubes (Sierra Agua Verde, Sonora, Mexico). The scale bar is 30 mm.

Fig. 5. Polished longitudinal section of a chaetetid. The scale bar is 1 cm.

species of Carboniferous *Chaetetes* in North America could be synonyms. This preliminary report does not describe the detailed taxonomy of the chaetetids collected in the Sierra Agua Verde by our team.

Chaetetids of the La Joya Formation are present in two stratigraphic levels, 19 and 60 m above the base of the section, respectively (Fig. 2). They are represented by many silicified massive structures with a hemispherical–columnar shape (Figs 3–5). The chaetetid skeletons are comprised of a series of thin and long tubes, quadrate–hexagonal in cross-section with an average maximal dimension of 0.500–1.000 mm, with a clinogonal microstructure and increasing by longitudinal parting (Figs 3–7). The primary walls, not perforated, show at regular intervals some quasi-tabulae, but no growth bands are distinct. Monaxon megascleres are entirely missing in our specimens. Often, the chaetetids of the Sierra Agua Verde are in life position and exhibit columnar structures up to 50 cm in height and approximately 35 cm in diameter (Fig. 5). Accumulations of chaetetids grew by vertical development of cloned individuals and trapping of micritic sediment, i.e. constituting bafflestones (Figs 3 & 4). Limestones either with chaetetids or devoid of them do not differ significantly, and the lithological and palaeotopographic differences between bafflestones and wackestone–packstone deposit areas are generally faint, as we do not observe preserved palaeoslopes such as those illustrated by Krainer *et al.* (2003) in the *Anthracoporella*

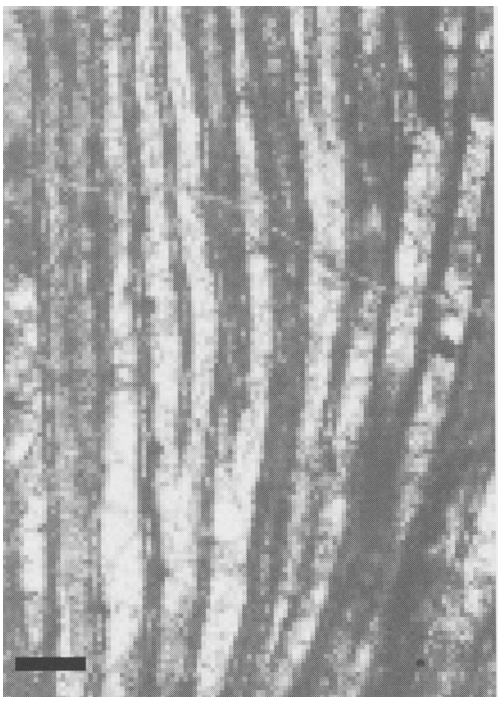

Fig. 6. Longitudinal section of a chaetetid showing the growth of the tubes by longitudinal parting. The scale bar is 1 mm.

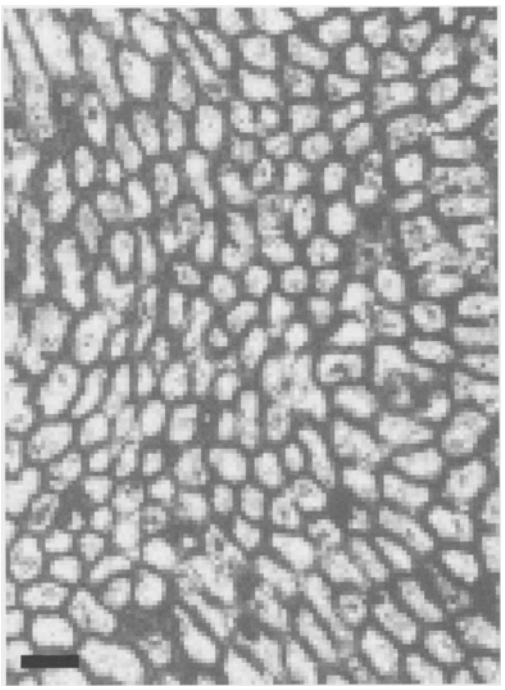

Fig. 7. Transverse section of a chaetetid showing the tubes and their quadrate to hexagonal cross section. The scale bar is 1 mm.

mounds of the Carnic Alps (Austria). Hence, the chaetetids in the Sierra Agua Verde constitute cluster reefs in the sense of Riding (2002, p. 190) or reef mounds such as those of Arizona (Connolly 1990). The columnar forms are dominant among these reef mounds, as in Kansas outcrops described by Suchy & West (2001), or the Hueco Mountains (west Texas) and Whetstone Mountains of southern Arizona (Connolly *et al.* 1989; Connolly 1990). Among the environments inhabited by chaetetids summarized by Connolly *et al.* (1989, p. 147), the Sonora occurrence is similar to that described for the outcrops of the Mason County (central Texas) located in the Atokan part of the Marble Falls Formation. The common characteristics are the association with foraminiferal wackestones and packstones, the *Chaetetes* reef mounds situated below normal wave base, the low faunal diversity, an estimated relief of 1–2 m, and the evidences of episodic storms.

Environments and facies

Diverse accumulations of fusulinids, phylloid, and other algae, sponges and corals are visible in the field (Fig. 2) and in thin sections; for example, fusulinellids *Fusulinella llanoensis*, phylloid algae *Eugonophyllum* sp., problematic ungdarellacean algae *Komia eganensis* (sometimes difficult to distinguish from *Pseudokomia*), corals (*Michelinia, Syringopora*), chaetetids and crinoids (Buitrón-Sánchez *et al.* 2007). The micritic matrix is homogeneous, and no siliciclastic input is obvious in the bioclastic wackestone, packstone or floatstone microfacies. Some beds are diagenetically dolomitized and silicified with poorly preserved fusulinellids. Indicators of shallow-water environments (i.e. within the zone of normal water activity), such as oolites, microbialites, current figures, granular carbonate cements, palaeosols or other sequence boundaries, are totally lacking along the stratigraphic column, which remains from base to top of late Atokan age (see above) and exhibits consequently the characters of a TST deposited in a strongly subsident platform.

The biota of the chaetetid beds is characterized by an epifaunal macrofauna (crinoids and fusulinellids that probably lived upon these crinoids, in view of the absence of algae and the consequent impossibility of an epiphytic way of

life) and infaunal small foraminifers, living in the superficial centimetres of the bottom carbonate mud. In the sediments associated with the *Chaetetes* the tests of fossils are well preserved, rarely encrusted by microbial biofilms and preferentially composed of an exclusive species of *Fusulinella*. A sorting by buoyancy is probable because of the absence of juvenile stages and uniform size of the adult *Fusulinella* tests entirely filled by microsparite, i.e. transported empty to the terminal deposit. They are believed to have been relatively deeply deposited, i.e. at the limit of the photic zone, because green algae are not present in the assemblages. The absence of staffelloid foraminifers and other indicators of shallow waters, and the abundance of crinoids, brachiopods and bryozoa, are other characteristics of relative depth. Nevertheless, in the succession, shallower environments can be identified when: (a) *Fusulinella* are associated with *Staffella*; and (b) phylloid algae form bindstones or platestones with abundant micrite. Chaetetids are generally preserved in life position, showing a clinogonal increase (Fig. 5), with the tubes directed upwards and outward. No specimens grew downwards, contrary to the specimens of the Hueco Mountains described by Stanton *et al.* (1997). Preservation *in situ* appears to be common in these quiet environments, as our taphonomic studies in progress indicate that the disarticulation of crinoids was the result of mass transport accelerating the muscular and articular post-mortem decay (Buitrón-Sánchez *et al.* 2007).

Discussion

As indicated above, in the Sierra Agua Verde, the chaetetid cluster reefs were constructed during the deposition of an Atokan transgressive systems tract (TST). Inversely, the Kansas chaetetid buildups were developed during a Desmoinesian HST (Suchy & West 2001) and exhibit associated syringoporid tabulate corals *Multithecopora* or algal crusts and storm events, all these phenomena are not recorded in Sierra Agua Verde and we propose to interpret the chaetetid biotopes to have been located below storm wave base and photic zone; i.e. to approximately −100 m of depth (according to the synthetic data of Bosscher & Schlager 1992; Wright & Burchette 1996; Biju-Duval & Savoye 2001; Cojan & Renard 2003). This proposed palaeobathymetry is consistent with the lateral equivalence to *Fusulinella* wackestones having a matrix of homogeneous micrite, and with the absence of photophile algae in the microfacies, absence of current or storm sedimentary figures, absence of oolites and absence of stromatolites, and because the Recent coralline sponges are known from 10 to 185 m (Fallon *et al.* 2005). The life habit of *Chaetetes* here was relatively restricted, as it can occupy areas 'from intertidal to below wave base' (Connolly *et al.* 1989), and in some cases quoted by these authors the phylloid algal mounds can be in turn capped by *Chaetetes* constructions (Connolly *et al.* 1989, text-fig. 5). Algae appear with *Eugonophyllum* and *Komia* in the overlying beds of La Joya Formation, thus suggesting deposition in water depths of more or less 25 m (see discussion in Connolly *et al.* 1989, p. 153). This important variation of the deposit depths, from −100 to −25 m (Fig. 8a), indicates a strong local subsidence, responsible for the creation of a regional palaeoslope and rapid variations of the accommodation on the carbonate platform (Fig. 8b).

A bathymetry of 'much less than 100 feet (~30 m)' is indicated for the *Chaetetes* of Kansas by Suchy & West (2001, p. 432), and shallower than that of the underlying phylloid algal beds. Consequently, the bathymetrical relations between *Chaetetes* bioconstructions and phylloid algal bioconstructions vary according to the series and the outcrops. In the Sierra Agua Verde, we have supposed that the *Chaetetes* grew deeper (*c.* −100 m) than the phylloid algae *Eugonophyllum* (*c.* −25 m) (Fig. 8a).

In the literature exists a discussion about the types of substrates of chaetetids (Connolly *et al.* 1989; Stanton *et al.* 1997). The associated carbonate microfacies in the Sierra Agua Verde are devoid of pressure-solution features, deformation or beacking of fusulinellids and sutured contacts between grains. That seems to indicate an early cementation of the overlying beds, and consequently a firm–hard substrate for the local chaetetids. Moreover, *Chaetetes* can support agitated waters (Connolly *et al.* 1989). Generally, a strong hydrodynamism permits a rapid cementation of the granular sediments. Consequently, in agitated environments, the chaetetids have still more probably a hard substrate. Nevertheless, Suchy (pers. comm. 2006) suggests that the chaetetids attached themselves to softgrounds held together by covalent forces within the muds or by algal or bacterial mats that left no visible trace. Bromley & Heinberg (2006) admit also that in many cases 'there is an organic membrane or layer of glue between the skeleton and the substrate'. However, owing to the large dimensions of some individuals, their base must be strengthened by rapid sedimentary inputs to stop the chaetetids from taking a tumble and permit them to hold in vertical position (Fig. 8a).

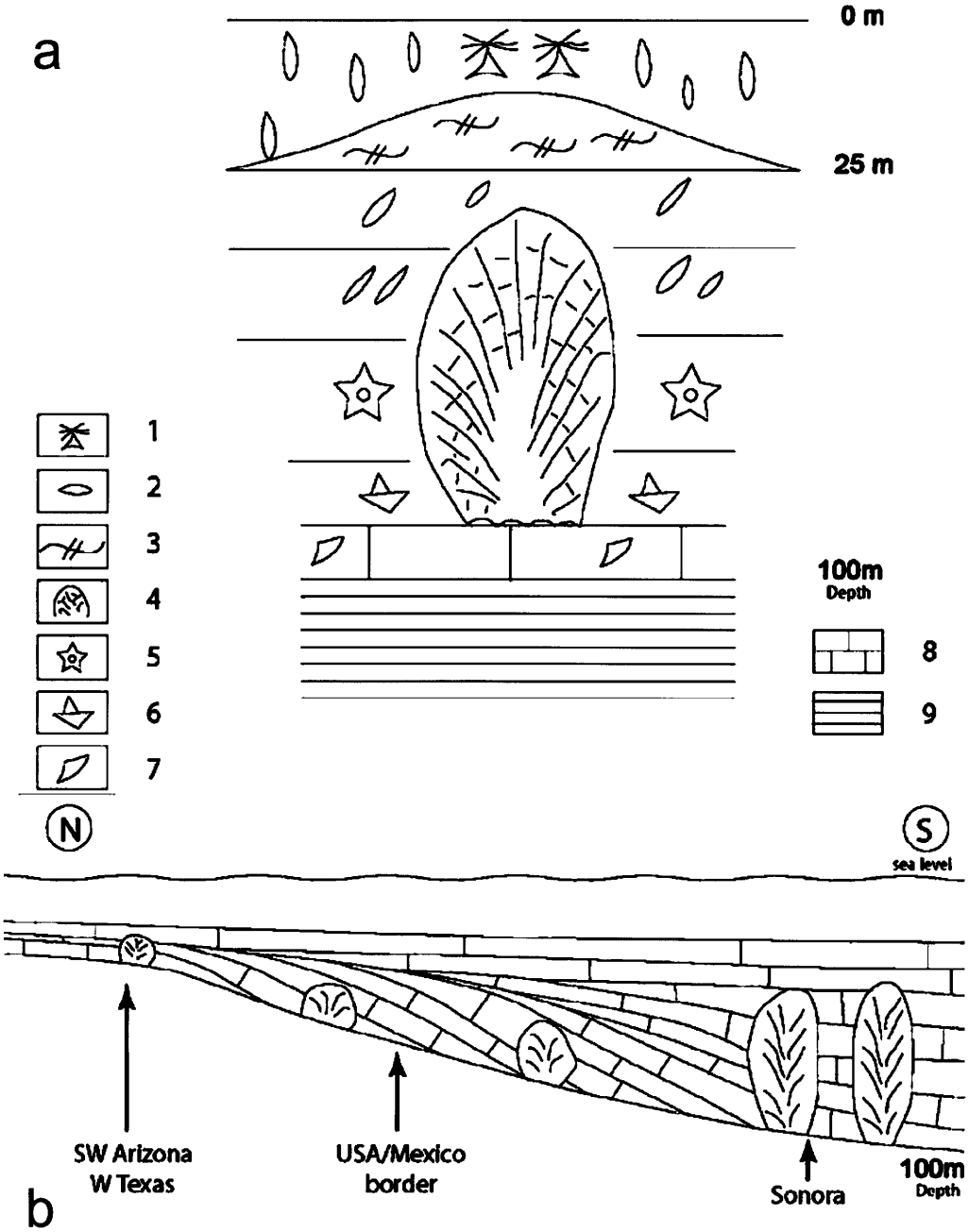

Fig. 8. Reconstructions of environments of deposits. (**a**) Idealized parasequence showing the succession of the deposits, biotopes and corresponding bathymetries. 1, dasyclads; 2, fusulinids; 3, phylloid algae; 4, *Chaetetes*; 5, crinoids; 6, brachiopods; 7, solitary corals; 8, limestone; 9, shales. (**b**) Palaeogeographical reconstruction from Arizona to Sonora during the Atokan.

Suchy & West (2001) used growth rates of extant coralline sponges (more or less 0.15–1.2 mm year^{-1}, according to Fallon *et al.* 2005) to make inferences about the longevity of the chaetetids preserved in the rocks and thus the duration of deposition of the beds. We have obtained more or less similar data (life time of the biggest chaetetid up to 3 ka (3000 years) and time of deposit of a chaetetid bed (10–20 ka)). Consequently, using those as a standard, we propose to discuss and compare these data with the growth rates of fusulinids (probable average longevity of 3 years; compare with Vachard & Bouyx 2002) and crinoids in order to estimate, with precise biochronometres, the sedimentation rate all around and within the bioconstructions of chaetetids (Gómez-Espinosa's PhD). A life time of the chaetetids of up to 3000 years, compared with probable average longevity of 3 years for the fusellinellids and an intermediary time for the crinoids, allows a precise correlation of the growth of the chaetetids and their successive trapping of fusulinellid wackestone–packstone and/or crinoid rudstone to be made (see also Buitrón-Sánchez *et al.* 2007, fig. 4), and eventually allows a calculation of the frequency of storms during the Atokan in Sonora. Symbiosis with heterotrophic bacteria and not autotrophic algae, as in many modern sponges, may be implied by the probable growth of our chaetetids in the disphotic or aphotic zone but we lack precise arguments.

The *Chaetetes* might be also proposed, as well as the Recent coralline sponges (Fallon *et al.* 2005), as a recorder of water temperature in order to verify the eventual episodes of cold waters that can occur in some tropical environments (Weidlich 2007). Nevertheless, owing to the large spectrum of recorded habitats, it is difficult to accurately express nowadays if chatetids were warm or cold, stenotherms or stenotopes. A control by studies of sequence stratigraphy might allow to the true biotopes of chaetetids to be accurately expressed.

Finally, the most comparable ecological conditions exist in the Atokan Marble Falls Formation of central Texas. According to the characters summarized by Connolly *et al.* (1989, text-fig. 3), the chaetetid bioconstructions in SW Arizona and east Texas seem to correspond to shallower environments; consequently, during the Atokan, a slight slope towards the south existed near the current boundary between Mexico (Sonora) and the United States (Arizona) (Fig. 8b), and another one, or the prolongation of the latter one, in central Texas.

Associated fusulinellids in the Sierra Agua Verde are classical species of the southern USA, e.g. *Fusulinella llanoensis* (Skinner & Wilde 1954; Groves 1991). Smaller foraminifers are similar to the assemblages of Marble Falls (Groves 1992). Among the algae, the incertae sedis *Komia* is also widespread in North America (Mamet *et al.* 1987). In the two geodynamic domains of Sonora, Craton and Caborca Terrane (González-León 1989; Sedlock *et al.* 1993), the microfossil assemblages are similar. Apparently, these two domains were not isolated during the Carboniferous–Permian. Continuity with the central Mexican Mixteco Terrane is evident at least as early as the Missourian (Late Pennsylvanian), based on the identity of species of *Triticites* (Vachard *et al.* 2000*b*). The continuity of a carbonate platform as early as the Middle Pennsylvanian, between Sonora and South America, via Oaxaquia and Maya Blocks, is probable (Fig. 9), as some species of *Fusulinella* from Sonora are very similar to some *Fusulinella* from South America (for example *F. peruana* (Meyer) described from central Peru by Dunbar & Newell 1946). The platform reconstructed here (Fig. 9) seems to be the unique possible means of migration for these foraminifers, strictly benthic, living in rather shallow waters and devoid of pelagic stages (see discussion in Vachard & Bouyx 2002). However, the Middle Pennsylvanian *Chaetetes* are also known into South America (Suchy & West 2001). These data validate the previous palaeobiogeographical reconstructions of our team (Vachard *et al.* 2000 *a–c*). The North American Craton was separated from the Gondwanan continent of southern America by a remnant of the Rheic Ocean, where some individualized tectonostratigraphic terranes were present , such as Mixteco and Oaxaquia, exhibiting a carbonate platform (Fig. 9). Flysch basins are developed in the intervening parts of the Pennsylvanian of Mexico (Fig. 9). In the Mixteco and Oaxaquia terranes, *Chaetetes* have not been found owing to the weak development of limestone in this area, which was probably the bottom of an ocean at the time of deposition. However, a carbonate platform is probably present elsewhere as the chaetetids are known in the Carboniferous of South America (Suchy & West 2001, p. 431), as are fusulinellids (Dunbar & Newell 1946; Newell *et al.* 1953).

Conclusions

- The Atokan *Chaetetes* bioconstructions of the Sierra Agua Verde (Sonora) can be correlated

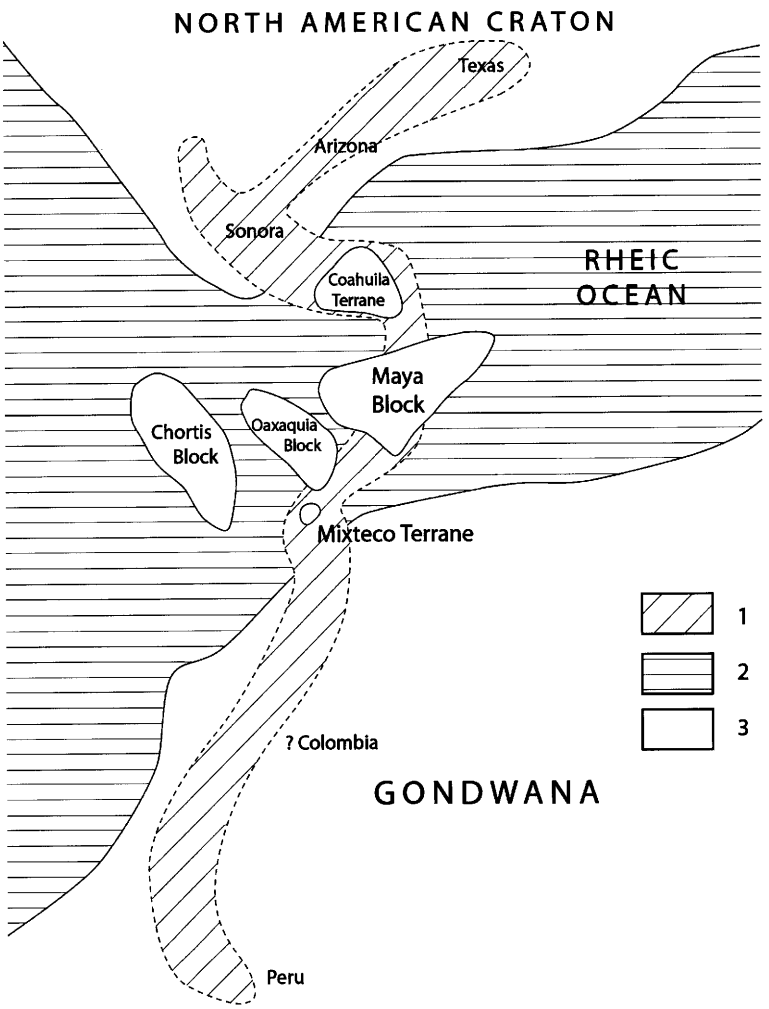

Fig. 9. Atokan palaeogeography from Sonora to Peru showing an hypothetical carbonate platform as a possible migration seaway for the chaetetids and fusulinellids. 1, carbonate platform; 2, flysch basins; 3, mainlands. Not to scale.

with coeval buildups of central Texas; the presence of the fusulinellid group *Fusulinella llanoensis* confirms the biogeographical affinity with the Texas assemblages; the algae *Komia* and *Eugonophyllum* are abundant in both areas.

- The Sierra Agua Verde and central Texas environments are relatively deeper and were less similar to the environments and constructions of Kansas, Arizona and eastern Texas.
- Contrary to the Kansas reefs, no associated syringoporid tabulate corals *Multithecopora* or algal crusts have been observed, confirming the deeper palaeobathymetry of the Sonora outcrop.
- In the Sierra Agua Verde, the colonies of *Chaetetes* were located below wave base (generally located by the authors to be *c.* −100 m). Algae appear with *Komia* and *Eugonophyllum* in the topping beds (whose deposit depth decreased probably to 25 m).
- The chaetetid reef mounds of the Sierra Agua Verde were accumulated within a TST of the late Atokan.

- The growth of chaetetids in firm, lithified substrate is inferred.
- Symbiosis with heterotrophic bacteria and non-phototrophic algae is suggested by the probable growth of the Sierra Verde chaetetids in the disphotic or aphotic zone.
- Life time of the chaetetids up to 3000 years, and a probable average longevity of 3 years for the fusellinellids, allow the to precise correlation of the growth of the chaetetids and their successive trapping of fusulinellid limestone. The crinoids, which have an intermediary longevity, provide some regional encrinites partially enveloping the chaetetids and must also be studied from this point of view.
- Although the biotopes are slightly different (shallower), in Sonora, Arizona and Texas the three provinces were connected in only one tectono-stratigraphic domain with similar fossil assemblages. This domain was necessarily related to the Mexican terranes of Oaxaquia and Mixteco, as the unique way through the Rheic Ocean, for the chaetetids and fusulinellids migrating to South America.

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