

EDIACARAN AND CAMBRIAN INDEX FOSSILS FROM SONORA, MEXICO

by FRANCISCO SOUR-TOVAR*, JAMES W. HAGADORN† and TOMÁS HUITRÓN-RUBIO*

*Museo de Paleontología, Departamento de Biología Evolutiva, Facultad de Ciencias, Universidad Nacional Autónoma de México, Ciudad Universitaria, México DF, Mexico, CP 04510; e-mail: fst@hp.fciencias.unam.mx

†Department of Geology, Amherst College, Amherst, MA 01002, USA; e-mail: jwhagadorn@amherst.edu

Typescript received 29 June 2006; accepted in revised form 9 October 2006

Abstract: The Cambrian index fossil *Treptichnus pedum* is reported from the Puerto Blanco Formation near Pitiquito, Sonora, Mexico, and new occurrences of the Neoproterozoic index fossil *Cloudina* are reported from the underlying La Ciénega Formation. Considered together, these fossils constrain the location of the Ediacaran/Cambrian boundary in Mexico. The suite of fossils in this sequence is important because it provides an independent biostratigraphic datum for constrain-

ing the position of Laurentia during the onset of metazoan diversification, for testing proposed lithostratigraphic correlations among western North American Neoproterozoic–Cambrian successions, and for testing regional tectonic paradigms such as the Mojave-Sonora Megashear hypothesis.

Key words: *Treptichnus pedum*, *Cloudina*, trace fossils, Early Cambrian, Sonora, Mexico.

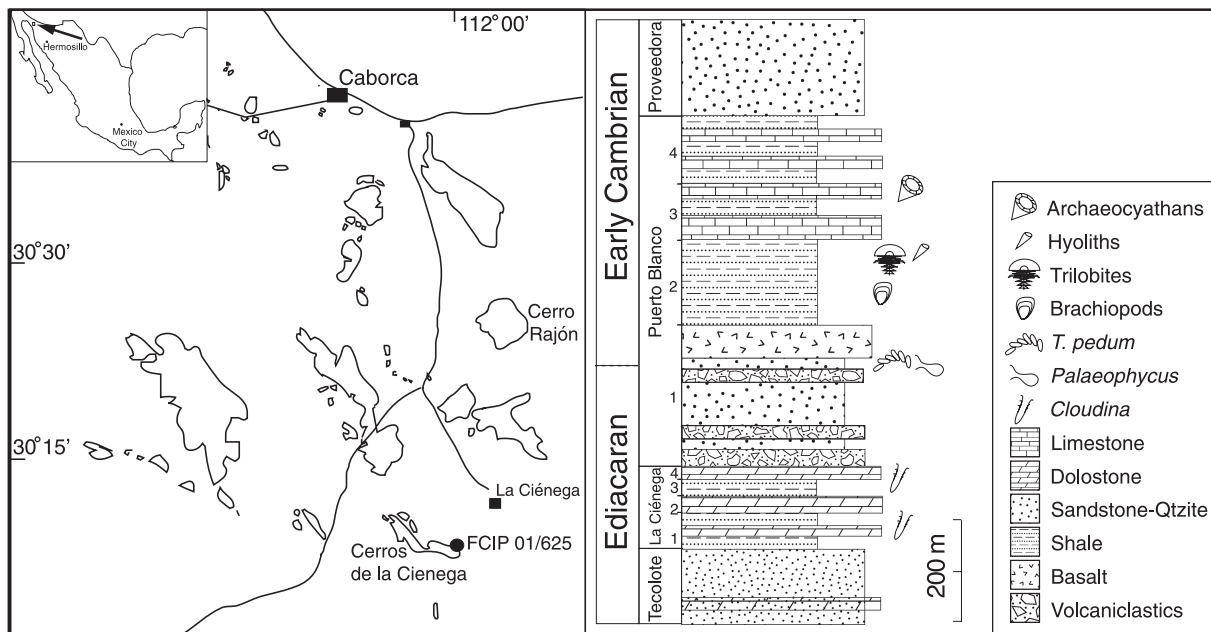
TRACE fossils provide key insights into biological events during the Neoproterozoic–Phanerozoic transition, including the globally synchronous advent of vertically orientated burrowing in marine sediments. The first appearance of the trace fossil *Treptichnus pedum* represents the onset of this burrowing behaviour, and is used to define the location of the Ediacaran/Cambrian boundary in sections throughout the world (Narbonne *et al.* 1987; Landing 1994; Knoll *et al.* 2006). Its occurrence is particularly useful in successions characterized by mixed lithofacies, which best provide an opportunity to calibrate global changes in ocean chemistry and tectonics with large-scale evolutionary changes (e.g. Corsetti and Hagadorn 2000; Corsetti *et al.*, 2003). The stratigraphic succession in Sonora, Mexico, provides a thick, well-preserved target for such work, because it contains an interfingering sequence of macrofossil-bearing siliciclastic strata, microfossiliferous and chemostratigraphically relevant carbonate strata, and potentially datable volcanic horizons of negligible thermochemical alteration, all spanning the Ediacaran–Early Cambrian interval (Stewart *et al.* 1984; Stewart and Poole 2002; Corsetti *et al.*, 2003). Although palaeontologic (Lochman 1948, 1952, 1953; Cooper 1952; McMenamin *et al.* 1983; McMenamin 1984), magnetostratigraphic (Barr and Kirschvink 1983) and chemostratigraphic (McMenamin *et al.* 1992) studies have been conducted in this part of the succession, these strata have not been fully used in a regional or global context because the position of that boundary was not known (but see Stewart *et al.*

1984). Here we report biostratigraphically relevant fossils that constrain the position of the Ediacaran/Cambrian boundary in the Sonoran succession.

GEOLOGIC CONTEXT

Neoproterozoic–Early Palaeozoic strata of Mexico are only exposed in northern Sonora, and units spanning the Ediacaran/Early Cambrian boundary are best exposed in a series of mountains near Caborca, Pitiquito and Sahuaripa (Stewart *et al.* 1984; Stewart and Poole 2002; Corsetti *et al.* in press). Fossils figured herein were collected *in situ* from stratigraphically intact, continuous exposures of the La Ciénega and Puerto Blanco formations (Text-fig. 1). Previously reported fossils from these units, discussed below, were collected from nearby exposures in Cerro Rajón (McMenamin 1984, 1996; Stewart *et al.* 1984). The latter occurrences were field-checked and previously figured specimens examined in person by one of us (JWH).

In the study area the La Ciénega Formation is over 170 m thick and consists of four units (1–4, from bottom to top; Eells 1972; Stewart *et al.* 1984). Unit 1 is dominated by dolostone and sandy dolostone, with minor interbedded quartzite, shale and basalt; several occurrences of tubular microfossils have been reported (McMenamin *et al.* 1983, 1994; McMenamin 1996) and are thought to be internal molds of *Cloudina* (Grant 1990). Unit 2 is predominantly dolostone and sandy dolostone, and Unit



TEXT-FIG. 1. Locality map and generalized stratigraphic column, indicating location of study sites and logged section in Cerro La Ciénega. All samples were collected near FCIP 01/625. Graphic log for outcrops in the Caborca area (after Stewart *et al.* 1984) indicates the lowest stratigraphic position of relevant Cambrian biomineralized and trace fossils, and occurrences of Neoproterozoic body fossils. The highest possible position of the Ediacaran/Early Cambrian boundary is indicated by a dashed line.

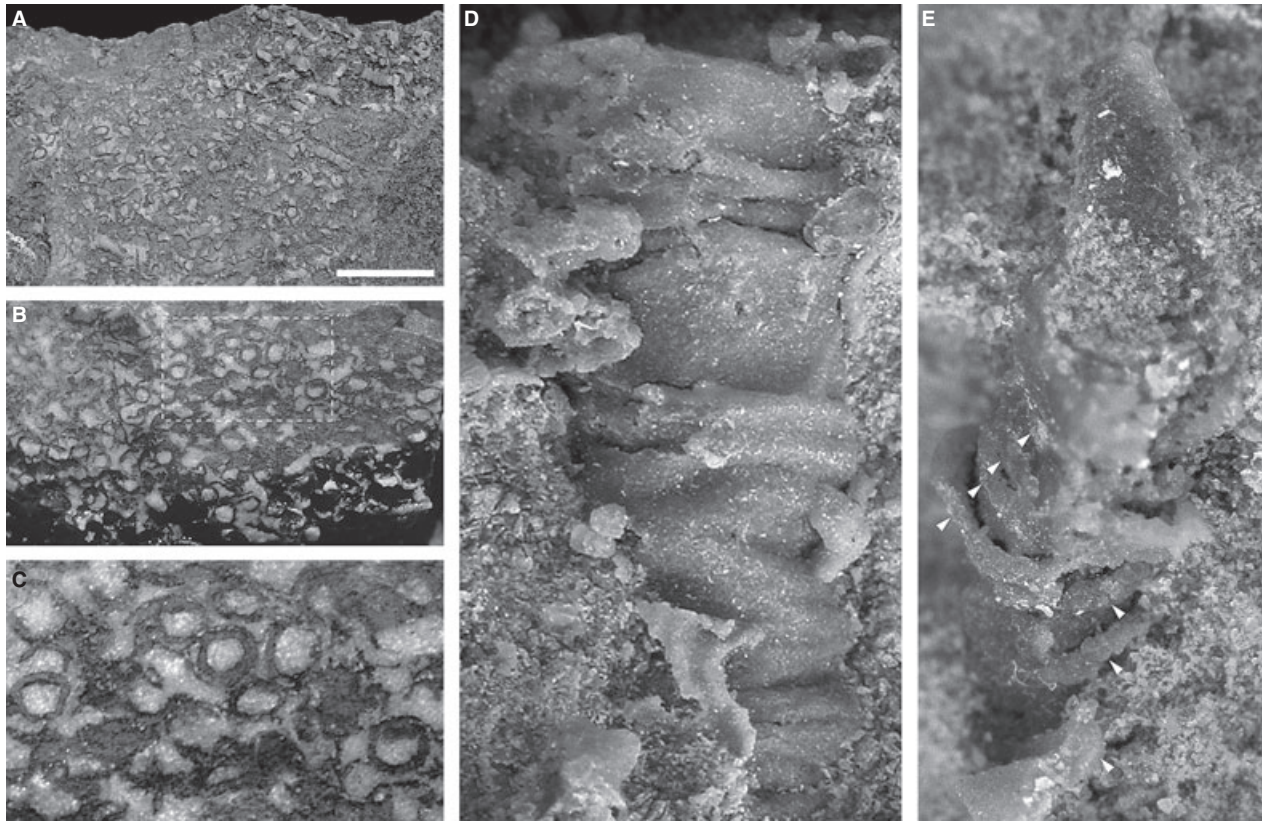
3 contains interfingering siltstone, quartzite, dolostone and basalt. Unit 4 is predominantly dolostone or intraclastic dolostone. Although one possible trace fossil specimen has been figured from Unit 3 (McMenamin 1984, pl. 6, figs 1–2; 2001, 2003) and two possible trace fossil occurrences in Unit 3 are noted in a biostratigraphic range diagram (Stewart *et al.* 1984, fig. 9) and catalogue (McMenamin *et al.* 1994), during the course of our fieldwork we were unable to identify metazoan-produced trace fossils on the soles or surfaces of subtidal–intertidal interbedded shales and sandstones occurring in Units 1 and 3. Although this single specimen has been described as an arthropod trace (either *Monomorphichnus multilineatus* or *Rusophycus multilineatus*; McMenamin 2001, 2003) and could suggest a Cambrian age for these strata, our examination of this specimen suggests that it is an inorganic structure.

The Puerto Blanco Formation is over 700 m thick in the study area and contains four units (Cooper and Arellano 1952; Longoria 1981; Stewart *et al.* 1984). At its type section in the nearby Proveedora Hills, Unit 1 is 285 m thick; in the studied region it typically consists of interfingering volcanoclastic sandstone and conglomerate, basalt, quartzite, siltstone, and silty dolostone. The bed-parallel trace fossil *Palaeophycus* (originally tentatively referred to *Planolites* and ‘*Scolicia*’; McMenamin, 1984, and pers. comm. 2006; Stewart *et al.* 1984) occurs in interbedded mudstones and quartzites of Unit 1. Unit 2

is predominantly siltstone with minor quartzite and limestone. Non-age-diagnostic brachiopods, such as *Obolella* and *Lingulella*, occur 30 m above the base of this unit, and a trilobite cephalon fragment was collected 120 m above the base, suggesting assignment of the middle–upper part of the unit to the *Fallotaspis* Zone (Stewart *et al.* 1984). Although their exact stratigraphic position within the unit was not reported, trace fossils such as *Rusophycus* and *Palaeophycus* are common (McMenamin 1984; Stewart *et al.* 1984), including typical Cambrian forms such as *Plagiogmus* (tentatively reported as *Scolicia* sp. in Stewart *et al.* 1984 and *S. alperta* in McMenamin 1984, pl. 7, figs 5–6; McLroy and Heys 1997). Unit 3 is predominantly archaeocyathan-bearing limestone with a middle siltstone member that bears abundant biomineralized fossils and trace fossils; and Unit 4 is dominantly interbedded limestone, dolostone, quartzite, and siltstone characterized by *Skolithos* piperock, and abundant biomineralized fossil coquinas that bear trilobites of the *Fallotaspis* Zone (Stewart *et al.* 1984).

PALAEONTOLOGY AND BIOSTRATIGRAPHY

In units 1 and 4 of the La Ciénega Formation there are abundant dolomitized and silicified cloudinid-dominated packstones and wackestones. Such coquinas are nearly

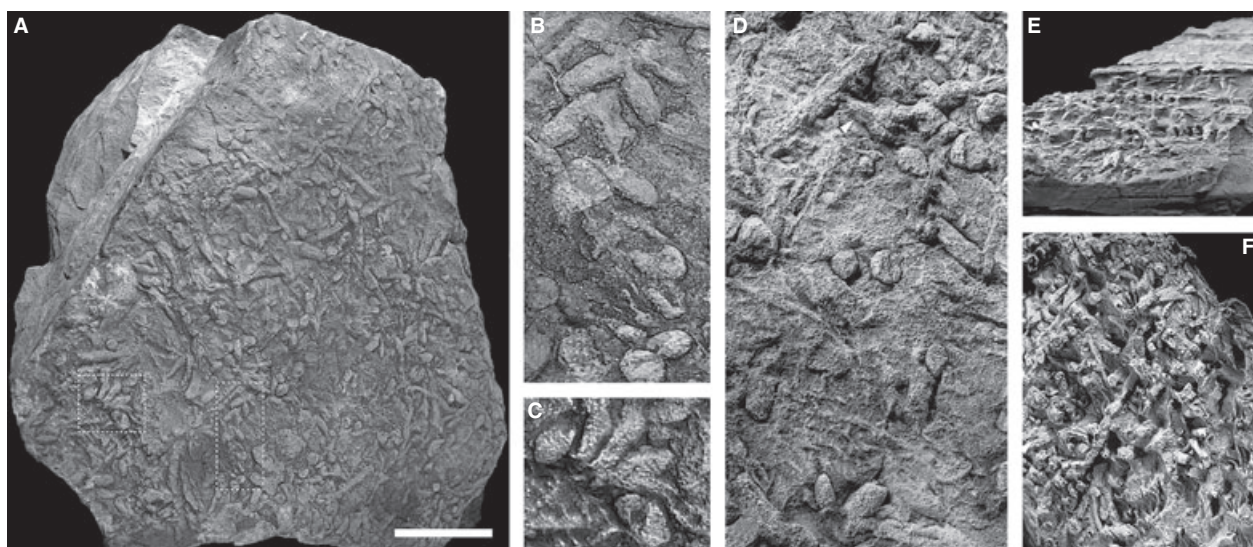


TEXT-FIG. 2. A, field photograph of *Cloudina*-dominated wackestone bed in the La Ciénega Formation in which internal and external silicified molds of tubes are visible. B, polished hand sample from a silicified cloudiniid horizon, illustrating (C, see inset in B, close-up) cross sections through single and eccentrically nested tube walls. D–E, silica-replaced cloudiniids in which the surrounding dolomite has been etched away; note the flared and folded wall margins. E is photographed so that the reader is looking down the long axis of the tube; note the prominent flared segments; the first seven flarings near the base of the tube are arrowed. Scale bar represents 1.36 cm in A, 1.14 cm in B, 0.95 mm in D and 0.60 mm in E.

identical to skeletal packstones reported in the Deep Spring Formation of Nevada (Signor *et al.* 1987) and Reed Dolomite of California (Taylor 1966), and are similar to occurrences in the Nama Group, Namibia (Germs 1972a; Grant 1990), Huqf Group, Oman (Conway Morris *et al.* 1990; Amthor *et al.* 2003), and Miette Group, British Columbia (Hofmann and Mountjoy 2001). The La Ciénega cloudiniids differ in style of preservation because they occur both as steinkerns and external molds in dolomite, and as silica-replaced fossils (Text-fig. 2; Hagadorn and Fedo 2000). Not only are isolated fossils silicified within carbonates, similar to occurrences in the Dengying Formation of South China (Chen *et al.* 1981; Conway Morris *et al.* 1990), but entire packstone horizons also are replaced by bedded chert. Cloudiniids from the La Ciénega Formation have straight to curved tube-like morphology, and consist of eccentrically nested and deeply nested funnels; evidence of flaring wall structure and folded to curved funnel termination is visible in lateral and cross-sectional views (Text-fig. 2). Similar to cloud-

iniids reported from the Dengying Formation of South China (Hua *et al.* 2005), the tubes are open throughout their length rather than consisting of a cone-in-cone morphology (Hagadorn and Fedo 2000). The fossils are 2.4–2.9 mm in diameter, and range from 0.5 to 2.2 cm long, a size range consistent with assignment to the size-based cloudiniid taxon *Cloudina hartmannae* (Germs 1972a). The recrystallized tube walls are 0.2–0.4 mm thick. Although its phylogenetic affinity is uncertain, *Cloudina* exhibits budding and branching behaviour similar to that in serpulid annelids (Hua *et al.* 2005).

Bed-parallel trace fossils occur in Units 1 and 2 of the Puerto Blanco Formation, but it is not until the top of Unit 1 that vertically to obliquely inclined burrows occur in abundance. Burrowing at some horizons is intense, often significantly disrupting bed surfaces and making observation of discrete traces difficult (Text-fig. 3); bedding-plane bioturbation indices range up to 4 and ichnofabric indices up to 2 (Droser and Bottjer 1986; Miller and Smail 1997). The most notable fossil in these



TEXT-FIG. 3. A–D, bed soles characterized by abundant treptichnid bioturbation, including preservational variants of *Treptichnus pedum* and *Planolites*-like axial burrow systems; samples taken from outcrop near the highest siliciclastics in Unit 1 of the Puerto Blanco Formation. B, see inset in A; close-up of alternating teardrop-shaped probes. C, see inset in A, close-up of an echelon set of probes. D, vertical shafts from broken probes and possible treptichnid axial system (arrowed). E, side view of weathered silicified dolostone beds riddled with vertically inclined burrows, in sample taken from an outcrop *c.* 260 m above the base of the Puerto Blanco. F, view of weathered bed sole of a similar horizon, illustrating horizontal to obliquely inclined galleries and networks. Scale bar represents 2 cm in A and D, 4.3 cm in E, and 4.9 cm in F.

bioturbated beds is the three dimensional burrow *Treptichnus pedum*, which consists of a system of probes or segments arranged in an arcuate, straight, or quasi-palmate pattern.

T. pedum burrows are preserved in convex hyporelief in dolomitic sandstone. Some burrows exhibit partial loops characterized by probes orientated on the convex side of the burrow turn. Where burrows are less deeply scoured by deposition of the overlying bed or probes are broken, the obliquely inclined shafts and lower part of the axial system that connects the probes is visible (Text-fig. 3). The probe shapes vary, and include lobate, teardrop-shaped and curved morphologies. Relative to the burrow system, probes are arranged in obliquely aligned rows, as serially arranged imbricated segments, or in an alternating zigzag pattern. The shape of probes may vary as a function of depth of scouring by the overlying bed; probes are typically 7.4 mm long and 5.4 mm wide at their widest point. Unlike material from Namibia (Germs 1972*b*; Geyer and Uchman 1995; Jensen *et al.* 2000), it is not clear if the Sonoran material contains vertically stacked teptichnoid-type probes, and the overlapping nature of traces on studied surfaces inhibits assessment of branching relationships. No reproducible pattern of ornamentation occurs on the Sonoran *Treptichnus* probes. These burrows probably record deposit-feeding behaviour, and although the producer of the burrow is not known, priapulids, arthropods, molluscs or enteropneusts have been suggested as tracemaking candidates (cf. discussions

in Fillion and Pickerill 1990; Geyer and Uchman 1995; Jensen *et al.* 2000). The lowest occurrence of *T. pedum* is *c.* 260 m above the base of Unit 1 of the Puerto Blanco Formation, in the upper portion of the unit. Higher in the formation, *T. pedum* is interstratified with beds bearing horizontally orientated trace fossils such as *Palaeophycus*, *Plagiogmus*, *Planolites* and *Rusophycus*.

At some horizons, vertically to obliquely inclined shafts occur, sometimes in association with treptichnid burrows, and are preserved in full relief in cross section and convex hyporelief on bed soles (Text-fig. 1). Vertical burrow shafts are often silicified, and because they are visible in full relief in three dimensions, vertical burrows can be seen to be intersecting with silicified obliquely inclined to horizontal galleries (Text-fig. 3E–F). Vertical shafts and galleries average 10 mm in diameter and may reach lengths of 8 cm. Until larger outcrop samples can be serially sectioned, and larger bed soles excavated, it is unclear if these unusually preserved traces represent a new ichnotaxon or if they represent unusually preserved *Arenicolites*, which are common in earliest Cambrian sandstones of south-west Laurentia. These fossils warrant mention, however, because they represent vertically inclined burrowing behaviour, a signature characteristic of Phanerozoic bioturbation, and because they complement the treptichnid-based assignment of the upper part of Puerto Blanco Unit 1 to the Early Cambrian.

Barring a significant hiatus at the boundary within Puerto Blanco Unit 1, or discovery of stratigraphically lower burrow probe systems (*sensu* Jensen *et al.* 2000;

Gehling *et al.* 2001), these new fossil occurrences constrain the position of the Ediacaran/Cambrian boundary to lie within the mixed carbonate-siliciclastic-volcanic Unit 1 of the Puerto Blanco Formation.

All figured fossils and several large unfigured slabs are deposited in the Museo de Palaeontología, Facultad de Ciencias (FCMP), Universidad Nacional Autónoma de México (UNAM), under catalogue numbers FCMP 01/373, 01/377, 01/378, 01/379 and 01/625. Figured samples and field photographs come from outcrops at Cerro la Ciénega, near Rancho Fatima, located at 30°07'617"N, 111°59'627"W.

SIGNIFICANCE

The Sonoran succession lies in a central position within the much-debated reconstruction of the supercontinent Rodinia (Stewart *et al.* 2002) and is an important Precambrian/Cambrian boundary section. The section contains both siliciclastic lithofacies needed for macrofossil preservation and carbonate strata needed for chemostratigraphic analysis and microfossil preservation. Integration of these approaches is needed to compare them to coeval successions in the south-western USA in order to test the lithostratigraphy-based Mojave-Sonora Megashear hypothesis (Silver and Anderson 1974; Anderson and Silver 1979), and the proposed relationships of the Puerto Blanco–La Ciénega formations with the Stirling–Wood Canyon and Reed–Deep Spring formations in the US (Stewart *et al.* 1984). The Sonoran section also contains volcanic and volcanoclastic rocks, which are needed to test the validity of characteristic remnant magnetization and to determine pole positions across the Ediacaran/Early Cambrian transition. This interval may include, or be synchronous with, part of an apparent South polar wander path for North America during the Intertial Interchange True Polar Wander (IITPW) event (Kirschvink *et al.* 1997; Evans 1998). Preliminary work suggests that any original magnetite in La Ciénega–Puerto Blanco sedimentary rocks and basalts should retain primary magnetization (Barr and Kirschvink 1983); overlying strata have conodont alteration indexes of 2–3 (Poole *et al.* 1995), and limestones in the succession bear primary sea-water $\delta^{13}\text{C}$ signals (McMenamin *et al.* 1992; F. Corsetti, pers. comm. 2000). These characteristics are important because no magnetostratigraphies exist across the Ediacaran/Cambrian boundary, and sequences in which the boundary is bracketed by volcanic rocks are rare.

Because the location of the Precambrian/Cambrian boundary interval was not previously known within the Sonoran stratigraphic sequence, the thick pretrilobitic portion of this succession has not been effectively taken into account in tectonic, palaeomagnetic, or geochemical

studies, or directly compared with confidence to coeval successions in the south-western US and elsewhere. Discovery of stratigraphically well-constrained, *in situ* occurrences of *T. pedum* and *Cloudina* represents a logical first step toward calibrating the timing of regional volcanism, constraining the location of Laurentia, and comparing regional palaeoecological changes to larger-scale changes in ocean chemistry and evolution occurring across the Ediacaran–Early Cambrian transition.

Acknowledgements. We are grateful to R. Amaya-Martinez, F. Corsetti, J. Kirschvink, J. Lipps, I. de la Mora, I. Nieto, G. Pasquetti, T. Raub and J. Stewart for assistance in the field and helpful conversations, and M. McMenamin for sharing his fossil material, advice and unpublished data. We thank H. Hernandez for photographic equipment, and D. Navarro and L. C. García for technical assistance. This work forms part of the project 'Palaeozoic invertebrates of Mexico' which is financed by the Dirección General de Asuntos del Personal Académico of UNAM, projects IN228803-2 and IN214806-2.

REFERENCES

- AMTHOR, J. E., GROTZINGER, J. P., SCHRÖDER, S., BOWRING, S. A., RAMEZANI, J., MARTIN, M. and MATTER, A. 2003. Extinction of *Cloudina* and *Namacalathus* at the Precambrian–Cambrian boundary in Oman. *Geology*, **31**, 431–434.
- ANDERSON, T. H. and SILVER, L. T. 1979. The role of the Mojave-Sonora megashear in the tectonic evolution of northern Sonora. 59–68. In ANDERSON, T. H. and ROLDAN-QUINTANA, J. (eds). *Geology of northern Sonora*. Geological Society of America, Cordilleran Section, Meeting Guidebook, Field Trip 27. Boulder, CO.
- BARR, T. D. and KIRSCHVINK, J. L. 1983. The paleoposition of North America in the early Paleozoic; new data from the Caborca sequence in Sonora, Mexico. *Eos*, **64**, 689–690.
- CHEN, M., CHEN, Y. and QIAN, Y. 1981. Some tubular fossils from Sinian–Lower Cambrian boundary sequences, Yangtze Gorge. *Bulletin of the of the Tianjin Institute of Geology and Mineral Resources, Chinese Academy of Geological Sciences*, **3**, 117–124.
- CONWAY MORRIS, S., MATTES, B. W. and CHEN, M. 1990. The early skeletal organism *Cloudina*: new occurrences from Oman and possibly China. *American Journal of Science*, **290-A**, 245–260.
- COOPER, G. A. 1952. Brachiopoda. 36–48. In COOPER, G. A., ARELLANO, A. R. V., JOHNSON, J. H., OKULITCH, V. J., SOYANOW, A. and LOCHMAN, C. (eds). *Cambrian stratigraphy and paleontology near Caborca, northwestern Sonora, Mexico*. Smithsonian Miscellaneous Collections, **119**, 258 pp., 33 pls.
- and ARELLANO, A. R. V. 1952. Introduction and stratigraphy. 1–23. In COOPER, G. A., ARELLANO, A. R. V., JOHNSON, J. H., OKULITCH, V. J., STOYANOW, A. and LOCHMAN, C. (eds). *Cambrian stratigraphy and paleont-*

- ology near Caborca, northwest Sonora, Mexico. Smithsonian Miscellaneous Collections, **119**, 258 pp., 33 pls.
- CORSETTI, F. A. and HAGADORN, J. W. 2000. Precambrian–Cambrian transition: Death Valley, United States. *Geology*, **28**, 299–302.
- 2003. The Precambrian–Cambrian transition in the Southern Great Basin, USA. *The Sedimentary Record*, **1**, 4–8.
- and STEWART, J. H. in press. Neoproterozoic diamictite-cap carbonate succession and $\delta^{13}\text{C}$ chemostratigraphy from eastern Sonora, Mexico. *Chemical Geology*.
- DROSER, M. L. and BOTTJER, D. J. 1986. A semiquantitative classification of ichnofabric. *Journal of Sedimentary Petrology*, **56**, 558–559.
- EELLS, J. L. 1972. Geology of the Sierra de la Berruga, northwestern Sonora, Mexico. Unpublished MS Thesis, San Diego State University, San Diego, CA, 77 pp.
- EVANS, D. A. 1998. True polar wander, a supercontinental legacy. *Earth and Planetary Science Letters*, **157**, 1–8.
- FILLION, D. and PICKERILL, R. K. 1990. Ichnology of the Upper Cambrian? to Lower Ordovician Bell Island and Wabana groups of eastern Newfoundland, Canada. *Palaeontographica Canadiana*, **7**, 1–83.
- GEHLING, J., JENSEN, S., DROSER, M. L., MYROW, P. and NARBONNE, G. M. 2001. Burrowing below the basal Cambrian GSSP, Fortune Head, Newfoundland. *Geological Magazine*, **138**, 213–218.
- GERMS, G. J. B. 1972a. New shelly fossils from the Nama Group, South West Africa. *American Journal of Science*, **272**, 752–761.
- 1972b. Trace fossils from the Nama Group, south-west Africa. *Journal of Paleontology*, **46**, 864–870.
- GEYER, G. and UCHMAN, A. 1995. Ichnofossil assemblages from the Nama Group (Neoproterozoic–Lower Cambrian) in Namibia and the Proterozoic–Cambrian boundary problem revisited. 175–202. In GEYER, G. and LANDING, E. (eds). *Morocco 95, the Lower–Middle Cambrian standard of western Gondwana*. Beringeria, Special Issue, **2**, 269 pp.
- GRANT, S. W. F. 1990. Shell structure and distribution of *Cloudina*, a potential index fossil for the terminal Proterozoic. *American Journal of Science*, **290**, 261–294.
- HAGADORN, J. W. and FEDO, C. M. 2000. Terminal Neoproterozoic cloudiniids from southwestern North America. *Geological Society of America, Abstracts with Programs*, **32**, 300.
- HOFMANN, H. J. and MOUNTJOY, E. 2001. *Namacalathus-Cloudina* assemblage in Neoproterozoic Miette Group (Byng Formation), British Columbia: Canada's oldest shelly fossils. *Geology*, **29**, 1091–1094.
- HUA, H., CHEN, Z., YUAN, X., ZHANG, L. and XIAO, S. 2005. Skeletogenesis and asexual reproduction in the earliest biomineralizing animal *Cloudina*. *Geology*, **33**, 277–280.
- JENSEN, S., SAYLOR, B. Z., GEHLING, J. G. and GERMS, G. J. B. 2000. Complex trace fossils from the terminal Proterozoic of Namibia. *Geology*, **28**, 143–146.
- KIRSCHVINK, J. L., RIPPERDAN, R. L. and EVANS, D. A. 1997. Evidence for a large-scale reorganization of Early Cambrian continental masses by Intertial Interchange True Polar Wander. *Science*, **277**, 541–545.
- KNOLL, A. H., WALTER, M. R., NARBONNE, G. M. and CHRISTIE-BLICK, N. 2006. The Ediacaran period: a new addition to the geologic time scale. *Lethaia*, **39**, 13–30.
- LANDING, E. 1994. Precambrian–Cambrian boundary global stratotype ratified and a new perspective of Cambrian time. *Geology*, **22**, 179–182.
- LOCHMAN, C. 1948. New Cambrian trilobite genera from northwest Sonora, Mexico. *Journal of Paleontology*, **22**, 451–464.
- 1952. Trilobites. 60–161. In COOPER, G. A., ARELLANO, A. R. V., JOHNSON, J. H., OKULITCH, V. J., SOYANOW, A. and LOCHMAN, C. (eds). *Cambrian stratigraphy and paleontology near Caborca, northwestern Sonora, Mexico*. Smithsonian Miscellaneous Collections, **119**, 258 pp., 33 pls.
- 1953. Corrections to trilobites in Cambrian stratigraphy and paleontology near Caborca, northwestern Sonora, Mexico. *Journal of Paleontology*, **27**, 486–488.
- LONGORIA, J. F. 1981. Regional geology of northwest Sonora. *Geological Society of America, Cordilleran Section, Field Trip Guidebook*. Hermosillo, Mexico, 174 pp.
- McILROY, D. and HEYS, G. R. 1997. Palaeobiological significance of *Plagiogmus arcuatus* from the Lower Cambrian of central Australia. *Alcheringa*, **21**, 161–178.
- McMENAMIN, M. A. S. 1984. Paleontology and stratigraphy of Lower Cambrian and Upper Proterozoic sediments, Caborca region, northwestern Sonora, Mexico. Unpublished PhD thesis, University of California, Santa Barbara, CA, 218 pp.
- 1996. Ediacaran biota from Sonora, Mexico. *Proceedings of the National Academy of Sciences, USA*, **93**, 4990–4993.
- (ed.) 2001. *Paleontology Sonora: Lipalian and Cambrian*. Meanma Press, South Hadley, MA, 113 pp.
- 2003. Origin and early evolution of predators: the ecotone model and early evidence for macropredation. 379–400. In KELLEY, P., KOWALEWSKI, M. and HANSEN, T. (eds). *Predator–prey interactions in the fossil record*. Kluwer Academic/Plenum, New York, NY, 464 pp.
- AWRAMIK, S. M. and STEWART, J. H. 1983. Precambrian–Cambrian transition problem in western North America: Part II. Early Cambrian skeletonized fauna and associated fossils from Sonora, Mexico. *Geology*, **11**, 227–230.
- ROWLAND, S. M., CORSETTI, F., DIX, A. M. and NANCE, R. P. 1992. Vendian body fossils(?) and isotope stratigraphy from the Caborca area, Sonora, Mexico. *Paleontological Society, Special Publication*, **6**, 206 pp.
- PITTENGER, S. L., CARSON, M. R. and LARRA-BEE, E. M. 1994. Upper Precambrian–Cambrian faunal sequence, Sonora, Mexico, and Lower Cambrian fossils from New Jersey, United States. *New York State Museum Bulletin*, **481**, 213–227.
- MILLER, M. F. and SMAIL, S. E. 1997. A semiquantitative field method for evaluating bioturbation on bedding planes. *Palaios*, **12**, 391–396.
- NARBONNE, G. M., MYROW, P. M., LANDING, E. and ANDERSON, M. M. 1987. A candidate stratotype for the Precambrian–Cambrian boundary, Fortune Head, Burin Peninsula, southeastern Newfoundland. *Canadian Journal of Earth Sciences*, **24**, 1277–1293.

- POOLE, F. G., STEWART, J. H., REPETSKI, J. E., HARRIS, A. G., ROSS, R. J., KETNER, K. B., AMAYA-MARTINEZ, R. and MORALES-RAMIREZ, J. M. 1995. Ordovician carbonate-shelf rocks of Sonora, Mexico. 267–276. In COOPER, J. D., DROSER, M. L. and FINNEY, S. C. (eds). *Ordovician Odyssey: Short papers for the Seventh International Symposium on the Ordovician System: Pacific Section SEPM*. Fullerton, CA, 498 pp.
- SIGNOR, P. W., MOUNT, J. F. and ONKEN, B. R. 1987. A pre-trilobite shelly fauna from the White-Inyo region of eastern California and western Nevada. *Journal of Paleontology*, **61**, 425–438.
- SILVER, L. T. and ANDERSON, T. H. 1974. Possible left-lateral early to middle Mesozoic disruption of the southwestern North American craton margin. *Geological Society of America, Cordilleran Section, 78th Annual Meeting, Abstracts with Programs*, **6**, 955–956.
- STEWART, J. H. and POOLE, F. G. 2002. Inventory of Neoproterozoic and Paleozoic strata in Sonora, Mexico. *United States Geological Survey, Open-File Report*, **02-0097**, 50 pp.
- McMENAMIN, M. A. and MORALES-RAMIREZ, J. M. 1984. Upper Proterozoic and Cambrian rocks in the Caborca Region, Sonora, Mexico: physical stratigraphy, biostratigraphy, paleocurrent studies, and regional relations. *United States Geological Survey, Professional Paper*, **1309**, 36 pp.
- AMAYA-MARTINEZ, R. and PALMER, A. R. 2002. Neoproterozoic and Cambrian strata of Sonora, Mexico; Rodinian supercontinent to Laurentian Cordilleran margin. *Geological Society of America, Special Paper*, **365**, 5–48.
- TAYLOR, M. E. 1966. Precambrian mollusk-like fossils from Inyo County, California. *Science*, **153**, 198–201.