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Response to Comment on "Bilaterian Burrows and Grazing Behavior at >585 Million Years Ago"

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Gaucher *et al*. suggest that their field observations and petrographic analysis of one thin section do not support an Ediacaran age for the trace fossils–bearing strata of the Tacuarí Formation. We have strengthened our conclusion of an Ediacaran age for the Tacuarí Formation based on reassessment of new and previously presented field and petrographic evidence.

Gaucher *et al*. (*1*) call into question the stratigraphic relationship between the granite and the trace fossil–bearing rhythmites described by Pecoits *et al*. (*2*). Gaucher *et al*. (*1*) suggest that the granite is not intrusive but rather the basement of the sedimentary succession. They base their conclusions on the following arguments: (i) the illustrations provided by Pecoits *et al*. (*2*) do not demonstrate an intrusive relationship through the sedimentary strata; (ii) the rhythmites do not show recrystallization or metamorphism as a consequence of the intrusion; (iii) the cleavage described is localized and brittle in nature and was not produced by the Sierra Ballena Shear Zone [active until 551 to 537 million years ago (Ma)], and hence, the Tacuarí Formation must postdate shearing; and (iv) outcrops corresponding to the Carboniferous/Permian San Gregorio Formation show identical trace fossils indistinguishable from those of the Tacuarí Formation. We address each of these points below.

First, the geological map presented in Pecoits *et al*. (*2*) (figure S1), at a scale of 1:20,000, is criticized for not being illustrative enough of the intrusive relationship between the granite and the Tacuarí strata. Oddly, however, Gaucher *et al*. (*1*) provide a map at scale 1:500,000 to illustrate their point that what separates the Tacuarí Formation from the granite is a fault contact, while ignoring our figure S8 (*2*), which clearly shows an intrusive relationship. Indeed, in this outcrop, the rhythmites have actually been intruded in two different directions (Fig. 1). The contact near fossil site C similarly shows the cross-cutting relationship [figure S3 in *2*)]. In this case, Gaucher *et al*. (*1*) take no notice of the outcrop-scale relationships and instead prefer to show five photographs from just one hand sample that they assigned to fossil site C to discredit the intrusive nature of the

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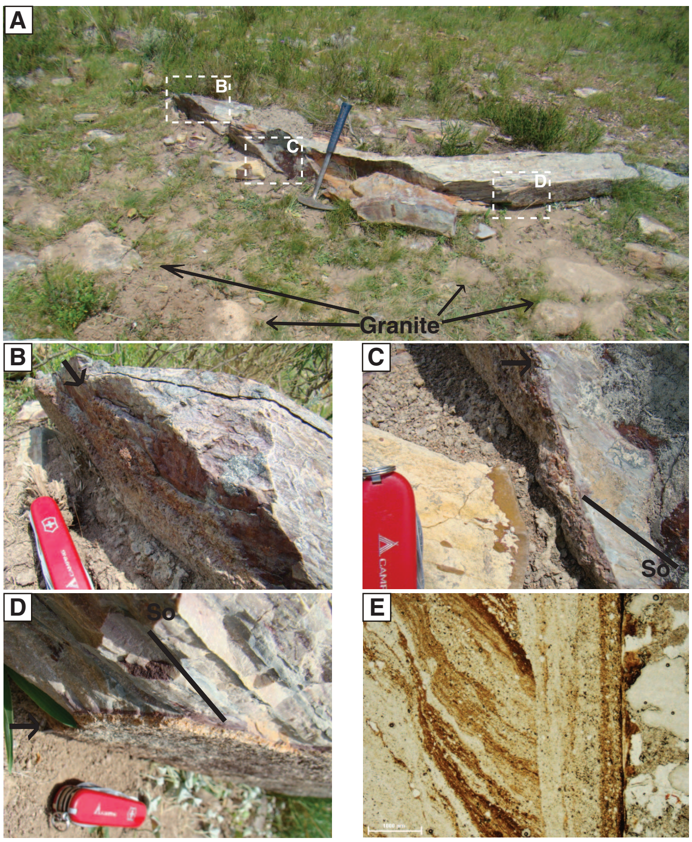

Fig. 1. Contact relationship between the intrusive granite and fossil-bearing strata (rhythmites) of the Tacuarí Formation. **(A)** General view of the outcrop where the rhythmites have been intruded in two different and almost perpendicular directions. **(B to D)** show detailed views of the contacts. Notice in all photos the sacaroid texture due to recrystallization and silicification, and the cross-cutting relationship with the rhythmites. So, sedimentary layers. **(E)** Microphotograph of the contact illustrating the development of chilled margins. Compare with figure S8, E and F in (*2*). **(F)** Well-exposed outcrop, not discussed in the comment (*1*), showing clear intrusive features of the granite into the Tacuarí rhythmites. Notice the irregular and sometimes knife-sharp contact oriented perpendicular to sedimentary strata and the deformation (concave-upwards) produced by the intrusion. The contact between the granite and the Tacuarí Formation is traced in red [see figure S5 in (*2*) and www.eurekalert.org/multimedia/pub/45105.php for more details on this outcrop]. As in (A), feldspars in the granite have been partially decomposed to kaolinite due to recent weathering. The same process is seen in the Tacuarí diamictites where clasts of granite have been deeply weathered when exposed to surface conditions. This is one of the many examples we have previously illustrated (*2*) where our conclusions support that the igneous intrusion (our 585-million-year-old granite) is younger than the sedimentary rock (the 600-million-year-old trace-bearing strata). None of our ages have been questioned in Gaucher *et al*. (*1*).

Table 1. Comparative distribution of micro- and macrofossils between Carboniferous-Permian units and Ediacaran successions from Uruguay and other correlative deposits from Brazil, Argentina, South Africa, and Namibia. None of the numerous taxa occurring in the Paleozoic units (including 72 widespread species of pollen and spores, cephalopods, porifera, radiolarians, and brachiopods) have been found in the Tacuarí Formation (*4*–*11*). Conversely, the latter contains very similar organic-walled microfossils as those from other Ediacaran units of Uruguay, Argentina, Brazil, South African, and Namibia of undisputed Ediacaran age (*12*–*15*). Furthermore, the lithology, mineralogy, and geochemistry of the San Gregorio and Tacuarí formations are quite dissimilar. This is unsurprising because a sufficient body of evidence currently exists to support that these are two different units (*4*, *6*–*9*). First, the Tacuarí Formation is highly deformed (with faulting, tilting, folding, and shearing), whereas the younger successions are undisturbed (i.e., flat lying), as are all Carboniferous-Permian units that belong to the Chaco-Paraná Basin in South America. Second, and as we previously demonstrated (*2*), the provenance between the Carboniferous/Permian units and the Tacuarí Formation is completely different, as exemplified by the zircon populations and ages in both units. The Phanerozoic sandstone sample contains a large proportion of zircon detritus younger than 600 million years old, with the youngest U-Pb zircon age node occurring at 533.1 ± 4.6 Ma, whereas the main zircon age population in the Tacuarí sample occurs at 805.1 ± 6.1 Ma, with the youngest population at 600.1 ± 8.5 Ma.

		Carboniferous Permian		Lower Ediacaran		Upper Ediacaran				
		Tres Islas Fm (Uruguay)	San Gregorio Fm (Uruguay)	Tacuarí Fm (Uruguay)	Maldonado Gp (Uruguay)	A° del Soldado Gp (Uruguay)	Corumbá Gp (*Brazil*)	Sierras Bayas-C° Negro (*Argentina*)	Congo Caves Gp (*South Africa*)	Port Nolloth and Nama Gps (*Namibia*)
	Cloudina					■	■	■	■	■
Organic-walled microfossils	*Leiosphaeridia sp.*		■							
	L. tenuissima			■	■	■	■	■	■	■
	L. minutissima			■	■	■		■	■	■
	Lophosphaeridium spp.				■	■				
	Myxococcoides distola			■		■				
	M. siderophila			■		■				■
	M. spp.					■	■		■	
	Soldadophycus bossii			■	■	■	■		■	■
	S. major			■	■	■			■	■
	Bavlinella faveolata					■	■		■	■
	Coniunct. conglobatum					■			■	■
	Synsphaeridium sp.					■		■		■
	Lophosph. montañae					■				
	Glossopteris flora	■								
	Fishes		■							
	Cephalopods		■							
	Porifers		■							
	Radiolarians		■							
	Brachiopods		■							
Pollen and Spores	*Plicatipollenites malabarensis*	■	■							
	Limitisporitis rectus	■	■							
	Protohaploxypinus limpidus	■	■							
	Cannanoropollis densus	■	■							
	C. janakii	■	■							
	C. mehtae	■	■							
	Caheniasaccites densus	■	■							
	C. ovatus	■	■							
	Potoniesporites brasiliensis	■	■							
	P. magnus	■	■							
	P. novicus	■	■							
	Leiotriletes directus	■	■							
	L. virkii	■	■							
	L. corius		■							
	Retusotriletes simplex		■							
	Grossuporites microgranulatus		■							
	Granulatisporites austramericanus	■	■							
	Anapiculatisporites tereteangulus	■	■							

Table cont.

		Tres Islas Fm	San Gregorio Fm
Pollen and Spores	*Brevitriletes cornutus*	■	■
	B. levis	■	■
	B. leptoacaina		■
	B. parmatus		■
	Converrucosisporites confluens	■	■
	C. micronodosus	■	■
	Cristatisporites chacoparanensis		■
	C. crassilabratus		■
	C. inconstans	■	■
	C. menendezii		■
	C. microvacuolatus	■	■
	C. morugavensis	■	■
	Horriditriletes ramosus		■
	H. uruguaiensis	■	■
	Convolutispora ordonezii		■
	Lunbladispora areolata		■
	L. irregularis		■
	Murospora bicingulata	■	■
	M. torifera	■	■
	Vallatisporites russoi	■	■
	V. arcuatus	■	■
	V. vallatus		■
	Brazilea plurigenus		■
	B. scissa	■	■
	Tetraporina punctata	■	■
	Deusilites tenuistriatus	■	■
	Pilasporites sp. B		■
	Costatascyclus crenatus		■
	Latusipollenites quadrisaccatus		■
	Stellapollenites talchirensis		■
	Mabuitasaccites crucistriatus		■
	Stiromonosaccites cicatricosus		■
	Colpisaccites granulosus		■
	Limitisporites scitulus		■
	Platysaccus papilionis		■
	Scheuringipollenites circularis		■
	S. maximus		■
	S. medius	■	■
	S. ovatus	■	■
	Hamiapollenites fusiformis	■	■
	Lueckisporites densicorpus		■
	Lunatisporites variesectus	■	■
	Protohaploxpinus bharadwajii	■	■
	P. goraiensis		■
	P. rugatus	■	■
	Straitoabieites multistriatus		■
	Vittatina costabilis	■	■
	V. subsaccata	■	■
	V. wodehousei	■	■
	Weylandites Lucifer	■	■
	W. magmus		■
	Marsupipollenites striatus		■
	Pakhapites fusus	■	■
	P. ovatus		■
	Botryococcus	■	■

granite [figure 1, B to F, in (*1*)]. We do not want to speculate on the origin of this sample, but we see no evidence that it comes from fossil site C; it is not the ferruginized basal sandstone we previously documented [figure S3C in (*2*)]. Furthermore, fossil site C is characterized by a discordant contact between the Tacuarí strata and the intrusive granite [figure S3, B to D, in (*2*)] and not what is shown by Gaucher *et al*. (*1*) in their figure 1, B to F.

Second, Gaucher *et al*. (*1*) argue that their single petrographic thin section of the above-mentioned sample does not show clay recrystallization or neoformation of metamorphic minerals. Unfortunately, they did not cite any published x-ray diffraction analyses, clay-mineral crystallinity indices, or more extensive documentation to support their claims. Furthermore, the authors cast doubt upon the existence and origin of the xenoliths [as recorded in (*2*)] by simply stating "no evidence was presented to support this." This is not true, because not only have we extensively described and illustrated the presence of xenoliths [figure S9 in (*2*)], but we provided further evidence supporting an intrusive relationship between the granite and the Tacuarí Formation, namely: (i) pushed-up and folded country rocks; (ii) granite chilled margins at the contact; (iii) baked contacts in adjacent sedimentary rocks that show bleaching, silicification, hematitization, and occasional quartz-bearing cavities; (iv) partial assimilation of country rocks; (v) discordant contacts that truncate sedimentary layering and cleavage; and (vi) satellite dykes that are rooted in the main pluton and penetrate the host rock. All of these features were illustrated in figures S3 to S9 (*2*), yet they are disregarded by Gaucher *et al*. (*1*). They then go on to state that the interpretation of the granite as dykes is not supported by their observations (*1*). Yet, we repeatedly referred to the intrusive granite as a "granite body" [supplementary material (SM) p. 3 in (*2*)], "batholith" (SM p. 4), "dome-shaped intrusion" (SM p. 5), "diapiric" intrusion (SM p. 8), and "pluton" (SM pp. 4, 8, and 13). Even in the geological map [figure S1 in (*2*) and its caption], it is patently clear that the form of granite emplacement is not solely represented by cross-cutting dykes.

Third, the Sierra Ballena Shear Zone (SBSZ) has been active since ~800 Ma, when high temperature deformation dominated (*3*). Subsequently, in the late Neoproterozoic and early Cambrian, the conditions during deformation were substantially different. At that time, the deformation observed in the shear zone took place under regional low-grade conditions, as indicated by metasediments of associated strike-slip basins (including the Tacuarí Formation) and by microstructures typical of these conditions (*3*). The suggestion by Gaucher *et al*. (*1*) that we did not describe these features in Pecoits *et al*. (*2*) is false; we acknowledged the localized and brittle nature of the cleavage in the Tacuarí Formation [SM p. 7 and 8 in (*2*)]. It should also be made clear that one very important aspect not discussed in Gaucher *et al*.

(*1*) is that the granite, dated at 585 Ma, is virtually undisturbed by the shear zone [figure S4 in (*2*)]. This is because the shear zone in this area predates the intrusion of the granite; therefore, the shearing only affected the older Tacuarí Formation along narrow shear corridors as we have previously demonstrated (*2*). This observation is further supported by the presence of foliated xenoliths belonging to the Tacuarí Formation "floating" in the nonfoliated granite [figure S9 in (*2*)]. Therefore, the last reactivation of the SBSZ, particularly in this area, is constrained between ~600 Ma (the maximum depositional age for the Tacuarí Formation) and ~585 Ma (the age of the intrusive granite).

Fourth, Gaucher *et al*. (*1*) mention that pollen, spores, and similar trace fossils were recovered from Permian/Carboniferous dropstone-bearing shales of the San Gregorio Formation, which are indistinguishable from those of the Tacuarí Formation. None of the fossils reported for the San Gregorio Formation have ever been reported to exist within the Tacuarí Formation (*4*–*6*). This is not a trivial aspect because the San Gregorio Formation is characterized by its diverse and ubiquitous fossiliferous content (*6*–*11*), whereas the Tacuarí Formation is not (Table 1). Avoiding this incongruence, Gaucher *et al*. (*1*) suggest that freshwater and glacial conditions were responsible for the lack of fossils in the Tacuarí Formation. Surprisingly, the Tacuarí Formation does contain fossils—the same fossils (acritarchs) that Gaucher and collaborators have previously described in other Neoproterozoic successions from Uruguay, Argentina, Brazil, South Africa, and Namibia (*12*–*15*). With regards to the trace fossils, we did not report fossils from the Tacuarí Formation like those depicted by Gaucher *et al*. (*1*) (*Gordia* and *Cruziana* isp., both of which occur over a large breadth of geological time). However, because both the San Gregorio and the Tacuarí trace fossils represent bedding-plane grazing or motility tracks, there is a morphological similarity. That similarity should not be used to demonstrate stratigraphic equivalence.

In summary, we refute the comments by Gaucher *et al*. (*1*). The authors do not provide a detailed geological map of where their samples were collected nor do they offer any demonstrable proof (i.e., radiometric ages or geological field relationships) to support that their fossil-bearing strata are actually Permian/Carboniferous in age. Furthermore, the Neoproterozoic-aged Tacuarí Formation is compositionally, structurally, and paleontologically different from the Permian-aged San Gregorio Formation.

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